Back

By Richard Johnson

Designing a Midrange Horn

This cone speaker covers 200Hz and higher frequencies, up to three octaves of the audio band.

Before we get to the project part, I'll describe some design characteristics of midrange horns. Across the mid-frequency band, midrange frequencies have a ray characteristic and act less like waves. As rays, the frequencies tend to not bend around corner reflectors. Thus, the horn path is typically straight and not folded when it comes to midrange.

The only exception is using a circular duct with circular corners, as musical instruments—trumpets, trombones, and the like—are built. The off-axis frequency will vary depending on the horn expansion type. High-frequency beaming is another term used to describe the off-axis variance in frequency.

There is less of a need to use mutual coupling[1]—for example, a corner or double cabinets—to extend the lower midrange frequencies as with bass horns. The practical midrange horn mouth size is within reach of the builder compared to low-frequency sizes. I will show that a quarter wavelength horn is sufficient for midrange bandwidth. Quarter wavelength corresponds to the corner position or a 1/8 space horn expansion. Reactance annulling[2] extends the frequency response at or near the cutoff (in this case 200Hz) allowing a flat response right down to 200Hz. The same effect used to extend bass horns response is applicable to midrange horns.

A circular horn mouth provides identical off-axis response coverage in the horizontal and vertical plane. This is not always desired. An excellent compromise is to make the expansion in the horizontal plane tractrix curved and the expansion in the vertical plane radial (straight angled) expansion. This will minimize beaming in the horizontal plane and help remove or reduce floor reflections due to the beaming in the vertical plane.

THE INITIAL PROJECT

I started this project by building a midrange/midbass horn for a friend who wanted to use a 12″ driver—the JBL 2020H—to cover the midrange/midbass frequency band. Throughout this article, I use my custom horn calculator software tool, Hyperhorn, for horn design.

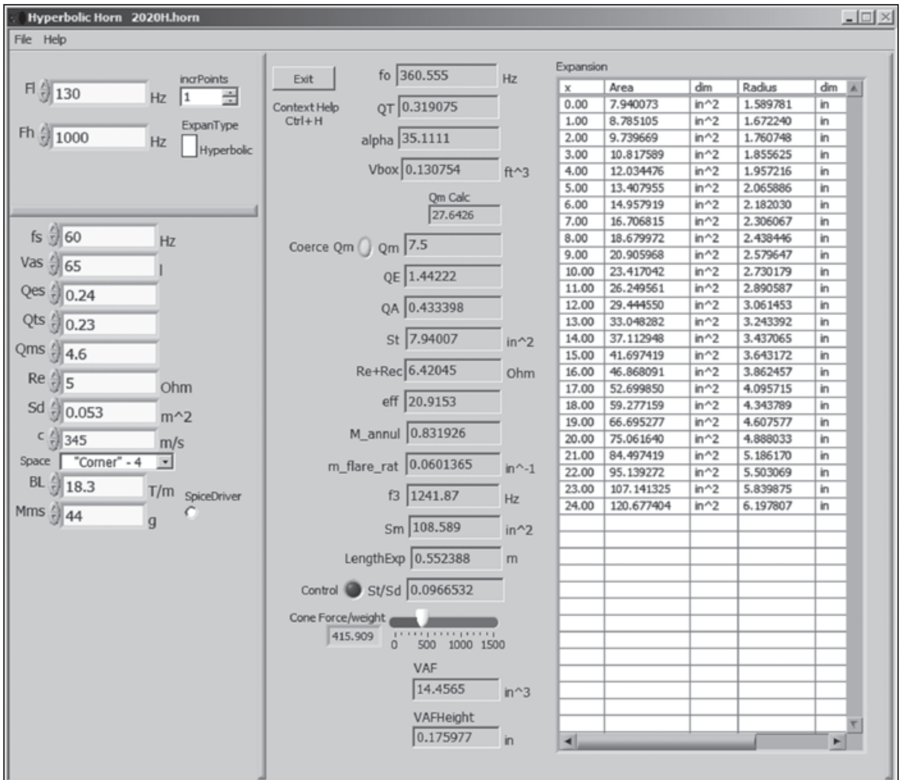

FIGURE 1: Hyperbolic horn design for the JBL 2020H driver. The chosen low and high cutoff frequency is 130Hz and 1kHz. The horn length requires a length of 60cm (24″).

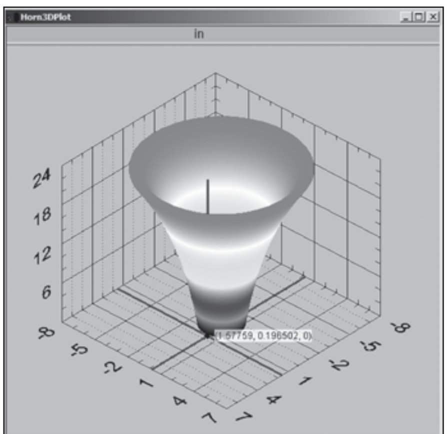

FIGURE 2: Three-dimensional plot of horn design in *Fig. 1*.

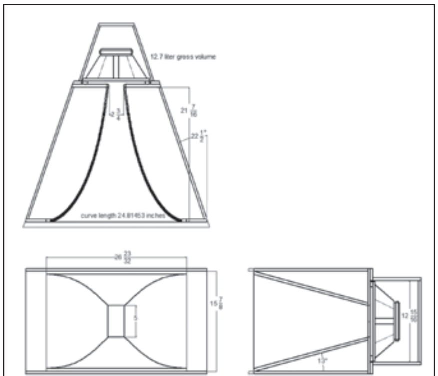

FIGURE 3: CAD drawing of horn designed in *Fig. 1*. A wood brace (not shown) near the mouth is glued on the internal side to stiffen the tractrix curve.

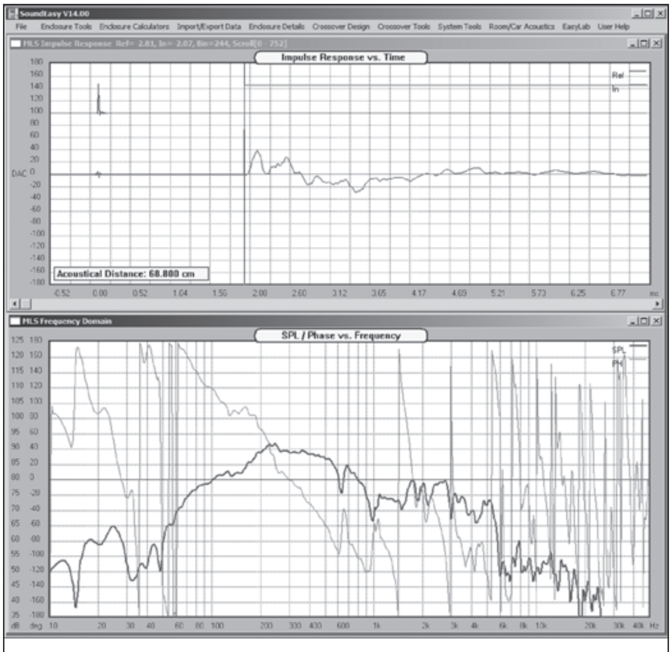

FIGURE 4: **SoundEasy measurement data for the horn shown in *Fig. 3* CAD drawing.**

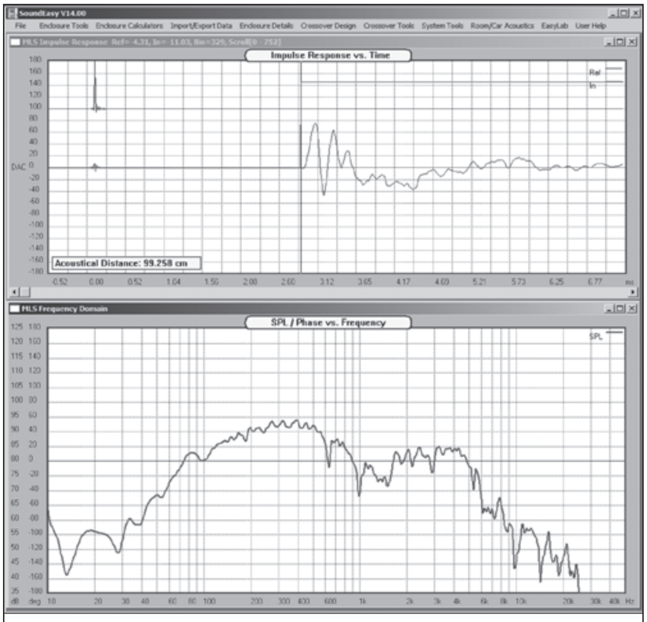

FIGURE 5: **Frequency response for a double stack JBL 2020H tractrix horn of *Fig. 3*. The frequencies below 200Hz are raised where there was a dip shown for a single cabinet.**

Enter the Thiele/Small data of the woofer and the horn calculator does the number crunching (**Figs. 1** and **2**). This driver appeared well suited because it was designed specifically for midbass/midrange. **Figure 3** shows the dimensions of the horn via a CAD drawing, while **Fig. 4** depicts the frequency response of this horn cabinet in free air, i.e., mounted on a speaker stand.

At this point let's access the JBL 2020H tractrix horn design and note where it does not meet the design requirement. Rolloff begins at or near 700Hz and there are two nulls positioned in the band of interest. One null occurs just above 600Hz, and the second is at about 1kHz. Studying my CAD drawing, I was scratching my head over the reason for the nulls. In the CAD drawing (**Fig. 3**), I could not find a length corresponding to a half-wavelength at the null frequencies shown in **Fig. 4**.

Because this horn covered midbass frequencies, my plan was to use double stack cabinets to cover below 200Hz, and the midbass will mutual couple once the horns are stacked. **Figure 5** shows the double stack horn frequency response. Considering the bass begins somewhere below 200Hz, the horns are part midbass and part midrange. Two disappointments turned out to be that the upper rolloff starts too low, not meeting the 1kHz requirement, and the nulls occurring at 600Hz and 1kHz, which I mentioned.

The problem, clearly, is the horn design does not couple the frequencies above 700Hz to allow horn loading. Above 700Hz the response behaves like a direct radiator but has increased efficiency due to directivity gain. Notice in my design calculator (**Fig. 1**) the throat (St) requirement is 7.94 in^2 (51.2cm^2). The ratio of throat area to the woofer diaphragm, St/Sd, is 0.0966, which is too small because it's impractical to construct and position over the woofer's curved cone surface. My compromise shown in the CAD drawing

(**Fig. 3**) is a throat size of 5 × 2.75, i.e., 13.75 in^2 (88.71cm^2), a St/Sd ratio of 0.1673. I'll explain later how I arrived at this value.

The throat size has a relation to the horn's bandwidth. Wide-frequency or high-frequency bands require a small throat size. Manufacturers of metal or hard plastic midrange horns sometimes use a phase plug to couple high frequencies into the horn's throat entry. The phase plug mounts a few mm from the driver cone and is meant to allow, ideally, an identical path length to the throat at all points from the cone. Inadvertently, my design includes a volume of air just in front of the cone, essentially a 700Hz low-pass filter.

The front volume between the woofer cone and throat is determined by two issues. The cone surface is not flat but curved, and I include a 15/32″ lip; i.e., the thickness of the wood material, around the woofer frame where it mounts to accommodate the cone's excursion of 5mm. Study **Fig. 3** where the woofer bolts to the horn to visualize the issue regarding the front volume.

As a side note to the speaker system, the double stacked horns are crossed over electronically to mate with a 2″ commercial compression horn with a sensitivity rating of 110dB for 1W input. The double stack 12″ horn SPL required attenuation to match the 110dB, 1W sensitivity!

I should mention that the horn expansion in the CAD design (**Fig. 3**) is tractrix[3] and my calculator refers to hyperbolic. At a mouth size of 1/8 wavelength the tractrix expansion reaches the 1/8 space mouth size at a linear distance of 6″ (**Fig. 6**). Due to the tractrix equation, the horn mouth is calculated at x = 0. Therefore, **Fig. 6** plot shows the horn flipped on its Z-axis compared to the **Fig. 2** plot mentioned above.

Figure 7 shows the tractrix horn taken out to full size. Notice the linear length is 34″ and the corresponding tractrix curve length is not shown but hidden (horizontal scroll) inside the expansion table. I arbitrarily chose a throat size of 13.75 in^2 (88.7cm^2) and recalculated the tractrix curve to get a linear distance of 21.4375″ at a curve length meeting 24″. Essentially, I take the quarter wavelength hyperbolic linear length (24″) and draw the tractrix curve until its curve length reaches 24. My chosen throat area is close enough to 7.93 in^2 (St) throat calculation.

To draw the tractrix points including all my drawings, I use DeltaCAD drawing software to plot the tractrix lines (**Fig. 3**). For a small fee, DeltaCAD is available from their website, www.deltacad.com. DeltaCAD has a BASIC language script to automate some of its drawing parameters. I set the script to draw the tractrix radius points using circles the thickness of the wood material. When I build the horn, the tractrix curve is printed out on paper at the real size for tracing.

The tractrix curve length taken out to the hyperbolic length and using double stack cabinets for midbass appears to load the 12″ driver appropriately from the impedance plot of two stacked horns (**Fig. 8**). The impedance phase huddles around the 0° line above roughly 130Hz out to 1kHz.

THE MIDRANGE HORN PROJECT

I went back to my horn calculator and SoundEasy (Bodzio Software) to redesign a midrange horn to meet the 200Hz to 1kHz frequency band. The first step is to find a driver that has a lower cone mass than the JBL 2020H. The driver should also match or exceed the magnetic field strength of the JBL 2020H.

I compared two candidates against the 2020H using the magnetic field strength (BL) in units of T/m and the mechanical mass of the diaphragm (Mms) in gram units. Divide these two numbers to get the force/weight unit. A comparison of the three drivers is shown in **Table 1**.

I chose the BC 8PE21 for the project and thought that finally a manufacturer had produced a driver specifically for midrange horns. The BC magnetic field strength falls between the JBL 12″ and 10″ driver. Its cone mass, though, is 18 grams, which gives it a force/weight ratio of 922! That value is almost twice the values of the JBL drivers. The BC 8PE21 driver also has a high power rating of 200W RMS, which is similar to the JBL's ratings.

For this 8″ horn design, I flush-mount-

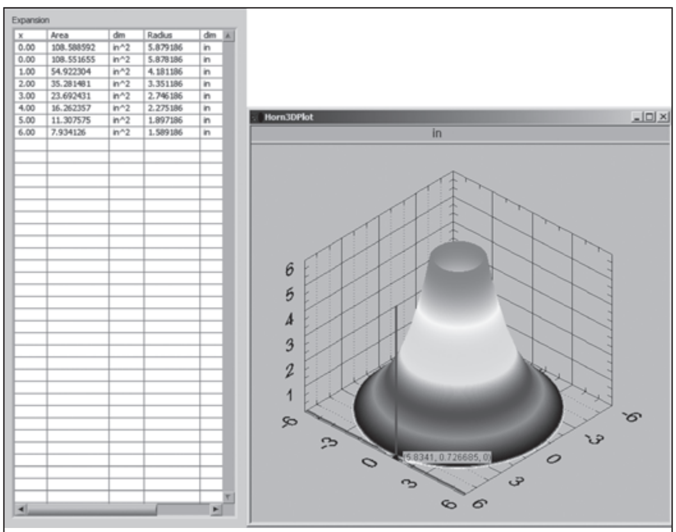

FIGURE 6: The 1/8 space tractrix expansion for an equivalent mouth size of the hyperbolic expansion. The horn length is only 6″ and does not meet the 24″ for the hyperbolic design.

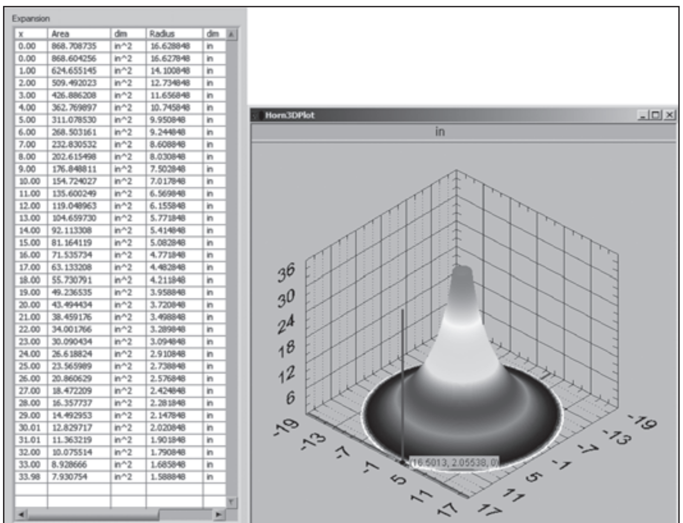

FIGURE 7: The full space tractrix horn expansion for a mouth size that is equivalent or exceeds the hyperbolic horn length. The tractrix length is 34″, so I need only 24″ to meet the hyperbolic length.

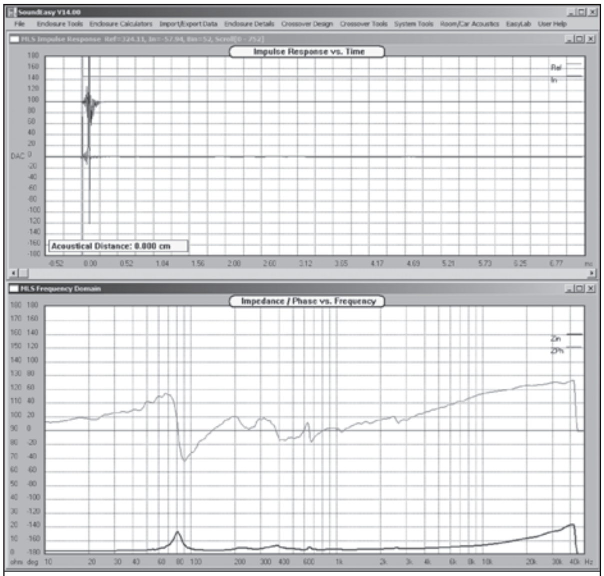

FIGURE 8: Impedance plot of double stack tractrix horn. Lower line is impedance magnitude. The upper line is impedance phase.

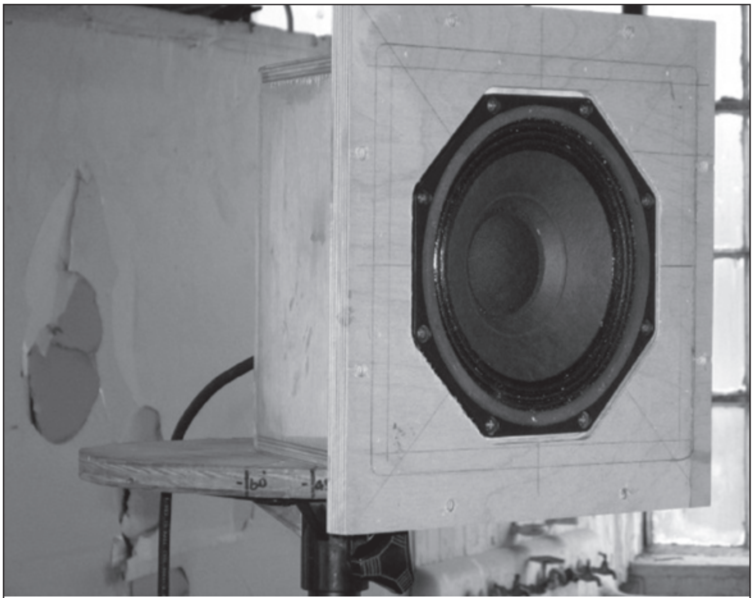

PHOTO 1: Sealed rear chamber and BC 8PE21 200mm (8″) driver of the horn shown in the CAD drawing of *Fig. 11*.

ed the driver to the rear chamber to eliminate any extra front volume acting as a low-pass filter. This is relevant because the design is intended for midrange and not midbass; besides, its maximum excursion is only 1mm. Because this driver is small—200mm (8″)—the front volume will turn out quite low.

I started the design by entering the Thiele/Small data into my horn calculator—I chose a bandwidth starting from 170Hz to 1kHz (**Fig. 9**). I then took the calculated data and entered it into SoundEasy to plot the frequency response and impedance response simulation (**Fig. 10**).

Armed with this data, I went forward with the design and drew my CAD drawing of the BC 8PE21 midrange horn. In **Fig. 11**, you see the design is similar, and I've flush-mounted the driver to the rear sealed chamber. **Photo 1** shows the finished rear chamber with the driver mounted as in the drawing. The rear chamber with the driver mounts to the horn throat.

Now I'll take some time to go over some points of the horn construction. I first read about bending wood from the personal website of Mark Winquist long before this writing. To bend wood, cut a side of wood grain with slits spaced incrementally apart. The depth of the cut should leave the last ply of wood grain in place, typically 1/8″ thickness. Most important, when you cut the slits the wood grain should align parallel to the path of the horn; if not, the bending will cause the wood to break instead of bend. **Photo 2** shows the horn assembly clamped with threaded rod on a jig to hold everything in place. **Photo 3** shows the horn removed from the jig before assembling any additional wood pieces.

The top and bottom pieces are cut using a band or jig saw at a 90° angle to the wood. I then used an oscillating orbital spindle tabletop sander with a tilting table to sand out the tractrix curve at an angle of 14½° approximating the CAD tractrix curve by hand. I then tacked the top and bottom pieces to an angled piece of wood and set the assembly in the jig for clamping using threaded rod.

MEASUREMENTS

After assembly, I measured the finished horn to access my design. The frequency response is measured at a distance of 91.375cm (36″) from the cone. The horn occupies almost 22″; thus the microphone is just over 14″ from the mouth of the horn. **Figure 12** shows the frequency response results. The bandwidth appears to meet the 200Hz to 1kHz target bandwidth in the design. The null centered at 800Hz needed investigation, and I was also concerned about the second null located at 2466Hz.

I decided to find out whether the null at 800Hz is due to either the horn path or the horn's rear sealed chamber. Because I could just detach the horn's rear chamber with the driver mounted to the rear, I took the frequency response of the BC 8PE21 driver in its rear chamber and compared the response. In **Fig. 13**, I compare the frequency response of the sealed box by itself versus its horn. I also took a close mike measurement and plotted this shifted -30dB in order to show smoothness in the measurement.

From **Fig. 13** it's clear the null at 800Hz is due to the rear sealed chamber! The drawing of the horn (**Fig. 11**) shows a rear chamber with a constant height of 9″ in the vertical plane. If I take the speed of sound as 13560 inches/sec, the half-wavelength corresponding to 800Hz frequency is 8.475″, i.e., just under the chamber's 9″ height, alas! I can apply the same principle to the JBL 2020H horn I previously built. The JBL tractrix has a constant rear chamber height of 12.9375″. A 1kHz null frequency wavelength is 13.56″, just over the rear chamber's 12.9375″ height.

I'm not an acoustician, but this tells me the nulls are due to the box modal resonance of the six sides of the rear sealed

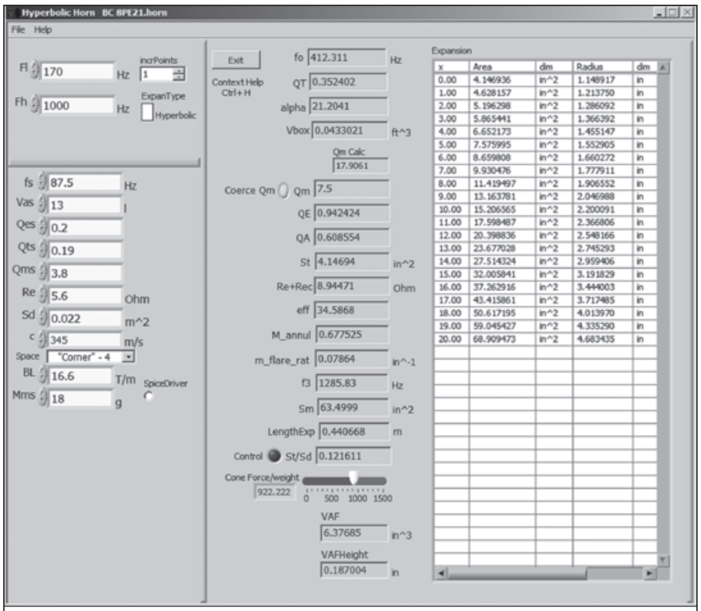

FIGURE 9: Thiele/Small data and Leach design parameters for the BC 8PE21 200mm (8″) driver. The chosen bandwidth is 170Hz to 1kHz. The required horn length is 50.8cm (20″).

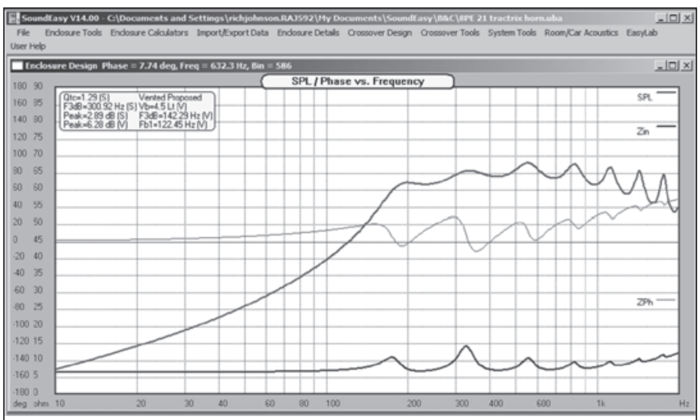

FIGURE 10: SoundEasy plots the horn data from the horn parameters in *Fig. 9*. At the 20Hz vertical line, the bottom plot is impedance magnitude, the top line is impedance phase, and the middle line is the frequency response.

TABLE 1 A comparison of magnetic strength divided by cone mass for three candidate horn drivers.

	JBL 2020H	JBL 2012H	BC 8PE21
Cone force/weight	416	517	922
BL	18.3T/m	15.5T/m	16.6T/m
Mms	44g	30g	18g

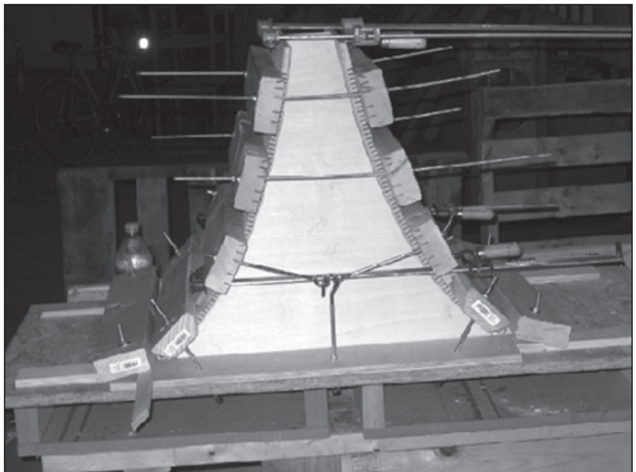

PHOTO 2: The BC 8PE21 200mm (8″) tractrix horn clamped to the threaded rod jig.

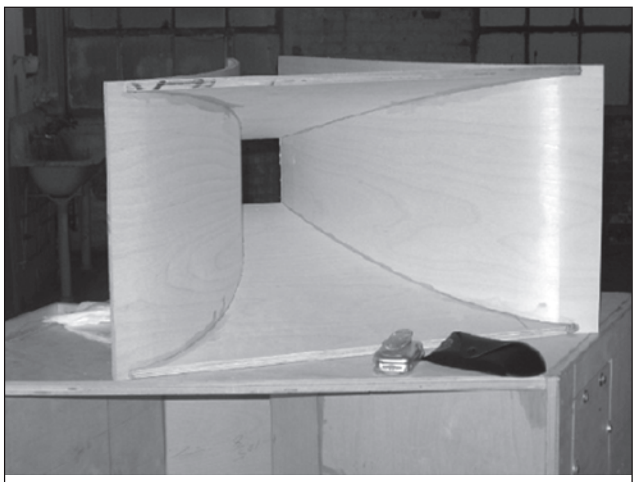

PHOTO 3: Horn removed from the jig prior to any wood assembly.

chamber! Because the rear chamber top and bottom pieces are parallel, the standing wave pattern dominates the enclosure modes[4]. Hmmm, maybe I should have stuck with one of the golden ratios of 1.59, 1.26, and 1 or similar for the rear chamber.

Next, the second null, located at 2466Hz, comes from the horn path because the null does not appear in the frequency plot of the rear sealed chamber. I traced my steps back to when I smoothed the tractrix horn curve by hand for the top and bottom piece of the horn duct using an oscillating orbital sander. It's very difficult to trace the curve accurately by hand. Most will not get the curve exactly right doing it by hand.

Study both CAD drawings of **Figs. 3** and **11**, and you'll notice the tractrix angle adjacent to the horn wall is small near the throat then becomes 90° at the mouth. If I were to do this again, I would use a straight edge near the throat for tracing instead of the tractrix line to avoid parallel surfaces during construction. If you're equipped to trace the tractrix line perfectly, then by all means do so.

I decided to resolve the 1kHz null fre-

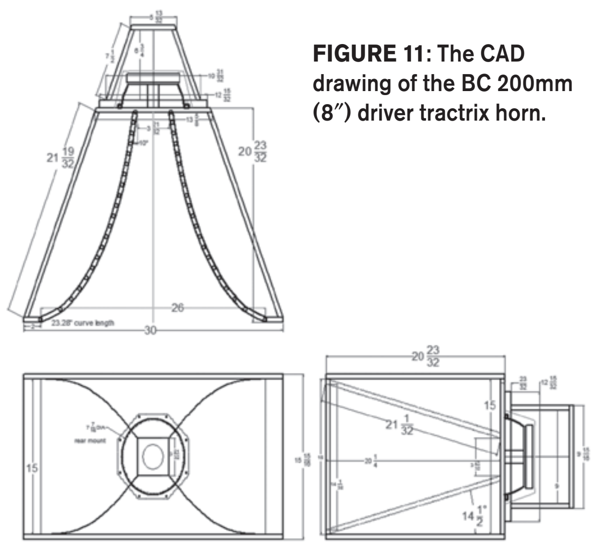

FIGURE 11: The CAD drawing of the BC 200mm (8″) driver tractrix horn.

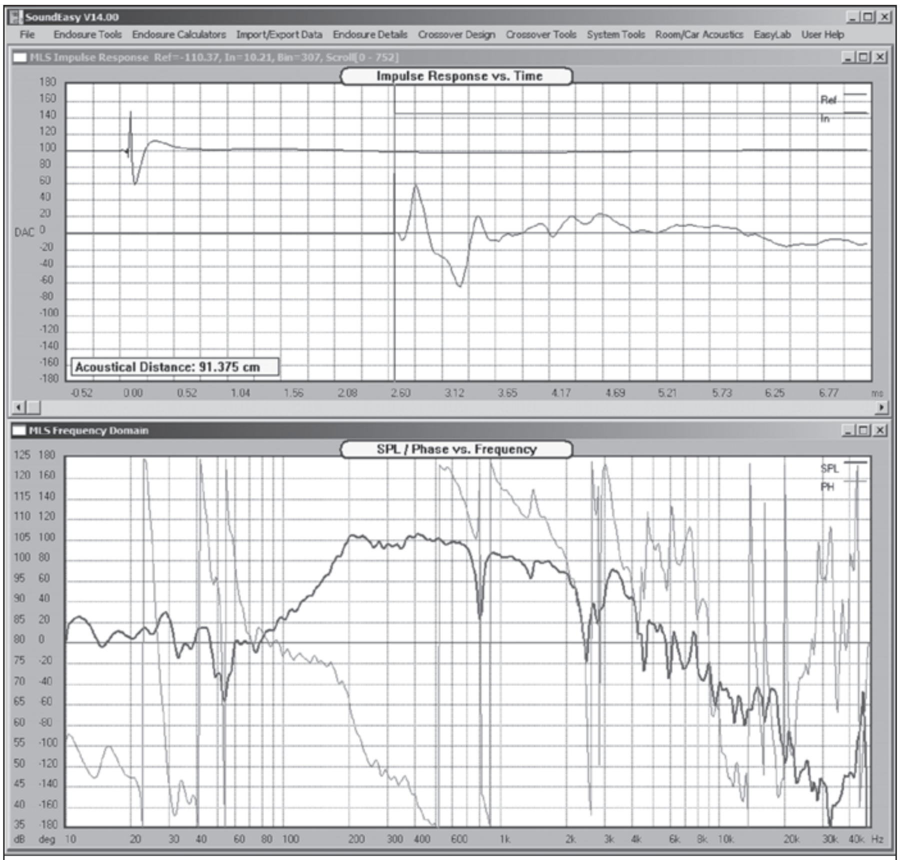

FIGURE 12: Frequency response of BC 200mm (8″) tractrix horn shown in the CAD drawing in *Fig. 11*. At 10Hz line, the top line is frequency and the bottom line is phase.

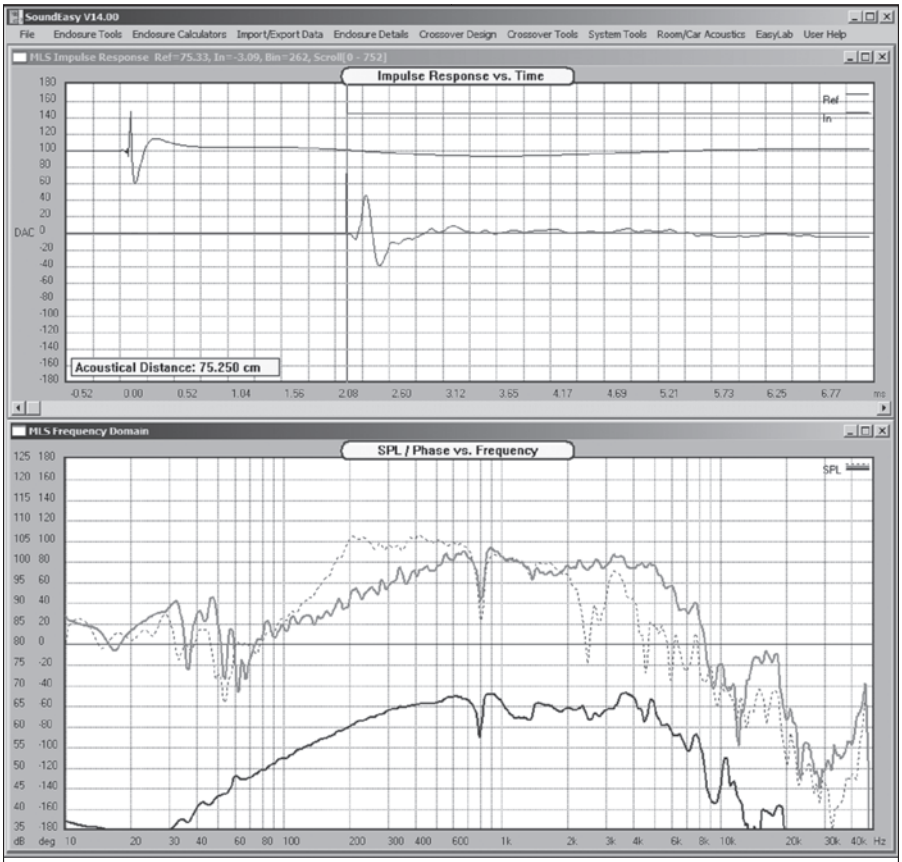

FIGURE 13: The frequency response of the BC 200mm (8″) driver in its sealed back chamber without the horn duct attached. The original horn response plot is the dotted line. At 200Hz the top line is the horn's response; the bottom line is the close mike response of the driver in its sealed box. The middle line is the frequency response of the rear sealed chamber at 75.250cm (29.6″).

quency by making a CAD drawing change and rebuilding the rear sealed chamber (**Fig. 14**). I modified the rear chamber so that the top piece now angles at 18°. This should reduce the 800Hz null in the original frequency response mentioned above, although I have no data to prove this yet. The reduction does not violate the rear back volume because the original calculation is 0.0433ft^3, or 75 in^3 (1.23 liters). The volume I built originally is 435.735 in^3 (7.14 liters). The volume sizes I mention don't account for the driver's volume occupied in the rear chamber. The occupied volume will take the rear volume lower, approaching the required 1.23L. Envision a liter of carbonated soda—that's my required volume.

I don't want to reduce the depth of the rear box because the driver is vented and air needs to circulate behind the driver's vent hole, which is located on the woofer's magnet at the center. Leaving space behind the magnet vent is critical in bass horns because the cone movement is greater compared to midrange horns. It could mean the difference of a burned-out coil should your woofer need to handle high power. Nevertheless, leave space for the magnet to cool when building the rear chamber.

From studying **Fig. 13**, it's clear the

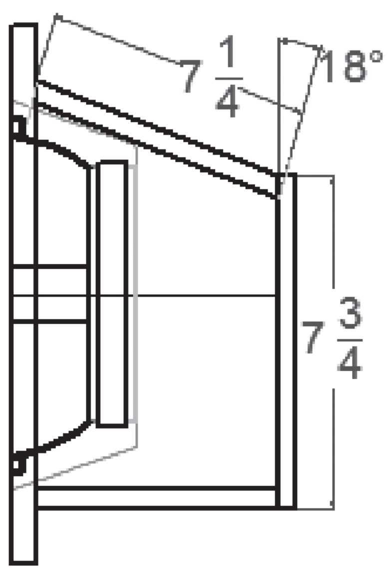

FIGURE 14: Side view of the new rear sealed chamber to replace the one in the drawing of *Fig. 11*. The top view is unchanged. The 18° cut is really a compound angle of 18° in one plane and 6° in the other.

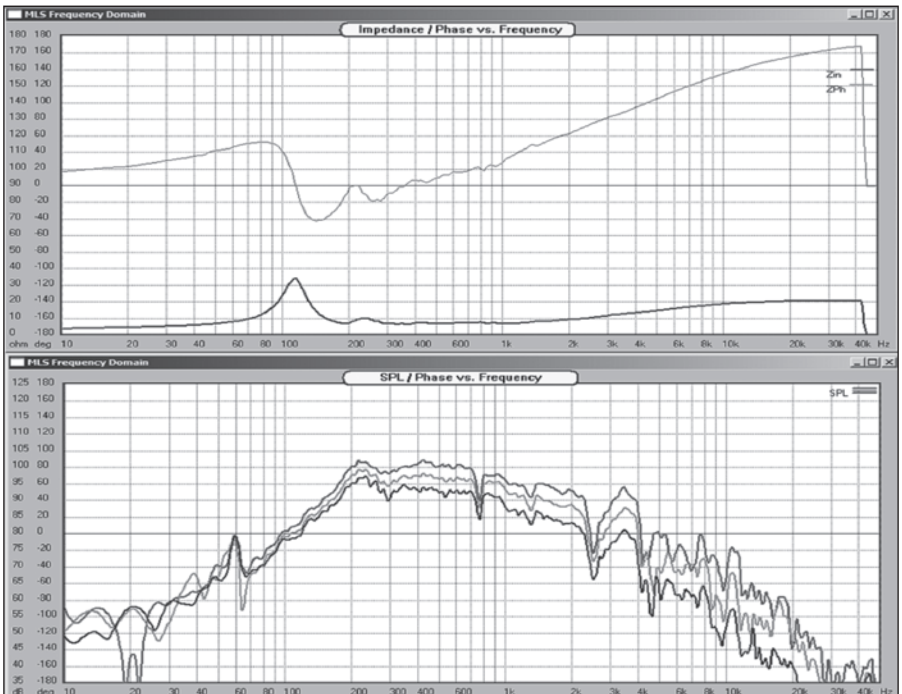

FIGURE 15: Impedance and frequency response of the BC 200mm (8″) tractrix horn. Top plot is impedance, the lower line is impedance magnitude, the top line is phase. The bottom plot is frequency response at 0, 30, and 45° horizontal.

horn loading occurs from 200 to almost 1kHz. Beyond 1kHz the frequencies are not raised in SPL as the 200-1kHz horn passband shows. The driver provides some directivity increase above 1kHz, which is a good trade-off because it comes close to matching the SPL of the horn's passband. **Figure 15** shows the impedance response and frequency response at 1m distance for three angles.

Notice the impedance reactance is cancelled by the rear chamber because the impedance phase at 200Hz is near the 0° line. The line clearly shows a phase change in slope at 200Hz as a result of the sealed back chamber. The inductive rise with increasing frequency in the impedance phase plot is due to the driver voice coil inductance.

The frequency response at three angles confirms I have very good dispersion up to 1kHz. Ignore the 60Hz spike, which is due to AC power hum from the use of an external soundcard. The persistent hump just above 200Hz of the three angles is probably due to the proximity effect of the test microphone located too close to the horn cabinet edge. In the far field the hump just above 200Hz should not persist.

I intended to mate the tractrix horn with a 2″ compression horn driver that is crossed over using an electronic filter near 1kHz. Thus, a LPF will attenuate the BC 8PE21 tractrix horn beyond 1kHz. With this in mind, I decided there's no need to correct the 2466Hz null, leaving the horn as it is.

All that was left was constructing a new rear sealed chamber. I discovered, to my surprise, the new 18° angle of the top piece required a compound angle cut for the top to properly fit the angled and tapered sides. My CAD drawing is 2D. A 3D CAD tool is needed to discern the angle. Luckily, after some trial and error, that angle turned out to be 6° tilt. **Photos 4** and **5** show the pieces just prior to construction and after I made the cut.

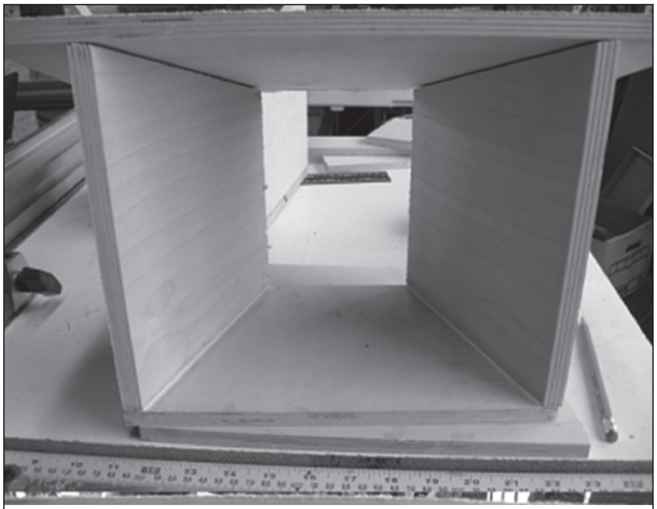

PHOTO 4: New chamber construction before attaching the top and before compound angle (6°) cut.

PHOTO 5: After the cut, the top piece now fits tight to the side pieces.

Before the glue had time to dry, I set the horn on a speaker stand to take measurements. **Photo 6** is the pre-finished new rear sealed chamber attached to the horn.

Figure 16 shows that there is some reduction in the null at 800Hz, but it's not completely gone. The dotted line is the original frequency response shown for comparison. Although five sides of the rear chamber were now unparallel, the null was not completely gone!

SoundEasy can

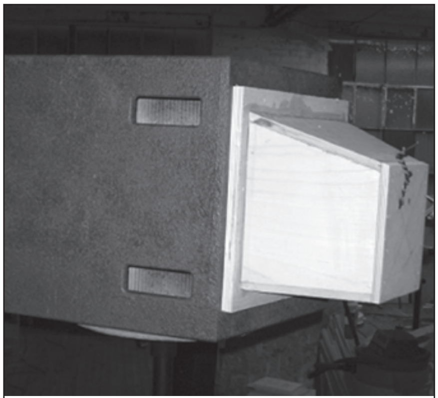

PHOTO 6: The new rear sealed chamber is stapled to the horn throat for initial frequency response test.

model an enclosure's modes using Finite Element Method (FEM), but at this stage I never simulated any sealed chamber boxes using SoundEasy FEM analysis. I don't think acoustic stuffing would remedy this because the volume is quite small. If I were to do this again, seeking perfection, I would test the rear chamber for response irregularities before moving on to a final design.

Thus far, all frequency response measurements posted are performed at a 1m distance or less. The horn occupies much of this measurement distance. My point is that a 1m distance is an unrealistic listening position and what's needed is a far field measurement. In a multi-way speaker or horn system, the drivers combine in some coherent manner at the listening position.

I repositioned the horn and test microphone to an over-the-head vertical position (~9′) in a huge room to minimize floor reflections. I moved the microphone distance to 8′. **Figure 17** shows the far field frequency response including three horizontal angles—0, 30, and 45. Once again, the spike at 60Hz hum is due to AC hum, so you should ignore it.

Now, after the results of **Fig. 17**, I can say the operating frequency range of the BC 8PE21 tractrix horn is 200Hz to 2k! If the horn's tractrix path is drawn with greater accuracy, as I explained in the middle of this article, a 3k upper limit is surely within reach.

To sum things up, I have shown that a wideband cone midrange requires a low cone mass driver. The horn driver, without use of a phase plug, requires coupling to the horn throat for horn loading; other-

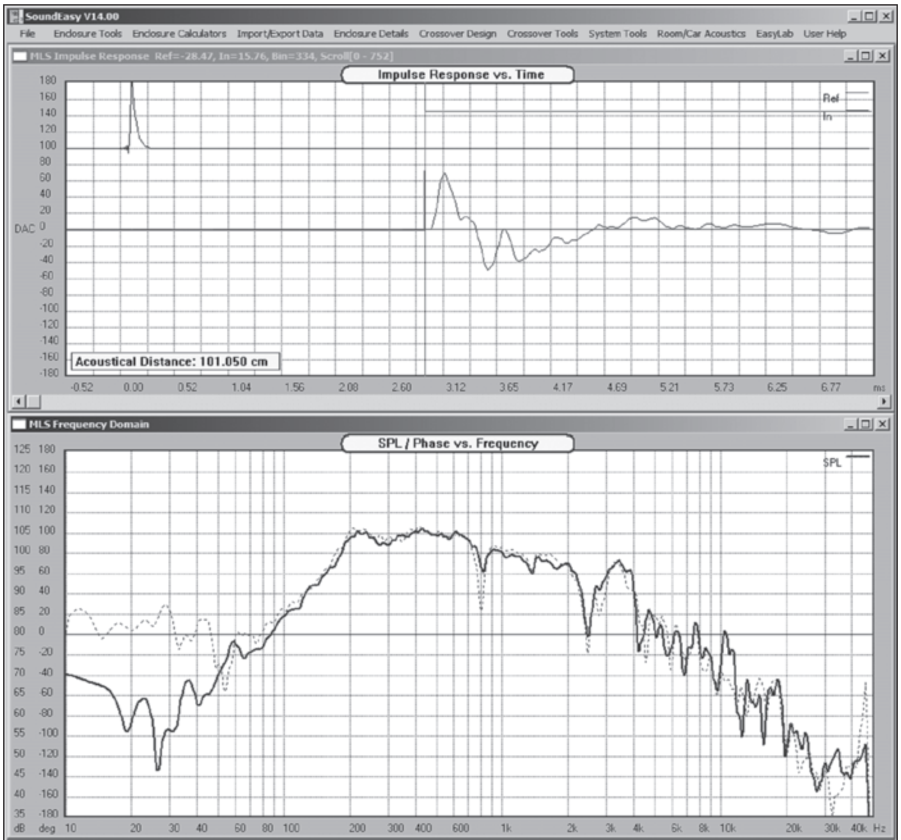

FIGURE 16: Frequency response of the new rear sealed chamber attached to the horn duct as in *Photo 6*. Solid line is frequency of new sealed chamber; dotted line is original's frequency response. The 800Hz null is suppressed.

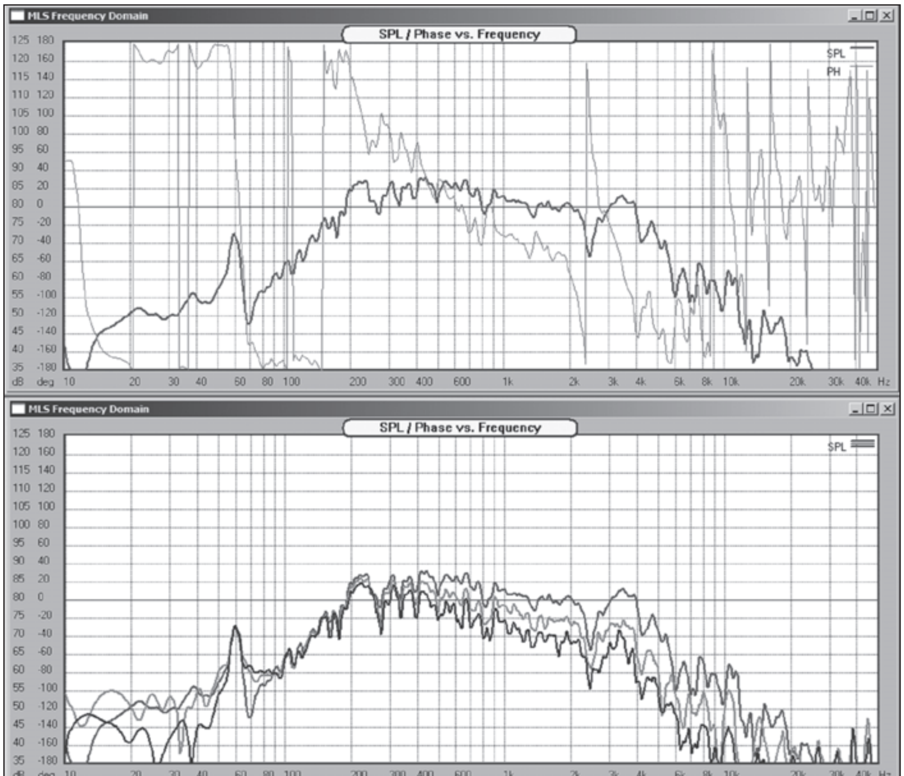

FIGURE 17: Far-field frequency response of the BC 8PE21 tractrix horn. The top plot is response measured at 8′. Between 200Hz to 2kHz the frequency magnitude hovers near the 0dB centerline. The bottom plot is the 8′ frequency response at three angles—0, 30, and 45°. A 60Hz AC hum artifact exists, so you should ignore the spike at 60Hz.

wise, a low-pass filter of the front volume may be in effect. You may use a tractrix curve length of the same linear length as hyperbolic for improved off-axis response.

When possible, simulate or measure your driver in its rear chamber before selecting the rear chamber shape and size. For the tractrix curve to be effective, its mouth should extend the 90° bend a few inches before the horn mouth ends. You must avoid parallel surfaces in the horn duct, or else corresponding nulls will appear in the frequency band. Include far-field measurements when accessing midrange horn frequency response.

POSTSCRIPT

I mentioned above that SoundEasy is capable of simulating the rear chamber box response using FEM analysis. Up to now, I never used the Delauney FEM analysis in SoundEasy, so I would now learn. If the analysis can predict the nulls in the midrange band, I could change the rear chamber design prior to any construction!

Keep in mind I'm a novice at the FEM analysis, and to really use the feature the SoundEasy manual should be referenced. In a nutshell, here's my SoundEasy (SE), version 14, Delauney FEM procedure. One plane of the rear chamber's internal dimension is laid out on an XY grid in cm units. The total volume is set via the grid size of X, Y, and Z parameters.

The software calculates a mesh of nodes using nine layers in the Z-axis. All nodes are now labelled with mesh node numbers. The position of the driver is set using mesh node numbers. Either four or nine nodes are used to set the driver position; i.e., points on the driver frame where it bolts to the enclosure.

SE calculates the frequency response using Delauney FEM analysis. The process is CPU intensive, so a single frequency response run could take five minutes or more. Calculating just the enclosure nodes, though, is quick.

Figure 18 is the simulated frequency response of SoundEasy Delauney FEM analysis using the original rear chamber of the BC 8PE21 200mm (8″) tractrix horn. **Figure 19** shows parameters used to generate the Delauney FEM frequency response. The analysis shows the infamous 800Hz null that appeared in my finished horn measurement! Wow, I could have prevented the null if armed with this information ahead of time.

To summarize, a midrange horn's rear chamber usually requires a small volume where the internal dimension could result in nulls located in the horn's passband. It is a wise step to first simulate before construction and test for nulls in the passband. I assume that using golden ratios for the internal dimensions of rear chamber is critical for smooth midrange. The issue also exists when designing basshorn, but more often, the null(s) fall outside the passband of the bass frequencies.

With that said, I can now explain the cause for nulls outside the passband in my first article, "An Excellent DIY BassHorn," December 2007 *audioXpress*. In the article the "huge null located between 500Hz–600Hz" is a result of the basshorn's rear chamber mode behavior as I have dealt with this issue in this article for midrange horns. I hope DIYers will use this information to build better cone midrange horns and avoid the design issues described in this writing. *aX*

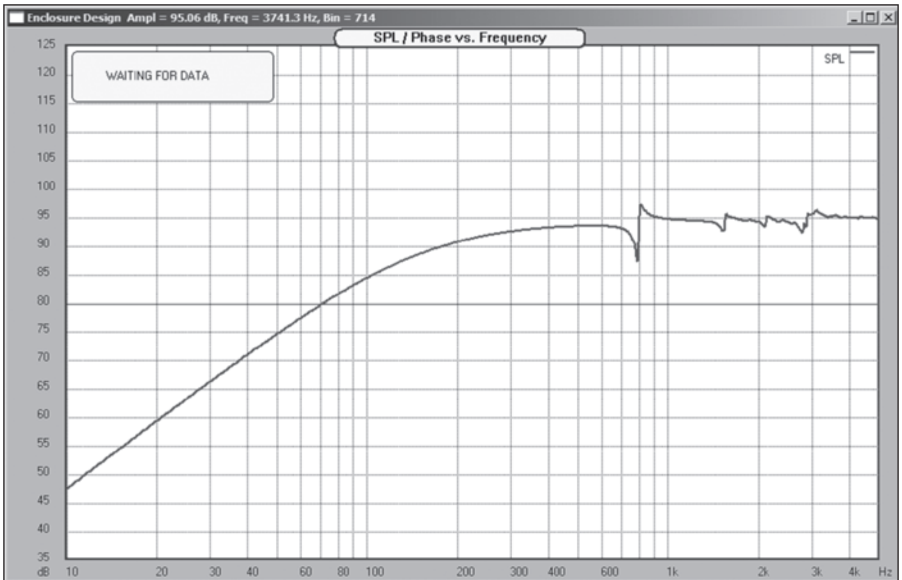

FIGURE 18: SoundEasy Delauney FEM analysis frequency response of the original rear chamber of the BC 8PE21 tractrix horn.

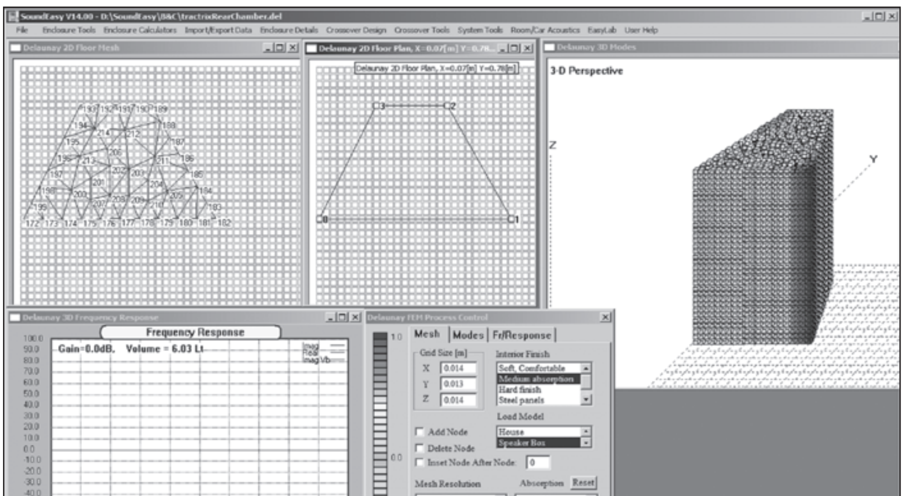

FIGURE 19: SoundEasy Delauney FEM window. The top view of the rear chamber is drawn using node number counterclockwise. X, Y and Z units set the internal volume.