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Speaker Builder

THE LOUDSPEAKER JOURNAL

G.L. Augspurger

Exploring THE Practical Details OF Transmission Lines

Paul Kittinger

A Fresh, New Shape FOR Danish Drivers

Jim Moriyasu

Fitting A Tweeter & Crossover TO HIS Hawaiian Design

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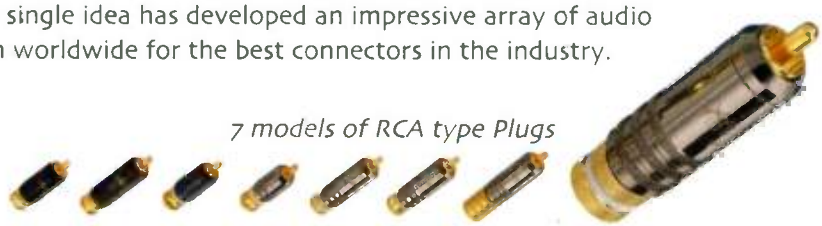

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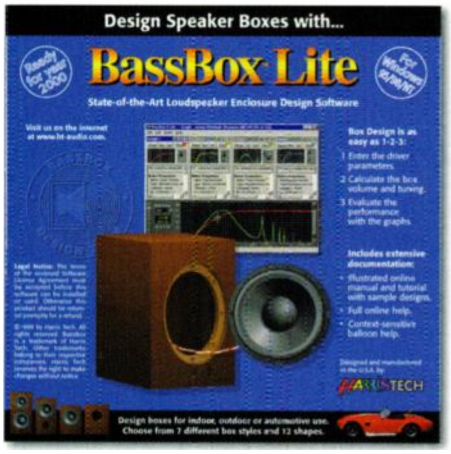

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Harris Technologies, Inc. is introducing the BassBox™ Lite, a new addition to its speaker box design software for Microsoft® Windows™. BassBox Lite is a streamlined version of its popular BassBox Pro software and is available on CD-ROM or diskettes. Its efficient user-interface simplifies the design and offers a wide variety of popular box models, from the closed box to the passive radiator boxes. BassBox Lite includes the same nine powerful graphs for analyzing the performance of a speaker, however the graphs are integrated into the main window so that the program will more easily fit into the limited display resolution of notebook computers. For more information, contact Harris Tech at (616) 641-5924, or visit the website at www.ht-audio.com.

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FIELD STUDIO MONITOR

Fostex recently introduced the NF-1 near field studio monitor, featuring radical new designs in driver and enclosure technology. The NF-1's new 6.5″ hyperbolic parabolic woofer design not only adds more strength than the conventional cone, it also contributes to a wider horizontal dispersion and extremely low distortion. The cone material is a combination of wood and banana pulp fibers, which provides a distortion-free cone. The tweeter employs a polyurethane film lamented cloth diaphragm for frequency response up to 40kHz. The woofer operates at full-range from 50Hz to 10kHz. Fostex Corporation of America is located in Norwalk, California.

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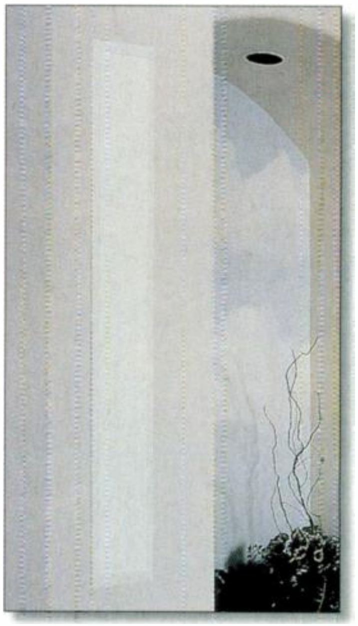


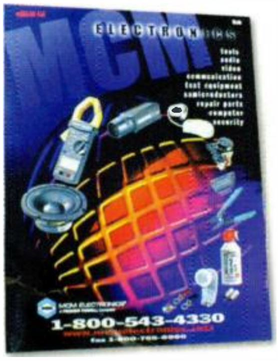
IN-WALL SPEAKERS

Sonance introduced its Silhouette speaker line, which includes an elongated aluminum extrusion that easily fits within the standard wall construction to create a space-saving design. The three models contain an elliptical 6″-wide cone woofer, a 4″ cast magnesium cone midrange, and a 1″ Hi-Fi concave titanium dome tweeter with a glass fiber reinforced polymer chassis. The 4″ mid-range driver design was chosen after scientific research into the interaction between the drywall components and loudspeakers; the drywall/stud interface is most susceptible to resonance in the 150Hz to 200Hz band. Sonance products can be viewed on the web at www.sonance.com, or call (949) 492-7777 for a catalog.

Reader Service #137

HI-FI SWAP

The fourth annual Southern California Hi-Fi Swap will be held indoors, on Sunday, April 30, 2000, at the Holiday Inn Buena Park, located at 7000 Beach Blvd. This indoor swap offers equipment that includes current high-end, vintage parts, tubes, etc. Free parking is available, with admission prices of $3 after 10am, and for the early birds, $5 at 9am. Set up for sellers at 8am, with tables at $40, each. Call (909) 931-9686 for space reservations and (714) 522-7000 for directions. Or visit the website at www.upscaleaudio.com for more information.



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About This Issue

We're pleased to welcome back to these pages an author whose impressive handiwork we've seen before. **Paul L. Kittinger** has published three of his tower projects in previous issues. But this time he outdoes himself with a unique design that is anything but a traditional rectangular cabinet. It features high-quality drivers and a professionally designed crossover ("Danish Delight," p. 8).

Speaker expert **G. L. Augspurger** provides much-needed research on transmission-line design in this three-part series ("Transmission Lines Updated," p. 24). Part One lays the groundwork for his test procedures and predictions.

Louis McClure shows us how to determine the correct proportions to use in building any-size enclosure ("Determining Optimum Box Dimensions," p. 42). The procedure is easy to follow, and the results will be "golden," if you adhere to the correct ratios.

We saw in Part One of this series ("The Menehune MX-1," p. 30) how author **Jim Moriyasu's** compact design packs a big punch in a small system. Part Two focuses on crossover work and measures subsequent tweeter, midbass, and woofer responses of this satellite/subwoofer pair.

Perhaps one of the most difficult parts of woodworking is making long cuts–ripping through a 4′ × 8′ sheet of fiberboard, for instance. **Michael Kessler** shows you how to do it–without an assistant or the use of a table saw ("Tools, Tips & Techniques," p. 54).

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JOHN STUART MILL

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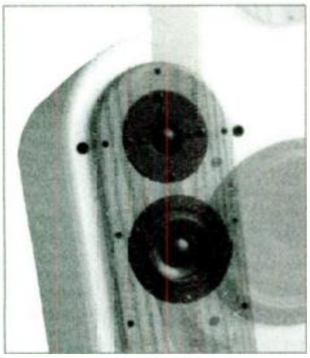

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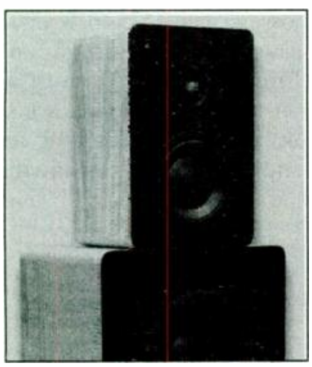

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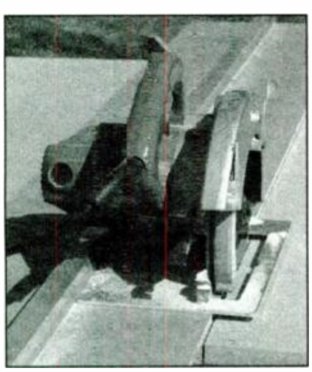

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FEATURES

DEPARTMENTS

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This two-part article describes a 3-way floor-stander with very high-quality drivers, whose unusual cabinet shape is designed to aid its sonic performance.

Part 1

Danish Delight

By Paul L. Kittinger

Having previously designed and built four 3-way tower speaker systems, but feeling an itch to do another one, I sat down and decided what I wished to accomplish. The designs in my previous articles (*SB* 5/97, 2/98, and 1/99) were all housed in conventional rectangular cabinets. This time I intended to challenge my design and fabrication skills and make unique-looking cabinets whose shapes would provide sonic benefits. As you look at *Photos 1*, *2*, and *3*, I believe you'll agree that the cabinet is different, whether or not you like its appearance.

I also arrived at two other goals for this project: I would choose very good drivers and have the crossover designed with one of the popular software programs instead of generalized "textbook" equations. I achieved both of those goals; all the drivers are from the Danish manufacturer Scan-Speak, hence the Danish reference in the name, and I had Meniscus use LEAP® to design the crossover.

Specific performance parameters I aimed to achieve were a Q_{TC} as close to 0.7 as possible, an f_3 of 40Hz or lower, and a sealed, acoustic suspension cabinet. Before proceeding, I must advise you not to tackle this design if it's your first project. It requires careful, tedious cutting and assembling to ensure that the

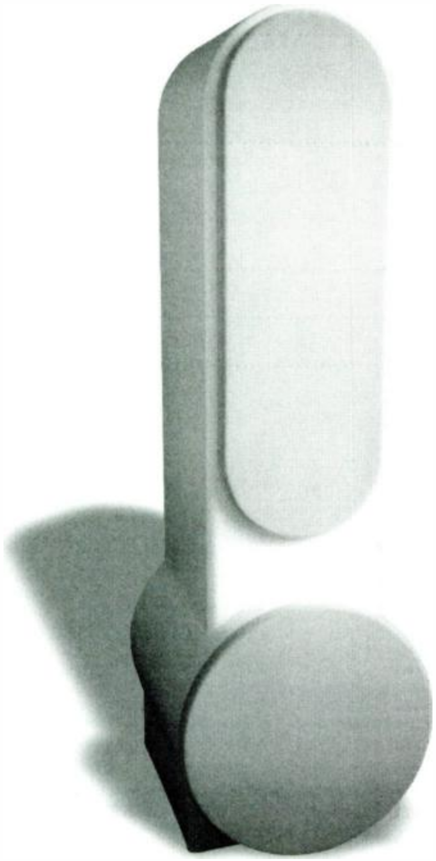


PHOTO 1: System front view, with grilles.

PHOTO 2: System front view, without grilles.

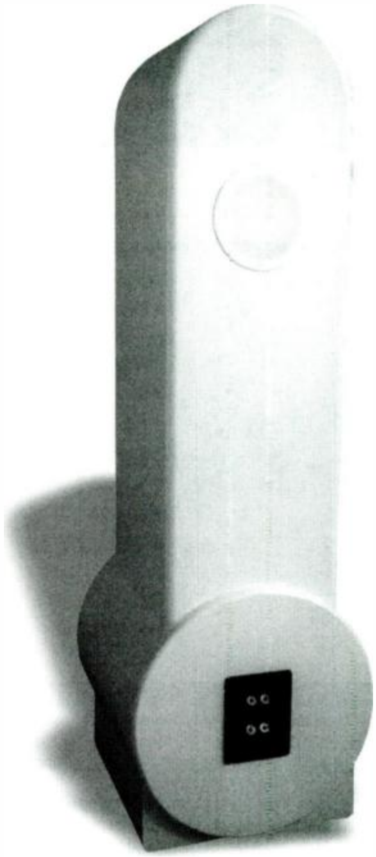


PHOTO 3: System rear view.

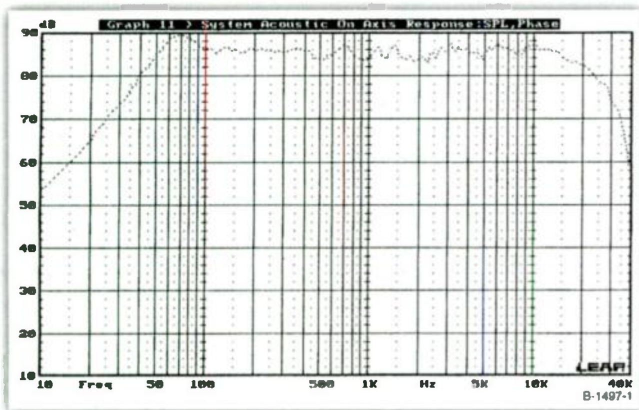


FIGURE 1: The system's acoustic on-axis response.

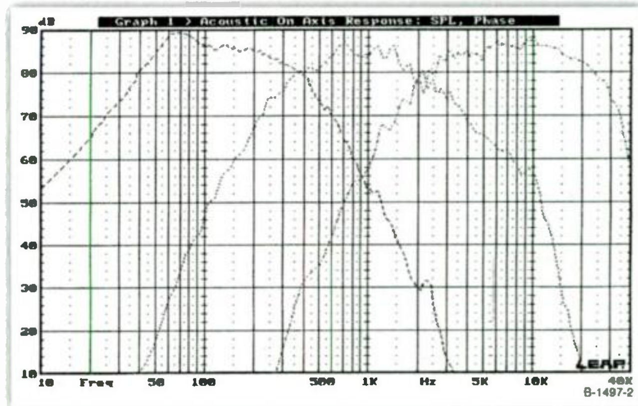


FIGURE 2: Crossover effects on driver's responses.

cabinets go together correctly, as well as end up with a good-looking finish.

The shape of the cabinet does provide sonic benefits, but if you really don't like its appearance, you may not think the sonic results will justify the effort. One more comment is warranted: I'm definitely not a highly skilled woodworker, so some of the methods or tools I use may not be the best way to go. But they worked for me, and I'm happy with the results.

THE SHAPE

While there are numerous speaker systems that perform quite well and are highly regarded in spite of having rectangular cabinets, such a box is not an optimum shape. Large, flat panels need proper bracing and construction to minimize their resonating and coloring the sound, and sharp edges cause early reflections that smear the sound in the upper mids and highs.

It has been proven that a spherical shape is just about perfect, but I would not be able to build a spherical enclosure without considerable difficulty even if I wished to, certainly not from typical materials. I decided, however, that I could use multiple "donuts" of wood glued together to build a cylinder whose curved walls wouldn't resonate like flat panels, if at all.

To minimize reflections, I could round over the edges of the cabinet near the midrange and tweeter, and by making it as a two-piece assembly, I could minimize its width around these same drivers. Finally, by using a mounting baffle made from a composite of several materials, I could probably keep the midrange and tweeter essentially free of vibration-induced colorations.

Basically, the cabinet is an assembly of a horizontal, 13½″-diameter cylinder housing the woofer and crossover assembly, and a 9½″-wide tower, housing the midrange and tweeter, attached tangentially to the cylinder. All the volume available inside the cylinder and tower is allocated for the woofer. Overall, the cabinet is 42½″ tall, not counting feet or spikes, and about 15″ deep at its maximum. Its finished weight is between 70 and 75 lbs.

WHAT'S INSIDE?

I chose Scan-Speak drivers—a 10″ woofer, a 5″ midrange, and a 1″ soft-dome tweeter—because of their specifications, reputation, and recommendations from other designers. Using drivers from the same manufacturer and of the same materials has the advantage of consistent "voicing" (primarily between cone-type woofers and midranges).

The woofer works into an acoustic suspension volume of 1.7–1.8ft^3 (nominally 50 ltr); theoretically, this results in an α of about 4.5, a Q_{TC} close to 0.9, an f_3 around 36Hz, and an f_6 around 26Hz. To prevent unwanted reinforcements or cancellations due to backwaves from the woofer, both the inside of the cylinder rear and the underside of the tower top are lined with "subwoofer" Deflex®. To achieve a final Q_{TC} of about 0.7, the bottom half of the tower walls and the walls of the cylinder are lined with ⅝″-thick acoustical foam. In addition, I placed 15 oz of Acousta-Stuf® throughout the cabinet.

As in two of my previous designs, the midrange enclosure is an open-back tunnel densely lined with Acousta-Stuf for acoustical loading. To my ears, midrange drivers used this way sound more open and detailed without having the "boxy" or "cupped-hands" sound that can easily occur with sealed subenclosures. The crossover is composed of third-order high-pass sections and fourth-order low-pass sections for the filters' corner frequencies of 400 and 2.3kHz.

PERFORMANCE DATA

Even though I own a Mitey Mike 2® (MM2) amplifier and calibrated microphone, I don't have the software and other equipment needed to use it fully. Rather than show the cobbled-together response curve that might result from using my MM2 in a less than ideal situation, I offer *Fig. 1* as Meniscus's LEAP-predicted graph of the system's acoustic on-axis response. Similarly, *Fig. 2* shows the LEAP-predicted responses of the individual drivers as affected by their crossovers.

Figure 1 shows, at about 70Hz, a peaking of the woofer's response that results from LEAP expecting a Q_{TC} of 0.9 based on the cabinet's 50-ltr volume, but does not take into account the effects of acoustical fill material that lower the Q_{TC}. I did, however, use my MM2 and *Stereophile's* Test CD2 to make close-miked measurements of the woofer's frequency response in the finished cabinet. When graphed (not shown), these measurements showed an f_3 of 35–36Hz and a nonpeaking response above f_3, indicating that the Q_{TC} is close to 0.7 as expected.

The system's impedance curve, as predicted by LEAP (not shown), indicates a minimum of slightly more than 4Ω, a maximum of about 8.5Ω (except at the low-end resonant frequency), and an average impedance of 6Ω or higher, which should make the system an easy load to drive. I didn't attempt to measure the overall sensitivity, but according to the graph of *Fig. 1*, it should be around 85–87dB measured at 1m. I have several amplifiers of different output power ratings. In my room at sane volume levels, 40 clean watts per channel (into 8Ω) are adequate, but more power allows a wider dynamic range, as you would expect.

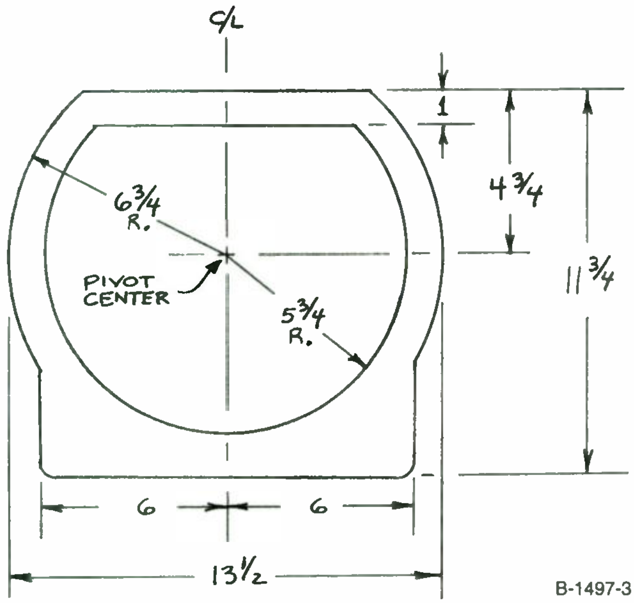


FIGURE 3: Part-A details.

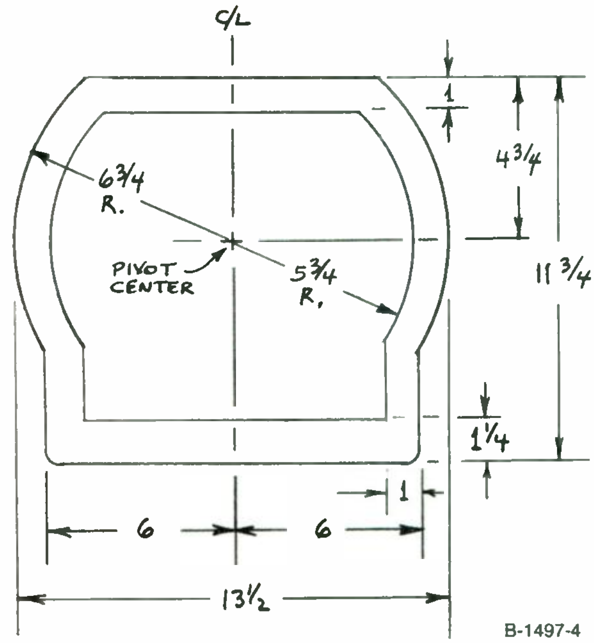


FIGURE 4: Part-B details.

CABINET MATERIALS

Except for internal bracing, grille boards, and subpanels for midrange and tweeter, the cabinet is entirely made of medium-density fiberboard (MDF), both 1″ and ¾″ thick. Cylinder walls are 1″ thick, the arched top of the tower and the flat base of the cylinder are 1¼″, the woofer-mounting baffle is 1½″, and all four sides of the tower are ¾″.

You will notice, however, that the midrange and tweeter are not mounted directly to the tower's baffle. Rather, there is a subpanel of solid, ½″ oak attached to the ¾″ MDF panel with 12 screws along its perimeter and the seven bolts used to mount the midrange and tweeter. A layer of BVD Pad® is attached to the back of the oak subpanel, sandwiched between it and the baffle.

The resulting mounting panel for the midrange and tweeter is a composite of three different materials having a combined thickness of slightly more than 1¼″. This composite panel is essentially dead with regard to vibration. To further isolate the midrange and tweeter from cabinet vibrations and to seal the tweeter in its mounting hole, each has a gasket of 0.040″-thick Neoprene™ rubber under its mounting flange.

A cylindrical shape doesn't really need internal bracing, at least not in this size, but the tower does. I used 12-ply, ¾″-thick Baltic birch plywood (BBP) to make the three

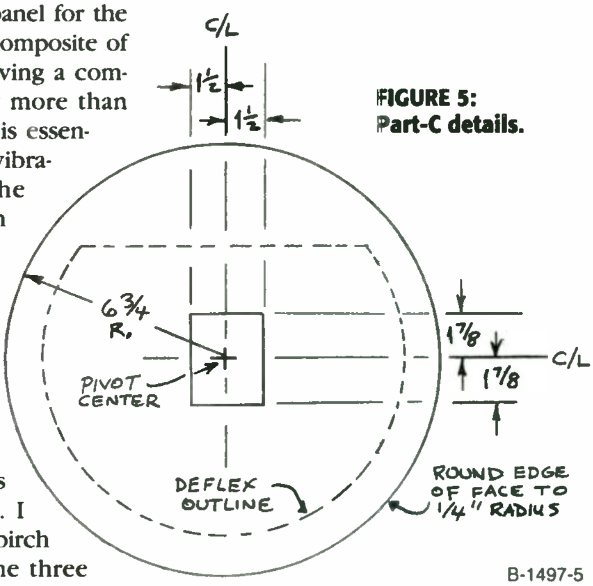


FIGURE 5: Part-C details.

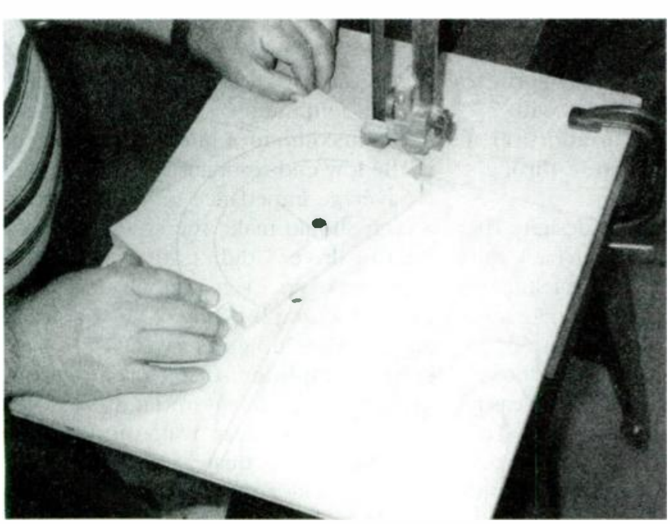


PHOTO 4: Cutting arches on band saw.

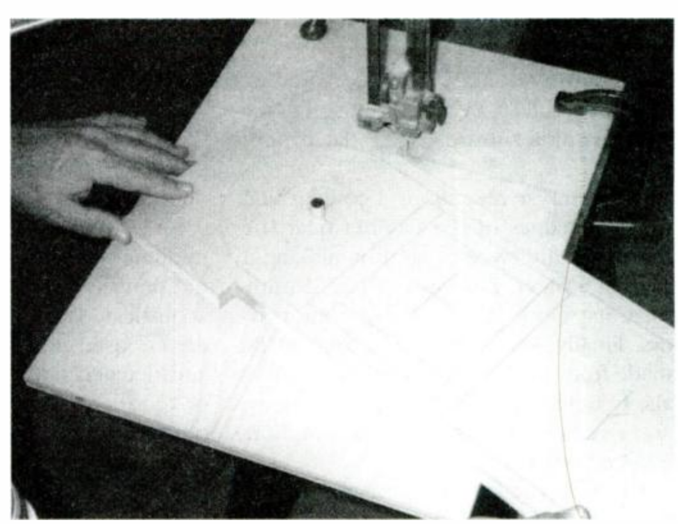


PHOTO 5: Cutting front and rear panels on band saw.

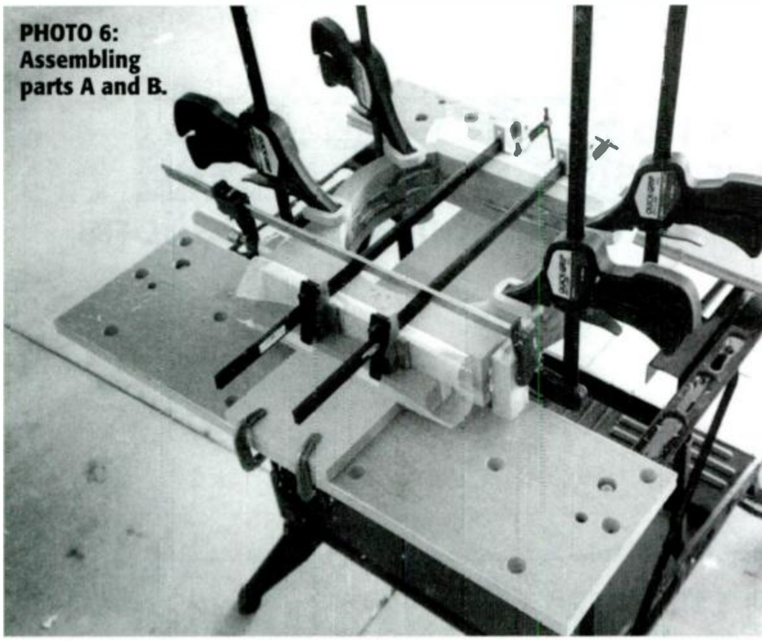


PHOTO 6: Assembling parts A and B.

full-perimeter shelf/braces and the vertical glue blocks (I call them "runners") used inside the tower. For convenience, I also used the BBP to make the midrange tunnel and both grille boards. To further damp panel resonances in the tower, I applied one layer of BVD Pad to most of its internal walls.

CUTTING AND ASSEMBLY REQUIREMENTS

The most difficult steps are cutting and assembling the cylinder and tower top pieces. It isn't possible to cut the cylinder circles (donuts) or the half circles (arches) for the tower top with enough accuracy or consistency using a handheld jigsaw. Instead, I made a fixture from a sheet of plywood that I could clamp onto my band-saw table (*Photos 4* and 5). I cut a slot in the plywood to clear the band-saw blade, and three holes for inserting a pivot post at various radial distances from the blade. I used a ½"-diameter wood dowel for the pivot post.

I clamped the plywood base with this pivot post onto the band-saw table with the distance between the saw blade and the center of the pivot post set for the proper cutting radius.

Each piece cut on this band-saw fixture had a ½"-diameter hole to fit over the pivot post (*Fig. 3* for part A and *Fig. 4* for part B have the pivot-post holes labeled "pivot center"). Thus I was able to accurately and consistently cut the outer portions of the cylinder, tower-top pieces, and tops of the front and rear panels of the tower.

I also used this fixture to cut the inside portions of the tower-top pieces, although there it isn't necessary to be so accurate. I had no choice but to cut the inside portions of the cylinder pieces (parts A and B) with a jigsaw, but there again, accuracy was not necessary. You also need to cut the outer portions of parts C, D, and E for the cylinder (*Figs. 5–7*) on the band-saw fixture, and the outer portions of the lower grille boards (*Fig. 8*) as well.

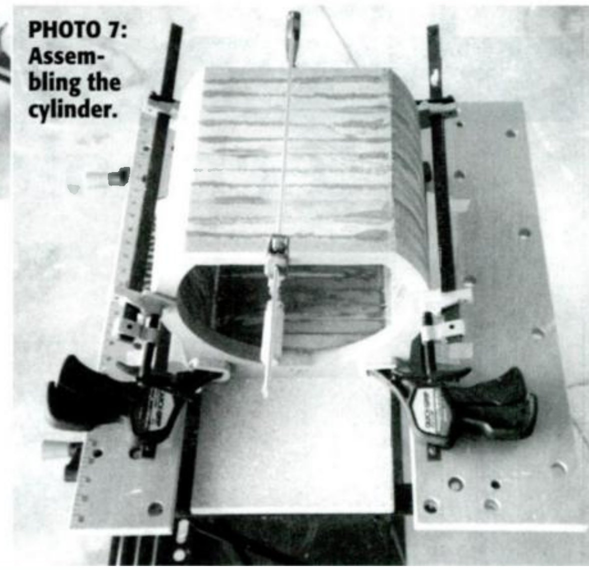


PHOTO 7: Assembling the cylinder.

To maximize the benefits from using this band-saw fixture, it's important to locate the pivot holes accurately in all the pieces and reference all cutting dimensions from them, as well as to drill out the pivot holes accurately.

You need many clamps for this project. You will be gluing a lot of pieces, but you must not clamp too many to-

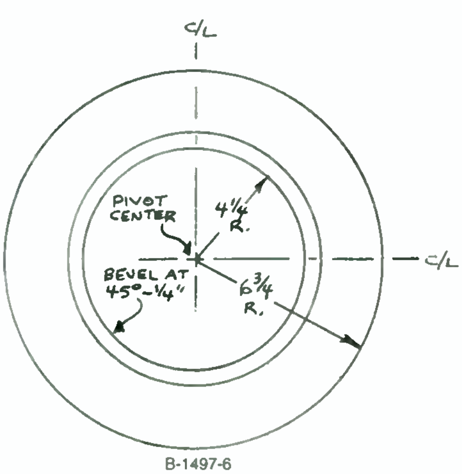


FIGURE 6: Part-D details.

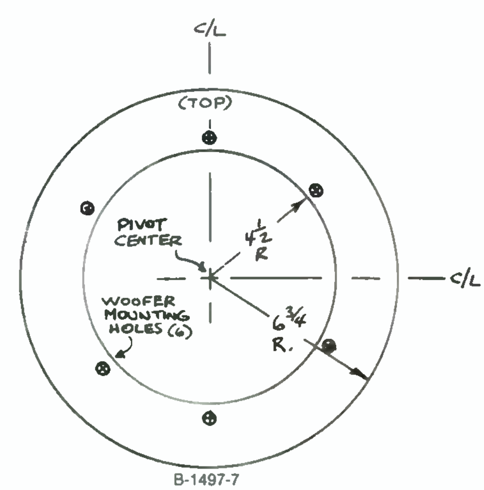


FIGURE 7: Part-E details

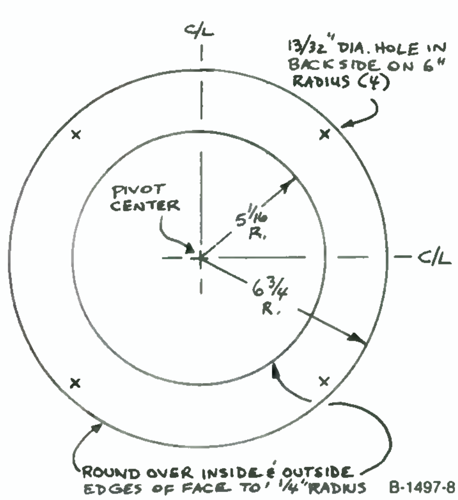


FIGURE 8: Lower grille-board details.

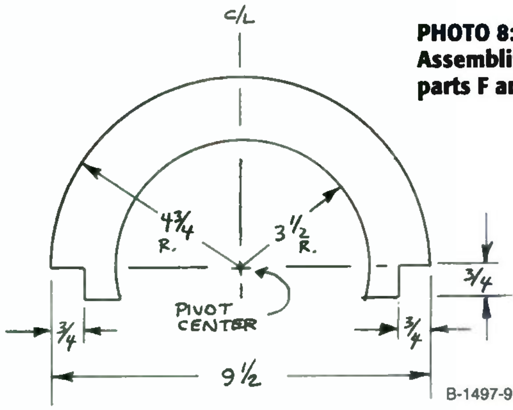


FIGURE 9: Parts F and G details.

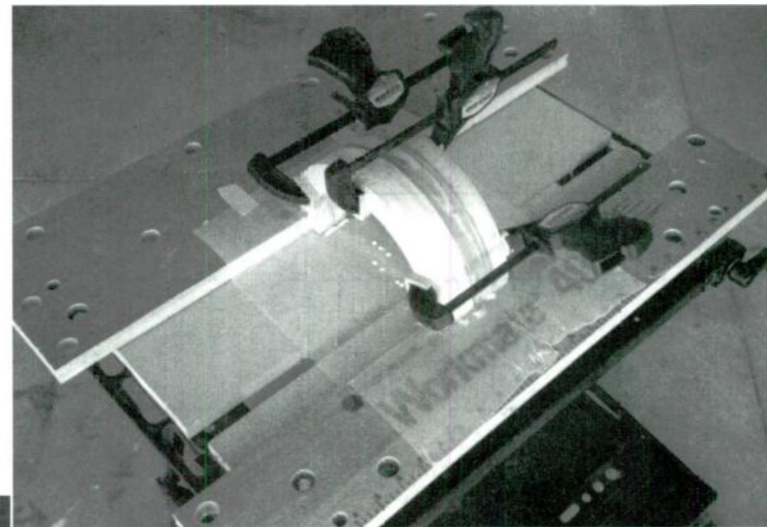


PHOTO 8: Assembling parts F and G.

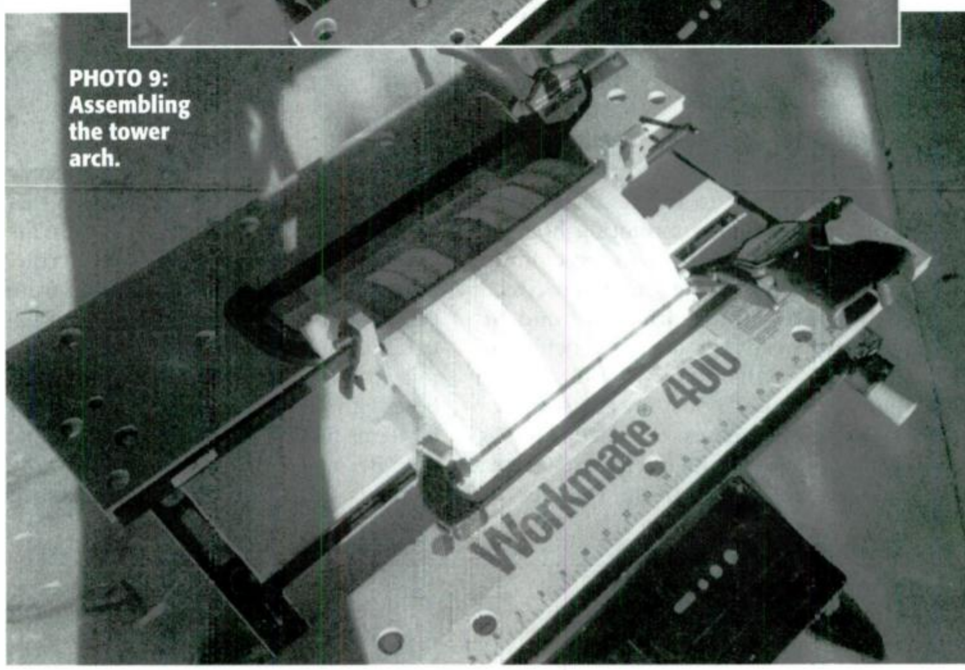


PHOTO 9: Assembling the tower arch.

gether at one time, or you are likely to end up with crooked assemblies. For the cylinder, I glued three pieces together at a time, either one of part A with two of part B, or three of part B (*Photo 6*). Then, to make the whole cylinder, I clamped together four of these three-piece subassemblies (*Photo 7*).

In *Figs. 3* and *4* you see that the tops and bottoms of parts A and B are straight, as are the sides that form the base. These straight surfaces must be cut accurately and consistently, and then the three individual pieces clamped so they square up horizontally side-to-side and top-to-bottom before you clamp them vertically.

TOWER-TOP ASSEMBLY

The half-circle top of the tower is assembled in a similar fashion from six F parts (1″ MDF) and six G parts (¾″ MDF) (*Fig. 9*). You can glue and clamp four of these pieces together simultaneously (*Photo 8*), and then make the whole top by gluing and clamping three of these subsections together (*Photo 9*). When gluing the top arch pieces, I used the notches in their bottom corners to align and square them between the clamping jaws of my Workmate® bench.

Assuming you've cut the pieces accurately for the cylinder and top arch, your success at putting them together depends on your planning and how careful you are when gluing and clamping. The better you assemble these parts to each other, the less sanding of their outsides you'll need to do later to achieve a good-looking surface.

Time for a pop quiz. If you glue together 12 pieces of 1″-thick wood, as you must with parts A and B to make the cylinder, the overall thickness after gluing will be exactly 12″. True or false? This is false for two reasons, the obvious one being that the glue does occupy some room, especially for an accumulation of 11 joints. A less obvious reason is that sometimes MDF is actually thicker than nominal, and if it has absorbed water vapor, it will be even thicker.

When I first brought home my 1″ MDF, its thickness measured about 1.015″. By the time I got around to cutting it, the thickness had decreased to about 1.007″ (apparently it dried somewhat). Then, after I had glued together the 12 pieces of parts A and B and allowed them to dry for 24 hours, the overall thickness measured 12.06″, or about 1.005″ per piece including glue joints. When I cut the pieces for the tower sides, which are nominally 12″ wide, it was necessary to make them 12-1/16″ wide to match the cylinder's overall assembled depth.

On the materials list and figures showing the dimensions of the tower sides, their width is shown as 12″. You will need to make this width whatever is necessary to match your cylinder's depth, but it will probably fall between 12 1/32″ and 12 1/16″. Similarly, when cutting the tunnel pieces and shelf/braces from the BBP, you'll need to increase their nominal 10½″ lengths by the amount the tower-side width exceeds 12″. If you don't take the actual depth of the cylinder assembly into account when cutting the side panels and other parts, the front and back of the tower assembly won't line up with the flat portion of the cylinder's top.

THE CROSSOVER ASSEMBLY

Figure 10 shows the schematic for the crossover, and *Fig. 11* is its assembly drawing. On the schematic, the terminals labeled "A" through "G" correspond to the labeling of the terminal-strip "posts" shown in *Fig. 11*. *Table 1* lists crossover components, drivers, and other parts I used. Most are available from a number of suppliers (I bought all my crossover components from Meniscus).

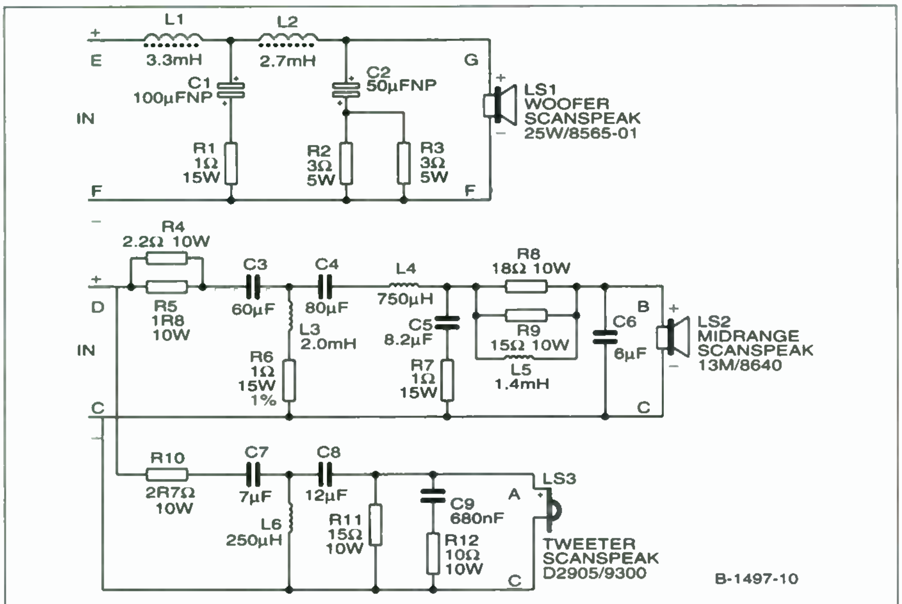


FIGURE 10: Crossover schematic.

It's necessary to locate and pre-drill crossover-assembly mounting holes inside the base of the woofer cylinder early in the cabinet-assembly process. It is best, therefore, either to build the crossovers early, or at least to determine in advance where you will locate their mounting holes. I built my crossovers on ¼″-thick MDF bases, 8¼″ deep by 9¼″ wide, which is about the largest size that fits into the bottom of the cylinder. Because of the dense parts population that resulted, I oriented inductors at right angles to each other and kept the ferrite-core coils as far away as possible from the air-core coils to minimize mutual coupling and inductance.

I attached components to the MDF base with silicone sealant, with the heavier items further secured by plastic cable ties. Because I like to be able to make changes easily, I used a terminal strip that accepts slip-on solderless connectors for connecting to the drivers and input-terminal cup posts. Some of the posts on this terminal strip have multiple "fingers" that allow you to connect several slip-ons to the same post. All other connections on the crossover between components and this terminal strip are soldered, however.

DUPLICATING THE DESIGN

If you intend to replicate the performance of my Danish Delight design, you should not use parts that are significantly different from those I used, especially the woofer inductors, L1 and L2, and the series midrange inductors, L4 and L5. Substituting other inductors with significantly different resistances for these four will affect system Q_{TC} and the sensitivities of the woofer and midrange drivers. The resistances of the other inductors, L3 and L6, are not as crucial, but air-core types are still the best choice.

I used ferrite-core inductors in the woofer crossover because they're smaller and have lower DC resistances than

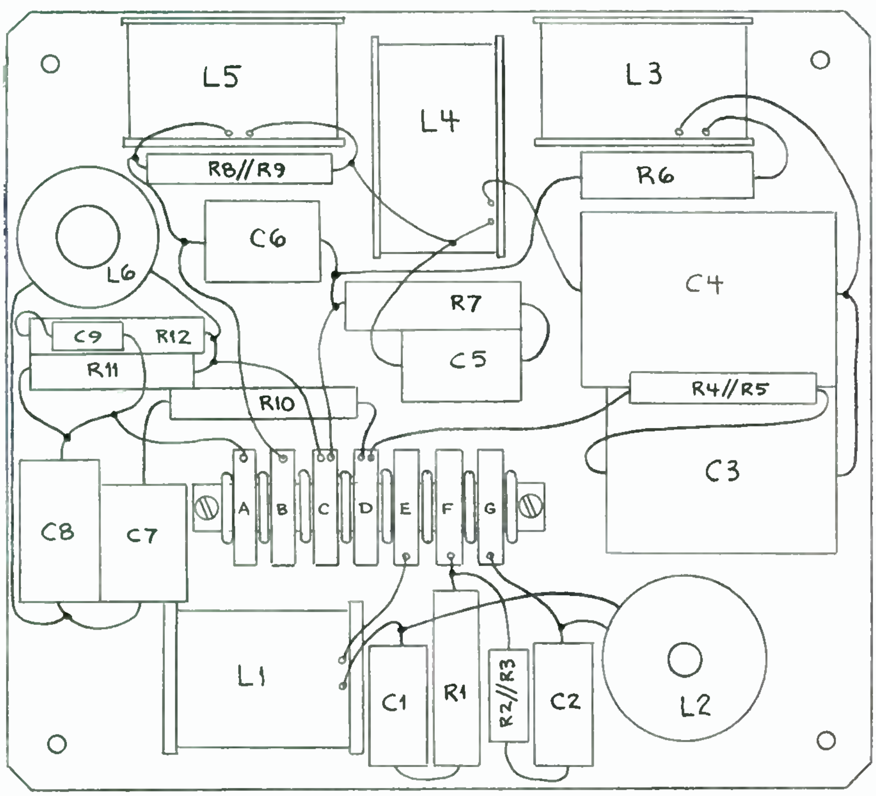


FIGURE 11: Crossover assembly drawing.

TABLE 1
CROSSOVER AND MISCELLANEOUS COMPONENTS

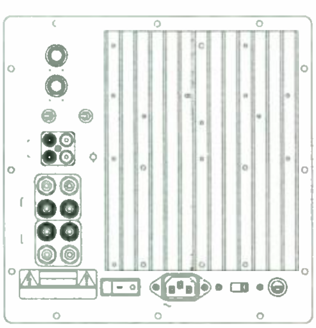
DESIGNATOR/ NAME	VALUE, DESCRIPTION, (SUPPLIER)
L1	3.3mH, 0.22Ω, 16g, ferrite-core
L2	2.7mH, 0.29Ω, 16g, ferrite-core
L3	2.0mH, 18g, air-core
L4	0.75mH, 0.37Ω, 16g, air-core
L5	1.4mH, 0.55Ω, 16g, air-core
L6	0.25mH, 20g, air-core
C1	100µF, nonpolarized electrolytic
C2	50µF, nonpolarized electrolytic
C3	60µF, metallized polypropylene
C4	80µF, metallized polypropylene
C5	8.2µF, metallized polypropylene
C6	6µF, metallized polypropylene
C7	7µF, metallized polypropylene
C8	12µF, metallized polypropylene
C9	0.68µF, Mylar
R1, R6, R7	1Ω, 15W, ceramic
R2, R3	3Ω, 5W, ceramic
R4	2.2Ω, 10W, metal-oxide film
R5	1.8Ω, 10W, metal-oxide film
R8	18Ω, 10W, metal-oxide film
R9, R11	15Ω, 10W, metal-oxide film
R10	2.7Ω, 10W, metal-oxide film
R12	10Ω, 10W, ceramic
Woofer	25W/8565-01, Scan-Speak (Vifa)
Midrange	13M/8640, Scan-Speak (Vifa)
Tweeter	D2905/9300, Scan-Speak (Vifa)
Terminal cup	TD-CUP
Grille fasteners	Miniature male and female (ball & socket) sets (MAG)
Damping material	BVD Pad, 3 sheets at 18″ × 31″ (MAG)
Acoustical fill	Acousta-Stuf, 3 pounds (PE)
Acoustical foam	5/8″ thick, 1 sheet 27″ × 42″ (MSC)
Acoustical absorber	Deflex, "Subwoofer," 3 at 340mm Diameter (MSC)

Subwoofer Amplifiers

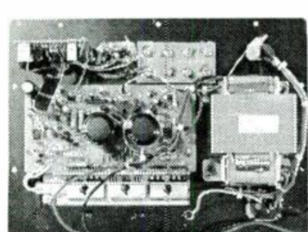
KG-5150: 200 Watts @ 4 Ohms
KG-5230: 300 Watts @ 4 Ohms

Madisound is pleased to offer the **KG-5150** and **KG-5230 Subwoofer Amplifiers with Electronic Crossovers** for powered subwoofer systems. We have worked hard to find subwoofer amplifiers that have adjustable electronic crossovers and have enough power to deliver good bass without added distortion. We are confident that we now have products that can meet the demands of both home theater or high end audio systems. Powered subwoofers are a versatile addition to your audio system. With the variable crossover and volume control, you can match a subwoofer to any existing system. These amplifiers can be used with single or multiple woofer systems (a total impedance of 4 to 8 ohms is recommended). The crossover can be turned off if you are using the amplifier with a system that already has a built in crossover.

- **Class AB**
- **Discrete high current drivers and output devices**
- **LED power indicator**
- **Woofer volume control**
- **50Hz to 100Hz continuously adjustable low pass 12dB electronic crossover**
- **Crossover on/off switch**
- **Low and High level input, summed to mono signal**
- **Low and High level all pass output**
- **Phase inverter switch**
- **Master power switch**
- **Auto power on/off activated by input signal**
- **4dB boost @ 25Hz**



KG-5230

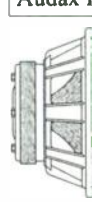


Rear view of KG-5150

Specifications:	**KG-5150**	**KG-5230**
Power output Watt@ 8 ohms / 4 ohms	150 / 200	175 / 300
THD	0.03%	0.08%
S/N ratio @ rated power	95dB	85dB
Input sensitivity @ 100Hz - low level	75mV	150mV
Input sensitivity @ 100Hz - high level	3.5V	2V
Input impedance	22k ohms	22k ohms
Variable Low Pass Crossover Freq.	50-100Hz	50-100Hz
Weight	10.5 lbs	14.5 lbs
Dimensions W x H inches	11 7/16 x 8 1/4	9 7/8 x 9 7/8
Cutout hole W x H inches	10 7/16 x 7 1/4	8 7/8 x 8 7/8
AC Voltage	115 or 230	115 / 230 switchable
Price Each	**$169.00**	**$225.00**

Woofer Suggestions (Including 4dB boost)

Item	Size	Ft^3	S/V	3"Ø	F_3	W
Madisound 1252DVC	12"	3.5	S	-	25.7	75
Madisound Swan 305	12"	4.25	V	5.5"	23.5	200
Eclipse W1238R	12"	3	V	8.75"	28.7	200
Peerless 850410	10"	1.25	V	7"	34.5	200
Peerless 831727	10"	2.25	V	10"	26.7	220
Peerless 850146	10"	3.1	V	8.1"	23.8	220
Peerless 831857	12"	6	V	7"	23	220
Peerless 831857	12"	3	S	-	28	220
Scan-speak 25W/8565	10"	3	S	-	26.7	100
Scan-speak 25W/8565-01	10"	3	V	10"	25.7	100
NHT 1259	12"	3.5	S	-	23.8	300
Vifa M26WR09-08	10"	1.7	V	7.6"	33.4	130
Dynaudio 30W100	12"	5.5	S	-	24.7	130
Dynaudio 30W100XL-4Ω	12"	4.5	S	-	25.7	130
Eton 12-680/62 Hex	12"	2.4	V	7"	27.7	200
Audax HT300Z2	12"	3.1	V	7.75"	28	150



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P.O. BOX 44283
MADISON, WI 53744-4283 U.S.A.
TEL: 608-831-3433 FAX: 608-831-3771
e-mail: info@madisound.com
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air-cores. For size reasons, I used nonpolarized electrolytic capacitors in the woofer crossover. As long as you use the correct values, you can use different capacitors, but I would advise against using nonpolarized electrolytic capacitors anywhere except in the woofer section, even though they are smaller and less expensive than metallized polypropylene or Mylar types (I used the Solen brand of polypropylene capacitors).

For resistors R4, R5, and R8–R11, you ought to use a good-quality, noninductive type (I used the Lynk brand). Capacitors should have tolerances preferably of 5%, and no worse than 10%, with ratings of at least 100V. Resistors and inductors should have tolerances of 5% or better. In three places I paralleled resistors to achieve a specific value or a higher power rating. You can replace R2 and R3 with a single 1.5Ω 10W resistor. R4 and R5 make a 1Ω 20W resistor. Similarly, R8 and R9 make an 8.2Ω 20W resistor.

Note that I built the crossover to accommodate biwiring or passive biamplification, which means there is one pair of input terminals for the woofer and its crossover, and a separate pair for the combined midrange/tweeter crossover. To avoid creating ground loops and unwanted interactions between drivers, each driver has its own ground wire going back to the terminal strip. Of course, since there is only one pair of input terminals for both midrange and tweeter crossovers, the ground wires from these two drivers are tied together at the terminal strip.

One "tweaky" thing I did to my crossover assemblies was to stick one layer of BVD Pad onto the bottoms of their bases, followed by a layer of self-adhesive, dense, ⅛"-thick foam rubber. I did this to minimize transmission of cabinet vibrations into crossover components. I can't confirm that this technique makes the system sound better, but the compressible foam rubber helped compensate for any unevenness in the cylinder bottom where the crossover is mounted.

MENISCUS ACCOMMODATES

As stated previously, I had Meniscus design this crossover using LEAP software, taking into account performance data for the three drivers and dimensions and shape of my cabinet. Both the woofer and midrange drivers have high-amplitude resonant peaks above their normal passbands, the woofer's at about 2.5kHz, and the midrange's at about 11kHz. These peaks needed to be adequately suppressed in order to minimize their colorizing or distorting the sound, so electrical fourth-order low-pass sections were necessary.

On the other hand, I knew there wouldn't be enough room on my smallish crossover board for more than six inductors, which meant the high-pass sections for midrange and tweeter could not be more complex than electrical third-order. The Meniscus design accommodated these requirements and included a correction circuit (R8 and R9 in parallel with L5) for a rising response in the midrange's passband. I also requested Meniscus to optimize the response on the tweeter's axis (±3" vertically) at a listening distance of 7–10' (see the sidebar for more information on Meniscus's crossover-design services).

For wiring to the crossover and drivers, I used two kinds of wire. To connect the terminal-cup posts to the crossover inputs and the crossover outputs to the woofer and midrange, I used good-quality stranded, twin, 16-gauge copper cable (similar to Monster® cable). Between the crossover output and the tweeter I used Nordost Octava®, which was given to me by a friend who owns an audio store. This cable is a flat assembly of eight solid-copper conductors, four used for the positive lead and four for the negative. You may use wiring of your favorite flavor, of course. Note that all three drivers are wired in phase.

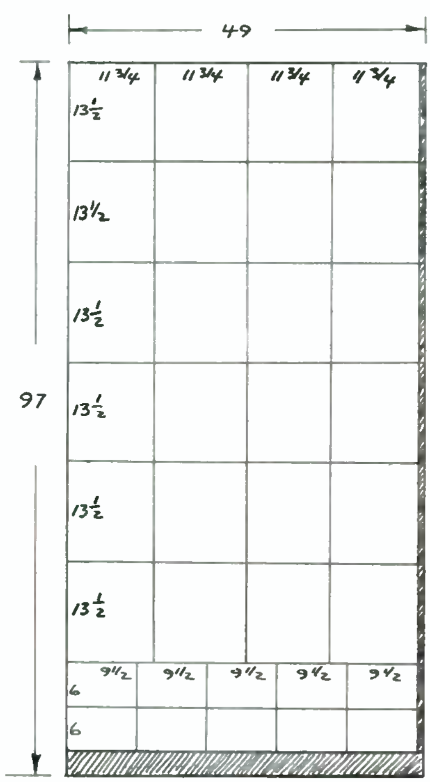

FIGURE 12: 1" MDF cutting guide.

CUTTING AND ASSEMBLING

It takes three sheets of wood to build a pair of these systems: a 4' × 8' sheet of 1" MDF (plus a little bit more), a 4' × 8' sheet of ¾" MDF, and a sheet of ¾" BBP (which is actually 23/32" thick). My sheet of BBP was 5' × 5', which is about twice what I needed. In addition, you need ½"-thick oak for the mounting sub-panels and ¼" MDF for crossover bases and tunnel-exit grille boards.

Figures 12, 13, and *14* show cutting layouts for both MDF sheets and the BBP sheet, and *Table 2* lists all the wood pieces with the initial sizes to which you need to cut them. You should set your table saw for one cutting dimension and make all necessary cuts at that setting on all three sheets before changing to another cutting dimension. This ensures that you'll end up with identically dimensioned cuts. For accuracy, you need to make sample cuts on scrap wood and verify that they're correct before making the final cuts.

Start by cutting out all A, B, C, D, and E parts from both sizes of MDF, as well as the lower grille boards from the BBP. All these parts fit together one way or another. Using a band-saw fixture such as I used, cut out the circles (parts C, D, and E), partial-circle shapes (parts A and B), and the lower grille boards from the rectangles in preparation for the first assembly steps.

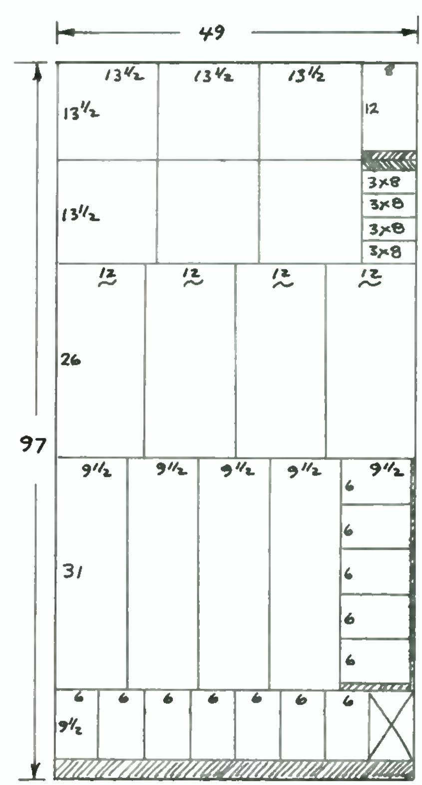

FIGURE 13: ¾" MDF cutting guide.

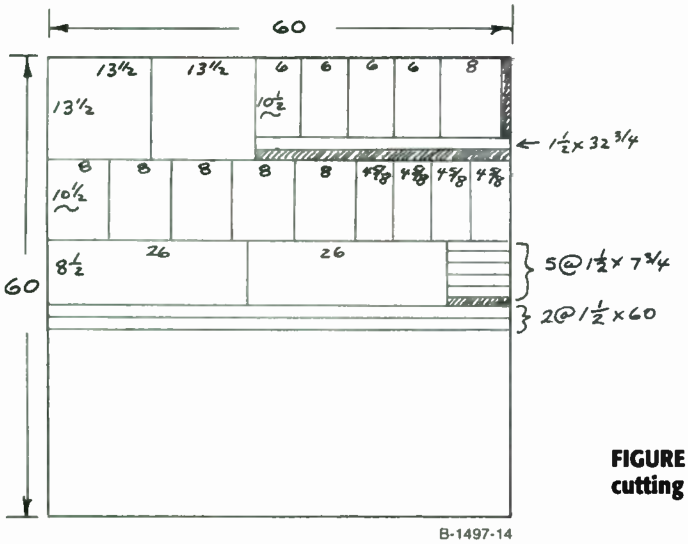

FIGURE 14: ¾" BBP cutting guide.

Because parts A and B are not complete circles and have some straight sides, you'll need to cut the curve on one side in the band-saw fixture, then flip the part over on its other face to cut the other curve. However, you should first do the straight cutting at the sides of the bases of parts A and B on the band saw. When you drill the pivot-post holes in these parts, use a brad-point or similar drill bit that has a small, very sharp point for starting the cut and that cuts very cleanly. You need to locate the centers of these holes as accurately as possible, and they should not be oval shaped.

JIGSAW CUTS

With the outside shapes finished on the band saw, cut out the insides of all A and B parts with a jigsaw, and then assemble the main part of each cylinder. When you cut out the insides of the B parts, try to make the bottom horizontal cut as straight as possible so you'll have a fairly uniform base to which to attach the crossover.

Using carpenter's wood glue, clamp together only three parts at a time as shown in *Photo 6*. Square up the three parts with three horizontal clamps in both directions; then clamp the pieces with four to six vertical clamps. As soon as everything is squared up and securely clamped, you can wipe off the excess glue both inside and out. After letting the glue set for an hour or two, remove the clamps for use on the next set of three. Continue doing this until you have eight sets of the three-piece subassemblies (four sets consisting of one part A and two of part B, and four sets consisting of three of part B).

When the glue in these three-piece assemblies has dried for 24 hours, you can glue and clamp them together to make the cylinders (*Fig. 15*). For this step, after applying carpenter's glue in the three joints, I simply placed them between the jaws of my clamping worktable, sitting on a piece of wood to hold them up between the jaws. By closing the worktable clamping jaws snugly (but not too tightly) against the flat sides of the base, I was able to square them. Then, I applied several bar clamps to pull the four subassemblies tightly together while the glue set (*Photo 7*).

Once the glue in these two assemblies has thoroughly dried, you can measure their depths, which will probably be slightly more than 12". Use this measurement for the correct width of the side panels of the tower and to determine the excess over 12" that you must add to the 10½" lengths of shelf/braces and tunnel pieces.

CUTTING REMAINING PARTS

You can now cut out all remaining parts from the MDF and BBP sheets (you'll need to come up with a little more of the 1" MDF to make two of the F parts). Remember that you should set the table saw to one cutting dimension and make all the cuts you need at that setting before changing to another. The cutting guide for the BBP (*Fig. 14*) doesn't show any layout for cutting the 1½"-wide runners to length. Just cut these out as needed from 1½"-wide strips of the BBP.

Now you can cut out the F and G parts (*Fig. 9*) for the top arch of the tower, using the band-saw fixture and the pivot post at a shorter radius. While you have the fixture set up on the band saw, you should also cut the arched tops of the front and rear panels (*Figs. 16* and *17*). After you've cut the arch at the top of the rear panel, you'll need to plug the pivot hole, gluing in a short length of ½"-diameter dowel for this. It's probably best to assemble the top arches at this time, following a procedure similar to that used to build the cylinders.

These assemblies are a bit easier to put together, since you can place the notches in their bottom corners between the jaws of a clamping table for squaring them up. I glued and clamped four parts together at a time; then, after the glue dried, I glued three of the subassemblies together to complete an arch assembly (*Photos 8* and *9*). When I glued these parts together, the parts sequence alternated between two of part F and three of part G, and so on, so that a finished tower top consisted of six of part F and six of part G (*Photo 9*).

CUTTING THE HOLES

Before you can perform any more assembling, you'll need to cut out the inner parts of the shelf/braces (*Fig. 18*); the hole for the terminal cup in part C (*Fig. 5*); the holes in parts D and E to clear the woofer (*Figs. 6* and *7*); the holes in the front panel (baffle) for midranges and tweeters (*Fig. 16*); and the hole in the rear panel for the tunnel exit (*Fig. 17*). You also need to cut out the inside circle of the woofer grille boards (*Fig. 8*) and

TABLE 2
SIZES AND QUANTITIES OF WOOD PARTS

(Quantities are for two systems; all dimensions in inches)

SIZE	QUANTITY	FOR/DESCRIPTION
1" MDF		
11¾ × 12½	24	Parts A and B
6 × 9½	12	Part F
1½ × 3	4	Side panel tunnel brace
¾" MDF		
13½ × 13½	6	Parts C, D, and E
8 × 12	1	Tower assembly jig
3 × 8	4	Tower assembly jig
12 × 26*	4	Tower side*
9½ × 31	4	Tower front and back
6 × 9½	12	Part G
¾" BBP		
13½ × 13½	2	Lower grille board
6 × 10½*	4	Tunnel top and bottom*
8 × 10½*	6	Shelf/brace*
4⅝ × 10½*	4	Tunnel side*
8½ × 26	2	Upper grille board
1½ × 11	8	Runner
1½ × 6	16	Runner
¼" MDF		
8¼ × 9¼	2	Crossover base
5¼ × 5¼	2	Tunnel grille board
½" SOLID OAK		
6⅞ × 24	2	Sub-panel

*See text for correct width or length of these parts.

both insides and outsides of the upper grille boards (*Fig. 19*).

You can do all of this cutting with a hand-held jigsaw, but if you use a recessed grille board on the tunnel exit as I did, you'll need to cut the hole in the rear panel very accurately. As you can see in *Figs. 16* and *17*, the sides of both front and rear panels have a ¾″-wide notch running up from their bottoms for 26″. This is best done as a two-step process, first by cutting from the bottoms of these panels not quite the whole 26″ length on a table saw, then finishing the cutting with either a band saw or jigsaw. The ¾″ notch width needs to be fairly accurate to allow proper fitting of these panels between the tower-side panels.

The oak sub-panels (*Fig. 20*) need extremely accurate cutting of the two driver-clearance holes and accurate routing of recesses for the driver-mounting flanges. If you take your time and are careful, you can cut out the main holes for these drivers with a scrolling blade in a jigsaw. Then, with a rabbeting bit in your router, you can cut away a ½″-wide recess to the proper depth for the drivers' mounting flanges. If you have a plunge-type router, which I don't, you might wish to buy the Jasper Model 200 Circle Jig® for it to make this task much easier and more accurate.

PROCEED WITH CAUTION

As a cautionary note, after you cut the rectangular pieces from the MDF and BBP sheets and before proceeding to cut them further, make sure you draw on them all the necessary lines and hole locations you'll need to use later. This is especially important for the band-saw pivot holes, because other dimensions are referenced to them; once you drill out a pivot hole, it's difficult to use the hole's center as a dimensioning reference.

Using a drill press (not a hand-held drill) and a drill bit just large enough to pass a #3 nail, drill through both upper and lower grille boards the centers of the holes that will be enlarged later from behind to hold the grille-board fasteners. Now, using your router and a ¼″-radius bit, round over the outer edges of the oak sub-panel face, both inner and outer edges of the faces of the upper and lower grille boards, and the outer edges of part C. Cut out and attach Deflex to the inside rear of part C with Weldbond® adhesive (*Fig. 5* shows the outline of the Deflex). With a sharp knife, cut a small hole in the Deflex at the center of the terminal-cup cutout for a wire pass-through.

SIDE PANELS

Build up the side panels as shown in *Fig. 21*. Starting at the bottom, nail and glue the 1½″-wide "runners" cut from the BBP to the insides of the side panels (six per panel). Temporarily clamp 1″-wide and about 10″-long strips of the BBP where the shelf/braces will eventually go for proper vertical spacing of the runners. Similarly, clamp 1″-wide and about 24″-long strips of the ¾″ MDF to the

MENISCUS SERVICES

There are many companies such as Meniscus that offer box- and crossover-design services and can work from very general to very specific requirements you provide. I do my own box design, and, until this one, also designed my own crossovers, using "textbook" equations. An optimum crossover design is almost impossible to attain using these equations, and that's where LEAP and other crossover-design programs come into play.

The dimensions of your cabinet and the drivers' locations on the baffle greatly influence the sound and affect optimization of the crossover design. All the companies providing these services will use your (or their) cabinet dimensions, but Meniscus is unique, I believe, in building full-scale models of the baffles for use during the crossover-design process. The ability to make measurements on the same size and shape of baffle as the builder's allows better modeling for acoustic centers, mutual coupling, edge diffraction, and polar response, for instance.

Since I designed the Danish Delight's shape to aid its sonic performance, you can imagine how beneficial Meniscus's process was. Mark Sayer and his staff at Meniscus were willing to work within the somewhat restricted and often very specific parameters I dictated, never failing when I asked questions to explain what they did and why, and always willingly accommodating any changes I desired.—**PLK**

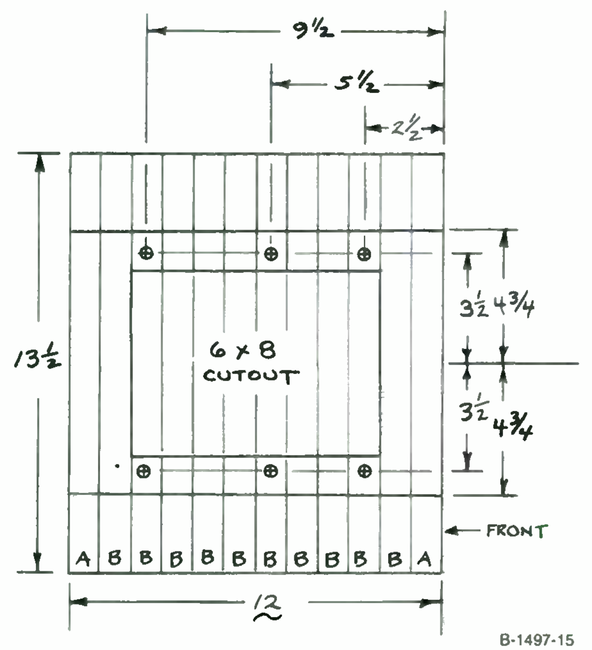

FIGURE 15: Top view of cylinder.

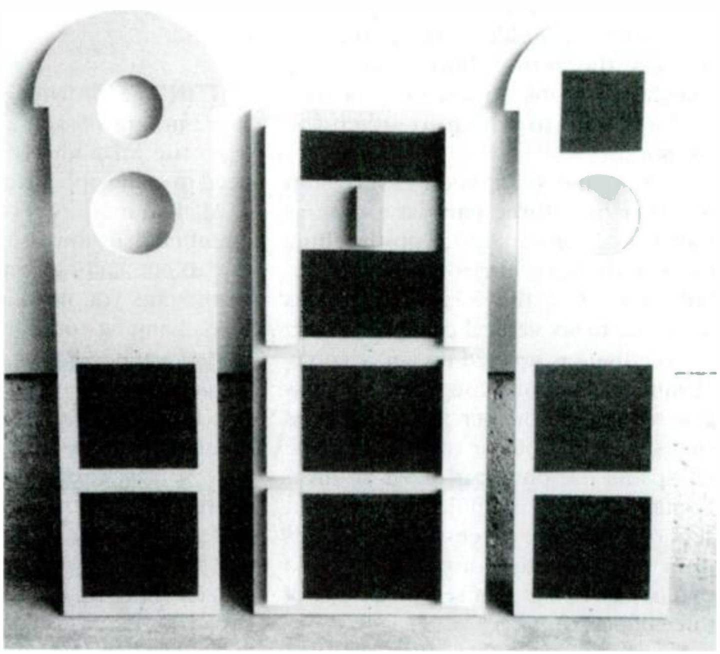

PHOTO 10: BVD pad locations.

The Process of Design.

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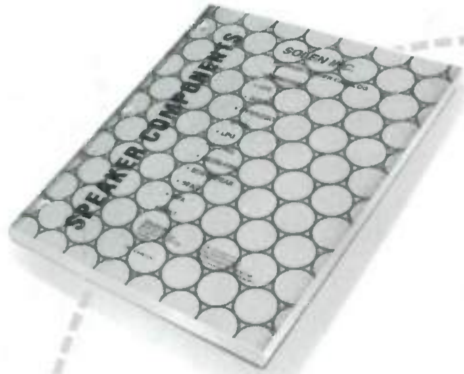

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front and rear edges of the side panels to create the proper recess depth for the front- and rear-panel runners. Apply carpenter's glue to the backs of the runners and attach them to the side panels with pairs of 3d, 1¼″ finishing nails spaced about every 2″ or 3″ along the runners.

Before it dries, remove the excess glue from the outside edges of the runners and between the runners where shelf/braces will be located. A short piece of 1″-thick MDF (1½ × 3″) also needs to be nailed and glued to the inside of each side panel as shown. Once the glue has dried on the runners, apply a bead of silicone sealant along their inside edges, but don't get any sealant in the horizontal slots where the shelf/braces will be located.

Then, as shown in *Photo 10*, attach rectangles of BVD Pad, followed by rectangles of the ⅝″ foam sheet. The foam is needed only on the sides below the upper shelf/brace slot. Before attaching any of the BVD Pad, vacuum and wipe off the panels with a tack cloth to remove all dust particles. I found it useful to roll the top of the BVD Pad with either a baking or laminate roller to firmly stick it down.

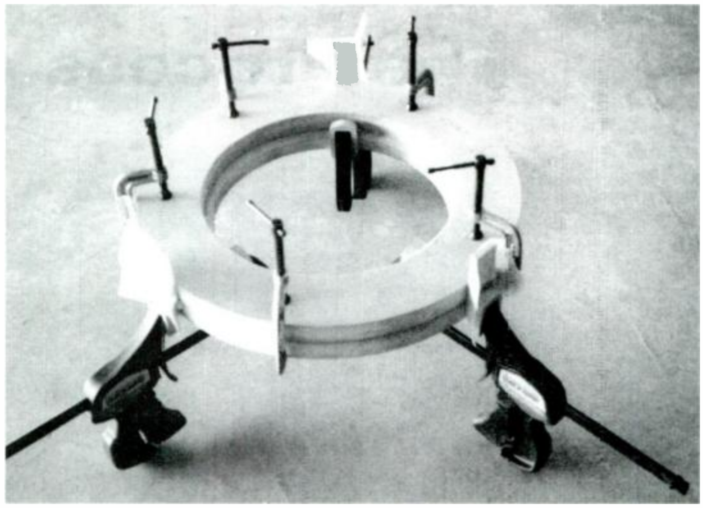

PHOTO 11: Assembling parts D and E.

MISCELLANEOUS SUBASSEMBLIES

Parts D and E need gluing and clamping together as shown in *Photo 11*. Before assembling these two pieces together, bevel the hole in part D as shown in *Fig. 6*. Use a 45° chamfering bit in your

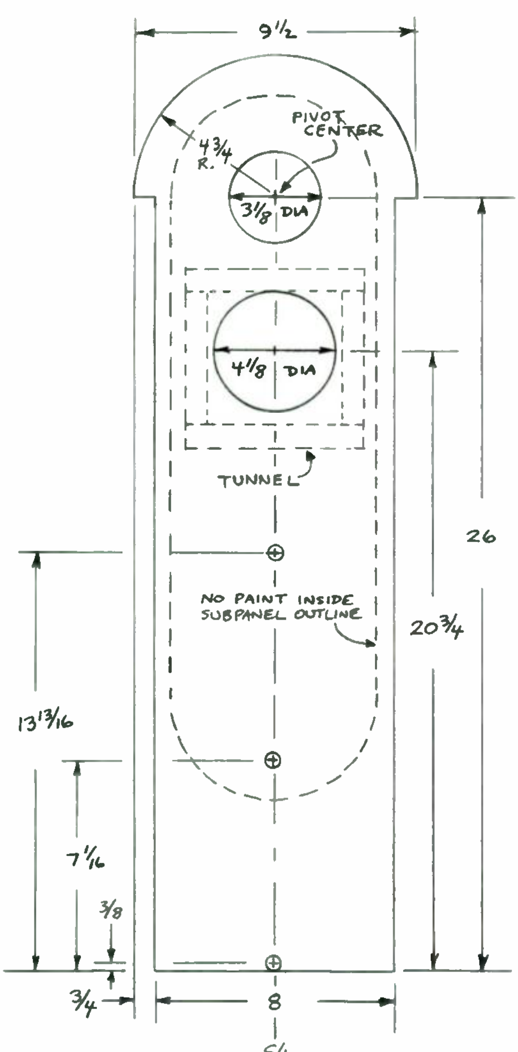

FIGURE 16: Front panel details.

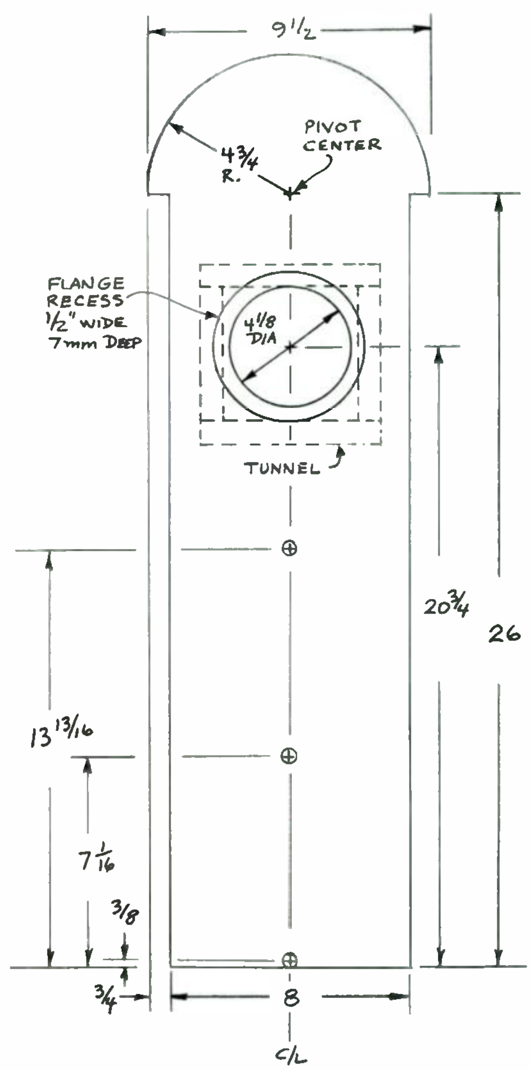

FIGURE 17: Rear panel details.

router to create a bevel ¼″ deep and ¼″ wide on one side of part D, thus providing a smoother transition from the 9″ hole in part E to the 8½″ hole in part D. Glue part E to the face of part D having this bevel.

After parts D/E have dried, locate and drill six mounting holes for the woofer in part E. Temporarily place the woofer centered in the part-E cutout and mark the mounting-hole locations through its flange. I drilled these for 8/32 T-nuts in all but one of the locations, and you can hammer in the T-nuts from the rear on part D. The sixth hole (the one at the top) can't use a T-nut, but must be drilled and threaded for an 8/32 wood screw.

With the cylinder assembled, accurately locate on its flat top the centers of the six clearance holes for #8 screws and draw the 6″ × 8″ outline for the cutout as shown in *Fig. 15*. Use the actual left-to-right centerline of the top's width for locating the screw clearance holes left-to-right, and the front of the cylinder assembly for determining the front-to-back locations of the holes. Drill out the six screw holes slightly larger than necessary to allow a little movement for alignment later on during assembly, and cut out the rectangular hole with a jigsaw (*Photo 12*). Note that the six clearance holes are not equally spaced front to back.

The drawings for parts A and B (*Figs. 3* and *4*) show that the outside corners at the base bottom are rounded. Do this with a round-over bit of ½″ radius in a router. If not already done, mark the locations of mounting holes for the crossover in the flat bottom, and then drill pilot holes and prethread them for #8 particleboard screws. This is an opportune time to line the curved walls of the cylinder with some of the ⅝″ sheet foam, using spray adhesive to attach it.

ATTACHING SUBASSEMBLIES

Now you can attach the part D and E subassembly to the front of the cylinder as shown in *Photo 13*, using carpenter's glue and clamps. Just to make sure these parts were securely fastened, I also used three #8, 1¾″-long, countersunk particle-

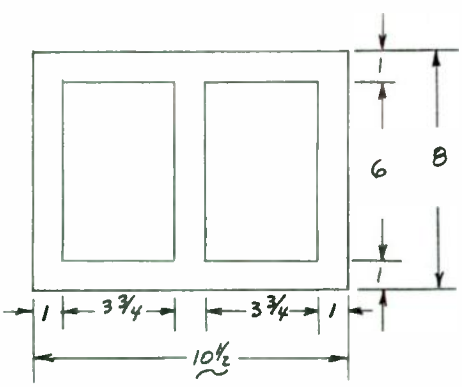

FIGURE 18: Shelf/brace.

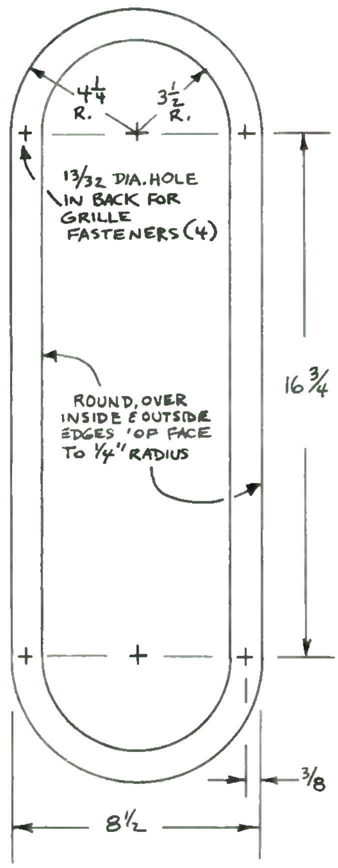

FIGURE 19: Upper grille-board details.

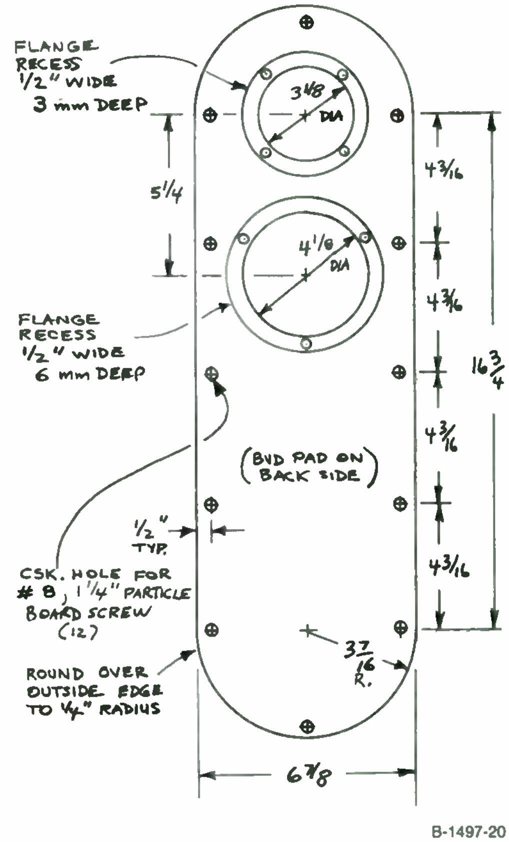

FIGURE 20: Oak sub-panel details.

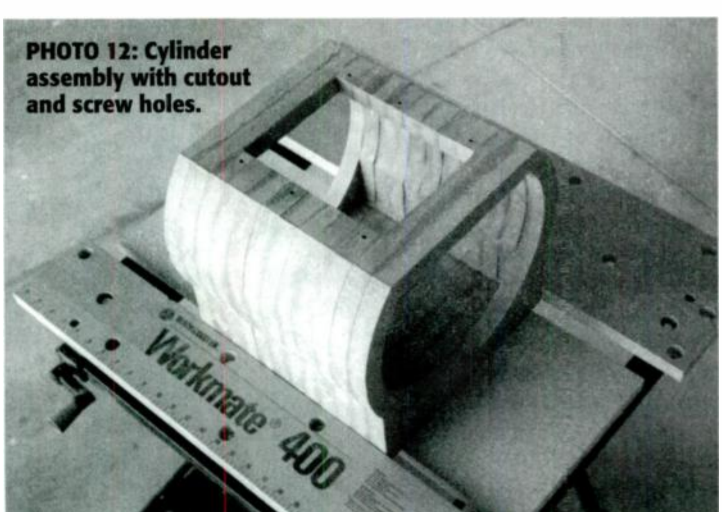

PHOTO 12: Cylinder assembly with cutout and screw holes.

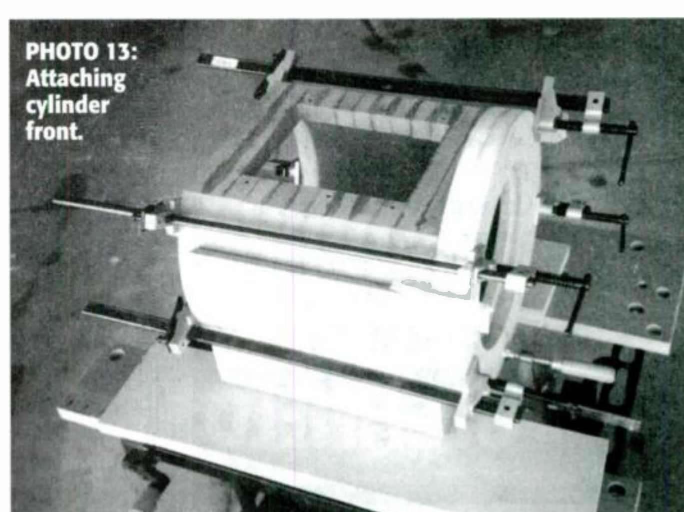

PHOTO 13: Attaching cylinder front.

board screws at 90° locations through parts D and E into the cylinder walls. Later, I filled the countersunk holes with wood filler.

After the glue has dried, locate and drill four holes in the face of part E for grille-board fasteners (I used miniature ball-and-socket fasteners that require 13⁄32"-diameter holes). Place the lower grille board on part E, center it and temporarily clamp or tape it down. Insert a #3 nail through each of the four pilot holes for the fasteners, and hammer the nails enough to mark the face of E. Remove the clamps and grille board, and with a 13⁄32" brad-point drill bit, drill holes in the face of E and the back of the grille board to depths that will accept both halves of each of the four grille fasteners. Finally, use silicone sealant to seal the seam inside the cylinder where part D is glued to its front.

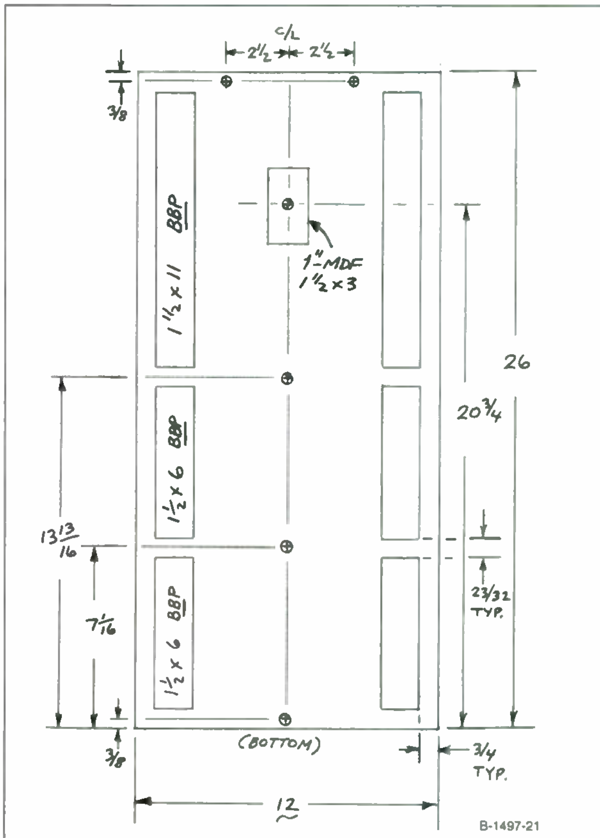

FIGURE 21: Side panel assembly.

Construct the midrange tunnel by gluing and clamping together two pieces of 4⅝" × 10½" BBP (the sides) to two pieces of 6" × 10½" BBP (the top and bottom) so that the latter overlap the edges of the side pieces. Before gluing, attach a piece of 4" × 10" BVD Pad to the inside centers of the tops and bottoms. You can use a few small nails through the tops and bottoms into the edges of the sides for alignment and initial assembly, but the clamped glue joints will actually hold the tunnel pieces together.

After the glue has dried, seal the four inside-corner seams with silicone sealant along the complete length of the tunnels. If you've decided what kind of wire you will use to connect the midrange to its crossover, now is a good time to drill a pass-through hole of the proper size in the bottom of the tunnel. Make this hole just big enough to allow a snug fit around the wire. Also, you can attach a layer of the ⅝" foam sheet (5½" × 10") to the outside bottom of the tunnel, using spray adhesive.

The small grille board used on the tunnel exit is made from ¼" MDF. It's a ring with a 5 1⁄16" outer diameter and a 4⅛"-diameter inner hole (no drawing shown). If you don't wish to bother making this grille board, you can simply attach a metal or plastic screen inside the tunnel's exit hole. That way, you also won't need to rabbet a flange recess around the exit hole. Use a screen with a large mesh (more open than closed) to avoid unwanted reflections.

In Part 2, we'll assemble the enclosure, sand and paint the surface, add the crossover and drivers, and then kick back and listen to the results.

SUPPLIERS

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This distinguished author's research on pipe configuration and stuffing material in transmission lines was the topic of a recent paper at AES.

Part 1

Transmission Lines Updated

By G. L. Augspurger

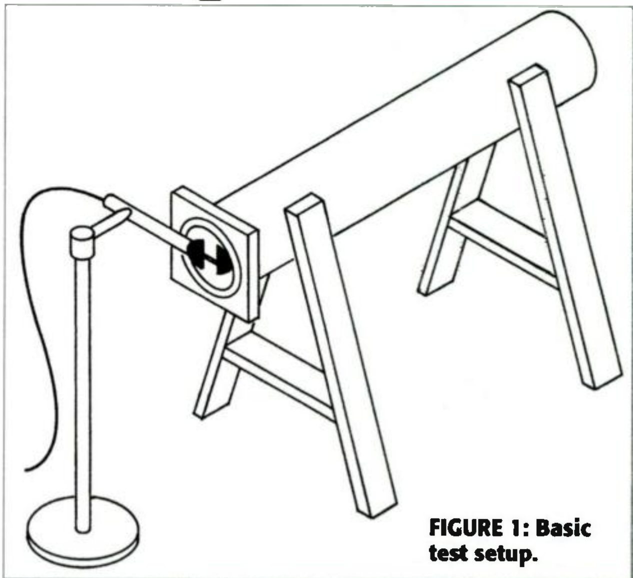

FIGURE 1: Basic test setup.

Every now and then I receive inquiries from amateur loudspeaker builders who seek reliable guidelines for transmission-line design. Although any kind of waveguide can legitimately be called a transmission line, most experimenters are interested in loudspeakers coupled to damped, nonresonant pipes. If everything works out just right, such a system can be dramatically neutral in quality in contrast to a comparable vented box or even a stuffed closed box.

About a year ago I began to compile a brief transmission-line bibliography. But after going through my own library and checking various technical journals, it became apparent that most existing literature consists of strongly voiced opinions. Actual test results are rare and often contradictory.

TESTING PIPES

So I decided to build and test a few damped pipes with different loudspeakers and stuffing materials. This seemingly simple exercise gradually grew into a full-blown research project, the goals of which were to develop a computer analog capable of modeling transmission-line systems, to validate the model by testing a variety of designs, and to develop basic performance relationships similar to the Thiele/Small analysis of vented boxes. I presented my findings at the 107th convention of the Audio Engineering Society in September 1999.

For the readers of *Speaker Builder*, however, I wish to go more deeply into the practical aspects of the study and to elaborate upon two areas I only touched on in the AES paper. First, that the behavior of stuffing materials is not what we have been led to believe, and second, that the effects of pipe geometry (not just length) are both unexpected and important.

The familiar symbols I use (*Table 1*) are mostly the same as those used for vented-box analysis. I have added f_P as a shortcut label based on the physical length of the air path, such as "a 100Hz pipe." The pipe's actual fundamental resonance f_0 is affected by a number of additional factors, including end correction, pipe geometry, and stuffing material.

TEST METHODS

The simplest transmission line is a straight pipe with a loudspeaker on one end. I used 3″-diameter fiber tubes to make pipes 2′, 3′, and 5′ long. I also made a 6′ pipe from 4″-diameter PVC tubing and built several pipes with rectangular cross sections.

Figure 1 shows my basic test setup. I set the test pipe horizontally on a trestle, about 40″ above the floor, and connected a calibrated Bruel & Kjaer 4134 microphone to my TEF20 analyzer. I ran sweeps from 20Hz–1kHz with a frequency resolution of 10Hz, giving accurate readings down to about 25Hz, and also ran impedance curves using the voltage-divider method. The TEF system stores all measurements as sets of complex data points, preserving both amplitude and phase.

I made frequency-response tests using nearfield microphone placement. This technique[1] allows you to measure loudspeaker and pipe outputs separately, but there is a certain amount of crosstalk. Most of the unwanted sound travels directly through air, some comes from scattered room reflections, and some is transmitted as vibrations in the pipe walls.

By blocking the end of the pipe, I was able to measure leakage from the loudspeaker at the other end. Crosstalk in the 2′ pipe was about –25dB. It was down more than 30dB in the 5′ and 6′ pipes. If

TABLE 1
SYMBOLS USED

f_3	–3dB corner frequency of low-frequency rolloff
f_P	nominal quarter-wave pipe resonance frequency
f_0	actual pipe fundamental-resonance frequency
f_S	speaker resonance frequency
f_L	frequency of lower impedance peak
f_H	frequency of first upper impedance peak
Q_{TS}	total Q of speaker
V_{AS}	volume of air having compliance equivalent to speaker cone suspension
V_P	internal volume of pipe, including coupling chamber
V_C	internal volume of coupling chamber

pipe output is 20dB below cone output, then its contribution to combined system output is less than 1dB, so even in short pipes you can disregard the effects of crosstalk.

Although I was not aware of it at the time, my test procedures were almost the same as those used by Letts in 1975.[2] To the extent that measurements overlap, our results agree closely.

With accurate measurements of speaker output and pipe output, total system response is then equivalent to the complex sum of the two, and does not need to be measured separately. However, when a microphone is located very close to a small sound source, a movement of only 1 or 2mm can shift the level of measured response by more than 1dB. Such an error in relative level has little effect on combined response, but it corrupts damping calculations and subsequent computer modeling.

MINIMIZING ERRORS

To minimize such errors, I first made sure that cone areas closely matched pipe areas so that no scaling was needed. Then, for each measurement I carefully aligned the microphone with the edge of the pipe or the edge of the loudspeaker frame. Finally, I verified that cone and pipe data could indeed be summed by also making several system-response measurements with the microphone equidistant from speaker and pipe, at one apex of an equilateral triangle.

So far, so good, but nothing ever goes exactly according to plan. Since damped transmission lines are lossy systems, I naively assumed that small air leaks would not be a problem. Well, a tiny hole to bring the wire out isn't a problem, but a speaker-mounting panel that doesn't seat properly or a joint in the pipe that isn't caulked can dramatically alter system response. Curiously, leaks seem to affect stuffed pipes more than empty ones.

Then I ran into a really sneaky effect. Small speakers typically have relatively large magnets. If such a speaker is mounted on a pipe or a thick baffle board, its backwave must travel through a short, constricted passage between the cutout and the magnet. At low frequencies, the air in the passage effectively adds mass to the cone. With my little test speaker mounted on a 3″-diameter pipe, f_S dropped from 175Hz to 135Hz, and Q_{TS} increased from 0.54 to 0.65.

Another gremlin involved defective test leads. Commercial molded test leads often have crimped connections

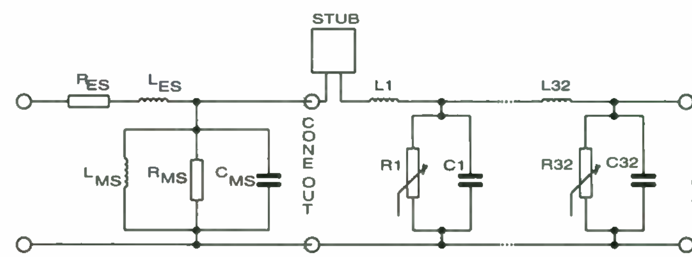

FIGURE 2: Transmission-line analog circuit.

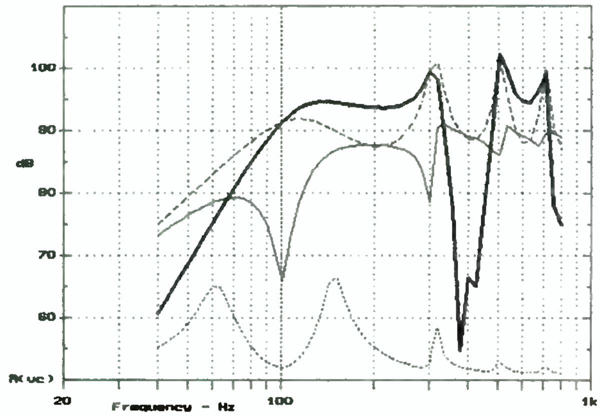

FIGURE 3: Response of loudspeaker on undamped straight pipe. Impedance (bottom), cone output, pipe output, and system response (bold).

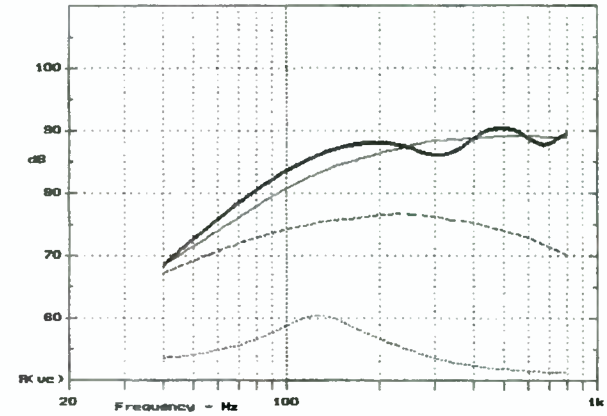

FIGURE 4B: Response of loudspeaker on straight pipe with moderate damping. Impedance, cone output, pipe output, and system response (bold).

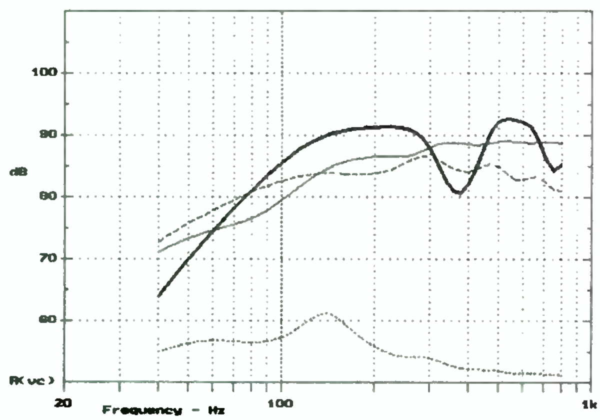

FIGURE 4A: Response of loudspeaker on straight pipe with light damping. Impedance, cone output, pipe output, and system response (bold).

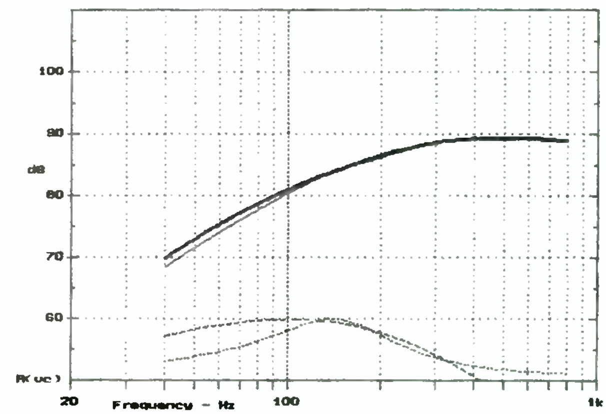

FIGURE 4C: Response of loudspeaker on straight pipe with heavy damping. Impedance, cone output, pipe output, and system response (bold).

under that nice vinyl jacket. Eventually corrosion sets in, and you now have a few diodes and a few ohms of series resistance as part of your test hookup. If the patch cord connects a 50Ω generator to a 5kΩ input, it works just fine, but if it connects a power amplifier to a 4Ω loudspeaker, the measurements are worthless.

COMPUTER SIMULATIONS

One goal of this project was to develop a computer analog to predict the behavior of various kinds of damped pipes driven by various speakers. Undamped pipes and horns are well understood. Relatively simple methods for modeling arbitrary horn shapes have also been described.[3,4]

I elected to work up a computer version of Locanthi's horn analog[5] and modify it for transmission-line modeling (*Fig. 2*). This circuit makes it easy to investigate arbitrary pipe shapes, and you can include damping as any combination of parallel and series resistance. Moreover, there is a certain elegance in using an electrical transmission line to model an acoustical transmission line. Those interested in a more detailed explanation of the computer model can obtain a preprint of my AES paper.[6]

As with other transmission-line models, the hangup is the stuffing. But at the start of this study, the computer program was required only to mimic known performance with one loudspeaker and then to calculate what would happen when using a different loudspeaker. In this regard, its predictions have proven to be remarkably accurate. Most of the gremlins described in the previous section were discovered because test results did not match computer curves.

After I had accumulated several dozen sets of test results, I was able to derive empirical models for different kinds and densities of damping materials and include them in the computer analog. I am still tinkering with these, but results agree closely with measured performance for a variety of pipe sizes and shapes.

LOUDSPEAKER AND PIPE BEHAVIOR

What happens when you put a loudspeaker on one end of a pipe and then gradually add stuffing? *Figures 3* and *4* show a typical example of what I actually measured. These are computer plots, but they are derived from measurements on a 3′ pipe. To make the curves easier to read, the physical length of the pipe is scaled down so that its quarter-wave resonance is exactly 100Hz.

According to some transmission-line theorists, the loudspeaker's cone resonance should match pipe resonance. The speaker I used for this example has a cone resonance of 100Hz. Q_{TS} is 0.46 and V_{AS} is 0.11ft³.

What about speaker diameter and pipe diameter? Thiele/Small analysis should have taught us that cone diameter is not directly related to anything.

The precept is just as true for pipes as it is for boxes. Instead of the familiar V_{AS}/V_B, I will use the ratio of pipe volume V_P to V_{AS}. In this example, pipe volume is about $0.22ft^3$, so V_P/V_{AS} equals 2.

An undamped cylinder closed at one end resonates at odd multiples of its fundamental frequency. That the speaker cone is heavily loaded at these frequencies, just as in a vented box, is clearly shown in *Fig. 3*. The light solid line represents cone output, the dashed line is pipe output, and the heavy solid line is combined system response.

The cone is acoustically clamped at 100, 300, and 500Hz. Pipe output peaks slightly above these frequencies. The two are alternately in and out of phase at 200, 400, and 600Hz. Below 100Hz, pipe output is effectively out of phase with cone output, and combined response rolls off at 24dB per octave.

VOICE-COIL IMPEDANCE

The dotted line at the bottom of *Fig. 3* shows voice-coil impedance relative to DC resistance. 20dB indicates a 10:1 change, 6dB indicates a 2:1 change and so on. Why is impedance plotted logarithmically? Because that's the way it is supposed to be plotted. This way, impedance curves of different speakers can be compared directly, no matter what their individual voice-coil resistances. If you plot "real" numbers on a linear scale, you can only compare tests run with that particular speaker.

The impedance curve of this undamped pipe is obviously similar to that of a matched, vented box. A minimum at 100Hz is flanked by two peaks: f_L at about 64Hz, and f_H at 150Hz. Additional peaks at higher frequencies will disappear as you add damping.

Before looking at what stuffing actually does, consider what it is supposed to do. Benjamin Olney, the inventor of what we have come to call the transmission line, definitely expected pipe output to reinforce cone output at low frequencies.[7] He was intrigued by the fact that an undamped pipe acts as a pure delay line at its halfwave frequency. (Note that cone and pipe outputs are equal at 200Hz, and their combined output is 6dB greater.) Therefore, Olney argued that damping should be minimal in the halfwave region, but soak up unwanted upper resonances.

For this to happen, you need some kind of magic lowpass stuffing that goes from negligible damping to more than 18dB of attenuation in less than an octave. Unfortunately, real-world materials require several octaves to make the transition. Even a wisp of damping material largely squashes the pipe's fundamental resonance. It is true that bends or folds will supply additional attenuation, but only at relatively high frequencies.

BLANKET EFFECT

Figure 4a shows what happens when the test pipe is loosely filled with polyester blanket at a density of 0.5 lb/ft^3. This is a typical packing density for transmission lines, but in a short pipe it is less than optimal. Cone and pipe outputs still show the effects of resonances, and pipe attenuation above 200Hz is minimal. However, the 100Hz fundamental resonance has all but disappeared. The lower impedance peak no longer exists, and f_H has become a gentle bump. Note that cone and pipe outputs are additive down to about 85Hz, and that the low-frequency slope is now 18dB per octave.

When you increase stuffing density to 1.5 lb/ft^3, the result is a well-behaved transmission line. *Figure 4b* indicates nonresonant response with a 2dB sag at 300Hz and gentle rolloff below 200Hz.

Below 100Hz the slope is about 12dB per octave. Although pipe output is well below cone output, the two are additive over a range of more than two octaves. The only identifiable "resonance" in the impedance curve is f_H.

Additional stuffing (more than 2 lb/ft^3) gives the performance of *Fig. 4c*. This is a purist's transmission line, in which pipe radiation is negligible. Going beyond this point is self-defeating, since additional damping simply reduces cone movement at low frequencies.

These three figures are the foundation for understanding transmission-line performance. They are typical of long pipes and short pipes, big speakers and little speakers. Although appropriate stuffing densities vary, almost any fibrous material will exhibit the behavior shown. You can use these curves to develop some initial observations about transmission-line performance:

1. The system response of 4b would be flatter if the speaker's sensitivity above 300Hz were decreased by 2dB. Also, since the system behaves somewhat like a closed box, it seems reasonable that f_S should be lower than f_P. Finally, to reduce passband ripple, you might increase damping just a bit. After experimenting with adjustments of individual parameters, I came up with the response of *Fig. 5*. Now, f_3 matches f_P, and f_S is an octave lower.
2. In *Fig. 5*, pipe output and cone output add constructively down to 40Hz or so. It follows that it should be possible to set f_3 as much as an octave below f_P by adjusting loudspeaker parameters with no change in stuffing density. *Figure 6* shows how a nominal 109Hz pipe can be "tuned" to 65Hz. Efficiency goes down as well, just as you would expect from analogous closed box alignments. For a given f_3, there is some advantage in choosing a shorter, fatter pipe, because passband ripple shows up at higher frequencies where it is easier to control.
3. For a different cutoff frequency derived from either of these curves, you must scale pipe length and f_S accordingly. The relationships described previously still stand. In this case, what does not scale is stuffing density. Since the air path of a 50Hz pipe is twice as long as that of a 100Hz pipe, I expected a given density to yield equivalent results. Not so. The longer pipe requires lighter stuffing, and the relationship is not a simple one.

SIMPLE TRANSMISSION-LINE ALIGNMENTS

Table 2 summarizes the loudspeaker/pipe relationships of *Figs. 5* and *6*, which you can use as multipurpose alignments. To achieve the classic, slightly bass-shy alignment of *Fig. 4b*, simply reduce Q_{TS} by half, thus raising midrange sensitivity by 3dB. To simulate an infinite pipe, increase stuffing density by about 50% and assume that f_3 will go up about 25%.

Well and good, but what is the stuffing density for these alignments? For a 100Hz pipe, you can realize the performance shown with 1.75 lb polyester blanket or Acousta-Stuf. For a 50Hz pipe, the corresponding density is 1.0 lb/ft^3. Other materials require different densities. There is no direct correlation between pipe length and stuffing density.

These examples are only two of hundreds of possible alignments, but they

TABLE 2
LOUDSPEAKER/PIPE RELATIONSHIPS

FIGURE	F_3/F_P	F_S/F_P	V_{AS}/V_P	Q_{TS}
5	1.0	0.50	2.0	0.46
6	0.6	0.33	1.0	0.36

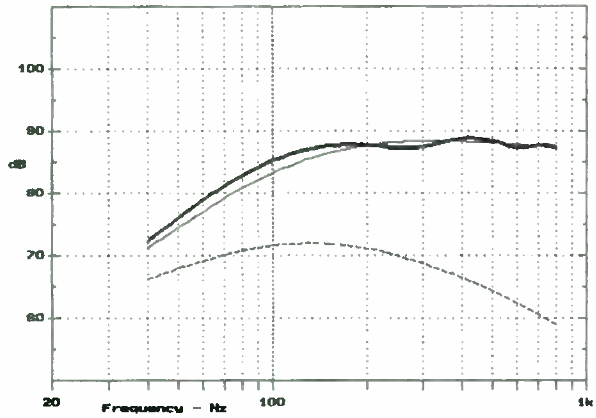

FIGURE 5: Response of straight pipe with improved alignment. Cone output, pipe output, and system response (bold).

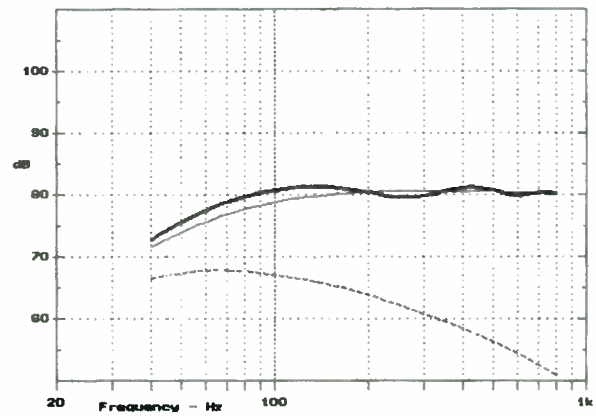

FIGURE 6: Response of straight pipe with alternate alignment. Cone output, pipe output, and system response (bold).

are typical of what you can do with a basic transmission line. Efficiency is 2–5dB less than a comparable closed box, no matter which low-frequency rolloff you prefer. Fortunately, as I will show in Part 3, it is possible to improve the situation by building something other than a simple straight pipe.

DIRECTIONAL EFFECTS

To conclude Part 1, I wish to point out a peculiarity of transmission-line response measurements. I stated that the complex sum of cone output and pipe output yields system response. This is understood to be on-axis system response. That is, the microphone is equidistant from the loudspeaker and the mouth of the pipe. If the pipe is folded so the two sound sources are close together, then it is also equivalent to acoustic power response.

But if pipe output is appreciable and the two sources are even a fraction of a wavelength apart (an inevitable by-product of a straight pipe), then some interesting directional effects are generated, and power response no longer tracks on-axis response. In a typical listening room, the perceived low-frequency response is dominated by reflected sound energy. Therefore, a folded transmission line may indeed sound different than an otherwise identical straight pipe, because its power response and directivity are different. To the best of my knowledge, Geoffrey Letts is the only researcher who has commented on this.[2]

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Named for the diminutive Menehune of Hawaiian legend, this small speaker system works hard to deliver maximum quality sound. Part 2 measures system response.

Part 2

The Menehune MX-1

A Compact Satellite/Subwoofer System

By Jim Moriyasu

PHOTO 1: Scan-Speak D2905/9300 Morel MW142 and Vifa M22WR ready for SPL testing.

TWEETER CROSSOVER DESIGN

Since the Scan-Speak 2905/9300 has a resonance at 569Hz, I deemed 2kHz[8] as a safe point for a fourth-order Linkwitz-Riley (L-R) crossover. Also, the Morel MW142 cone has a breakup resonance near 4kHz, so it seemed a good idea to roll off the driver as soon as possible. I detected this problem by impulse testing with LAUD and transforming the impulse into a cumulative spectral decay or waterfall plot (*Fig. 21*).

Also of importance is the driver's off-axis response, since this affects the loudspeaker system's power response.[9] Since the 30°–45° measurements of the MW142 show that it starts to roll off in the 2kHz–3kHz region, a lower tweeter crossover helps maintain a broad loudspeaker-system power response. The trade-off, of course, is lower power handling for the tweeter. I regularly use the fourth-order Linkwitz-Riley crossover because it has a high attenuation rate, a low Q of .49, and low sensitivity to the time delay between drivers.[10]

Setting the system's sensitivity is the next step, since the tweeter and midbass crossover will be "padded" down with resistors. A quick look at the woofer's response at 100Hz suggests a system sensitivity of 87dB (*Fig. 22*).

An analysis with LEAP's crossover-design utility showed that because of the 63µs delay between the tweeter and midbass, a 1dB dip develops at the

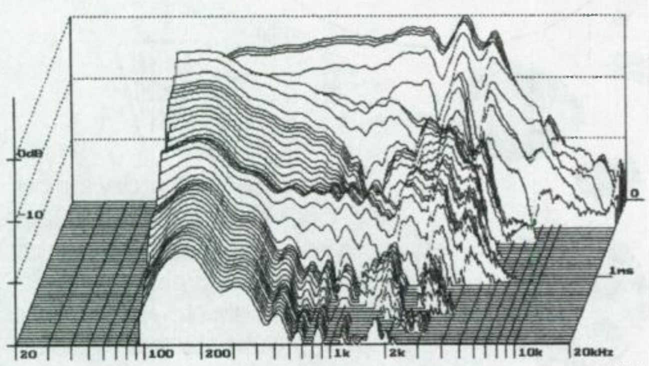


FIGURE 21: Cumulative spectral decay of Morel MW142 in .19ft³ enclosure measured at 1m.

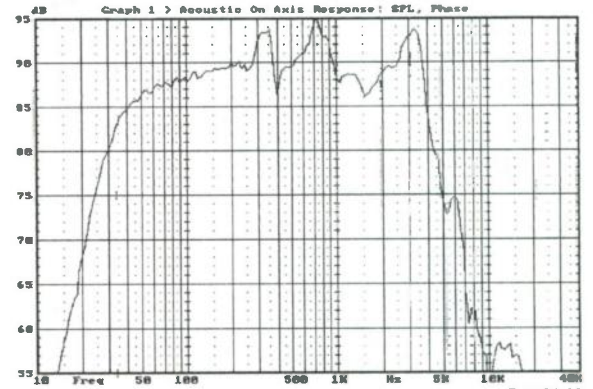


FIGURE 22: Groundplane SPL measurement of Vifa M22WR in Woodstyle WS803 enclosure without crossovers.

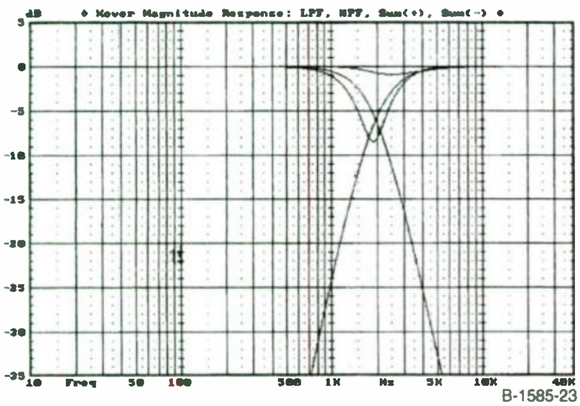


FIGURE 23: Simulated crossover responses of 2.0kHz fourth-order Linkwitz-Riley crossover with 63µs delay to midbass.

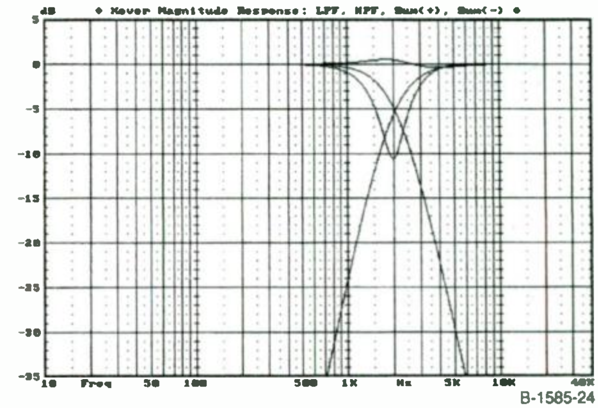


FIGURE 24: Simulated crossover responses of 2.2kHz fourth-order low-pass with 2.0kHz high-pass crossover with 63µs delay to midbass.

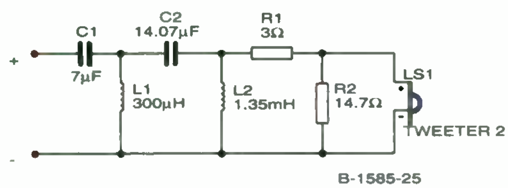


FIGURE 25: Theoretical fourth-order Linkwitz-Riley crossover with L-pad.

crossover point if both the woofer and tweeter have a 2000Hz crossover (*Fig. 23*). If the woofer and tweeter were staggered or the enclosure were tilted to equalize the path length to the driver and zero out the time delay, this problem wouldn't exist. However, by "overlapping" crossover frequencies, you can lessen the dip with the trade-off of having a slight peak. By raising the woofer crossover point to 2.2kHz and leaving the tweeter at 2kHz, a 0.6dB increase in the response is followed by a 0.5dB decrease (*Fig. 24*).

L-R CROSSOVER NETWORK

Using the crossover-utility theoretical values, I set up a fourth-order L-R crossover network for the tweeter with a crossover point at 2kHz for LEAP to optimize (*Fig. 25*). *Figure 26* shows LEAP's passive-network optimization screen, with the theoretical crossover "hooked up" to the measured tweeter response before optimization.

This shows that using theoretical values for the crossover does not result in the tweeter's response tracking the fourth-order L-R target very well. The lower line is the impedance curve of the tweeter with the crossover. The target response is set at 87dB with a crossover at 2kHz and a fourth-order L-R slope. The crossover components are shown in the upper-left corner.

Because of this poor tracking response, I then had LEAP optimize the values for the two capacitors, two inductors, and the series resistor; I left the parallel resistor alone so that the circuit impedance would stay within 5 to 10Ω. I set the optimization cursors so that only the tweeter's response from 1.262kHz to 12.962kHz would be optimized. *Figure 27* shows the result of the optimization.

Now the tweeter's response tracks the target quite closely. However, L2 is now 11.181mH, which is so large that you can probably remove it from the circuit. This makes sense; since the tweeter has its own 12dB/octave rolloff around 1kHz, the crossover doesn't need to do as much work.

I have usually found that if a driver has a second-order acoustic rolloff, all you need to generate a combined fourth-order acoustic response is a second-order electrical crossover. For example, in an earlier design,[11] I easily accomplished a fourth-order crossover with a second-order electrical circuit at 1.5kHz. In this design, however, the driver's roll-off starts a little lower than the crossover point, so this wasn't possible.

So I had LEAP optimize a second crossover to produce the results in *Fig.*

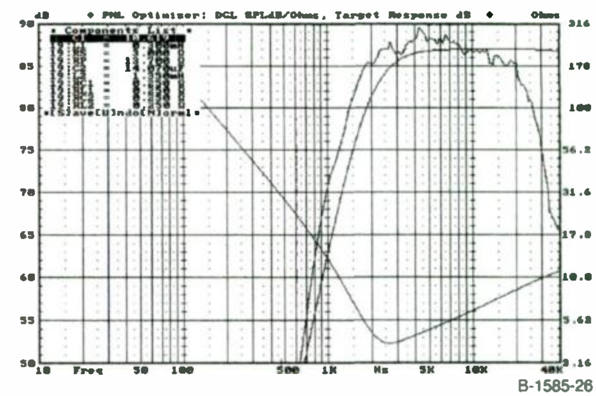


FIGURE 26: Theoretical tweeter-crossover response compared to fourth-order L-R target.

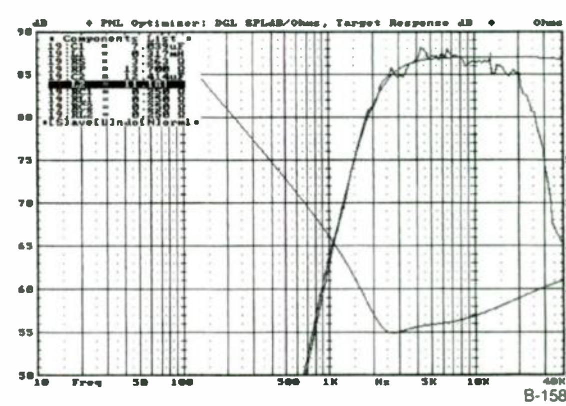


FIGURE 27: Optimized tweeter-crossover response compared to fourth-order L-R target.

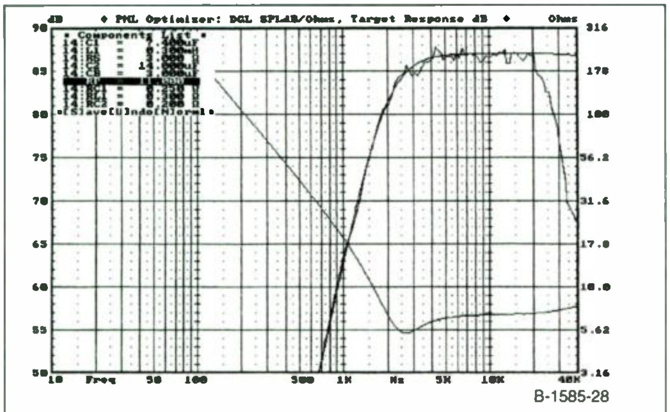


FIGURE 28: Final optimized tweeter-crossover response compared to fourth-order L-R target.

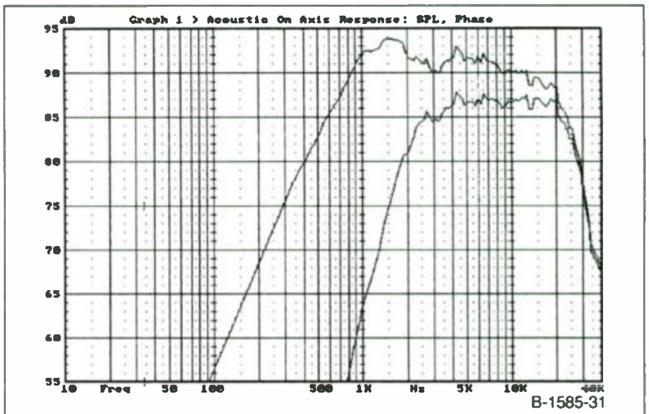


FIGURE 31: Tweeter SPL response with and without the optimized crossover of *Fig. 29*.

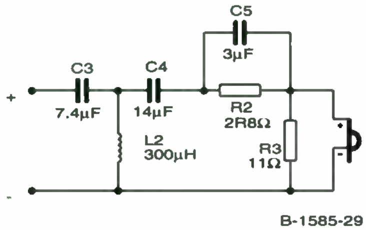


FIGURE 29: Final tweeter-crossover circuit.

28. I removed L2 from the circuit, and since the tweeter's response above 10kHz is drooping a little, I paralleled a "boost" capacitor, CB, with the series resistor. The capacitor doesn't really provide any boost; it actually shorts the resistor above 10kHz to reduce the resistor's effect, and so only seems to provide "boost." The optimized network now tracks the fourth-order target with an acceptable level of error.

FINAL TWEETER CROSSOVER

Since the optimization produces values to the nearest .001, I rounded them to the nearest whole value or actual value. For example, if the optimization produces a value such as 6.915μF and Solen makes a 6.8μF capacitor, I will change the value to 6.8μF as long as it doesn't cause the response to deviate more than 0.5dB from the optimized response. *Figure 29* shows the final tweeter crossover.

While it seems relatively easy to make LEAP optimize a crossover, it doesn't mean that you should accept whatever LEAP spits out. A listening test is the final arbiter. However, it makes good engineering sense to pay attention to the crossover's impedance curve and the Q of the crossover's transfer function.[12] As *Fig. 28* shows, the impedance of the tweeter and crossover is between 5 and 10Ω. Below 2kHz, the impedance rises as the crossover takes effect.

Figure 30 shows the crossover's transfer function; it has a modest "knee," which implies a Q of more than .707 but probably less than 1.0. I think these two considerations are important because the loudspeaker system's impedance curve should not present a difficult load to an amplifier.

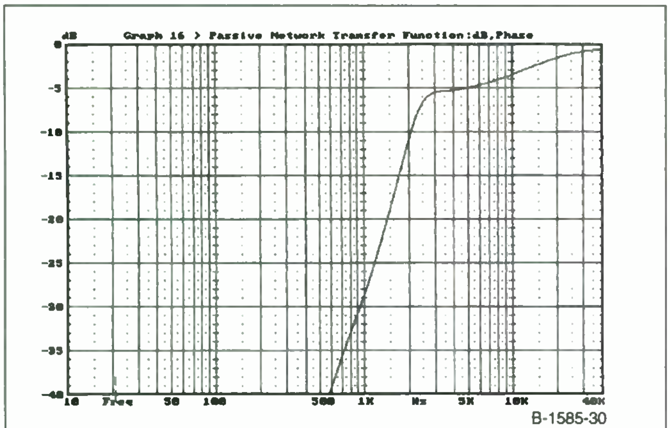


FIGURE 30: Final optimized tweeter-crossover transfer function.

Figure 31 shows the tweeter with and without the crossover network shown in *Fig. 29*. As you can see, the unfiltered tweeter response starts to roll off at 1kHz and actually has a falling response above this level. Evident at 3kHz is a 2 to 3dB notch caused by cabinet-edge diffraction. Otherwise, its response is quite smooth out to 20kHz. With the filter in place, the response is plus or minus 1.40dB compared to the target.

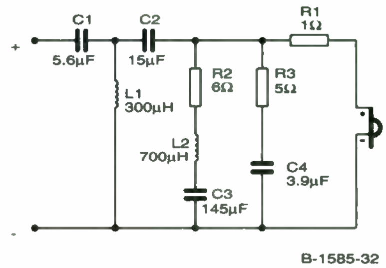


FIGURE 32: Optional tweeter crossover with RLC series notch and RC Zobel networks.

With regard to power handling, it is important to note that the tweeter's SPL response is down 24dB at 1kHz and 48dB at 500Hz. Since the system is designed to play to 101dB, this means that at 1kHz the tweeter will be at 77dB and at 500Hz at 53dB. This suggests that it shouldn't have too much of a problem with power handling, since it takes only 1W to generate the 90dB to 93dB unfiltered response in *Fig. 31*.

As an additional exercise, I also designed and optimized a crossover (*Fig. 32*) that has an RLC conjugate, or series notch filter,[13] to damp the tweeter's resonance and a Zobel or conjugate network to flatten its impedance curve. This crossover's transfer function has a slightly lower Q and a flatter impedance curve than the final crossover, but I didn't choose it because of the complexity of the additional parts required. At a future date, I intend to build this crossover and run listening tests.

MIDBASS PASSIVE CROSSOVER DESIGN

The measured SPL response of the MW142 in the enclosure is shown in *Fig. 33*. While the response is quite smooth

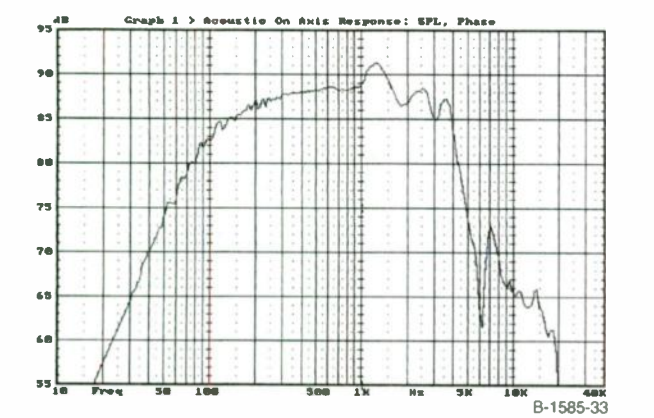


FIGURE 33: Measured SPL response of MW142 in enclosure.

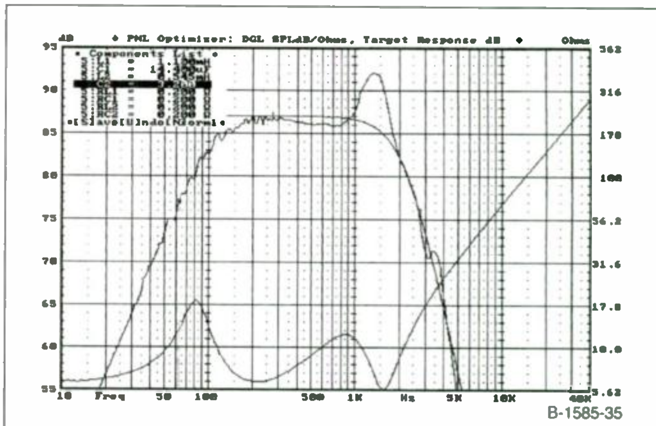


FIGURE 35: Theoretical midbass crossover response compared to fourth-order L-R target.

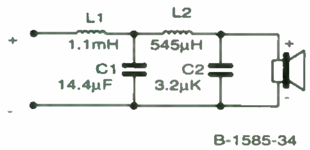


FIGURE 34: Theoretical trial fourth-order L-R low-pass crossover circuit.

below 1kHz, there are diffraction peaks at about 1.25kHz and 2.5kHz. The stiff cone has a sharp rolloff above 4kHz.

To begin crossover optimization, I set up a "textbook" fourth-order L-R for LEAP to optimize (*Fig. 34*). This crossover is shown in *Fig. 35* "hooked up" to the midbass response before optimization. Obviously a problem exists with the network and Morel's impedance curve, since there is a severe dip in the impedance at 1.6kHz that results in an increase in the peak at 1.25kHz.

Well, back to the drawing board, or at least to LEAP's conjugate network-design utility. After some trial and error, a Zobel composed of a 7Ω resistor and a 23μF capacitor produced the flattened impedance curve shown in *Fig. 36*. With the Zobel attached, the response is much better, as seen (before optimization) in *Fig. 37*. The impedance curve still shows a slight dip at 2kHz, but it's probably okay to go ahead and have LEAP optimize the network, except for the Zobel components. The results look pretty good (*Fig. 38*). C2 is now .606μF, so you can eliminate it. L2 is .368mH and might

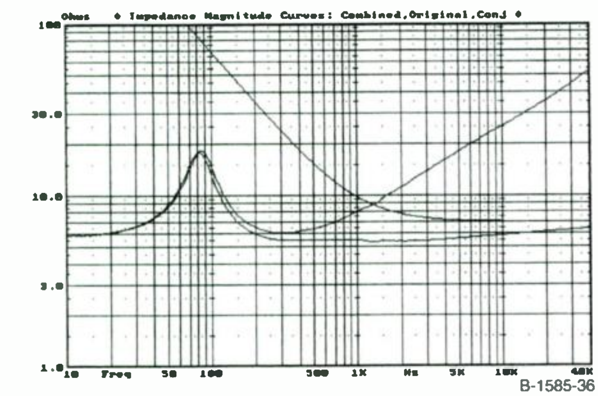


FIGURE 36: Simulated midbass impedance curves with and without RC Zobel network.

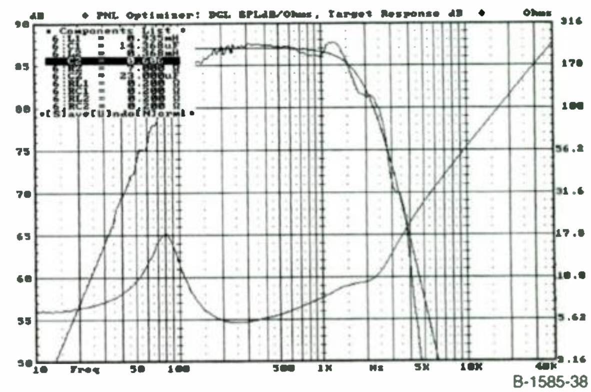


FIGURE 38: Optimized midbass crossover with RC Zobel response compared to fourth-order L-R target.

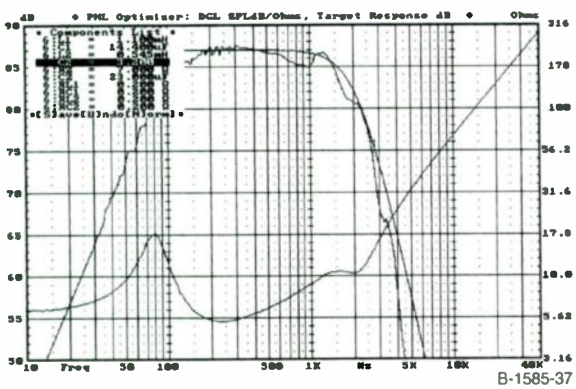


FIGURE 37: Theoretical midbass crossover with RC Zobel response compared to fourth-order L-R target.

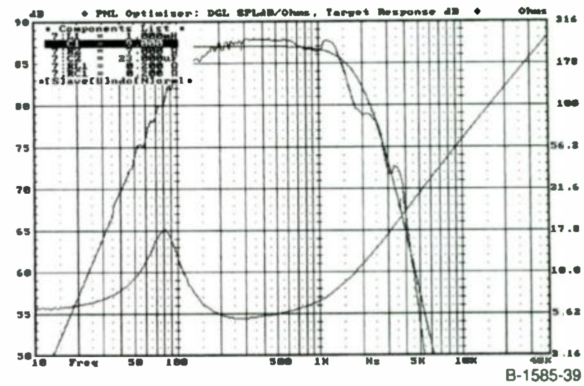


FIGURE 39: Optimized second-order network response compared to fourth-order target.

also be a target for removal.

So I reduced the crossover to a second-order network and ended up with the optimized results shown in *Fig. 39,* along with the final crossover in *Fig. 40.* The passive-network transfer function (*Fig. 41*) suggests the crossover has a low Q. Visible between 100 and 300Hz is a small 0.5dB rise that is caused by interaction with the series inductor in the crossover. Also evident before 100Hz is a 0.4dB shelf caused by the inductor's resistance. *Figure 42* shows the Morel MW142 with and without the network.

SYSTEM CROSSOVER

As a system, the tweeter and midbass responses cross over around 2kHz, as shown in *Fig. 43*. The midbass response is a little irregular, so it makes it difficult to tell. *Figure 44* shows how the two responses combine with the in-phase and reverse connection. The 18dB-deep notch at 2kHz shows that the crossover is very much out of phase when connected with the reverse connection. This suggests that the crossover is properly designed and very much in-phase for the normal or in-phase connection because it operates so very poorly when it is connected reverse-phase.[14]

Figure 45 shows the system impedance, which should be an easy load for a power amplifier.

Using LEAP's conjugate utility, as an additional exercise I designed a series RLC network to flatten the peak at 1.25kHz. It was effective, but did require a 3mH coil. I could have used a small ferrite coil with high resistance, but since I thought the peak was due to diffraction and not to a cone resonance, and that it would smooth out off-axis, I didn't think that damping it was necessary. As it turned out, the Zobel, which is simpler to implement, works just fine.

As I did for the tweeter, I also designed and optimized a crossover (*Fig. 46*) that has an RLC conjugate, or series notch filter, to damp the midbass's resonance at 80Hz. This crossover's transfer function has a slightly lower Q than the existing one, as well as a very flat impedance curve, since the 80Hz impedance peak is flattened by the series notch filter. I didn't choose it because of the

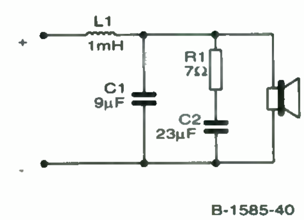


FIGURE 40: Final midbass crossover circuit.

complexity and cost of the additional parts required. At a later date I intend to build and run listening tests between the two crossovers. I suspect it may provide marginal benefits, even if the satellite is played at very high levels, since the active crossover takes place at 175Hz, meaning that the midbass's response is down more than 24dB at its system resonance of 80Hz.

MIDBASS ACTIVE CROSSOVER DESIGN

The design of the active crossover requires less work than with passive networks, since you have less circuitry to play with, so to speak. The LEAP optimization routine allows you to use half-,

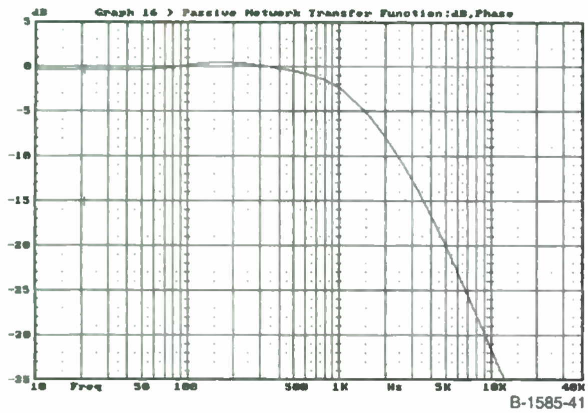


FIGURE 41: Final optimized midbass crossover transfer function.

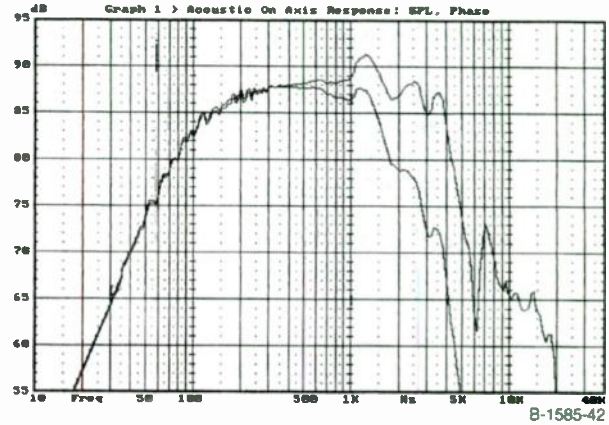


FIGURE 42: Simulated midbass SPL response with and without the optimized crossover of *Fig. 40*.

first-, and second-order high/low pass filters as well as a few other handy functions such as a time delay and shelving equalizer. The only parameters to optimize are the crossover frequency, filter Q, and output level. There are no Zobels, series notch filters, or "boost" capacitors, for instance.

Since I had no experience building active crossovers and power supplies from scratch, I needed an active crossover that I could customize. Fortunately, I was able to get in touch with Fred Janosky of Audio Arts, and he sent me his excellent crossover, the XVR-1.[15] You can configure it with first-, second-, or third-order filters, and it comes complete with a case and power supply.

It is somewhat limited for this project, however, in that it has two filter blocks for the low-frequency section and one for the high-frequency section. Since I intended to use one of the low-frequency filter blocks for a rumble filter, only one block would be available for a low-pass filter. That meant that the low-pass filter could only be a first-, second-, or third-order network, and I would have no way of realizing a fourth-order low-pass crossover.

Since the midbass has an acoustic second-order rolloff, combining it with a second-order electrical filter would result in a fourth-order response. The bottom line was that the crossover between the woofer and midbass would need to be asymmetrical.

Also, the only references at my disposal, Lancaster's *Active Filter Cookbook* and LEAP's *Application Manual*, dealt only with adjusting the Q of second-order networks. Thus a third-order low-pass choice was eliminated. So the active-crossover topology ended up being second-order low-pass for the woofer, and fourth-order high-pass for the midbass.

LEAP's crossover-design utility shows that because of the 112µs time delay between the drivers, a 175Hz second-order Butterworth low-pass woofer response coupled with a 175Hz fourth-order Butterworth high-pass midbass response would produce a 1dB hump at 150Hz and a 1.25dB dip at 250Hz for the in-phase connection. The reverse connection is worse, with a 3dB dip at 140Hz and a 2dB peak at 240Hz (*Fig. 47*).

However, as *Fig. 48* shows, lowering the woofer crossover point to 135Hz smooths the in-phase connection to ±0.5dB. The reverse connection ends up with a 7dB valley at 150Hz. I also tried other combinations of Linkwitz-Riley and Butterworth filters, but settled on the Butterworth second-order/fourth-order pair.

So I "hooked" up to the midbass a textbook second-order Butterworth high-pass active filter with a Q of .707 at 175Hz. *Figure 49* shows what it looks like before optimization. Also, bear in mind that this includes the passive low-passive network. The optimized results

FIGURE 43: Simulated individual midbass and tweeter SPL responses with crossovers.

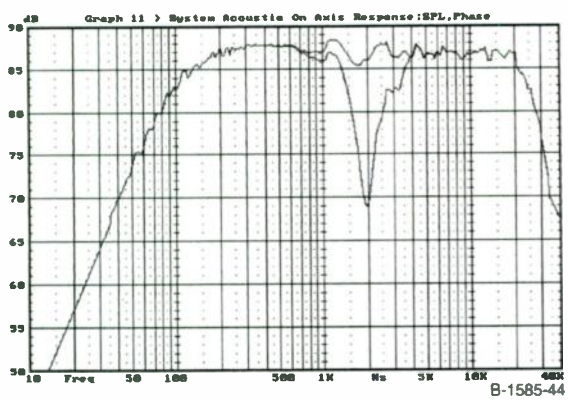


FIGURE 44: Simulated summed midbass and tweeter SPL responses with crossover, in-phase and reverse-phase.

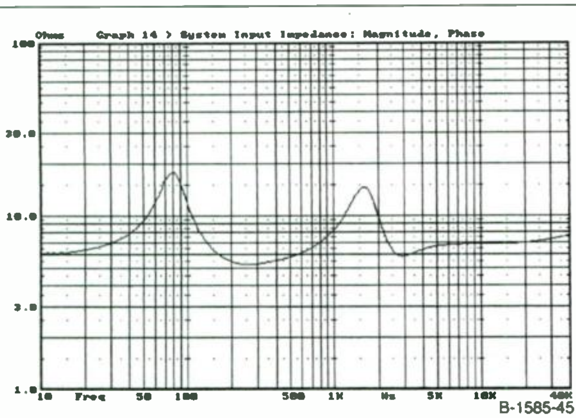
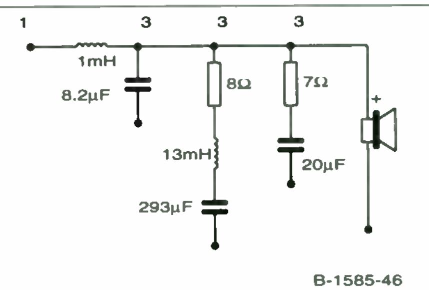


FIGURE 45: Simulated system impedance of combined midbass and tweeter crossovers.

FIGURE 46: Optional midbass crossover with RLC series notch and RC Zobel networks.



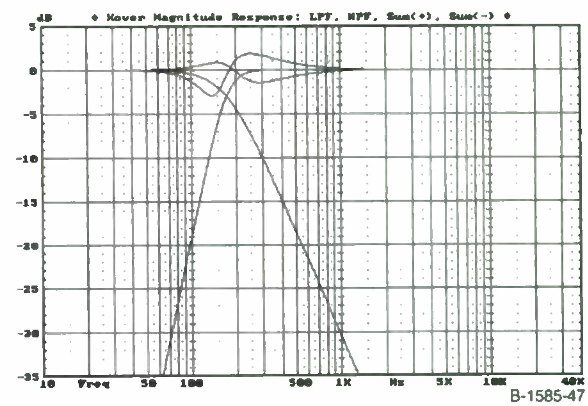


FIGURE 47: Simulated SPL responses of 175Hz second-order low-pass Butterworth crossover with 175Hz fourth-order high-pass crossover with 63µs delay to midbass and 187µs delay to woofer.

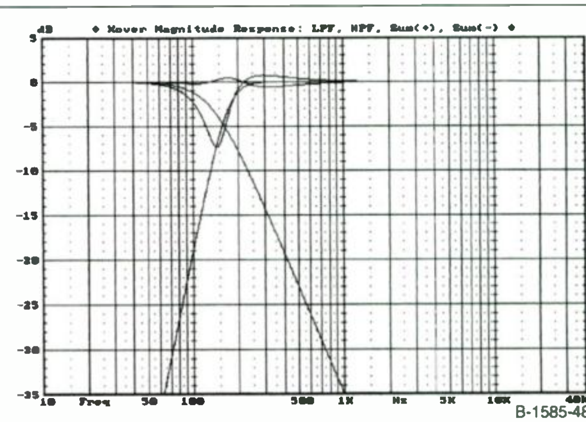


FIGURE 48: Simulated SPL responses of 135Hz second-order low-pass Butterworth crossover with 175Hz fourth-order high-pass crossover with 63µs delay to midbass and 187µs delay to woofer.

will vary quite a bit depending on where you place the cursors. In this case I had the software optimize the response between 128.63 Hz and 757.45Hz as seen in *Fig. 50*. If I had moved the cursor lower in frequency, it would have generated more error in the area between 150Hz and 300Hz. In this case the filter doesn't track the response very well below 125Hz, but this should not be a problem. So now you have a preliminary high-pass active crossover to the midbass

TABLE 1
PARTS LIST

2	Scan-Speak D2905/9300, 1″ tweeter, from Meniscus
2	Morel MW142, 5″ midbass, from Meniscus
2	Vifa M22WR, 8″ woofer, from Meniscus
2	Woodstyle WS803, .88ft^3 cabinet, clear finish, from Madisound
2	Woodstyle WS602, .189ft^3 cabinet, clear finish, from Madisound
4	GB cup, input panel, from Madisound
1	Sheet of 1″ open cell foam for damping, hardware store
1	Acousta-Stuf, 1 lb, Mahogany Sound
1	3″, black ABS plumbing pipe (usually 8′ length), hardware store
2	90°, long-sweep, elbow, 3″, ABS plumbing pipe, hardware store
24	#6 × ¾″ black screws, from Meniscus
12	#8 × 1″ black screws, from Meniscus
1	Roll of foam weather-stripping tape, from Meniscus
1	8′ of 16 gauge wire, red/black jacket, from Parts Express
CROSSOVER PARTS (FROM MENISCUS)	
2	L1, 1.0mH, 16 ga, .11Ω, 500W, Quantum super ferrite
2	C1, 9.0μF, 250V, 5%, Solen
2	R1, 7Ω, 15W, 5%, wirewound sand filled
2	C2, 22μF, 100V, 10%, nonpolar electrolytic
2	C3, 6.2μF, 250V, 5%, Solen
2	C3, 1.0μF, 250V, 5%, Solen
2	C3, 0.22μF, 250V, 5%, Solen
2	L2, .3mH, 16 ga, .23Ω, 500W, air-core
2	C4, 12.0μF, 250V, 5%, Solen
2	C4, 2.0μF, 250V, 5%, Solen
2	C5, 3.0μF, 250V, 5%, Solen
4	R2, 5.6Ω, 10W, 2%, Lynx
2	R3, 10Ω, 10W, 2%, Lynx
2	R3, 1Ω, 10W, 2%, Lynx

Note: C3, C4 and R2 are paralleled to produce the specified value

ELECTRONIC CROSSOVER

XVR–1, from Audio Arts

MEASUREMENT EQUIPMENT AND CAD SOFTWARE

Liberty Audiosuite, from Liberty Instruments
Loudspeaker Measurement System (LMS), from LinearX
Loudspeaker Enclosure Analysis Program (LEAP), from LinearX

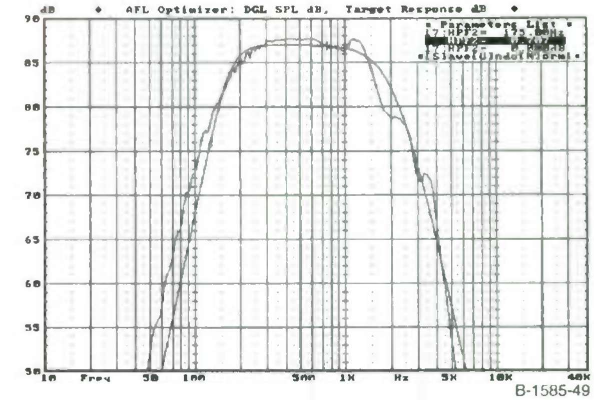


FIGURE 49: Simulated midbass SPL response with textbook second-order high-pass active filter at 175Hz and Q of 0.707.

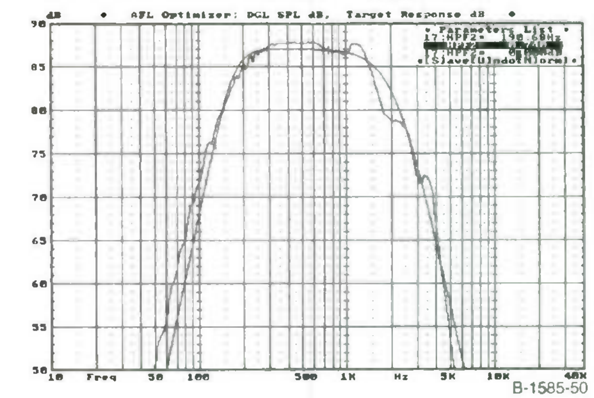


FIGURE 50: Simulated midbass SPL response with optimized second-order high-pass active filter at 175Hz and Q of 0.707.

with an f_3 at 190.68Hz and a Q of 0.740.

WOOFER ACTIVE-CROSSOVER DESIGN

The initial values of the woofer's active low-pass crossover are set at 135Hz with a Q of 0.707. With data from the simulations, I set the high-pass "rumble" filter to 32.5Hz, with a Q of 1.176. In *Fig. 51*, which is before optimization, it appears that the high- and low-pass filters overlap, resulting in a response that is 1.5dB too high. After optimization, the response now tracks the target with very little error. The filter values are an f_3 of 119.74Hz and Q of 0.610 for the active low-pass, and an f_3 of 32.91Hz and a Q of 1.042 for the active "rumble" section

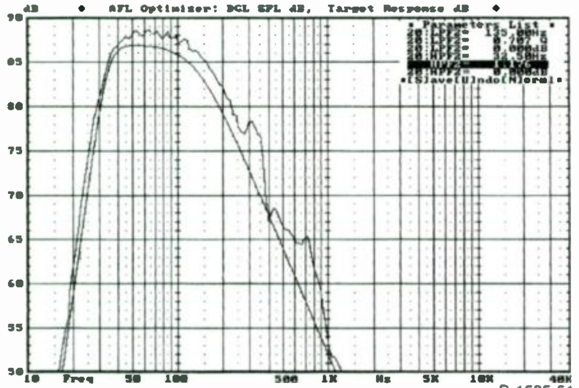

B-1585-51

FIGURE 51: Simulated woofer SPL response with "rumble" filter at 32.5Hz with Q of 1.176, and low-pass crossover at 135Hz with Q of 0.707.

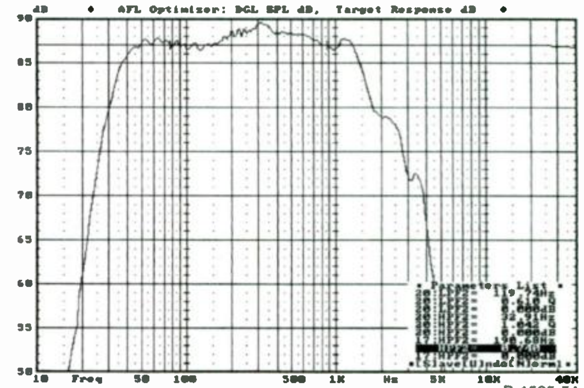

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FIGURE 54: Simulated woofer and midbass SPL response with optimized "rumble" filter, low-pass and high-pass active filters with woofer connected reverse-phase.

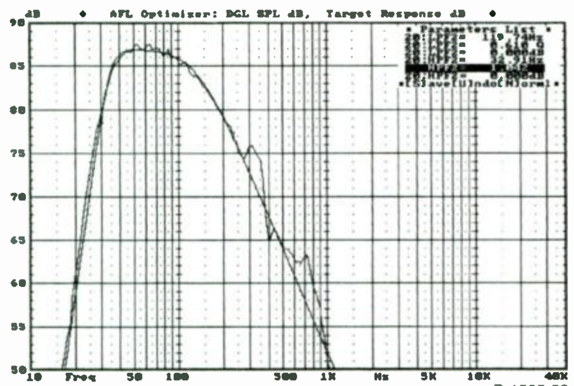
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FIGURE 52: Simulated woofer SPL response with optimized "rumble" filter at 32.91Hz with Q of 1.042, and low-pass crossover at 119.74Hz with Q of 0.610.

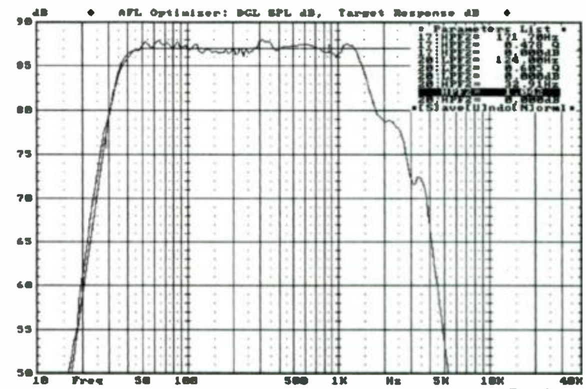
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FIGURE 55: Simulated woofer and midbass SPL response with optimized "rumble" filter, low-pass and high-pass active filters with woofer connected reverse-phase after additional optimization of low and high-pass sections.

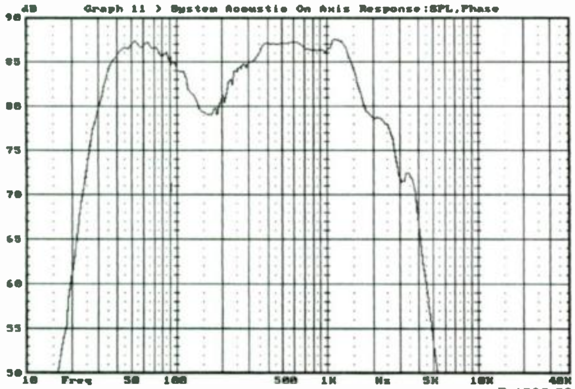
B-1585-53

FIGURE 53: Simulated woofer and midbass SPL response with optimized "rumble" filter, low-pass and high-pass active filters.

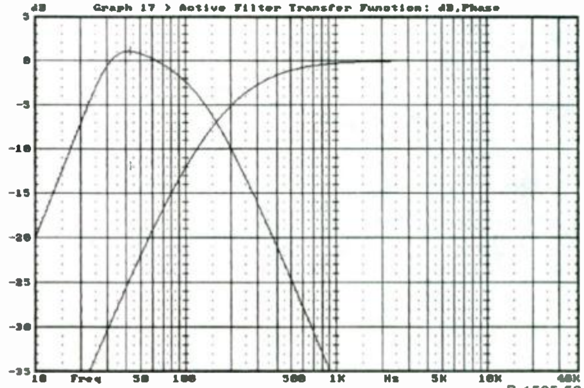
B-1585-56

FIGURE 56: Simulated transfer function for *Fig. 55*.

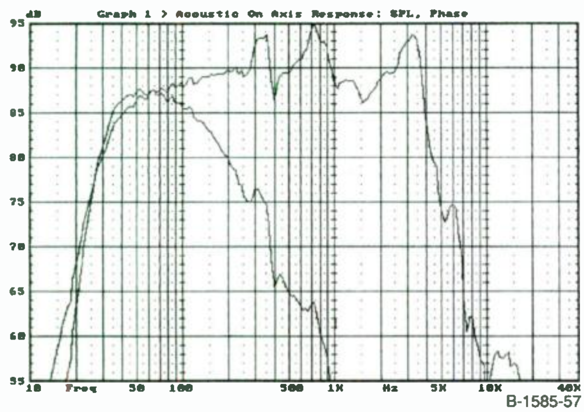

FIGURE 57: Simulated SPL response of woofer with and without active filters.

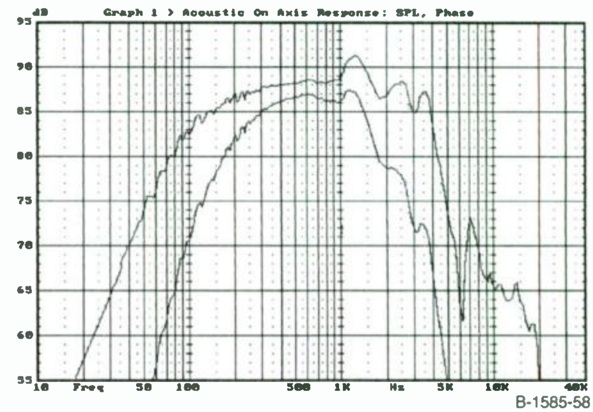

FIGURE 58: Simulated SPL response of midbass with and without active filters.

(*Fig. 52*).

How do the three active filters work as a system? Well, I almost always design crossovers with the drivers connected normally or in-phase, that is, with the driver positive to the positive input from the amplifier. The LEAP crossover utility indicated that an in-phase connection should not have an 8dB dip. However, I obviously forgot to consider the additional phase shift from the "rumble" filter, a problem that is shown in *Fig. 53*. I tried to solve this with the LEAP active-filter optimizer, but no amount of computer power can correct this problem.

However, reversing the woofer polarity (*Fig. 54*) works just fine. Following additional optimization (*Fig. 55*) you now have an active low-pass filter with an f_3 at 124Hz and a Q of 0.605, and an active high-pass filter with f_3 at 171.7Hz and a Q of 0.478. Between 100Hz and 200Hz, the response is nearly flat. The "rumble" filter remains at an f_3 of 32.91Hz with a Q of 1.042, since I was optimizing active filter values only for the 135Hz/175Hz crossover.

The active-filter transfer functions are shown in *Fig. 56*. The "rumble" filter response is down nearly 20dB at 10Hz; at 42.951Hz it provides 1.06dB of boost, which is 1dB lower than the simulation in *Fig. 11* (Part 1).

The woofer with and without the active filters is seen in *Fig. 57*. By the way, the 350Hz peak and 400Hz dip in the unfiltered woofer response is due to "organ pipe" resonances or port standing waves.[16] This appeared in *Fig. 1* (Part 1), since I modeled the woofer with LEAP's Port Standing Wave feature turned on. The peaks at 800Hz and 3.2kHz are break-up modes, showing up in a waterfall plot as ridges that take several milliseconds to decay. The M22WR is definitely not a candidate for a two-way system. *Figure 58* shows the midbass with and without the active and passive filters.

CROSSOVER DESIGN SUMMARY

Figure 59 shows the summation of the three drivers and their active and passive

TABLE 2
ACTIVE FILTER COMPONENTS

WOOFER LOW-PASS SECTION	
C4	0.10µF
C3	0.068µF
R4	15.4k
R5	15.4k
WOOFER HIGH-PASS "RUMBLE" SECTION	
C5	0.10µF
C6	0.10µF
R7	100k
R10	23.2k
MIDBASS HIGH-PASS SECTION	
C8	0.10µF
C9	0.10µF
R13	8.87k
R14	9.76k

filters. The cursor is at 33.773Hz with an SPL of 83.882, indicating that the low-frequency cutoff or –3dB point is about 34Hz. In *Fig. 60*, the reverse-phase polarity situation shows deep nulls in the response at the crossover points. This suggests that the crossover is properly designed and very much in-phase for the normal or in-phase connection, because it operates so very poorly when it is connected reverse-phase.[13]

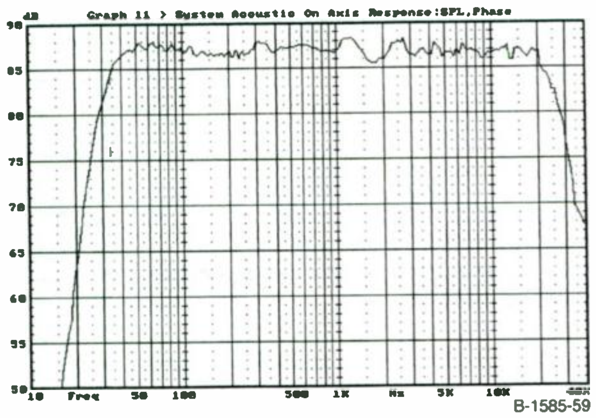

FIGURE 59: Simulated system response of tweeter, midbass, and woofer with final optimized passive and active filters.

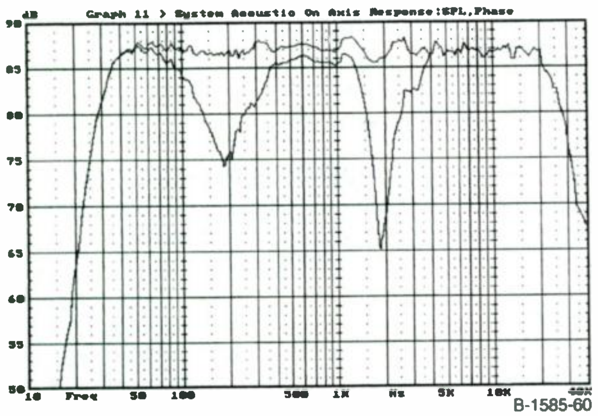

FIGURE 60: Simulated system response of tweeter, midbass, and woofer with final optimized passive and active filters showing in-phase and reverse-phase connections.

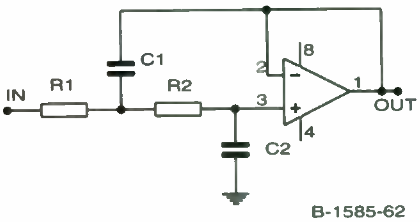

FIGURE 62: Second-order low-pass filter circuit.

ACTIVE CROSSOVER

A partial schematic of the Audio Arts XVR-1 crossover is shown in *Fig. 61*. *Table 1* is a list of the essential components that are part of the filter block. The resistors are ¼W and 1% tolerance. The capacitors are 2%, polypropylene or polystyrene. Voltage isn't critical for them as long as they fit on the PC board. The other parts are listed in Janosky's *Speaker Builder* article.[15]

You may have noticed that I haven't included any output-level increase or decrease with the active filter for either the midbass or the woofer. In fact, the schematic in *Fig. 61* shows that I've omitted R8 and jumped R9. (R8 and R9 provide boost to the low-pass section in the XVR-1. A 5k linear pot then controls the level.) However, with R8 and R9 in place there was an awful oscillation. Fred Janosky thought the problem was caused by the interaction of the high Q rumble filter interacting with R8 and R9. Eliminating them from the circuit solved the problem.

Fortunately, the lack of level controls didn't pose a problem for this system, since the sensitivity of the midbass was similar to that of the woofer. However, it does mean that you need to use a matched pair of

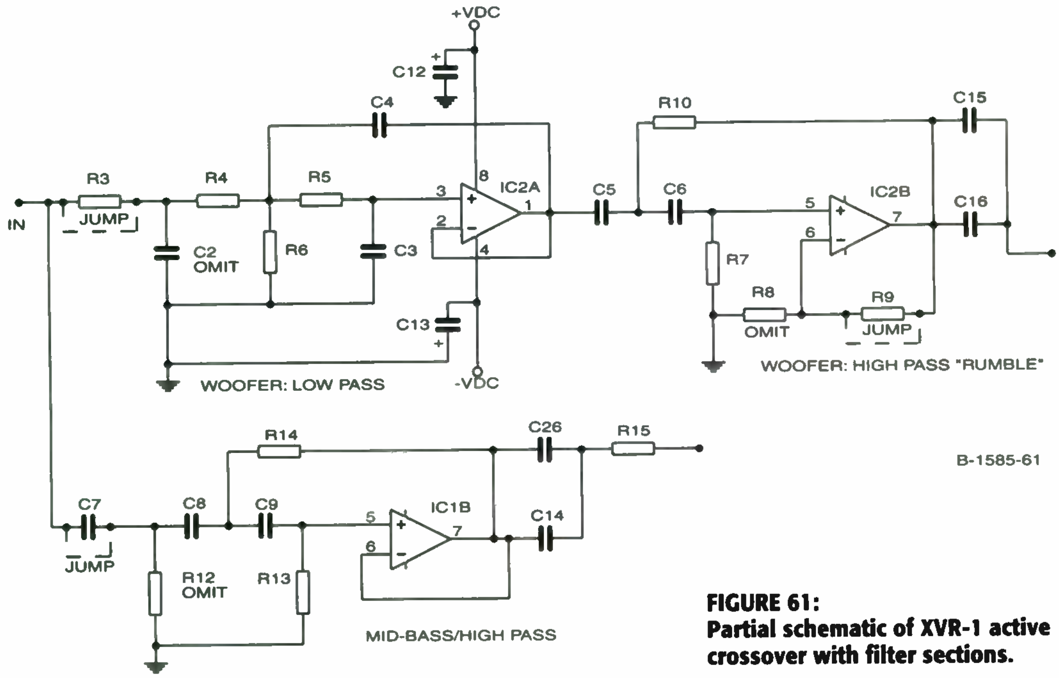

FIGURE 61: Partial schematic of XVR-1 active crossover with filter sections.

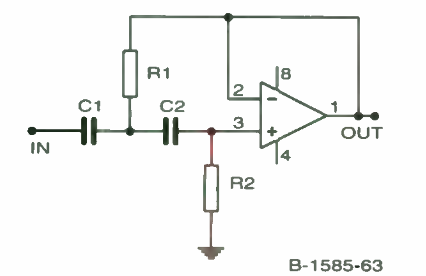

FIGURE 63: Second-order high-pass filter circuit.

stereo amplifiers or install level controls on one of the amps.

While Lancaster's *Active Filter Cookbook* was a useful reference, I used equations in the LEAP *Application Manual* to calculate component values. They are reproduced here with permission from LinearX, the developer of LEAP and LMS.

SECOND-ORDER ACTIVE-FILTER DESIGN

Figure 62 shows the low-pass circuit with the essential components that you must determine once you have calculated optimal values for crossover point (Fo) and Q. To design the circuit, you define Kr = R2/R1 and Kc = C2/C1. Now letting Kr = 1.0 produces the following design formulas:

$$R2 = R1$$
$$Kc = 1/(4 \times Q \times Q)$$
$$C1 = 1/(2 \times \pi \times R1 \times Fo \times \sqrt{Kc})$$
$$C2 = Kc \times C1$$

All you do is pick a value for R1; then the remaining values are calculated from Q and Fo.

Figure 63 shows the circuit to be used for the high-pass stage. To design the circuit, define Kc = C2/C1 and Kr = R2/R1. Now, let Kc = 1.0, and the following design formulas are produced:

$$Kr = 4 \times Q \times Q$$
$$R2 = Kr \times R1$$
$$C1 = 1/(2 \times \pi \times R1 \times Fo \times \sqrt{Kr})$$
$$C2 = C1$$

Again, you pick a value for R1, and the remaining values are calculated from Q and Fo.

Before we're able to construct the enclosure and crossover, and listen to the unit, we need to measure responses of the satellite and subwoofer. The third and final part of this series will bring you those results.

SOURCES

Audio Arts
610-693-6740
audioarts@enter.net

Liberty Instruments
513-755-0252
bwaslo@one.net
www.libinst.com

LinearX
503-612-9565
sales@linearx.com
support@linearx.com
www.linearx.com

Madisound
608-831-3433
info@madisound.com
www.madisound.com

Mahogany Sound
334-633-2054

Meniscus
616-534-9121
sales@meniscusaudio.com
www.meniscusaudio.com

Parts Express
725 Pleasant Valley Drive
Springboro, OH 45066
800-338-0531

Vermet Machine Company
Hammond, Indiana
219-931-5406
(actually, contact your local air conditioning equipment wholesaler)

REFERENCES

8. Vance Dickason, *Loudspeaker Recipes 1*, 1994, Audio Amateur Press, p. 9
9. Joseph D'Appolito, *Testing Loudspeakers*, 1998, Audio Amateur Press, p. 69.
10. Vance Dickason, *The Loudspeaker Design Cookbook*, Fifth Edition, 1995, Audio Amateur Press, p. 108.
11. James Moriyasu, "A Vifa Compact 2-Way," *Speaker Builder* 6/99.
12. Vance Dickason, *Loudspeaker Recipes 1*, 1994, Audio Amateur Press, pp. 19–22.
13. Vance Dickason, *The Loudspeaker Design Cookbook*, Fifth Edition, 1995, Audio Amateur Press, p. 119.
14. Vance Dickason, *Loudspeaker Recipes 1*, 1994, Audio Amateur Press, p. 23.
15. Janosky, F., "The XVR–1 Two-Way Electronic Crossover," *Speaker Builder* 2/96, p.18.
16. D'Appolito, op.cit. p. 87.

Using the same proportions as those used by the builders of the Great Pyramid, you, too, can build a structure that will stand the test of time.

Determining Optimum Box Dimensions

By Louis C. McClure

Often when you purchase a new driver, you find that the manufacturer has included a box size recommended for optimum results. This may include a box volume for both the sealed-box (infinite baffle or acoustic suspension) and the vented, or ported, type of enclosure, such as the bass reflex.

This value is often referred to as the V_{AS}, or the equivalent volume of air to equal the compliance of the cone's suspension. The compliance consists of the mass of the cone and voice coil, as well as the stiffness of the surround and the spider, referred to as the suspension of the driver.

ENCLOSURE PROPORTIONS

There are many different configurations to choose from when you're building a loudspeaker enclosure, ranging from a horn, a cube, a pipe, or a rectangle, to a number of other shapes, each having its own peculiar characteristics, merits, and faults. Usually, however, the choice is a rectangular box, whether a sealed-box or vented type. This article concerns the dimensions of the rectangular box.

Suppose, for example, the specifications included with your driver recommend an enclosure with a volume or V_{AS} of $3.2ft^3$. You can use this value in formulas to determine the ideal box size for the particular driver when designed for a specific Q_B (the Q of the finished enclosure).

Armed with the required volume, you can proceed to calculate the internal physical dimensions of the box. You could, of course, design a cubical enclosure (having equal dimensions of height, width, and depth) by converting the required internal volume in cubic feet into cubic inches by multiplying by 1728, and then finding the cube root of the result, which would be the desired height, width, and depth.

The cubical enclosure would be satisfactory for use as a subwoofer, because it tends to boost the total output of the enclosure by reinforcing the internal standing waves. Many commercial subwoofer boxes are designed in this manner, but this article is not primarily concerned with the application to the subwoofer, but with the usual two-way or three-way enclosure that covers the entire audio frequency range.

Through experience, many manufacturers have adopted as a rule-of-thumb the "golden" proportion or ratio, which relates the dimensions of the enclosure according to the ideal ratio of .618 (see sidebar). For example, using whole-number dimensions of, say, 6 units deep, 10 units wide, and 16 units high, the ratio of depth to width = 6:10 = .600, and the ratio of width to height = 10:16 = .625. Dimensions such as these result in so-called aspect ratios with values fairly close to the ideal .618, a ratio that has been determined to produce the best sound, since it leads to choosing approximate dimensions having no common factors that would tend to emphasize internal resonance.

CALCULATING INTERNAL DIMENSIONS

Assuming a desired net internal volume of $3.2ft^3$, you then proceed as follows:

1. Convert $3.2ft^3$ into cubic inches by multiplying by 1728, giving a product of $5{,}530in^3$.
2. Then assuming the aspect ratio of 6-10-16, multiply these numbers together, giving a product of 960.
3. Next, divide the total cubic inches, 5,530, by 960, giving a quotient of 5.76.
4. Now find the cube root of 5.76, which is approximately 1.79. (If you have no scientific calculator, find the logarithm of 5.76 from a table of common logs, divide it by 3, and find the antilog of this value. Or, you can use the old stand-by, the slide rule. While it is not as accurate, with care you can obtain satisfactory results.)
5. Finally, multiply 1.79 by the three values of the aspect ratio, yielding, respectively, $6 \times 1.79 = 10.74$ (the depth), $10 \times 1.79 = 17.9$ (the width), and $16 \times 1.79 = 28.64$ (the height).
6. Having made these calculations, check your work by multiplying the width, height, and depth of the box to compare with the original desired volume of $5{,}530in^3$. Due to rounding off the numbers, there may be a slight difference—a fraction of 1% of the volume as determined in step 1—but it is insignificant.

That's all there is to it! Or, you can choose other aspect ratios—7-11-17, for example, or 34-55-89—and proceed in the same manner as with the previous example. Remember that these are internal dimensions. Also, departures of as much as 5% from the optimum value will have only a very slight effect upon the sonic performance.

MAKING ALLOWANCES

If you are dealing with a small box volume in relation to the volume represented by the drivers installed in the box, then you may wish to make the internal volume slightly larger to compensate for the drivers' volume. If the driver displacement is not given in the specifications, you can calculate its approximate displacement (or volume) as follows:

To find the volume (in cubic inches) of the cylindical magnet, use the formula

$$V = \pi r^2 h,$$

where r is the magnet's radius and h its thickness, or height. Assuming the magnet to be 4.5″ in diameter (2.25″ in radius) and 1″ in thickness, the volume would be

$$3.1416 \times (2.25)^2 \times 1 = 15.9\text{in}^3.$$

Now calculate the volume of the cone with the formula

$$V = \tfrac{1}{3}\pi r^2 h.$$

Assuming the cone is 9″ in diameter and 2″ high at the apex, the volume would be:

$$\tfrac{1}{3} \times 3.1416 \times (4.5)^2 \times 2 = 42.41\text{in}^3.$$

(The volume of the cone assumes that the cone comes to a peak, or apex. In the real world, however, the peak of the cone is engaged in the magnet assembly, and so is included in the volume of the magnet and not the cone. But it makes so little difference that it may be ignored.)

Adding the volume of the magnet assembly (15.9in^3) to the volume of the cone (42.41in^3) gives a total driver volume of 58.31in^3. This is still only slightly more than 1% of the 5,530in^3 required for the box, so the driver's volume is insignificant in this case. As long as the combined volumes of the drivers do not exceed 5% of the total box volume, you may disregard them in the calculations.

Whatever proportions you use, the dimensions of depth, width, and height should not be exact multiples of any one number. For example, you should not use 8, 16, and 24, since these are all exact multiples of eight and would give rise to objectionable resonances within the box.

For a subwoofer, a cubic box is often used for this very reason. It covers a relatively narrow band of frequencies, and the box resonance reinforces the output. You can also use it in conjunction with a ported enclosure to further reinforce the low frequencies.

THE GOLDEN RATIO IN MATHEMATICS

The number expressing the golden ratio (also known as the golden mean, proportion, and section) is derived from dividing a line segment so that the ratio of the shorter part to the longer part is equal to the ratio of the longer part to the entire line segment (*Fig. 1*). If the length of the entire segment is unity and you let the longer part be x, the shorter part is 1 − x, and the resulting proportion is

$$\frac{1-x}{x} = \frac{x}{1}, \text{ or } x^2 = 1 - x \quad [1]$$

A little rearranging gives the quadratic equation

$$x^2 + x - 1 = 0. \quad [2]$$

Comparing this to the general form of the quadratic equation, $ax^2 + bx + c = 0$, and using the quadratic formula, $x = (-b \pm\sqrt{b^2 - 4ac})/2a$, the positive value of x (the longer segment) turns out to be 0.61803..., rounded off for practical purposes to 0.618. By subtraction, the length of the shorter part is 0.382, which, as equation [1] shows immediately, is the square of the longer segment.

You may find it interesting that x is irrational, a never-ending decimal fraction, whereas you can (theoretically) find the *exact* point of division through a geometric construction. In *Fig. 2*, ABC is a right triangle with the length of AB chosen (for convenience) as 2 units, and BC (perpendicular to AB) constructed as 1. By the Pythagorean Theorem, AC = $\sqrt{5}$. Drawing an arc with center C and radius = BC = 1 locates point D on the hypotenuse such that AD = $\sqrt{5} - 1$. From A, draw an arc with radius AD, cutting AB in G, which is the point that divides AB into the golden ratio. The longer part AG = $\sqrt{5} - 1$, and the shorter part GB = $2 - (\sqrt{5} - 1) = 3 - \sqrt{5}$. Using these values, you can then show that GB/AG = AG/AB is an identity.

The golden number also results from other mathematical processes. Such a one is the Fibonacci series: 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, and so on. A little inspection will reveal how the series is built up. Take the ratio of successive pairs of terms of this series and see what happens: 1:1 = 1; 1:2 = .5; 2:3 = .67...; 3:5 = .6; 5:8 = .625; 8:13 = .61538...; 13:21 = .61904...; 21:34 = .61764...; 34:55 = .61818...; and so on.

The golden ratio appears in many contexts; for example, in the ratio of the segments of the diagonals of a regular pentagram, in certain proportions of the Great Pyramid, in the measurements of the five regular geometric solids, and, most remarkably, in nature. If you can obtain a large, mature sunflower, notice that the spirals on the head of the blossom go both clockwise and counterclockwise. Carefully count the number of spirals going in one direction and then the number going in the other. Take the ratio of the smaller result to the larger and compare with the ratios in the Fibonacci series.

Surely this is a remarkable proportion, and—built into the dimensions of a speaker enclosure—it is no wonder that it can produce a remarkably fine sound.

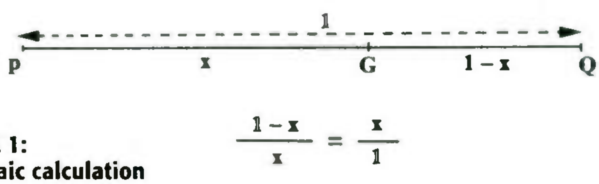

FIGURE 1: Algebraic calculation of the golden ratio.

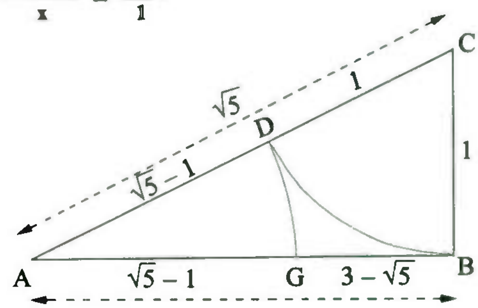

FIGURE 2: Geometric construction of the golden ratio.

SB Mailbox

GAMMA VALUES

I found Mark Wheeler's article the most interesting and educational article I've read in a long time ("Navigating Speaker Design," *SB* 7/99, p. 34). I commend him on excellent DIY info that I will find beneficial.

I do, however, have a few questions.

1. Does the gamma.a comparison also apply to tweeters?
2. Should all drivers in a two- or three-way speaker have comparable gamma.a values?
3. I have BassBox 6 and its attendant driver database. I picked a subset consisting of all available drivers from the most popular manufacturers (i.e., Vifa, Seas, Scan-Speak, Morel, Focal, Audax, and so on). Out of the hundreds of drivers, only a small percentage had gamma.a values above nine! I don't have the numbers handy but the majority of the most commonly applauded drivers (i.e., Vifa P17WJ, Scan-Speak 18W/8554, and so forth) have values less than nine and a significant number were below seven.

So my question is, am I correct in expecting the "good" drivers to have higher gamma.a values—or, help me understand the results of my computations.

Paul Beasley
Duluth, GA

Mark Wheeler responds:

I'm pleased that Paul Beasley has found my articles useful. I have found that, all other things being equal, higher gamma and gamma.a values do make a more musically-engaging driver. "All other things being equal" is the crucial phrase here.

There are many other factors to consider when selecting the drivers for a system appropriate to your needs, and no one factor should be allowed to predominate in designing a well-balanced system. There are many commercial examples of speakers that pursued one Holy Grail at the expense of all else, and at best these can be described as "niche products."

I have built some excellent-sounding (no modesty here) systems using drivers with gamma.a of 6 to 8 from some of the manufacturers you mention. However, I have become more excited by the musical experience of speakers I have built using drivers of gamma.a above 12. I have heard a system built by Russ Andrews that sounded thrilling and lifelike, which used bass and mid-range drivers with gamma.a approaching 20. However, this system did have a very distinct sonic signature that some may not find to their taste. One of the joys of designing your own system is juggling the various design criteria to suit your own priorities.

It's not easy to get enough information to establish this amount of specification about a tweeter. Most manufacturers tend to mention sensitivity and approximate dome diameter (though not area), but others, including Focal, do provide enough information to calculate gamma.a for tweeters. There are other, more significant factors that may dictate your choice of tweeter.

Polar response of the drivers at the crossover frequency is very important. I continue to be irritated that polar responses are rarely published, and these are essential for good driver integration and overall in-room system response. Twenty years ago Richard Allen provided a full set of frequency response and polar response plots for the drivers in its catalog. This would have been a much more expensive proposition at that time for a small manufacturer, so there's no excuse now.

I have found that loosely matching gamma.a in a system does contribute to the overall coherence of the system. The wildly incoherent examples I mentioned were of combinations of driver in which one gamma.a was more than twice that of the other.

Good luck with your projects, they will stretch your mind and provide hours of enlightening exploration. Ultimately you will enjoy the satisfaction gained from making something that works really well and knowing why it does.

I found the article by Mark Wheeler both interesting and helpful (*SB* 7/99, p. 34). I did however have one question that I didn't see covered in the article. What effect, if any, does doubling up the drivers (as in an MTM arrangement) have on the acceleration of air that Mark documents?

And if it has an effect, is there a different formula for that, or do you modify the existing formula?

Philip Souza
Auburn, CA

Mark Wheeler responds:

As gamma is calculated from the magnetic force (BL product) divided by the moving mass (kg) of each driver, it remains the same for each driver, no matter how many drivers there are. This was the figure which seemed to indicate the resolving capabilities of each driver, and indeed would indicate the same of a system of multiple drivers.

The gamma.a product is affected. You would assume that the doubling of the cone surface area would effect a doubling of gamma.a. This was the figure that seemed to indicate the dynamics of the driver, and was useful to be in a similar ball park from driver to driver in a well-integrated system.

SPEAKER CABLES

In a recent issue there was an article on making speaker wires ("Do I Need a New Speaker Cable?" *SB* 7/99, p. 38). In all my years reading *Speaker Builder* (and in all of the back issues I have reviewed), I have not seen the issue of the length of speaker wires addressed. The speakers in my system are not an equal distance from my amplifier. I am currently using speaker wires of the same length and bundling the excess. For a new set of wires, would it be better to make them of two different lengths or to bundle the excess, as I currently do.

I hope that you will respond that there is no difference but I suspect that the difference in resistance between the two wires may have some effect.

Mike Devins
Romeo, MI

Jesse W. Knight responds:

You have raised a very interesting question, which is not easy to answer.

Speakers vary widely in sensitivity to cable resistance, and I have found no way to predict all the effects of, say, adding ½Ω to a speaker wire. This leads me to think that your best approach would be to experiment by adding cable until you hear a change in sound quality. I would try this with inexpensive #16 zip cord.

Ideally, have someone else patch and unpatch this added cord while you listen. This will make your experiment a blind test. Once you find that critical added length that you can reliably hear, you might set your limit for this type of wire at half this critical length.

Many heavy speaker cables have too much spacing between the wires, which leads to excess inductance. A twisted pair of THHN stranded #12 wires will outperform these, as the insulation is quite thin. Parallel zip cord is also good, but watch polarity.

Some researchers claim we can hear changes in time adjustment, for stereo signals that amount to only a few microseconds. If this is true, speaker cables need to be identical lengths. I have not found this to be an important factor in getting good sound. I never buy matched pair drivers, as the selection is very limited and the price is high. To me, it makes more sense to buy bigger woofers. Even with matched drivers and 1% tolerance crossover components, the time adjustment left-to-right will still not be perfect. Finally, very few people have totally symmetrical rooms for listening.

I have not measured or heard any detrimental effect of bundling excess wire. Any effects are at RF frequencies and can be ignored, in my opinion. Bundling is a good way to keep things symmetrical. When a two-conductor cable is coiled, it only becomes more inductive for common mode signals, not for the signal from your amplifier. Coiled, bundled, or straight, the speaker gets the same signal.

BRACING THE BOX

I enjoyed your "Navigating Speaker Design" articles. I would like some clarification of bracing issues in part 3, "Listening to Walls" (*SB* 8/99, p. 32).

You talk about ¼" hardwood braces being very effective. I have assumed the ¼" face was the edge of the brace glued to the wall, but would appreciate confirmation.

Frank Habrle
Auckland, New Zealand

Mark Wheeler responds:

Theoretically, reducing the width (the dimension of the face glued to the panel) of a brace has much less effect on its stiffness than reducing its depth (that is, the dimension perpendicular to the panel). Consequently, I would always recommend gluing the narrower side of the brace to the panel.

The purpose of the experiment was to determine whether it was the mass of the brace or some other property that affected its performance, by equalizing the masses of the different materials. I did try gluing the braces both ways round, to confirm whether theory was borne out in audible practice. Again the results were far less obvious than those differences observed by different materials, which suggested to me that the material selection is a more important factor. These were deliberate experimental conditions rather than recommendations for future practice.

It always makes sense to use your materials in the most effective and efficient manner possible. Therefore, I always recommend that you glue bracing with the section perpendicular to the panel face. The same timber that performed well as a 6mm × 25mm (¼" × 1") wide brace would be expected to perform even better as a 12mm × 25mm (½" × 1") wide brace, and would be easier to handle and shape at this size. For longer brace dimensions, I would probably choose 12mm × 50mm (½" × 2") glued to the panel on its 12mm (½") face.

It is better to brace along the longest dimension (contrary to popular practice) since this raises the first resonant frequency higher, and of course, the subsequent harmonics.

Unfortunately, the best results were obtained with very dense tropical rainforest hardwoods, which had been harvested some two decades ago, before we became as aware of environmental considerations. I already had these in stock and would be reluctant to purchase any more now. Perhaps we should try growing them in special *Speaker Builder*'s glasshouses in our backyards so that our children can continue our activities!

I would like to add some thoughts to Mark Wheeler's comments regarding the choice of adhesives "to be as critical as the choice of bracing materials" ("Navigating Speaker Design," *SB* 8/99, p. 32). The use of PVA (white, all purpose) glues is widespread but not necessarily the best. I personally do not care for them. But not because of their ineffectiveness. Let me explain my logic on the selection of adhesives and their use in cabinet joinery.

If you are familiar with the magazine *Fine Woodworking* and others, you are probably aware of the many types of adhesives available. I am not making any specific brand recommendations, but I think that any of the modern adhesives are capable of making solid joints, provided you use sound woodworking techniques.

Joints must be carefully made, with smooth machining that can be achieved by carbide saw blades and router bits. The tools must be accurately squared up and true before cutting and machining. Take your time. Measure everything at least twice. Use appropriate steel rules and squares, not yardsticks or pocket tape measures. This is not house carpentry, and making panels to the nearest ¼" is not good enough.

You should inspect and judge the factory edges and quick-sawn lumber yard edges with a good square before use. The joints must be absolutely clean, dry, and fit together perfectly. If the fit is not square, rework the joint until it is perfect. You must smooth out saw swirls along the edge, as most glue will not fill these gaps.

If you do not have access to a proper table saw (the ideal machine to cut cabinet panels), then I suggest a router and a solid metal-edge clamp as a guide for square edges. Cut your panels slightly oversize, and then use the straight edge and router to true everything up perfectly. This tool combination can allow you to cut rabbets on panel edges, which multiply the glue bonding surface area. Use rabbets on panels thinner than ¾".

Once you have cut all of the panels, a test assembly, or dry practice session, with all the clamps and appropriate wooden blocks is essential. You will need a clean flat table to work on. Take your time, plan ahead: will you need an assistant to help you with large panels and heavy clamps? Arrange this beforehand. Make sure everything is right, without the glue! Clean everything, vacuum the joints to remove small particles and dust. Debris in a joint can ruin your pristine work.

If you're a perfectionist, leave the cabinet clamped up dry, and re-inspect it again the next morning when you're fresh and clear. Begin the actual glue application only after you are completely satisfied with everything.

Measure your "wet time," how long the glue joint can be exposed before it begins to set up. Some glues set up even faster—especially if it is hot and dry (like in Arizona)—than the labels would lead you to believe. Try a test yourself with some scrap wood. You will need some time to assemble your project (30 minutes is the absolute minimum). Many adhesives allow this much and more time, so choose one of these products.

You must ensure that every surface is wetted with the glue. Some cabinet makers use a stiff brush to work the glue into the joints, while others use the various applicators (rollers) available. My method involves a generous application, and then working a spackling or taping knife along the joint, pressing the glue into the material and removing the excess simultaneously. Keep a dry cloth in one hand to clean up your taping knife.

Once the joint is wetted and ready for assembly, carefully position the work and begin clamping. Apply the pressure in stages, as the assembly progresses. A bead of glue should squeeze out along the entire joint.

In this case, I again prefer the modern non-running adhesive types rather than the white or yellow glues which run easily, despite the fact that they are easy to clean up, don't stain the wood, and are easy on your tool's edges.

The newer glues, especially the two-part dry (resorcinol-formaldehyde) types will last almost indefinitely. But, I don't favor these because they're hard on my carbide tools and some have wet times as short as 10 to 15 minutes.

Screws and nails do not apply adequate pressure to make good joints. You really need good clamps, and clamp pressure is the key. The load range of applied pressure using clamps is very wide, from about 25 with spring clamps to over 2000psi using the "Jorgensen" types. Screws and nails cannot uniformly match this pressure, and often poor joints are the result.

To quote from *Fine Woodworking*'s article on glues and gluing, "applying an adhesive in a form which can flow onto and into the wood surface and wet the cell structure, and then applying pressure to spread the adhesive uniformly thin and hold the assembly undisturbed while the adhesive solidifies." It continues, "internal stress becomes intolerably high if the glue lines are too thick. *Glue lines should not be more than a few thousandths of an inch.*" Again, I do not think simple nails and screws can achieve this close tolerance.

Working with fine particleboard, with carefully machined edges, you can make the glue joint disappear, after proper clamp pressure. Do you achieve this with your current techniques?

Use wood blocks to distribute the pressure along the joints. Imagine a right triangle of pressure projecting down from the clamp to the joint, then you'll have an idea. You can visualize this during the dry assembly, and arrange to have everything on hand before the wet glue work begins.

Also, don't apply so much pressure that you begin to pull the opposite end of the joint apart. This is counterproductive to good joinery. Working with a partner can simplify this procedure by constantly checking the opposite end of the cabinet, as you assemble and apply clamp pressure.

Lastly, leave the clamps in place overnight to permit proper cure time. This is longer than the time it takes for the glue to set up, usually considerably longer. If the joint is under stress, extended clamp time can ensure optimum joint strength.

As a home speaker builder, you can take the time and effort to make certain that everything is right. I suggest that proper machining and careful assembly be given as much, if not more, time than any other portion of the project.

I commend Mark for his investigations into actual and observed effects of cabinet construction techniques. I think his findings should spark some research into why hardwoods, construction materials, and related items were so easily identified by the listeners.

A good speaker-building approach means that everything counts!

Lester Mertz
Mesa, AZ

Mark Wheeler responds:

I thank Lester Mertz for his detailed and informative response. I agree with his comments about good fit and finish of cabinet joints. I find "sash cramps" work well for loudspeaker cabinet panel clamping during adhesive curing.

PVA and acrylic white glues were inferior to two-pack epoxy and formaldehyde-based adhesives in all our experiments. Our first attempts at adding bracing to existing commercial cabinets would not have been particularly well clamped during curing due to logistical problems, but the results remained consistent. I also suspect that most speaker building amateurs struggle to reach the levels of expertise and craftsmanship described by Lester, so the gap-filling properties of some adhesives would be particularly advantageous to them.

We later developed a test jig for wood and glue which seemed to correlate well with our cabinet experiments. The methodology was not as academically rigorous as I had hoped, to commit the jig to publication, but results seemed to imply that the effects correlated with the speed of sound in the material and possibly the bandwidth of sound through the material.

Screws have special disadvantages with some modern adhesives which react with ferrous metals, causing the screw to expand and damage the wood.

HORN WORK

I had been thinking along lines similar to those of your "Dome Horn" article (*SB*

3/99, p. 10) to boost the low end of a 3" Vifa mid dome (D75MX-31-08). I require only a 6dB boost at 300Hz, so the horn may not need to be very long. Even a 3dB boost at 300Hz would double the power handling and simplify network problems.

Currently I am using these mids in my Musician's Speaker (*SB* 8/96, p. 10) as a replacement for the KO 40. The Vifa has better transient response, and workshop dirt does not stick to the cloth dome. To lower the resonance to 300Hz, I ran a 4" PVC schedule 40 pipe from behind the Vifa mid through the back of the cabinet. This pipe is open at its back and is filled 100% with fiberglass. Rigidly mounted front and back, it also stiffens the front baffle, which is 17" × 26", and the mid is near the middle for lowest possible response step.

Vifa's response and impedance curves are based on using a small canister, which I did not purchase, as the 500Hz resonance would be totally unacceptable. Without the canister, I expect the very low Q becomes even lower. Raising the Q via the network has provided a good provisional solution for moderate power applications.

Before I start experimenting, I would appreciate any suggestions you might have. I am totally green when it comes to horns and am not a higher-math person. Is there a chart-and-graph approach to horn work? Can I expect a drop in resonance to, say, 250Hz or lower?

In conclusion, your work should be of interest to many people. Many thanks for sharing it with us.

Jesse W. Knight
Woburn, MA

Dome Construction

One unit featuring Vifa's 3" dome developed a buzz after being repeatedly mounted and unmounted. I carefully repaired this by removing the plastic housing and horn from the magnet structure and recementing the dome fabric to the horn.

While I had it apart, I made an approximate drawing of the internal design to further understand the design (*Fig. 1*). Later I used a carpenter's contour gauge to complete the cross section of the dome and horn so this detail would be quite accurate in the drawing.

A. Voice coil, quite substantial for a midrange in terms of cross section and heat dissipation. Leads, however, are the same wire as the winding making X max of 0.5mm a limit that cannot be exceeded without eventual failure. (This is based on failure in Peerless KO 10 tweeters, which also have this lead wire design.) Using braided leads would increase moving mass of the dome; hence, this is probably a good design decision.

B. Cloth dome doped black.

C. Internal protection grille. Besides its protecting function, I suspect the high solidarity of this grille functions much the way cloth applied to the basket of a cone driver does in terms of lowering the Q.

D. The eight D markings outline the

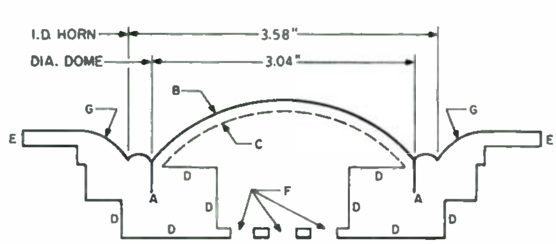

FIGURE 1: Sketch of Vifa 3" dome D75MX-31-08.

magnet structure that encloses the voice coil (A). Note that the center hole in the magnet structure is quite large, forming a chamber that ends in a flow restricted vent back plate containing seven holes (F). Not shown is a thin layer of felt covering the holes.

E. Mounting flange.
F. Horn flare.

Dick Crawford responds:

Thank you for your recent letter regarding a horn suitable for a 3″ mid dome. To achieve your desired 6dB of horn gain at 300Hz, I expect you would require a horn length of 6″ to 9″. I would not recommend a horn longer than 9″ due to credible articles claiming that horns longer than this cause problems with the transient response.

Suppose you use a 6″ long horn. I suggest a mouth diameter of 8″ to 12″, with an exponential horn flare. With a throat of 3″ diameter, a mouth of 9″ diameter, and a length of 6″, an exponential horn will increase its diameter by an expansion rate of about 1.15 for each 0.75″ of travel from the throat to the mouth. (I use 0.75″ travel because of the way I construct my horns.) For example:

DISTANCE FROM THROAT (INCHES)	HORN DIAMETER (INCHES)
0	3.00
0.75	3.45
1.50	3.97
2.25	4.56
3.00	5.25
3.75	6.03
4.50	6.94
5.25	7.98
6.00	9.18

Given these dimensions, the unit becomes more of what the loudspeaker industry calls a waveguide than a horn. In fact, the horn is acoustically short at 300Hz, and most of the horn gain is in the increased directivity. The horn's directivity should be similar to that of a 10″ driver.

I expect that your use of a 4″ PVC pipe at the rear of the 3″ dome (to replace the rear canister) should lower its resonance slightly, as will a horn at the front. I would not expect a decrease in resonance of more than 20%, and probably less. This is particularly true with 3″ domes that have an internal-protection grille. These grilles help control the motion of the dome by providing an acoustic impedance at the rear of the dome, but the acoustic impedance of the grille can dominate any effect of a horn or pipe on the resonance of the 3″ dome. I still recommend your 4″ PVC pipe as a rear chamber, as it should give fewer reflections than the normal canister.

If you have a calculator, you can design an exponential horn in a few minutes using lower math (as opposed to higher math). Assume an expansion rate (1.15 per 0.75″ in the previous example), and then multiply the horn diameter by that rate for each 0.75″ of travel along the horn. In the example, the expansion rate of 1.15 is multiplied by the horn diameter at 0″ (3″ diameter) to give 3.45″ diameter at 0.75″. For the diameter at 1.5″ of travel, you multiply the diameter at 0.75″ (3.45″) by 1.15 to get 3.97″. At 2.25″ travel the diameter is 4.56″ (3.97″ × 1.15).

Continue this method until you reach the mouth of the horn. If the final size of the horn is too large, reconfigure using a smaller expansion rate. And again, and again, if necessary. This is definitely lower math, but you will obtain results faster than learning higher math.

The construction technique in my article "A Dome Horn" should work OK, but with a 6″ horn length there will be many (8) layers of ¾″ board. Thank you for your interest.

TWEETER BARGAIN

I stumbled onto a great, sweet tweeter deal from MCM Electronics that I'd like to keep to myself but, in good conscience, cannot. I bought a pair of upgrades for one of my big Sony TVs because they are shielded, but decided to try them out in one of my experimental speaker setups first. And, as of now, I'm never taking them out.

On my fully-tubed system they are smooth, detailed, transparent, deep, and wide. And I'm comparing them to ribbons, planar, and domes. The driver, with an odd design, features a clear dome of less than one-half-inch diameter.

Specifications in the MCM catalog are as follows: frequency response: 2.5kHz–20kHz. Recommended crossover: 6dB at 5kHz or 12dB at 4kHz. Nominal impedance: 4Ω. Power handling: 20/40W RMS/peak. I've pushed them hard for two weeks and they haven't squawked yet.

I have accumulated all types of tweeters from various manufacturers over the years, but these opened my ears to music I've been listening to for a long time. I'm over 50 and have been doing "hi-fi" since I was a kid. I can honestly say this is the bargain of the century (at least for this half). I don't know who the manufacturer is, but something has, for once, gone terribly right. It proves you finally don't need to go broke to get high quality.

The best part? They're $3.99 each.

No kidding. Even cheaper by the tens. I bought another dozen so I can upgrade every speaker in sight and have several pairs in reserve for 10 years from now. They can be ordered by phone at (800) 543-4330. Part #58-4560. I encourage everyone to get on the gravy train with me.

Mike Robbins
Pittsburgh, PA

LDC INDEX

Here's a piece of information that should interest other readers of *Speaker Builder*, if they don't already know about it.

A very complete index for the *Loudspeaker Design Cookbook* is on the internet. Dickason's book is very good, but lacks an index, which makes it difficult to find things. Anyone who owns the *LDC* will want to print a copy of the index to keep with his book. The website also has a list of corrections. Here's the location: http://www.a1.com/mfr-eng/ldc.htm

This site is Mark Rumreich's, who has written articles for Audio Amateur publications. His new speaker-design software, Subwoofer Design Toolbox, is very well written, easy to use, and useful. I also recommend his *Car Stereo Cookbook* (which *does* have an index).

Alan Hoover
HooverA@tce.com

Dickason's book is organized by subject headings, and his table of contents is, in effect, a virtual index.–Ed.

DRIVER SUBSTITUTE

Readers might be interested to note that the Audax 10″ driver currently listed in Madisound's Spring Cleaning Sale has very similar parameters to the Lowther unit used in "All-Fun Horn," *SB* (5/99, p. 10) and might do service for someone choosing to try a two-way version of the project on a budget.

Jerry Stump
Buffalo Lake, MN

HELP WANTED

I have been in search for a distributor for some time that can sell me inductor coil bobbins, so that I can wrap my own inductors. I hope that someone out there will have some insight and maybe some information regarding my dilemma.

Brian Kuder
thirdeye@acdlink.com

I am searching for someone with a high-end design background who can help me alleviate excessive bass extension in the very bottom of the spectrum in a pair of three-way transmission-line speakers. If you know of anyone who is even moderately knowledgeable in this, I would very much appreciate a referral. I am about to begin re-vamping a pair of Baltic 90s without changing the crossover design.

While TL designs are inherently suppose to give you more bass extension than the crossover and drivers would otherwise, these take the goal too far, resulting in boominess, overhang, etc. Any assistance in this would be greatly appreciated.

Mark Rucker
shakur2000@hotmail.com

Readers with information on these topics are encouraged to respond directly to the letter writers at the addresses provided–Eds.

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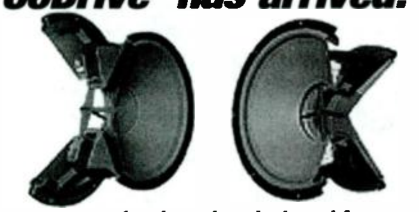

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AD INDEX

CLASSIFIEDS

GOOD NEWS/NEW PRODUCTS

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Alchemy DST powered digital intercom, $70; six rectangular Infinity EMIT tweeters, $40 each; JPS intercon .5m, $80; Acoustat direct drive amplifiers modified by Danny Fanny, $2600/pair; Acoustat panels, eight-9″, four-8″, $30, each. Offers considered on all. Joe (609) 397-8315 (NJ-EST).

Two JBL 375 drivers and oval-shape horns out of Paragon's, new aluminum diaphragms, excellent condition, $1,250/pr. JBL Century L-100, three sets include Alnico midrange and woofer, mint, $500/set. Two Sansui 9090 receivers, 120W/channel RMS, mint, $175 each. Alan Feinstein, 5743 Yellowrose Ct., Columbia, MD 21045.

Electrostatic step-up transformers, David Lucas, plus battery high voltage bias supply, all unused (new $250), $125. Jung 3-way electronic crossover, (*SB* Vol. 3 #3), dual mono, 8 voltage regulators, gold jacks, $100. (616) 364-3017, E-mail renardthefox@ameritech.net.

New drivers from Audax, Dynaudio, Morel, SEAS, Vifa, and more. Used only for testing. Priced well below retail. Also some finished speaker systems. Send for list. Contact Joe D'Appolito at audioltd@worldpath.net, or 34 Rust Pond Road, Wolfeboro, NH 03894.

ESS Transar/ATD electronic crossover, $150; Altec 420A 15″ biflex speaker, $150; JBL D140R 15″ woofer, $150; Hundreds classical LPs, free list; Morel MW224 9″ woofers double magnets; hexatech coils, $70/pair; Dynaco: ST70, $150; AF6, $80. Jerry Feldstein (718) 339-0435.

Pair of Musician 2B speakers, utilizing Dr. Penfold's full range driver. Beautiful mahogany cabinets. Truly a collector's item. Very few ever sold. $400/pair. Call or e-mail for more information. Also a pair of Eton 11″ Kevlar woofers. $225/pair. Ron Collier, (804) 780-0331, roncollier@erols.com.

Yardsale guidelines

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Tools, Tips, & Techniques

DAVEY'S AMAZING CIRCULAR-SAW JIG

By Michael Kessler

Do you have trouble making long cuts? Have you ever coerced your loving spouse into helping you push a 75 lb, 4′ × 8′ sheet of fiberboard through the table saw? Or even worse, did you spend so much on the raw drivers for your last speaker project that you had to put off buying a table saw once again?

If your answer is "yes" to any of these questions, this cheap and easy-to-make jig may be your guide to less frustrating speaker building.

Many of us have seen fellow woodworkers clamp various types of guides, called "rip fences," to their workpiece to make straight cuts with their circular saw. While satisfactory results sometimes may be achieved with a rip fence, it can be cumbersome to use. Unless it is of really high quality, it can bend a little as the cut is made, resulting in a less-than-adequate fit and finish on the final product.

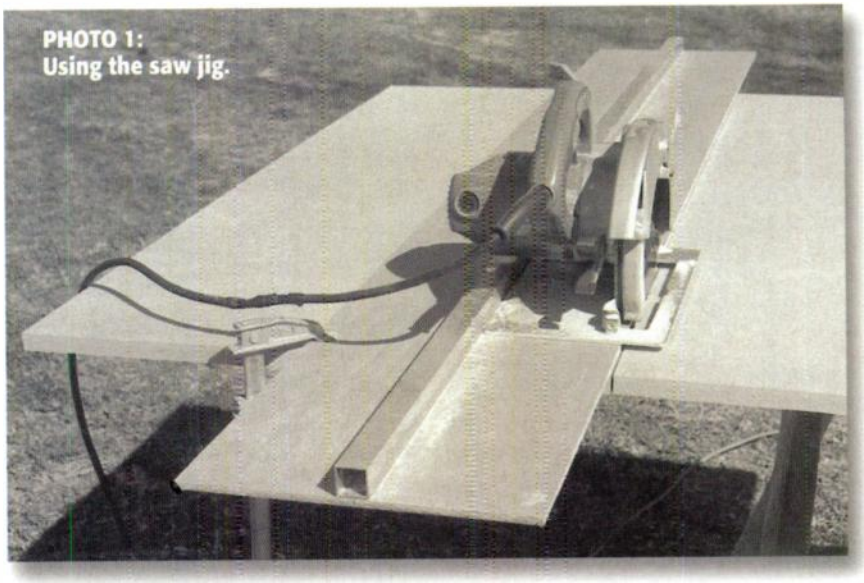


PHOTO 1: Using the saw jig.

An additional difficulty with a traditional rip fence is that you must measure the exact distance from the blade to the edge of the saw to determine where to place the fence. This can add time and aggravation to the project. My friend Davey Adams showed me this "amazing" improvement on the old style guide that eliminates the problems of the others.

CONSTRUCTION

I made my jig from a long, straight piece of square aluminum tubing and a scrap piece of fiberboard paneling equal in length to the tubing. You could use any long piece of stock in place of the aluminum tubing as long as it is perfectly straight and between ¼″ and ¾″ in height.

You should fasten the long, straight piece of stock lengthwise in the approximate middle of the paneling. Don't worry about aligning it to the exact middle, because you will cut the edges later. You can attach it using countersunk screws through the bottom of the paneling, but use great care during this step to ensure that the long, straight piece remains straight while it is being screwed on, as this will be the guide for the shoe of your saw.

Then you should place the edge of the shoe of your circular saw against the long, straight piece of stock. Cut off the edge of the paneling, with the shoe of the saw running along the long, straight piece. After this is completed, set the saw for a 45° cut and cut off the other edge of the paneling. That's it. The jig is finished (*Photo 1*).

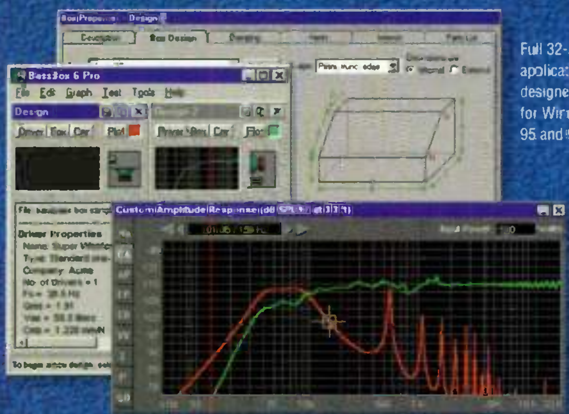
Making a cut with this jig is easy. Mark a line where you wish to cut and clamp the jig to the workpiece so that the edge of its paneling runs along the mark. Set the shoe of your saw against the long, straight piece and make your cut. You will soon discover that this jig is much easier to set up than a traditional fence. Also, since the paneling supports it, it cannot bend during the cut. As an additional bonus, you can use the 45° edge for long miter cuts.

With a little practice you will be able to make quick, straight cuts using this simple jig. Perhaps your spouse will appreciate the newfound quality in your speaker cabinets and give you carte blanche for your next project.

Design Loudspeaker Boxes

with BassBox Pro

State-of-the-art loudspeaker enclosure design software that is easy to use and has many professional-strength features.



Full 32-bit applications designed for Windows 95 and 98.

Includes the WORLD'S LARGEST Driver Database with the parameters and the dimensions for many thousands of drivers!

- Includes an innovative Design Wizard.
- Includes a huge driver database with the specs for thousands of drivers
- Models many box types including: closed, vented, B6 vented, double and triple-chamber bandpass and passive radiator boxes.
- Vents can have any shape including round, square and rectangular and can include flared ends.
- 18 single-chamber box shapes and 4 multi-chamber shapes are provided.
- Acoustic measurements of both the driver and the listening environment can be imported from many popular measurement systems, including CLIO, IMP, LMS, JBL/SIA Smaart MLSSA and TEF-20.
- Includes 9 performance graphs: normalized and custom amplitude response, max acoustic power, max electric input power, cone displacement, vent air velocity, impedance, phase response and group delay.
- Plot vent "pipe" resonance.
- A 3-D drawing of the box is drawn to scale automatically whenever a box dimension or parameter is changed.
- Creates box drawings with dimensions and parts lists.
- An "Expert" mode helps to identify "bad" parameters.
- A passive network can be incorporated into a design.
- Passive networks can be imported from X•over Pro.
- Includes a procedure for testing driver and passive radiator parameters.
- Handles multi-driver designs, including isobaric & bessel designs.
- English and/or metric units can be used.
- Can be customized with user preferences.
- Includes an extensive online manual with tutorials and sample designs with step-by-step instructions.
- Includes context-sensitive balloon help.
- Includes an illustrated 204 page printed manual.

BassBox 6 Pro: $129.00* *Plus shipping & handling.

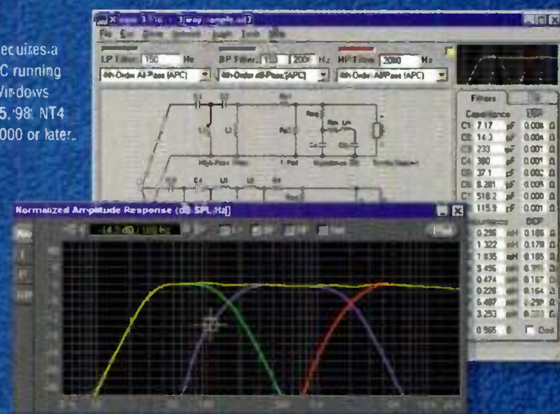
At the time of this printing shipping and handling fees were $7 in the U.S., $9 in Canada and $23 for all other destinations.

Design Crossover Networks

with X•over Pro

Versatile passive network design software for crossovers, filters, impedance EQ and L-pads with DCR/ESR estimator.

Requires a PC running Windows 95, 98, NT4 2000 or later.



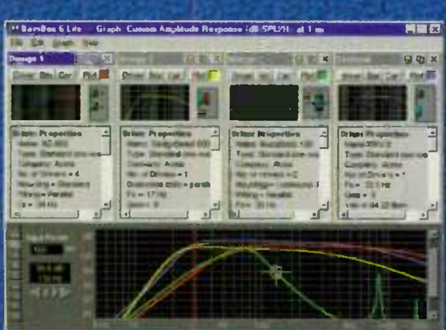
- Design 2-way and 3-way passive crossover networks.
- Design separate low-pass, band-pass and high-pass filters.
- Filters can have 1st, 2nd, 3rd or 4th-order slopes.
- Filter types and orders can be mixed in a crossover network.
- Design "L-pad" attenuators.
- Design impedance equalization networks (Zobels).
- Impedance EQ can include: the the resonance peaks of both driver and box and the inductive reactance of the voice coil.
- Includes a huge driver database with the specs for thousands of drivers. (Includes tweeters.)
- Advanced algorithms use the driver Thiele-Small and box parameters to model the net speaker (system) response.
- Includes 4 performance graphs: normalized amplitude response, system impedance, phase response and group delay.
- Graphs can include the driver acoustic and box response.
- Schematics and component lists can be printed and exported.
- Includes an easy-to-use component ESR and DCR estimator.
- Includes a convenient parallel-series value calculator.
- Includes a versatile component color stripe decoder.
- Can import driver and box data from BassBox Pro.
- Can be customized with user preferences.
- Includes an extensive online manual
- Includes contextual balloon help.
- Includes an illustrated 169 page printed manual.

Buy a Pro Bundle with both BassBox Pro and X•over Pro for $199* and save $29!

X•over 3 Pro: $99.00* *Plus shipping & handling

Also available: BassBox Lite

BassBox Lite is a streamlined version of BassBox Pro without the driver database.



BassBox Lite provides 85% of the most powerful features of BassBox Pro. It offers a streamlined user interface which integrates the graphs into the main window and merges the driver and box properties into a single window. Pro and Lite design files can be exchanged.

- Includes a full online manual with tutorials for beginners and step-by-step sample designs. (A Design Wizard & printed manual are not included.)
- Driver data can be saved in design files and re-used later. (The driver database is not supported.)
- The 8 most popular single-chamber box shapes are supported. All 4 multi-chamber shapes are supported.
- The bass boost in simple acoustical environments can be modeled. (Measurements cannot be imported.)

BassBox 6 Lite: $69.00* *Plus shipping & handling.

Visit us on the worldwide web at **www.ht-audio.com**.

Our internet website includes additional information and support for our software.

Special discount pricing is available for licensed users of older versions of BassBox and X•over who wish to upgrade. Please contact Harris Tech for details.

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TITANIC 1200

Titanic 1200 Subwoofer

The Dayton Loudspeaker Company assembled a team of the best speaker designers in the industry with one thought in mind ... to build the finest A/V subwoofer on the market! These engineers were chosen because of their expertise and pioneering designs of long excursion, high output subwoofers. A dozen prototypes were built and rigorously tested before we were satisfied with the final design parameters. With specifications like 16Hz Fs, 14mm Xmax (linear), 90dB SPL (2.83V) and 350W power handling, we're sure you will agree that this subwoofer is truly, Titanic!

Only the finest components are utilized: a heavy cast aluminum basket, a talc-filled polypropylene cone, SantopreneR rubber surround, an ultra high power voice coil assembly with a high temperature resistant ApicalR former, and quality, high tech adhesives to hold it all together. All of these components cost more, but are worth it!

ONLY $149.80 ASK FOR #295-400

Lets talk Performance!

The 12" Titanic was designed primarily as a sealed box woofer. One possible design is a 3 cubic foot sealed box with 50% fill. This design produces deep, accurate bass to 25Hz. You will be overwhelmed by the incredibly realistic low frequency that this driver will produce. Go ahead, put the T/S parameters into your favorite box design program and see for yourself what the Titanic 1200 can do!

Try it for 30 days ... If you don't feel this is the best A/V subwoofer you've ever heard, we'll refund your money! The Titanic 1200 is covered by our 5 year warranty.

Thiel-Small Parameters

◆Power handling: 350 watts RMS/ 450 watts max. ◆Voice coil diameter: 2" ◆Voice coil inductance: 1.96 mH ◆Nominal impedance: 4 ohms ◆DC resistance: 3.66 ohms ◆Frequency response: 16-400 Hz ◆Magnet weight: 84 oz. ◆Fs: 16 Hz ◆SPL:90dB 2.83V/1m ◆Vas: 9.894 cu. ft. ◆Qms: 8.22 ◆Qes: .42 ◆Qts: .407 ◆Xmax: 14.2 mm ◆Net weight: 14.6 lbs. ◆Dimensions: A: 12-1/8", B: 11-1/8", C: 6-9/16", D: 6", E: 2-3/4"

ONLY $119.80 ASK FOR #300-729

TITANIC Subwoofer Cabinet

This cabinet was designed to make the Titanic woofer "Sing." 3 cu. ft. cabinet with a substantial 1" MDF braces to couple all cabinet sides and help eliminate unwanted panel resonance. One inch thick MDF (medium density fiberboard) is acoustically superior to particle board, plywood, and OSB. Dado and Slot joinery coupled with screws and polyurethane glue (not included) make this cabinet virtually "Dead." The MDF exterior is easily painted or veneered to your liking. (Finishing Instructions Included Free). Inside dimensions: 17-3/4" cubed ◆Exterior dimensions: 19-3/4" cubed ◆Woofer hole: 11-1/8" ◆Net weight: 50 lbs. ◆Shipping knocked down.

250 Watt Class D Subwoofer Amplifier

- Perfect mate for Titanic Subwoofer
- High efficiency amplifier
- Made in the U.S.A.
- Advanced Class-D Topology
- Reliable/stable operation
- Low distortion
- High pass filter for satellite speakers

ONLY $249.80 ASK FOR #300-795

All subwoofer amps are not created equal!

Today you have many choices when it comes to an amplifier for your next subwoofer project. In our quest, we have seen them all and tested many. The heart of any subwoofer system is the amplifier; do you really want to trust your "Audiophile grade" subwoofer system to an amplifier made in China? This American made, **TRUE 250 WATT** amp produces earth shaking bass, especially when mated with our 12" Titanic subwoofer. Class D amps are nearly 95% efficient creating less heat making them more reliable and stable while producing less distortion. This amp features both high and low level inputs, phase reversal switch, level control, auto on/off (activated by input signal), and a second order (12dB) electronic low pass filter that is continuously variable from 40 to 160 Hz. It also features a 6dB high pass filter (90Hz @ 8ohm) output for satellite speakers. The amp has overload and fuse protection for years of reliable use. The highly efficient amplifier sums the right and left stereo inputs to a mono output, so that only one amp is required per system. Rated power output: 250 watts into 4 ohms @ 0.1% THD. Signal to noise ratio: 100dB (A-weighted). Dimensions: 10" W x 10" H x 2-1/2" D. Net weight: 4 lbs.

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