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THE LOUDSPEAKER JOURNAL

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A REFLEXHORN HYBRID
by BILL FITZMAURICE

WE AUDITION & TEST AUDAX A651
by DENNIS COLIN & JOSEPH D'APPOLITO

UPGRADING KEF's CS5 SYSTEM
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LET'S DUMP DAMPING FACTOR
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THE AR-3a
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TRUE AUDIO DESIGN

True Audio has released Version 2.1 of its WinSpeakerz, "The Speaker Design Toolbox." A 32-bit application, the loudspeaker simulation software now runs under Windows NT as well as Windows 95. MacSpeakerz is also available for use with Macintosh computers. To download an evaluation copy or to order either program, visit True Audio's website at http://www.trueaudio.com. True Audio, 349 W. Felicita Ave., Ste. 122, Escondido, CA 92025, phone/FAX (760) 480-8961.

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CANTON ACTIVITY

Canton Electronics introduces the Fonum AS 30 and Karat AS 4, two new active subwoofers for home-theater and two-channel audio environments. These units offer dual ported 9" woofers, a built-in mono 100W amp, an adjustable crossover-frequency range from 50–150Hz, and bass level controls. The two active subwoofers can be operated in both stereo and Dolby Surround systems. Canton Electronics Corp., 915 Washington Ave. S., Minneapolis, MN 55415, (612) 333-1150, FAX (612) 338-8129.

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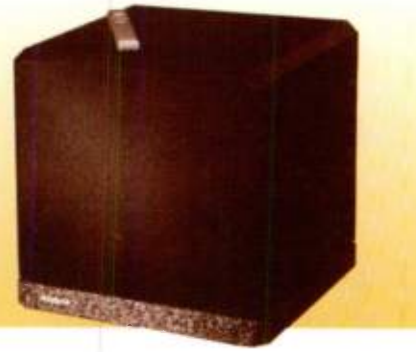
BOUSQUET: NEW ALMA EXEC

Effective September 1, Carol Bousquet was appointed as the Executive Director for the American Loudspeaker Manufacturers Association (ALMA) on an interim basis. In addition to having served on the ALMA Board of Directors for four years, the new director chairs the Boston Section of the Audio Engineering Society and the AES Women in Audio Committee. Bousquet looks forward to "being an integral part of the Association's new future direction with great anticipation." ALMA's new contact address is: 39 Ames Rd., Groton, MA 01450, (508) 448-5658, FAX (508) 448-6851, E-mail cbous@ma.ultranet.com.

POWERED SUBS

Velodyne Acoustics announces two new subwoofers, the FSR-12 and FSR-15. The FSR-15's driver size is 15" and includes a power reserve of 250V RMS and 750W of peak output power. The FSR-12, with a 12" driver, includes 120W and 265W of peak output power. Both are finished in black woodgrain vinyl with a cloth grille and granite-like trim. Velodyne Acoustics, Inc., 1070 Commercial St., #101, San Jose, CA 95112, (408) 436-7270, FAX (408) 436-7276.



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About This Issue

Trying unsuccessfully to hold our enthusiasm in check, we have to admit that this issue represents a collection of some of the finest material ever to appear in *Speaker Builder*.

Bill Fitzmaurice breaks new ground and, in the process, smashes traditional concepts about folded horns. He places the horn-loaded woofer in a ported box and feeds the front-wave *and* port output into the horn. With this so-called snail horn design (which resembles the outline of a snail's shell), the author may very well have realized his quest for the ultimate bass-guitar speaker system ("The Snail Horn," p. 6).

We continue our discussion of horns—this one the classic KEF CS5. **Douglas Hurlburt** completes the metamorphosis of a vintage unit with a new crossover and enclosure design applied to the classic drivers, and significantly improves the KEF sound ("From Caterpillar to Butterfly," p. 20).

Next, we present the "mother of all DIY restorations projects." **Tom Yeago** begins a five-part series unlike any we've seen. He completely dissects a pair of AR3*a*s and rebuilds them from the inside out. You can apply his extensive modifications to other speaker systems as well ("Remaking the AR-3*a*, Part 1," p. 30).

Engineer **Juan Castillo** from Mexico examines the use of resistors for signal attenuation in crossover designs ("Crossovers and Resistors," p. 36).

We are pleased to bring you the first of a series of unprecedented speaker kit reports. For this issue, **Dennis Colin** assembles and performs listening tests on the Audax A651. **Joe D'Appolito** then applies his extensive testing talents on this unit in his lab. The result sets a new standard for kit evaluation ("Test Drive," p. 42).

Continuing our high-quality testing, **Vance Dickason** evaluates two tweeters from Morel, comparing his measurements against the manufacturer's specifications ("Driver Tests," p. 58).

You've undoubtedly encountered the term damping factor before, but what exactly is it, and is it important? **Dick Pierce** cuts through the hype and delivers the straight scoop about its value ("Loudspeakers 101," p. 52).

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The peculiar evil of silencing the expression of an opinion is, that it is robbing the human race; posterity as well as the existing generation; those who dissent from the opinion, still more than those who hold it.
JOHN STUART MILL

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Printed in the USA.

Speaker Builder (US USSN 0199-7920) is published every six weeks (eight times a year), at $32 per year, $58 for two years; Canada add $8 per year; overseas rates $50 one year, $90 two years; by Audio Amateur Corporation, Edward T. Dell, Jr., President, at 305 Union Street, PO Box 494, Peterborough, NH 03458-0494. Periodicals postage paid at Peterborough, NH and an additional mailing office.

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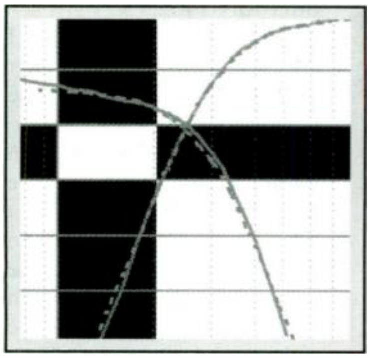
THE LOUDSPEAKER JOURNAL

VOLUME 18 NUMBER 6 SEPTEMBER 1997



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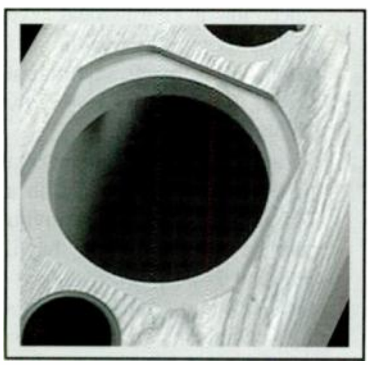

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THE SNAIL HORN

By Bill Fitzmaurice

The completed Snail—small, but very powerful.

Once again I embarked on the endeavor to produce the ultimate bass-guitar cabinet—but one with a volume of less than 6 ft^3. My Superbass cabinet (*PA* 1/97) certainly works well enough—in fact, it's overkill in a small club. Why carry more than you must is my motto, so I set about designing a smaller cabinet to house an EVM-12L that I have on hand for gigs where Superbass is too much.

A good reference point for what this driver can do is Bruce Edgar's "Showhorn" (*SB* 2/90), but that cabinet is too large—and also would require mid-drivers, which I wanted to avoid. Instead, I decided on a set cabinet size, 24″ high, 19½″ wide, and 20″ deep. This would allow—using ¾″ plywood as material—a mouth opening of 405 in^2, a bit more than half that of the Showhorn.

My goal for the flare frequency would be 100Hz. Having the horn one-quarter wavelength long required about 33″, which I could achieve by using a folding design with a side view resembling a snail's shell—hence the name (*Fig. 1*). If the Showhorn's performance was any indicator, I could expect a steep rolloff on the low end below 100Hz, with a usable high-frequency of 500Hz—all in all, not a worthwhile endeavor for an instrument with a range from 42Hz to over 5kHz.

MAKING ASSUMPTIONS

These values, however, presumed the correctness of several assumptions made not only by Bruce Edgar, but also by most other horn designers, about the workings of horns and their drivers. But my own previous experiences contradict these assumptions.

The first is that horns will work only to a certain cutoff frequency, below which they will cease to function. In the past, I have fed horns with duct outputs they were technically too small to "pass," yet the performance below the nominal cutoff was nonetheless enhanced.

The second assumption is that in a horn system you must enclose drivers in a sealed chamber. Even the ancient Altec A-4, a masterpiece of empirical design that you still find in half of America's movie theatres, worked very well with a horn coupled to a bass-reflex box—a very poorly designed preThiele/Small box, at that.

Finally, assumption three is that "mass rolloff" of the driver makes any high-end response from a folded horn impossible. But I have played through many a folded-horn cabinet, notably the Ampeg SBT (circa 1970), which used Altec 15″ drivers with acceptable, if not astounding, high-end response.

BREAKING RULES

So, tossing assumptions aside, I also decided to break another rule—I would feed not only the front wave of the driver, but also the output of a duct into the horn throat. Two reasons underlie this: first, by feeding the duct into the throat—rather than venting it separately outside the cabinet as I did with Superbass—I could use the entire frontal area of the cabinet as horn mouth. Also, I was convinced that the horn would have an amplifying effect on the port output, even though that output would theoretically be below the horn's passband.

Rather than put the driver in a closed box, I would put it in a T/S cabinet, tuned for maximum output in the desired passband, and send that cabinet's total output into a horn, much like placing a cabinet in a room corner to enhance bass. Using Keele's Pocket Calculator program,[1] with the EVM-12L parameters of F_s = 55Hz, Q_{ts} = 0.23, and V_{as} = 2.9 ft^3. I arrived at a box volume of 0.64 ft^3, with a resulting F_3 of 112Hz and a box tuning of 87Hz—perfect for its intended use for guitar, but an octave too high for bass. With some alignment "jamming," I thought I could get an F_3 lower than 112Hz.

The next rule I decided to break was that folded horns had to consist of a series of flat panels. Straight horns use curved panels, so why not do the same with a folded horn? The woodworking skills required are not that great, though there is no substitute for having the right tools—more on that later.

I put my design on paper, using a flare taper also of my own making—a hyperbolic design (*Fig. 1*). Then out to the workshop to build it. To my knowledge, no one has ever built a box like this before, so I devised the construction techniques as I went—some aberrations in the photos accompanying the article reflect that fact.

CONSTRUCTION

The first step in constructing this box is to lay out the horn pattern on a piece of ¼″ scrap plywood (*Photo 1*), cut to the dimensions of the cabinet side: 22½″ high by 19¼″ wide (*Table 1* is the parts list). Starting at one end of the plywood, make marks following the horn flare as detailed in *Table 2*. From the point where the horn turns 90°, make the dimension marks relative to that shift.

After 16 points are determined, the horn again turns 90°. Its final section is flat, since it coincides with the driver baffle. Draw a straight line from the last point to a point 2″ above the lower edge of the panel at the mouth opening. Drive a 1″ brad into the pattern at each of the marked points. Cut a thin sliver of plywood, about ¼″ thick and 24″ long. Using another brad to secure one end of the sliver, bend it to follow the path of the nails and trace the resulting curve onto the pattern (*Photo 1*).

Remove the brads and trace a second curve ½″ inside the first. This, together with the first curve, outlines the thickness of what will be the actual horn panel. In the case of the baffle, the inner trace is ¾″ inside the first. Cut the excess plywood from the curved sections on the pattern—a saber saw will do, but a small band saw works much better.

Now cut out the two cabinet sides. I used ¾″ plywood, though ½″ would suffice, since the sides are so well braced by the horn that vibration is not an issue (if you opt for ½″ sides, be aware that it will make the cabinet ½″ narrower, which will alter the dimensions of the top, bottom, and back pieces). First with one side, and then the other in mirror image, trace the horn pattern directly onto the sides (*Photo*

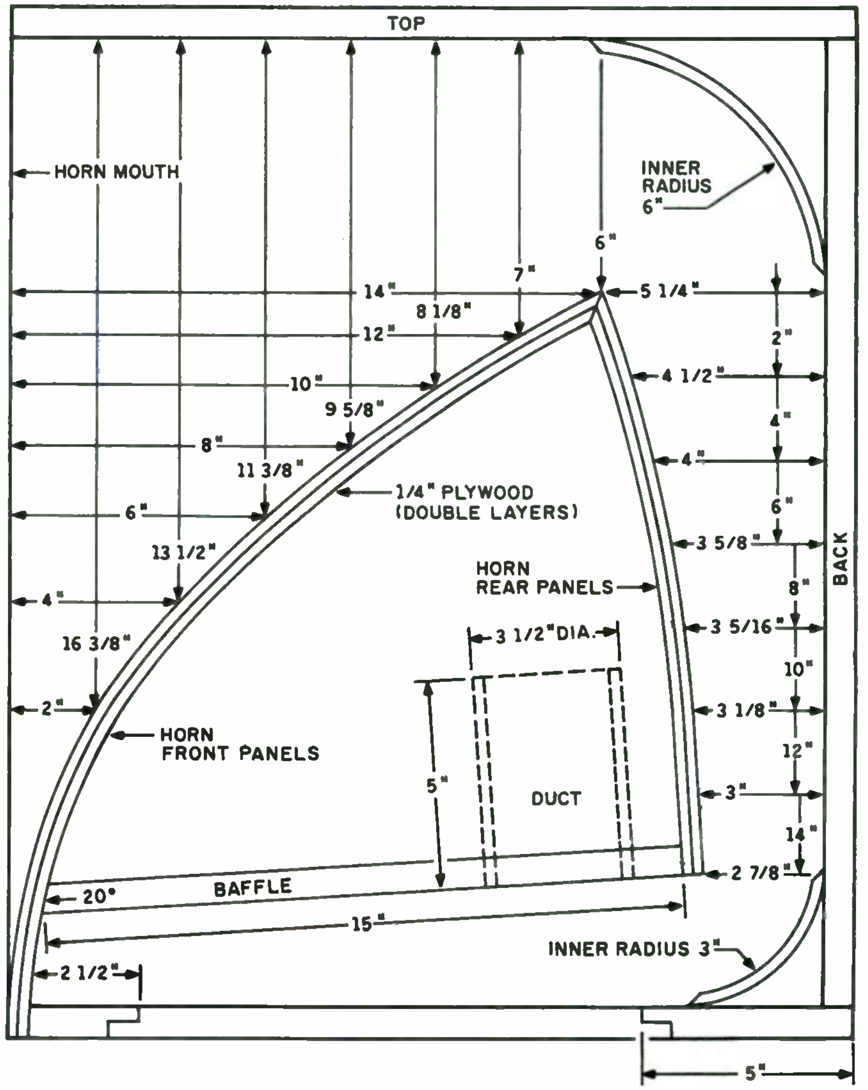

FIGURE 1: Cabinet side view—the Snail shape is clear. Front horn-panel intersect points are measured from panel edge at mouth opening and inside of top panel. Rear horn-panel points are measured from the intersection of front and rear panels and inside of the cabinet back. Note that baffle's leading edge (intersection with front horn panels) is cut at a 20° angle.

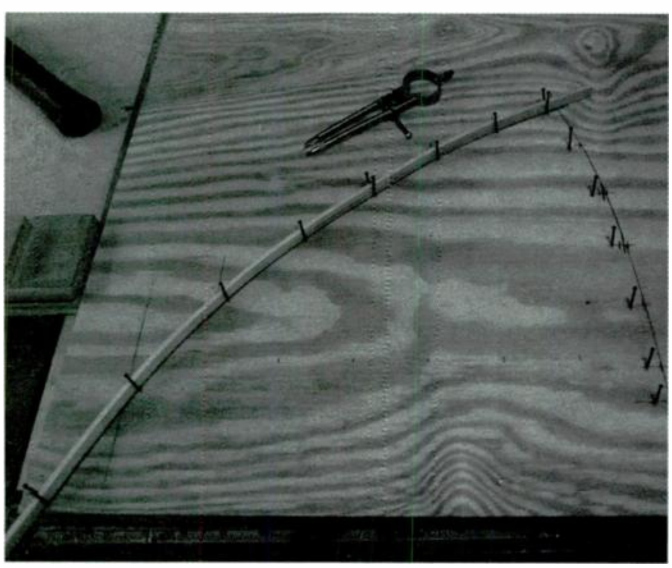

PHOTO 1: Tracing plotting points on plywood to produce the pattern.

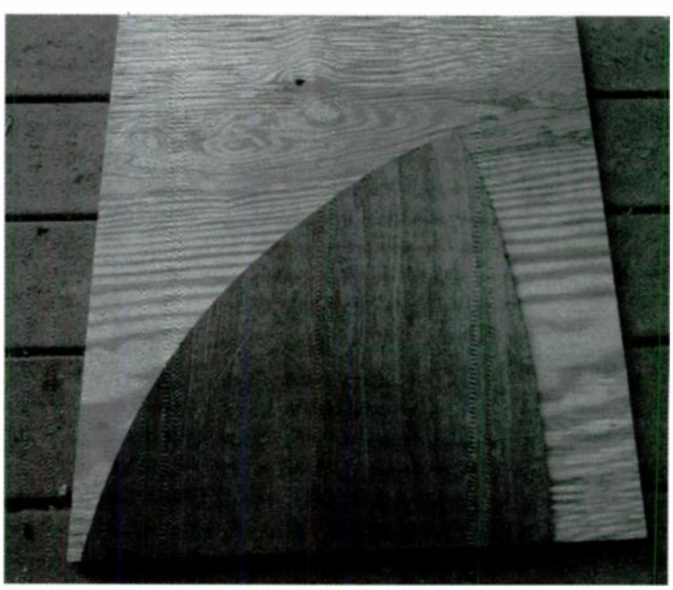

PHOTO 2: Tracing pattern to side.

2), lining up the bottom of the pattern with the bottom of each side, and leaving a ½″ gap between the pattern and the leading edges of the sides at the mouth opening.

On a table saw, cut from the pattern the selvage on the baffle-joint line. Place the patterns back on the sides and trace the baffle location (*Photo 3*). Note that there will be a small "tail" where the horn extends below the baffle. Finally, cut the pattern again on a band saw 1½″ inside the pattern edge, and bisect the pattern at the "point" of the curves. The resulting three pieces (*Photo 4*) are the patterns used to trace the horn braces, which you can cut either from ¾″ stock or from so-called 5/4″, which actually measures 1″ thick. The 5/4″ is stronger and makes construction easier, though ¾″ will do in a pinch. I used ¾″ on the braces attached to the cabinet walls, but 5/4″ on the inner braces for extra strength. You can cut the braces from nominal 6″-wide pieces of stock 18″ long—four sets in all. Here a band saw really works better than a saber saw, which seldom gives a true 90° cut.

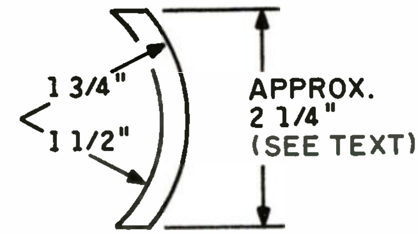

FIGURE 2: Throat wing deflections—end view.

GLUING AND SCREWING

Assembly procedure is standard, using woodworkers' glue—except where construction adhesive or a hot-melt glue gun is specified—and drywall screws of either 1″, 1¼″, or 1 5/8″, choosing the longest that will not penetrate too far. Predrill and countersink all screw holes. If you intend to round off the cabinet edges (for carpet covering), be sure to countersink all screw heads about 3/16″.

Glue and screw the two larger braces to the sides at their marked positions. Cut the baffle, with the angled end (cabinet front) cut at 20°. Mark and drill out the driver-mounting bolt holes and the driver hole (11 1/8″ diameter) with the driver centered on the panel. Rout a ¼″-deep recess in the baffle to accommodate the driver frame, making sure the driver fits.

With either a hole saw or a saber saw, cut a 3½″ hole for the duct, placing it as close as possible to the driver and baffle edge, and as far as possible from the rear of the baffle. Install 3/16″ T-nuts in the baffle-mounting bolt holes. Glue and screw the baffle in place to both cabinet sides (*Photo 5*), and attach the short horn-brace pieces to each side below the baffle.

Next cut the bottom front, 2½″ by 19½″. Plywood that is nominally ¾″ thick seldom measures exactly that—it's usually more like 23/32″; therefore the actual cabinet width may well be 19 7/16″. If you make the sides from ½″ plywood, the actual width may be 18 15/16″, so measure your stock carefully to determine how wide to cut the remaining parts.

Use either a table saw or router to dado one edge of the bottom front to one-half the panel thickness, ¾″ in from the edge. Then glue and screw it in place, leaving ½″ clearance to the cabinet front (*Photo 6*). At this point, also screw (but not glue, because it's temporary) a 19½″ × 1″ brace across the cabinet top to stabilize the structure.

INSTALLING THE HORN PLATES

Now install the two remaining sets of braces 5″ in from each side panel, screwing and gluing them to the baffle and to each other at the point (*Photo 7*). Try fitting the driver again to make sure its frame does not touch the braces. You may omit the smaller pieces between the baffle and the bottom, since the span is so small.

The horn plates are next, each one fashioned of two pieces of ¼″ plywood, with a layer of adhesive in between, producing, in effect, a flexible panel of ½″ plywood. Cut the plywood slightly narrower than the cabinet's interior width to make assembly easier, and a bit longer than the finished size (you trim it after installation).

Install the rear horn plates first. Apply the construction adhesive generously between the two sheets—it cures slowly, whereas regular woodworking glue might cure too fast. The two layers must be free to slide against each other before the adhesive cures to allow for the different radii when you bend them.

Temporarily attach the two panels together at one end only with a couple of screws, apply a generous bead of adhesive to the braces, and screw the panels to the "point" of the horn. Drill the pilot holes through the panels only as you bend them into place, since the bending process will shift the pieces relative to one another. Use at least two long (24″) clamps to gradually pull the double panels into place, driving screws every two to three inches along the braces, until the bottom of each double panel is screwed to the baffle (*Photo 8*). Using a saber saw, trim the

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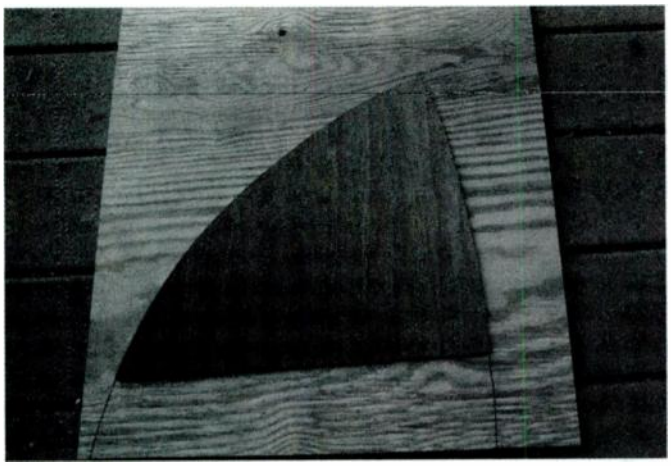


PHOTO 3: Tracing the baffle location on the side.

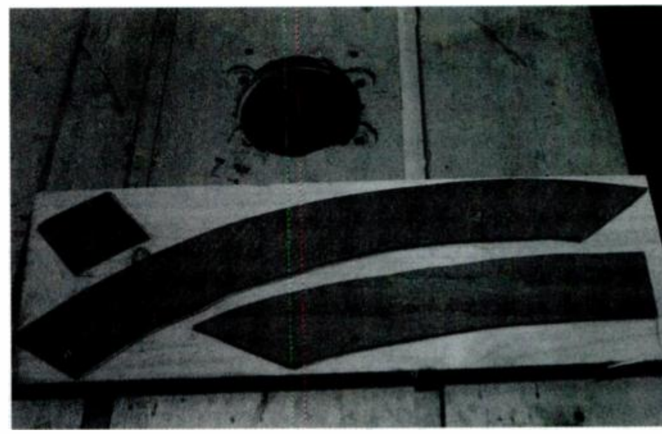


PHOTO 4: Tracing the three horn-brace pattern pieces onto 5/4″ stock.

excess panel length at the baffle, and then round off the joint with a sander.

Cut three pieces of 1″ × 1″ stock to fit the spaces between the braces at the horn "point," gluing and screwing them to the installed horn panel after removing the temporary holding screws. Install the front horn plates in the same fashion as the rear, again starting at the horn point and working toward the cabinet front. Trim any excess panel at the cabinet front, and sand the panel edges at the horn point to make a smooth rounded joint. With the panels in place, the structure is now stable, so you can remove the temporary brace (*Photo 9*).

Drill a ¼″ hole through the rear horn panel for the speaker wire to pass through; you will eventually mount the jack in the rear of the completed cabinet. Use 12- or 14-gauge speaker wire, caulking around the hole with hot-melt glue for an airtight seal. Line about half of the chamber with acoustic foam. Rim the driver-mounting hole with neoprene weatherstripping, attach the wires to the driver, and bolt the driver in place for testing.

TUNING THE BOX

While I used an EVM-12L, a number of other drivers will work, with some caveats. They must be high-efficiency MI drivers (95dB/W or more), with F_s between 40 and 60Hz, and Q_{ts} of 0.30 or less. An excellent alternative at a low price is the Eminence Cast Frame 12″. In any event, you should tune the box to your driver, even if it is an EVM, to take into account specific variations.

Tuning is easy if you have a sound generator or test-tone CD and a sound meter. No serious speaker builder should be without these tools. Set the sound meter about a yard away from the front of the speaker, and feed a test tone of 40 to 42Hz into it.

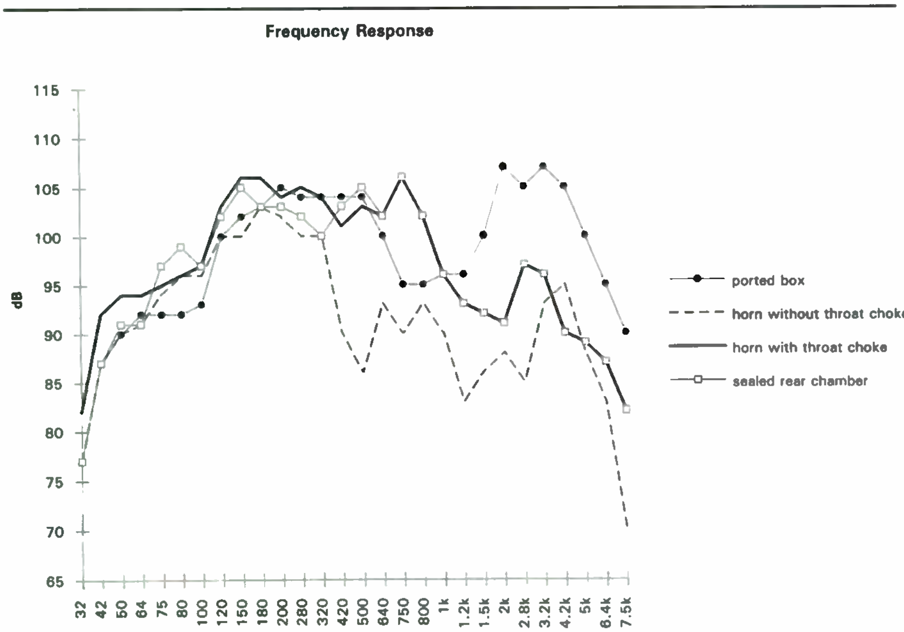


FIGURE 3: Frequency responses.

Insert a length of 3″ PVC into the porthole, using hot-melt glue to seal around the edge—you can easily strip this away with a screwdriver blade to remove the duct so as to try different lengths.

The longest pipe that will fit is about 10″, though if necessary you can use a longer piece by extending the duct beyond the baffle. Try shorter pieces in 1″ increments until the meter gives its peak reading. For my driver, the pipe ended up 5″ long.

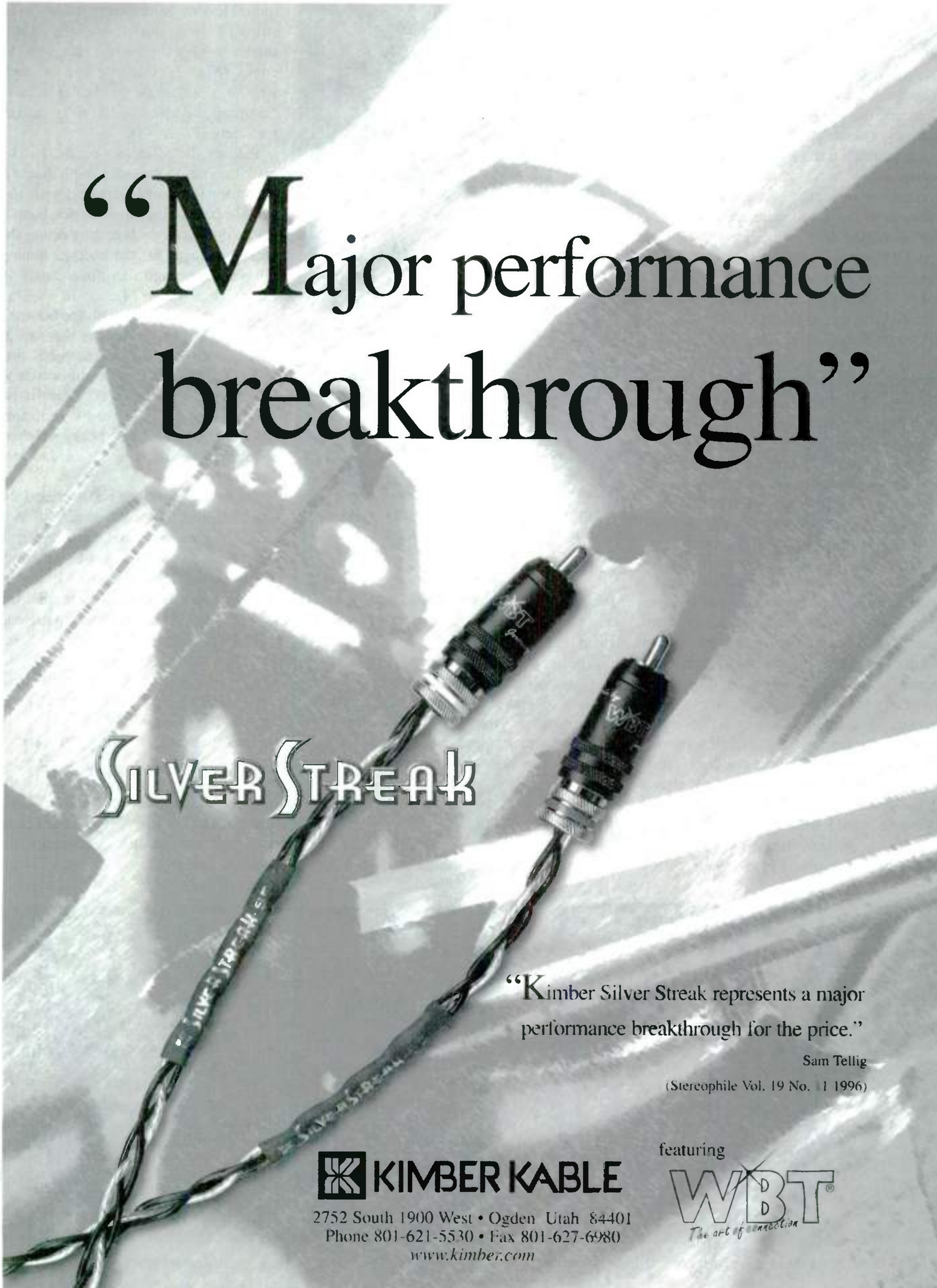
Next, feed a 30Hz test tone to the driver at a fairly high level, listening for air leaks in the box. If you do find some, you can quickly seal them with the hot-melt glue gun. If you plug any leaks, you must repeat the tuning process, but if the box is tight, mount the duct permanently, again with the hot-melt glue. If you have a router table, use a ¼″ cornering bit to chamfer both ends of the duct, thus minimizing port noise. Now remove the driver for the time being.

The top, back, and rear bottom are now assembled as a separate structure, with the actual width dependent on the cabinet width as described above. The front edge of the rear bottom is dadoed in the same fashion as the front bottom.

CORNER REFLECTORS

I gave a lot of thought to the corner reflectors, since Edgar paid them so much attention as possible sources of high-frequency attenuation. I suspected that only a curved reflector would work well. The trouble was that even ¼″ plywood would be difficult to bend to a 6″ radius, and impossible to bend to 3″. If only I could find a ready-made item that would work.

Looking around my shop, I found myself staring at a length of 6″ PVC pipe left over from my last project. The answer came in a flash. Using a high rip-fence extension on a table saw, you can first halve and then quarter a piece of 6″ PVC, giving you a perfect



Reader Service #65

3″ radius. Take care in cutting it, however, for the PVC will tend to close up and bind the sawblade on the initial rip cut. Use a belt sander or a jointer to chamfer the edge, and cut it to a length of $17^{15}/_{16}$″. Centering this piece to the bottom joint of the back assembly, glue and screw it in place, predrilling the PVC for the screws (*Photo 10*).

The top reflector is a bit trickier. Measure 8″ around the circumference of the remaining PVC and slice the pipe lengthwise at that point. Again, chamfer the leading edges of the piece. Glue and screw one leading edge, centered on the plywood, to the top piece, with the leading edge 6″ from the back. Now use a heat gun to gradually heat the pipe. When softened, it will bend easily, allowing you to glue and screw the other edge to the back piece (*Photo 11*).

At this point, mate the back assembly to the horn assembly. Using woodworking glue, coat all the mating edges well, and use drywall screws every 6″ or less.

Next, cut the middle bottom piece and dado it at both ends, to match the dadoes on the other bottom pieces. Finally, install the throat-choke reflectors. I tried over a dozen configurations for the throat choke, with varying results. One thing I am sure of is that sound waves in a horn throat do not like flat surfaces; curves work much better, not only to minimize out-of-phase reflections that ruin high-frequency performance, but also to boost low-frequency performance far beyond theoretical projections.

The difficult part for the builder is fabricating curved surfaces. I surmised that a dome-shaped reflector directly over the driver cone would work best. Scrounging in my garage, I found the perfect shape—an old hubcap about 10″ in diameter with a dome about 2½″ high. I drilled three holes near the edge and used drywall screws to fasten it to the bottom piece, centered laterally, but as close to the front edge as possible (*Photo 12*). I added weatherstripping at the joint to prevent vibrations, and stuffed the cap with polyfoam for the same reason. You can still buy these hubcaps at an auto-parts store or junk yard—but check your garage first.

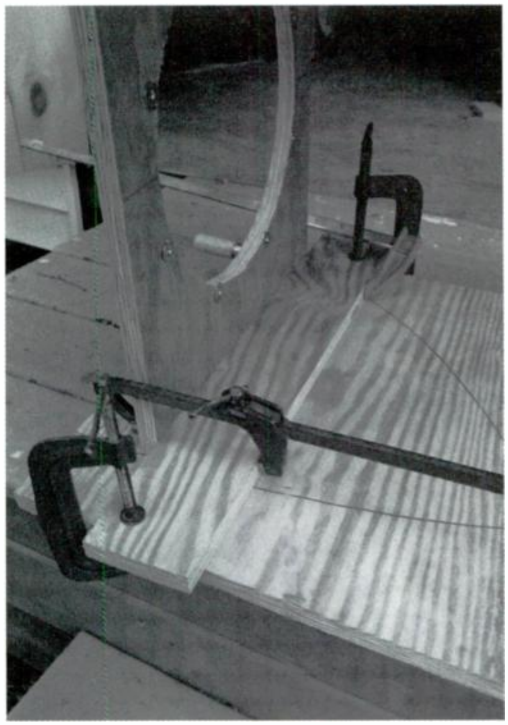


PHOTO 5: Attaching baffle to side. Note guide board clamped to side at joint line, and baffle clamped to it to hold it perfectly aligned until screwed in place.

WING REFLECTORS

The wing reflectors are also made of PVC, but now 3″ in diameter. Rip it on the table saw to create two 2½″-wide strips 12″ long, and use a jointer or belt sander to give the correct shape at the edges (*Fig. 2*). Cut one end of each strip at a 60° angle on the table saw, clamping the piece to the miter gauge for safety (*Photo 13*).

Placing the reflectors on the baffle, mark the ends to the exact width that will fit under the front bottom (with the sawed-off ends flush with the side bottom edge), draw straight lines connecting the points, and saw off the excess, running the pieces through the jointer again to true the lines (*Photo 14*).

Install the reflectors with the hot-melt glue gun, gluing the edges that are in contact with the baffle and the sides, and holding the pieces in place for a minute or so while the glue sets. There is no need to glue the edges of the reflectors to the bottom, but you should weatherstrip them to give a tight seal and prevent vibration.

Stuff the area on the baffle behind the reflectors with polyfoam. Attach ¾″ wide × ¼″ thick neoprene weatherstripping to the flanges on the front and back bottom pieces created by the dadoes, and to the side edges that will mate with the bottom plate. Now screw the middle bottom piece in place, driving screws only into the cabinet sides. Then drill three evenly spaced ¼″ holes through each flange, remove the middle bottom, and, from inside the cabinet, insert $^{3}/_{16}$″ T-nuts into the ¼″ holes.

Replace the driver, install your jack of choice in the cabinet back, and wire it up. Screw the bottom back in place, with the screws into the cabinet sides, but bolts into the three T-nuts on the flanges. Add chest handles to the cabinet sides and casters to the bottom if you wish.

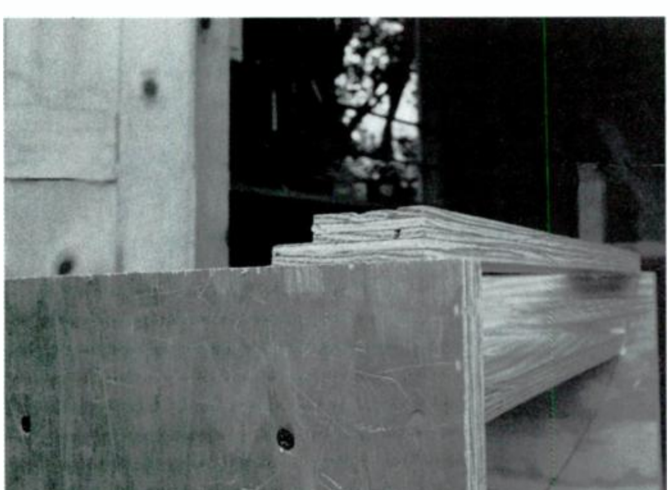


PHOTO 6: Bottom front in place; note dado of its rear edge.

PHOTO 7: Braces in place; note temporary brace across top of unit.

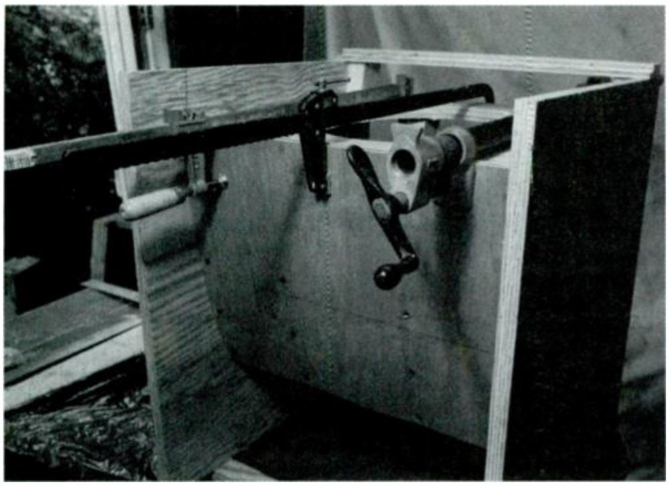


PHOTO 8: Using long clamps to pull horn plates in place for screwing.

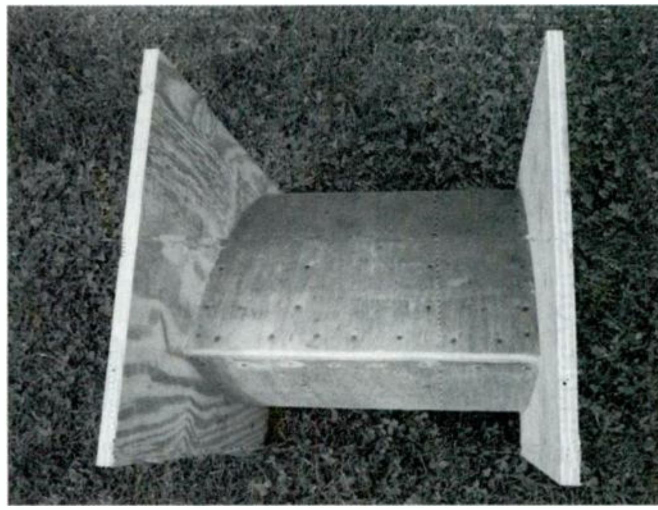


PHOTO 9: Horn-plate installation complete.

The design of the box completely shields the driver from the elements, making it reasonably weatherproof for travel. I would not cover it with carpet unless you intend to make a vinyl weathercover; in any case, do not use carpet inside the horn, since it would attenuate highs. Painting is the easiest finish; an alternative is formica. Black "slate" texture is very attractive and durable. Finally, aluminum corner edging makes for a roadworthy and "roadie-proof" cabinet.

A NEW THEORY?

When I started this project, I thought it might be some improvement on traditional folded-horn performance, but when I tested it and found out what I had, my view changed. I think this design could render "tried and true" folded-horn theory obsolete, to the same extent that T/S parameters rendered the then-existing bass-reflex theory obsolete. Since I haven't seen this configuration described before, I claim its invention as my own. Following is a look at the testing results and my interpretations thereof.

First, examine the response plot of the ducted cabinet only (*Fig. 3*). If I had tuned the cabinet for a maximum flat response, the predicted F_3 according to Keele would have been 112Hz. Assuming a rolloff below that of 24dB/octave, with a nominal efficiency of 100dB/W, you would expect to have an efficiency of about 73dB at 56Hz, with considerably less at 42Hz. By "jamming" the alignment with a larger box and a lower box frequency, 56Hz comes in at about 91dB, while the 42Hz level of 87dB is a good 20dB above the maximally flat alignment.

Note that this 12″ driver works very well right out to 6.4kHz, though that's not too surprising, considering it is designed as an electric-guitar speaker to be used without any midrange driver. It *would* be surprising if simply loading the driver into a folded horn would make its response die above 400Hz, as postulated by Edgar et al.

Now, moving on to the first set of points for the horn cabinet—without the throat choke—the horn loading had no effect below 75Hz, where it started to kick in gradually (up 2dB). From there, the horn did have a generally beneficial effect, but response was very ragged, and Edgar's predicted dip at 400Hz did show up—at 500Hz, the change from the ducted cabinet was −18dB.

As I kept sweeping up the range, however, response did not decline as mass rolloff would predict. Listening to the cabinet as I swept the generator, and looking at the plot results, I knew instinctively that the only logical reason for the massive dip centered at 500Hz was phase cancellation.

PHASE-CANCELLATION EFFECTS

If you think of a folded horn as a twisted straight horn, and then picture a straight horn, you see that the folded horns are missing phasing plugs at the throat. Straight horns, most especially tweeters, have used phasing plugs for decades to control phase-cancellation effects. Why not folded horns?

Pulling off the access-plate bottom piece, I tried a few arrangements to keep high frequencies from reflecting off the inside of the cabinet in the throat area, only to merge with the original signal again out of phase, thus causing cancellation effects. The result was the three reflectors comprising the throat choke. Not only did this get rid of the "hole" around 500Hz, but it also improved the loading at the throat for low frequencies.

The final choke design was the best compromise between bandwidth and overall efficiency. I measured response with the dome reflector alone, with the wing reflectors alone, and in combination. As compared to the nonthroat-choked version, all of the sensitivity increases below 200Hz result from the dome reflector, which enhances the loading of the throat at low frequencies, as confirmed by "before and after" impedance measurements.

The enhancements above 200Hz, which I believe are due to reductions in phase cancellations, are caused by the side reflectors. The overall result is response from a folded horn that I have never seen described.

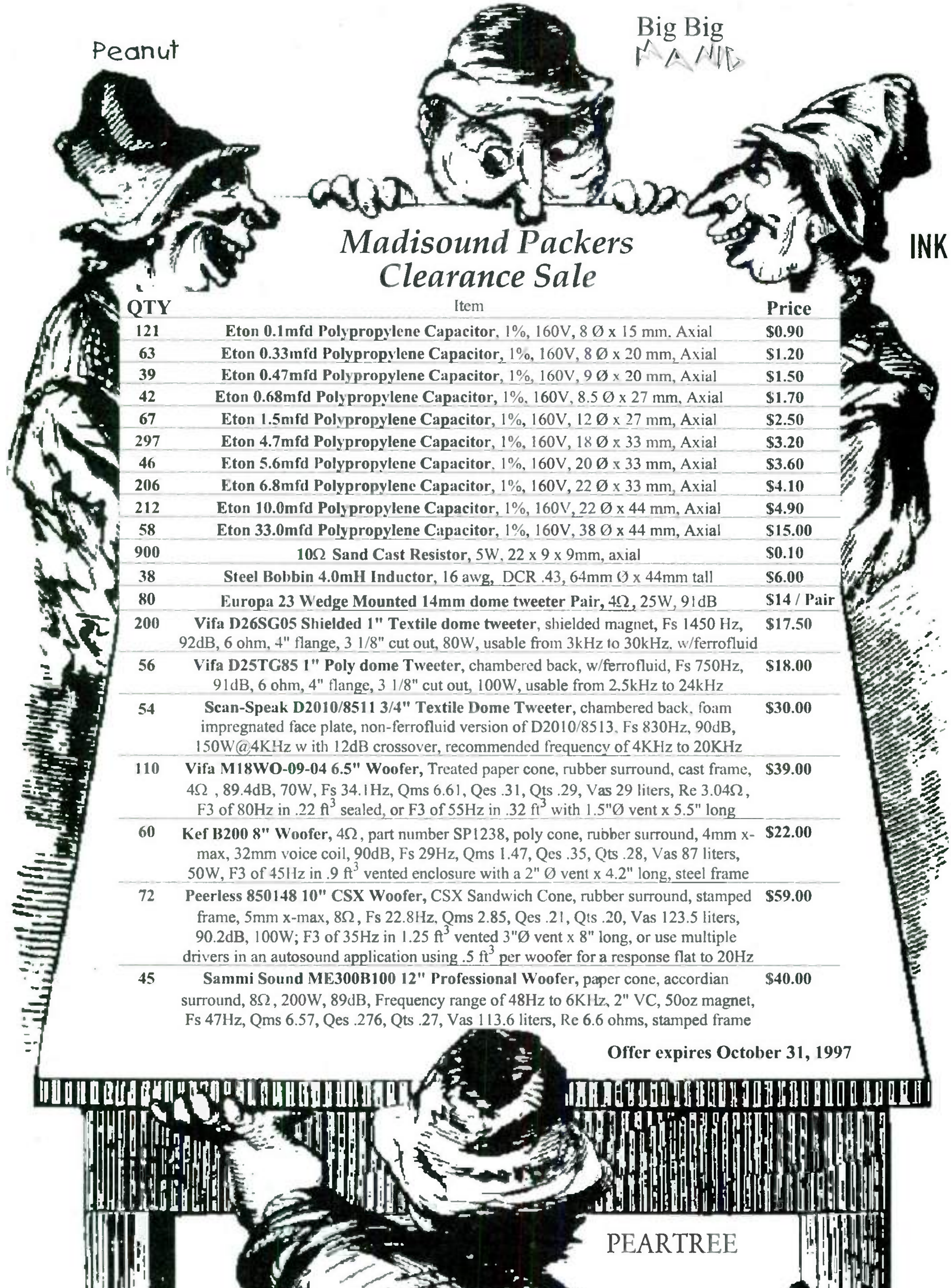
Note how efficiency at 32Hz is up by 5dB—not bad from a horn which has a predicted cutoff of 100Hz. The source of the 32Hz tone is the port—as is most of the output below 100Hz—which I confirmed by

TABLE 1

PARTS LIST

¾″ plywood (½″ optional; see text)—cabinet walls, baffle
¼″ plywood—horn plates
¾″ and/or 5/4″ × 6″ pine—horn braces
Woodworkers' glue, construction adhesive, hot-melt glue
1″, 1¼″, and 1 5/8″ drywall screws
3″ and 6″ PVC drain pipe
Dome-shaped hubcap
Speaker wire, jack
Paint or other exterior finish
Aluminum edging
Carry handles, casters
3/16″ bolts and T-nuts
Neoprene weatherstripping
EVM 12-L or equivalent driver
Estimated total cost: $250 with EVM 12-L; $170 with 12″ Eminence Cast

Part sizes—all nominal (see text)	
Sides (2)	22½″ × 19½″
Baffle	18″ × 15″
Bottom front	2½″ × 19½″
Bottom middle	13½″ × 19½″
Bottom rear	5″ × 19½″
Top	20″ × 19½″
Back	22½″ × 19½″
Horn plate, rear (2)	13½″ × 17 15/16″
Horn plate, front (2)	23¼″ × 17 15/16″
All other parts as noted in text	



Madisound Packers Clearance Sale

QTY	Item	Price
121	**Eton 0.1mfd Polypropylene Capacitor**, 1%, 160V, 8 Ø x 15 mm, Axial	$0.90
63	**Eton 0.33mfd Polypropylene Capacitor**, 1%, 160V, 8 Ø x 20 mm, Axial	$1.20
39	**Eton 0.47mfd Polypropylene Capacitor**, 1%, 160V, 9 Ø x 20 mm, Axial	$1.50
42	**Eton 0.68mfd Polypropylene Capacitor**, 1%, 160V, 8.5 Ø x 27 mm, Axial	$1.70
67	**Eton 1.5mfd Polypropylene Capacitor**, 1%, 160V, 12 Ø x 27 mm, Axial	$2.50
297	**Eton 4.7mfd Polypropylene Capacitor**, 1%, 160V, 18 Ø x 33 mm, Axial	$3.20
46	**Eton 5.6mfd Polypropylene Capacitor**, 1%, 160V, 20 Ø x 33 mm, Axial	$3.60
206	**Eton 6.8mfd Polypropylene Capacitor**, 1%, 160V, 22 Ø x 33 mm, Axial	$4.10
212	**Eton 10.0mfd Polypropylene Capacitor**, 1%, 160V, 22 Ø x 44 mm, Axial	$4.90
58	**Eton 33.0mfd Polypropylene Capacitor**, 1%, 160V, 38 Ø x 44 mm, Axial	$15.00
900	**10Ω Sand Cast Resistor**, 5W, 22 x 9 x 9mm, axial	$0.10
38	**Steel Bobbin 4.0mH Inductor**, 16 awg, DCR .43, 64mm Ø x 44mm tall	$6.00
80	**Europa 23 Wedge Mounted 14mm dome tweeter Pair**, 4Ω, 25W, 91dB	$14 / Pair
200	**Vifa D26SG05 Shielded 1" Textile dome tweeter**, shielded magnet, Fs 1450 Hz, 92dB, 6 ohm, 4" flange, 3 1/8" cut out, 80W, usable from 3kHz to 30kHz. w/ferrofluid	$17.50
56	**Vifa D25TG85 1" Poly dome Tweeter**, chambered back, w/ferrofluid, Fs 750Hz, 91dB, 6 ohm, 4" flange, 3 1/8" cut out, 100W, usable from 2.5kHz to 24kHz	$18.00
54	**Scan-Speak D2010/8511 3/4" Textile Dome Tweeter**, chambered back, foam impregnated face plate, non-ferrofluid version of D2010/8513, Fs 830Hz, 90dB, 150W@4KHz w ith 12dB crossover, recommended frequency of 4KHz to 20KHz	$30.00
110	**Vifa M18WO-09-04 6.5" Woofer**, Treated paper cone, rubber surround, cast frame, 4Ω , 89.4dB, 70W, Fs 34.1Hz, Qms 6.61, Qes .31, Qts .29, Vas 29 liters, Re 3.04Ω, F3 of 80Hz in .22 ft^3 sealed, or F3 of 55Hz in .32 ft^3 with 1.5"Ø vent x 5.5" long	$39.00
60	**Kef B200 8" Woofer**, 4Ω, part number SP1238, poly cone, rubber surround, 4mm x-max, 32mm voice coil, 90dB, Fs 29Hz, Qms 1.47, Qes .35, Qts .28, Vas 87 liters, 50W, F3 of 45Hz in .9 ft^3 vented enclosure with a 2" Ø vent x 4.2" long, steel frame	$22.00
72	**Peerless 850148 10" CSX Woofer**, CSX Sandwich Cone, rubber surround, stamped frame, 5mm x-max, 8Ω, Fs 22.8Hz, Qms 2.85, Qes .21, Qts .20, Vas 123.5 liters, 90.2dB, 100W; F3 of 35Hz in 1.25 ft^3 vented 3"Ø vent x 8" long, or use multiple drivers in an autosound application using .5 ft^3 per woofer for a response flat to 20Hz	$59.00
45	**Sammi Sound ME300B100 12" Professional Woofer**, paper cone, accordian surround, 8Ω, 200W, 89dB, Frequency range of 48Hz to 6KHz, 2" VC, 50oz magnet, Fs 47Hz, Qms 6.57, Qes .276, Qts .27, Vas 113.6 liters, Re 6.6 ohms, stamped frame	$40.00

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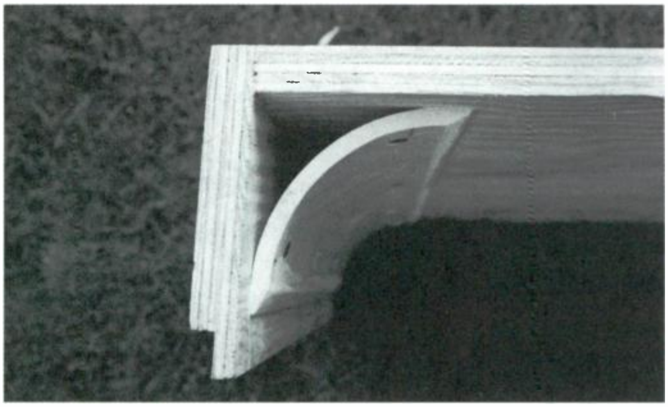

PHOTO 10: Detail of lower reflector; note chamfered edges and dado of bottom piece.

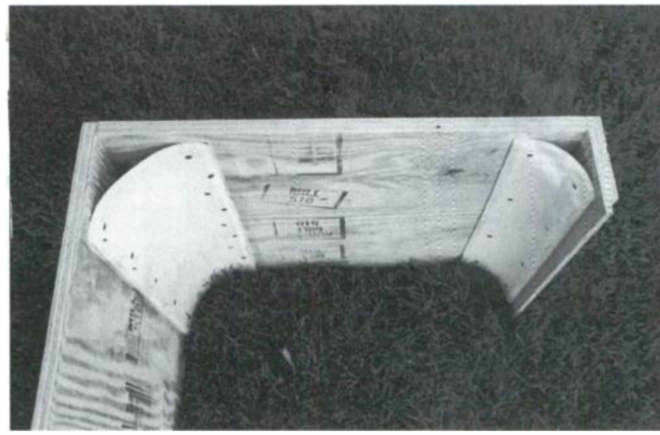

PHOTO 11: Both reflectors in place.

close-field measurements on the ported cabinet. Not only does the horn pass frequencies coming from the port; it boosts them as well. A look at the impedance chart (*Fig. 4*) gives a clue as to the reason .

The massive 55Ω peak at 100Hz is replaced with smaller peaks at 50 and 150Hz, while minimum impedance rises from 7Ω to 9Ω, showing the loading effect of the horn upon the driver, even below the flare frequency. It would seem that there are two F_bs (as in a double-chamber reflex)—one for the horn at about 100Hz, which corresponds to its cutoff point, and the other at about 32Hz for the rear chamber, which is about 10Hz lower than the chamber's F_b prior to its mating with the horn.

THE MUSIC GOES DOWN AND 'ROUND

When a ducted box fires into a horn, the box's F_b decreases. Compare this with the Superbass, which differs from the Snail in that the port output is not fed to the horn. The Superbass also has impedance peaks, at 50Hz and 180Hz, with corresponding response peaks at those frequencies and a response dip in between. The Snail has no such dip. So, the mating with a horn of a ducted cabinet's port output and front-wave output works better—both in low-frequency extension and flatness of response—than feeding only the front wave into the horn and the port directly into the air.

Now if mating the horn to the T/S box lowers the box's F_b below its original frequency, what would be the effect if you shorten the duct, thus raising the rear chamber's F_b so that when you add the horn, the rear chamber's F_b is at the originally intended frequency? To answer that question, I took out the 5″ duct and replaced it with both shorter and longer ones to make sure the cabinet performed as well as possible.

Different-sized ducts made no improvement—the 5″ duct gave the best overall performance. Since the average sensitivity gain of the horn over the ducted cabinet alone was only an average of 3–4dB up to 180Hz, and roughly equal to the ducted cabinet above that (with notable exceptions at 750–800Hz—up by 11 and 7dB), I wondered whether the lack of a sealed rear chamber was costing efficiency, so I sealed off the port.

From 32 to 64Hz, the ducted rear chamber was superior; from 75 to 80Hz the sealed chamber was better; from 100 to 500Hz it was a toss-up; and from 640Hz up, the two were identical. The lack of phenomenal sensitivity increases had nothing to do with the rear-chamber configuration, but simply reflected the small size of the horn.

NO MASS ROLLOFF

As to mass rolloff, my results show it to be nonexistent, at least in this particular horn/driver combination. With the throat choke, the horn remains as efficient as the ducted cabinet all the way up to 1kHz, above which the capacitive losses caused by the bends in the horn have a roll-off effect. But no "brick-wall" rolloff occurs, as proponents of mass-rolloff would predict.

It is possible that a larger, more efficient horn might exaggerate the differential between frequencies the horn boosts and those it does not, giving the appearance of

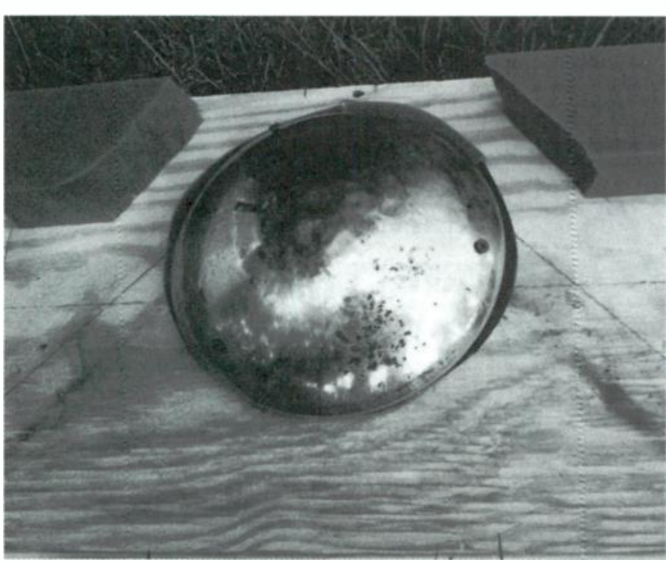

PHOTO 12: The dome reflector installed on the middle bottom.

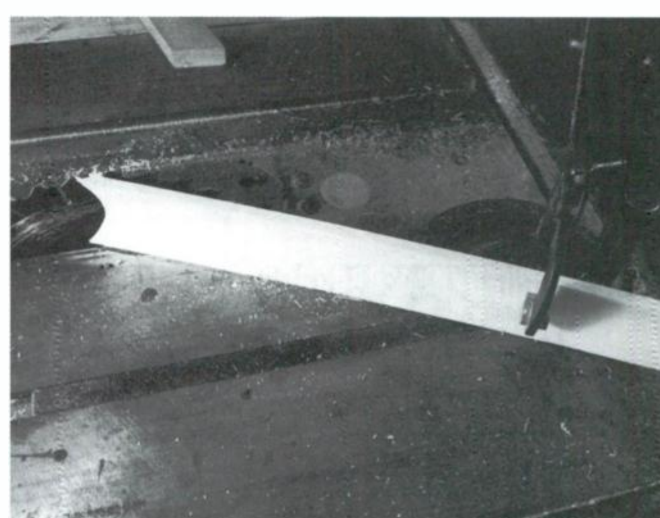

PHOTO 13: Cutting the wing reflector to 60° angle with PVC clamped to table saw miter gauge.

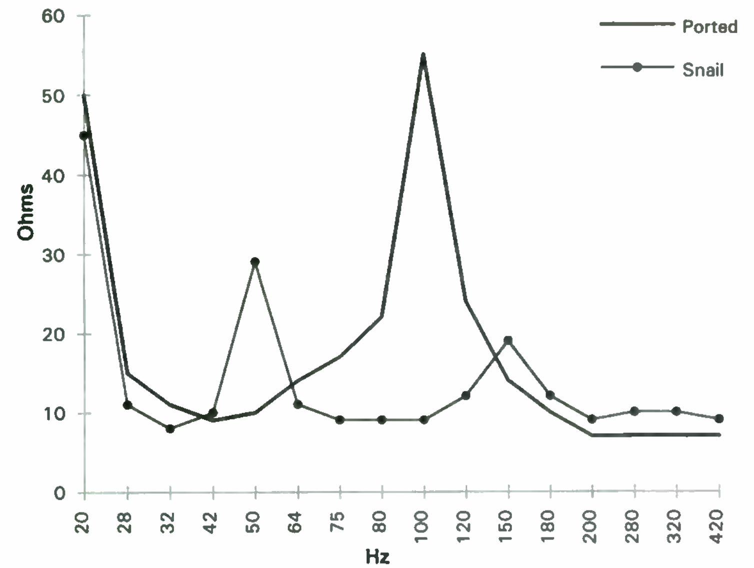

FIGURE 4: Impedance chart.

exaggerated high-frequency rolloff. This implies that rolloff is not as much a matter of attenuation as it is a lack of loading by the horn at higher frequencies.

A horn does not intrinsically cause a rolloff of high frequencies; what actually happens is that as frequencies increase and the corresponding wavelengths decrease, the horn ceases to load those frequencies, so they are no longer boosted in volume. For this particular horn/driver, the loading action ceases above 1kHz. Coupled with capacitive losses from the horn bends and phase-shift losses at the throat, the output drops as frequency increases.

A more efficient horn capable of passing lower frequencies with higher sensitivities would accentuate to a greater degree the difference in levels between frequencies the horn loads, as opposed to those it does not. Logic dictates that if the horn throat were significantly smaller, you could extend the loading to higher frequencies, although at some point, too small a throat would have an adverse effect on the low-frequency response. Further experimentation is required to confirm this hypothesis.

After testing the finished Snail, which I did outdoors with the cabinet on a deck, I tried it against a wall, and also facing the wall. Surprisingly, I got no more bass extension or efficiency in either case. However, lifting the cabinet to a position 3 feet above the deck did result in about a 2dB loss up to about 100Hz. I did not test the cabinet in a corner or indoors.

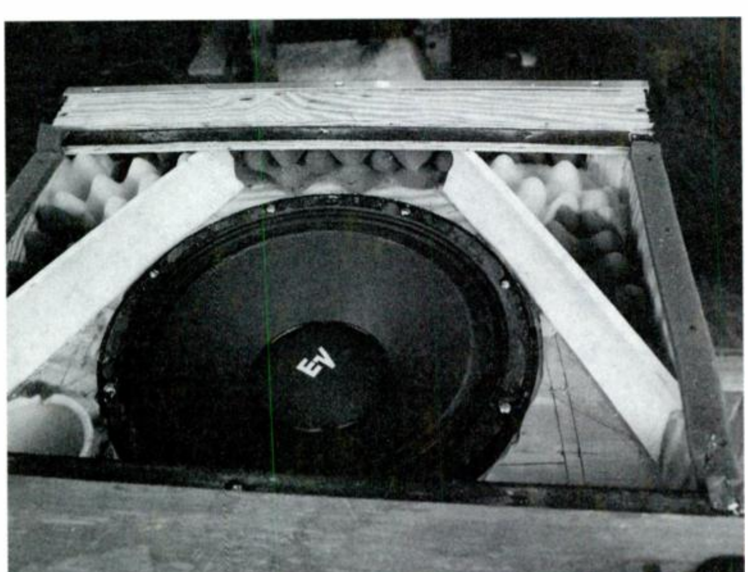

PHOTO 14: Wing reflectors in place on baffle; acoustic foam filling void area behind.

DESIGN ANOMALIES

I believe a great deal of what is happening here was touched on back in *SB* 4/90 and 6/90, when Bruce Edgar examined anomalies in Klipsch throat designs. At first, he attempted to explain them mathematically; later, he recanted. One negative aspect of T/S theories has been the subsequent attempts to mathematically model every facet of cabinet design, to the detriment of good old-fashioned "seat of the pants" empiricism.

It seems likely that the Klipsch throat anomalies might well be phase-derived, but that this factor has been overlooked in the quest for mathematical modeling. My personal disadvantage of not being particularly math-oriented forces me to look at things from a different point of view—and with different results.

To summarize, you can significantly improve the performance of a horn-loaded woofer by not placing it in a sealed chamber, as is the prevailing practice, but in a T/S-aligned ported box, with both port and driver front wave feeding the horn throat. Careful attention to the design of the throat in a folded horn can minimize high-frequency rolloff, which I believe is caused not by mass rolloff, but by phase cancellations stemming from poor throat design. It can also minimize decoupling of the horn's loading when the throat dimensions are too large in comparison to the frequency's wavelength.

When the horn is loading a ducted box, as described above, rather than a driver in a sealed chamber, the low-frequency cutoff point decreases, at least to the extent that the severity of the rolloff below the flare frequency is greatly reduced. The design of the throat area can boost low-frequency performance over that predicted strictly on the basis of the horn length or mouth area. My future experiments will be directed at achieving wider bandwidth and flatter response through better throat design.

SNAIL APPLICATIONS

As to applications for the Snail, this is one great bass guitar cabinet or PA bass bin, with far more punch than you'd expect from a single 12″ driver. The same driver in a T/S cabinet has at least 6dB less efficiency from 32 to 100Hz, and 3dB less from 100 to 150Hz, which translates into a lot of power. It will easily outperform typical commercial cabinets using four 10s or even two 15s, and it doesn't need a 500W amp to do it.

Compared to my own Superbass, it seems louder with identical input, since it does not have a response "dip" in the 80–160Hz range that you psychoacoustically perceive as heavy bass, although its high-end response is definitely inferior to the Superbass with its midrange drivers. The tone is more "retro," good for a "big bottom" effect, but not suitable for a "slap and pop" style without additional midrange drivers.

Could you use it for stereo? Maybe. A 15-band EQ would allow it to give flat response from 42–3.2kHz, with 100dB efficiency on average, and 127dB capability from 120–800Hz. Coupled with a tweeter of adequate efficiency and power handling, it would be the basis of a seriously loud system. However, the EVM costs about $160. The Eminence Cast is half that, but do you really need 200W drivers?

The beauty of a horn is its ability to make a little power go a long way. If you're on stage and need to get 127dB from a 200W amp, it's the only way to go. It works best in the home in getting 100dB from a single-ended 30W tube amp with headroom to spare. A cabinet that will do just that is on my list of future projects. Stay tuned.

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TABLE 2

HORN DIMENSIONS

Distance from horn mouth:	Horn dimension (to top edge of panel):
0″	22½″
2″	16 3/8″
4″	13½″
6″	11 3/8″
8″	9 5/8″
10″	8 1/8″
12″	7″
14″	6″
Distance from horn turn:	Horn dimension (to back edge of panel):
0″	5¼″
2″	4½″
4″	4″
6″	3 5/8″
8″	3 5/16″
10″	3 1/8″
12″	3″
14″	2 7/8″

REFERENCES

1. Keele's pocket-calculator program.

$VB = 15\ Q_{TS}^{2.87}\ V_{AS}$

$F3 = 0.26\ Q_{TS}^{-1.4}\ f_S$

$FB = 0.42\ Q_{TS}^{-0.9}\ f_S$

FROM CATERPILLAR TO BUTTERFLY

By Douglas H. Hurlburt

The KEF CS5 is one of several Constructors Series speaker systems that KEF designed for the do-it-yourself (DIY) market. It consists of the venerable KEF B200G (SP1075) low/midrange driver, the T33A (SP1074) soft-domed high-frequency (HF) driver, and the B139 passive radiator, which is the B139B (SP1044) low-frequency (LF) driver without a voice coil or magnet assembly.

MAKING EXCEPTIONS

My involvement with the KEF CS5 began in 1982 when I purchased a matched set of drivers, with assembly instructions. I followed the manufacturer's instructions for fabricating the 44 ltr. enclosure and crossover, with two exceptions: first, I based my enclosure on a 12″ × 12″ footprint instead of the 11″-wide × 12.25″-deep footprint of the KEF design; second, I deleted the series 600μF non-polar electrolytic capacitor in the low-frequency leg of the KEF crossover to eliminate the sonic degradation typically associated with this type of capacitor.

For the crossover, I used coils of #14 magnet wire on nylon bobbins and polypropylene capacitors. I measured all components on an LCR bridge at 1kHz to ensure the correct values. It sounded better than the equivalent KEF unit offered for sale at the time; but now—some 13 years later—it is apparent that the sonic signature and imaging was certainly not state-of-the-art. Being a dedicated DIYer, and not wishing to immediately make the significant investment required for a new speaker system, I decided to see what improvements I could make to the CS5.

Never having designed a speaker system before, I broke the job into two parts: enclosure and crossover. In this way, I could judge the effects of each part on the whole as the job progressed. I decided in advance to budget plenty of time for this project, both to avoid shortcuts driven by time constraints and to spread the inevitable costs.

The job took about one year from start to finish; however, at no time was I without a working system for long. The maximum down time was only a few days, occurring intermittently when I switched drivers from one enclosure to the other, made measurements, or removed old crossover components to install new ones. The short down time also enabled me to listen to "old" and "new" versions without significant loss of aural memory.

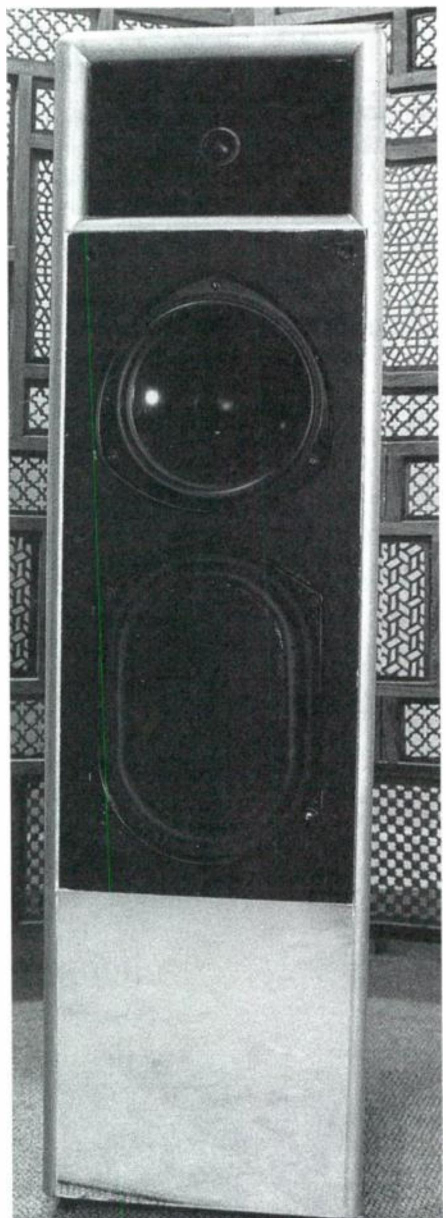

PHOTO 1: Front view of enclosure without grille.

THE ENCLOSURE

I intended the new enclosure design to achieve three things: precise alignment of the drivers; sufficient volume for improved LF response; and elimination of enclosure resonances. To attain these goals, I designed two separate volumes, one for the B200G/B139 combination (LF) and one for the T33A. I again opted for a 12″ × 12″ enclosure footprint, and used 1″-thick medium-density fiberboard (MDF) throughout with heavy bracing (*Photo 1*).

The LF volume had a totally flush front baffle (without grille cloth and frame) with an internal height of 32″. After allowing for a ½″ inset of the back baffle, a space for two horizontal "shelf" braces (spaced 12″ apart and located above and below the B139), the B200G/B139 combination, and assorted glue blocks for all of the interior joints, the enclosed volume remaining was 45.75 ltr. I thought this should be sufficient to allow for the later subtraction of the crossover volume; as the design progressed, however, I found I had to subtract additional volume.

I placed the T33A above the LF volume in a separate HF chamber that was 6″ high, resulting in a 9″ vertical separation between the centers of the B200G and the T33A. At the base of the enclosure was a separate 3″-high sealed chamber with a 1″ access hole in the bottom, making the total finished height of the enclosure 45″. The mid-point between the B200G and T33A was 38″ above the

ABOUT THE AUTHOR

Douglas H. Hurlburt earned a Ph.D. in EE from McGill University in 1972. His career has included the development of microwave integrated circuits, surface acoustic wave (SAW) devices and systems, and ultra-wide-band spread-spectrum communications systems and airborne radar systems.

After 14 years at MIT Lincoln Labs and also serving as a program manager at the Defense Advanced Research Projects Agency (DARPA), he joined Decision-Science Applications, Inc., where he continues to provide consulting and program-management assistance for the Department of Defense and other agencies.

Audio has been his life-long hobby, and he enjoys designing and building many of his system components. He provides audio-system consulting from his home, where he lives with his wife and three dogs, the latter being a better judge of high-quality sound than many humans.

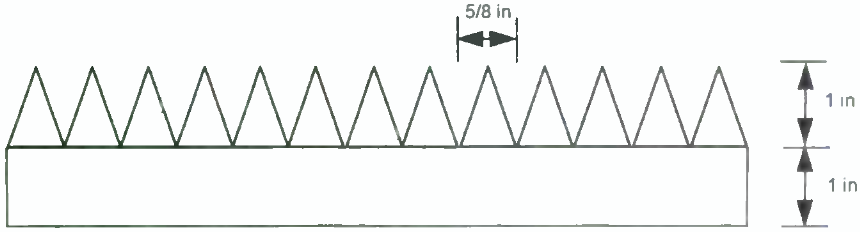

FIGURE 1: Cross section of acoustic foam used in enclosure.

floor—at my ear height when seated in my listening position.

I cut the pieces of the enclosure to form inset joints at all the panel intersections (always use carbide-tipped tools when dealing with MDF). The assembly consisted of clamping and gluing, followed by caulking of all interior joints to prevent air leaks.

Finally, I braced all interior joints with glue blocks cut from $^3/_8$" quarter-round molding stock. For amplifier connections, I mounted a pair of high-quality speaker-cable connectors on a separate panel inset into the back of each enclosure at the bottom of the LF volume.

To provide time adjustment of the drivers, I inset the T33A baffle by 1 $^3/_8$". Since the sides of the enclosure were not cut back for the T33A, I had to form a smooth transition from the HF baffle to the edges of the enclosure to prevent diffraction problems. I did this with sections of wood molding cut to form a shallow rectangular flared horn.

Finally, to reduce reflections from this horn, I covered the surfaces with black velvet, believing that the fine short vertical fibers that create this material would be an excellent attenuator of incidental high-frequency sound energy.

ENCLOSURE RESONANCES

I then addressed the issue of enclosure resonances, of which there are two types: those propagated through the cabinet material, and those associated with the interior volume. To deal with the first, I chose a very rigid design with no large unsupported panels, and used 1" MDF throughout. However, to further suppress cabinet propagation, I lined the sides of the LF and HF chamber interiors

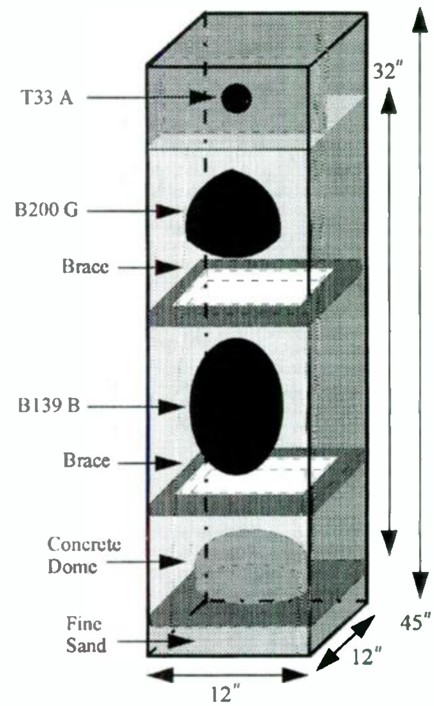

FIGURE 2: Diagram of enclosure.

with $^1/_8$" Sorbothane™. I used the very soft—and highly sticky—version, obtained directly from the manufacturer, Sorbothane, Inc.

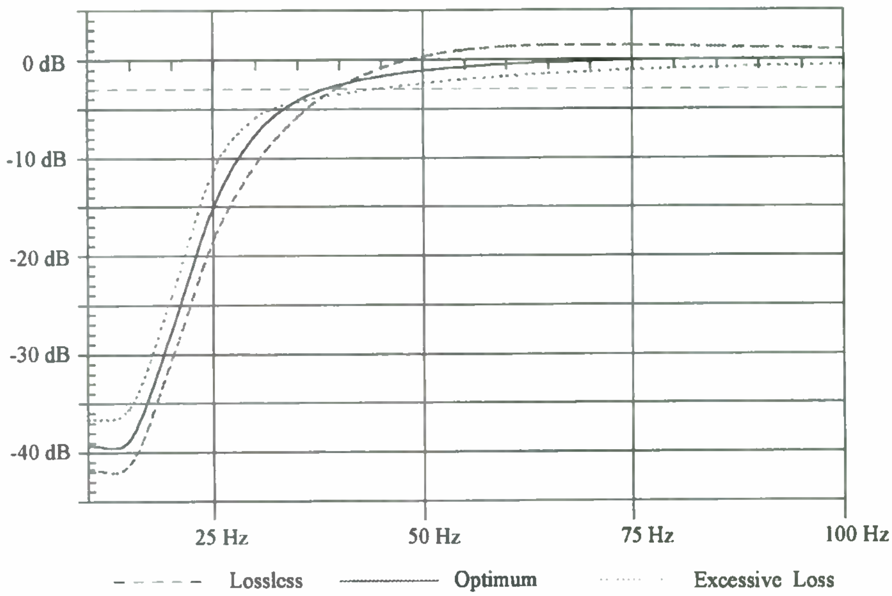

FIGURE 3: Predicted response for three fill options.

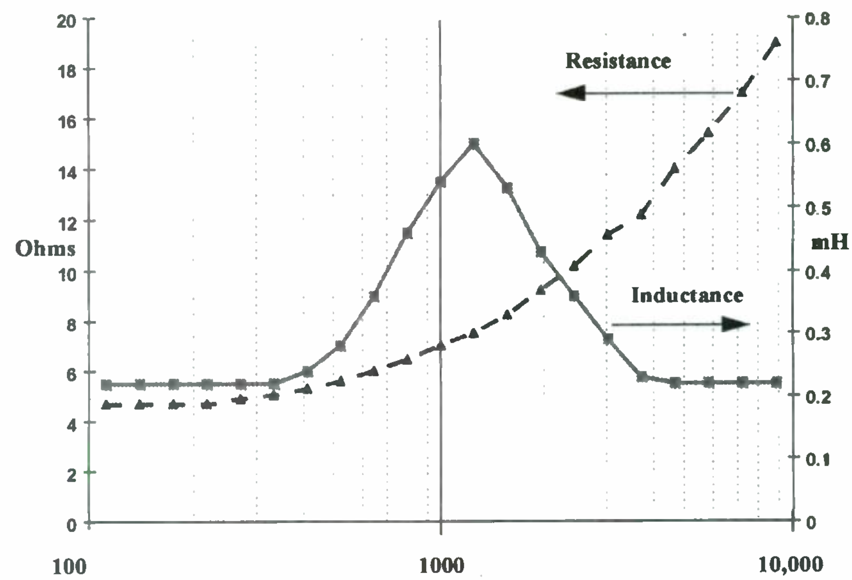

FIGURE 4: Effective series R and L of B200G vs. frequency.

Spray-on contact cement and the judicious use of a stapling gun sufficed to secure this material to the inner surfaces.

To eliminate the second type of resonance, I used sections of Cutting Wedge™ acoustic-foam absorber panels (from System Development Group) that have a wedge-shaped cross section, as shown in *Fig. 1*. I cut the sections to fit snugly against the interior sides and top, and aligned them horizontally for maximum acoustic absorption. This provided most of the enclosed volume with surfaces that were highly absorptive from about 300Hz to the very highest frequencies, while also significantly increasing the *effective* LF volume. (More about this later.)

My only remaining concern was the ½-wave-height resonance within the LF enclosure, occurring at about 225Hz. Since the foam absorber panels would attenuate the harmonics of this, I had to be concerned only with the fundamental. Rather than try to absorb this resonance, I fabricated a diffuser in the form of a 9″ hemispherical dome cast in concrete, with a hole through the center.

I hoped that the hemispherical shape at one end would create multiple effective column lengths, so that no single resonant frequency could dominate. I secured the dome to the bottom of the LF volume (on top of a sheet of $^1/_8$″ Sorbothane) with a lag screw, and then covered it with fibrous acoustic damping material and a panel of the acoustic foam that lined the enclosure.

SAND FOR STABILITY

After completing the enclosure, I set it upside down and poured in approximately 40 lbs. of

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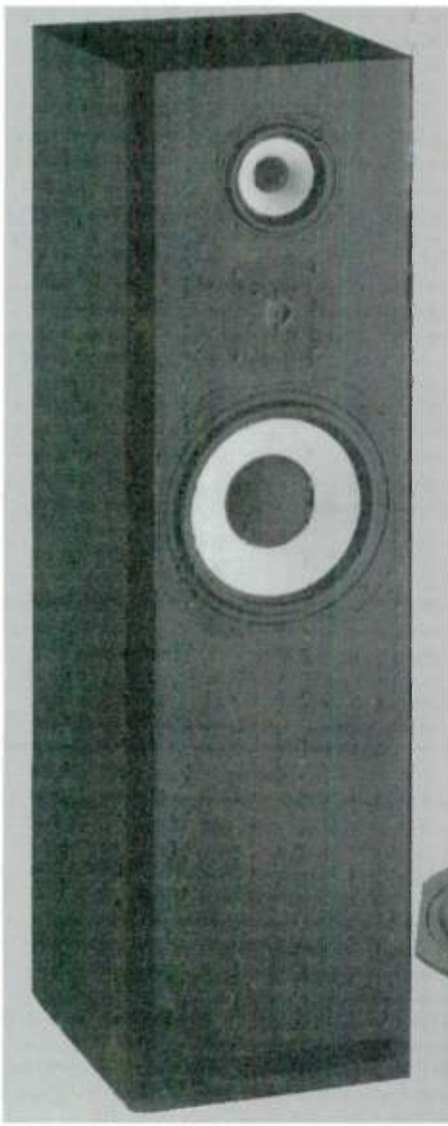

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5N411L		$45.00
10K611 (Similar to 10K617)		$139.00
12V726S		$175.00
4K211		$55.00
5V4411	.5" BASS DRIVER	$50.00
8V413	SAME AS 8V412 W/PHASE PLUG	$60.00
5V313S	SAME AS 5K013L W/POLY GLASS	$45.00
5V412DB	STANDARD MODEL OVERSTOCK	$45.00
TC100TD	SAME AS T90 W/LARGE PLATE	$35.00
TC100TIF	SAME AS T90TIF W/LARGE PLATE	$35.00
TC120KFG4	.4 ORM FERRO FLUID	$50.00
6V013	STANDARD MODEL OVERSTOCK	$55.00
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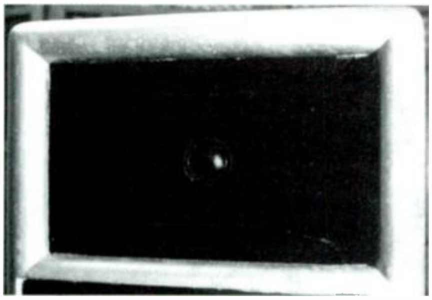

PHOTO 2: T33A installation.

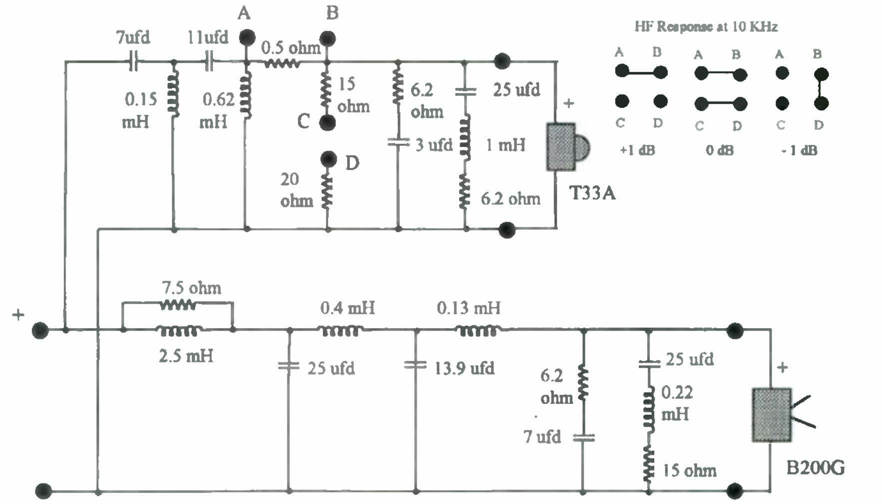

FIGURE 5: Final crossover network.

fine-washed dry sand to fill the 3″ bottom chamber. This provided additional mass for stability and a damping mechanism for any residual resonances within the MDF. I sealed this chamber with a 12″ × 12″ × $^3/_{16}$″ aluminum plate screwed into the bottom of the enclosure against a 12″ × 12″ × $^1/_8$″ gasket of Sorbothane. It was topped off with four 1.5″ × 1.5″ cone-point isolators, fastened to each corner of the bottom plate.

After installing the drivers, I verified the tightness of the LF enclosure by pressing on the diaphragm of the B139—be sure *never* to press on the B200G! If properly sealed, the B200G should move out, and then very slowly move back to its rest position. (A small air leak is always required to prevent atmospheric-pressure changes from causing undesirable static displacement of the drivers.) *Figure 2* is a pictorial view of the final enclosure. *Photos 2* and *3* are close-ups of the T33A installation and the concrete dome at the bottom of the LF volume, respectively.

MAKING MEASUREMENTS

My use of the dome diffuser and planned inclusion of the crossover components would reduce the basic LF volume to about 41.2 ltr., so it was necessary to check the predicted LF response, a move that later proved to be very fortuitous. Since no specifications were available for the B139, it was necessary to measure the pertinent parameters. At the same time, I decided to measure those of the B200G to see how they compared with the KEF specs.

I used the measurement procedures included in BassBox 5.1™. The parameters for the B200G were all in order, except for an increase in the resonant frequency to 36.25Hz from the specified 28Hz. This was due to a reduced compliance, possibly caused by aging of the cone surround.

Measurements of the B139 parameters were inconsistent and obviously incorrect. Discussions with the developers of BassBox led me to devise a different technique for measuring the passive-radiator parameters, as well as a means of determining the various system losses.

Using my technique, which gave consistent and repeatable results, I found that the V_{AP} for the B139 was 175 ltr., and the mechanical resonant frequency, f_P, was 17Hz. The V_{AP} agreed very well with the spec compliance for the B139B driver. Using a second set of measurements with the piston of the B139 loaded with an additional 60g, I was able to determine that the mass of the B139 piston was 93g, or twice that of the B139B driver. KEF achieved this increase by replacing the B139B voice-coil form with a steel form for the B139.

Using additional measurements, I was also able to determine the mechanical Q of the B139 (Q_M = 4.4), as well as the additive losses and effective enclosure-volume

change due to the presence of acoustic absorbing material within the enclosure. I found that the effective volumetric factor of the filled enclosure, Γ, given by

$$\Gamma = (V_{effective} / V_{unfilled}),$$

had a range of 1.0 to 2.0, depending on the amount and type of fill. And, since every value of Γ has an attendant loss factor, a wide range of system performance is possible. (The increase occurs because the enclosure makes a transition from the adiabatic condition without fill to an isothermal condition with fill and Γ = 1.4. However, I have shown that it is possible to create a non-isothermal condition that virtually doubles the effective volume of the enclosure, but with high internal loss.)

FILL-OPTION RESPONSES

Figure 3 shows LF performance predictions using the system parameters, as measured, and the response function including system losses for three different enclosure fill options. You can see that the response curve for the lossless case, indicating no acoustic fill in the enclosure (Γ = 1) has an approximate 1.5dB rise through the 50–100Hz region. This would lead to a somewhat "boomy" bass and a poorly controlled passive radiator. The curve labeled "Excessive Loss" results from having more acoustic fill than required (Γ = 2).

The curve labeled "Optimum" (Γ = 1.38) represents, in the author's opinion, the best attainable combination of fill and driver/passive radiator parameters for this system. I achieved this with the acoustic foam plus a 2″ layer of nylon-based fiber fill placed only over the crossover components. I could achieve this same value of Γ using only the fiber fill, without the foam; however, the interior losses were excessive, resulting in a predicted response similar to that of the excessive-loss curve in *Fig. 3*.

The addition of any type of absorbing fill, while it causes the effective volume of the enclosure to increase, also removes energy from the internal pressure wave that is driving the passive radiator. A reduction in the amount of internal fill can reduce this energy loss, but it also reduces the ability to control the passive radiator and eliminate undesirable resonant modes within the enclosure.

Thus, the final configuration is a delicate balancing act between the increased effective volume and too much loss. In my opinion, it is better to sacrifice some flatness in response in order to gain a more highly damped, and thus overall smoother, system.

EXTERIOR FINISH

The choice of exterior finishing is a personal matter. In my case, I used painted ½″ quarter-round molding to round all edges, and I covered the flat surfaces (top, sides, and front below the B139) with mirror panels. (The use of mirrored surfaces tends to make the enclosures disappear in a room surrounding, except when viewed directly from the front or back.)

I cut grille-cloth frames (to cover only the B200G and B139) from solid ¾″ flat wood stock and rounded them on all interior and exterior edges to reduce diffraction. After covering, I fastened these to the front baffle with "mushroom" clips. The result, with the grille removed to show driver placement, is shown in *Photo 1*.

The final weight of each enclosure after installation of drivers and crossover was 150 lbs. Once in place, they tend to stay there, and any attempt to stimulate resonances by knocking on the sides will seriously damage your knuckles.

Listening to this new enclosure, but with the original crossover, I observed some modest improvement in imaging and a lower, very well-controlled bottom end. The latter is no doubt due to the proper amount of damping material within the enclosure. It was definitely an advance, but I thought it was possible to do better.

CROSSOVER

The original KEF crossover was a combination of second- and third-order designs crossing over at 3.5kHz. The highpass (HP) leg is a third-order Chebyshev filter with the overshoot and sidelobe characteristics typical of this type. The reason for using a Chebyshev with its very steep skirt (relative to others of identical order) was probably the relatively high (≅ 1kHz) resonant frequency of the T33A and the 3.5kHz crossover frequency—plus the economies of building a filter of few components versus a more sophisticated one. To further protect the tweeter, KEF included a network to insert a null at about 1kHz.

The lowpass (LP) leg was second order electrically, using a series 2.9mH inductor shunted by 82Ω, followed by a 7μF capacitor in shunt with the B200G. This was assisted by the mechanical rolloff of the B200G starting at about 3.5kHz, resulting in a net third-order response. The series 2.9mH inductor compensated for the baffle diffraction below about 600Hz, where the baffle width approached ½ wavelength. As is typi-

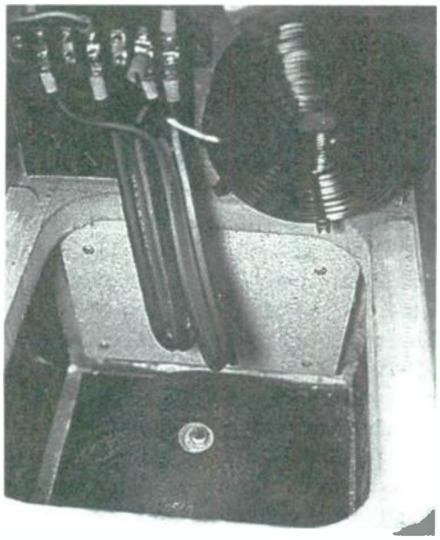

PHOTO 3: The concrete dome.

cal with third-order networks, the drivers were connected out of phase.

Some simple calculations showed that the 2.9mH inductor and 7μF capacitor did not give a 3.5kHz crossover point, so obviously something else was happening. To help sort it out, I prepared a detailed computer model of both the LP and HP legs, including a complete electrical and mechanical model of each driver.

I then measured the transfer function (voltage out versus voltage in) as a function of frequency for both the LP and HP legs of the KEF crossover, with the drivers connected and the passive radiator removed. I also performed a separate set of measurements on the drivers to determine the frequency-dependent L and R of their coils.

What I found was both interesting and illuminating. The HP leg performed more or less as predicted, but the circuit losses were higher than expected, resulting in a lower than predicted circuit Q. By altering the losses built into my model, I was able to faithfully replicate the measured HP results. I also found that the T33A radiation impedance was low and that, except near resonance, the T33A could be represented by 0.1mH in series with 6Ω across its entire operating range.

ANOTHER STORY

The LP leg and B200G were a different story. First, the effects of the radiation impedance were considerable. Above 300Hz, the effective coil resistance changed from the DC value of 4.6Ω to a steadily rising resistance with a slope proportional to the square root of the frequency. In addition, the effective coil inductance, which appeared to be 0.22mH at frequencies below 300Hz and above 4kHz, rose to a peak of 0.6mH at

about 1.25kHz, then slowly fell again to the residual value, as seen in *Fig. 4*.

The KEF engineers used this driver-impedance variation to advantage. The 2.9mH inductor starts an approximate 2dB/octave rolloff at 100Hz, so that the response is about 6dB down near 600Hz—as desired—and you would expect this slope to continue if the load impedance of the driver did not change significantly. However, the shunt 7μF capacitor resonates the effective B200G coil inductance at about 1.25kHz, thus creating a much higher impedance loading the 2.9mH inductor.

The net effect is to put a "shelf" in the transfer function that you don't observe when using an 8Ω resistor for a load. The presence of this "shelf" implies that the B200G has an essentially flat frequency response, rather than the gradually rising response that typifies many current low/midrange drivers. Above 2kHz, the rolloff resumes, as desired, but attenuated somewhat by the 82Ω resistor shunting the 2.9mH inductor.

Once I understood the KEF-designed crossover and—most importantly—the drivers, I decided on a design strategy for a new crossover. I would use Linkwitz-Riley (L-R) networks, since their Q of 0.5 represents the condition for critical damping. Also, I would totally compensate the driver impedances across their respective frequency ranges so that the load impedance for each network (LP and HP) would be constant.

Finally, I would lower the crossover frequency to 3kHz so that the B200G would cut off electrically prior to reaching its mechanical limits. Hence, I needed fourth-order networks to ensure that the T33A would be sufficiently attenuated at 1kHz. (The final design had ≅ 38dB of attenuation at 1kHz, which was more than provided by the original KEF design.)

USING BUTTERWORTH

After both mechanical-resonance and high-frequency compensation of the T33A, the effective load impedance was 4.5 ±0.5Ω from 1kHz to 20kHz. However, based on the results from my computer model, it was evident that small fractional ohms of loss in the L and C components could have a serious effect on the Q of the HP network. So, rather than use a standard HP fourth-order L-R design, I started with a (lossless) fourth-order Butterworth design, secure in the knowledge that the actual measured Q would be less.

After assembly, a measurement of the HP transfer function confirmed that the final Q was about 0.6. By slightly reducing the HP input capacitor, I was able to lower the Q to 0.5, and the final transfer function exactly matched what you would expect of a fourth-order L-R with the crossover point 6dB down at 3kHz.

To compensate the B200G, I used the original 7μF capacitor in series with 6.2Ω to resonate the peak of the coil inductance, while also preventing the shunt impedance from dropping at high frequencies. I also added a shunt Zobel network to flatten the resultant impedance around 1.25kHz, resulting in a load impedance of 5.0 ±0.5Ω from 100Hz to 5kHz. (Compensation of the mechanical resonance was not required.)

In addition, I replaced the 2.9mH coil with a 2.5mH coil to provide a more accurate 2dB/octave slope over the desired range. This was shunted with a 7.5Ω resistor (two 15Ω/10W resistors in parallel) to provide the proper level prior to the 3kHz rolloff.

Again, rather than a typical LP fourth-order L-R design, I used a third-order Butterworth, crossing over at 3kHz, after the 2.5mH series coil. Since component losses have less impact at the lower frequencies, I found the response to be 3.5dB down at 3kHz, not 6dB, with a Q of about 0.7.

The insertion of a shunt 25μF capacitor after the 2.5mH coil provided the necessary fourth element of the LP network, the additional 2.5dB of attenuation at 3kHz, and the proper resultant Q. The measured transfer function was very close to the desired fourth-order L-R response, with only a minor deviation at frequencies above 5kHz, where the B200G is ineffective.

THE FINAL NETWORK

The final crossover network is shown in *Fig. 5*. The connectors A–D provide a ±1dB variation in the HF response at 10kHz, either by altering the HF compensation (+1dB) or adding a 1dB pad (−1dB). *Figure 6* shows the measured transfer functions for the LP and HP sections in the 0dB configuration.

PHOTO 4: Rear view of enclosure.

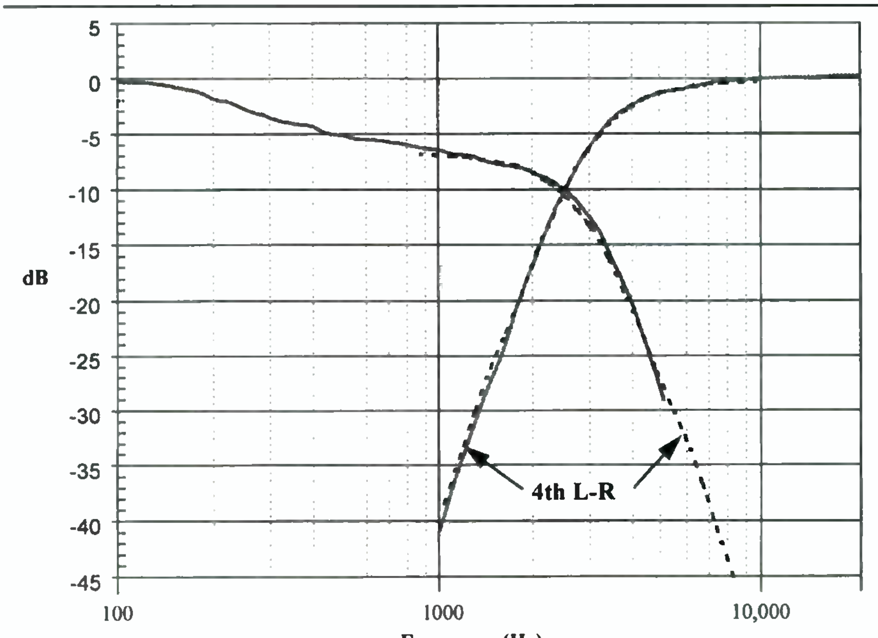

FIGURE 6: Measured transfer functions of LP and HP sections.

An ideal fourth-order L-R response, with the appropriate offsets, is overlaid on these curves for comparison. Note that the apparent 7dB imbalance between the transfer functions at 3kHz is the difference in sensitivity between the two drivers. Using a sound-level meter, the 2m on-axis responses of each driver, measured separately, at 3kHz were within 0.5dB.

Photo 4 shows the rear of the enclosure with the input terminals and the implementation of the ±1dB variation in the HF response through the use of jumper wires at the back of the HF volume.

I built the crossover network on large barrier-type electrical strips, using parts of the highest practical quality from North Creek Music Systems. All coils are 10-gauge, except the shunt coils used to compensate driver impedance, which are 12-gauge. The HP network is behind the B139B, along with the 2.5mH coil, the 7.5Ω resistor, and the shunt 25μF capacitor. The remainder of the LP network is behind the B200G, and all the T33A compensation is in the T33A enclosure.

The connections are made using heavy-duty terminal lugs that are both crimped and soldered, and I ran separate wires for signal and ground from the input terminals to each section of the crossover network. I used single-wire sections of heavy-gauge speaker cable for wiring where needed, and I secured heavy components with construction adhesive. After installation, I covered everything with a 2″ layer of fibrous acoustic damping material.

RESULTS

It was with some degree of trepidation that I connected the speakers to my power amp and proceeded to judge the results of my efforts. The first 30 seconds of listening literally blew me away, and now—many months later—my opinions are only reinforced by my own ears and those of numerous audiophile friends.

All traces of the infamous KEF "sound" were gone. The sound stage was rock solid, very wide—often appearing greater than the physical separation of the speakers—and with a depth that can go into the next room. It also accurately presents variations in elevation (height) on the part of the performers. Moreover, the overall clarity and dynamics of the sound are significantly improved over the original CS5, giving the impression of more space between performers and a greater sense of "being there" than I have heard on all but the very finest systems.

I have not made an accurate measurement of the overall response, but the drivers blend seamlessly, and the transient response is remarkably quick and tight throughout the audible range. The system has proved remarkably capable of handling low-frequency impulses, often a problem for passive radiator systems. The "sock it to you" impluse is felt, but without any perceptible overhang or blurring of the sound.

In short, while I know there are speaker systems that offer more than this revamped CS5, I believe I have shown that with some effort and attention to detail, it is possible to obtain truly state-of-the art results with a DIY project. I was pleasantly surprised to observe what could be achieved with 15-year-old driver technology, and I only wish that KEF had invested more time and money in its crossover designs, because the drivers are certainly worthy of the effort.

SOURCES

Sorbothane, Inc., Kent, OH (216) 678-9444.

System Development Group, Frederick, MD, (800) 321-8975.

North Creek Music Systems, Old Forge, NY, (315) 369-2500.

REBUILDING THE AR-3*A*, PART 1

By Tom Yeago

Like lots of *SB* readers, I became a hi-fi geek back in the late '60s, in which innocent days the AR-3*a* was considered top dog of the loudspeaker pecking order, if I may mix a metaphor. When the 3*a* appeared, almost 30 years ago now, Acoustic Research (AR) commanded about 25% of the market and was essentially showing the rest of the industry the way. Sure, the box and woofer had been around since 1959 or so, but the mid and treble domes were new and smaller, revamped, I think, by Chuck McShane, and the crossover had been revised, too.

A LEGENDARY SPEAKER

The AR-3*a* became something of a legend for AR, heading the line until 1976. It enjoyed a reputation as a technical *tour de force*, with bass that still amazed, considering the box was so small. The magazines loved it, although the level of investigative expertise was laughable by today's standards. And AR's marketing wrapped the 3*a* in a mantle of scientific gee-whiz and high-octane music-celeb endorsements. Who could doubt the veracity of the speaker against such evidence?

Not I. But I couldn't afford a pair. The stereotype owners came from the more affluent strata; all they wanted to know was what was best, and how much to make out the check for.

So my curiosity about the 3*a* persisted, even when it disappeared from the line. I heard a pair only once. Nice enough, but they were sitting on the floor in a fairly small room, so how could you tell? The curious thing about the 3*a* is how it persisted even after it was discontinued. The new models were thinly disguised variants that fooled no one. The power-handling issue was solved by quadrupling the mids and tweeters, driving them through an autotransformer/switch lash-up and repackaging into the LST, which became something of a classic in its own right.

Then there was the 9, I believe, which doubled up on woofers, added an 8″ mid-bass, and was housed in one of the early tower formats. AR should be given credit for solving the power-handling problem for the industry when it introduced ferrofluid into the magnetic gap. But after that, it's been pretty much downhill. The company was sold and resold, declining slowly and sadly to the point where AR is now just another outfit with a line of vented boxes. Vented boxes bearing the AR name...how the mighty hath fallen.

Still and all, the AR-3*a* remains fixed as an icon, a speaker to be reckoned with. Sure, it was history, but didn't Mark Levinson base his all-out speakers (after the stacked QUAD phase, that is) on AR drivers?

A MAJOR REBUILD

So I bought a pair, cheap. Worth messing with as a project? I think so. But then, I rebuilt this pair in a major way. This wasn't the usual "noodle with the crossover, brace the box, add some felt to the baffle, and you're done" deal. I did all that, yes, but I also disassembled, modified, and rebuilt each of these drivers. I meddled with the magnet structures, I rewound voice coils, I stiffened moving structures. The modified unit is shown in *Photo 1*. *Photo 2* is a close-

PHOTO 1: The finished product. Note the stock appearance until you remove the grille. The foam-filled woofer cone, baffle amendments, new treble facia, and felt stapled to grille frame are visible.

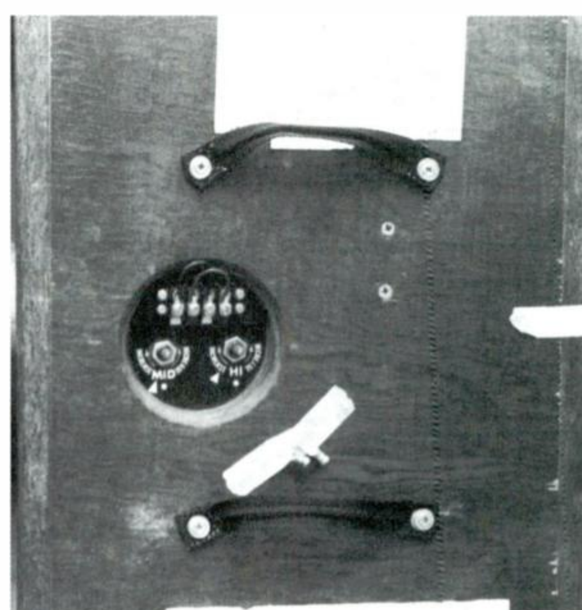

PHOTO 2: The back of the box, which still looks pretty stock, except for the webbing lift straps, input terminals, and those two enigmatic deck screws.

up of the back of the finished speaker.

It took a fair amount of time (although most of it was spent re-engineering the things), but surprisingly little cash. Designing required nothing more than a cheap slide rule and a giveaway solar-powered calculator. The most sophisticated tooling was my variable-speed, reversible Craftsman plugged into a Variac—although a drill press would have been nice.

The 3*a*s were advertised in the local shopper at $25, but they were on the ragged side, so I beat the guy down to $15—little enough to satisfy my curiosity, I thought. The boxes showed the expected wear and tear, and the bottoms looked as though they'd been sitting on a basement floor, for there was mild but general water damage. But the grille linen was intact, and both of those great brass AR badges were present.

The woofers were mismatched: one newer, stamped-frame unit with rotted foam surround; one older, cast-frame unit with the cloth surround and ribbed cone. The newer one didn't respond to a battery—not a good sign. The mid-domes were mismatched, too. One was the newer type, with the AR logo molded into the thick plastic flange. The other was an obviously older type I hadn't seen before. The flange was of flimsy thin plastic, and instead of four screws holding the flange to the top plate, no visible means of attachment was evident.

The paper dome on one of the treble units was dented in, but all the dome units "ticked" in response to a battery. I was in a bad mood for some reason, so I pointed out all the defects and walked away with 110 lb of loudspeaker for about $0.14 a lb.

Rummaging through the back *SB* issues I have, the only 3*a* rebuild article I could find appeared in 3/88 ("A Low-Cost Upgrade for the AR-3," by Bruce Edgar). It involved ditching AR's domes for a cone-dome combo and converting the crossover to a first-order arrangement, but the woofer was left undisturbed.

PREJUDICES

Like any self-respecting hi-fi geek, I've evolved a set of more or less rational notions about loudspeakers. We hold these opinions, however well-grounded, to be self-evident. What's the fun of this hobby if we can't more or less indulge ourselves here? We need not cater to the unenlightened masses by churning out designs they will purchase. We are free to pursue nonsense and the improbable to any extent that satisfies us.

For example, I think vented boxes are a bad idea. Okay, not a *bad* idea, exactly—just an idea that's too clever by half. An idea that has its place, but that place isn't necessarily center-stage. Let me put it this way: why is it a good idea to extend bass response by stacking up resonances, when resonances are exactly what we're trying to exterminate everywhere else in a speaker's response?

Sure, you dramatically reduce cone excursion, but only over a very limited band. And yes, you can use a cheaper woofer, but what do you get for your trouble? You get a hole in the box that lets noise out. You get bass that's delivered by proxy, instead of directly from the cone. You get compromised transient response in the bass. You get a highly tuned system that relies on the spider and surround to retain their characteristics despite age, temperature, and humidity. You get bass that drops like a stone below resonance.

What I'd prefer is an air-suspension sys-

ABOUT THE AUTHOR

Tom Yeago has been an audio buff since puberty. A Virginian (the Shenandoah Valley), his formal training is in economics, aka the dismal science. Besides noodling about in hi-fi matters, he has also devised a reorganization scheme to address inadequacies in the public school system.

tem, with a system Q of about 0.5 and a system resonance in the 30–35Hz range. This, as Colloms points out in *High Performance Loudspeakers*, integrates well with the low-frequency gain you find in typical rooms, and gives boffo transient response. Unfortunately, to achieve this in a reasonably sized box, you need a woofer whose characteristics would be largely unheard of today.

I recall a letter in *SB* from a reader who sought such a woofer. Vance Dickason (I believe) noted in his reply that such a woofer would have an f_0 in the neighborhood of 15Hz, a V_{as} (assuming a 12″ unit) of 250–400 ltr, and a Q_e in the 0.25 range, giving a total speaker Q (or Q_{ts}) in the 0.2–0.25 range.

This is done with a very heavy cone and an extremely robust magnet structure. Such a beast would be very expensive to build and would require either a healthy voice-coil overhang or an even more outlandish magnet structure for decent X_{max}. They are, alas, no more; they are dinosaurs. Well, dinosaurs they may be, but capable dinosaurs. And what good is a hobby like this if we can't build such beasts?

But I digress. My low-Q prejudices extend to mids, and even to tweeters. I've always thought it sensible to manipulate their low-end response just as we do a woofer in a sealed box.

HEADROOM PUZZLE

Power handling, or headroom, is another puzzle I fret over. On the low end of a driver's response, this is an X_{max} issue; over most of the band, it's a question of dumping the heat from the voice coil. With the AR-3*a*, the mid-dome is the main issue. It's shy on piston size to go down to 500Hz, although its working diameter is 1.8″, not the nominal 1.5″, which is its voice-coil diameter. Anything I can do to increase the crossover frequency and increase its X_{max} will be appreciated. This being a three-way system, tweeter X_{max} isn't as critical an issue, but improvement never hurts.

When considering drivers in general, I go for rigid structures every time. A hard cone is good to find. A speaker that is well-behaved in this regard makes things easier for everyone. I therefore view AR's 1.5″ soft-dome mid with suspicion. The treble dome, being a hard-pressed paper unit, makes more sense to me.

If a piston is driven by a linear motor, does not flex (and so presents a simple mass load to the motor), and there are no physical oddities or attempts to reproduce wavelengths of dimensions comparable to those of the structure, then you'll get flat axial and power response up to the high end, where power response will fall off (again, assuming no breakup) but "beaming" will maintain on-axis response for another octave or so. But then you're trying to reproduce wavelengths comparable to the dome (or cone, or whatever).

IMPEDANCE ANNOYANCES

Stupid impedances annoy me, too. A loudspeaker's impedance should be more than 4Ω, and resistive in nature. I see far too many speakers under test in the funny papers with impedances hovering around 2 or 3Ω, or swooping all over the chart. This is another fine mess vented boxes have gotten us into.

A simple hump in the bass I can tolerate, but two sharp impedance spikes in the bass, plus one or two other crossover-related peaks is just asking for trouble. Doesn't anyone remember Keele's discussion of the "oil-can effect" (*Audio*, Sept. '89, I think), or that a speaker might actually be paired with a modern tube amp? Are we not bottle buffs?

I think a lot of the pros are simply passing the buck with these crazy impedances. Either they can't be bothered to do it right, or they're fishing for a couple of extra dB on the sensitivity spec. Well, I say it's spinach and to hell with it. Give an amp a simple, resistive load to work on and it'll be forever grateful, even if it was made in Japan.

On a related topic, that goes for individual drivers, too. Give me a couple of nice, resistive drivers, and I won't need a '486 driving an IMP informed by a Mitey Mike in order to design a decent crossover. Practically speaking, this tends to mandate mechanical damping at a driver's low-end resonance, which implies ferrofluid and using wideband drivers to keep some distance from the fundamental rolloffs when picking crossover points.

I might also mention that I'm an unrepentant opportunist where hi-fi is concerned. If I can bend an option to suit me, I probably will. And why address a problem with one solution where two or three will do? Sometimes problems are best addressed by working at them from several directions at the same time. Notice I say "addressed" instead of "solved." We're talking loudspeakers here, where problems are seldom solved, only beaten back to the point that time is better spent elsewhere.

Finally, a word about appearance. In working on old gear, I go for the stock cosmetics every time. How many speakers nowadays have such distinctive, understated lines? Or all that actual walnut? And check out the subtle receding bevel on the (solid) wood frame. The linen grille cloth stays, too, if I can find a way to cope with excessive treble transit losses. And yes, edge diffraction/reflection will be a problem. We'll see about that. The brass badges stay, no matter what. These units will look bone stock, unless you're extremely familiar with the type, or you take off the grille.

THE MATH

I'm a big Evelyn Waugh fan. His early books (*Scoop* and the like) are comic masterpieces. Waugh used to describe his writing process as "putting the words down and pushing them a bit." Which is how I approached these 3*a*s. These are the equations I poked and prodded:

$$f_s = \frac{1}{2\pi(M_{ms}C_{ms})^{1/2}}$$

$$Q_e = \frac{2\pi f_s M_{ms} R_{dc}}{(Bl)^2}$$

$$Q_m = \frac{2\pi f_s M_{ms}}{R_{ms}}$$

where:

- f_s = the driver's resonant frequency, free of a box or any other encumbrance on its compliance. The way you account for the mass load of the air on the cone will affect this slightly.
- π we know, or ought to.
- M_{ms} is the mass in kg of the moving system (cone, motor coil, form, surround, and suspension bits that move, as well as the air load, depending on how much of a stickler you are).
- C_{ms} is the compliance of the moving system in meters per newton. This is a question of how supple the suspension and surround are. Plop a woofer on its back, lay 37 modern pennies on the cone, and measure the defection. As it happens, 37 modern (zinc) cent pieces weigh very nearly 102 gm, which will exert a force of 1 newton on the cone. Do this to an AR 12″ woofer, and you'll see a deflection on the order of 1.3mm; C_{ms} = 0.0013m/N.
- Q_e is the electrical "Q" of the unit, that describes how well the motor (B, l, and R_{dc}) controls the unruly physical realities of mass (M_{ms}) and, implicit in f_s, compliance. The lower the Q_e, the firmer the motor's grip on the cone. This has a lot to do with motor efficiency, but not much to do with acoustic output, because S_d, or piston area, doesn't enter into it. All the motor "sees" is the mass, and the acoustic load (sound output) is so small you can safely ignore it.
- R_{dc} is the DC resistance of the voice coil,

in ohms. If you're looking at the system Q (Q_{tc}), you should include Rs that are external to the driver and in series, such as crossover inductors.

- B is the flux density in the magnetic gap, in Teslas (T). This is an indication of the strength of the magnet system. If the gap is sizable in dimension, like this woofer, and you want a lot of flux (analogous to current) in that gap, you need an impressive magnetic structure.
- l is the length of wire in the magnetic gap, in meters. This motor has a circumference of 16cm and two layers of 56 turns each, and is 1″ (2.54cm) tall. Half the motor coil is in the gap at a time, so l = approximately 9m.
- Q_m is the mechanical "Q" of the unit, describing how the driver would behave around resonance if not electrically connected, i.e., not hooked up. It is typically quite large (because R_{ms} is typically relatively low)—on the order of 5 or greater.
- R_{ms} is the mechanical resistance or friction of the moving system. It is typically low, unless the woofer has a lossy rubber surround, there's ferrofluid in the gap, or the driver has to huff its back wave through felt or a similar material. It is measured in mechanical ohms, whatever they may be.

It's also handy to be able to find V_{as}, which is the volume of air that will give a cone the same compliance as its mechanical suspension. I wasn't about to mess with the driver's suspensions, so I'll get to V_{as} later.

In his *Loudspeaker Design Cookbook*, Vance Dickason tells how you can discover experimentally such parameters as Qs. I prefer the formulas because they're more susceptible to manipulation. It's obvious that if you want to decrease Q_e (which is by far the dominant player in a driver's total Q, if a woofer; domes tend to be different), the quickest way to go about it is to increase B (see Equation 2). Changing l will help, but R_{dc} will also rise. Same goes for any changes to M_{ms}; it will move Q_e in the desired direction, but M_{ms} also acts on f_s, only half as fast, mathematically speaking.

For example, suppose you increase a cone's mass by 150%, i.e., so that it weighs 2.5 times what it did. If you think in terms of dB, that's up 4dB. But f_s will drop by about 37%, to 63% of what it was (down 2dB). So Q_e only rises by 58% (i.e., up 2dB), and that's not mentioning output, which will drop by 2.5^2 (or 8dB), all else held constant.

With this woofer, I managed to increase both B and l, but I also wanted a lower f_s, so I increased the cone's mass. Total Q, or Q_{ts}, wound up at about 0.18, down from about 0.32.

Bl, I repeat, is where the action is if you're after low-Q, low-resonance woofers. I think of Bl as a figure of merit for a woofer's motor. I am annoyed that there's no easy way to ascertain a woofer's B. Unfortunately, the only way is to determine l, and then Bl via the weight/deflection/current method described in the *LDC*, and then divide Bl by l.

TOOLS AND TECHNIQUES

I still had a plastic balance from an old AR turntable, good down to 50mg and up to 30g or so, but I needed something useful up to 2kg, so I made a balance. For the axle and bearings, I pulled apart the kind of common outer-rotor synchronous motor that you find in washer and dryer timers. For the beam, I screwed together two hacksaw blades with 6-32 hardware and drilled a hole exactly in the middle for the axle.

I spread the blades apart ½″ or so at the axle, and mounted this in a chunk of 2 × 2, drilling in from the end. I mounted the bearings in the hole, and then notched the 2 × 2 for clearance for the beam. On one end of the beam, I hung an improvised pan for weights, counterbalanced by extra 6-32 hardware on the other end (*Photo 3*).

I can clamp this balance just about anywhere. For weights I use coins (30g per $0.11) and odd pieces of steel I've weighed. To weigh something, I just hang it from the free end with thread and pile weights on the other until I'm satisfied. As little as ½g will trip it easily.

Once I had made the balance, I realized it might help in determining B. I cut out a piece of $^1/_8$"-thick transformer iron about the size of a postage stamp, drilled a hole in one end, hung it from the balance, and glued a piece of rubber "continuous grommet" on the bottom (*Photo 3*). To get some notion of B, I clamped the scales above the gap so that the iron (let's call it a probe) hung straight down, bridging the magnetic gap and held away from the pole pieces a mm or so by the rubber. I made sure everything was square, then started piling on the weights until it tripped, pulling the probe free of the magnet structure.

MEASURING GAP STRENGTH

It doesn't give me an absolute number for B, but I figure I have a good enough indicator of the gap's relative strength by how much weight it takes to trip. Now I can determine reasonably well the effect on flux density of the changes I make. I have no confidence it would give useful results for different gaps, say a 1mm gap of relatively small surface (like the mid dome) versus the 2mm span and large face area of the woofer gap. But with two gaps of the same dimension, the iron-on-a-string works well.

It sure beats jerry-rigging a Bl setup by holding the spider and cone in place with masking tape—which works, by the way, but is surely a nuisance.

My other tools and tricks are nothing special. I've already mentioned the drill plugged into the Variac. I also used the Variac as a 60Hz signal source for my voltage divider when making my inductors. You'd better know how to solder, and which end of a voltmeter is up. The *Stereophile* test CD (#2, I think) has warble tones from an Old Colony warbler, which is handy in lieu of a signal generator.

Some strong reading glasses (3.5 or so) will help when you're rewinding the tweeter voice coil. You will also need milder ones (1.5 or so), depending on how good your close-in focusing is. I also used a 16× loupe, which was useful, except that it kept falling out of my eyesocket.

STICKY STUFF

Chief among the glues is slow-cure epoxy. Devcon "2-ton" has a 30-minute set, which is pretty good. But any "extended working time" epoxy is probably okay. "Quick-set" or "5 minute" epoxies are to be avoided like the plague when you're doing something like winding a motor coil. For mixing epoxy, I use the nonstick backing paper from adhesive vinyl sheets (you know, bumper stickers). Once the epoxy beads up and begins to set, you can wipe it clean and mix another small batch. You'll be doing a lot of small batches.

I also use a lot of one of my favorite substances, DAP "Alex Plus" acrylic latex caulk plus silicone. 35-year durability, it says on the tube, which holds 300cm^3 and costs $1.75. It's a fairly tenacious adhesive, fills gaps well, and comes in colors only an audiophile could love (black, bronze, gray—you know the palette). It's rubbery, but not bouncy, easy to clean up if you get at it before it begins to set, and so cheap you can use it with abandon.

I also use a lot of masking tape, mostly to *clean* things, such as minute particles of steel from magnetic assemblies before gluing. Or out of the gap itself. Or from my hands before I go near a clean gap. Not bad for cleaning LPs, too.

PHOTO 3: My homemade balance in action. The transformer iron is bridging the woofer gap, and various weights hang off the left side. The gap's holding about 900g here. Another 200g will pull it free. Coins and small weights go in the pan. Larger weights hang from the hardware.

Buy a deck of playing cards. They make precision, throw-away shims, or you can mix epoxy on them, or use them as squeegees to spread glue.

Get yourself a dial caliper. I used a plastic one for this project, and it worked fine. It's reliable down to about 0.003″. They are cheap—you see them in many tool catalogs. A ruler, even if it's a nice stainless steel one, won't cut it on this project. I don't know how I ever got along without my caliper.

A nice piece of thick glass, ¼″ or so, about 12″ square, is also useful as a certifiably flat surface. Get two, just slightly larger, and you can warm LPs to flatness in the sun.

BLADES AND NEEDLES

I also found that the thin, sharp blades from disposable razors are very handy when clamped in an X-acto knife handle. They're usefully flexible, and you can break them into any shape you need with a pair of small pliers. Also, a big needle, 3″ or 4″ long, is useful to poke, prod, and shift. Many woodworkers are familiar with the many uses of old tire inner tubes; probably more common these days are bicycle inner tubes. Just hie thee down to a bike shop, and they'll give you all the old inner tubes you desire. You can cut them up into any size piece of elastic you need.

Now for some comments on hygiene. Cleanliness is good, but if you're working around strong magnetic fields, especially open magnetic gaps, unusual care is called for. These things seem to pull bits of iron and steel out of thin air. It's a good practice to have separate "normal" and "clean" work and storage areas—in different rooms if possible.

Wash your hands. Use masking tape to lift filings and grime from your fingerprints. Be aware of steel that might be lurking in your clothes or hair. I masked the woofer gap right away on disassembly, and kept it masked, but still there was unidentifiable grime stuck to the masking tape I used to clean out the gap before mounting the cone.

Also, keep a notebook. Record your measurements and actions as you go, especially if you don't work on two mids at the same time, say. It's entirely too easy to forget details, and it only takes a moment to make a note or a quick sketch.

Those who have read this far will have their patience rewarded. All these preliminaries are necessary. Next time, I'll take a close-up look at the inside of the AR-3*a*.

CROSSOVERS AND RESISTORS

By Juan Castillo

Whenever we design a crossover network for a new loudspeaker project, we almost always end up using resistors for attenuation purposes, in order to match the more efficient tweeter with the rest of the system. Your best bet for achieving the desired attenuation is with correct L-pad values. But you may want to use a single resistor instead, or you simply can't find the exact required values at the moment.

I wondered what would happen if I used resistors for attenuating a tweeter in the following five situations:

1. Using a single resistor between the tweeter and the crossover;
2. Using a single resistor before the crossover;
3. Using a well-designed L-pad with different attenuation rates;
4. How much error in the resistor values is acceptable when using a well-designed L-pad?
5. What would happen if I place just any resistor value in an L-pad configuration?

For all of the measurements, I used a Dynaudio D 260 Esotec tweeter mounted off center (for diffraction purposes) in a slim speaker enclosure, with a high-pass second-order crossover at about 3.9kHz that consisted of a 5μF Solen capacitor and an air-cored, handmade 0.34mH coil, with a DC resistance of only 0.08Ω to avoid interactions. I made the measurements with CLIO 3.2, with maximum length sequences (MLS), placing the microphone on axis exactly one meter away from the tweeter.

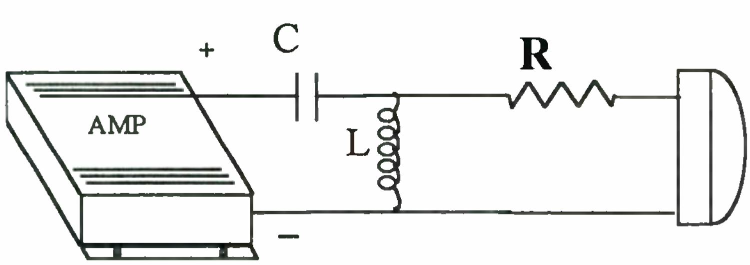

FIGURE 1: A single resistor between tweeter and crossover.

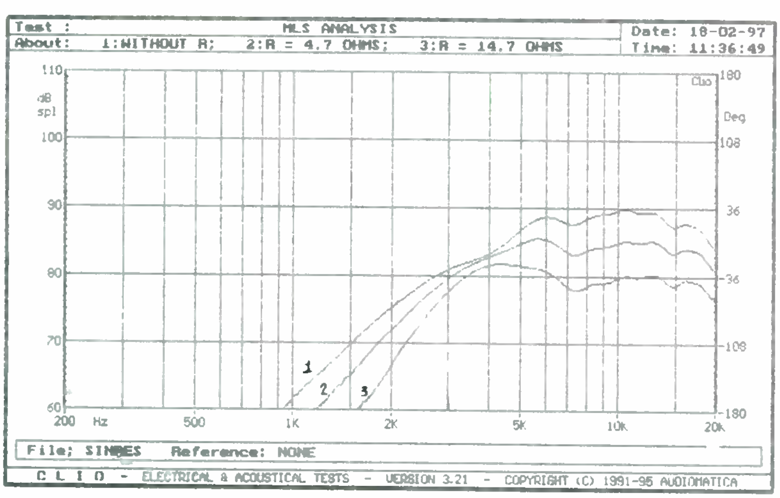

FIGURE 2: Case #1 measurements. Curve 1 has no resistance; curve 2 shows a 4.7Ω resistor between crossover and tweeter; curve 3 uses a 14.7Ω resistor between crossover and tweeter.

CASE #1

With a single resistor between the tweeter and the crossover (*Fig. 1*), the crossover "sees" a greater impedance than what it was designed for, thus changing its behavior (*Fig. 2*). Curve 1 is the response of the tweeter-crossover, with no resistor at all, for reference. Curve 2 is with a 4.7Ω resistor, and curve 3 shows a 14.7Ω resistor.

As you can see, increasing the resistor value increases the general attenuation of the response, but lowers its crossover point and changes its shape and slope. The greatest change is near the crossover point, where almost no attenuation takes place, no matter how large the resistor value. The curves normalize as the frequency increases.

TABLE 1

R_p, R_s, and Z_{eq} FOR THREE ATTENUATIONS

Attenuation in dB (A)	R_P (Ω)	R_S (Ω)	Z_{eq} (Ω)
–4dB	10.6	2.3	6.21
–8dB	4.1	3.7	6.17
–12dB	2	4.6	6.11

ABOUT THE AUTHOR

Juan Castillo began designing loudspeakers as a hobby when he was 14 years old and received his mechanical/electrical engineer degree in 1991 from the Universidad Anahuac del Sur, Mexico City. He opened "SUONO," a retail shop in Mexico City in 1992, installing professional car-audio systems and designing high-end home loudspeaker systems. In 1993, he opened the first Mexican-based car-audio installer's institute. In 1996, he became an international trainér for Boston Acoustics, covering Latin America.

CASE #2

When you use a single resistor before the crossover (*Fig. 3*), all the curves start from virtually the same point, the distance between them increasing with the increasing frequency, and decreasing somewhat at the finish (*Fig. 4*). Note that curve 3 has in general more high-frequency content than the reference curve, with a softer slope. Again, the resistor, besides attenuating, changes the shape of the response.

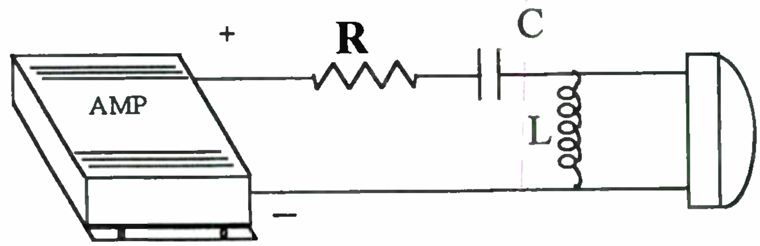

FIGURE 3: A single resistor before the crossover.

CASE #3

The third scenario involves a well-designed L-pad (*Fig. 5*). Using the following formulas, I obtained the correct values for the series and parallel resistance and the equivalent impedance of the system (see Max R. Knittel, "Microcomputer-Aided Driver Attenuation," *SB* 1/85, pp. 24–27):

$$R_p = \frac{10^{(A/20)} Z_D}{1 - 10^{(A/20)}}$$

$$R_s = Z_D - \frac{1}{\frac{1}{R_p} + \frac{1}{Z_D}}$$

$$Z_{eq} = \frac{1}{\frac{1}{R_p} + \frac{1}{Z_D}} + R_s$$

Where
R_P = Parallel resistance
R_S = Series resistance
Z_D = Driver impedance
A = Attenuation in dB, as a negative value (example: −6dB)
Z_{eq} = Equivalent impedance of the circuit

As Knittel recommended, I measured the impedance of my tweeter near the crossover frequency and found it to be approximately 6.2Ω. Using the above formulas, I calculated resistor values and corresponding Z_{eq} for three different attenuations (*Table 1*).

Using these values, I obtained the curves in *Fig. 6*. Curve 1 is without resistors, for reference, and curves 2, 3, and 4 are for −4, −8, and −12dB, respectively.

So, if there was ever any doubt about it, the L-pad works as promised, changing neither the equivalent impedance of the circuit, the crossover point, nor the shape of the response.

CASE #4

More often than not, you just can't find resistors having the exact values as calculated from the formulas. And, as any good speaker builder knows, it's not a good idea to place

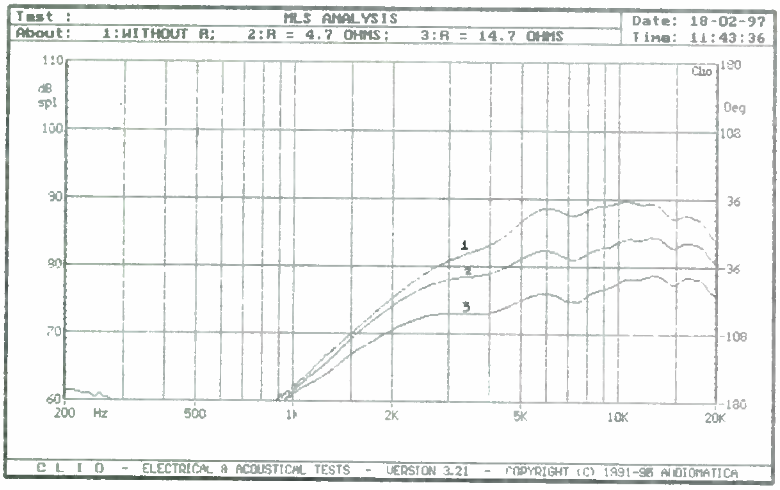

FIGURE 4: Case #2 measurements. Curve 1 has no resistor; curve 2 is with a 4.7Ω resistor before crossover; curve 3 uses a 14.7Ω resistor.

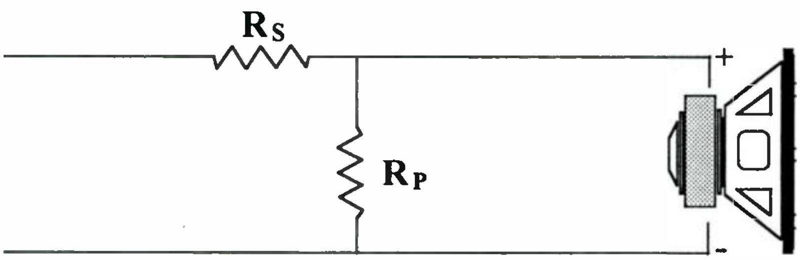

FIGURE 5: Using a well-designed L-pad.

several resistors in series in order to achieve the calculated values, so what should you do instead?

In *Fig. 7* you see, besides the reference curve, two more pairs. One curve of each pair is based on exact calculated values, and its mate has values that are 10% off. I used resistors that were 10% above the calculated values, with final equivalent impedances as follows:

Curve 1: No resistors, for reference;

Curve 2: L-pad for –4dB exactly, and the other using R_P = 11.7Ω, R_S = 2.5Ω and Z_{eq} = 6.55Ω.

Curve 3: L-pad for –12dB exactly, and the other using R_P = 2.2Ω, R_S = 5.1Ω and Z_{eq} = 6.7Ω.

Figure 8 shows only one attenuation group, corresponding to –12dB. The center curve represents the exact calculated values, the one above it values 30% higher, and the one below values 30% lower.

Curve 1: –12dB, 30% above calculated: R_P = 2.6Ω, R_S = 6Ω and Z_{eq} = 7.83Ω.

Curve 2: –12dB, exact calculated values.

Curve 3: –12dB, 30% below calculated: R_P = 1.4Ω, R_S = 3.22Ω and Z_{eq} = 4.36Ω.

Figure 7 shows that using resistors that are about 10% off the calculated values makes little difference, but it's another story if they're 30% off. You can see also that the curves do not behave symmetrically if you go above or below the calculated values.

CASE #5

The last situation is to use any resistor combination in an L-pad until you achieve the level of attenuation you wish. *Fig. 9* illustrates that the response can be completely altered.

The values, for approximately 10dB of attenuation, are as follows: R_P = 10Ω, R_S = 10Ω and Z_{eq} = 13.9Ω. Note the abrupt change in the equivalent impedance.

CONCLUSION

Whenever you need to attenuate a driver, it's a good idea to stick with the calculated values of an L-pad if you wish to avoid any change in the response, or if you have no means to compensate for those changes. As the graphs show, however, you can use resistor values as much as 10% off with minimum consequences.

It should be clear, too, that whenever you use a single resistor, changes in the response

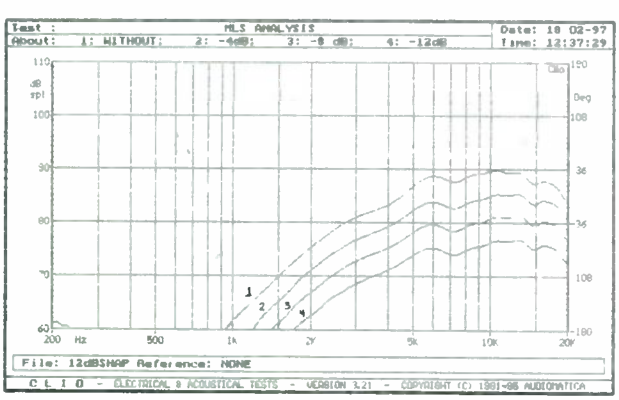

FIGURE 6: Diagram of calculated resistor values for three different attenuations. Curve 1 is without L-pad; curve 2 is with L-pad at –4dB; curve 3 is with L-pad at –8dB; curve 4 is with L-pad at –12dB.

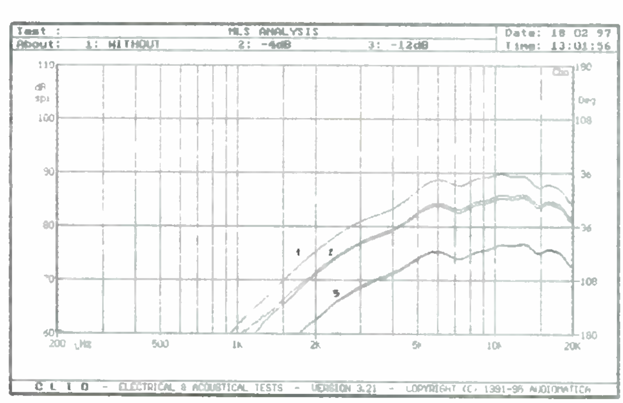

FIGURE 7: Using various resistor values. Curve 1 is without L-pad; curves 2 show a –4dB L-pad and a 10% error; curves 3 use a –12dB L-pad and a 10% error.

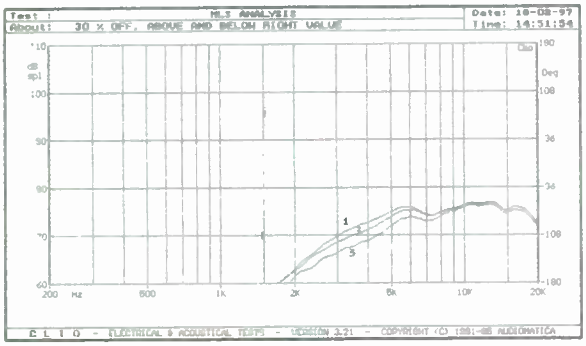

FIGURE 8: Measurements at −12dB L-pad and 30% error above calculated values (curve 1); at −12dB L-pad (curve 2); and at −12dB L-pad and 30% below calculated values (curve 3).

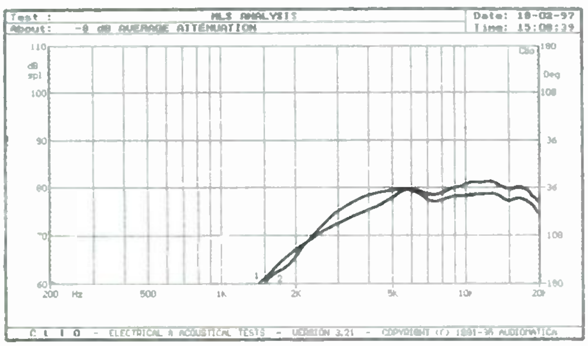

FIGURE 9: Altered responses. Curve 1 is at −8dB L-pad, and curve 2 uses two 10Ω resistors.

shape, crossover point, and slope will take place. The same thing happens when you use two arbitrary values as an L-pad.

The main idea here is that resistors should be used not only as attenuation pads, but as tools in your goal to achieve a desired response. You can see the great effect they can have, if modeled properly, on the final response of a loudspeaker system.

OF NOTE IN
Audio Electronics

Issue 4, 1997

- Class-A Power Modules
- Line/Mike Pad for Video Camera
- Unleash Your AC Power Line
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I & J Fisnar, Inc.	www.ijfisnar.com
Innovative Technology, Inc.	www.itvss.com
Institute of Electrical and Electronics Engineers	http://standards.ieee.com
Kenwood	www.kenwoodusa.com
LinearX Systems Inc.	www.linearx.com
Marchand Electronics	www.marchandelec.com
Metaxas Audio Systems	www.metaxas.com
Metaxas Electrostatic Technologies	www.metaxas.com.au
Newform Research Inc.	www.barint.on.ca/newform/
Nirvana Audio	www.nirvanaaudio.com
NOVA Elektronik GmbH	www.compfinder.com
Parts Express International	www.parts_express.com
PC Instruments Inc.	www.pcinstruments.com
Peavey Electronics Corp.	www.peavey.com
Reed Exhibition Companies	www.showbizexpo.com
Sennheiser Electronic Corporation	www.sennheiserusa.com
SmartLinc	www.smartlinc.com
Sonic Foundry	www.sfoundry.com
SoundTech/Washburn International	www.washburn.com
SpectraRTA	www.soundtechnology.com
Synergetic Audio Concepts	www.synaudcon.com
Technomad	www.technomad.com
Tekna Sonic Inc.	www.teknasonic.com
Telulex	www.telulex.com
The Binaural Source	www.btown.com/binaural.html
True Audio	www.trueaudio.com
WHMA	www.whma.org

Product Review

THE AUDAX A651 LOUDSPEAKER

Reviewed by Dennis Colin

The Audax A651 loudspeaker, Zalytron Industries Corp., 469 Jericho Tpke., Mineola, NY 11501, (516) 747-3515, FAX (516) 294-1943; Orca Design and Manufacturing Corp., 1531 Lookout Dr., Agoura, CA 91301, (818) 707-1629, FAX (818) 991-3072.

PHOTO 1: Empty enclosure without grille.

This unit features a two-way design with an Audax HM17020 6.5″ HD-A woofer and AW02553 1″ aluminum dome tweeter, in an 18 ltr (0.64ft^3) vented enclosure with QB3 alignment and f_3 = 55Hz. The crossover is fourth-order Linkwitz-Riley at 3kHz. This is one of the Vance Dickason Signature Series kits.

ASSEMBLY

I epoxied the crossover components on separate woofer and tweeter boards—each 6″ × 4″ × ½″—screwed them to the bottom and rear (behind tweeter) panels, respectively, then mounted the terminal cup. After uttering 110dB profanity while soldering inside the 7½″ width interior through a small woofer hole, I highly recommend wiring before installing, unless you have a highly trained small pet!

Next, I mounted as much Black Hole damping material as I could fit, covering all surfaces except the bottom (occupied mostly by the woofer crossover). Then I filled the remaining volume with loosely packed fiberglass. I soldered the wires to the drivers, then installed them. The supplied woofer gaskets were too large, but easy to cut to fit.

Listening Tests

My equipment includes a Nakamichi AV-1 receiver (100W/ch), Yamaha CDC755 CD changer, microphone test—Thermo Electron 814C Omni Capacitor—for clarinet and voice, Sony TC-W5 cassette player, and Miracord turntable with Shure R700E cartridge.

My listening room is approximately 20′ × 18′ × 8½′ (≈3,000ft^3), and is moderately damped with large stuffed chairs and couch, 10′ front wall drapes, and full carpet. Rear and side walls are reflective but dispersed by a stairwell and passageways. The wood floor is rigidly supported. The room sounds good with other speakers, including the two-way Linaeum with 360° tweeter (Radio Shack Optimus Pro LX5), the A/D/S 300C mini-monitor, and my full-range bipolars with 10″ Focal woofer and coincident mid/tweeters.

SPEAKER PLACEMENT

Placed on 25″ stands, the A651s were 3′ from, and centered within, the 20′ front wall. Initially they were six feet apart, but I in-

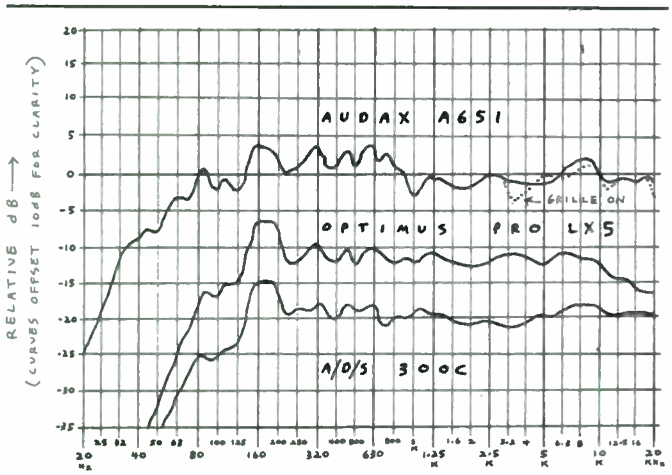

FIGURE 1: Graph of the near-field response, with the mike 2′ from the speaker on tweeter axis, both 39″ from the floor, and the speaker 4′ from the wall. Curves are separated by 10dB mike gain change, for clarity.

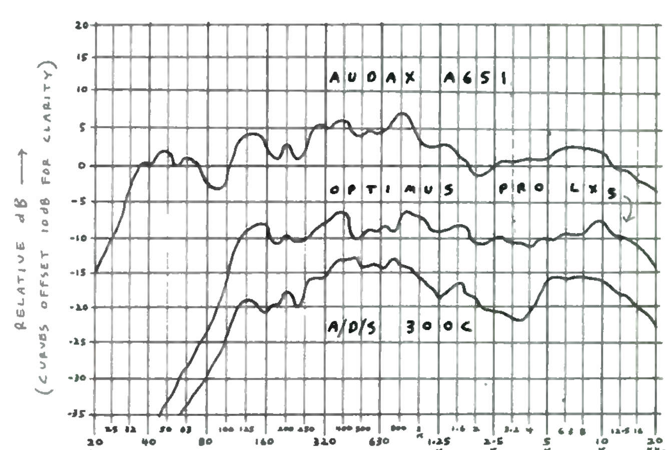

FIGURE 2: The distance is now at 3m, which causes the response to be close to total integrated speaker output. Turning the speaker backward or facing it upward made little difference in response.

creased the separation to 11′, so the couch listening position formed an equilateral triangle with the speakers.

SOURCE MATERIAL

CDS

Stereophile Test CD—Stereophile STPH 004-2
"Tango," Julio Iglesias—Columbia/Sony CK 67899
"Two Fisted Mama," Katie Webster—Alligator ALCD 4777
"Marches in Hi-Fi," Fiedler, Boston Pops—RCA 09026-61249-2
"Dedicated to the One I Love," Linda Ronstadt—Electra 61916-2
"The Grand Tour," Aaron Neville—A&M 31454 00862
"Natural High," The Commodores—Motown MCD 08014 MD
"Rhapsody in Blue," Gershwin—Mercury 434341-2
"The Concert," Barbra Streisand—Columbia C2K 66109

LPS

"The Blue Danube," Ormandy, Philadelphia Orchestra—Columbia MS 6217
"Mozart Symphony No. 36," Istvan Kertesz, Vienna Philharmonic Orchestra—Super Analogue Disc, KIJC—9128
"Blues, Ballads, and Jumpin' Jazz," Lonnie Johnson and Elmer Snowden—Analogue Product APR 3001
"Strong Persuader," Robert Cray—Mercury/Hightone 830 568-1M-1
"Malaguena," Dick Dia and Orchestra—AudioFidelity AFSD-6129B
"Magnificent Mandolins," Dick Dia and Orchestra—AudioFidelity AFSD-5963A

CASSETTES

"Slippin' In," Buddy Guy—Silvertone 01241-41542-4
"Faith," George Michael—CBS CT 40867
Miscellaneous Rock, Blues, & Jazz recordings from Radio and DSS

LIVE SOURCES

Clarinet and voice

LISTENING TESTS

I've played the test music (see "Source Material") often over the last several years and have become familiar with the large variations in instrument tonality even among "audiophile" recordings. Having heard live symphonies and bands since age 6, I've noted which instruments on which recordings, through a variety of excellent loudspeakers, tend to sound most consistently like the real live thing.

However, I still depend on memory (not having an orchestra in my house) as well as personal preferences. But I believe I've identified the significant features of the A651 to a reasonable degree of accuracy:

PHOTO 2: The Audax kit comes with cabinet insulation (top), instructions, caps, resistors, tweeter, coils, input connectors, and drivers (center).

1. Very natural sounding with most sources.
2. Slightly emphasized lower midrange, audible with violins and male voices, the latter sounding somewhat muffled.
3. Exceptionally clean bass, surprisingly deep and powerful for a 6½″ woofer system tuned for f_3 = 55Hz. Very well damped; excellent bass detail and transient sharpness. With a sine-wave source, the A651 produced clean 40Hz up to 8W drive, 30Hz up to 4W (re 8Ω).
4. Smooth, clean, extended highs.
5. Quick, accurate transient response—drums, cymbals, guitar, and piano are very realistic.
6. Imaging is pin-point; crossover is so space-coherent that even with pink noise, the image and tonality are free from smearing or "phasing" sound both on- and off-axis.
7. Dispersion is very good; tonality hardly changes moving around the room.
8. Soundstaging is deep, wide, and accurate.
9. Sense of 3-D ambience is probably as good as is possible with a forward-only radiating speaker. I favor a bipolar design, which sounds most spatially realistic (to my ears in this room).
10. The A651 had no problem producing the rated maximum 100dB SPL. With a rated sensitivity of 86.5dB, 1W/1m, this takes an average of 22W. But even when I dared to push the 100W/channel amp, the sound was very clean. (Don't try this at home!) Since most music has at least a 10:1 peak/average power ratio, a 100W/channel amp can be safe if you're careful.

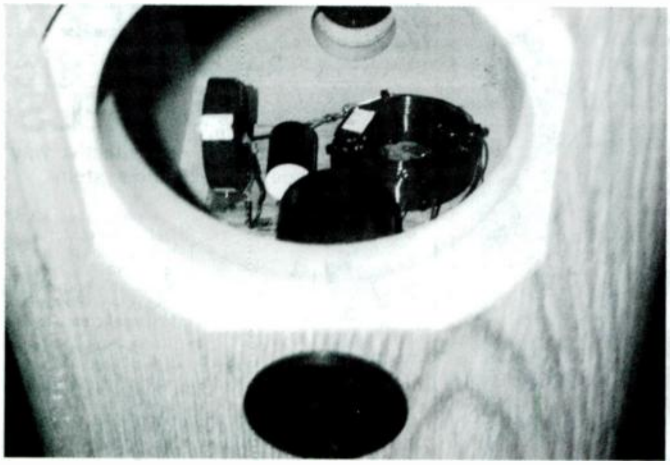

PHOTO 3: Woofer crossover installed.

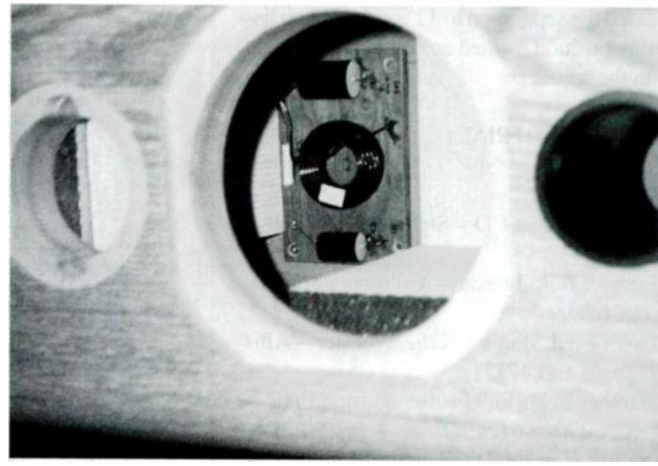

PHOTO 4: Tweeter crossover and damping panels (three, increased to four, per cabinet) installed.

LISTENING TESTS WITH LIVE SOURCES

I used the Thermo-Electron Omni Capacitor mike (±2dB, 10Hz–30kHz) to feed live clarinet (courtesy of my wife) and voice (courtesy of Mr. and Mrs.) into the A651.

I observed the following:

1. Female voice was very natural.
2. Male voice had slight lower-midrange coloration, somewhat muffling and resonant.
3. Clarinet was so real-sounding that the difference, as far as tonal reproduction goes, could be no more than the effect of moving the instrument about the room. Apparently, the low notes have most of their harmonic energy below the frequency range affecting the male voice, since I heard hardly any tonal coloration with these clarinet tones.

TRANSIENT RESPONSE

1. On Lonnie Johnson's snappy guitar pickin', the A651 reproduced the bite, twang, and tone very well; the 300C was just about as good; the Pro LX5 had less bite, perhaps due to masking by room reverb. The A651 did remarkably well in reproducing initial string transients.
2. While people don't normally listen on their speakers to the sound of two spoons clinking together, this is an excellent transient test—the sound is repeatable, familiar, and makes an extremely sharp transient with enough ringing to sustain a tone, but not enough to blur the transient "immediacy."

Only with this test could I hear the 300µs of delay dispersion caused by the fourth-order 3kHz A651 crossover. I could hear a very quick downward-swooping effect on the impulsive "clink." I couldn't hear this on the Pro LX5, which has a near-first-order crossover. But the tonality was near-perfect on the A651, slightly less so on the Pro LX5.

3. With electronic step pulses (such as a 1Hz square wave), I could clearly hear the "delay sweep": first the high "tick," then the midrange, and then the delayed port output.
4. At no time with any music was I aware of time-smearing due to the small (300µs) delay dispersion of the A651 (observable on an oscilloscope with square waves). If you don't listen to recorded spoons, no problem!

FREQUENCY RESPONSE IN LIVE ROOM

I decided to measure the three speakers in an upstairs room, which is a good acoustic inte-

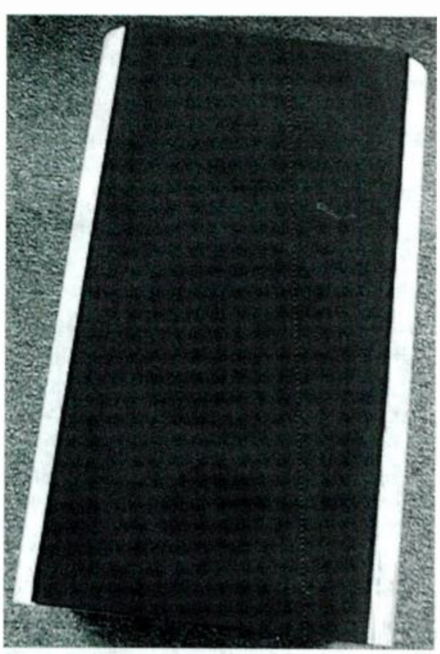

PHOTO 5: Cabinet with grille in place.

COMPARISON WITH PRO LX5 AND A/D/S 300C

The 300C is a two-way mini-monitor/car speaker with a 1″ dome tweeter. Both speakers have a 5″ woofer and are much smaller than the A651, so I didn't bother with bass comparisons. I observed the following before I measured the near- and far-field frequency responses:

1. The A/D/S sounded a little smoother in the midrange.
2. The Pro LX5 had the best upper midrange and spatial realism, but at the expense of some precision of focus compared to the other two units. It also had the best consistency between near- and far-field sound, but the A651 was close.
3. The A651 had the best imaging and freedom from crossover audibility.

MANUFACTURER'S SPECS

Frequency response: 55Hz–19kHz ±2.2dB on-axis
Maximum output: 100dB SPL
Sensitivity: 86.5dB SPL @ 1W, 1m
Extension dimensions: 16.375″ H, 9″ W, 11.75″ D

The enclosure measures 17.5″ × 10.5″ × 13″, with all surfaces 1.5″ thick. It features double wall thickness and a rounded front. The kit components include an installed vent, flush-mount driver openings, detachable grille, drivers, gaskets, terminal cups, and Black Hole damping pads. The crossover components consist of Axon 5% "Truecaps," Axon 1% resistors, and 4½ lbs. of copper air coils.

Only 17½″ high, the cabinets, which Joe D'Appolito calls "battleship cabinets," weigh 34 lbs each. Indeed, when rapped, they make only a little more sound than my brick fireplace wall!

The well-written instructions include construction details, response graphs, suggested room placement, and specs for a 26″ stand. Also, the tweeter crossover layout shows L3 wired differently from the schematic (all four A Series kits in the brochure include the same error). According to the designer, the schematic is correct.

grator—very reflective but dispersive due to 45° sloped side walls; no strong standing waves except for a ≈4dB peak around 160Hz (visible on the response plots). The room volume is 2100ft^3; RT 60 (reverberation time to –60dB decay) is approximately one second, corresponding to an average absorption coefficient of 0.083 for 2100ft^3 volume and 1040ft^2 surface area.

SOME NOTES

1. The near-field response of A651 shows a ≈3dB "shelf" around 800Hz, more so in far field. This explains the emphasized lower midrange with male voice and violins. Note that I wrote down my listening impressions before measuring response. Also, I came to the same conclusions with limited listening in the live room, as in the moderately dry living room.

2. Above 300Hz, the Pro LX5 and 300C have flatter responses than the A651.

3. Only the Pro LX5 has a far-field response both similar to its near field and fairly flat. This is most likely why it has superior spatial reproduction.

4. The A651 grille caused a ≈2dB dip at 3.5kHz, ≈½ octave wide, and ≈1dB changes at higher frequencies. Its audibility was very small; it slightly reduced high-frequency dispersion, but was hardly noticeable in normal listening.

A651 CONCLUSIONS

1. Very natural and satisfying with most material.

2. Audible 3dB shelf drop above 800Hz (measured) mostly on male voices (very sensitive to upper/lower harmonic balance). Upper violin tones were the only other sources noticeably affected. Lower violin, and cello, and bass viol tones were reproduced with ethereal naturalness.

3. My best jazz recording is *St. James Infirmary* (Stereophile test CD). The A651 provided a dramatically real musical presence, with bass, drums, cymbals, and horns captivatingly present within a sense of lush 3-D spatial ambience.

4. The same was true of "Malaguena"—the Stravinsky piece on the Stereophile test CD—"Tango," and New Orleans goodies recorded from DSS, regarding reproduction of guitar, strings, horns, and percussion.

5. With the 800Hz shelf corrected—perhaps by crossover equalization—I believe that all naturally recorded material would sound close to perfect.

6. To my ears, only some excellent bipolars reproduce a more solid 3-D sense of presence.

7. The A651's image precision and focus are extremely good.

TESTING THE AUDAX A651 LOUDSPEAKER KIT

By Joseph D'Appolito

I ran a series of impedance, frequency response, and distortion tests on the Audax A651 kit constructed by Mr. Colin. *Figure 3* is a plot of system impedance magnitude and phase over the full audio range. Below 100Hz, the magnitude plot displays the classical double-peaked curve of a vented system. A minimum impedance of 9.6Ω at 41.6Hz indicates the system tuning frequency, f_B. The overall impedance minimum is 6.3Ω at 212Hz.

This system easily earns an 8Ω rating. However, the impedance is strongly capacitive at 90Hz, reaching a phase angle of –60°. This is a region of typically high power demand. Some tube amps and amps with poor low-frequency stability may have a problem with this load.

A small glitch occurs in the impedance magnitude and phase between 700 and 800Hz. This may be a small cabinet resonance or an internal back-wave reflection. The large difference between the 9.6Ω and 6.3Ω minima is a cause for further investiga-

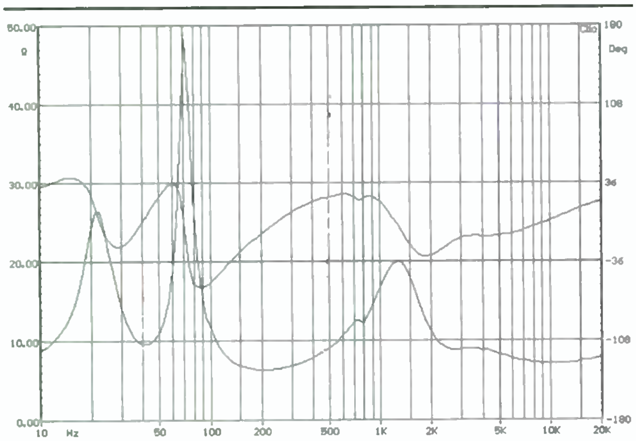

FIGURE 3: System impedance magnitude and phase over the full audio range.

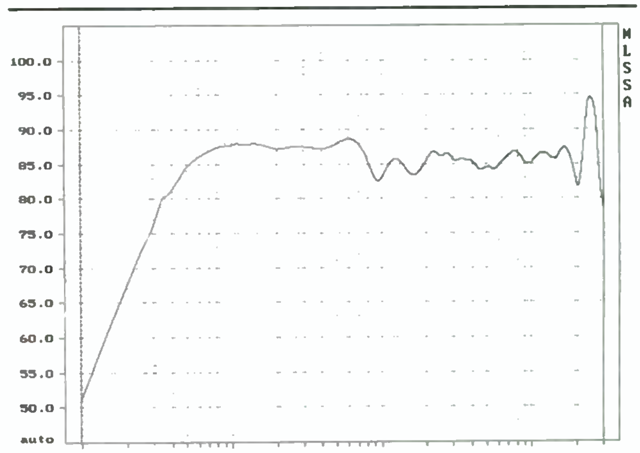

FIGURE 4: Half-plane system response at 48″ on tweeter axis.

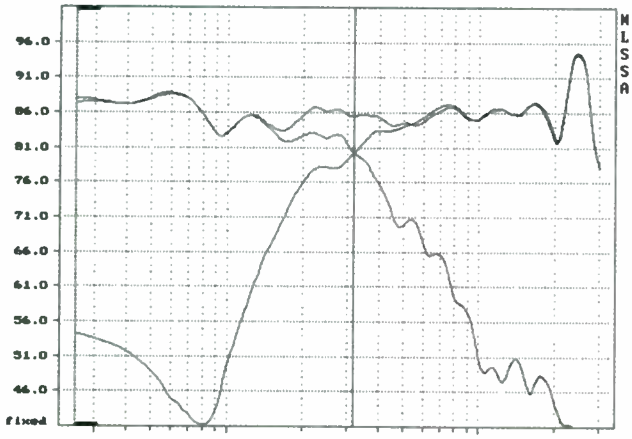

FIGURE 5: System and driver frequency responses.

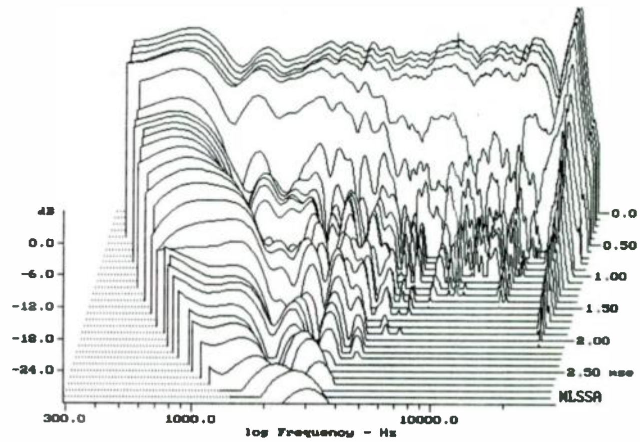

FIGURE 6: Cumulative spectral decay.

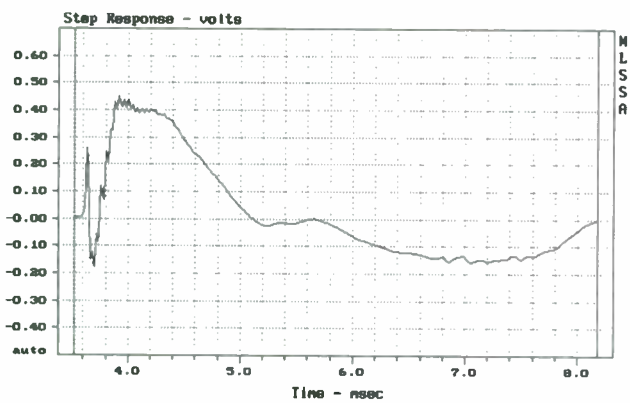

FIGURE 7: System step response.

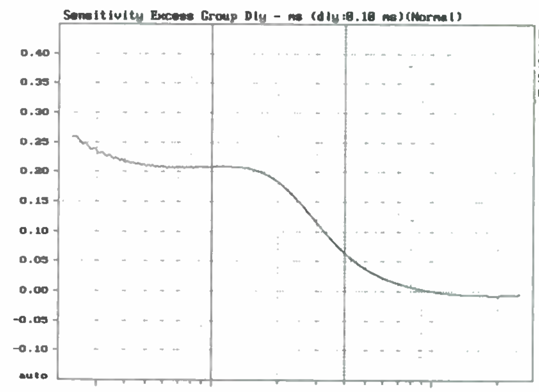

FIGURE 8: Excess group delay.

tion. Both minima should be only slightly larger than the total DC resistance of the voice coil and crossover coils. The much higher value at 41.6Hz suggests that the port is highly overdamped. We'll further examine this point later.

Figure 4 shows a composite hemispherical on-axis frequency response for the system. Quasi-anechoic data above 250Hz taken with the microphone placed on the tweeter axis at 48″ is combined with near-field woofer and port data below 250Hz for a complete curve. The plot is normalized to one meter distance to get system sensitivity. Average sensitivity in the two octaves around 1kHz is 86.5dB SPL/2.83V/1m. However, response shelves down by 2dB above 1kHz relative to its value below this frequency.

Average sensitivity in the 100–500Hz range is 87.5dB. Above 1kHz the number is 85.5dB. The system −3dB point on the low end is 49Hz relative to the 87.5dB level. This response could lead to a warm upper bass and a recessed midrange sound. The metal-dome tweeter displays a typical "oil-can" resonance, peaking 10dB at 25kHz.

Figure 5 illustrates the action of the

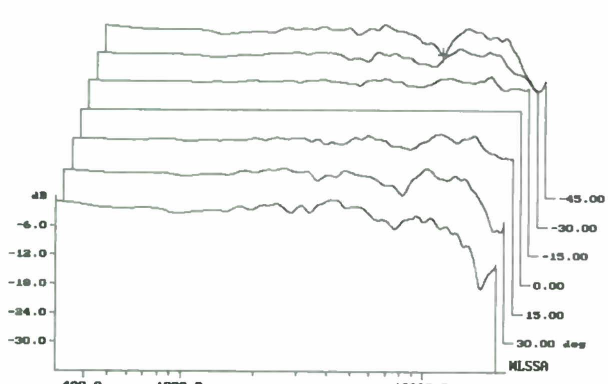

FIGURE 9: Horizontal polar response.

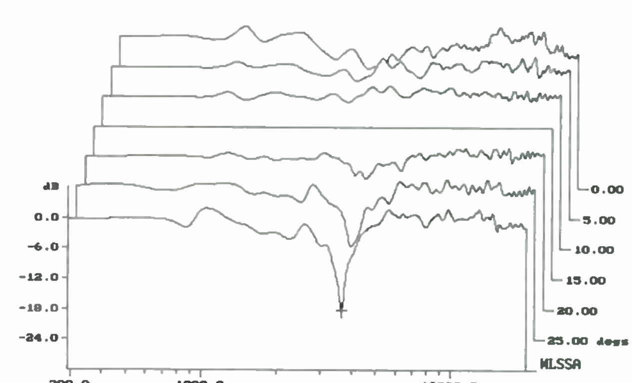

FIGURE 10: Vertical polar response.

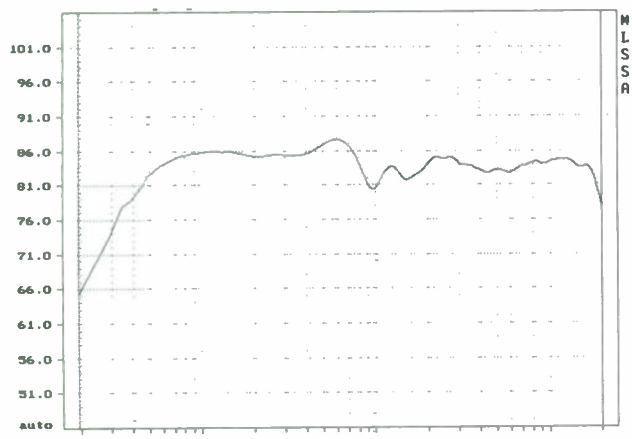

FIGURE 11: Average response over horizontal angle of ±30°.

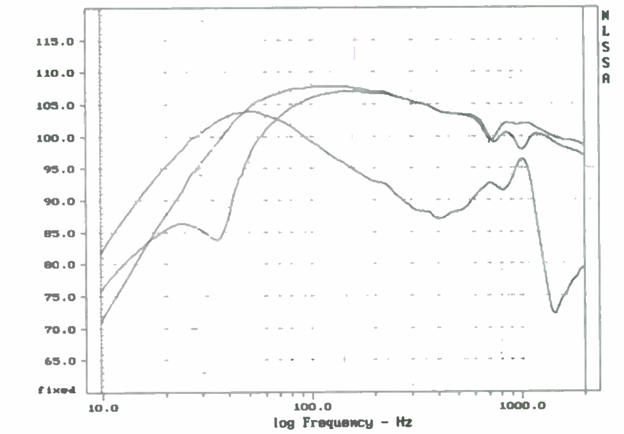

FIGURE 12: Low-frequency near-field woofer, port and their sum.

crossover network and system frequency response on an expanded scale, together with the individual driver responses. Crossover occurs at 3180Hz. The response of each driver is down 5.5dB at the crossover frequency, indicating that the woofer and tweeter are essentially in-phase at this point. From this plot, it is clear that the shelving is caused entirely by the woofer. If this system is representative of all A651s, a minor redesign of the crossover may be needed to correct the shelving.

Figure 6 is a cumulative spectral decay plot for the A651 system and shows the frequency content of the system decay response following an impulsive input at time zero. The first three milliseconds (ms) are shown with a total response range of 30dB. Above 8kHz and from 0.5 to 1.4ms, you can see the hashy response typically associated with metal-dome tweeters. I believe this is the behavior which gives metal-dome tweeters the "air" about which so many listeners comment. A great deal of decay energy is in the midrange lasting out to about 2.5ms.

Perhaps most significant, however, is the long curving ridge starting out at about 600Hz which slowly decays with rising frequency to about 3kHz at 3ms. This decay ridge is associated with the woofer and its crossover. It could add a touch of muddiness to the midrange.

Figure 7 shows the system step response and the initial rise of the tweeter followed by the woofer response about 0.2ms later. The woofer and tweeter are in phase; but with fourth-order acoustic crossovers, this system is not time-coherent. Another view of this behavior is in *Fig. 8*, which plots excess group delay versus frequency referenced to the tweeter's acoustic phase center.

Above 10kHz, the excess group delay is essentially zero, as it should be since it is referenced to the tweeter in this frequency range. The excess group delay rises with decreasing frequency to a first plateau at 2kHz. The value here (0.2ms) corresponds to the woofer delay relative to the tweeter.

Below 500Hz, excess group delay begins to rise again, due to the 24dB/octave low-frequency roll-up of the vented system. The

The Audax A651 kit was tested in the laboratories of Audio and Acoustics, Ltd., using the MLSSA and CLIO PC-based acoustic data-acquisition and analysis systems with an ACO 7012 ½" laboratory-grade condenser microphone and a custom-designed wideband, low-noise preamp.

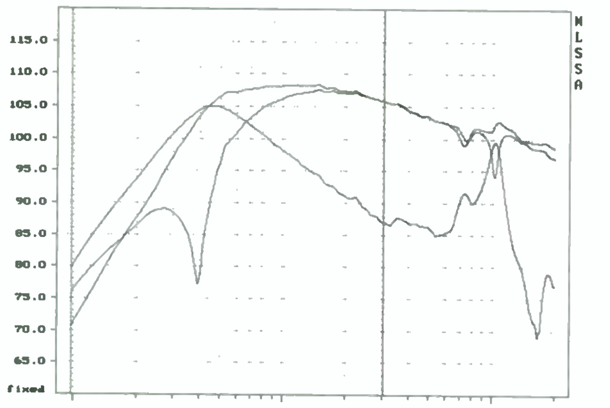

FIGURE 13: Woofer, port, and their sum after fiberglass removal.

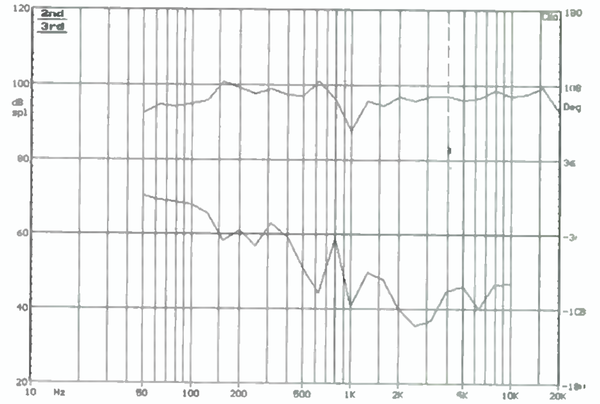

FIGURE 14: Second-harmonic distortion versus frequency in 1/3 octave steps.

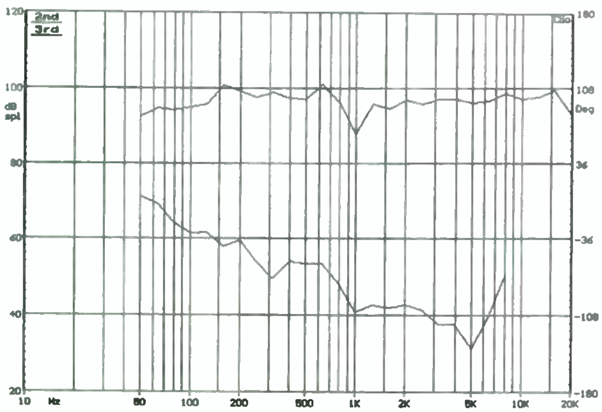

FIGURE 15: Plot of third-harmonic distortion results.

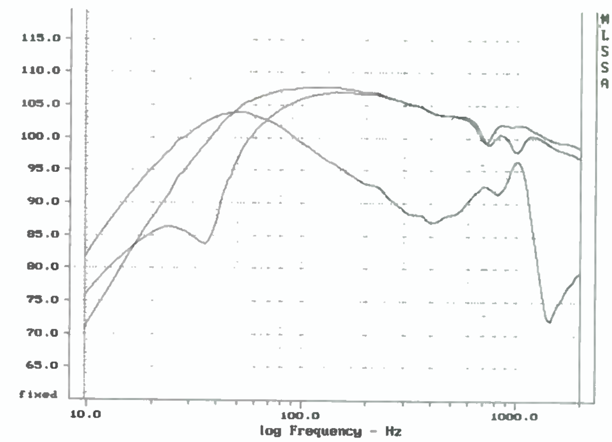

FIGURE 16: Effect of grille on frequency response.

phase error due to the sharp low-frequency roll-up extends out well beyond f_3. Excess group delay is a much more accurate indicator of driver time offset than the qualitative picture the step response provides.

Figure 9 is a waterfall plot of horizontal polar response in 15° increments from 45° left to 45° right when facing the speaker. All off-axis plots are referenced to the on-axis response, showing a straight line at 0°. You can see the expected rolloff of tweeter response at the higher frequencies and larger off-axis angles. At 45° and 15kHz tweeter response is down 10dB. You can't beat physics!

One off-axis anomaly exists at 30° and beyond, where a dip of 6.5dB in response is centered around 7.7kHz. This might lead to a small timbrel mismatch between direct and reverberant responses, but overall, horizontal polar response is quite good.

Figure 10 is a waterfall plot of vertical polar response. Responses are shown in 5° increments from 15° below horizontal (−15°) to 15° above. All off-axis plots are referenced to the on-axis response (shown as a straight line at 0°). Response is quite uniform from +5 to −10°.

A strong response suck out occurs at the crossover frequency for angles of 10° or more above horizontal. Standing NBA stars may hear something very different than the more vertically challenged among us. There is also a broader, shallower dip in response 15° below the horizontal. Tilting the speaker back a few degrees should maximize vertical coverage for standing and sitting listeners.

Figure 11 shows the average response over a 60° angle (±30°) in the forward direction. A slight trough in the 3–8kHz range is caused by the dip in off-axis response just starting out around 30° as discussed above. A much larger dip in response exists between 800Hz and 2kHz. Still, this response is not too different from the on-axis response and indicates good direct field horizontal coverage in the primary listening area with only a small timbrel change. Image stability should be good.

Figure 12 is a plot of the woofer and port near-field responses along with the complex sum of the two. Woofer output should show a deep notch at f_B, indicating proper reflex action. The purpose of a vented system is to limit cone motion around f_B. Only a rather small dip occurs at 35Hz. This plot further proves that the port is overdamped.

Upon removing the woofer, I found that some fiberglass lining material had fallen to the bottom of the enclosure, partially blocking the port opening. Removing the fiberglass and rerunning the curves yielded *Fig. 13*, which shows a deep notch at f_B decreasing cone motion an additional 15dB. The full depth of the notch does not show on this figure because I smoothed the data 1/10 octave for better presentation. As is typical of many vented systems, high frequencies within the enclosure are "leaking" out of the port.

Port response peaks sharply at 1kHz and is actually out of phase with the woofer, causing a dip in overall response. According to Mr. Colin, this port noise can be heard. Placing the port opening on the rear of the enclosure is perhaps the best solution to this problem. Trying to soak up the high frequencies with additional stuffing material may adversely affect reflex action.

I ran harmonic distortion tests at an average SPL of 90dB at 1m, and placed the microphone at 0.5m to reduce room contamination. I analyzed only the first 20ms of data at each frequency to further reduce

REVIEWER'S COMMENTS ON JOE D'APPOLITO'S MEASUREMENTS

1. The relatively sudden but low amplitude "shelf" drop around 800Hz, and the resonant decay in the "waterfall" plot around this frequency, explains the lower-midrange coloration I heard. Since the response anomaly is in the opposite direction to, and much more sudden than, the normal cabinet-diffraction "shelf" boost, I believe it is inherent in the woofer response. It is certainly not cabinet resonance, with 1½" thick, rounded walls!

2. I believe the off-axis response variations and rolloffs (normal for most speakers) result in an integrated-room-sound different enough from the direct sound to explain the spatial superiority of the Linaeum unit, with its fairly constant-spectrum dispersion. But with the A651, the measurements did not show significant tonality changes off-axis as I moved about the room.

3. I didn't push the A651's bass power-handling ability, so I didn't hear the extra reserve that Joe's port-output/cone-motion measurement shows is gained by not having fiberglass obstructing the woofer/port (as I originally did). Some bass depth should also be gained by minimizing port damping, but the main advantage is much less cone excursion near the port resonance.

4. The –20dB decay roughness shown by the waterfall plot in the tweeter region is attributed by Joe to the metal dome. But I noticed treble roughness only at very loud levels, and that may have been harmonic distortion of the tweeter or the amplifier.

5. Except for the small "shelf" anomaly, the on-axis response is very flat and extended. This correlates with my general perception of naturalness.

6. Contrary to many opinions, I believe sound quality correlates well with measurements if they are as extensive and detailed as Joe D'Appolito's. In particular, when I saw the waterfall plot, I said, "Yes, that's what it sounds like!" That's because the ear is very sensitive not only to the "first arrival" spectrum (discriminating nature of source), but also to the variations present in delayed sounds (with live sounds, this conveys a "picture" of the environment).

So the reason the A651 sounds very natural with most sources is (1) the on-axis response variations are small in amplitude, and (2) most of the impulse response decays to –20dB in only a few milliseconds.

room contamination. This limits the lowest analysis frequency to 50Hz.

Figure 14 is a graph of second-harmonic distortion versus frequency in 1/3 octave steps. The upper plot is frequency response SPL, while the lower plot indicates the distortion SPL. Second-harmonic distortion at 50Hz is 23dB below woofer output level, or 7%. Distortion falls below 1% above 150Hz and is at the 0.1–0.22% level above 2kHz.

Third-harmonic distortion results are plotted in *Fig. 15*. Again we have about 7% at 50Hz, 1% above 150Hz, and about 0.1% above 1kHz. Considering the size of the woofer, you should expect the relatively high distortion at lower frequencies. Distortion performance above 150Hz is good.

Please note that I conducted all of the above tests with the grille off. *Figure 16* shows the change in response over a 200Hz–20kHz range caused by the grille. There is very little effect below 2kHz. Between 2.4kHz and 3.8kHz, the grille causes a dip of roughly 3dB. Above 4kHz the grille produces somewhat random response variations totaling about 5dB peak-to-peak.

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Loudspeakers 101

MUCH ADO ABOUT DAMPING FACTOR

By Dick Pierce

Much ballyhoo surrounds the concept of damping factor. It's been suggested that it accounts for the alleged "dramatic differences" in sound between tube and solid-state amplifiers. The claim has been made (and is partially cloaked in some physical reality) that a low source resistance aids in controlling the motion of the cone at resonance and elsewhere; for example: "Reducing the output impedance of an amplifier and thereby increasing its damping factor will draw more energy from the loudspeaker driver as it is oscillating under its own inertial power."[1]

This is certainly true, to a point. But many of the claims made, especially for the need of triple-digit damping factors, have no basis in reality, be it theoretical, engineering, or acoustical. This same person even suggested: "A damping factor of 5...grossly changes the time/amplitude envelope of bass notes, for instance. ...the note will start sluggishly and continue to increase in volume for a considerable amount of time, perhaps a second and a half."

DAMPING FACTOR: A SUMMARY

What is damping factor? Simply stated, it is the ratio between the nominal load impedance (typically 8Ω) and the source impedance of the amplifier. Note that all modern amplifiers (with some extremely rare exceptions) are essentially voltage sources whose output impedance is very low. That means their output voltage is independent of load impedance over a wide range.

Many manufacturers trumpet their high damping factors (some claim figures in the hundreds or thousands) as figures of some importance, hinting strongly that those amplifiers with lower factors are decidedly inferior as a result. Historically, this started in the late '60s and early '70s when the widespread availability of solid-state output stages made it possible to avoid the effects of high plate resistance and output-transformer windings traditionally found in tube amplifiers.

Is damping factor important? Maybe. I will do an analysis of the effect of damping factor on resonance, which many proponents claim is the most significant speaker property and where speaker motion is at its highest.

Damping factor and its effects on loud-

TABLE 1

EFFECTS OF DAMPING FACTORS ON SYSTEM PERFORMANCE

Damping FACTOR	R_S ohms	Q_{EC}'	Q_{TC}'	G_H(max) dB	Decay time SECONDS
∞	0	0.925	0.707	0.0dB	0.04
2000	0.004	0.926	0.707	0.0	0.04
1000	0.008	0.926	0.708	0.0	0.04
500	0.016	0.927	0.708	0.0001	0.04
200	0.04	0.931	0.71	0.0004	0.04
100	0.08	0.936	0.714	0.0015	0.04
50	0.16	0.948	0.72	0.0058	0.04
20	0.4	0.982	0.74	0.033	0.041
10	0.8	1.04	0.77	0.11	0.043
5	1.6	1.15	0.83	0.35	0.047
2	4	1.49	0.99	1.24	0.056
1	8	2.06	1.22	2.54	0.069

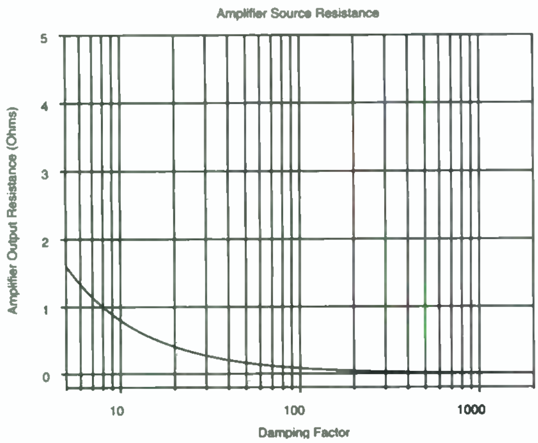

FIGURE 1: Amplifier resistance vs. damping factor.

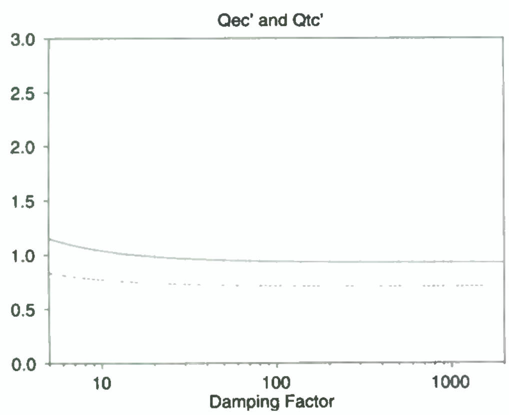

FIGURE 2: Speaker motion (Q_{EC} and Q_{TC}) vs. damping factor.

speaker response is not some black art or magic science. It is not even so complex as to prevent anyone with a reasonable grasp of high-school math from understanding it. Thiele[2] and Small[3] and many others dealt with it exhaustively decades ago.

SYSTEM Q AND DAMPING FACTOR

The definitive measurement of speaker motion is known as Q. Technically, it is the ratio of the motional impedance to losses at resonance. It is intimately connected to the response of the system in both the frequency and the time domains.

A loudspeaker system's response at cutoff is determined by the total Q, designated Q_{TC}, which represents the total resistive losses in the system. Q_{TC} consists of two components: the combined mechanical and acoustical losses, Q_{MC}, and the electrical losses, Q_{EC}. The total Q_{TC} is related to these components as follows:

$$Q_{TC} = \frac{Q_{MC}\,Q_{EC}}{Q_{MC} + Q_{EC}} \qquad (1)$$

Q_{MC} is determined by the losses in the driver suspension, absorption losses in the enclosure, leakage losses, and so on. Q_{EC} is determined by the combination of the DC resistance of the voice-coil winding, lead resistance, crossover components, and amplifier source resistance. Thus, it is the electrical Q, Q_{EC}, that is affected by the amplifier source resistance, and thus by the damping factor.

The effect of source resistance on Q_{EC} is simple and straightforward. From Small:[3]

$$Q_{EC}' = Q_{EC}\,\frac{R_E + R_S}{R_E} \qquad (2)$$

where Q_{EC}' is the new electrical Q with the effect of source resistance; Q_{EC} is the electrical Q assuming zero source resistance (infinite damping factor); R_E is the voice-coil DC resistance; and R_S is the combined source resistance.

It's very important here to note two points. First, in nearly every loudspeaker system that has any pretenses of high-fidelity, the majority of the losses are electrical in nature, usually by a factor of 3 to 1 or greater. This is shown by the fact that the electrical Q, Q_{EC}, is lower by a factor of three or more than the mechanical Q, Q_{MS}. Second, of those electrical losses, the largest part, by far, is the DC resistance of the voice coil.

Now, once you know the new Q_{EC}' that is due to nonzero source resistances, you can recalculate

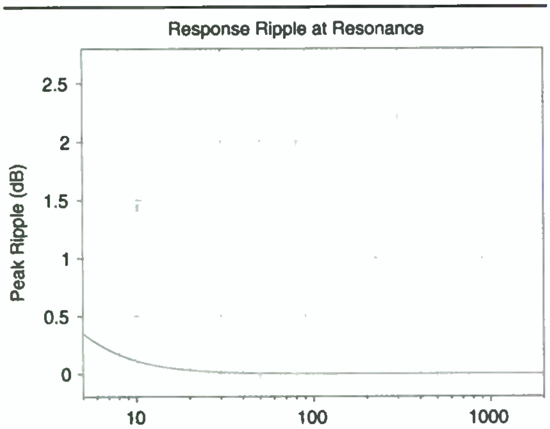

FIGURE 3: Peak ripple (dB) vs. damping factor.

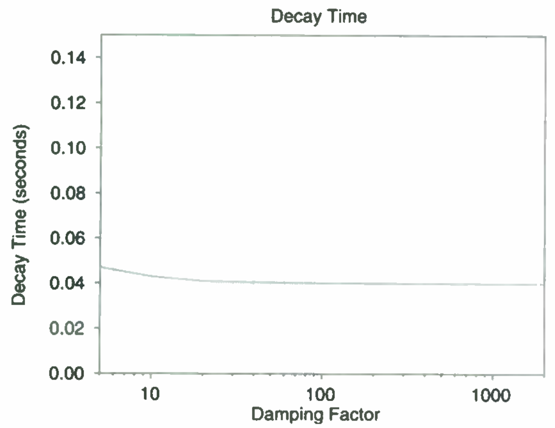

FIGURE 4: Decay time (in seconds) vs. damping factor.

the total system Q as needed, using equation (2), above. The effect of the total Q on response at resonance is also fairly straightforward. Again, from Small:

(3)

$$G_H(max) = \sqrt{\frac{Q_{TC}^4}{Q_{TC}^2 - 0.25}}$$

This is valid for Q_{TC} values greater than 0.707. Below that, the system response is overdamped, and there is no response peak.

You can also calculate how long it takes for the system to damp itself out under these various conditions. The scope of this article precludes a detailed description of the method, but the figures I'll show later are based on both simulations and measurements of real systems, and the resulting decay times are based on well-established principles of the audibility of reverberation times at the frequencies of interest.

EFFECTS OF DAMPING ON SYSTEM RESPONSE

With this information in hand, you can examine the exact effect of source resistance and sampling factor on real loudspeaker systems. Take an example of a closed-box, acoustic suspension system, one that has been optimized for an amplifier with an infinite damping factor. Assume this system has a system resonance of 40Hz and a system Q_{TC} of 0.707, which leads to a maximally flat response with no peak at system resonance.

The mechanical Q_{MC} of such a system is typically about 3. Taking that as a model and rearranging equation (1) to derive the electrical Q of the system, you find that, with an infinite damping factor, it is 0.925. The DC resistance of the voice coil is typically about 6.5Ω.

Table 1 shows the effects of progressively lower damping factors on the system performance. The first column is the damping factor, using a nominal 8Ω load. The second is the effective amplifier source resistance that yields the damping factor (*Fig. 1*). The third column is the resulting Q_{EC}' caused by the nonzero source resistance. The fourth is the resulting new total system Q_{TC}' (*Fig. 2*). The fifth column is the peak that results directly from the loss of damping control because of the nonzero source resistance (*Fig. 3*). The last column is the decay time to below audibility in seconds (*Fig. 4*).

ANALYSIS

Several things are apparent from this table. First and foremost, any notion of severe overhang or extended "time amplitude envelopes" resulting from low damping factors simply does not exist. You see, at most, a doubling of decay time (this doubling is true no matter *what* criteria are selected for decay time). The figure of 70ms is more than one order of magnitude lower than that suggested by one person, and this represents what I think we can all agree is an absolute worst-case scenario—a damping factor of 1.

Secondly, the effects of this loss of damping on system frequency response is nonexistent in most cases, and minimal in all but the worst-case scenario. If you select 0.1dB as the criterion for the absolute best in terms of the audibility of such a peak (and this is probably overly optimistic by at least a factor of 2–5), then the data in the table suggests that *any* damping factor over 10 will result in inaudible differences between such a damping factor and one equal to infinity. It's highly doubtful that a response peak of $^1/_3$dB will be reliably identifiable, thus lowering the limit another factor of 2 to a damping factor of 5.

All this is well and good, but the argument that these minute changes may be audible suffers from even more fatal flaws. The differences that we see in Q figures up to the point where the damping factor is less than 10 are far less than the variations seen in normal driver-to-driver parameters in single-lot productions. Even those manufacturers who deliberately sort and match drivers are not likely to match a Q_T figure to better than 5%, and those numbers will swamp any differences in damping factor greater than 20.

Furthermore, the performance of drivers and systems depends upon temperature, humidity, and barometric pressure, and those environmental variables will introduce performance changes on the order of those presented by damping factors of 20 or less. And I have completely ignored the effects of the crossover and lead resistances, which will be a constant in any of these figures and further diminish the effects of nonzero source resistance.

CONCLUSIONS

There may be audible differences that are caused by nonzero source resistance. However, this analysis and mode of measurement and listening demonstrates conclusively that the differences are not due to the changes in damping the motion of the cone at the point where it is at its most uncontrolled: system resonances. I have not looked at the frequency-dependent attenuative effects of the source resistance, but that's not what the strident claims are about. Rather, those who advocate the importance of high damping factors must look elsewhere for a culprit: motion control at resonance simply fails utterly to explain the claimed differences.

Dick Pierce
Hanover, MA

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Driver Test

By Vance Dickason

MOREL TWEETERS

This column reports on two tweeters from Morel—the MDT-12 neo soft dome and the MDT/DMS-37 horn-loaded soft dome.

Features: The Morel MDT-12 incorporates a 28mm treated cloth dome, a self-shielded neo magnet, and a plastic flange identical to the Morel MDT39/40/44-series. Unlike the 39/40/44 neo tweeters that are vented and equipped with a rear cavity, this tweeter is not vented. The unit has gold terminals, a replaceable diaphragm, and a faceplate which you can customize.

The Morel MDT/DMS-37 is a new high-efficiency horn-loaded 28mm soft dome. The DMS designates the shielded version, which is visually indistinguishable from the MDT unshielded version (except for the label). The main difference, then, is a bucking magnet on the DMS unit. Since MDT/DMS-37 uses a conventional magnet system with a vented pole and cavity, the metal cavity cup acts as a shield to the bucking magnet. Since the cup does not cover the entire magnet system or short the field back to the front plate, only a minor change in B_L should distinguish the performance of these two units.

Measurements: I used LinearX's LMS-gated sine-wave analyzer to produce the impedance curve in *Fig. 1*. This measurement shows that although the driver uses ferrofluid for cooling, the resonance is not completely damped by fluid viscosity (which likely improves transient performance). Resonance is approximately 1kHz, as indicated in the company specification for the driver.

I measured the SPL of the single sample available for the review. The on-axis frequency response, with the tweeter surface-mounted on a small 4″ × 9″ baffle, is shown in *Fig. 2*. Response declines from low to high in a fashion generally conducive to producing a flat response with a network. The anomalies in this measurement are partly due to the small baffle dimension used for

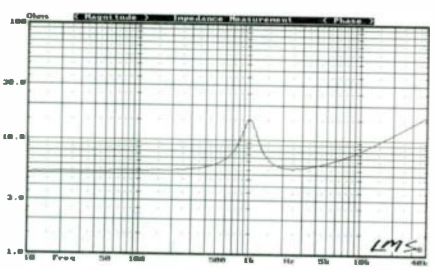

FIGURE 1: Morel's MDT-12 impedance curve.

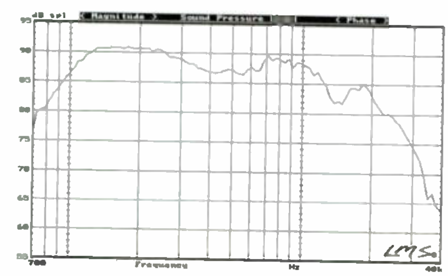

FIGURE 2: MDT-12 on-axis frequency response.

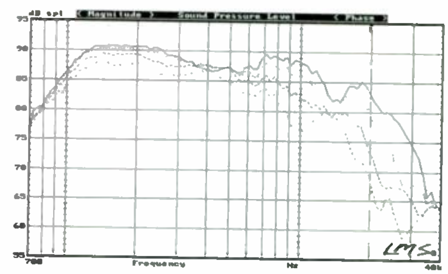

FIGURE 3: MDT-12 on- and off-axis frequency response (solid = 0°, dot = 15°, dash = 30°, dash/dot = 45°).

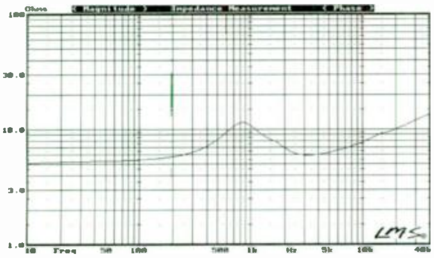

FIGURE 4: Morel's DMS-37 impedance curve.

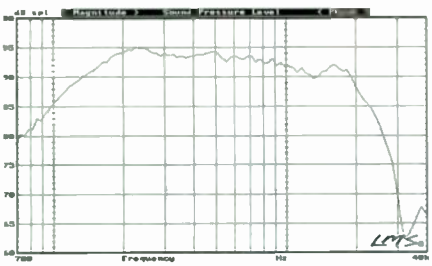

FIGURE 5: DMS-37 on-axis frequency response curve.

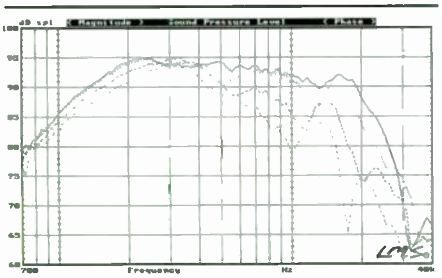

FIGURE 6: DMS-37 on- and off-axis frequency response (solid = 0°, dot = 15°, dash = 30°, dash/dot = 45°).

mounting. I guess that with proper inset mounting and a network, this device could be ±2dB from its crossover frequency to about 15kHz—about normal for a high-quality dome such as those Morel produces. *Figure 3* shows the off-axis response out to 45°.

I then measured the DMS-37 (*Fig. 4*). Although the tweeter's specification sheet did not mention the use of magnetic fluid, the somewhat damped look of the curve in the figure suggests that it may have fluid.

Figure 5 illustrates the on-axis frequency response of the driver inset, mounted on an 8″ × 15″ baffle and yielding a very smooth response out to 20kHz. With a network applied, the final SPL would likely be close to 93–94dB from a 2kHz–3kHz crossover point to 10kHz. This dome would then have a couple of dB more efficiency than the average tweeter dome and be suitable for a high-efficiency dual-woofer-type format. Off-axis response (*Fig. 6*) shows increased directivity and a rapid decline in off-axis beyond 30°, typical of horn loading of

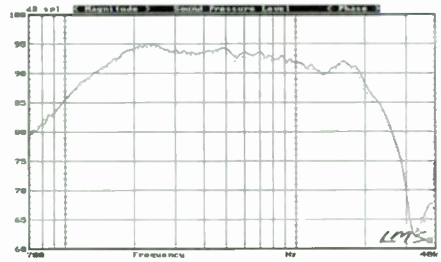

FIGURE 7: Comparison of DMS-37 (solid curve) and MDT-37 (dashed curve).

this type. *Figure 7* compares the DMS-37 and the MDT-37, which are impressively identical except for the MDT-37's slight decrease in SPL. For more information on these two tweeters, contact Morel Acoustics USA, 414 Harvard St., Brookline, MA 02146, (617) 277-6663, FAX (617) 277-2415. Also available from: Madisound, (608) 831-3433; Parts Express, (937) 222-0173; Zalytron, (516) 747-3415; Solen (Canada), (514) 656-2759; ITC Electronics, (213) 388-7502; or Goldsound, (303) 789-5310.

SB *Mailbox*

WIRE ON THE WEB

Further to John Day and Stephen Lampen's discussion ("Cable Characteristics," *SB* 4/97), Belden Wire & Cable Company released "Characteristic Impedance of Cables at High and Low Frequencies," a scientific view on the effects of wire. The informative essay, authored by the company's engineering department, is available in the Application Report section of Belden's Web Page at http://www.belden.com.

DESIGNING CROSSOVERS

I have a question regarding the phase relationships in acoustic Linkwitz-Riley (L-R) crossovers. I have been studying speaker design for about two years. Being an electrical engineer, I understand the electrical aspects.

However, though I have been studying the literature on acoustic aspects, one question remains unanswered. Is a fourth-order acoustic L-R truly achieved if, for example, a second-order electrical L-R is required for the woofer and a third- or fourth-order for the tweeter in a two-way system?

I have been using CALSOD, together with measurements taken from LMS, and

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have achieved good results in linearity with close to true Linkwitz-Riley acoustic rolloffs for both the low- and high-pass sections. However, I have been using strictly third-order electrical slopes. My intuition tells me that if I use different electrical slopes, though they may result in L-R acoustic slopes in amplitude rolloff, the phase characteristics will result in less than ideal response.

David Ralph
Montreal, Quebec, Canada

Siegfried Linkwitz responds:

When you design crossover networks for a multiway loudspeaker, you are trying to obtain high-pass, low-pass or bandpass responses of specified characteristics for each of the driver's acoustic outputs. You must keep in mind that the desired acoustic filter function is determined by the characteristics of the electrical network in front of the driver's terminals and by its frequency response. Since the driver is mounted on a baffle, its response also contains the effects of diffraction from the baffle edges.

Thus, the first step in designing a crossover is the measurement of the frequency response of the various drivers mounted on the baffle. Usually, you measure the response on the chosen design axis. Next, you would inspect the response to see how much additional filtering the electrical network must provide to obtain the desired low-pass or high-pass characteristic.

Say you are trying to design a fourth-order L-R crossover for a two-way system, with a 2kHz transition from woofer to tweeter. You might find that the measured rolloff of the woofer, at about 12dB/octave somewhere above 2kHz, requires merely the use of a second-order electrical network to achieve an overall 24dB/octave acoustic low-pass response. Likewise, the tweeter, which has a second-order high-pass response below its 1kHz resonance, may require only a second-order electrical high-pass to obtain a 24dB/octave acoustic high-pass response.

The circuit topology may even deviate from the textbook filter schematic or include resistors, but any circuit that achieves the desired acoustic response is fair game. For example, the acoustic center of the tweeter is normally in front of the woofer if both are mounted on the same baffle, and you might try to delay the electrical signal to the tweeter by the additional phase shift that a third-order high-pass introduces, compared to a second-order filter. All this is best simulated on a computer.

A very effective test that shows how closely you have achieved the fourth-order L-R characteristics in terms of magnitude and phase response is to reverse the polarity of one of the drivers and observe the depth of the null in the combined woofer and tweeter response. Since the woofer and tweeter outputs should be in phase at 2kHz for the L-R crossover, reversing the polarity of one driver will cause a cancellation of their outputs. A greater than 10dB notch is a good figure of merit. If this test is applied to a first- or third-order acoustic Butterworth crossover, then there should be no change in amplitude, because woofer and tweeter are 90° out of phase regardless of driver polarity.

If your L-R crossover meets the polarity test, then you are assured of maximum acoustic output on the design axis in the crossover region of the spectrum, and not at some other angle—as would be the case for the Butterworth design unless the drivers are coaxial or symmetrically M-T-M aligned.

INDUCTOR PERFORMANCE

Further to the recent articles in *Voice Coil* ("Components for Passive Crossovers, Part 2," December 1996, p. 16) and *Speaker Builder* ("Inductors for Crossover Networks," 7/96, p. 36) on crossover inductors, may I add some data taken from my forthcoming 5th edition of *High Performance Loudspeakers* (Wiley, 1997).

My tests of many inductors indicate that the recent blanket condemnation of ferrite-cored inductors is unjustified. The contentious printed results concern an economy bobbin ferrite-core inductor of indeterminate Asian origin. Testing one of these recently (my first acquaintance with it), I was appalled at the very poor performance—certainly unsuitable for any project of significant quality. My sample bobbin was 5cm diagonally by 3cm thick, and at power levels equivalent to 200W 4Ω, distortion was an unacceptable 10%. Even at lower powers (1–10W), a figure of 0.6%–2% was typical. However, these results are not at all typical of good ferrites.

In my experience, ferrite-cored inductors have the potential for design of the highest quality, not the lowest, as suggested in the articles. Consider a sample audio-grade ferrite core 80mm long by 19mm diagonally (Neosid). At the same power of 200W, the distortion is fine at 0.3%, while at lower powers it falls rapidly to 0.1% at 50W and an excellent 0.05% at a few watts and below. Iron and iron-laminated cores are similar, with the latter type superior at high frequencies, though not as good as high-quality ferrite.

An audio-grade ferrite toroid, 702mm diagonally by 16mm square section, gave astonishing results. At a 300W level, it was still better than 0.35% distortion, while at moderate listening powers of 0.1 to 10W, the residual was rock bottom at 0.035%.

I also have comparably good measurement data for the larger ferrite inductors used by reputable companies such as Yamaha and Sony.

Taking an overview, good ferrite provides the best of all worlds, namely:

1. Low wind length, reducing copper cost, resistance, self-capacitance, and the loss of transparency associated with excessive lengths of wire in series with a speaker;
2. Low distortion up to a high and definable upper power limit;
3. High Q;
4. Negligibly low variation of value with frequency;
5. Potential to self-screen or orientate the stray magnetic field according to core geometry (the air core has a relatively massive stray field).

Martin Colloms
London, England

Richard and Erin Honeycutt respond:

First, we wish to thank Mr. Colloms for his careful reading of our article, and for the additional information he provides.

Second, we offer two small corrections. We tested not one, but two ferrite-core coils (one bobbin and one toroid) of different designs and manufacturers. Further, Mr. Colloms' assumption that the coils are of Asian origin, while perhaps likely, is not certain. The coils we tested were obtained from popular American distributors who commonly supply crossover parts to amateurs as well as professional builders of short-run or custom designs.

It is good to learn of the availability of high-grade ferrites, but those who build speaker systems without pretesting crossover coils for distortion should be warned about indiscriminate use of ferrites, as both Mr. Colloms and we have discovered.

IN PHASE

I read with interest Dennis Colin's comments on crossovers with perfect phase linearity ("*SB* Mailbox," 3/97, p. 53). A couple of years ago, I designed an active crossover with characteristics similar to those described by Mr. Colin (a peak in the response near the crossover frequency and about a 107° phase shift). I would be grateful if someone could provide me with a reference so that I could compare the crossover circuits described by Mr. Colin to my own.

Andy Unruh
San Jose, CA

Dennis P. Colin responds:

I know of the existence of high-order linear-phase crossovers, but am not familiar with their design. I believe Mr. Unruh's design is the constant-voltage type, whose summed response has perfect amplitude flatness and zero phase shift (referring to summed output versus input, not the 107° interdriver phase difference Mr. Unruh mentions).

I am familiar with one method of obtaining this response: synthesizing a low-pass filter response (woofer drive) and subtracting it from the flat input signal (tweeter drive), or vice versa. This, however, results in a first-order rolloff (6dB/octave slope) for the subtraction-derived signal, regardless of the order of the directly synthesized signal. Of course, this can be useful where only one of the drivers needs a higher-order rolloff—for example, to minimize tweeter power dissipation.

Regarding linear-phase crossovers with higher than first-order rolloffs on both drivers, I'm unfortunately not knowledgeable about their design. So on this matter, I have more to learn from Mr. Unruh than vice versa; I would appreciate his correspondence (E-mail: dcolin@worldpath.net).

HELP WANTED

I am a Tannoy lover and collector and am always on the search for alternative cabinet designs. Is anyone out there aware of any aftermarket Tannoy designs that use horn loading, onken design or other methods? As you may know, the company is very secretive about the inner-cabinet design of its top-line speakers. If anyone has seen or is able to get design schematics of these, I'd very much appreciate hearing from you.

Gary Gill
phantom1@erols.com

Readers with information on this topic are encouraged to correspond directly with the letter writer at the Internet address provided. —Eds.

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