An Excellent DIY Basshorn

Analyzing measurements to determine when a basshorn speaker attains or departs from the target design; this design method is from the work of Dr. W. Marshall Leach, Jr., and articles by Dr. Bruce Edgar.

Builders usually choose a suitable woofer and design a basshorn cabinet around the woofer characteristics. I will begin a theoretical design using this method for the JBL model 2226H 15″ (38cm) basshorn driver.

A HYPOTHETICAL HORN

In order to gain the maximum output at the horn cutoff frequency, I use reactance annulling by way of a sealed back chamber. Leach states that reactance annulling occurs just above the driver fs, and this condition can be imposed if the hyperbolic horn equation annulling parameter (M) is a specific value. Stated another way, the lumped (driver and rear chamber) capacitive reactance cancels the inductive reactance of the throat and horn path. Thus the horn is purely resistive near the cutoff frequency.

Compared to other expansions, the hyperbolic area expansion gives the greatest output near the horn cutoff frequency. Because the hyperbolic curve is long and expansive near its mouth, its area expansion is *not* easily built using wood. To maximize cutoff frequency output, choose a flare rate in which the woofer's capacitive reactance begins to peak. This is usually a few (0-10) Hz above the driver resonance. The capacitive reactance in **Fig. 1** shows a peak beginning from 44.3Hz (measured fs) and reaching a peak near 60Hz.

For a perfect 50Hz full wavelength horn, this driver will be suitable for a horn cabinet that has a length of one wavelength of 50Hz; i.e., 271.8cm (107″) in length and a mouth diameter of 222.5cm (87.6″). A throat diameter of 23.7cm (9.33″) will maximize the acoustical output of the basshorn in its bandwidth. The Leach equation for the throat St is St = (2 * 3.14159 * fo * Vas * Qa)/((1+alpha)*345)) in units of m^2. The horn length, mouth, and throat dimensions are not always practical, but you can simulate this easily.

What would the ideal (50Hz) horn look like? In **Figs. 2** and **3** I simulate and plot the JBL 2226H woofer using the requirement of a full-size horn. The horn parameters are determined using reference 1.

One noticeable characteristic for the ideal hyperbolic horn is that Z-mag (bottom line) is nearly flat (i.e., highly damped). The Z phase (top line at

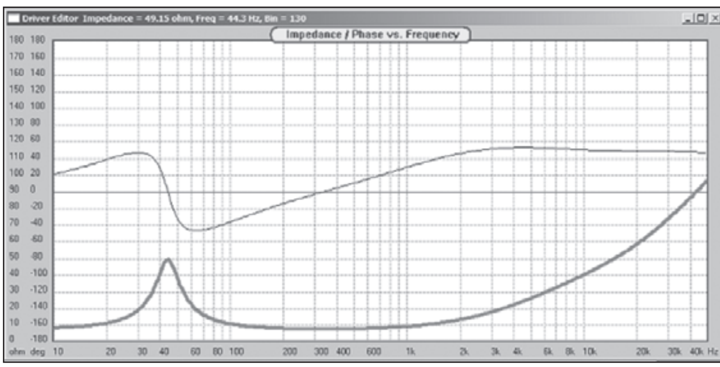

FIGURE 1: SoundEasy simulation shows impedance curve of JBL 2226H woofer. Below fs (44.3) the woofer phase is inductive and above fs its phase is capacitive peaking near 60Hz.

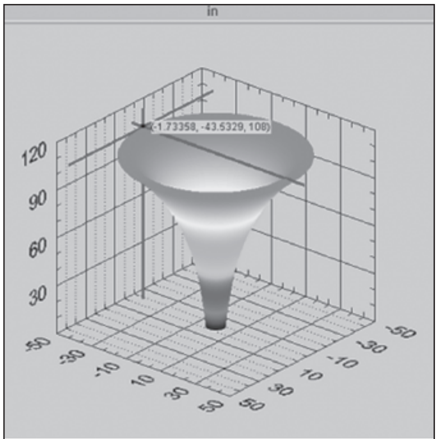

FIGURE 2: A perfect ideal circular 50Hz hyperbolic horn. Mouth dimension is 87.6″ diameter and the throat diameter is 4.7″.

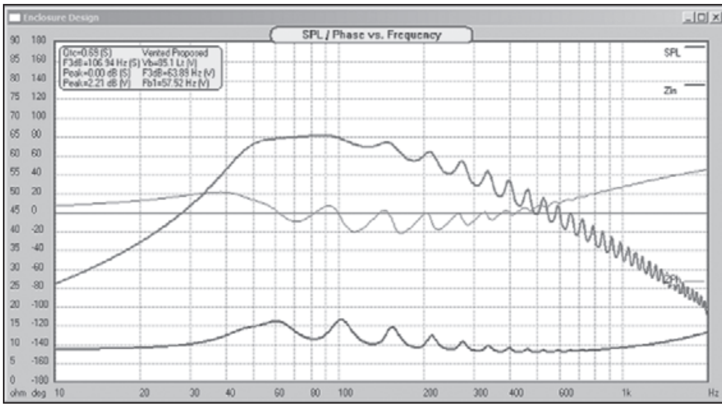

FIGURE 3: Theoretical frequency response of 2226H driver. At the 20Hz vertical frequency line, the bottom line is impedance magnitude, the top line is impedance phase. The middle is frequency amplitude.

10Hz) is essentially cancelled above fc (at the 50Hz cutoff frequency) compared to the driver by itself, as in **Fig. 1**. Its frequency bandwidth is roughly two to three octaves.

The squiggle in the horn output is due to the model's discontinuity at the horn mouth reflecting back into the throat. Because the horn length is nearly 10′ long, frequencies at three octaves above the cutoff frequency, 50Hz (fc), begin to roll off due to the wavelength being only one-tenth the fc dimension. At three octaves above fc these frequencies are not coupled well by the throat and at three octaves above fc these frequencies tend to obey the "intensity dissipates by 6dB when the distance is doubled" rule inside the horn expansion walls!

This 50Hz horn output level compared to its optimized bass reflex is shown in **Fig. 4**. Notice the horn's output is an acoustic 5dB higher in its passband and a minimum of 3 higher in the stopband range!

A CORNER HORN DESIGN

Now, the full-wave horn is impractical to build, so a little engineering compromise will make life easier. Design the horn for one-eighth the space (the corner position) and use the corner or multiple cabinets (for sound reinforcement) to couple the mouth size for loading down to fc. Using the Leach equation, a 1/8 size, 50Hz horn requires an estimated length of 1.54m (61″) and a mouth diameter of 76.2cm (30″ diameter).

When the horn is full size, the throat diameter should be 23.7cm (9.34″); i.e., throat vs. cone surface area ratio (St/Sd) is 0.5. For a 1/8 size horn, Leach's equation for the throat (St)—to maximize the horn output in the passband—is not applicable. When the horn is shortened, it violates the horn equation solution.

The rule of thumb for a shortened basshorn is to use a St/Sd of 0.5 to 0.8 for bass woofers. The lower value (0.5) will give slightly higher fh (upper cutoff), and the upper value (0.7) will give a slightly higher output near fc. Thus, use 0.7 St/Sd for this 1/8 size horn design.

Leach and Edgar explain that when the horn length is not taken out to full size the back chamber volume is usually near 2× the optimum size of a full-size horn. Through my own building (and simulation tools) of horns, I have confirmed this to be true. **Figure 5** is a plot showing the 1/8 size horn SoundEasy simulation.

If this horn were placed in an anechoic environment, its response would look like the **Fig. 5** simulation plot. This is the point I would like to stress. (Some readers may have used other simulation tools that account for a corner.)

Notice that the horn cutoff frequency (fc) is higher, the impedance magnitude (Z) begins to show peaks, and Z-phase shows it is no longer resistive above fc, but favoring capacitive reactance (or negative phase) in the passband.

But unless you're hanging basshorns in free air, you will always have them on a ground plane. If you add a ground plane or an equivalent second identical cabinet to couple the bass response, its response would look like the **Fig. 6** plot. Essentially this is a model of the horn with its area expansion taken out to a quarter space horn length size; i.e., 1.95m (77″).

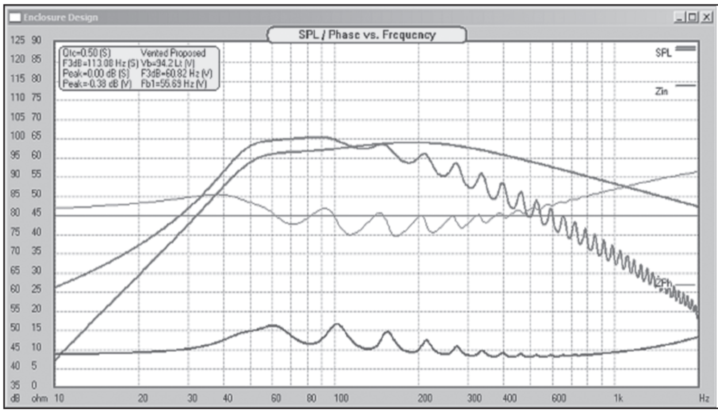

FIGURE 4: The 2226H vented box frequency response data is shown for comparison to horn output. At 50Hz the horn has 5dB higher output.

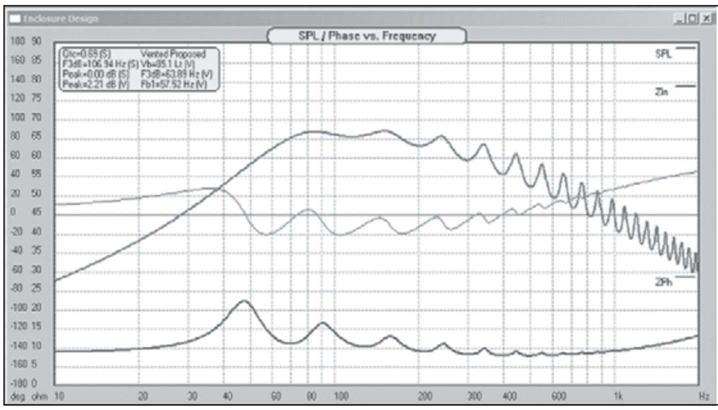

FIGURE 5: The 2226H frequency, phase, and impedance of a 1/8 size horn. The cutoff frequency is now higher and the impedance begins to peak at fs.

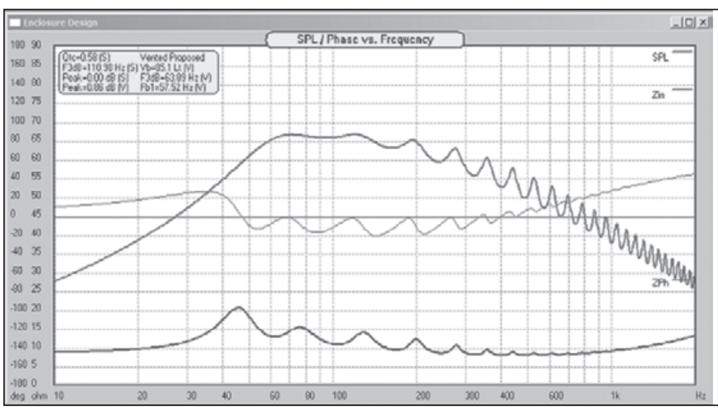

FIGURE 6: The 2226H quarter space horn frequency response, impedance, and phase.

As the area expansion approaches a full-size horn, the impedance phase is canceled due to the horn's (back volume and driver) capacitance canceling the horn's inductive peak, which is at just above the driver's fs value. Should you miss the target of the back volume, it will affect the fc output, and a high impedance peak of the driver and Vback shows up—either above (too small back volume) or below (too big back volume) the target fc. The simulations in **Figs. 7** and **8** each show a different volume—a back chamber volume of 3× and a volume of 1/3× for the quarter space horn simulated.

Figures 7 and **8** show impedance magnitude and impedance phase when a horn's rear chamber is mistuned. Assuming a 50Hz hyperbolic horn is quite near the theoretical horn expansion, the uncanceled rear chamber of the horn's SPL will look like **Fig. 7** or **8** when improperly tuned.

I have come across commercial bass cabinets with a higher or jagged cutoff frequency due to practical or cost-saving errors in the hyperbolic area expansion and again an incorrect back volume. I intend to show you what a correctly tuned horn looks like after building it. At the other extreme, if you happen to build your hyperbolic horn whose length is too long (i.e, beyond 50Hz quarter wavelength), the frequency response will be choked off due to the horn's own resistive path extending to a frequency below 50Hz, not taking advantage of the driver and Vback chamber canceling the horn inductance.

A REALIZED HORN

I have built several basshorn speakers using a combination of the Leach and Edgar approaches. I will share some aspects of the design here and present some measurements to prove the theory works!

(I once naively designed and built a horn path for 30Hz, with the driver fs at 35Hz. When I measured the SPL, the response was rolled off much higher than 30Hz. I later figured out I needed to use a woofer that had an fs at or below 30Hz.)

The driver I chose for the horn is the JBL 2226H 381mm (15″) woofer. Again, a 50Hz quarter space bass horn requires a mouth size diameter 77cm (30.3″), an estimated length of 155cm (61″), and a chosen St/Sd (because the horn is not a full wavelength) of 0.7. The circular estimate of this horn's hyperbolic expansion and 3D picture is shown in **Fig. 9**.

The 50Hz quarter space circular horn designed as a rectangular horn with a fixed width of 50.8cm (20″) will require a hyperbolic expansion as shown in **Table 1**. Notice that the goal of 30″ diameter (or 738 in^2 area) mouth is reached at 54″ length because I chose to start from a throat size of 613cm^2 (95 in^2); i.e., St/Sd = 0.7, because a shortened horn violates the horn equation.

A realized rectangle horn will only estimate the area expansion of the ideal circular horn shown in **Fig. 9**. As I mentioned, the chosen back volume will be twice the theoretical full space horn volume.

This realized 50Hz horn uses diagonal reflectors at the corners because they minimize parallel walls and thus minimize standing waves as the sound travels along the horn path. Dr. Edgar explains this in reference 2. All bass horns I have built used diagonal reflectors with great success.

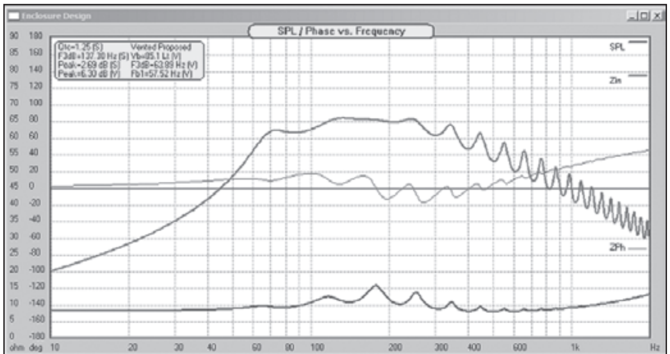

FIGURE 7: The rear volume is one-third the size of a full-size horn. This chokes off the lower frequencies. The impedance peak now shows up near 180Hz, and for the most part the impedance phase remains resistive.

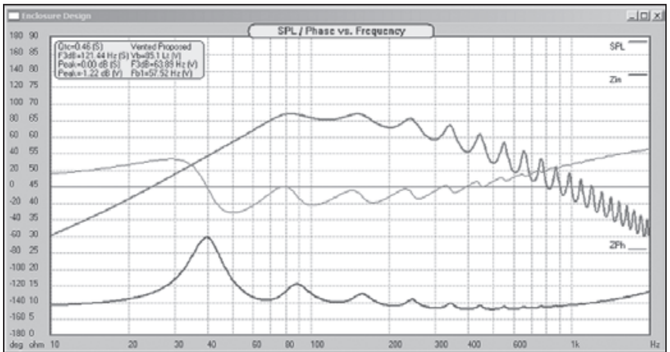

FIGURE 8: The rear volume is three times the size of a full-size horn. An impedance magnitude rise (at 40Hz) appears below fc (50Hz) frequency. The impedance phase shows inductive and capacitive peaks.

Figure 10 shows this bass horn based on all the information presented thus far. For brevity, the throat baffle is not shown. The front and side cutout is shown; the center vertical and horizontal pieces at the top are braces to keep vibration to a minimum.

I recommend ¾″ 11-ply Baltic birch (birch actual thickness is 23/32, so your drawing should be accurate to 1/32 of an inch). To cut costs as I did, use 3/4 MDF for the sides.

Baffle bracing is critical here. I used two pieces of birch to brace between the throat baffle and bottom facing piece. Cut a square or rectangular throat baffle and place the braces directly over the throat opening at two midpoints across the baffle. Like the front vertical brace, the baffle braces are cut, shaped, and glued on the edge thickness. If you omit the baffle, the horn driver SPL will flex the bottom piece of wood even at moderate levels, robbing you of thumping bass.

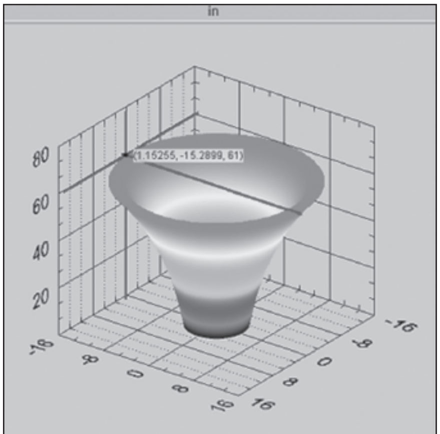

FIGURE 9: JBL 2226H woofer corner (1/8) space horn.

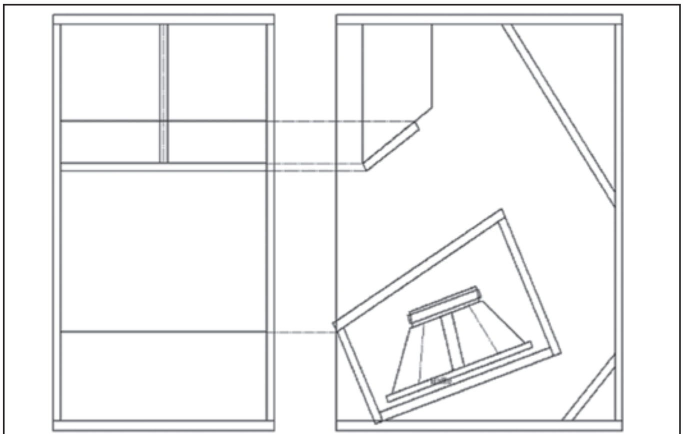

FIGURE 10: The front and side view of my 50Hz drawing design uses JBL 2226 15″ woofer and a sealed back chamber.

MEASUREMENTS

When measuring bass horn speakers, you often need to take the DUT outside away from any large obstruction or walls (other than the ground). When a large obstruction is nearby, the effect will show up as a shift in phase measurement, provided the path length from the driver to the measurement microphone is removed. Close mike measurement indoors will usually measure the horn speaker, including the floor and a wall, depending on where the mike is placed.

Figure 11 is the measured SPL and phase of the 50Hz horn. (Unfortunately, due to cable shortage at the time, I placed the DUT near a wall when I measured outside, so the phase shift between 12-40Hz shows this reflection clearly. Thus, a null at around 12Hz is evident.)

The **Fig. 11** plot is for a single cabinet placed on the ground. The response has a dip below 100Hz that is most likely due to the rectangle horn layout error estimating a circular expansion. The huge null between 500-600Hz is due to wave cancellation of the 2226H driver cutout opening that provides room for cone movement. JBL recommends a cutout opening of ~35.56cm (14″) when front-mounting the driver. As you can see, there are no nulls in the bottom end, thus proving Edgar's hypothesis of using diagonal corner reflectors and 90° bends.

Figure 12 shows the identical horn, but with the number of cabinets dou-

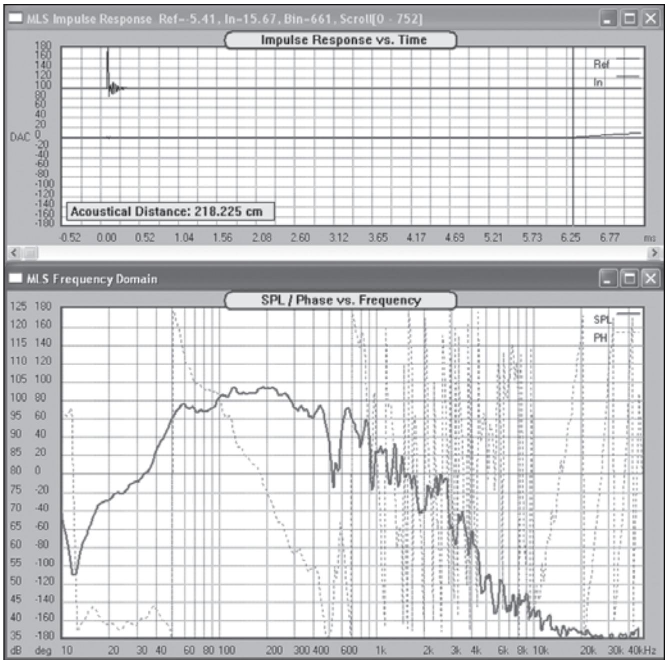

FIGURE 11: SPL and phase of 50Hz horn of Fig. 10.

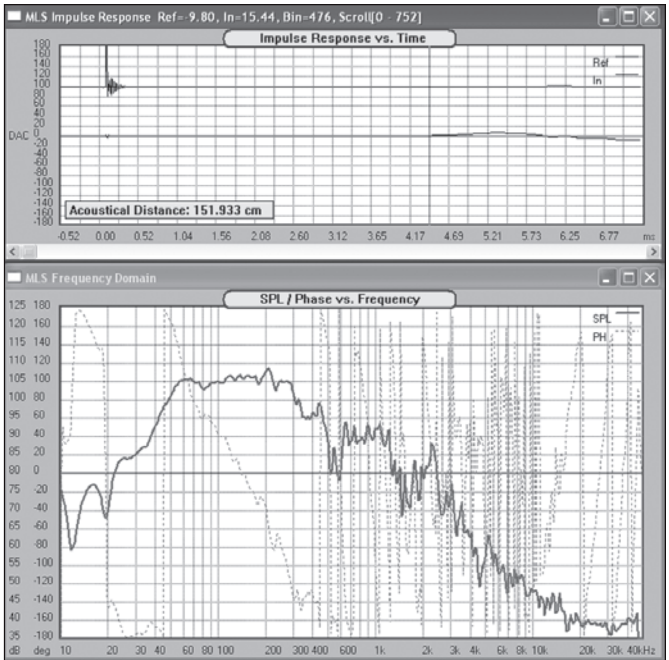

FIGURE 12: Double cabinet SPL and phase of 50Hz horn of Fig. 10.

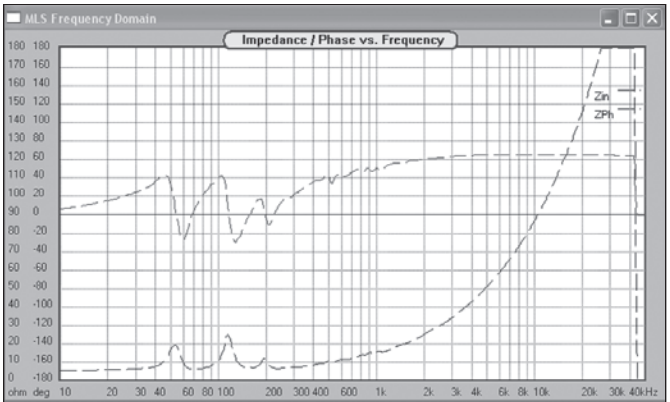

FIGURE 13: Impedance magnitude and phase of Fig. 10 horn.

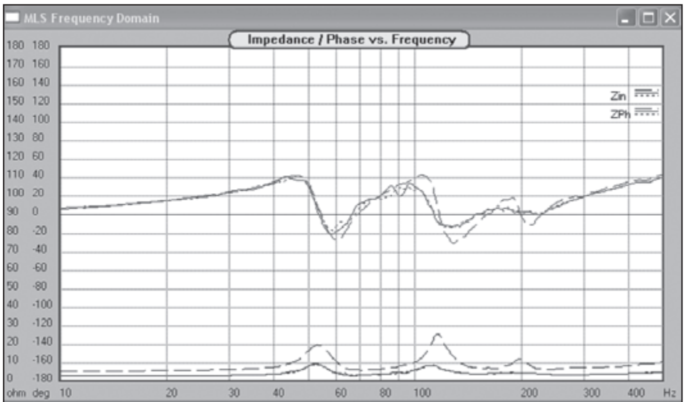

FIGURE 15: Same as Fig. 14 with double cabinet stacked on its side.

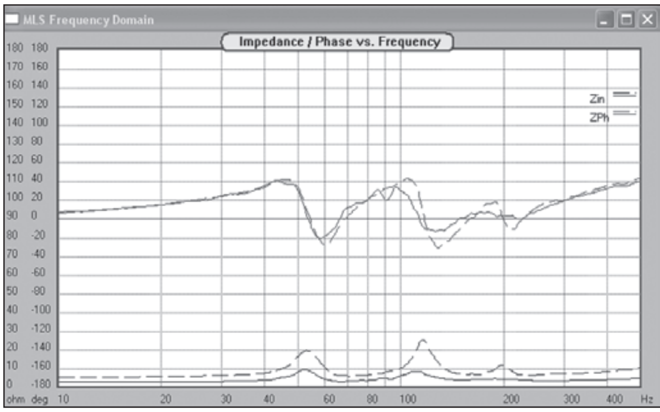

FIGURE 14: Two parallel and side-by-side basshorn cabinet impedance magnitude and phase drawn (solid lines) on top of the single basshorn impedance and phase (dashed line) as in Fig. 13. Peaks in magnitude are flattened and the impedance phase approaches resistive reactance.

bled (i.e., two cabinets side by side). The acoustical distance (driver to microphone) is 1.51933m, and the microphone is 1m from the ground.

The big difference here is that the bottom end no longer dips below 100Hz. It extends down to 50Hz and with this the 3dB bandwidth has shifted lower, from ~450 to ~300Hz. Between 50-300Hz (±2dB) this double cabinet bass horn will outperform any equivalent vented cabinet.

It appears that the design is on target, but how close is the design to the target back volume and horn expansion layout? To determine this, look at the impedance-phase response. **Figure 13** is the impedance-phase plot (0° at 10Hz) and impedance-magnitude plot (7Ω at 10Hz) of a single cabinet. The cabinet is standing vertically, i.e., as in **Fig. 13**. When taking impedance measurement, you should note the mounted position of the horn. (It makes a significant difference by affecting the mouth size.) As you can see, the measured plot has the characteristics discussed in the case of the theoretical horn that was simulated for a quarter space horn.

With the cabinet doubled and with the vertical cabinet position (as in **Fig. 10**), the impedance-phase and impedance-magnitude are shown in **Fig. 14**. As I mentioned, the Z reactance approaches zero, above fc, as the double cabinet's 50Hz is nearer to the full horn mouth size.

Just to prove a point, I placed the double cabinet on its side stacked on the floor and measured the impedance-phase and impedance-magnitude. Because the longest mouth dimension is closest to the ground, this will add more coupling to the mouth. Thus, the Z plot in **Fig. 15** is for two **Fig. 10** cabinets stacked on their sides. The measurement line is the dotted line. Clearly, the impedance-phase approaches zero (i.e., canceling).

Should you decide to build a horn, it is possible there will be other factors that produce resonance above fc. My design is one of the best-behaved bass cabinets I have built yet. In general, the more complex the horn layout, the more resonances appear.

One final note: Midbass or midrange horn design using a cone driver requires a different approach. Thus my use of basshorn in this discussion. *aX*

REFERENCES

1. *Introduction to Electroacoustics & Audio Amplifier Design*, Dr. W. Marshall Leach, Jr., 3rd Edition, 2003, ISBN 0-7575-0375-6.

2. "The Monolith Horn," Dr. Bruce Edgar, *Speaker Builder*, June 1993.

3. "The Show Horn," Dr. Bruce Edgar, *Speaker Builder*, February 1990.

4. SoundEasy Software version 10.0, Bodzio Software, Bohdan Raczynski.

TABLE 1

enter M annulling parameter 0.577273
enter m flare rate 0.0231294
enter throat area ft^2 0.663
enter desired length inches 61
enter fixed width of horn 20
string =

Z(frthroat)	Area/width	Area inch^2
0	4.7736	95.472
1	4.9045	98.09
2	5.0425	100.85
3	5.1879	103.76
4	5.341	106.82
5	5.5022	110.04
6	5.6717	113.43
7	5.8499	117
8	6.0372	120.74
9	6.2341	124.68
10	6.4409	128.82
11	6.6581	133.16
12	6.8861	137.72
13	7.1254	142.51
14	7.3766	147.53
15	7.6402	152.8
16	7.9167	158.33
17	8.2068	164.14
18	8.511	170.22
19	8.83	176.6
20	9.1645	183.29
21	9.5153	190.31
22	9.8829	197.66
23	10.268	205.37
24	10.672	213.45
25	11.096	221.92
26	11.54	230.79
27	12.005	240.09
28	12.492	249.84
29	13.003	260.05
30	13.538	270.76
31	14.099	281.97
32	14.686	293.72
33	15.301	306.03
34	15.946	318.93
35	16.622	332.44
36	17.33	346.59
37	18.071	361.42
38	18.848	376.95
39	19.661	393.22
40	20.513	410.27
41	21.406	428.12
42	22.341	446.83
43	23.321	466.42
44	24.347	486.94
45	25.422	508.44
46	26.548	530.95
47	27.727	554.54
48	28.962	579.24
49	30.256	605.12
50	31.611	632.22
51	33.03	660.6
52	34.517	690.34
53	36.074	721.48
54	37.705	754.09
55	39.413	788.26
56	41.202	824.04
57	43.076	861.52
58	45.039	900.77
59	47.094	941.89
60	49.247	984.95
61	51.502	1030