# A Small Reflex TL

Here's a new way of assembling a transmission line enclosure. You don't need the use of a table saw to build this compact loudspeaker enclosure, which gives excellent bass performance. **By Matt Hills**

I had been using my current PC speakers—a pair of Alpine 6½″ coaxial types with a capacitor in series with the tweeter—for a number of years. They started out in the doors of my old 1980 Toyota Tercel hatchback, but now they're mounted in small sealed boxes above my PC down in my basement workshop. They're pushing 20 years old now and it shows (and sounds!). I thought that the time was ripe to replace them with something nice and simple that could be constructed easily.

I always wanted to build a simple transmission line with Sonotube—perhaps a one-way design. It seems a perfect enclosure material if you stay within its limits. I had been thinking about a transmission-line enclosure based on concentric tubes of increasing diameters folded back on itself. If I may, I will coin the name "concentric reflex transmission line." A drawing of this type of enclosure is in *Fig. 1.* The finished pair of speakers is shown in *Photo 1.*

## DRIVER SELECTION

I looked around for a fairly efficient, broadband (full-range) driver in the 5–6½″ range. The Fostex Model Sigma 168 had a nice, flat response, but the $X_{MAX}$ spec of 1.25mm indicates that these are intended for horn designs. They were also a little pricey for this application.

Then I saw the little full-range Vifas at Parts Express. For less than 20 bucks US each, full range, rubber surround, and a cast (OK, injection-molded plastic) basket, what's the worst that could happen? They don't have an extremely low $f_s$ (self-resonance frequency), so the design could be fairly compact and I'd be able to exploit the low-frequency performance in a fairly lightweight, compact enclosure. With no tweeter or crossover, it would require only a couple of weekend's effort!

Or not—whizzer cones are best left to the Lowthers and Fostexs of the world. Not that whizzers are necessarily a bad idea, but I think that these folks must put a lot of effort into designing the mechanical system and choosing their materials for true high-end performance. The high-frequency response of this driver wasn't terrific. There was a huge (12dB deep) notch at about 8500Hz or so. This kind of high-frequency response was unusable.

The low-end response was another story. A brief audition in the first spin of the enclosure showed great promise in the bass and lower mids, but the highs were indistinct and distant. I removed the whizzer cones with an X-acto #11 blade by cutting as close to the dust cap as possible. Removing the whizzer exposed a gap in the voice coil, which I sealed with a drop of five-minute epoxy.

The published versus measured T/S (Thiele/Small) parameters are in *Table 1.* The Qs weren't too far off, but the $f_s$ was more like 57Hz (91.7Hz published). I measured these parameters prior to removing the whizzer cone.

I'm always leery of any driver $f_s$ spec with one-tenth hertz resolution. I think that it's meaningless to provide that much precision for a parameter that can change with room temperature. It may be the driver design nominal, although I don't know about that either because the web page advertisement stated that an $f_3$ (–3dB system frequency) of 75Hz was obtainable in a 0.25ft$^3$ vented box. It seems unlikely that a woofer could ever go 20Hz *below* its $f_s$


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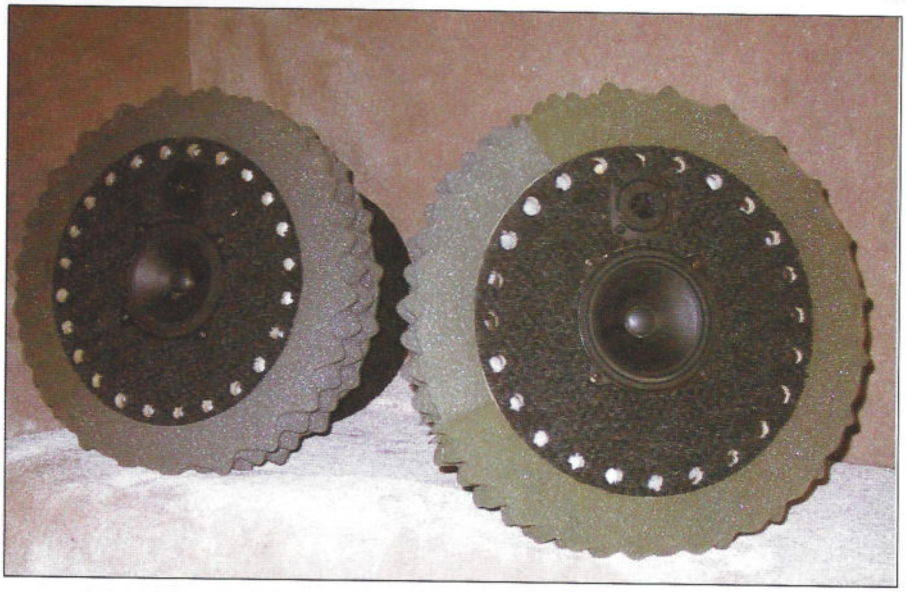

**PHOTO 1: The completed pair of speakers.**

after putting it *into* a box.

Anyway, it's just as well. All things being equal, I'd rather have a speaker that could do 65Hz than only 90Hz. This value of $f_s$ is just fine for the tube lengths I had in mind. In order to keep the design small (<1ft$^3$), I had hoped to use tubes about one foot long. This would result in an Fp (pipe resonance) of about 75Hz—this means a total equivalent pipe length of about 44–48", which is the line length of the enclosure shown in *Fig. 1*.

Since this is no longer a single driver design, I was in need of a tweeter—one small enough to fit on the baffle. The high frequencies for this design are handled by a small (10mm) Audax dome tweeter P/N TW010E10 that was on sale at Solen for about $8 each (Canadian). Since the Vifa drivers were reasonably well behaved up to about 6kHz (the recommended crossover frequency for the Audax tweeters), I thought that these would be a good match.

I would have liked to have crossed over at 3–4kHz, but this tweeter wouldn't tolerate the excursions. There was also nearly no tweeter output at those frequencies. Audax specified the recommended 6kHz high-pass response for the tweeters as a first order with a 2μF series capacitor.

## DRIVER RESPONSE

Some of you are probably already saying that the $f_s$ of the driver must be the same as the λ/4 length (Fp) of the line. I had been reading George Augspurger's[1] paper on transmission lines presented at the 107th AES convention in New York. He has some new ideas about modeling transmission-line behavior as a classical lumped element model of a transmission line normally found in textbooks dealing with microwaves and RF. With this model a SPICE simulator may be used to analyze the performance.

I find the symmetry of this approach quite pleasing. His measurements appear to bear out the validity of the models. The trick is to determine the losses and other line parameters used to compute the values of the Rs, Ls, and Cs in the final model. This is probably an empirical process but does not invalidate the approach.

Mr. Augspurger also supplies a range of $f_s$ to Fp ratios, which he says should produce satisfactory results for certain specific design types. He indicates that $f_3$/Fp ratios outside the range of 0.7–1.4 should be avoided if you don't want to sacrifice efficiency (and I suspect transient response). For this design the ratio would be about

$$57\text{Hz} / 74\text{Hz} = 0.77 .$$

There is certainly no end of debate in the field of loudspeaker design as to the exact merits, principles of operation, and design of transmission-line loudspeakers. What I can offer about the operation of this design is that the frequencies above about 300Hz are greatly attenuated at the rear of the cone, the

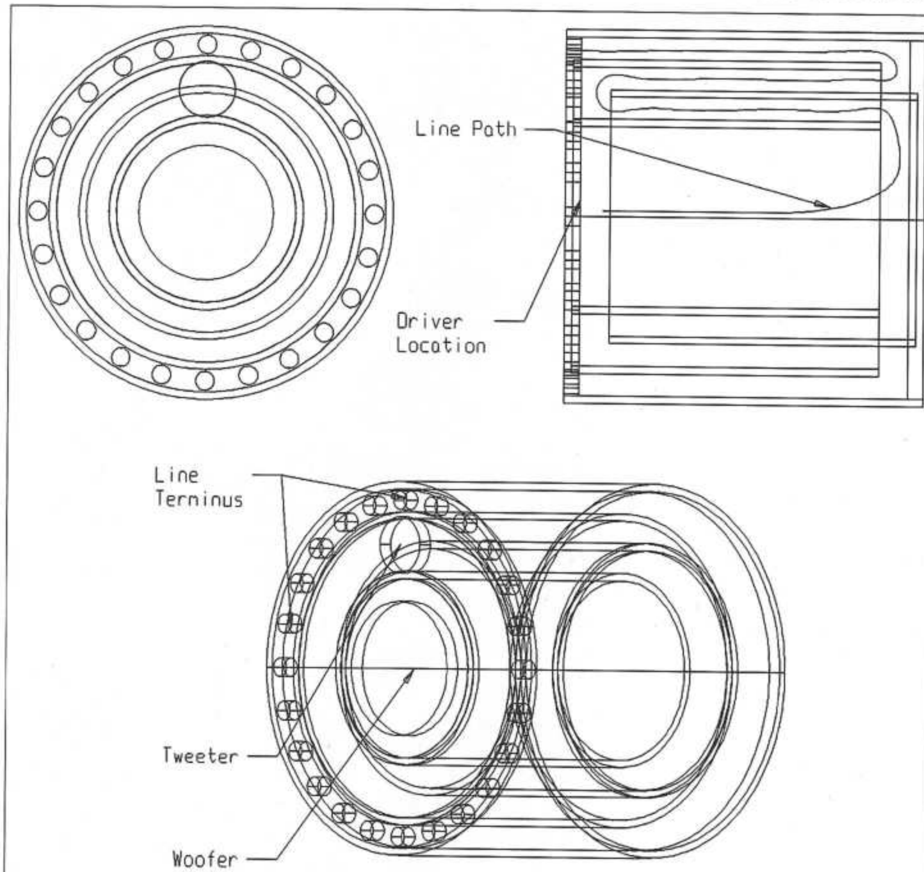


**FIGURE 1: Multiple views of the enclosure produced in 3-D CAD.**

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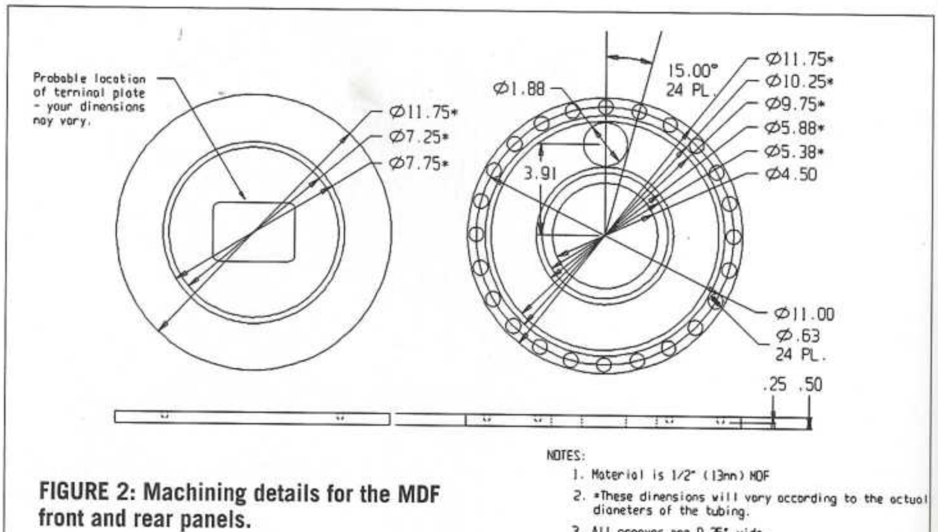


**FIGURE 2: Machining details for the MDF front and rear panels.**

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design does not have a fourth-order rolloff as vented designs do, and the $f_3$ of the system is equal to the $\lambda/4$ length chosen for the line length. There is also definite reinforcement of the bass frequencies by the enclosure.

## DESIGN AND TEST TOOLS

For this design I used SpeakerWorkshop V1.00 by Audua Inc.[2] This is the first time I've had access to such a tool for loudspeaker measurement. This is an all-inclusive loudspeaker system design package, which is available as a Beta test version on the Internet. It performs a wide variety of loudspeaker measurement and design functions, including near-field, on-off axis, and frequency-response measurements. It is also capable of MLS, sweep and simple sinusoidal measurements, file and design management as well as crossover design and simulation.

It also comes with some decent help files but still requires that you have a clue about what you are doing. Previous experience with CAD or measurement software is desirable. I can honestly say, however, that it is a most remarkable piece of software, and I have come to rely on it quite heavily. Once you get the hang of it, it becomes very easy to use. It is very helpful to construct a measurement jig for use with the package, as I have. More information about the jig is available on the Internet.[3]

My microphone is a calibrated Panasonic capsule from Liberty Instruments[4], and the preamp is a 20dB gain, TL072-based design similar to the Wallin preamp[3], but without the clipping indicators. I also use XOPT and an old SPICE simulator. XOPT is a crossover optimizer that is no longer available.

Note that I performed all frequency-response and impedance measurements with SpeakerWorkshop 1.00, and measured all frequency-response data at one-meter, one-third octave smoothed, and with a Sound Blaster Live Platinum 5.1 Live-Drive card set for 48kHz sample rate.

## CONSTRUCTION

The cutting details of the MDF pieces are given in *Fig. 2*. Particularly important is the fact that the tubes are nearly never the exact size that they are sold

**TABLE 1**
**T/S PARAMETERS FOR THE VIFA PARTS EXPRESS 299-246**

| PARAMETER | PUBLISHED VALUE | MEASURED VALUES |
|---|---|---|
| Frequency Response | 65–12000Hz | approx. 65–12000Hz |
| Resonant Frequency ($f_s$) | 91.7Hz | 57Hz (measured with SpeakerWorkshop and verified with HP 3577A network analyzer) |
| Sensitivity | 92dB/2.83V/1m | - |
| Magnet weight | 14.6 oz | - |
| Nominal Impedance | 4Ω | 4Ω |
| $Q_{MS}$ | 3.1 | 3.6 |
| $Q_{ES}$ | 0.80 | 0.663 |
| $Q_{TS}$ | 0.637 | 0.561 |
| $V_{AS}$ | 0.14ft$^3$ (3.96 ltr) | 0.452 (12.8 ltr) (All Q values and $V_{AS}$ measured by SpeakerWorkshop using added mass method) |
| $X_{MAX}$ | 4.5mm` | - |

as. It's probably the same reason why a 2 by 4 is never 2″ by 4″.

Measure the tube diameters before cutting a circle or groove, especially for the outer 12″ cut. It must be a snug fit inside the tube, but not so much so that it is impossible to assemble. The grooves for mounting the inner tubes are ¼″ deep as shown. That was enough to hold the tubes in place.

Refer again to the multi-angle view of the enclosure as given in *Fig. 1*. It is constructed from four different diameters of tubing, one inside the other. The tubes are assembled together with the MDF fronts and backs by gluing the ends of the tubes into slots routed into the MDF pieces. A Jasper circle jig or other fixture is a must for the routing. The tube sections are 10.25″ long for the 6″, 8″, and 10″ diameter pieces, with the outer 12″ diameter section 12″ long.

I cut the tubes with a hard-toothed cross-cut handsaw. The trick to getting a good square end cut on a tube is to wrap the tube with a piece of tractor-feed computer paper or similar long strip more than, say, 4″ wide. As long as the paper is tight to the tube, it will line up with itself once wrapped and define a cut line around the tube that is square.

The tubes and lengths selected result in a path length of about 44″. This gives a $\lambda/4$ length of:

$$1088 \times 12/(4 \times 44) = 74\text{Hz}$$

where 1088 is the speed of sound at sea level in ft/s. The approximate length in inches of the path is 44″.

Even though I selected 6, 8, 10, and 12″ tubes, it is the space between consecutive tubes that forms the line area, and you end up with a cross-sectional area nearly equivalent to a 6″ diameter tube (±22%). This is probably constant enough for an application like this. I have seen working designs with greater variations—more on the "minus" side—to allow the line to fit in an enclosure of the smallest possible external dimensions. The vent holes at the end add up to about 7.36 in$^2$, which is equivalent to about a 3″ diameter port. This is a constriction when compared to the rest of the line.

I selected the holes for appearance and convenience and simply drilled them with a ⅝″ drill bit. I have not quantified the effect of the constriction, but I am happy enough with the results to ignore it if there is one. They may be opened up to about double the area if desired.

I coated the edge of the front baffle with a thin layer of carpenter's glue, inserted it into the rear of the 12″ tube, and slid it in place to ease assembly. I glued the 6 and 10″ sections to the grooves routed into the front (baffle), with the 8″ section glued to the groove routed into the rear. The glue I used for this was regular yellow carpenter's glue, which adhered to the tube material very well, and the final bond was very sturdy.

## STUFFING

After the glue dries, start the enclosure stuffing, which is more like wrapping. The material in this case is the polyester fiberfill usually found in stuffed animals and pillows. You can purchase it at a fabric store in bags resembling pillows. It unfolds into a sheet and is sold by unit area, not by unit mass.

I stuffed the enclosure as indicated in *Table 2*. In the future I would be inclined to purchase the material in bulk off a large roll (as I later discovered it was available). The folding and bagging puts puckers and irregularities in the material, which will hinder your ability to cut it into regular shapes. The material unrolled to about 80″ × 100″ × ½″ thick when uncompressed.

Each of the fill sections is made from multiple strips of the polyester material simply because I needed the length and it simplified the stuffing. In the case of the inside of the 6″ tube, for example, the breakdown was two pieces 90″ long plus a piece 70″ long. It's the total length of 250″ that mattered. To put things into perspective, this quantity of

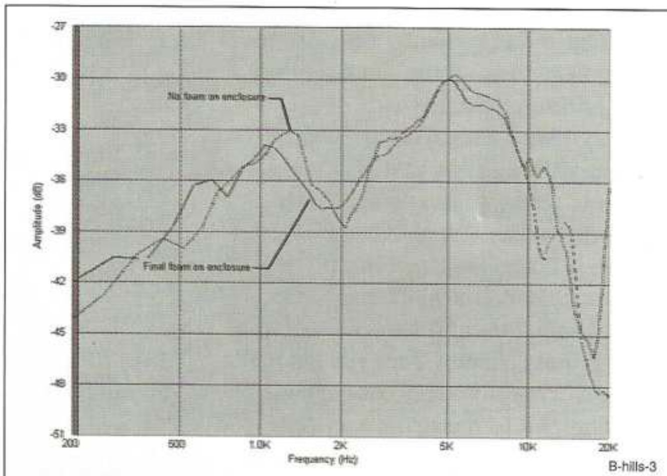


**FIGURE 3: Improvement in the frequency response around 2kHz by adding foam to the enclosure edge measured by SpeakerWorkshop.**

**PHOTO 2: Enclosure halves ready for stuffing (one enclosure).**

fiberfill weighed 5 oz. This equates to about 0.31 lb. In a 6″ diameter tube 10″ long, that equates to 1.9 lb/ft$^3$, which is the approximate stuffing density used throughout, except for the last section, which is about 1.25 lb/ft$^3$.

I rolled the 6″ tube stuffing with moderate tension until I obtained a cylinder about 9.25″ long by 8″ in diameter, and then inserted this into the 6″ tube along with the wire for connecting the woofer, which runs along the inside wall of the tube. The wire for connecting the tweeter runs down the exterior of the 6″ tube and is held in place with tape. I used a small diameter wooden stick (like the handle of a wooden spoon) to aid in wrapping the exterior of the 6″ tube with stuffing. I wrapped the polyester strips around the handle of the wooden spoon and inserted the stick into the space between the 6 and 10″ tubes and fixed the polyester to the outside of the 6″ tube. I then spun the stick so that the polyester wrapped around the outside of the 6″ tube in a manner similar to spinning cotton candy onto a paper serving cone.

I simply wrapped the exterior of the 8″ tube by hand and gently stuffed the four pieces for the interior of the 12″ tube evenly into place with a ruler. You can hold external tube wraps on the 6″ and 8″ tubes in place with a rubber band or a section cut from support hose (panty hose). Try not to compress the stuffing too much.

I tried a couple of different stuffing densities—a low density stuffing (<1 lb/ft$^3$) and the final one (nearly double

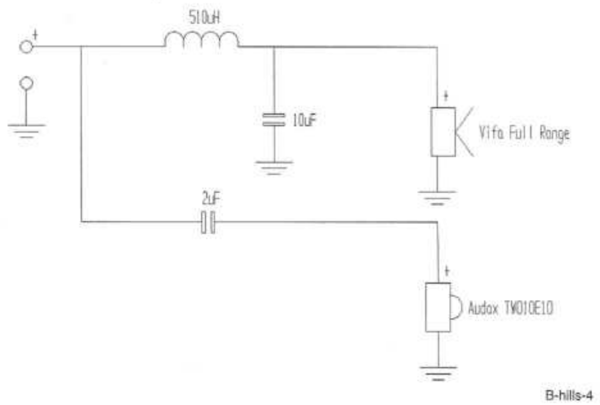


**FIGURE 4: A schematic of the crossover network.**

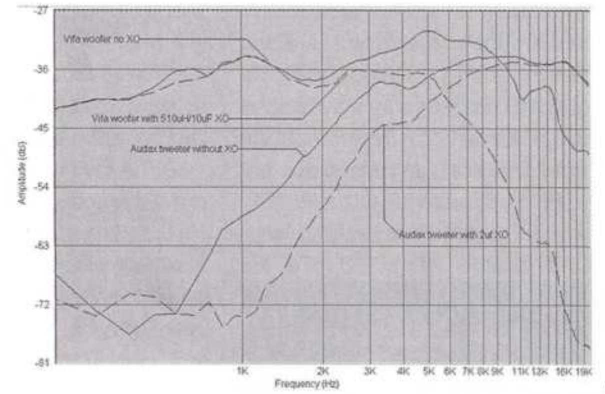


**FIGURE 5: Plot of individual driver responses with and without the effects of the crossover network measured by SpeakerWorkshop.**

that) given in *Table 2.* I listened to and measured both stuffings, and ultimately selected the higher density stuffing more on the basis of measurement of the low-frequency performance (near field) than listening tests. Both stuffings sounded acceptable. A complete parts list is provided in *Table 3.* The stuffed enclosures are shown in *Photo 2.*

## A MINOR GLITCH

The selection of enclosure shape is critical to the performance of a loudspeaker. As it happens, I've selected one of the worst shapes for an enclosure. I've seen Olsen's plots[5] regarding the effect of enclosure shape on frequency response plenty of times since I first became interested in loudspeaker design. Spheres are the best; cylinders are not the best.

My measurement of the frequency response showed a 6dB suckout at 2kHz. This is purely a result of the selection of a cylinder with a driver in the center of one end, and because the driver is equidistant from all of the enclosure edges. It's roughly a half wavelength from the driver edge to the enclosure edge at 2kHz. Any edge-diffraction effects are maximally reinforced in the far field.

A way to deal with this would be to select a different shape for the MDF baffle (but, of course, still route a round groove for the tubes). To bear out my theory, I cut a 12″ diameter hole in a 2′ × 4′ piece of Styrofoam and inserted the enclosure front into the hole so that the drivers were flush with the surface of the Styrofoam mimicking a 2′ × 4′ baffle. The frequency response flattened out. Perhaps a 14″ × 14″ square or an obround shape would have been a better choice for the baffle to minimize the degree of the effect.

Another way to deal with this is to apply some form of edge treatment to suppress the diffraction and subsequent cancellation phenomenon. This is the solution I chose. You can introduce a lossy material at the edge of the baffle; I selected a waffle or convoluted foam normally used as packing in shipping boxes. The foam was about 2½″ thick and was cut into 3″ wide strips for wrapping around the enclosure edge.

This approach is similar to one often employed to smooth ripples in antenna radiation patterns at antenna test ranges and in certain fixed installations. In those cases a lossy carbon-loaded foam (E-field) or ferrite-loaded paint (H-field) is employed. For acoustic applications foam works just fine.

*Figure 3* shows the results of a one-

**TABLE 2**
**DIMENSIONS OF FILL MATERIAL FOR THE ENCLOSURE**

| SECTION | POLYESTER FILL SIZE |
|---|---|
| Inside of 6″ tube | 250″ × 9.25″ |
| Outside of 6″ tube | 220′ × 9.25″ |
| Outside of 8″ tube | 250 × 9.25″ |
| Inside of 12″ tube | Four strips 7″ × 78″ |

**TABLE 3**
**PARTS LIST**

| DESCRIPTION | QUANTITY |
|---|---|
| 6″ forming tube | 2′ |
| 8″ forming tube | 2′ |
| 10″ forming tube | 2′ |
| 12″ forming tube | a bit more than 2′ |
| 2 MDF | approximately 4ft$^2$ |
| polyester stuffing | approximately 3 lb |
| speaker wire | approximately 5′ |
| 10µF bi-polar cap | 2 |
| 2µF polyester or polypropylene cap | 2 |
| 510H/0.3Ω coil | 2 |
| Vifa full range Parts Express P/N 299-246 with whizzer cut off | 2 |
| Audax TW010E104 tweeter | 2 |
| Terminal cup | 2 |
| screws, putty, glue, foam, carpet, and so on | as required |


PHOTO 3: The assembled crossover network.

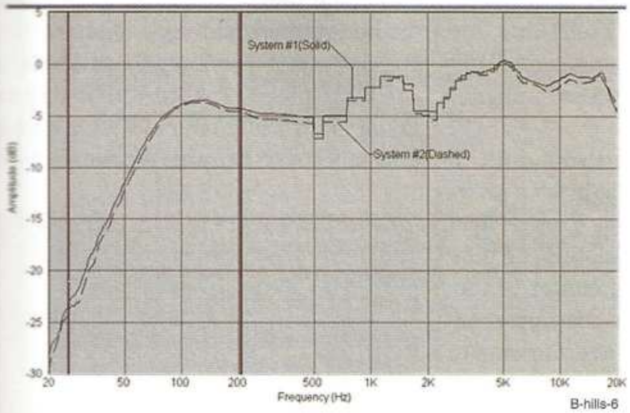


**FIGURE 6: The total response of both systems measured by SpeakerWorkshop.**

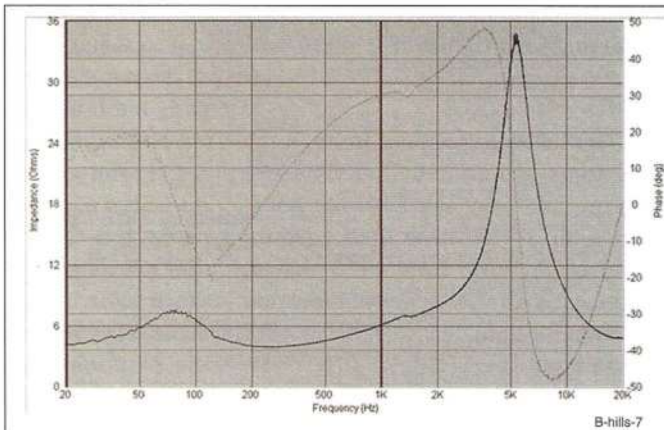


**FIGURE 7: Plot of the system impedance measured by SpeakerWorkshop.**

foot diameter enclosure with and without a small foam ring. The suckout doesn't disappear, but it is reduced.

You assemble the enclosure by resting the front baffle assembly on its front and inserting the rear section with a twisting motion in the direction of the stuffing wrap to keep it from coming undone. When you're about to insert the rear panel, brush carpenter's glue on to the edge of the MDF panel and gently tap it into place.

## THE CROSSOVER

The crossover schematic with drivers is shown in *Fig. 4*. A first-order high pass is used on the tweeter (per Audax) and a second-order low pass for the woofer. The assembled crossover is shown in *Photo 3*. All components are hot-melt-glued to the terminal cup. All connections are made by soldering, and Teflon sleeving is used for the insulation of any bare leads.

I tried to get by with a first order on the woofer, but the peak in the response at 5kHz needed to be tamed. The crossover shown provided the flattest frequency response. A plot of the driver responses with and without the crossovers is given in *Fig. 5*, with the total response in *Fig. 6*. The staircase effect in *Fig. 6* is probably due to the resampling after splicing the near-field low-frequency data to the on-axis response. It can be removed with smoothing; however, I left it in as the data had already been smoothed once.

I measured the data below 500Hz in the near field about 3″ from the baffle in an attempt to sum the port and driver responses. I then spliced it into the on-axis 1m response using SpeakerWorkshop. The system impedance is shown in *Fig. 7*.

## MORE CONSTRUCTION

You can mount the drivers on the front baffle with screws and seal the drivers against the baffle with plumber's putty or other gasket material. The woofers and terminal cups use #8 × ¾″ pan-head screws; the tweeters use #6 × ½″ pan-head screws. The drivers are electrically connected in phase. The other ends of the wires are, of course, connected to the crossover per the schematic.

Mount the terminal cup with sealing putty and glue the industrial carpet to the front baffle with contact cement and tube—cut the holes for the drivers and terminus details afterward (trust me!). When the driver holes are cut, insert the drivers for fit. Then use the driver flanges as templates for cutting the carpet so you can mount the drivers on the wood. The foam for the edge diffraction is held in place with hot-melt glue.

## SOUND

I've been listening to these units in my living room system (much to my wife's chagrin), and they sound pretty good. There's more real bass than I would have ever expected from a 5¼″ driver, and the cone excursion doesn't look too high even for loud, low bass, although I haven't tried the TELARC *1812 Overture* yet! The highs are unremarkable, but for an $8 tweeter they're acceptable. All in all, they are much better than the little Alpines I've been using. They are easy to drive and mount (hanging by light chain and hooks from the floor joists above my workbench).

## FINAL THOUGHTS

This type of enclosure is limited to smaller "mid-bass" drivers. I'd hate to see such a design attempted with a 12″ woofer. Assuming that the depth can be tolerated, I could see extending the enclosure to 18″ long, giving a low end of about 45Hz assuming four sections. Beyond that, tube diameters up to 24″ are available, and if you had the patience you could build a reflex of ten tubes. An 8″ deep enclosure could render an 80″ path, but it would be two feet in diameter. Not a pretty sight.

If I was going to do this again, I might not use a circular baffle. An alternative is to offset the tubes axes so that they are tangent to one another, so that the woofer is not in the center of the baffle. This would reduce the ripples in the response. As they are, however, they sound better than the low cost would indicate (especially the bass), and I'm happy with their appearance—foam and all!


### REFERENCES

1. Loudspeakers on Damped Pipes—Part One: Modeling and Testing, Part Two: Behavior, by G.L. Augspurger, presented at the 107th convention of the Audio Engineering Society, Sept. 24–27, 1999. New York City, 24–27 Sept. 1999, Preprint No. 5011.

2. Website of Audua Inc., Designers of SpeakerWorkshop—www.speakerworkshop.com.

3. Website for information about the Wallin preamp and Jig II for use with SpeakerWorkshop—www.gti.net/wallin/audio/audio.html.

4. Website of Liberty Instruments—www.libinst.com.

5. Olsen H. F., "Direct radiator loudspeaker enclosures," JAES, 17 No. 1, 22–29 (1969).



I would like to thank my wife Margo for her support and my friend Pat Hill for suggesting that I write this article in the first place. I would also like to thank Mark Zachmann at Audua for his assistance with SpeakerWorkshop. ❖


### ACKNOWLEDGMENTS

1. This design is certainly not meant to compete with the recent "THOR" design published in the May '02 issue of *aX*. I believe that while it may share many of the attributes of a transmission-line design, it probably isn't the high-resolution instrument that "THOR" is. It does, however, represent a compact design that doesn't compromise too much on line length in order to save space. The design was also meant to introduce what I believe is a new idea using concentric tubes to produce a compact transmission-line design.

2. Recently *aX* published "THOR," a scientifically designed transmission-line loudspeaker based on the work of G.L. Augspurger[1]. "THOR" incorporated a number of features said to give good low-frequency performance, which could also be modeled on a computer (a tapered line, offset drivers from the end of the line, and an air volume behind the driver). My concentric reflex design doesn't borrow as much from Augspurger, nor was it modeled on a computer. I simply tried to stay within the range of $f_s$/fp (woofer resonance frequency to pipe resonance frequency) recommended in the paper. The notion of a compact transmission line has always interested me, given the smaller living rooms I've had to live with. Unfortunately, there is no room for a λ/4 line at 20–40Hz in my house. This was a method I conceived to address the issue of speaker size.