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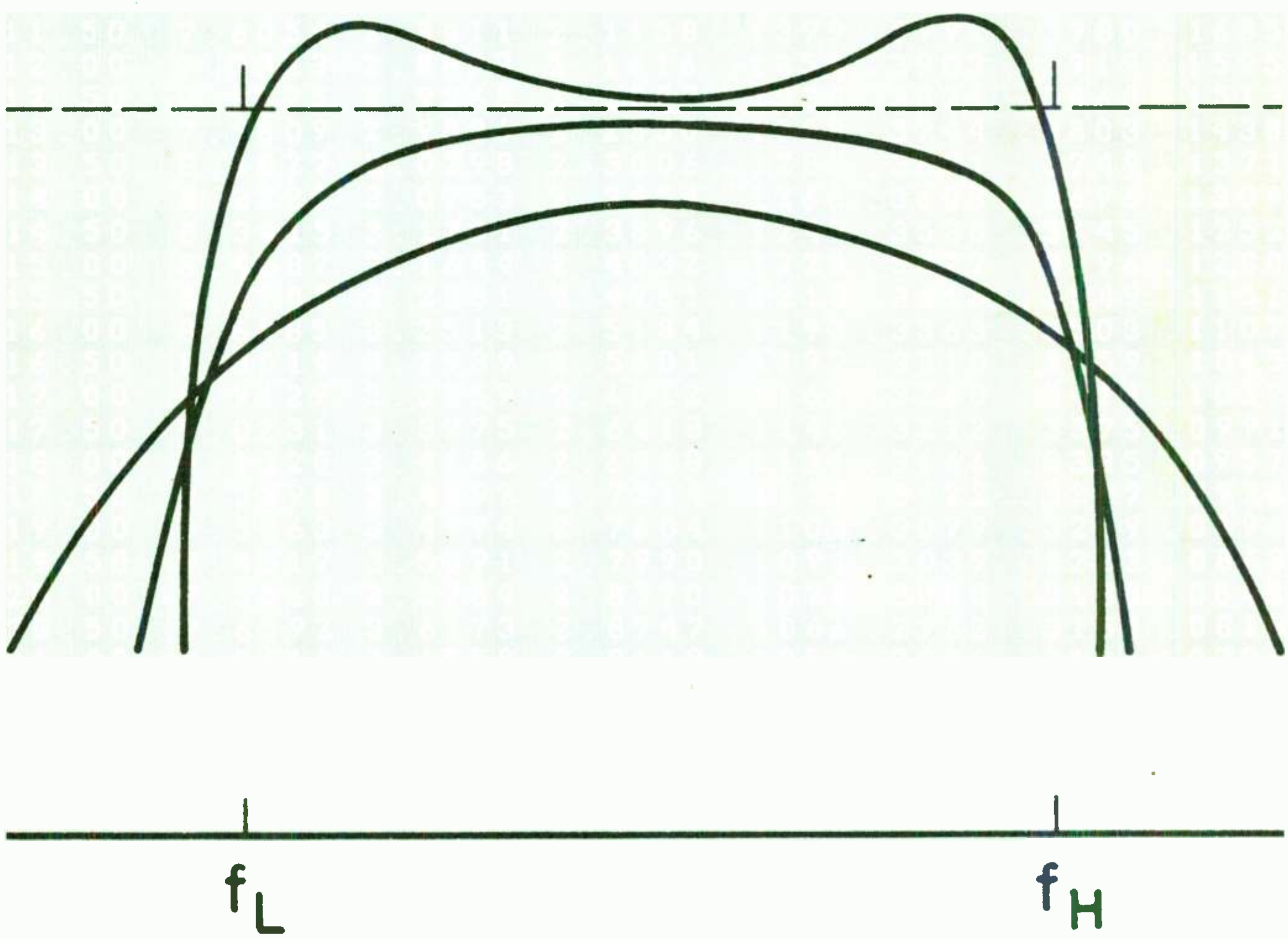
# SPEAKER BUILDER



## PASSIVE THREE-WAYS

# Good News

The ATH-V7 represents a marked departure from other stereophones offered by **AUDIO-TECHNICA** in recent years. It is a return to standard-sized phones designed chiefly for home or studio use. A frequency-response range of 20Hz to 20kHz and improved comfort are the phones' two strongest selling points.

Weighing in at just more than six ounces, the ATH-V7 has a foam-padded circumaural ring, which supports the phones at a slight distance from the outer ear and seals out extraneous noise. The phones' broad headband and continuously adjustable head size are added comfort factors. The unit includes a combined straight and coiled 2-meter cord that is terminated in a standard ¼-inch phone plug.

Write to Audio-Technica, 1221 Commerce Drive, Stow, OH 44224, for details.

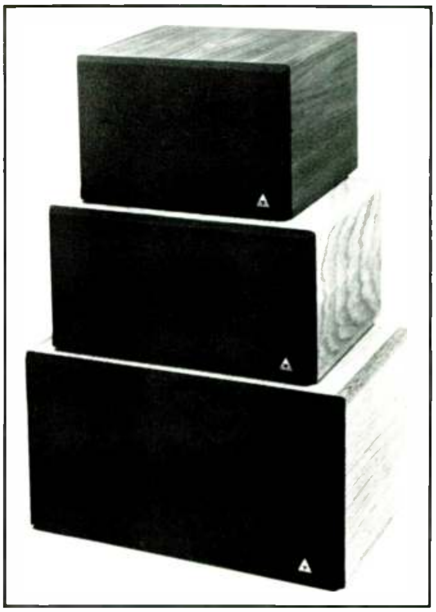
***Fast Reply #GH22***

The **ACOUSTIC DESIGN GROUP** has introduced four new subwoofers known as the High Speed Woofer (HSW) series. These bookshelf-sized components use the same 70W amplifier that powers the Triad 70's woofer and feature all-wood cabinet construction. The units may be positioned horizontally, for a rack or shelf installation, or vertically. All roll off at 12dB/octave above 110Hz and reportedly deliver accurate sound down to 24Hz.

The HSW-100 is the smallest and least-expensive speaker in the line, employing just one 6½-inch Vifa driver. The HSW-150 has one 8-inch driver, while the HSW-200 contains two 6½-inch drivers. The largest unit, the HSW-300, contains a pair of 8-inch drivers.

To find out more about the HSW series, contact the Acoustic Design Group, 0826 Highway 133, Carbondale, CO 81623.

***Fast Reply #GH1036***

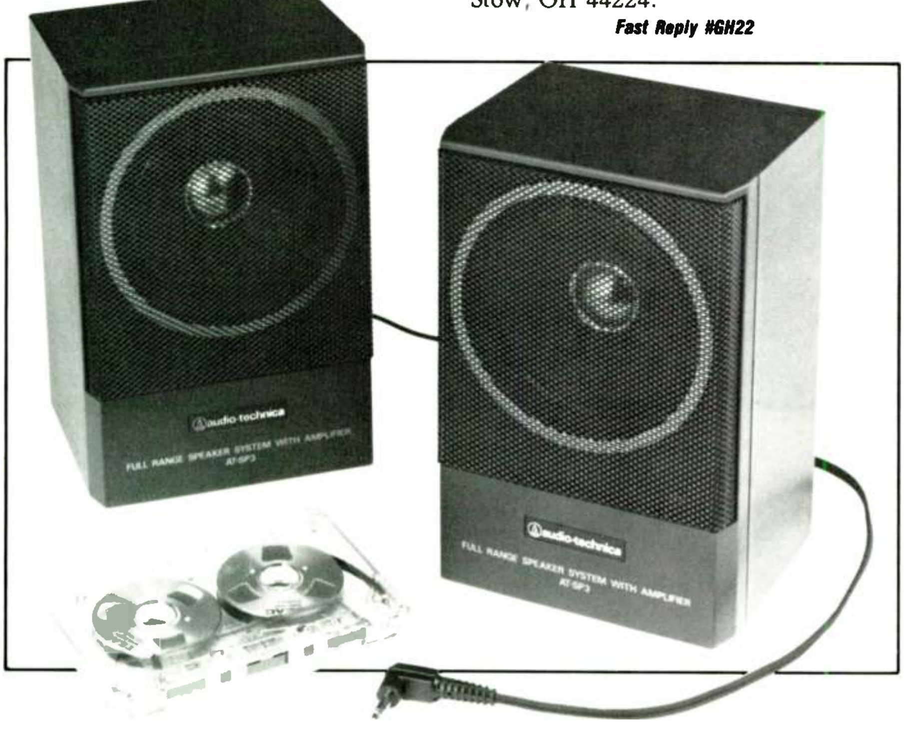


The **AUDIO-TECHNICA** AT-SP3 mini-speakers are designed primarily for use with pocket-sized tape recorders and AM/FM receivers to convert them to miniature stereo systems. They can, however, be used with a full-sized radio, recorder or TV set for low-level, semiprivate listening. Despite their small size, the speakers are said to reproduce sound faithfully over a 200Hz to 16kHz frequency range.

The AT-SP3 speakers measure only 6 by 3⅞ by 3¼ inches. Powered by four "C" cells per speaker or by a 6V DC battery eliminator (optional), they feature a 3-inch driver and a compact, built-in amplifier. Packed with each pair is a 2-meter cable with one stereo mini-plug and two mono mini-plugs for easy connection to associated electronics.

For additional information, contact Audio-Technica, 1221 Commerce Drive, Stow, OH 44224.

***Fast Reply #GH22***



The Model One, **ACOUSTAT's** first single-panel electrostatic system, is ideal for small to moderate-sized listening rooms.

The new speaker incorporates Acoustat's proven electrostatic panel and drive technology. It has an 18-inch subwoofer with a 10-inch, dual-voice-coil, floor-loaded dynamic subwoofer. The frequency response is 30Hz to 18kHz, ±3dB, while the sound pressure level is 108dB, measured at 15 feet in a 14-by-18-foot room. The unit's minimum power requirement is 75W/channel, and its nominal impedance is 4Ω. Like the company's larger systems, the Model One carries Acoustat's lifetime warranty.

Additional information is available from Acoustat, 3101 SW First Terrace, Fort Lauderdale, FL 33315.

***Fast Reply #GH323***

The Gold 3.0 ribbon satellite speaker is a phase-coherent line source capable of handling complex musical transients effortlessly and without coloration. The voice coil is made of pure gold to provide natural, transparent sound. Efficiency measures 91dB for 1W input at 1 meter, while frequency response is specified at 200Hz to 30kHz, ±3dB. The Gold 3.0's power-handling capability is 20W to 500W/channel RMS, and its impedance is resistive in either 2 or 4Ω configuration, ±0.1Ω 20Hz to 30kHz.

Details on the Gold 3.0 are available from **GOLD RIBBON CONCEPTS,** 211 East 11th Street, Iowa City, Coralville, IA 52241.

***Fast Reply #GH915***

**RAPID SYSTEMS** has announced two new products for IBM, Apple and Commodore personal computers. The first is an easy-to-use digital oscilloscope. This four-channel scope has a 2MHz sampling rate, 500kHz analog bandwidth and diode protection on all inputs. Its graphics display is color enhanced, using up to 138 by 288 pixels for data display (up to four traces) and four lines of text for initial (default) values of the scope's parameters. A fast, informative, menu-driven operation provides keyboard control of gain parameters for channels A–D, time base values, number of channels and trigger mode. All the post-processing capabilities of the computer are also available to store and retrieve waveforms from disk and analyze and process information. The device includes all the connections to the computer and a program disk. Probes are not included, but may be ordered separately.

The second product is a spectrum analyzer that incorporates all the features of the Rapid Systems oscilloscope. It is especially appropriate for applications such as signal, transient, frequency, ultrasound and audio analysis; Fast Fourier Transforms (FFTs); frequency counting; and chromatography. Special features include variable FFT order, sample frequency choices from 100Hz to 500kHz and input voltage choices (peak to peak) from 1.6 to 320V.

Both peripherals are available from Rapid Systems, 5415 136th Place SE, Bellevue, WA 98006.

*Fast Reply #GH948*

SPEAKER BUILDER
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## About This Issue

**Scott Ellis** leads the parade of articles (p. 7) with his mid and high-frequency drivers, mounted on flying pylons anchored by a dual-woofer bass enclosure. This is a demanding and sophisticated project, especially designed for woodworking wizards.

Subwoofers are steadily gaining popularity. **Phil Todd's** design, beginning on page 20, is exceptionally compact for its range and power, making it more acceptable in the listening room than many other units.

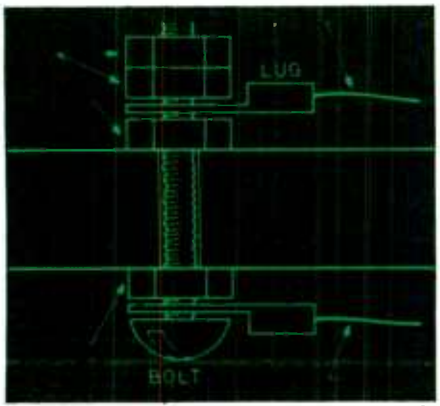
Contributing Editor **Bob Bullock** moves to three-way passive configurations in Part II of his crossover series (p. 26), offering helpful tables of data as well as more insight into how design choices affect radiation patterns.

**Gary Galo** has been busy evaluating drivers suitable for transmission-line designs (p. 40), especially those using some new material combinations. And several fine offerings in "Tools, Tips & Techniques" (p. 43), plus a very lively "Mailbox" (p. 46), complete this first-ever 56-page issue.

Next time, look for a primer on Fourier Transform analysis, along with a revealing exploration of the Strathearn and how to improve it, an ambience system, a sand-filled speaker stand, a construction project based on Ivor Tiefenbrum's famous Isobarik design, and more from Bob Bullock on the best way to do crossovers—electronically.

# SPEAKER BUILDER

VOLUME 6 NUMBER 2 MAY 1985



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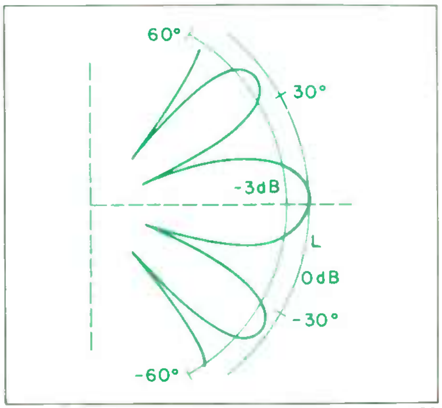

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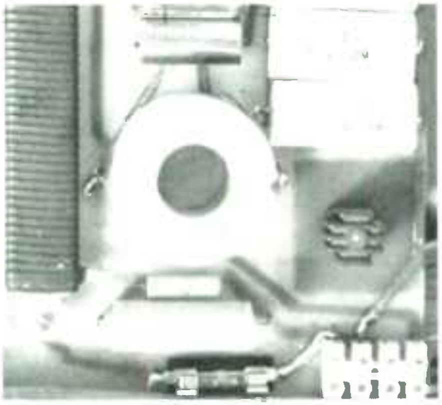


18

## FEATURES

## DEPARTMENTS

# Editorial

## RAFT REFITS

Spring is arriving in New Hampshire as I write this. The windows are opened late on these cool mornings, and the trees show clear signs of new leaves to come. Spring brings other signs as well. Construction projects bloom in all directions. Digging machines appear, and forms for concrete are set in place. Big-city projects attract onlookers, who line the fences and barriers.

I have accepted, as editor of this and our other publications, the spectator quotient in all humans. There is something attractive, not to say compelling, about watching someone else at work. Part of the charm is, I suppose, that someone else is doing the labor. But there is also the fascination of seeing something being made. Even the most basic building project has some unique charms. Further, the techniques a worker commands almost always contain surprises, information that is new and unexpected, especially if the spectator has done the task or has seen it done before. Something in many, if not most, of us wants to do the work.

While being a spectator and enjoying the vicarious pleasure of watching another at work is easy, it can become a habit, even a substitute satisfaction for the real thing—doing it yourself.

Recently, I received a letter that is fairly typical of those arriving in our office every three or four months. Like many of us, this reader had, until recently, had his elbows firmly planted on the site fence, watching intently while others wrestled their speaker projects into shape. His story is one of long hesitation, until he finally decided on his first system, which went together smoothly and produced results that filled him with delight. After reading and dreaming for five years, he was most surprised that he was a capable speaker builder.

In some ways, I believe, all of us have been slipped a nasty little piece of pernicious propaganda about ourselves and our abilities. "All thumbs" is the term this reader used about himself. It is no accident that many people feel the same way. "Why risk all that money on botching up a project, when you can, by paying a bit more, get the finished product in your living room tomorrow?"

Any of us who stops to think for a minute can come up with several good reasons why many sales pitches follow that line of reasoning. Then, too, the big ad agencies often imply that a particular manufacturer can make a product far better than you can.

Our attitudes about our own abilities are formed very early. Indeed, they seem to be in-born, but they are, in actuality, ideas we learned from someone—possibly even ourselves. And if we learned them, we can examine, question and probably change them.

Why do so many of us go through life thinking we are "all thumbs"? All of us require a set of basic beliefs about life's meanings and about ourselves. It takes courage to examine those assumptions because any challenge to them is risky, and changing them feels a bit like rebuilding your life raft while riding out a storm.

But our fears are always clues to our limitations. And those limits, as far as our skills are concerned, may be no more than fears. Our correspondent surprised himself. That inner voice, which speaks so insistently to most of us about our limitations, can be proved wrong if we are willing to think about the origins of our fears—and recognize what Madison Avenue has to gain by playing on them.

Fear has its uses, of course. No speaker builder should approach a power saw without a healthy awareness of its dangers. Although fear is a necessary ingredient in most innovative action, if it keeps us permanently in the bleachers and never allows us on the playing field, it is time to question our basic assumptions.

It's spring—a good time for cleaning out the rubbish and beginning anew. Try a kit first and surprise yourself. Believe in the surprises your latent skills present to you, and refuse to be cowed any longer by fear of failure.

When your kit project is complete, plan your next project—perhaps a scratch-built system. By taking chances, you will not only learn a great deal, you will no doubt find yourself on a finer life raft than ever before.—E.T.D.

# THE CURVILINEAR VERTICAL ARRAY

### BY SCOTT ELLIS

The trend in loudspeaker design has been toward systems with low time-domain distortion (phase coherency), reasonable amplitude vs. frequency response (flatness), minimal diffraction effects, and low distortion in the bass region. I took these characteristics into consideration when designing my Curvilinear Vertical Array (CVA) *(Fig. 1)*. I used a push-pull bass system in a B4 alignment, three large dome midranges and two ribbon tweeters.

The woofers are loaded by a large (200-liter) enclosure, while two of the midranges and the tweeters are suspended between upright pylons for minimum baffle diffraction. This allows you to shift the position of the midranges and tweeters with respect to the woofers and to each other. I constructed a series monopole crossover with high-quality components and used a Zobel compensation network to stabilize woofer impedance characteristics. Although some of you might wish to execute this design in a different way, my experience will give you some point of reference.

**THEORY.** A line array has a number of desirable properties. First, all its interference patterns are confined to the vertical plane. Each driver interacts only with its immediate neighbor, above or below. The lack of interference in the horizontal plane means that the array's dispersion is fan-shaped, with consistency throughout

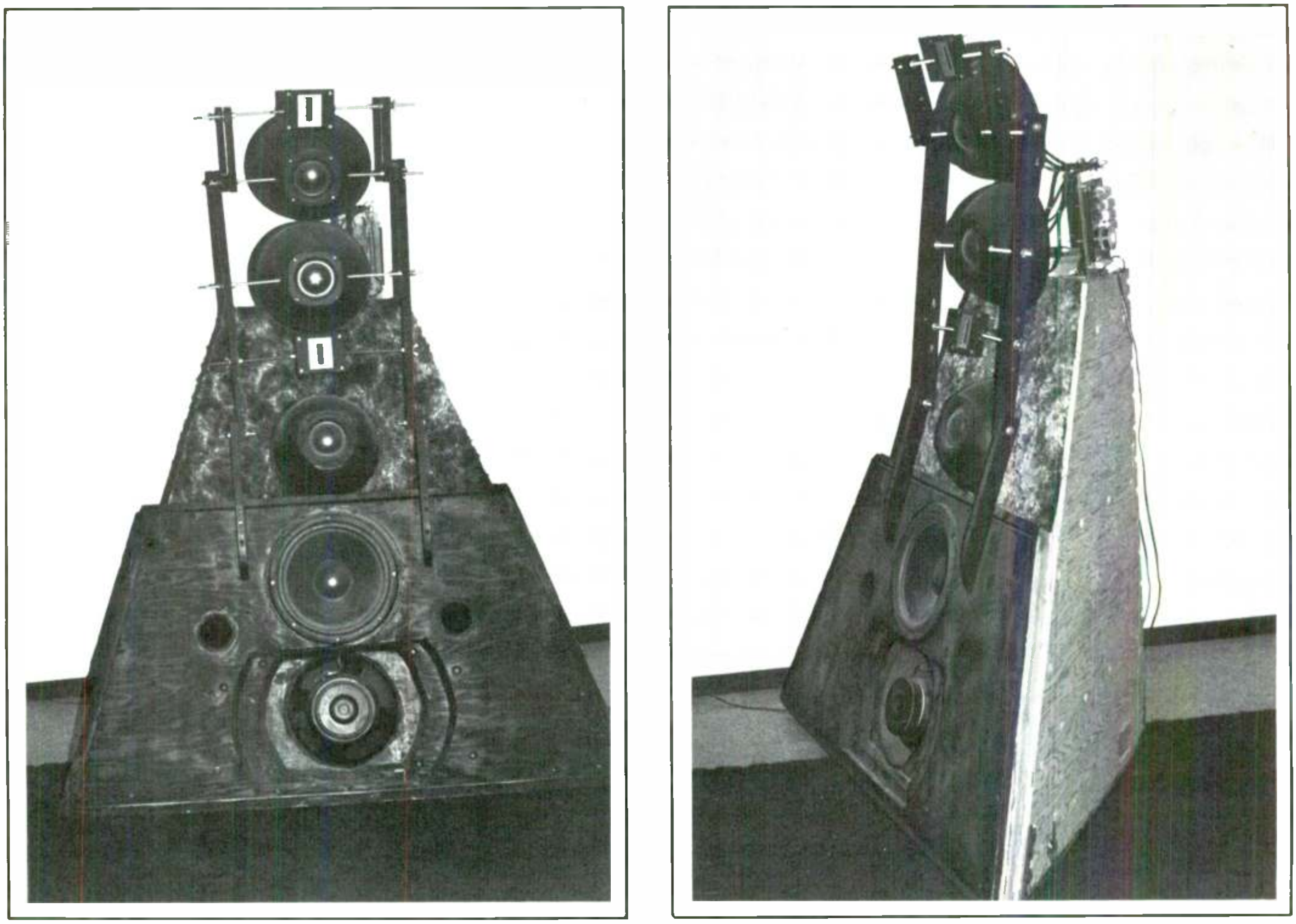


FIGURE 1: Front (a) and three-quarter (b) views of the Curvilinear Vertical Array (CVA).

the arc of the fan. This also translates into a slight gain in efficiency. All listeners have essentially the same perspective on the array, which helps ensure phase coherency. If you choose high-quality units with limited power-output capability, this design can still achieve acceptable power output, while preserving the drivers' other positive characteristics.

The line array also has a property that would seem to work against it. To maintain the same dispersion as frequency increases, the line must effectively "shrink" (get shorter). If it does not, the treble dispersion pattern becomes quite critical with respect to the height of the listener's ear above the ground plane, and eventually it is confined to a broad but very thin arc. Above or below this arc, the treble response becomes rough.

Several ways of shrinking the line exist.[1] First, you may locate the tweeters in the center and use absorbent materials as low-pass filters for all but the central drivers. The crossover may route only treble to the central drivers. With planar-type drivers, you can make the central cells smaller and thus have a higher operating range. When properly constructed, the line shrinks with increasing frequency until it is more or less a point source. Bear in mind, however, that the dispersion at high frequencies can be no greater than that of the smallest driver.

You may also curve the line slightly inward. A curved line has three advantages over a straight line: it allows you to place all the drivers equidistant from the listener's ear; it reduces ceiling reflections somewhat by aiming the top drivers downward; and it offers a slight gain in efficiency because the drivers are closer together and reinforce each other's output. Because the curved line is effectively smaller in the horizontal plane, however, its response off-axis is slightly higher than that of a straight line. This results from the formation of two side lobes, as Olson documents.[2] Sometimes the difference is audible with noise signals or when the listener is moving in a horizontal arc close to the array where the direct field dominates. In a typical listening room with music, reverberative effects dominate, and the lobes are not apparent. I think this is a minor problem in light of the CVA's other advantages.

**DESIGNING THE LINE.** The first step in designing the line is deciding what height can be tolerated. In some respects, the bass system will determine this. Assuming that the line array will be for the midrange up, the wavelengths involved make a true line array for bass prohibitively large. Because the line-array effect does not occur unless the line is long with respect to the lowest wavelength (about 1 to 2λ minimum), the height (line length) must be about 36 inches minimum if the array is to cover frequencies above 500Hz. This is the length of the midrange/tweeter array and does not include any contribution from the bass enclosure height.

If you use planar elements (e.g., planar magnetic or electrostatic), the height of the array will depend on the surface area required for acceptable power output. Naturally, you would like to make the planar array as large as possible, but in practice, you must compromise to fit the typical 8-foot room clearance.

The curvature of the line depends on the distance from the array to the listener's ear. *Figure 2* shows my listening room in elevation, with nominal ear altitude as the focus of the curvature (about 30 to 36 inches above ground plane). The arc represents the curvature the array would take at the desired listening distance. As you can see, the closer the ear is, the greater the curvature. Conversely, the greater the ear distance, the more gentle the curvature. At some distance, the curve might as well be a straight line because the path differences from the array elements and the ear will subtend a very shallow arc. In my experience, this happens at a distance about three to four times the array height. For a 6-foot-high array, this translates to a distance of 18 to 24 feet, which is not a problem in most listening rooms. You can construct the array so that you may adjust the curvature to suit the listening distance.

**DRIVER SELECTION & SPACING.** To select drivers for a line array, you may use the same criteria as for other systems, except (all other factors being equal) power output is not as important. I would advise that you choose the best drivers, regardless of how many you can afford. Don't be tempted to buy several cheap drivers just to fill up the line.

Several commercial systems have come out with line arrays of midranges and/or tweeters. Unfortunately, most place the midrange and tweeter lines side by side, creating horizontal interference patterns. In my experience, interleaving the midranges and tweeters works best and minimizes driver-to-driver discontinuity. The line effect is largely lost if you space the drivers farther than 1λ away at crossover. Keeping in mind the need to shrink the line, place the tweeters at or near the center. In some cases, only one tweeter, placed directly in the center, is necessary.

If you use drivers with similar dispersion characteristics (e.g., dome mids and dome tweeters), space the midranges and tweeters 0.75λ apart at crossover to minimize interference. If you use horn tweeters with cone or dome midranges, the spacing may be closer, as the typical rectangular horn

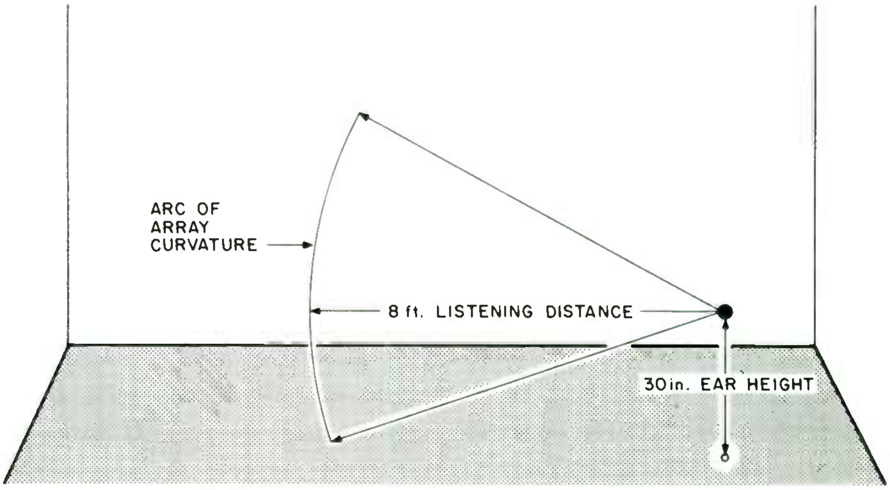


**FIGURE 2:** Array curvature versus listening distance and ear height in the author's listening room.

has a narrow vertical dispersion compared with its horizontal dispersion. Thus, vertical interference will be minimized. Do not turn rectangular horns on their sides (long dimension vertical). Doing so results in a narrow dispersion pattern and severe vertical interference. This does not apply to vertical slot horns, such as ribbon tweeters, which have some surprising interactions when used in multiples.

**CVA DESIGN.** As I mentioned before, I made a scale drawing of the listening area in elevation and then scribed an arc from the nominal ear altitude. Because the curvature varies with distance, I made it adjustable by suspending the top two midranges and the tweeters between pylons, which can pivot in the vertical plane. I mounted the drivers on minimum-area baffles, which are suspended between the pylons on $\frac{5}{16}$-inch threaded rods. This arrangement also allows me to "break down" the system for transport or storage.

In positioning the drivers, I referred to Heyser,[3] who has shown that the acoustical position of a driver is not a fixed point in space but a continuum of points lying in the voice-coil plane and behind it. Thus, rigid positioning on a fixed baffle cannot solve phasing problems, even if the voice coils lie in the same assumed plane. Heyser suggests that you must compensate for driver acceleration time. Since few of us have the equipment to conduct time vs. frequency tests, my approximation assumes that the woofer is slower than the midrange and that the midrange is slower than the tweeter. Because Heyser found that for many moving-coil drivers, the continuum of positions lies behind the front edge of the voice coil, I decided that I would place the rear edges of the voice coils (or the drive membrane for the tweeter) along the arc.

I made each pylon in four parts. The lower part of each attaches to the front of the woofer baffle *(Fig. 1b)*; the second midrange and first tweeter are suspended from the middle part of the pylons; and the top two pylon parts allow proper positioning of the third midrange and second tweeter.

One of the differences between a curvilinear array and the typical staggered vertical array is that although the voice coils might not appear to be in the same plane, the actual distance from each voice coil to the listener's ear is the same. This is why in *Fig. 1* the first midrange appears to protrude beyond the woofers. In fact, all the drivers fall along the arc, within the limitations of the pylons.

**BASS ENCLOSURE DESIGN.** Although the enclosure can be as large as you wish, practically it should be able to fit through a standard door. In an unpublished paper, Small[4] cites 200 liters as the minimum volume for acceptable efficiency at low frequencies using realizable drivers. Previously, I have used triangular cabinets, which are rigid, reduce internal standing waves and allow corner placement. In this case, I used a truncated tetrahedron, which allows the maximum volume without being too tall. The volume of a truncated tetrahedron is expressed as the following:

$$V = (\tfrac{1}{3}H)(b+b'+\sqrt{bb'})$$

where b is the area of the base, b' is the area of the cap, and H is the height *(Fig. 3)*.

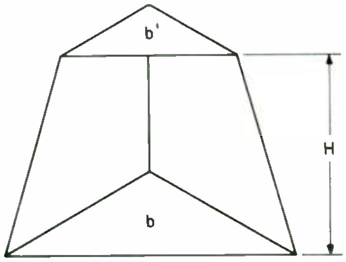


FIGURE 3: Designations for the tetrahedral volume formula (see text).

In the CVA, diffraction effects are controlled by the baffle shapes, suspension of the baffles away from other surfaces and appropriate use of absorbent materials. The tetrahedron shape of the woofer baffle has the advantage of making the transition from $2\pi$ loading (due to the woofer baffle) to $4\pi$ loading (room boundaries) quite gradual over the top two octaves of woofer response (500 to 125Hz). In addition, because of its size and shape, no absorbent material is needed on its face.

The midrange baffles are just the right size to minimally baffle the drivers above 500Hz, which ensures good passband efficiency and enhances cutoff below that point. Being hemispherical, they reduce diffraction effects in the passband. The tweeters have absolute minimum baffles—i.e., no baffles at all. The mounting blocks are behind the tweeter flanges.

The upper two midranges and the tweeters are suspended between the pylons. The pylons themselves are the minimum size for mechanical stability. The first midrange, being mounted in the top front panel, is a special case. Ideally, the surface from the driver to the panel should be tapered. This driver is mounted on a hemisphere, however, and the panel behind it is covered with deep-pile carpet. In addition, the ledge formed by the top of the woofer baffle escutcheon is covered with ¼-inch felt to reduce reflections.

Other authors[5] have described Thiele/Small alignment in detail, but I would like to emphasize that with two woofers, you must double $V_{AS}$.[6] Fellow speaker builder James Pharris ran the alignments for me on his personal computer, which saved time and frustration. To offset the slight $V_B$ loss from the protrusion of the subenclosure, I made the vents slightly longer than the results indicated. This is in keeping with Keele's recommendations.[7] I think that using two woofers in push-pull operation averages out driver parameter variances so that the tuning is not quite as critical as with a conventional single-woofer system.

I used Peerless TA-305F polypropylene woofers, which offer a good price/performance ratio. Their impedance and inductance are compatible with my crossover parameters. I chose SEAS H-204 midrange units, which have a 3-inch polyamide dome and a flat amplitude response. This unit's impedance curve is quite flat, too. Although I was concerned about the dispersion of the large diaphragm, listening tests dispelled my fears. The large diaphragm and the use of three drivers keep modulation (Doppler) distortion at a minimum. The midrange units, which come with a subenclosure, roll off fairly steeply below 500Hz, so I chose that point as the first crossover. Because these drivers' dispersion begins to roll off above 6kHz, that point became the second crossover.

The two JVC ribbon tweeters were the easiest to select. As Lampton notes,[8] their performance is superb, and they present a purely resistive load.

**ENCLOSURE CONSTRUCTION.** The main advantage of push-pull operation is a reduction of even-order harmonic distortion. Because the drivers are being driven in opposite directions, distortion due to nonlinearities are effectively canceled out. The lower driver faces into the enclosure, so the enclosure "sees" the two cones as moving in the same direction.

To have a flush front panel, the inner-facing (lower) woofer must be mounted in a well, and the well must allow you to align the two voice coils. The well must also be constructed so as to avoid Helmholtz-resonator effects and any tendency to horn-load throughout the woofer passband. Due to space limitations, I made the well cylindrical for the first 4.5 inches and then in two flaring sections.

The entire enclosure has double walls, the outer of plywood and the inner (stiffener) of particle board. *Figure 4* is a cutting guide for the plywood pieces. The stiffener dimensions are shown in parentheses. (See *Fig. 5* for a detail of the woofer baffle.) The walls are joined with construction adhesive and lag screws. I chose lag screws because you can drive them with a socket wrench, provided you drill the countersink holes large enough.

After you fasten the particle-board stiffeners to the plywood outer walls, varnish the stiffeners with polyurethane to prevent absorption of moisture. Two coats are necessary, as the particle board is quite porous. Note that the particle-board stiffeners stop about 2 inches short of the cabinet edge to allow clearance for the inward-facing woofer and the woofer-baffle stiffeners. Two 2-by-4 stiffener blocks reinforce the inside corner. One is located at the bottom intersection of the bottom stiffener and the side stiffeners; the other is located about halfway up the inside corner. Mount these so that the long faces of each block abut opposite stiffeners *(Fig. 6)*. Attach them with adhesive and lag screws. The bottom plate requires at least two coats of polyurethane to prevent moisture damage. Make sure you also cover the screw heads.

An escutcheon *(Fig. 7)*, which projects 2½ inches from the front edge of the woofer cabinet, carries the woofer baffle forward. The escutcheon also mounts the cleats for the woofer baffle and the cleat that secures the bottom edge of the top front panel. Due to the tricky compound angles involved, I strongly urge the use of a table saw or an adjustable, large-capacity miter box. I made my first cabinet with hand tools and had to recut more pieces than I care to remember. Because the exact angles depend on how the side panels fit, it is best to custom-fit each escutcheon to each cabinet.

Attach the escutcheon to the inside of the cabinet with flush-head wood screws. Tack the cleats into position with nails, then glue and screw them in. The cleats need not abut the inside stiffeners. After you have installed the escutcheon, attach the cleat for the top panel. Fasten the cleat to the top part of the escutcheon with glue and screws, and drive a wood screw through each side panel into the cleat.

Cut a 4½-inch hole in the top panel *(Fig. 8)* for the first midrange. The panel has a 3/16-inch groove routed ¼-inch deep up the middle to permit the lead to rest flush. This allows you to lay the carpet or other absorbent pad over it. After you have cut the top panel and its stiffener, epoxy them together and then clamp them at the edges with C-clamps. Two C-clamps should also hold the pieces together at the hole. Put the top panel into the oven at 250°F for 20 minutes. After you shut off the oven, leave the panel inside until the C-clamps are cool enough to touch.

Fasten the front panel to the cleat with a bead of construction adhesive and lay a bead of adhesive along the inside edges at the sides. Press the top panel into place and drive wood screws through it and into the cleat.

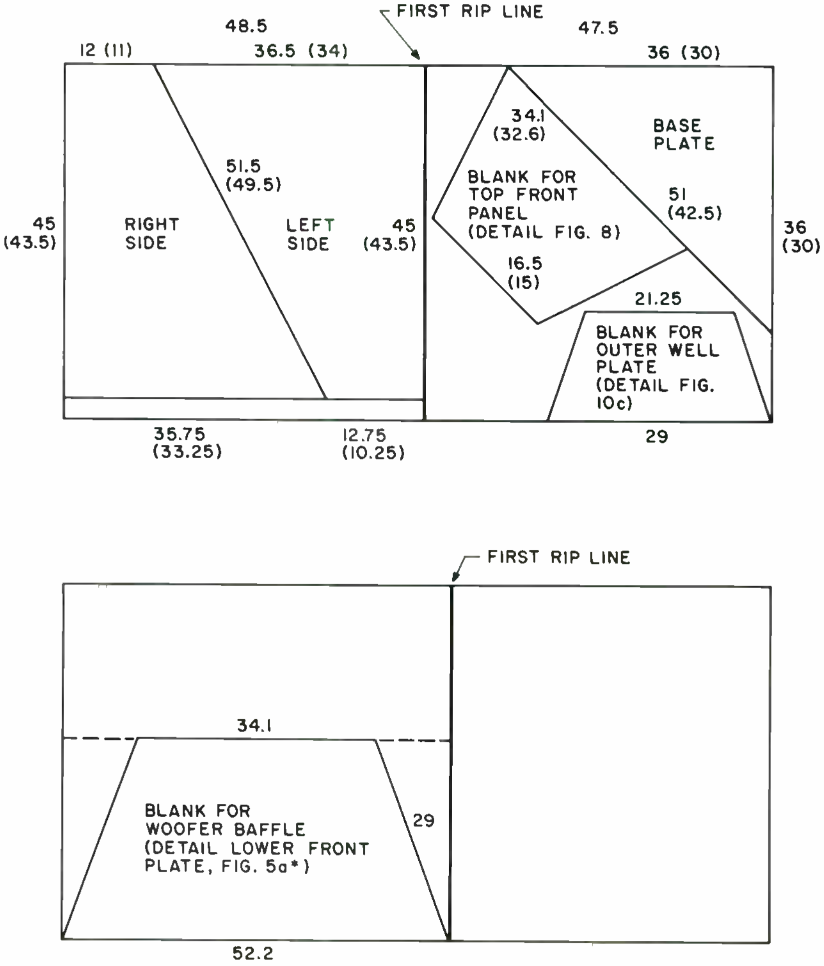
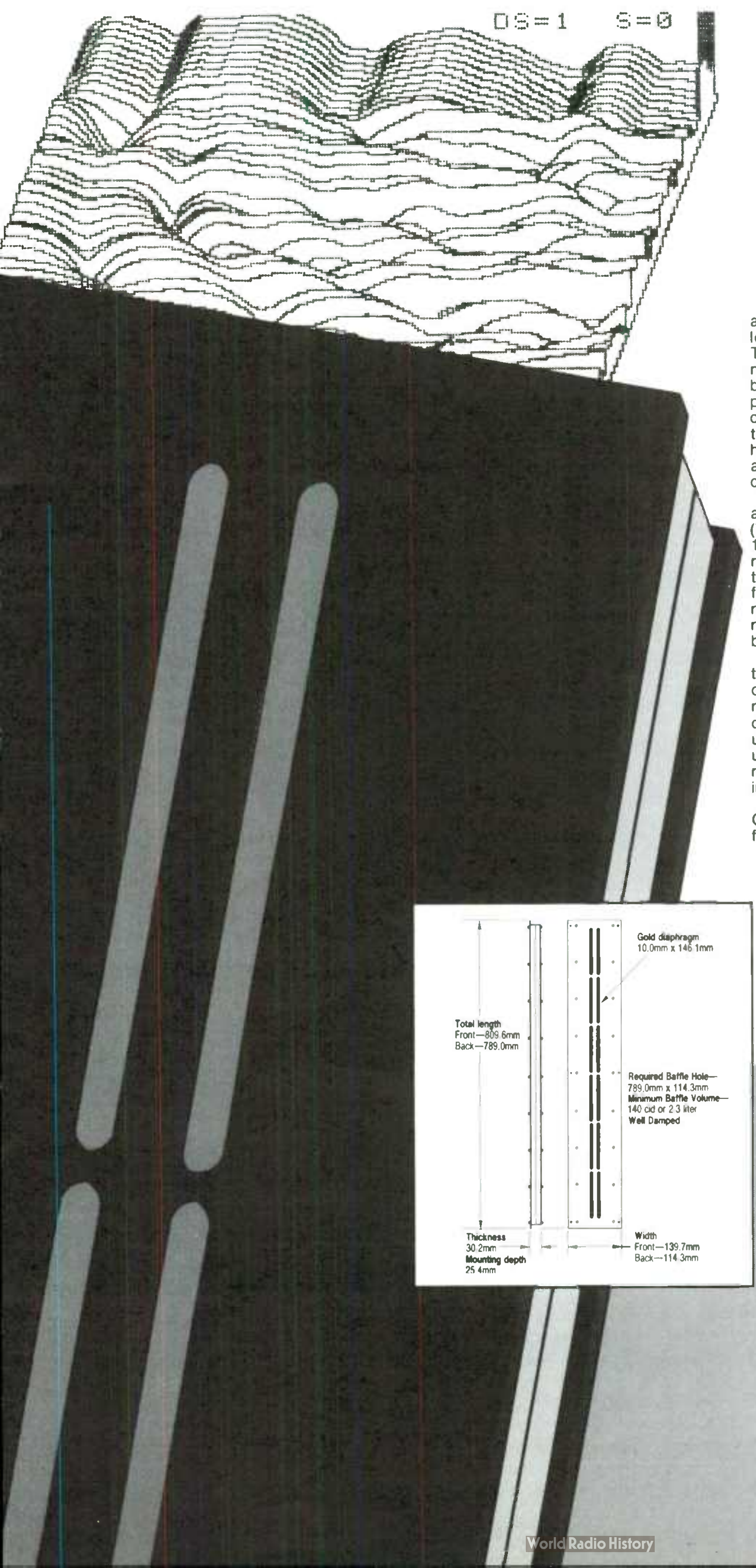


*FIGURE 5b SHOWS THE STIFFENER.

ALL DIMENSIONS IN INCHES.
——— PLATE CUTS
– – – – CONVENIENCE CUTS

**FIGURE 4: Cutting guide for the two sheets of ¾-inch plywood. Use the dimensions in parentheses when cutting the particle-board stiffeners.**



# THE GOLDEN RULES

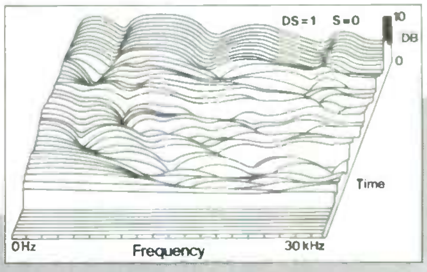
Historically, the ribbon loudspeaker has been an interesting alternative to high-performance loudspeaker design since the early 1930's. Though cost-effective production technology has not been available until now, ribbons were seen by many as an attractive solution to the inherent problems which continue to plague even the best dynamic, electrostatic, and field-type transducers today. Vacuum technology and computerization has enabled Gold Ribbon Concepts to present an affordable esoteric loudspeaker for the 21st century. For example. . . . . .

Most dynamic cone loudspeakers are rated at approximately 3% Total Harmonic Distortion (THD). The GOLD 3.0 ribbon satellite's THD is 1/10th (.3%) this amount. And with a moving mass close to a gram per 1100 grams of magnet, the rise and decay speed of the GOLD 3.0 is so fast that it can best be exhibited as a live sound reinforcement transducer, where the dynamic range exceeds even digital recording capabilities.

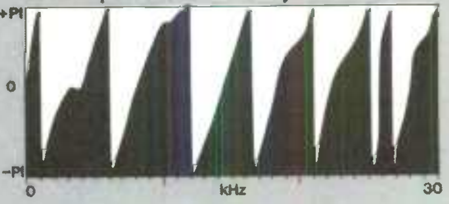
The GOLD 3.0 operates from 200 hz to 30kHz, thereby releasing speaker designers from the complex phase and distortion problems which result from the use of cross-over networks in the delicate vocal region above 200 Hz. And for unparalleled accuracy, Gold Ribbon Concepts uses computerized manufacturing techniques to match each GOLD 3.0 voice coil to within an incredible thickness tolerance of 25 atoms.

The performance of the Gold Ribbon Concepts GOLD 3.0 ribbon satellite is best illustrated in the full expression of a beautiful piece of music.

GOLD 3.0 Time Delay Spectrum Analysis



GOLD 3.0 Phase Response — Graphic Plot Delay



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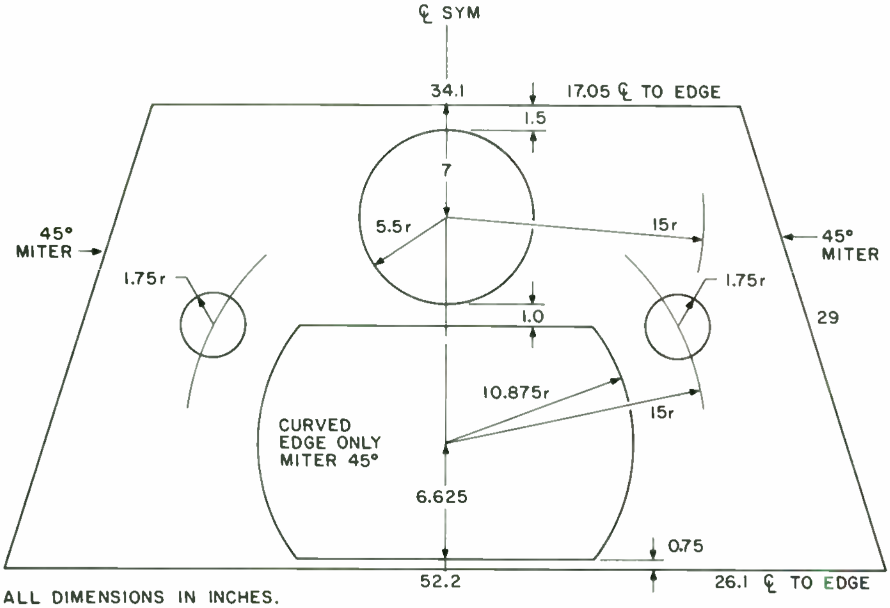

**FIGURE 5a: Detail of the woofer baffle.**

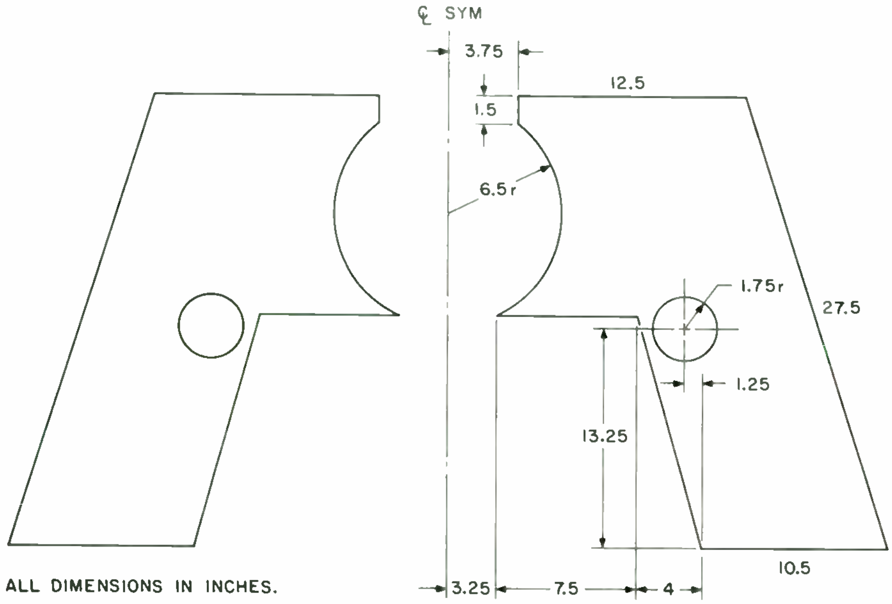

**FIGURE 5b: Detail of the woofer baffle stiffener.**

Also drive screws into the top panel (not the stiffener) from the cabinet sides. No cleats are used at the sides or top of the front panel. You should also drive screws through the inside of the top part of the escutcheon and into the front panel edge. All this gluing and screwing is vital to prevent flexure at this joint.

After you have attached the front panel, install the first midrange (see mounting details below). The subenclosure will protrude a few inches into the interior. Dry-fit the first midrange and its baffle into the hole and run a pencil around the edge where the baffle meets the front panel. Remove the midrange and baffle and run construction adhesive in the circle and around the hole, slightly overlapping the line. Line the inside of the first midrange baffle with Thermatex®, then stuff it with dense plastic foam. (The aerosol-type rigid foam also works.)

Thermatex is a tape made by RDM Products that consists of ground cork in a rubber matrix. It is commonly used to wrap air-conditioning pipes and is much neater than roofing tar or hot modeling clay. It is also fine for gasketing, although I cannot recommend it for large areas, as it costs about $1.40 per square foot. I also used it to damp the woofer frames and midrange subenclosures. You can find it at plumbing, heating and air-conditioning supply houses or at appliance suppliers.

Cut a notch in the top center of the midrange baffle to allow the lead to pass into the routed channel in the top panel. Press the midrange and baffle into the bead of adhesive and lay the entire cabinet down, supporting it from the sides so that the front panel faces up. This allows gravity to pull the midrange baffle down onto the glue. Don't worry about the seam of glue at the edge of the baffle. It will not show after you install the carpet pad.

After at least eight hours of drying time, set the cabinet upright and put a bead of sealant around the inside edge of the subenclosure where it passes through the front panel. Now put a double-layer of Thermatex on the part of the subenclosure that protrudes into the interior.

The next step is installing the enclosure cap *(Fig. 9)* and its stiffener. Note that the cap and the stiffener are the same size and are both made of ⅝-inch particle board. Epoxy-bake them together as you did the front panel, then drill four ⅛-inch holes for the woofer leads. Run a bead of adhesive around the top edges of the side and front stiffeners, then set the cap into the triangle formed at the top of the cabinet, tapping it into place with a plastic mallet. Before the adhesive sets, drill twelve (four per edge) countersunk holes for the wood screws that will pass through the cap into the stiffeners. Doing this while the glue is still tacky allows it to set around the screws, forming a solid bond. Because the midrange subenclosure and crossover will cover the top of the cap, no

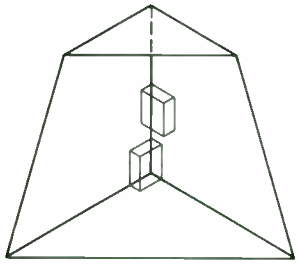

**FIGURE 6: Placement of the inside stiffener blocks.**

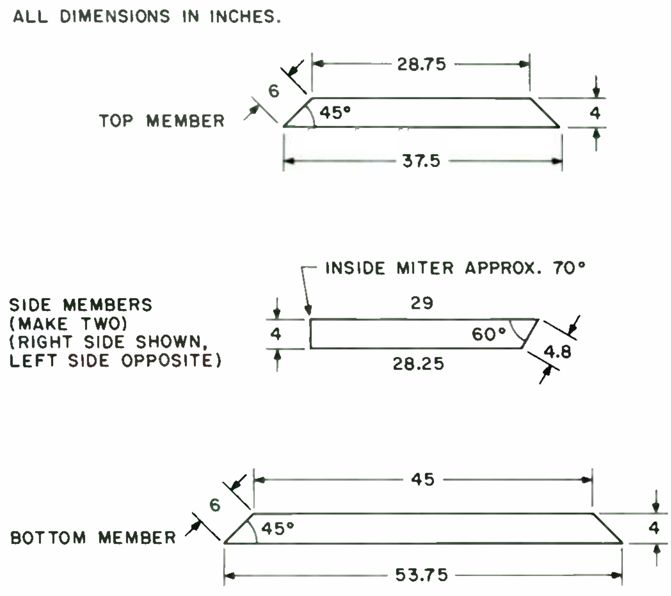

**FIGURE 7: Cutting guide for the escutcheon, which projects 2½ inches from the front edge of the woofer cabinet and carries the woofer baffle forward.**

decorative finish is required. Give the cap a coat of polyurethane to protect it.

The well *(Fig. 10a)* is made of six hexagonal boards with the woofer opening cut in the middle *(Fig. 10b)*. Epoxy the boards together, bake them in the oven at 250°F for 30 minutes, then let them cool for an hour. Join the outer, flared section *(Fig. 10c)* to the well with lag screws and adhesive, then join the entire well assembly to the woofer baffle. Drill a 5/16-inch hole through the top of the well so that you can attach the #12 wire leads to the inner woofer terminals.

After you have installed the woofer in the well and attached the leads, fill the lead "tunnel" with sealant until it squirts out the other end. Allow the sealant to cure thoroughly before moving the leads. (See the section on crossover construction below for details on wiring the system.) Because the #12 leads are so large, it is difficult to solder them to the woofer terminal in the normal way. You must bend the lead into a crook around the terminal, "tack-solder" it against the terminal, then immobilize it with glue. To achieve a finished look, line the inside of the well with 1/8-inch felt.

Cut holes in the woofer baffle and two stiffeners for the two vent ports, which are located by swinging a 15-inch arc from the center of each woofer. Cut the vent tubes from 3/8-inch-thick mailing-tube stock and seal them into the holes with construction adhesive. (PVC pipe would also be fine for these vents.) Join the woofer baffle to the stiffeners with adhesive and lag screws.

**PYLON AND MIDRANGE/ TWEETER MOUNTING.** The pylons are made from 1-by-2-inch nominal larch stock *(Fig. 11)*, which my lumberman obligingly dressed to have true edges. The pylon joints pivot on 5/16-inch, 2½-inch-long bolts. *Figure 11* shows where to drill the holes in the pylons for the driver suspension rods and pivot bolts. Attach the lower part of each pylon to the front of the woofer baffle with two 10-2 wood screws apiece and install the carpet pad before the rest of the pylon parts.

The tweeters are mounted on blocks *(Fig. 12)*, which have T-nuts in their centers. I used pronged T-nuts, which must be driven into the wood after the hole is drilled. Each T-nut requires a 3/8-inch hole chamferred only to the depth of its barrel. The rest of the hole must be 5/16 inch to hold the threaded rod securely. Coat the barrel and inner face of the T-nuts with epoxy, then drive them in with a plastic mallet. Put the blocks in the toaster oven at 300°F for 20 minutes to cure. If some of the prongs stick out beyond the edge of the block, put the block in a vise and rasp the prongs down flush.

The midrange baffles *(Fig. 13)* are actually plastic food-storage bowls. They are the minimum size ($2\pi$) for proper loading at the crossover (500Hz), and being hemispherical,

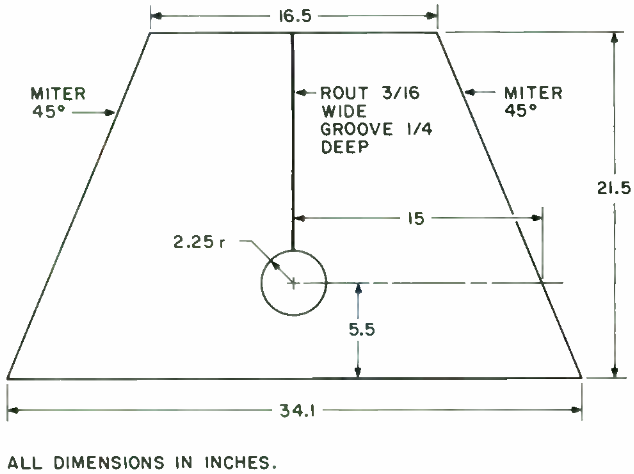

**FIGURE 8a: Detail of the top front panel.**

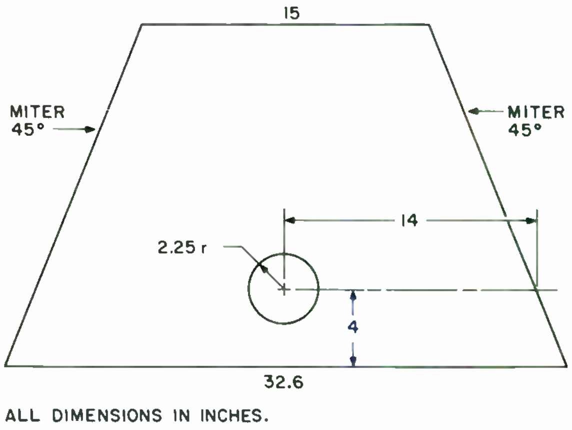

**FIGURE 8b: Detail of the top front-panel stiffener.**

they have little diffraction effect.

Cut the opening at the base of the bowls *(Fig. 13a)* with a fine-toothed (24 teeth per inch) saber saw blade at low speed. Be sure to leave openings at the sides and bottom of the 4½-inch circle for the T-nuts and leads. [Of course, the baffle for the first midrange does not require mounting holes, although you must cut it short to hold the midrange in the proper position *(Fig. 13b)*.] After you cut the openings, scuff the outside with No. 1 steel wool. This roughens the slick surface of the plastic so it will accept paint more readily. I painted my baffles flat black to match the pylons, then set them aside.

Next, mount the T-nuts in the two top midrange subenclosures *(Fig. 13c)*. Ideally, you should use metal collars with tapped holes, but machine shop work is quite expensive. You might be able to make wooden collars at home, but I could not make one that was thin enough to fit inside the baffle and strong enough to hold the midrange. I finally gathered up my courage and very carefully drilled ⅜-inch holes on either side of the subenclosure, just behind the magnet structure. A collar-type stop, set to about ¼ inch on the drill bit, is helpful here.

After brushing the plastic crumbs away from the hole, I inserted a brad-type T-nut, which has no prongs and is usually fastened with brads or small screws. I tried gluing these in with epoxy and silicone sealant, but neither would adhere to the plastic. Finally, I resorted to the same adhesive I used to join the wooden parts. The T-nuts must be seated squarely in the holes to ensure a straight mounting on the threaded rods.

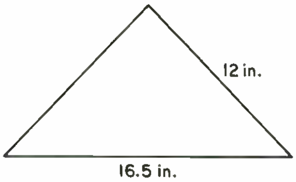

FIGURE 9: Cutting guide for the enclosure cap and stiffener. Both are made of ⅝-inch particle board.

After gluing in the T-nuts, wire the leads (see the section on crossover construction) and mount the drivers to the base of the baffles with machine screws and nuts, using neoprene-backed washers for added holding power on the uneven inner surface. If you see a tiny gap between the driver frame and the baffle base, caulk it with a bit of black silicone seal. The openings for the threaded rods on either side of the baffle are the most difficult to make. I finally used a soldering iron to make an oval opening for the rod to pass through, but a drill press and a jig to hold the baffle in place would probably work better.

The threaded rods are 5/16-inch stock. Although you can cut the rod with a hacksaw (cutting in the "valley" between the thread crests), I recommend having the pieces professionally cut and finished for ease in mounting the hardware. The ends that attach to the T-nuts should have a half-inch wrap of Teflon plumber's tape to hold the threads securely. Use wing nuts to secure the threaded rods to the pylons, with washers on each side and a nut on the inside.

**CROSSOVER DESIGN & CONSTRUCTION.** As I noted earlier, I

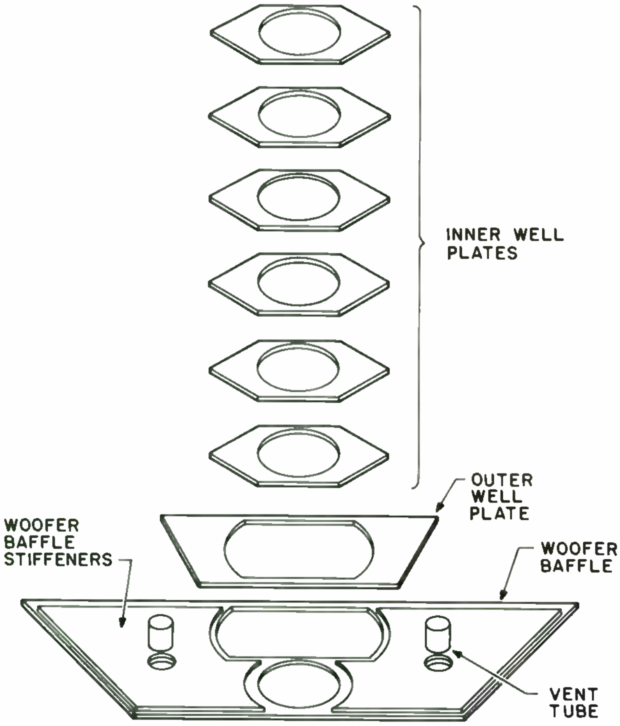

FIGURE 10a: Exploded view of the woofer baffle and well structure.

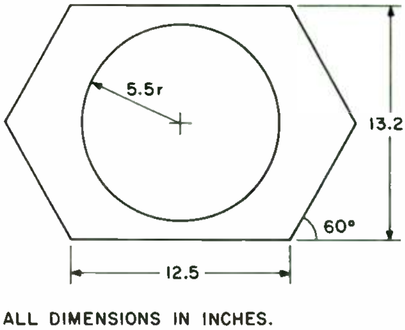

FIGURE 10b: Cutting guide for the inner well plates (make six). Use ⅝-inch particle board.

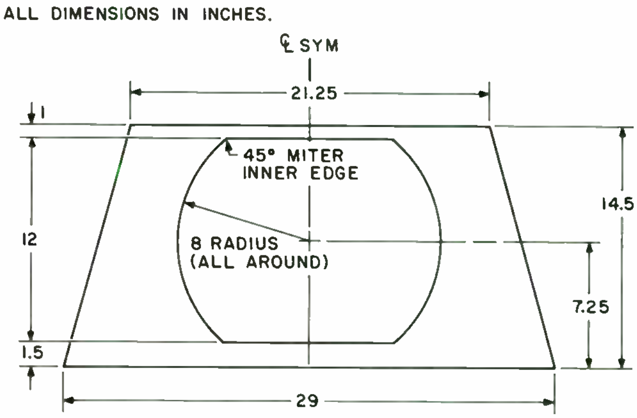

FIGURE 10c: Cutting guide for the flared outer well plate. Use ⅝-inch particle board.

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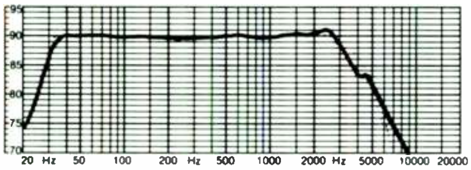
- **We are the only manufacturer to give Fast Fourier frequency responses on each individual speaker.**
- **We are the only manufacturer to give individual Thiele-Small parameters and offer to match pairs and fours.**
- **We are the only manufacturer to offer a limited LIFETIME warranty.**

The two speakers shown on this page are the first in the new line of speakers from Sherman Research. For the next month they will be on sale through SRC AUDIO to Speaker Builder subscribers only. This sale will end February 28, 1985. If you want the best speaker, the best technical information, the best warranty, and THE BEST PRICE, you can't pass up this offer.

## 20.3W8
## 8" POLYPROPYLENE WOOFER

The 20.3W8 features the perfect balance of a highly damped cone and a minimum reactence butyl surround. This coupled with extremely accurate manufacturing tolerances, that assure perfect centering, gives a phenomenally flat frequency response. Every aspect of the 20.3W8 has been optimised for smooth low distortion speaker systems. The slightly rising frequency response symptomises low third harmonic distortion content. The perfect second order bessel roll-off at 2800 hz. allows seamless crossovers with minimum elements. Even the adhesives have been optimised to give resonance free coupling between cone and voice coil former. The 20.3W8 has truly advanced the state of the art in loudspeakers.



**Thiele-Small Parameters**

Fs = 33.75 Hz
Vas = 64.3 liters (2.27 cubic ft.)
Qe = .51
Qm = 2.124
Qt = .41
Cms = .0008755 m/N
Sd = .02139 m2
Re = 5.27 ohms

BL = 8.3
Mmd = .025 Kg
Acc = 314.56
Xmax = 5.1 mm
V.C. = 38 mm
Mgt. = .795 Kg
Pwr. = 180 watts RMS
Lvc = .98 mH
eff = 89.0 dB

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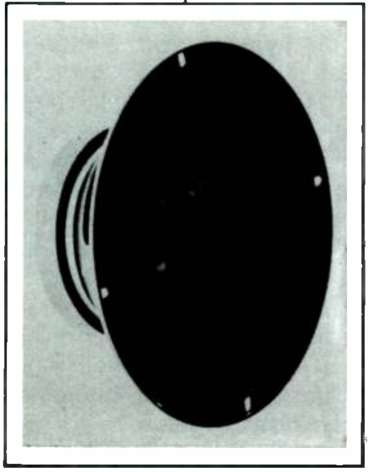
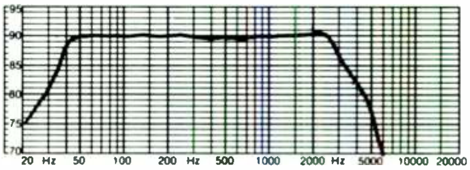


## 8" DVC SUBWOOFER

The Sherman Research 8" subwoofer is a perfect solution for those rooms that just won't allow two large monoliths or even one large subwoofer. If you crave bass and have such a room than you can't pass this offer up. In a small box of just over a cubic foot this speaker is capable of producing incredible low bass down to 40 Hz. Hide it away next to your bed or your easy chair. Build it into a coffee table or a bookcase. Even the smallest room has a nook or cranny big enough for this subwoofer. We recommend using a satellite with a 4-5 inch midbass for the best results although it can keep up with larger speakers. Full cabinet plans and crossovers are also available to take all the guess work out of your system. Experienced system builders should notice that the frequency response on this speaker is much the same as the single voice coil 8". This extended response should give some interesting possibilities such as adjusted response alignments and feedback systems. (Stay tuned to the SRC newsletter for more on these technologies.)



**Thiele-Small Parameters**

Fs = 30.5 Hz
Vas = 64.3 liters or 2.27 cubic ft.
Qe = .393
Qm = 3.19
Qts = .35
Cms = .0008755 m/N
Sd = .02139 m2

Re = 3.2 (per coil)
BL = 10.3
Mmd = .031 Kg
Acc = 332.6
Xmax = 5 mm
V.C. = 38 mm
Mgt. = .795 Kg
PWR = 80 Watts RMS
eff. = 88.9 dB

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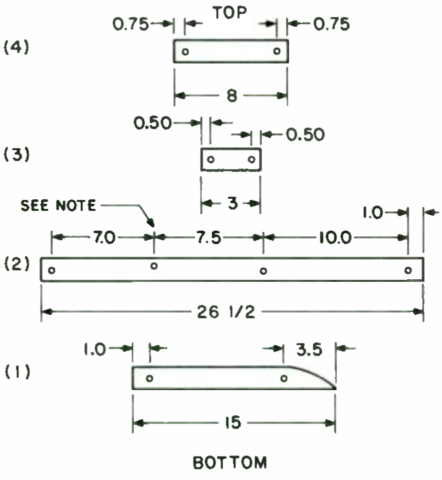


ALL DIMENSIONS IN INCHES.
NOTE: THIS HOLE IS 0.5 FROM TOP EDGE.

**FIGURE 11: Cutting guide for the pylon pieces, numbered from bottom to top. Use dressed 1-by-2-inch larch stock.**

ALL DIMENSIONS IN INCHES.

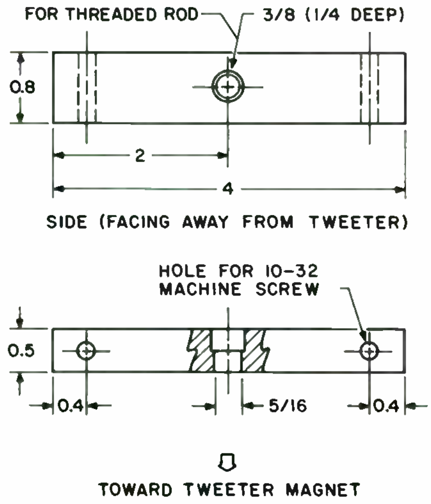


**FIGURE 12: Tweeter mounting blocks (make four).**

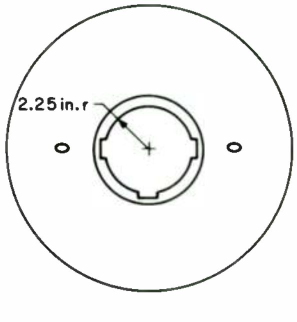
chose 500Hz and 6kHz as the crossover points and decided that I would try a series monopole, just as Lampton did.[8] Using multiple drivers meant that the system impedance would be 4Ω or below, with possible dips as low as 2Ω. As shown in *Fig. 14,* I wired the two woofers in parallel in opposite polarity. The three midranges in parallel divide down to 2.6Ω, so I inserted a 1Ω resistor in series with them to raise the impedance to a compatible level. The two tweeters in parallel are 4Ω.

I used a Zobel circuit on the woofer to stabilize the load impedance. The TA-305F woofer has an inductance of 2.4mH and a DC resistance of 5.5Ω. Two in parallel come out to 1.2mH and 2.75Ω. The Zobel circuit shown in the crossover schematic is a 2.5Ω, ±10% resistor in series with a 15.68μF capacitor. When the Zobel does make an audible difference, it seems to control excess upper bass output. I did not think it was necessary to attenuate the tweeters.

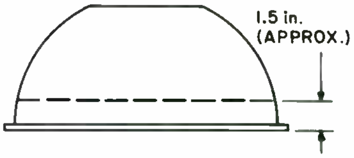
I laid out the crossover circuit on a double-sided, 6-by-9-inch glass-epoxy board *(Fig. 15).* Because the L1 inductor I used was so large and heavy, I had to mount it directly to the top of the cabinet. C1 consists of six 15μF Mylars and one 10μF polypropylene. C2 is a composite of polycarbonate (5μF and 1μF) and polystyrene (two 0.33μF) units. Cz consists of one 15μF Mylar and one 0.68μF Mylar. I salvaged midrange load resistor R1 from a computer terminal. It is a 25W, 1Ω, 1% unit, which uses an unetched area of copper as a heatsink. Practically, you may use any 1Ω resistor of 20W or greater. Note that the larger the wattage rating for a given resistance, the lower the series inductance. Zobel resistor Rz is a 75W, 2.5Ω, 10% unit, which is supported above the board on metal spacers.

The terminals for the crossover are European-style barrier strips. In retrospect, a different terminal style might have been better because the type I used will not accommodate all the leads required—in one case, three #16 and one #18. As it was, I had to join the leads externally to a bus, then insert the bus into the terminal. I wired the woofers with #12 solid wire supported on cable clamps along the inside wall of the cabinet. I left extra wire between the first cable clamp (located on the inside of the woofer baffle) and the second clamp to allow some slack for removing the woofer baffle. Connections to each woofer are brought out separately to a four-place terminal block atop the cabinet. A wiring harness connects the woofers to each other in appropriate polarity and to the crossover.

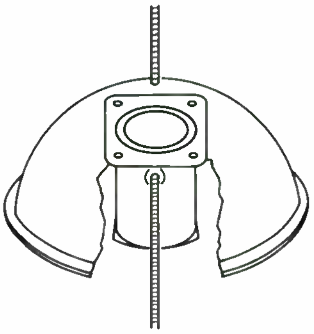
The tweeters and midranges are wired with #16 leads, while the lower midrange (M1) leads are laid in a routed channel behind the carpet pad. The crossover is mounted upright on one side of the cabinet top, and a nylon screw attaches the board to a Plexiglas beam that holds the board in place *(Fig. 16).*



(a) FRONT VIEW SHOWING CUTOUTS.



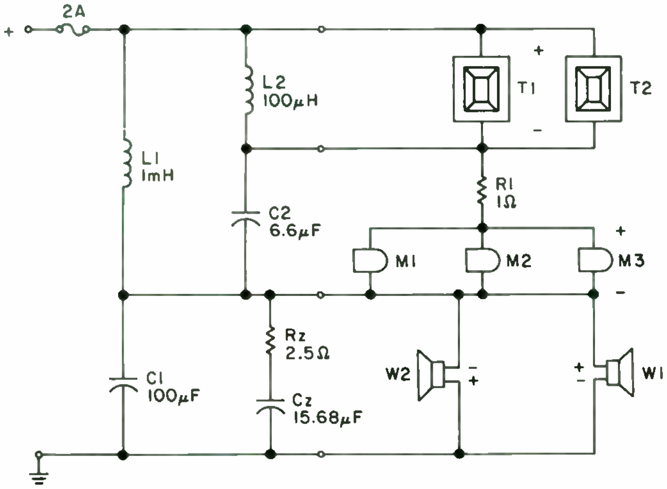
(b) FIRST MIDRANGE BAFFLE, SHOWING CUT LINE. (NOTE ABSENCE OF HOLES FOR RODS.)



(c) CUTAWAY SHOWING T-NUT AND SUSPENSION RODS (TWO TOP UNITS).

**FIGURE 13: The midrange baffles are made of plastic food-storage bowls. Cut and construct as shown.**

**VOILA!** A system this large (my finished CVA weighs in at more than 200 pounds) is awkward to move or store. I recommend that you assemble the woofer cabinet first, then move it into position before you attach the pylons. Although the system's triangular shape suggests that a corner placement would be ideal, I have no suitable corners in my home. I am curious about what effect corner placement would have on the response of a system with such broad horizontal dispersion. If anyone tries it, please let me know.



| | |
|---|---|
| L1 | 1mH inductor, DC resistance 0.5Ω or less |
| L2 | 100μH inductor, DC resistance 0.5Ω or less |
| C1 | 100μF, ±10%, 50V Mylar and/or polypropylene cap |
| C2 | 6.6μF, ±5%, 50V polycarbonate, polystyrene or polypropylene cap |
| Cz (P/O) | 15μF, ±10%, 50V Mylar cap |
| or Cz (P/O) | 0.68μF, ±10%, 250V Mylar cap |
| Rz | 2.5Ω, 75W, ±10% ear-mounting resistor |
| R1 | 1Ω, 25W, ±1% resistor |

**FIGURE 14: Schematic diagram of the CVA crossover.**

I put a Formica-type finish on the cabinet, although it is not shown in the photographs, and am working on a grille for the woofer baffle. Because I have two inquisitive cats, I also covered the woofers and midranges with expanded metal mesh.

Listening to the first CVA was somewhat surprising. One surprise was that I had to change the tweeter spacing from what "theory" predicted. If tweeters are as close together as possible, they will usually have little interference. The ribbon tweeter is a line source, however, not a point source. This means that even with the two tweeters mounted as closely together as possible, the distance between the top of the top ribbon and the bottom of the bottom ribbon is comparable to the wavelengths of the frequencies involved. This results in a rough response on-axis and an unpredictable response off-axis and above or below the midpoint of the tweeters. I tried a much wider spacing—more than 8λ apart at crossover—with the tweeters tilted so that their outputs converged at the nominal listening distance. This produced a much more uniform response, with little change as ear altitude varied.

A second surprise was that not only is there an optimum listening altitude, but there is also a minimum listening distance. This effect is apparently quite common in physically large systems using many drivers, where you can perceive discontinuity if you are too close. In this case, the minimum distance appears to be about 6 feet, which is comparable to the height of the array. As equipment becomes available, I plan to use the pulse method[9] to adjust driver positioning.

In the absence of objective (meas-

**MATERIALS LIST**

| | |
|---|---|
| (2) | 4 by 8 sheets of ¾" AA exterior plywood |
| (2) | 4 by 8 sheets of ⅝" or ¾" particle board |
| 20 feet | 1-by-2" larch stock (for pylons and cleats) |
| 1 gross | #6 1½" hex-head lag screws |
| ½ gross | #8 1½" brass flush-head wood screws |
| (2) | 11 oz. tubes of H.B. Fuller Max Bond construction adhesive (or equiv.) |
| (16) | 10-24 self-tapping hex-head sheet-metal screws (woofer mounting) |
| (1) | 6 oz. tube GE or Corning silicone caulk |
| (8) | 5/16", 2½"-long grade 2 bolts (pylon pivots) |
| (32) | 5/16" flat washers |
| (32) | 5/16" nuts |
| (6) | #8 2½" wood screws, slotted flush head (attach lower pylon head) |
| 1 quart | polyurethane varnish |
| (6) | ½" plastic cable clamps with appropriate screws |
| 12 feet | two-conductor, 12-gauge solid wire (standard house wire, white/black) |
| 15 feet | two-conductor, 16-gauge polarized stranded wire |
| (1) | roll Teflon pipe thread tape |
| (4) | brad-type 5/16" T-nuts |
| (4) | prong-type 5/16" T-nuts |
| (1) | 4 oz. epoxy glue set (Poly-Poxy or equiv.) |
| (1) | 2"-wide nylon brush |
| (1) | roll Thermatex (see text) |
| (3) | seven-liter plastic salad keepers |
| 1 quart | flat black paint (or desired color) |
| 10 feet | 5/16" coarsely threaded rod |
| (8) | 5/16" wing nuts |
| (2) | Peerless TA-305F 12" polypropylene woofers |
| (3) | SEAS H-204 3" polyamide dome midranges |
| (2) | JVC HSW 1101-01A ribbon tweeters |
| (1) | 6-by-9" double-sided glass-epoxy board |
| (4) | four-position barrier terminals |
| (2) | ½" metal stand-offs (for mounting Rz above board) |
| (2) | 8-32 1" machine screws |
| (2) | 8-32 nuts |
| (7) | 6-32 ½" nylon machine screws (mount terminals on crossover and crossover to upright) |
| (7) | 6-32 nylon washers |
| (7) | 6-32 nylon nuts (thick style) |
| (1) | chassis-mount fuse holder |
| (1) | 2A 3AG fuse |
| (1) | 2" angle iron (for crossover upright) |
| (1) | ~6" plastic square stock, ¼ by ½" (crossover upright) |
| (2) | 6-32 self-tapping sheet-metal screws (woofer terminal block) |
| 10 inches | 3" diameter PVC pipe or mailing-tube stock |
| (20) | 10-24 1½" pan-head machine screws (midrange and tweeter mounting) |
| (20) | 10-24 neoprene-backed washers |
| (20) | 10-24 nuts |
| — | plastic wire tie-wraps as required |

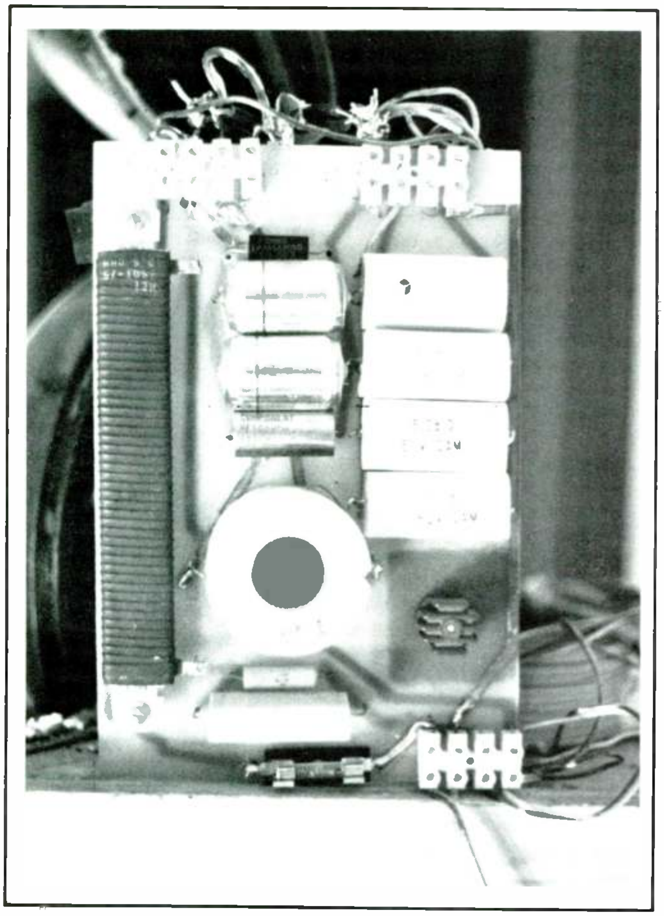


**FIGURE 15:** The author laid out the crossover circuit on a double-sided, 6-by-9-inch glass-epoxy board.

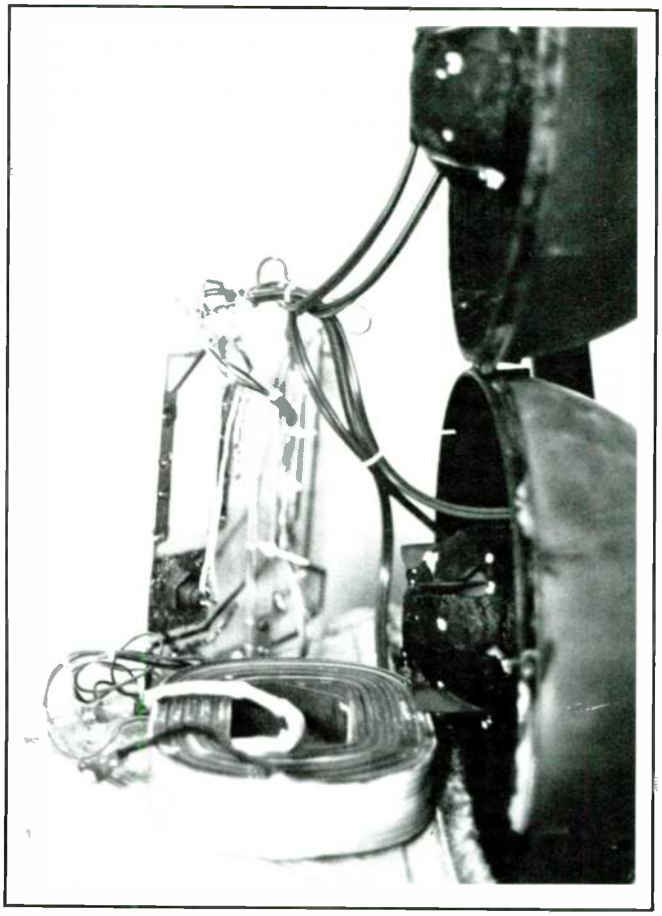


**FIGURE 16:** An inside view of the tweeter/midrange wiring and the crossover board mounting.

## Muses and Music

Since the music moves you, the muse is almost surely able to do so as well—the writer's muse, that is. Put pen to paper or better yet, typewriter ribbon to paper with a clear, orderly account of your adventure in audio construction, or any related field of endeavor leading to good listening. Send it along with a stamped return envelope. We pay modestly for articles, so write us about it and we'll answer promptly with suggestions and tell you whether or not we are interested. Some of our best articles come from people who have never before written for periodicals. And if your muse is as silent as a tomb, don't let that stop you. Write anyway and let's see what develops. We have a nice sheet of suggestions for authors which we will send to nearly anybody who asks for it.

ured) test results, I will refrain from pontificating about the CVA's performance, except to say that I feel my efforts have been amply rewarded. System efficiency is quite good, and my home-brewed 40W amplifier coasts along with plenty of power in reserve. Not being one to leave well enough alone (isn't that the root of all speaker building?), I am sure to make some minor changes down the line. Among them will probably be adding an active crossover with triamping and replacing the pylon-and-threaded-rod arrangement with a flexible spine to hold the midranges and tweeters from the rear, making them appear to float. Although several people have commented on the CVA's appearance, I feel that it would be right at home on the set of *This Island Earth* or *War of the Worlds.*

## ACKNOWLEDGMENTS

I wish to thank Thomas Best III for his gift of coils and caps; D.B. Keele for advice and correspondence; James Pharris for running the alignments; Brice Sowell for mechanical advice and hauling lumber; Ian White of Peerless for woofer application advice; and the Electronics Technology Department of Mississippi Gulf Coast Junior College, Jackson County Campus, for lab work.

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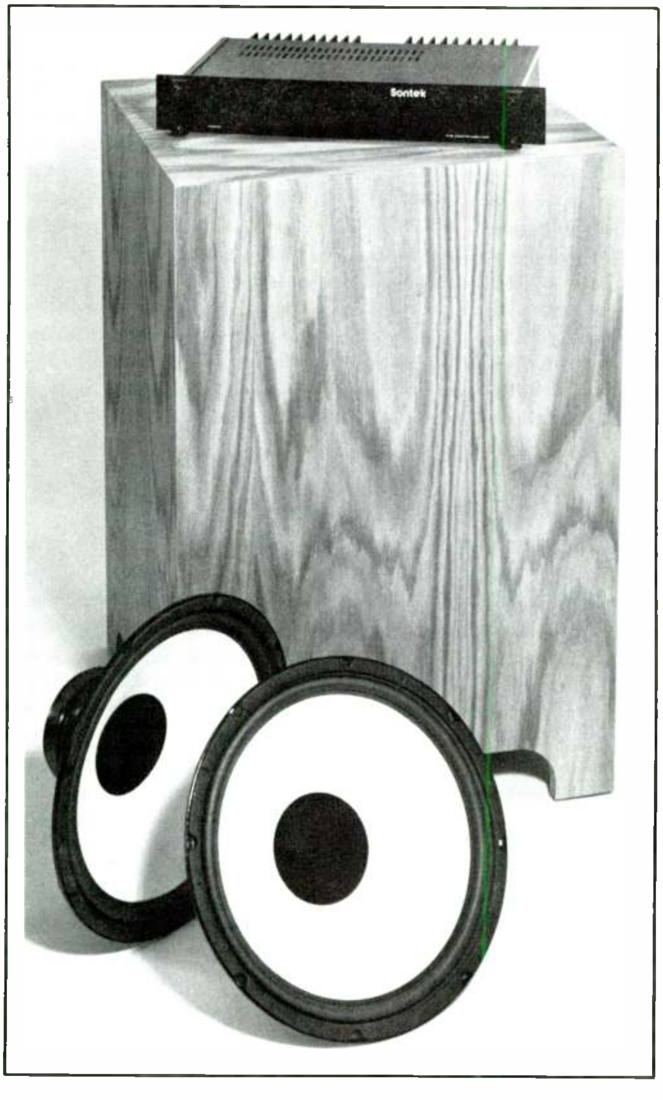
# CONSTRUCTING A SONTEK SUBWOOFER

BY PHIL TODD

A subwoofer is always a nice addition to an audiophile's system. The thought of having bass you can really feel is exciting, and the added benefits of reduced modulation distortion and overall clean sound are appealing. The aesthetics of a subwoofer are an important consideration, but many high-performance subwoofers do not fit easily into most listening environments. This has led to a host of subwoofers with small physical dimensions. To achieve the small size, however, something must be sacrificed. Often it is the sound.

The Sontek subwoofer is a purist's design. In my view, no subwoofer on the market sounds better, and few play louder. I have conducted listening tests against the most highly regarded subwoofers and think this design is more accurate. Although the Sontek subwoofer is no longer commercially available, this article will provide the details of home construction.



The Sontek subwoofer fits nicely into the listening environment and reproduces sound accurately.

**WHY USE A SUBWOOFER?** A subwoofer does two basic things for a hi-fi system. First, it lowers the amount of modulation distortion present in the satellite systems. This effect may or may not be subtle depending on the quality of the system you are using. I have often found that you must listen very carefully to hear the difference. Second, the subwoofer extends the amount of low-frequency power the system is capable of reproducing. This is generally rather easy to hear and can be quite dramatic, especially on a system that does not already have extended bass response.

I was rather surprised to find that I could hear a difference between sealed-box and vented-box subwoofers. (The Sontek is a sealed-box design.) I was even more surprised to hear a difference between a Q of 0.7 and a Q of 0.5 in a sealed box.

Q refers to the "quality factor" of a resonant circuit. A sealed-box loudspeaker is a second-order resonant circuit. A circuit's Q is defined mathematically, but when it is applied to loudspeakers, it defines the frequency response of the low-frequency cutoff region.

A Q of 0.7 is called a Butterworth response after the man who first defined it mathematically. The most outstanding characteristic of a Butterworth response is that it is maximally flat. This means that the frequency response is as flat as possible without even the slightest bit of peaking. If there were peaking in the frequency response, the Q would be greater than 0.7 and the frequency response would be called a Chebyshev response. The drawback to the Butterworth and Chebyshev frequency response is a ringing in the transient response.

If you choose a frequency response that is as flat as possible, but has no ringing, the response is called a Bessel response (again, after the man who first defined it mathematically). A Bessel response has a Q of 0.5 for a sealed-box system.

**AMPLIFIERS & CROSSOVERS.** Although the Sontek subwoofer will work well with many amplifiers, it is intended to be used with the Sontek B-1 bass amplifier because it uses the B-1's negative output impedance control. Negative output impedance allows you to tailor the subwoofer Q to your ears and the listening environment. With the B-1 bass amp, you can vary the Q of a sealed-box subwoofer simply by turning a potentiometer. This adjusts the amplifier's output impedance from 0 to −4Ω and thus changes the Sontek subwoofer's response from Butterworth (Q=0.7) to Bessel (Q=0.5).

The difference between the responses is discernible, as the Bessel response sounds more natural. The negative output impedance control will have a similar effect on the response of a vented enclosure, although the exact effect depends on the particular vented alignment. Indeed, the result might not even be desirable.

In general, audio power amplifiers have an output impedance that is very close to zero, but is still positive (usually several tens of milliohms). This is the most desirable characteristic for most of the audio frequency range. Only in the bass cutoff region might a different characteristic be desirable.

In *SB* 4/80 (p. 12), Bob Bullock mentions the possibility of adding a resistor in series with a woofer to control the frequency response in the cutoff region. The biggest drawback of this approach is that it wastes power and requires a larger amplifier to drive it. It is possible to synthesize this resistor electronically in the power amplifier so that it does not waste any power. Unfortunately, if you have too much resistance and wish to lower it, you cannot put a *negative* resistor in series with the woofer because they do not exist. You can, however, synthesize a negative resistance in the Sontek B-1 bass amp by adjusting the potentiometer that controls the amount of negative resistance.

This is not a new idea. Many tube power amplifiers had negative output impedance controls because the transformer-coupled outputs made it simple to do. These were called "variable-damping" circuits and were capable of both positive and negative output impedance control (see *Audio Cyclopedia*, Second Edition, Section 12.242, by Howard M. Tremaine).

As I said before, you can use the Sontek subwoofer with any power amplifier and electronic crossover combination. A power capability of greater than 50W is, however, desirable to drive the subwoofer to its full potential. Of course, more power is better up to a point. If you are planning to use a stereo power amplifier, you can get more power out by using both channels, but be sure your amplifier can handle the impedance. If you are using the bridge connection, each half of the amplifier will see an effective impedance of only 2Ω. You might want to consider rewiring the woofers in series so that the total speaker impedance is 16Ω. The bridged power amplifiers will then see only 8Ω apiece. If you are using a tube power amplifier, you can parallel the two 8Ω outputs.

Although any electronic crossover will work with the subwoofer, I think unity-sum and phase-linear types are best. I also recommend as low a crossover frequency as practical, generally one octave above the low-frequency cutoff of the satellites. Take care to limit the high-frequency signals to the subwoofer. Second-order or greater low-pass filter slopes are recommended for the subwoofer. It reproduces low frequencies beautifully, but it has a natural roll-off above 250Hz. When you are setting up the crossover, listen carefully to get the most accurate results. Listening to a test record, a sweep tone or pink noise can be very helpful.

The position of the subwoofer relative to the satellites is also important, as phase shift will occur if the distances from each unit to the listening position are different. The Sontek B-1 bass amplifier has controls to eliminate this phase shift. Also be aware that your listening room will have a number of standing waves, which will cause peaks and dips in the response. As discussed later, it is best to do all your adjusting from your favorite listening position.

An unusual feature of the Sontek subwoofer design is the placement of the drivers. Two drivers are placed face to face, which does two things. First, the even-order harmonics usually generated by the drivers tend to cancel, and this lowers the subwoofer's total harmonic distortion. The small air volume between the two cones also provides additional cone stiffness to prevent breakup. Second, both magnet/voice-coil assemblies drive the same cone area, so twice as much motor is available to control cone motion. This improves linearity.

Two subwoofer designs are available. One is based on 15-inch woofers and the other on 12-inch woofers. The sound is identical, but the 15-inch design will put out higher sound pressures, achieving 105dB SPL at 1 meter at 35Hz. The 12-inch design will be about 6dB less. The frequency response is shown in *Fig. 1*.

**POWER LEVELS.** Both designs are capable of producing very high sound pressures at low frequencies. This has some implications that are not always obvious to a first-time user. You will quickly learn at what frequencies your doors rattle, especially when they are closed. You will also notice that during certain passages, the pictures on the walls—and perhaps even the walls themselves—begin rattling. If there are any windows in the room, they will rattle, too. The dedicated audiophile will want to find each resonance and stop it. This might make the installation process a bit longer than intended. If you live in an apart-

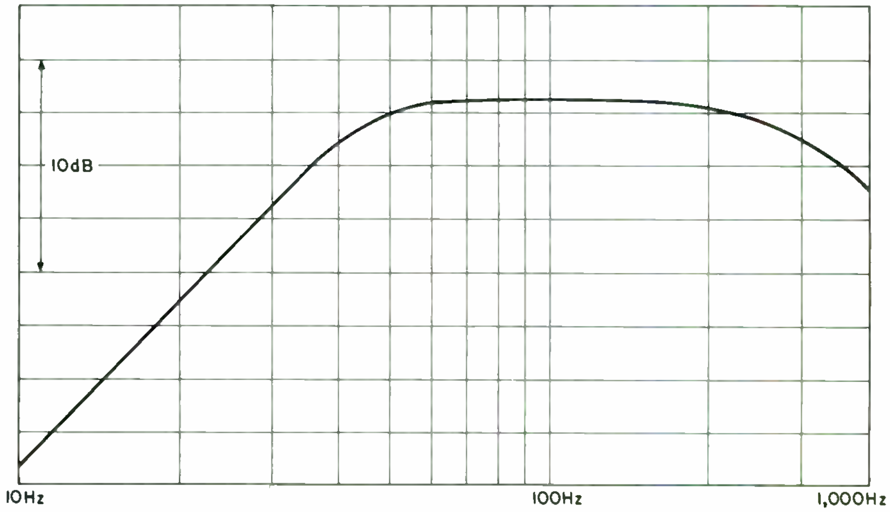


**FIGURE 1:** Frequency response of the Sontek subwoofer.

ment, this system is *not* recommended as a good way to meet your neighbors.

The ideal location for a single subwoofer is directly between the two satellites. (If you have two subwoofers, each one is located as close to a satellite as possible.) The ideal is not, however, always obtainable in practical situations. The most important considerations for subwoofer placement are the distance from the subwoofer to the listening position versus the distance from the satellites to the listening position and the placement of the subwoofer relative to the room boundaries for standing-wave control.

If the distance from the subwoofer to the listening position is not the same as the distance from the satellites to the listening position, an excess phase shift at the crossover frequency will cause a peak or dip in the response at the listening position. If you do not have a control on your crossover to adjust the relative phase of the satellites and the subwoofer, try to keep the two distances the same.

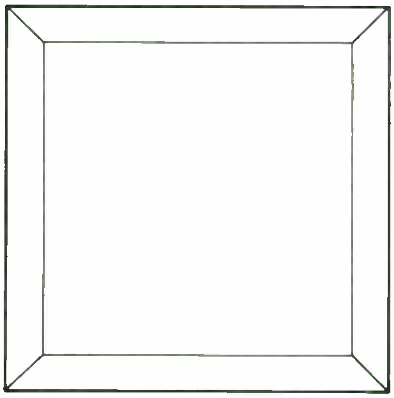


**FIGURE 2:** Using mitered joints allows you to use pre-veneered particle board for the enclosure sides.

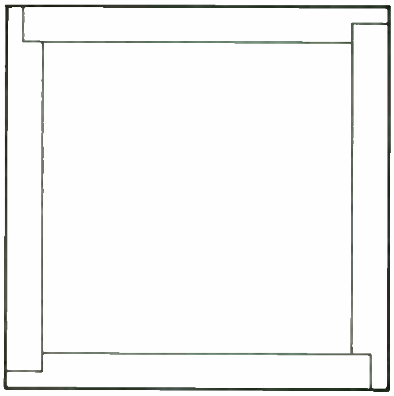


**FIGURE 3:** Using rabbet joints and "windmill" construction is simple because the pieces tend to self-align in assembly.

Standing waves will be present in all listening rooms at low frequencies. Generally, you should move the resonance to as high a frequency as possible so that natural room damping will be more effective. Place the subwoofer about one-third of the way from the closest walls. If you are interested in enhanced bass, place the subwoofer closer to the wall. You can achieve maximum enhancement by placing the subwoofer in a corner. The floor-to-ceiling resonance is difficult to control in this way, but it is generally higher in frequency than the other two resonances.

**CONSTRUCTION.** There are many ways to build the subwoofer. The two approaches I favor are the use of mitered corners and the use of rabbet joints. Mitered corners *(Fig. 2)* allow you to use pre-veneered particle board for the sides, although you will still have to veneer the top because of the edges. You may also use gluing cleats at the corners to improve the strength. With rabbet joints, you can use "windmill" construction *(Fig. 3)*, where all four side pieces are the same. Rabbet joints require that all sides, as well as the top, be veneered. You may use either a wood or laminate veneer. Using rabbet joints and windmill construction is one of the

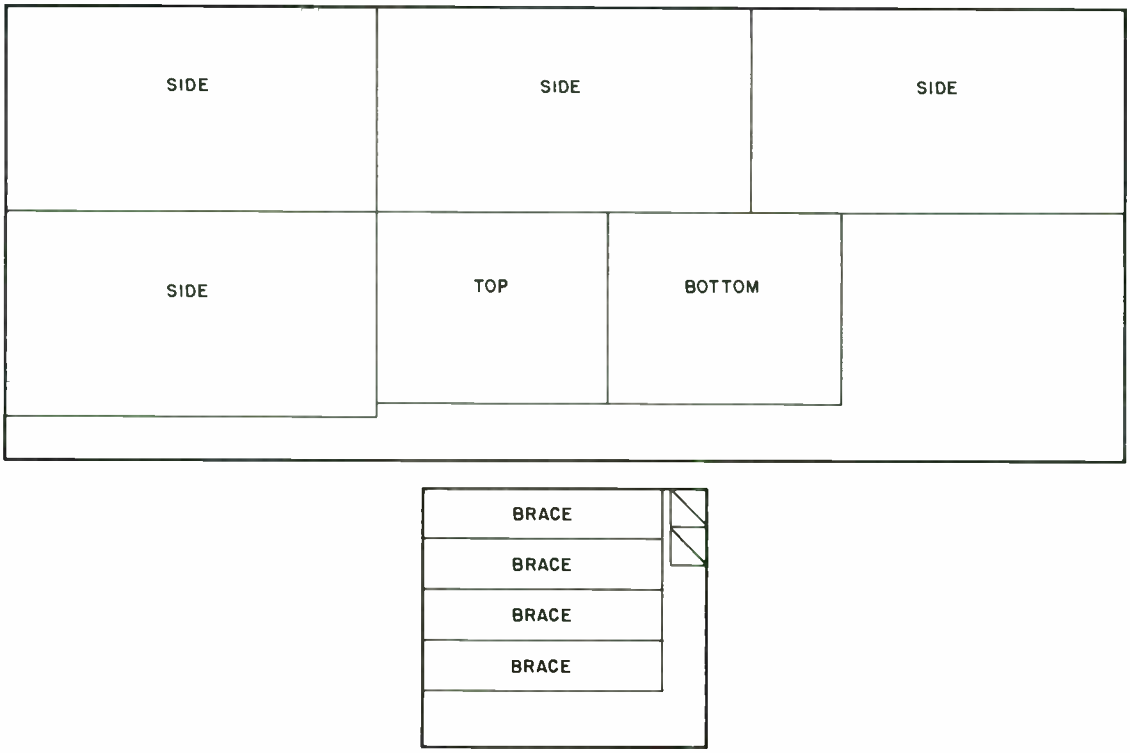


**FIGURE 4:** Cutting guide for the enclosure pieces and braces. For the enclosure, you will need a 4-by-8-foot piece of ¾-inch high-density particle board. For the braces, use a 2-by-2-foot piece of shop-grade or better ¾-inch plywood. The hardwood type is preferred.

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| POWER HANDLING | 80 watts |

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|---|---|
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| VOICE COIL | 1.5 " |
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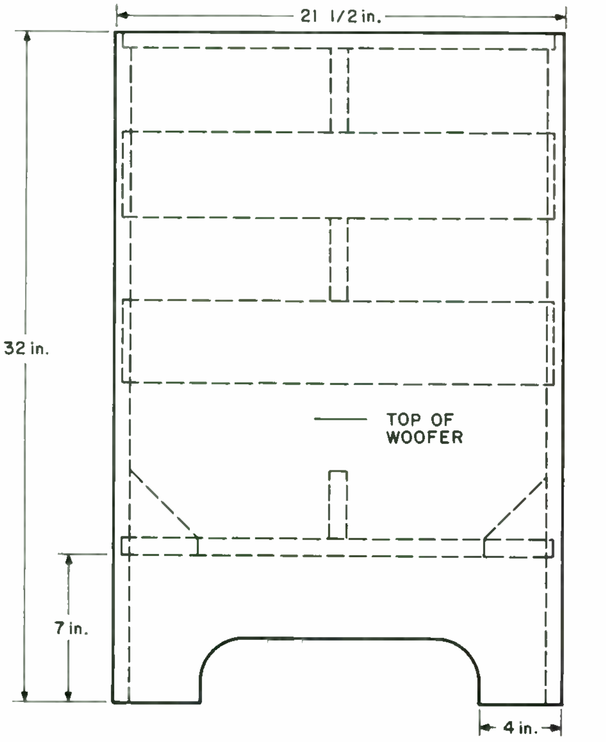

**FIGURE 5: Side view of enclosure assembly. Dimensions are given for a ¾-inch rabbet/dado.**

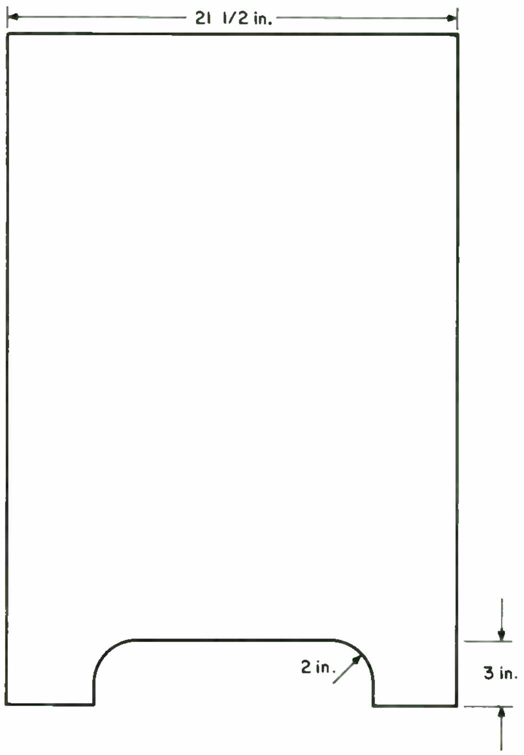

**FIGURE 6: Front view of enclosure assembly.**

simplest methods of construction because the pieces tend to self-align in assembly. The approach you choose will depend on your level of skill and your equipment.

I have not provided the exact dimensions of the pieces because they are slightly different for each approach. When you figure out the size of each piece in *Fig. 4,* be sure to allow for the type of joint you are using. The dimensions I have given are for ¾-inch particle board. If you use thicker material, you must adjust the dimensions so that the internal dimensions remain the same. Otherwise, the subwoofer's performance will change somewhat. The density of the particle board should be at least 50 pounds, but the heavier and thicker the better.

It is extremely important to make the braces *(Fig. 4)* of a good grade of ¾-inch plywood. Particle board is not stiff enough to keep the enclosure sides from vibrating, and the result is a mushy, unpleasant sound. Be sure the braces are glued securely to the enclosure walls. Install the braces in dado cuts that go only part way down the box sides. The dado must be in the center of the inside wall of the box, as shown in *Figs.* 5 and 7. (If you are using windmill construction, this will not be in the center of the piece, but all four sides will be the same.)

Assembly begins after you have cut out the pieces and the necessary dadoes and rabbets. See *Figs. 5–7* for side, front and bottom views. The drawings are for the 15-inch version of the subwoofer. The 12-inch version is identical except that the height of the cabinet is only 20½ inches, the mounting hole diameter is $11^{3}/_{16}$ inches, and the mounting hole circle is $11^{9}/_{16}$ inches. Also, only two 3-inch-wide braces are required. The woofer is a Becker 912A124, and only four pounds of dacron fill are required.

First assemble the sides of the box with the loudspeaker mounting baffle. A trial assembly is recommended before gluing to be sure all the pieces fit properly. The loudspeaker mounting baffle fits into a dado cut in the side pieces. When you have glued the sides, install the crossbraces and glue them in place. Be sure they go only as

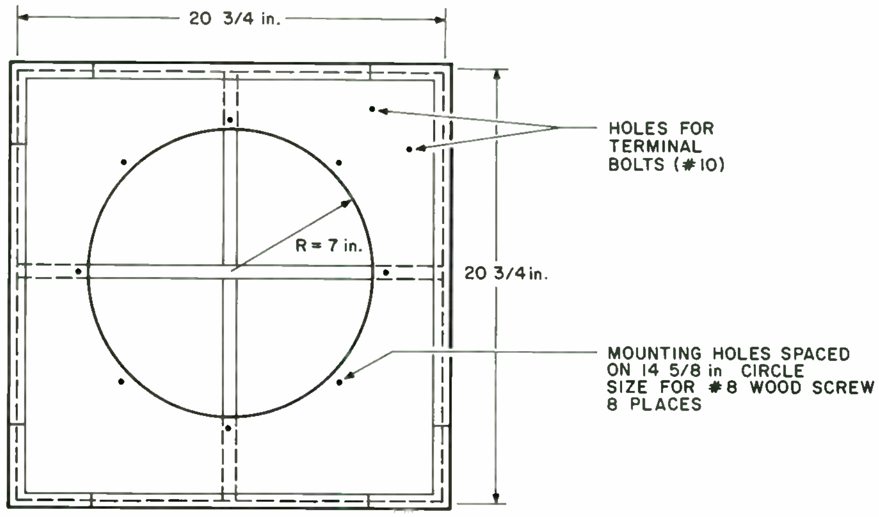

**FIGURE 7: Bottom view of enclosure assembly.**

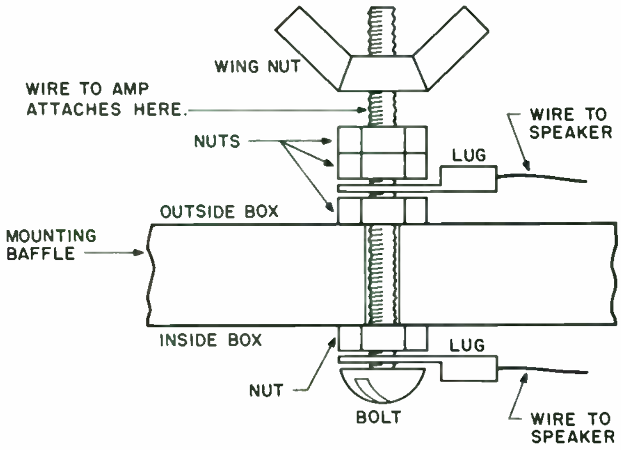

**FIGURE 8: Terminal bolt detail.**

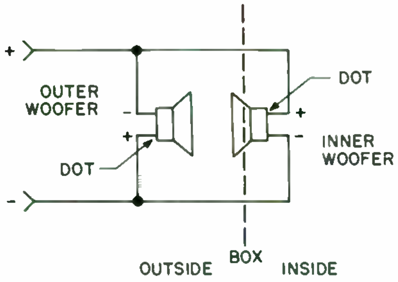

**FIGURE 9: Driver wiring diagram.**

low as necessary so that they do not interfere with mounting the woofers. Then install the small triangular braces. Finally, install the top and prepare the cabinet for the veneer.

Fill the cabinet with five to six pounds of dacron polyester batting. My suggestion is DuPont Holofill II, but you will find little difference between different kinds of fill in this application. When stuffing the box, pack the material most tightly at the top of the box and more loosely near the loudspeakers.

**DRIVER MOUNTING.** Install the brass feedthrough bolts at the end of the cables on the inner woofer first. Insert the bolts through the holes in the mounting baffle and tighten them in place with a nut *(Fig. 8)*. Mark the polarity of the bolts on the mounting baffle according to the polarity dot on the woofer, as shown in *Fig. 9*. The outer woofer will be connected later.

Install the loudspeakers with screws and use RTV silicone rubber to seal them in place. You will not need much RTV to make a seal. Be careful not to get any on the cones or the surrounds. Lay a bead of rubber around the edge of the loudspeaker mounting hole. Be sure the screw holes will seal, too. Align the speaker screw holes with the holes in the baffle and press the speaker into the mounting hole and the rubber *(Fig. 10)*. Be sure you achieve a complete seal between the speaker and the baffle. Next lay a bead of rubber around the spacers on the front of the loudspeaker. The bead should be just big enough to ensure a seal. Be sure to fill the gaps between the spacer sections on the front of the woofer. Repeat this on the second woofer and set them together face to face, making sure the screw holes on both woofers line up.

**MATERIALS LIST**

| | |
|---|---|
| (2) | 15-inch woofers (Philips/Amperex AD15240/W8 or Becker 915A15) |
| (8) | #8 wood screws, round head, 1¾ inches long |
| (2) | #10-32 brass machine bolts, round head, 2 inches long |
| (8) | #10-32 brass nuts |
| (2) | #10-32 wing-type nuts |
| (4) | 18-inch pieces of #16 AWG wire with lugs |
| 5½ lbs. | dacron batting |
| 1½ oz. | silicone rubber RTV |
| (1) | sheet ¾-inch plywood, 2 by 2 feet |
| (1) | sheet ¾-inch high-density particle board, 4 by 8 feet |

Insert and tighten the eight wood screws that secure the woofers in place. The volume of air between the two woofers must be sealed for proper operation of the subwoofer. You may use machine screws and T-nuts in place of the wood screws, but doing so is more awkward.

Attach the two wires from the outer woofer to the feed-through bolts and tighten the nuts as shown in *Figs. 8* and *9*. You can test the woofers' phasing with a 1.5V battery. If the phasing is correct, you will see a large cone movement when the battery is connected between the woofer terminals. If they are wired incorrectly, the cones will move very slowly. If this is the case, reverse the outer woofer's leads and repeat the test to verify that it is correctly wired. When you apply the positive end of the battery to the positive subwoofer terminal, the cone should move toward you and away from the box.

That's all there is to it. Now you have a fine subwoofer that will enhance the sound quality of your speaker system and fit nicely in your listening environment.

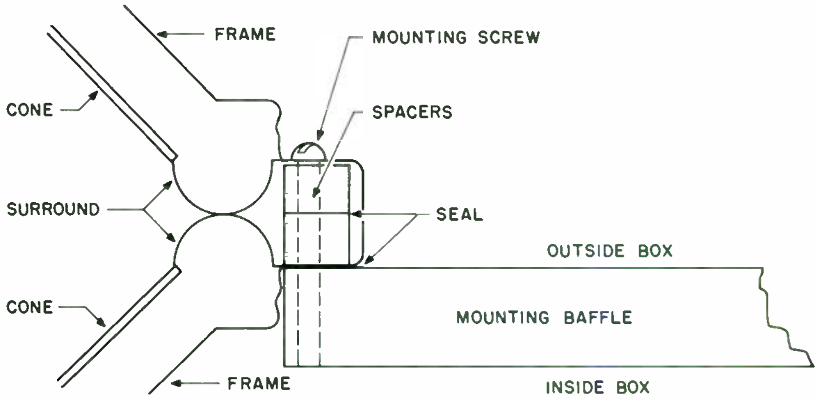

**FIGURE 10: Loudspeaker mounting detail.**

## PART II

# PASSIVE CROSSOVER NETWORKS

BY ROBERT M. BULLOCK III
Contributing Editor

Until recently, there has been very little published information dealing specifically with three-way crossover systems. It has always been assumed that they could be realized by some elementary interconnection (series, parallel) of the two-way systems I described in Part I. Although it is true that such networks do divide a signal into the requisite number of channels, Greiner and Allie[1] and I[2] have shown that they rarely possess the same characteristics as their two-way parents. Thus, if such a network is selected because of certain desirable capabilities of the two-way stages, there is no guarantee that the derived three-way system inherits these same capabilities.

Problems also arise from the way in which the two-way circuits are combined to form the three-way topology. For example, cascading passive two-way networks can introduce loading problems that are not always obvious and that can further degrade the three-way system's performance. Also, the necessary implementation of a bandpass filter for the middle channel of a three-way network can be accomplished in several ways, and it is not always clear which is preferable.

Because of these problems, I gave up trying to catalog the capabilities of the various two-way networks and derived new passive three-way systems[3] following the criterion that their design and capabilities be as similar as possible to the standard two-way systems. I want to concentrate on these new networks here because they offer the home builder a formula-based design with predictable capabilities that can be realized without sophisticated trial-and-error techniques.

**SPECIFICATIONS.** The fact that these new networks are similar to the two-way networks I described in Part I means that they meet the following specifications:

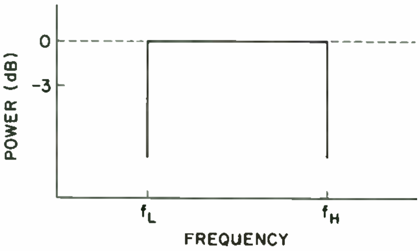

**FIGURE 1: Ideal bandpass filter response with corner frequencies $f_L$ and $f_H$.**

1. All crossover filters are realized by resistance-terminated LC ladders, complete with formulas for calculating the L and C values.
2. The crossover topology is a parallel filter arrangement.
3. It is possible to obtain both all-pass and constant-power crossovers from a single circuit topology.
4. The notion of crossover order applies. That is, crossover order is a measure of the ultimate stop band roll-off rate of each channel.

To satisfy these specifications, I used some new filter responses. Thus, the familiar Butterworth filter is not pervasive, and the actual filters required depend on the separation between the crossover frequencies.

Before proceeding with details, I should point out some limitations of the new crossovers. First, the topology I use is probably not the best for constant-power or first-order, three-way crossovers. Discussing alternate topologies, however, requires dealing with certain load-impedance questions that can be avoided with the topology I have chosen. Also, the parallel filter topology is probably not the best choice for active three-way crossovers, but I will have more to say about that when I cover active designs.

On the other hand, the new networks are especially well-suited for passively realizing higher-order, all-pass crossovers; they require a minimum number of components for a given order; and their similarities to standard two-way networks provide a valuable familiarity factor.

**CROSSOVER TYPES.** A three-way crossover divides a signal into three frequency bands, with the transition between bands occurring at two crossover frequencies, $f_L$ and $f_H$, where $f_L < f_H$. The low and high channels are created by passing the signal through a low-pass filter with corner frequency $f_L$ and a high-pass filter with corner frequency $f_H$. The middle channel is supplied by a bandpass filter with corner frequencies $f_L$ and $f_H$.

The preferred type of crossover in loudspeaker applications is the all-pass crossover (APC), but the constant-power crossover (CPC) is also in common use. If $V_I$ is the crossover input voltage, and $V_L$, $V_M$ and $V_H$ are the low, middle and high channel voltage outputs, respectively, then the crossover is an APC if

$$|V_L + V_M + V_H| = |V_I| \qquad (1)$$

and a CPC if

$$|V_L|^2 + |V_M|^2 + |V_H|^2 = |V_I|^2 \qquad (2)$$

for all frequencies.

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## FILTERS & SPEAKER SAVER

**KF-6: 30Hz RUMBLE FILTER.** [4:75] 2 channel universal filter card, 1% metal film resistors and 5% capacitors for operation as 18dB/octave; 30Hz, 0dB gain only. Each $19.75

**KH-2A: SPEAKER SAVER.** [3:77] Turn on/off protection & fast opto-coupler circuitry to prevent damage to your system. 4PDT relay & socket for 2 channels. Each $35.00

**KH-2B: OUTPUT FAULT OPTION.** Additional board mounted components for speaker protection in case of amplifier failure. Each $6.75

**KH-2C: COMPLETE SPEAKER SAVER KIT.** Includes KH-2A & KH-2B. Each $40.00

**KL-5 WILLIAMSON BANDPASS FILTER.** [2:80] 2 channel, plug-in board and all parts for 24dB/octave 20Hz-15kHz with precision cap/resistor pairs. TL075 IC's. Each $31.00

## CROSSOVERS

**KC-4A: ELECTRONIC CROSSOVER, KIT A.** [2:72] Single channel, 2-way. All parts including C-4 board and LF351 IC's. Choose frequency of 60, 120, 240, 480, 1k, 2k, 5k or 10k. Each $8.00

**KC-4B: ELECTRONIC CROSSOVER, KIT B.** [2:72] Single channel, 3-way. All parts including C-4 board & LF351 IC's. Choose frequency of 60, 120, 240, 480, 1k, 2k, 5k or 10k. Each $11.00

● **KF-7: CROSSOVER FOR WEBB TLS.** [1:75] Passive 4-way x-over, in pairs, assembled. Components are included for both STC and Celestion tweeters. Made by Falcon of England. CLOSEOUT Pair $50.00

**KK-6L: WALDRON TUBE CROSSOVER LOW PASS:** Single channel, 18dB/octave, Butterworth, [3:79] includes Bourns 3-gang pot. Choose 1: 19-210; 43-465; 88-960; 190-2100; 430-4650; 880-9600; 1900-21,000 Hz. Each $43.00

**KK-6H: WALDRON TUBE CROSSOVER HIGH PASS:** Single channel, 18dB/octave, Butterworth, [3:79] includes Bourns 3-gang pot. Please specify 1 of the frequencies in KK-6L. No other can be supplied. Each $45.00

**KK-6S: SWITCH OPTION.** 6-pole, 5-pos. rotary switch, shorting, for up to 5 frequency choices per single channel. Each $8.00; ordered with 2 kits above, Each $7.00

**KK-7: WALDRON TUBE CROSSOVER POWER SUPPLY.** [3:79] Includes board, x-fmr, fuse, semiconductors, line cord, capacitors to power 4 tube x-over boards (8 tubes), 1 stereo biamped circuit. Each $88.00

**SBK-A1: LINKWITZ CROSSOVER/FILTER.** [SB 4:80] 3-way x-over/filter/delay. 24dB/octave at 100Hz and 1.5kHz and 12dB/octave below 30Hz, with delayed woofer turn-on. Use the Sulzer supply KL-4A with KL-4B or KL-4C. Per channel $64.00
Two channels $120.00 SBK Board only $14.00

**SBK-CIA: JUNG ELECTRONIC 2-WAY CROSSOVER.** [SB 3:82] 30Hz filter with WJ-3 board & 4136 IC adapted as 1 channel x-over. Can be 6, 12 or 18dB/octave. Choose frequency of 60, 120, 250, 500, 1k, 2k, 5k or 10k. Each $24.75

**SBK-C1B: THREE WAY, SINGLE CHANNEL CROSSOVER.** [SB 3:82] Contains 2 each SBK-C1A. Choose high & low frequency. Each $49.70

**SBK-C1C: TWO CHANNEL, COMMON BASS CROSSOVER.** [SB 3:82] Contains 2 each SBK-C1A. Choose 1 frequency. Each $49.70

**SBK-C2: BALLARD ACTIVE CROSSOVER.** [SB 3:82 & 4:82] 3-way x-over with variable phase correction for precise alignment. Kit includes PC board ($5^{3}/_{8}$ x $9^{1}/_{2}$"), precision resistors, polystyrene & polypropylene caps. Requires ±15V DC power supply—not included. Can use KL-4A with KL-4B or C. Two channel $134.00

● CLOSEOUT: KITS NOT AVAILABLE AFTER PRESENT STOCK IS GONE.

## AIDS & TEST EQUIPMENT

**KH-7: GLOECKLER PRECISION 101dB ATTENUATOR.** [4:77] All switches, 1% metal film and 5% carbon film resistors to build prototype. Chassis, input/output jacks are not included. Each $50.00

**KL-3C: INVERSE RIAA NETWORK COMPLETE.** [1:80] 1 KL-3R and 1 KL-3H with 1% polystyrene capacitors. Alternate 600 ohm or 900 ohm $R_2'/C_2'$ components for 2 channels. Each $35.00

**KL-3R: INVERSE RIAA.** [1:80] Resistor/capacitor package complete. Contains stereo $R_2'/C_2'$ alternates. Each 25.00

**KL-3H: INVERSE RIAA HARDWARE.** [1:80] Box, terminals, gold jacks, and all hardware in KL-3C. No resistors or caps. Each $13.50

**KF-4: SINE-SQUARE AUDIO GENERATOR.** [4:75] Morrey's MOD kit for Heath IG-18 (IG5218). 2 boards and parts to modify the unit to distortion levels of parts per million range. Each $35.00

● **KG-2: WHITE NOISE/PINK FILTER.** [3:76] All parts, circuit board, IC sockets, 1% resistors, ±5% capacitors. No batteries, power supply or filter switch. CLOSEOUT Each $11.50

**KJ-6: CAPACITOR CHECKER.** [4:78] All switches, IC's, resistors, 4½" D'Arsonval meter, x-fmr and PC board to measure capacitance, leakage and insulation. Each $78.00

**KK-3: THE WARBLER OSCILLATOR.** [1:79] Switches, IC's, x-fmr and PC board for checking room response and speaker performance w/o anechoic chamber. Each $56.00

**KL-6: MASTEL TIMERLESS TONE BURST GENERATOR.** [2:80] All parts with circuit board. No power supply. Each $19.00

**KM-1: CARLSTROM-MULLER SORCERER'S APPRENTICE** [2:81] 4 boards and all parts for construction of the first half of a swept function generator with power supply. No knobs or chassis. Each $145.00

**KM-2: CARLSTROM-MULLER PAUL BUNYAN.** [3:81] All parts except knobs, chassis, output connectors and wire. Includes 2 circuit boards and power supply. Each $85.00

**KM-3: CARLSTROM-MULLER SORCERER'S APPRENTICE/PAUL BUNYAN** [2:81, 3:81] All parts in KM-1 and KM-2. Each $225.00

**SBK-D2 WITTENBREDER AUDIO PULSE GENERATOR.** [SB 2:83] All parts, board, pots, power cord, switches and power supply included. Each $70.00

**SBK-E4: MUELLER PINK NOISE GENERATOR.** [SB 4:84] All parts, board, 1% MF resistors, capacitors, IC's, and toggle switches included. No battery or enclosure. Each $27.50

## SYSTEM ACCESSORIES

**KH-8: MORREY SUPER BUFFER.** [4:77] All parts, 1% metal film resistors, NE531 IC's, and PC board for 2 channel output buffer. Each $14.00

**KJ-3: TV SOUND TAKEOFF.** [2:78]. Circuit board, vol. control, coils, IC, co-ax cable (1 ft.) and all parts including power x-fmr. Each $21.50

● **KJ-4: AUDIO ACTIVATED POWER SWITCH.** [3:78] Turn your power amps on and off with the sound feed from your preamp. Includes all parts except box and input/output jacks. CLOSEOUT Each $35.00

● **KK-14A: MacARTHUR LED POWER METER.** [4:79] 2-channel, 2-sided board and all parts except switches, knobs, and mounting clips for LEDs. LEDs are included. No chassis or panel. CLOSEOUT Each $60.00

● **KK-14B: MacARTHUR LED POWER METER.** [4:79] As above but complete with all parts except chassis or panel. CLOSEOUT Each $70.00

**SBK-D1: NEWCOMB PEAK POWER INDICATOR.** [SB 1:83] All parts & board. No power supply required. Two for $10.00 Each $6.00

**SBK-E2: NEWCOMB NEW PEAK POWER INDICATOR.** [SB 2:84] All parts & board, new multicolor bar graph display; red, green & yellow LED's for 1 channel. No power supply needed. Two for $15.00 Each $9.00

**KC-5: GLOECKLER 23 POSITION LEVEL CONTROL.** [2:72] All metal film resistors, shorting rotary switch & 2 boards for a 2 channel, 2dB per step attenuator. Choose 10k or 250k ohms. Each $36.75

**KR-1: GLOECKLER STEPUP MOVING COIL TRANSFORMER.** [2:83] X-fmrs., Bud Box, gold connectors, & interconnect cable for stereo. Each $335.00

**KL-2: WHITE DYNAMIC RANGE & CLIPPING INDICATOR.** [1:80] 1 channel, including board, with 12 indicators for preamp or x-over output indicators. Requires ±15V power supply @ 63 mils. Single channel. Each $49.00 Two channels. $95.00
Four channels. $180.00

**KS-7: SCOTCHCAL® PANEL KIT.** [2:84] One 10 × 12" sheet each of 4 types of pressure sensitive panel material (blk on aluminum, blk on transparent poly, blk on white poly, matte clear overlay), one pint of developer plus pads, and instructions. Requires a simple frame and a light source: ultraviolet, photofloods or the sun, plus your own press-on lettering materials. Postpaid. Each $34.50

**What's Included?** Kits include all the parts needed to make a functioning circuit, such as circuit boards, semiconductors, resistors and capacitors. Power supplies are not included in most cases. Unlike kits by Heath, Dyna and others, the enclosure, face plate, knobs, hookup wire, line cord, patch cords and similar parts are not included. Step by step instructions usually are not included, but the articles in ***Audio Amateur*** and ***Speaker Builder*** are helpful guides. Article reprints are included with the kits. Our aim is to get you started with the basic parts—some of which are often difficult to find—and let you have the satisfaction and pride of finishing your unit in your own way.

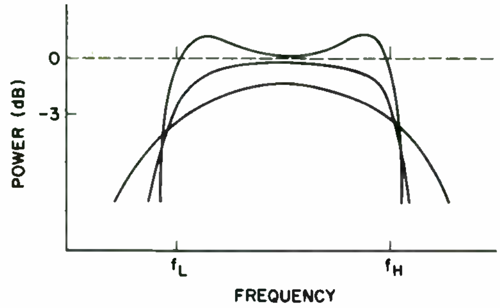


**FIGURE 2:** Three sample responses of physically realizable bandpass filters with corner frequencies $f_L$ and $f_H$.

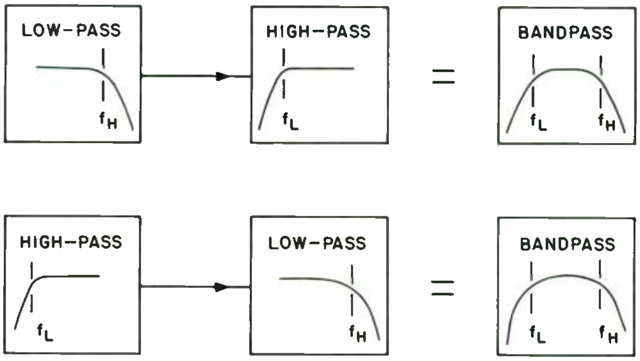


**FIGURE 3:** Block diagrams of bandpass filter networks obtained by cascading a low-pass network with corner at $f_H$ and a high-pass network with corner at $f_L$.

An ideal bandpass filter with corner frequencies of $f_L$ and $f_H$ ($f_L < f_H$) has a response curve as in *Fig. 1*. Electrical filters cannot produce this ideal, so practical bandpass responses have rounded corners, as in *Fig. 2*. You may think of a bandpass filter as being formed from a low-pass filter with corner frequency $f_H$ and a high-pass filter with corner frequency $f_L$, as in *Fig. 3*. Thus, one of the filters accepts the input, and its output becomes the input of the other filter. The two filters are said to be "cascaded" in this configuration. Clearly, one filter attenuates frequencies above $f_H$, and the other attenuates those below $f_L$ to form the bandpass response. It is also apparent that the ultimate high and low stop band roll-off rate is the same when both the low and high-pass filters have the same order, which is the arrangement I have chosen. Although the usage is a bit nonstandard, I define the order of this bandpass filter to be the common order of its low and high-pass stages.

## THE CROSSOVER TOPOLOGY.

*Figure 4* is a block diagram of the new crossovers' parallel filter topology. The actual circuit topologies for the low and high-pass filters are the same LC ladders I used in Part I, only now the sizes of the Ls and Cs are not calculated from the same formulas because new filter response shapes are needed. All filters have the same order, which I call the order of the crossover. So the ultimate stop band roll-off rate of each channel is 6ndB/octave for an nth order crossover, just as it was for two-way networks.

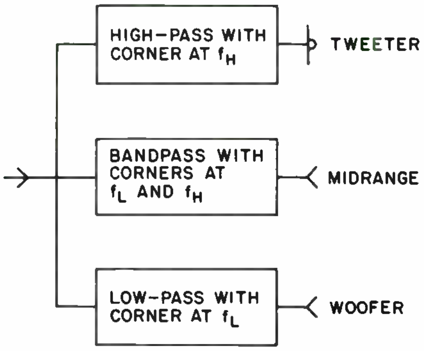


**FIGURE 4:** Block diagram of the three-way parallel filter crossover topology used in the new crossovers.

*Figure 5* is a block diagram of the bandpass filter topology. Here, each LC stage is a high or low-pass ladder without its resistor load. For example, *Fig. 6* is a third-order bandpass filter. The first stage is a third-order, low-pass section, while the second is a third-order, high-pass section. In spite of the topology, you cannot adjust the two stages independently to produce the right response. Instead, they must be aligned jointly to account for interaction between them. This makes the bandpass design formulas more complicated than the separate low-pass and high-pass formulas, but it is unavoidable.

Resistor $R_A$ in the bandpass circuit allows the bandpass gain to be attenuated. It is necessary because the raw bandpass output level is usually too high to match the other sections. I will describe other ways of handling this problem below.

## DESIGN PARAMETERS.

To calculate the circuit component values, you need several parameters in addition to the crossover order, crossover frequencies $f_L$ and $f_H$, and load resistances $R_L$, $R_M$ and $R_H$. The bandpass geometric center frequency ($f_M$) is given by the formula

$$f_M = \sqrt{f_L \times f_H} \qquad (3)$$

Radian frequencies are handiest for calculating component values, so the formulas are given in terms of the following equations:

$$W1 = 2\pi f_L \qquad (4)$$

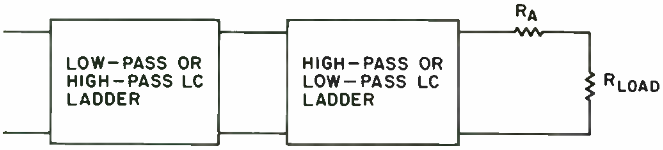


**FIGURE 5:** Block diagram of the bandpass filter topology used in the new crossovers.

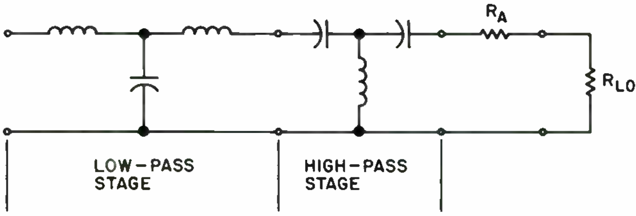
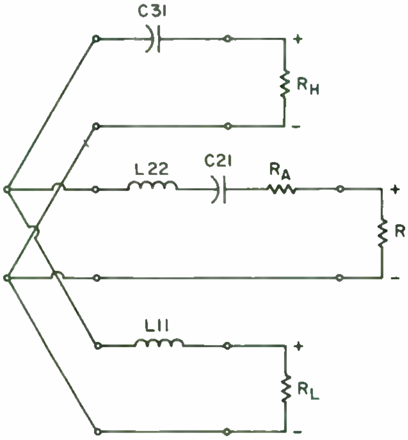


**FIGURE 6:** Example of the third-order bandpass filter topology used in the new crossovers.

NOTE: ALL CALCULATIONS FOR FIGS. 7-10 ARE TO BE DONE FROM LEFT TO RIGHT, JUST AS IN STANDARD COMPUTER NOTATION. THUS, A/B/C MEANS DIVIDE A BY B, THEN DIVIDE THE RESULTING QUOTIENT BY C. THIS IS EQUIVALENT TO A/(B × C). EXAMPLE:

$$1/2/3 = \frac{1}{(2 \times 3)} = \frac{1}{6}$$



$L11 = R_L/W1$
$C31 = 1/R_H/W3$
$R_A = R_M(A/H - 1)$
$R_O = R_A + R_M$
$C21 = A/R_O/W2$
$L22 = R_O/W2/A$

**FIGURE 7: Circuit topology and design formulas for the new first-order crossover networks.**

$$W2 = 2\pi f_M \qquad (5)$$

$$W3 = 2\pi f_H \qquad (6)$$

where $2\pi$ equals 6.283185. The correct component sizes depend on the spread (S) between the crossover frequencies, which is defined by the following equation:

$$S = \frac{f_H}{f_L} \qquad (7)$$

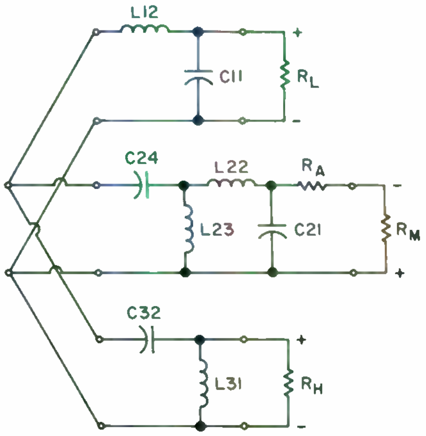
It is also convenient to use a parameter (R) defined by the formula:

$$R = \sqrt{S} \qquad (8)$$

so that the square root of the spread has to be calculated only once.

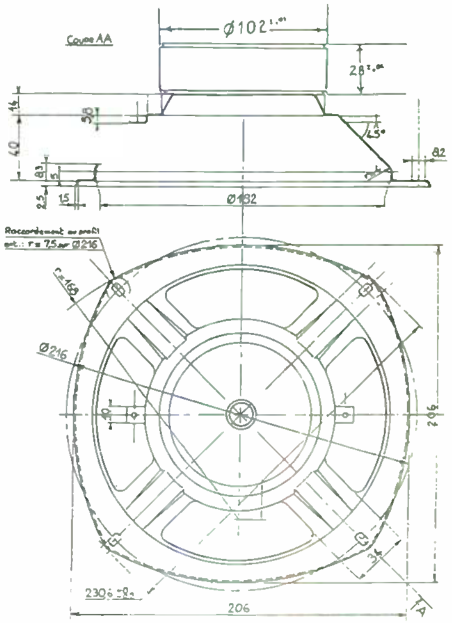
The component values are given in terms of ohms, henries and farads. It is usual to convert the latter two into millihenries and microfarads by multiplying by 1,000 and 1,000,000, respectively. Also, it is assumed that you have the values of $R_L$, $R_M$, $R_H$, W1, W2, W3, S and R available to use in the design formulas.

**FIRST-ORDER CROSSOVER.** The circuit and design formulas for this



$C11 = 1/a/R_L/W1$
$L12 = aR_L/W1$
$L31 = aR_H/W3$
$C32 = 1/a/R_H/W3$
$K = B - 1$
$E = A(1 - 1/K)$
$R_A = R_M(K/H - 1)$
$R_O = R_A + R_M$
$C21 = 1/A/R_O/W2$
$L22 = AR_O/W2/K$
$L23 = ER_O/W2$
$C24 = K/E/R_O/W2$

**FIGURE 8: Circuit topology and design formulas for the new second-order crossover networks.**



crossover are shown in *Fig. 7.* To use the formulas, you must find the value of the bandpass shape parameter (A):

$$A = \frac{R+1}{R} \qquad (9)$$

The gain parameter (H) is defined by the following formula if you want to design an APC:

$$H = \frac{R-1}{R} \qquad (10)$$

If you want to design a CPC, the formula for H is as follows:

$$H = \sqrt{S - \frac{1}{S}} \qquad (11)$$

I do not like to use first-order networks for the same reasons I explained in Part I. Note that polarity is observed in the bandpass section.

This APC network is also a constant-voltage crossover, as defined by Small.[4] As formulas (10) and (11) make explicit, however, the network cannot be an APC and a CPC simultaneously.

### SECOND-ORDER CROSSOVER.

*Figure 8* contains the circuit and formulas for a second-order crossover. For an APC, use the filter shape parameter (a), defined as follows:

$$a = \frac{2(S-1)}{\sqrt{S^2 - 2S}} \qquad (12)$$

and the gain parameter (H) from the formula

$$H = S + a^2 - 4 + \frac{3}{S} \qquad (13)$$

For a CPC, you can find these two parameters with the following equations:

$$a = \sqrt{2} \qquad (14)$$

$$H = \sqrt{S^2 - \frac{1}{S^2}} \qquad (15)$$

For either type of network, you can calculate the bandpass shape parameters (A and B) as follows:

$$A = \left(R + \frac{1}{R}\right)$$

~~$A = a\left(\frac{R+1}{R}\right)$~~ (16)

$$B = S + a^2 + \frac{1}{S} \qquad (17)$$

Note that the bandpass polarity is reversed in this network. This is crucial in obtaining the correct response in an APC and the best magnitude response in a CPC.

### THIRD-ORDER CROSSOVER.

*Figure 9* shows the circuit and formulas for a third-order crossover. There are now two filter shape parameters (a and b) and a gain parameter (H). For a CPC, these are defined as follows:

$$a = 2 \qquad (18)$$

$$b = 2 \qquad (19)$$

$$H = \sqrt{S^3 - \frac{1}{S^3}} \qquad (20)$$

It is not possible to give formulas for these parameters for an APC because they are related to S by complicated equations. Solutions of these equations for various values of S are listed in *Tables 1* and *2*. For exact results, you are restricted to the spreads listed in these tables. The results should not, however, be off by much, if you use the table value closest to your computed S.

Two tables are necessary because you can obtain a third-order APC with the bandpass polarity either observed or reversed. The preferred polarity is not clear, so I leave the decision to you. Just make sure you choose the parameters that are consistent with the polarity you select.

The bandpass shape parameters (A, B and C) are defined as follows:

$$A = bR + \frac{a}{R} \qquad (21)$$

$$B = aS + ab + \frac{b}{S} \qquad (22)$$

$$C = RS + a^2R + \frac{b^2}{R} + \frac{1}{RS} \qquad (23)$$

### FOURTH-ORDER CROSSOVER.

The circuit and formulas for the fourth-order crossover are shown in *Fig. 10.* There are now three shape parameters (a, b and c) and a gain parameter (H). For the CPC, they are as follows:

$$a = \sqrt{4 + 2(2^{1/2})} \qquad (24)$$

$$b = 2 + \sqrt{2} \qquad (25)$$

$$c = a \qquad (26)$$

$$H = \sqrt{S^4 - \frac{1}{S^4}} \qquad (27)$$

Again, formulas for the APC values of these parameters are not possible, so solutions are tabulated in *Table 3.* Because you must observe the bandpass polarity in this crossover, there is only one set of solutions. The bandpass shape parameters (A, B, C and D) are defined as follows:

$$A = cR + \frac{a}{R} \qquad (28)$$

$$B = bS + ac + \frac{b}{S} \qquad (29)$$

$$C = aRS + abR + \frac{bc}{R} + \frac{c}{RS} \qquad (30)$$

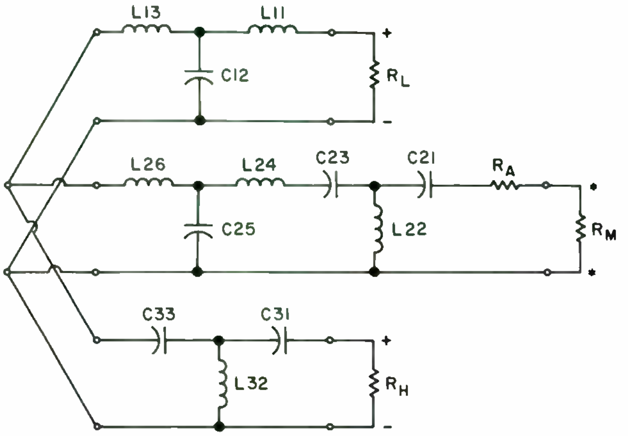
$$D = S^2 + a^2S + b^2 + \frac{c^2}{S} + \frac{1}{S^2} \qquad (31)$$

### DESIGN COMPUTATIONS.

You may be dismayed by the large number of calculations necessary to design a third or fourth-order crossover. The main contributor to this complication is the bandpass filter. Other circuits require less calculation, but any three-way crossover using such a circuit requires extensive trial-and-error adjustment to make it perform even approximately as an APC. If you want an exact formula-based crossover, you are stuck with the computation.

For those of you who can't stand the calculations, I have two other design aids. The first is a generic BASIC computer-aided design (CAD) program that does all the calculations for you. You tell the program the crossover type (APC, CPC), order (1, 2, 3, 4), crossover frequencies ($f_L$, $f_H$) and load resistances ($R_L$, $R_M$, $R_H$). It calculates the inductor values in millihenries, the capacitor values in microfarads and the resistor values in ohms, all keyed to the schematics in *Figs. 7–10.* In addition to its obvious advantages, this program accommodates any crossover frequency spread, not just those on a finite list. *(Editor's Note: Use Fast Reply No. 861 if you would be interested in obtaining a copy of the program on floppy disk. The program listing is available from SB if you send a self-addressed No. 10 envelope with 22¢ postage to Speaker Builder, Dept. B/CAD, PO Box 494, Peterborough, NH 03458.)*

The second design aid is a series of tables you can use to obtain normalized component sizes. You are again limited to a discrete set of crossover frequency spreads, and you must still

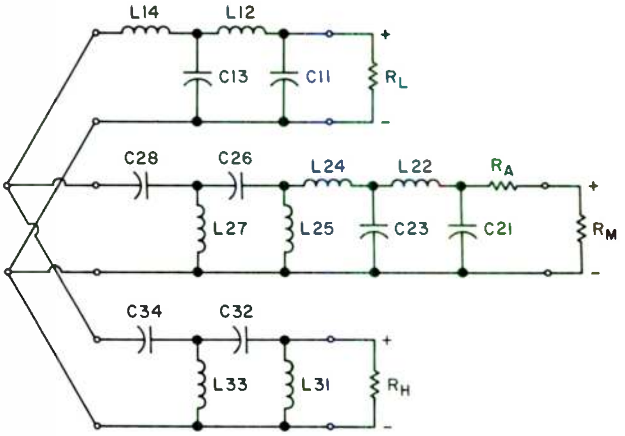


* SEE TEXT FOR POLARITIES.

$e = b - 1/a$
$L11 = R_L/W1/a$
$C12 = a/e/R_L/W1$
$L13 = eR_L/W1$
$C31 = a/R_H/W3$
$L32 = eR_H/W3/a$
$C33 = 1/e/R_H/W3$
$E = B - C/A$
$F = A(1 - 1/E)$
$K = C - A(B - 1)/E$

$G = B - 1 - K/F - EF/K$
$R_A = R_M(K/H - 1)$
$R_O = R_M + R_A$
$C21 = A/R_O/W2$
$L22 = ER_O/W2/A$
$C23 = K/E/R_O/W2$
$L24 = R_O/W2/F$
$C25 = F/G/R_O/W2$
$L26 = GR_O/W2/K$

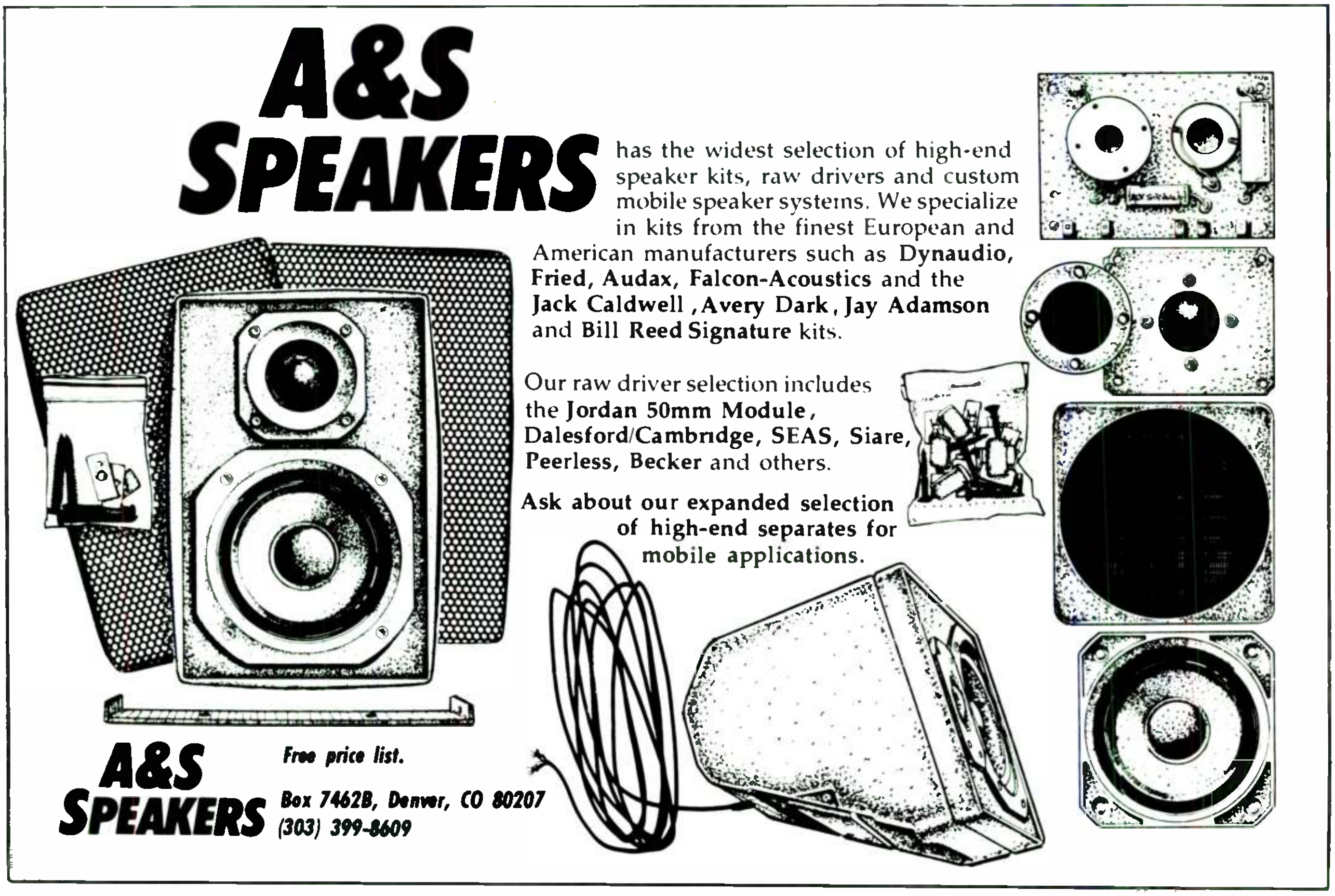
**FIGURE 9: Circuit topology and design formulas for the new third-order crossover networks.**



$e = b - c/a$
$f = c - a/e$
$C11 = 1/a/R_L/W1$
$L12 = aR_L/W1/e$
$C13 = e/f/R_L/W1$
$L14 = fR_L/W1$
$L31 = aR_H/W3$
$C32 = e/a/R_H/W3$
$L33 = fR_H/W3/e$
$C34 = 1/f/R_H/W3$
$E = B - C/A$
$F = D - C/A$
$G = C - AF/E$
$K = F - CE/G + A(B - 1)/G$
$M = B - 1 - AE/G + A/G$

$N = C - A(B - 1)/E - GM/K$
$P = A - A/E - G/K$
$Q = M - N/P$
$T = N - PK/Q$
$R_A = R_M(K/H - 1)$
$R_O = R_M + R_A$
$C21 = 1/A/R_O/W2$
$L22 = AR_O/W2/E$
$C23 = E/G/R_O/W2$
$L24 = GR_O/W2/K$
$L25 = PR_O/W2$
$C26 = Q/P/R_O/W2$
$L27 = TR_O/W2/Q$
$C28 = K/R_O/W2/T$

**FIGURE 10: Circuit topology and design formulas for the new fourth-order crossover networks.**



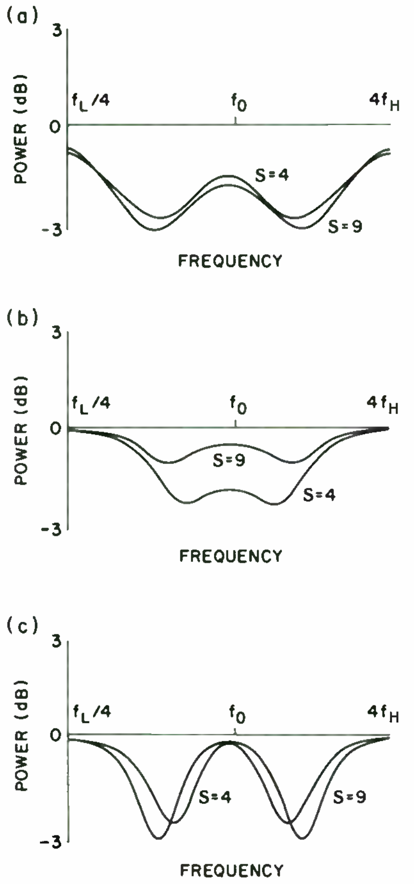


**FIGURE 11: Power responses for the new APCs with crossover frequency spreads of 4 and 9. FIGURE 11a is the second-order network, 11b is the third-order network, and 11c is the fourth-order network.**

## TABLE 1

### THIRD-ORDER APC SHAPE & GAIN PARAMETERS POSITIVE-POLARITY BANDPASS

| S | a | b | H |
|---|---|---|---|
| 2.0 | 1.4863 | 1.7241 | 2.8246 |
| 2.5 | 1.5607 | 1.7667 | 3.9383 |
| 3.0 | 1.6177 | 1.7987 | 5.1735 |
| 3.5 | 1.6625 | 1.8234 | 6.5203 |
| 4.0 | 1.6983 | 1.8430 | 7.9700 |
| 4.5 | 1.7276 | 1.8588 | 9.5151 |
| 5.0 | 1.7519 | 1.8719 | 11.1496 |
| 5.5 | 1.7724 | 1.8827 | 12.8686 |
| 6.0 | 1.7898 | 1.8920 | 14.6679 |
| 6.5 | 1.8048 | 1.8999 | 16.5440 |
| 7.0 | 1.8178 | 1.9067 | 18.4936 |
| 7.5 | 1.8292 | 1.9127 | 20.5142 |
| 8.0 | 1.8394 | 1.9180 | 22.6033 |
| 8.5 | 1.8484 | 1.9227 | 24.7586 |
| 9.0 | 1.8564 | 1.9269 | 26.9781 |
| 9.5 | 1.8637 | 1.9306 | 29.2601 |
| 10.0 | 1.8702 | 1.9340 | 31.6029 |
| 10.5 | 1.8762 | 1.9371 | 34.0050 |
| 11.0 | 1.8816 | 1.9399 | 36.4648 |
| 11.5 | 1.8866 | 1.9425 | 38.9812 |
| 12.0 | 1.8912 | 1.9448 | 41.5528 |
| 12.5 | 1.8954 | 1.9470 | 44.1784 |
| 13.0 | 1.8994 | 1.9490 | 46.8571 |
| 13.5 | 1.9030 | 1.9509 | 49.5877 |
| 14.0 | 1.9064 | 1.9526 | 52.3693 |
| 14.5 | 1.9095 | 1.9543 | 55.2010 |
| 15.0 | 1.9125 | 1.9558 | 58.0820 |
| 15.5 | 1.9153 | 1.9572 | 61.0112 |
| 16.0 | 1.9179 | 1.9585 | 63.9881 |
| 16.5 | 1.9203 | 1.9598 | 67.0119 |
| 17.0 | 1.9226 | 1.9609 | 70.0818 |
| 17.5 | 1.9248 | 1.9620 | 73.1971 |
| 18.0 | 1.9268 | 1.9631 | 76.3573 |
| 18.5 | 1.9288 | 1.9641 | 79.5616 |
| 19.0 | 1.9306 | 1.9650 | 82.8095 |
| 19.5 | 1.9324 | 1.9659 | 86.1004 |
| 20.0 | 1.9341 | 1.9668 | 89.4337 |
| 20.5 | 1.9356 | 1.9676 | 92.8090 |
| 21.0 | 1.9372 | 1.9683 | 96.2256 |
| 21.5 | 1.9386 | 1.9691 | 99.6832 |
| 22.0 | 1.9400 | 1.9698 | 103.1812 |
| 22.5 | 1.9413 | 1.9704 | 106.7191 |
| 23.0 | 1.9426 | 1.9711 | 110.2966 |
| 23.5 | 1.9438 | 1.9717 | 113.9132 |
| 24.0 | 1.9449 | 1.9723 | 117.5684 |
| 24.5 | 1.9460 | 1.9728 | 121.2619 |
| 25.0 | 1.9471 | 1.9734 | 124.9933 |
| 25.5 | 1.9481 | 1.9739 | 128.7621 |
| 26.0 | 1.9491 | 1.9744 | 132.5681 |
| 26.5 | 1.9501 | 1.9749 | 136.4109 |
| 27.0 | 1.9510 | 1.9753 | 140.2900 |
| 27.5 | 1.9519 | 1.9758 | 144.2053 |
| 28.0 | 1.9527 | 1.9762 | 148.1563 |
| 28.5 | 1.9535 | 1.9766 | 152.1427 |
| 29.0 | 1.9543 | 1.9770 | 156.1642 |
| 29.5 | 1.9551 | 1.9774 | 160.2206 |
| 30.0 | 1.9559 | 1.9778 | 164.3115 |
| 30.5 | 1.9566 | 1.9782 | 168.4366 |
| 31.0 | 1.9573 | 1.9785 | 172.5956 |
| 31.5 | 1.9579 | 1.9789 | 176.7884 |
| 32.0 | 1.9586 | 1.9792 | 181.0145 |

## TABLE 2

### THIRD-ORDER APC SHAPE & GAIN PARAMETERS NEGATIVE-POLARITY BANDPASS

| S | a | b | H |
|---|---|---|---|
| 2.0 | ****** | ****** | ******** |
| 2.5 | ****** | ****** | ******** |
| 3.0 | 2.6756 | 2.3133 | 7.0700 |
| 3.5 | 2.4820 | 2.2280 | 7.5411 |
| 4.0 | 2.3919 | 2.1872 | 8.6766 |
| 4.5 | 2.3346 | 2.1609 | 10.0538 |
| 5.0 | 2.2937 | 2.1418 | 11.5827 |
| 5.5 | 2.2625 | 2.1272 | 13.2290 |
| 6.0 | 2.2377 | 2.1155 | 14.9752 |
| 6.5 | 2.2174 | 2.1059 | 16.8107 |
| 7.0 | 2.2004 | 2.0978 | 18.7285 |
| 7.5 | 2.1860 | 2.0909 | 20.7233 |
| 8.0 | 2.1736 | 2.0850 | 22.7912 |
| 8.5 | 2.1627 | 2.0798 | 24.9287 |
| 9.0 | 2.1532 | 2.0752 | 27.1333 |
| 9.5 | 2.1447 | 2.0711 | 29.4025 |
| 10.0 | 2.1372 | 2.0675 | 31.7341 |
| 10.5 | 2.1304 | 2.0642 | 34.1264 |
| 11.0 | 2.1242 | 2.0612 | 36.5777 |
| 11.5 | 2.1187 | 2.0585 | 39.0865 |
| 12.0 | 2.1136 | 2.0560 | 41.6513 |
| 12.5 | 2.1089 | 2.0537 | 44.2710 |
| 13.0 | 2.1046 | 2.0516 | 46.9442 |
| 13.5 | 2.1006 | 2.0497 | 49.6699 |
| 14.0 | 2.0969 | 2.0479 | 52.4470 |
| 14.5 | 2.0935 | 2.0462 | 55.2746 |
| 15.0 | 2.0903 | 2.0447 | 58.1518 |
| 15.5 | 2.0873 | 2.0432 | 61.0777 |
| 16.0 | 2.0846 | 2.0418 | 64.0514 |
| 16.5 | 2.0820 | 2.0406 | 67.0723 |
| 17.0 | 2.0795 | 2.0394 | 70.1395 |
| 17.5 | 2.0772 | 2.0382 | 73.2523 |
| 18.0 | 2.0750 | 2.0372 | 76.4102 |
| 18.5 | 2.0730 | 2.0361 | 79.6123 |
| 19.0 | 2.0710 | 2.0352 | 82.8582 |
| 19.5 | 2.0692 | 2.0343 | 86.1472 |
| 20.0 | 2.0674 | 2.0334 | 89.4788 |
| 20.5 | 2.0657 | 2.0326 | 92.8524 |
| 21.0 | 2.0641 | 2.0318 | 96.2675 |
| 21.5 | 2.0626 | 2.0311 | 99.7236 |
| 22.0 | 2.0612 | 2.0304 | 103.2202 |
| 22.5 | 2.0598 | 2.0297 | 106.7568 |
| 23.0 | 2.0585 | 2.0290 | 110.3331 |
| 23.5 | 2.0572 | 2.0284 | 113.9485 |
| 24.0 | 2.0560 | 2.0278 | 117.6026 |
| 24.5 | 2.0549 | 2.0273 | 121.2950 |
| 25.0 | 2.0538 | 2.0267 | 125.0254 |
| 25.5 | 2.0527 | 2.0262 | 128.7933 |
| 26.0 | 2.0517 | 2.0257 | 132.5984 |
| 26.5 | 2.0507 | 2.0252 | 136.4403 |
| 27.0 | 2.0498 | 2.0247 | 140.3187 |
| 27.5 | 2.0488 | 2.0243 | 144.2331 |
| 28.0 | 2.0480 | 2.0238 | 148.1834 |
| 28.5 | 2.0471 | 2.0234 | 152.1691 |
| 29.0 | 2.0463 | 2.0230 | 156.1899 |
| 29.5 | 2.0455 | 2.0226 | 160.2457 |
| 30.0 | 2.0447 | 2.0222 | 164.3359 |
| 30.5 | 2.0440 | 2.0219 | 168.4604 |
| 31.0 | 2.0433 | 2.0215 | 172.6189 |
| 31.5 | 2.0426 | 2.0212 | 176.8111 |
| 32.0 | 2.0419 | 2.0209 | 181.0367 |

perform denormalizing calculations, but they are much easier. *Tables 4* and *5* are for the positive-polarity, third-order network; *Tables 6* and *7* are for the negative-polarity, third-order network; and *Tables 8* and *9* are for the fourth-order network. To save space, I have provided tables only for an APC, as it is generally considered the better choice in loudspeaker applications. *Tables 4–7* are keyed to *Fig. 9*, and *Tables 8* and *9* correspond to *Fig. 10*.

The low-pass normalized values are found in *Tables 4, 6* and *8*. To denormalize them to millihenries and microfarads, multiply each table inductor value by $1{,}000R_L/W1$ and each table capacitor value by $1{,}000{,}000/(R_LW1)$. The normalized high-pass values are found in the same tables and are denormalized by multiplying each table inductor value by $1{,}000R_H/W3$ and each table capacitor value by $1{,}000{,}000/(R_HW3)$.

The normalized bandpass values in *Tables 5, 7* and *9* are denormalized by multiplying the table $R_A$ by $R_M$, setting $R_O$ equal to $R_A+R_M$ (use the denormalized $R_A$), then multiplying each table inductor value by $1{,}000R_O/W2$ and each table capacitor value by $1{,}000{,}000/(R_OW2)$. Sample formula and table calculations appear in the Examples section at the end of this article. *Sample Runs 1–5* show some CAD program calculations.

**SPEAKER LOADS & RESPONSE.** Just as with the two-way networks, the loudspeaker loads must be equalized to appear approximately resistive to the crossover for at least an octave (preferably two) on either side of the operative crossover frequency. I covered these matters in detail in Part I, and the comments and remedies given there also apply here.

Unlike two-way crossovers, it is not possible to design a three-way system that is both an APC and a CPC using only ladder circuits. The new three-way, even-order networks all have approximately 3dB of ripple in their power responses, just as their two-way counterparts do. *Figures 11a* and *11c* show this for the second-order and fourth-order networks with crossover frequency spreads of two (S=4) and about three (S=9) octaves. The third-order APC has a ripple that decreases as S increases, but it is still well over 1dB, even with a three-octave spread *(Fig. 11b)*. In other words, the odd-order APC has a better power response than the even-order ones, but it is not as good as the two-way, odd-order network.

## TABLE 3

### FOURTH-ORDER APC SHAPE & GAIN PARAMETERS

| S | a | b | c | H |
|---|---|---|---|---|
| 2.0 | 2.4419 | 3.7487 | 2.7381 | 5.110 |
| 2.5 | 2.5548 | 3.7758 | 2.7480 | 6.764 |
| 3.0 | 2.6262 | 3.8222 | 2.7648 | 9.281 |
| 3.5 | 2.6737 | 3.8597 | 2.7784 | 12.416 |
| 4.0 | 2.7066 | 3.8879 | 2.7885 | 16.103 |
| 4.5 | 2.7304 | 3.9089 | 2.7960 | 20.316 |
| 5.0 | 2.7479 | 3.9249 | 2.8017 | 25.043 |
| 5.5 | 2.7612 | 3.9371 | 2.8061 | 30.279 |
| 6.0 | 2.7715 | 3.9466 | 2.8095 | 36.019 |
| 6.5 | 2.7797 | 3.9542 | 2.8122 | 42.263 |
| 7.0 | 2.7862 | 3.9603 | 2.8144 | 49.009 |
| 7.5 | 2.7915 | 3.9653 | 2.8161 | 56.256 |
| 8.0 | 2.7959 | 3.9694 | 2.8176 | 64.003 |
| 8.5 | 2.7995 | 3.9728 | 2.8188 | 72.252 |
| 9.0 | 2.8026 | 3.9757 | 2.8198 | 81.001 |
| 9.5 | 2.8052 | 3.9781 | 2.8207 | 90.250 |
| 10.0 | 2.8075 | 3.9802 | 2.8214 | 99.999 |
| 10.5 | 2.8094 | 3.9820 | 2.8221 | 110.249 |
| 11.0 | 2.8111 | 3.9836 | 2.8226 | 120.999 |
| 11.5 | 2.8125 | 3.9850 | 2.8231 | 132.249 |
| 12.0 | 2.8138 | 3.9862 | 2.8235 | 143.998 |
| 12.5 | 2.8149 | 3.9873 | 2.8239 | 156.248 |
| 13.0 | 2.8160 | 3.9882 | 2.8243 | 168.998 |
| 13.5 | 2.8169 | 3.9891 | 2.8246 | 182.248 |
| 14.0 | 2.8177 | 3.9899 | 2.8248 | 195.998 |
| 14.5 | 2.8184 | 3.9905 | 2.8251 | 210.248 |
| 15.0 | 2.8190 | 3.9912 | 2.8253 | 224.998 |
| 15.5 | 2.8196 | 3.9917 | 2.8255 | 240.248 |
| 16.0 | 2.8202 | 3.9922 | 2.8257 | 255.998 |
| 16.5 | 2.8207 | 3.9927 | 2.8258 | 272.248 |
| 17.0 | 2.8211 | 3.9931 | 2.8260 | 288.998 |
| 17.5 | 2.8215 | 3.9935 | 2.8261 | 306.248 |
| 18.0 | 2.8219 | 3.9938 | 2.8263 | 323.998 |
| 18.5 | 2.8222 | 3.9942 | 2.8264 | 342.248 |
| 19.0 | 2.8226 | 3.9945 | 2.8265 | 360.999 |
| 19.5 | 2.8229 | 3.9948 | 2.8266 | 380.249 |
| 20.0 | 2.8231 | 3.9950 | 2.8267 | 399.999 |
| 20.5 | 2.8234 | 3.9953 | 2.8267 | 420.249 |
| 21.0 | 2.8236 | 3.9955 | 2.8268 | 440.999 |
| 21.5 | 2.8238 | 3.9957 | 2.8269 | 462.249 |
| 22.0 | 2.8241 | 3.9959 | 2.8270 | 483.999 |
| 22.5 | 2.8242 | 3.9961 | 2.8270 | 506.249 |
| 23.0 | 2.8244 | 3.9962 | 2.8271 | 528.999 |
| 23.5 | 2.8246 | 3.9964 | 2.8271 | 552.249 |
| 24.0 | 2.8248 | 3.9965 | 2.8272 | 575.999 |
| 24.5 | 2.8249 | 3.9967 | 2.8273 | 600.249 |
| 25.0 | 2.8250 | 3.9968 | 2.8273 | 624.999 |
| 25.5 | 2.8252 | 3.9969 | 2.8273 | 650.249 |
| 26.0 | 2.8253 | 3.9970 | 2.8274 | 675.999 |
| 26.5 | 2.8254 | 3.9972 | 2.8274 | 702.249 |
| 27.0 | 2.8255 | 3.9973 | 2.8275 | 728.999 |
| 27.5 | 2.8256 | 3.9974 | 2.8275 | 756.249 |
| 28.0 | 2.8257 | 3.9975 | 2.8275 | 783.999 |
| 28.5 | 2.8258 | 3.9975 | 2.8276 | 812.249 |
| 29.0 | 2.8259 | 3.9976 | 2.8276 | 840.999 |
| 29.5 | 2.8260 | 3.9977 | 2.8276 | 870.249 |
| 30.0 | 2.8261 | 3.9978 | 2.8276 | 899.999 |
| 30.5 | 2.8261 | 3.9979 | 2.8277 | 930.249 |
| 31.0 | 2.8262 | 3.9979 | 2.8277 | 960.999 |
| 31.5 | 2.8263 | 3.9980 | 2.8277 | 992.249 |
| 32.0 | 2.8264 | 3.9980 | 2.8277 | 1023.999 |

## TABLE 4

### THIRD-ORDER LOW AND HIGH-PASS NORMALIZED COMPONENT VALUES
### POSITIVE-POLARITY BANDPASS

| | LOW-PASS VALUES | | | HIGH-PASS VALUES | | |
|---|---|---|---|---|---|---|
| S | L11 | C12 | L13 | C31 | L32 | C33 |
| 2.00 | .6728 | 1.4137 | 1.0514 | 1.4863 | .7073 | .9511 |
| 2.50 | .6407 | 1.3860 | 1.1260 | 1.5607 | .7215 | .8881 |
| 3.00 | .6182 | 1.3703 | 1.1806 | 1.6177 | .7298 | .8470 |
| 3.50 | .6015 | 1.3605 | 1.2219 | 1.6625 | .7350 | .8184 |
| 4.00 | .5888 | 1.3541 | 1.2542 | 1.6983 | .7385 | .7973 |
| 4.50 | .5788 | 1.3497 | 1.2800 | 1.7276 | .7409 | .7813 |
| 5.00 | .5708 | 1.3465 | 1.3010 | 1.7519 | .7426 | .7686 |
| 5.50 | .5642 | 1.3442 | 1.3185 | 1.7724 | .7439 | .7584 |
| 6.00 | .5587 | 1.3424 | 1.3332 | 1.7898 | .7449 | .7501 |
| 6.50 | .5541 | 1.3410 | 1.3458 | 1.8048 | .7457 | .7431 |
| 7.00 | .5501 | 1.3400 | 1.3566 | 1.8178 | .7463 | .7371 |
| 7.50 | .5467 | 1.3391 | 1.3660 | 1.8292 | .7468 | .7320 |
| 8.00 | .5437 | 1.3384 | 1.3743 | 1.8394 | .7472 | .7276 |
| 8.50 | .5410 | 1.3378 | 1.3817 | 1.8484 | .7475 | .7238 |
| 9.00 | .5387 | 1.3373 | 1.3882 | 1.8564 | .7478 | .7204 |
| 9.50 | .5366 | 1.3369 | 1.3940 | 1.8637 | .7480 | .7173 |
| 10.00 | .5347 | 1.3365 | 1.3993 | 1.8702 | .7482 | .7146 |
| 10.50 | .5330 | 1.3362 | 1.4041 | 1.8762 | .7484 | .7122 |
| 11.00 | .5315 | 1.3360 | 1.4085 | 1.8816 | .7485 | .7100 |
| 11.50 | .5300 | 1.3357 | 1.4124 | 1.8866 | .7487 | .7080 |
| 12.00 | .5288 | 1.3355 | 1.4161 | 1.8912 | .7488 | .7062 |
| 12.50 | .5276 | 1.3353 | 1.4194 | 1.8954 | .7489 | .7045 |
| 13.00 | .5265 | 1.3352 | 1.4225 | 1.8994 | .7490 | .7030 |
| 13.50 | .5255 | 1.3351 | 1.4254 | 1.9030 | .7490 | .7016 |
| 14.00 | .5246 | 1.3349 | 1.4281 | 1.9064 | .7491 | .7002 |
| 14.50 | .5237 | 1.3348 | 1.4306 | 1.9095 | .7492 | .6990 |
| 15.00 | .5229 | 1.3347 | 1.4329 | 1.9125 | .7492 | .6979 |
| 15.50 | .5221 | 1.3346 | 1.4351 | 1.9153 | .7493 | .6968 |
| 16.00 | .5214 | 1.3345 | 1.4371 | 1.9179 | .7493 | .6959 |
| 16.50 | .5207 | 1.3345 | 1.4390 | 1.9203 | .7494 | .6949 |
| 17.00 | .5201 | 1.3344 | 1.4408 | 1.9226 | .7494 | .6941 |
| 17.50 | .5195 | 1.3343 | 1.4425 | 1.9248 | .7494 | .6932 |
| 18.00 | .5190 | 1.3343 | 1.4441 | 1.9268 | .7495 | .6925 |
| 18.50 | .5185 | 1.3342 | 1.4456 | 1.9288 | .7495 | .6917 |
| 19.00 | .5180 | 1.3342 | 1.4471 | 1.9306 | .7495 | .6911 |
| 19.50 | .5175 | 1.3341 | 1.4484 | 1.9324 | .7495 | .6904 |
| 20.00 | .5170 | 1.3341 | 1.4497 | 1.9341 | .7496 | .6898 |
| 20.50 | .5166 | 1.3341 | 1.4509 | 1.9356 | .7496 | .6892 |
| 21.00 | .5162 | 1.3340 | 1.4521 | 1.9372 | .7496 | .6887 |
| 21.50 | .5158 | 1.3340 | 1.4532 | 1.9386 | .7496 | .6881 |
| 22.00 | .5155 | 1.3340 | 1.4543 | 1.9400 | .7496 | .6876 |
| 22.50 | .5151 | 1.3339 | 1.4553 | 1.9413 | .7497 | .6871 |
| 23.00 | .5148 | 1.3339 | 1.4563 | 1.9426 | .7497 | .6867 |
| 23.50 | .5145 | 1.3339 | 1.4572 | 1.9438 | .7497 | .6862 |
| 24.00 | .5142 | 1.3339 | 1.4581 | 1.9449 | .7497 | .6858 |
| 24.50 | .5139 | 1.3338 | 1.4590 | 1.9460 | .7497 | .6854 |
| 25.00 | .5136 | 1.3338 | 1.4598 | 1.9471 | .7497 | .6850 |
| 25.50 | .5133 | 1.3338 | 1.4606 | 1.9481 | .7497 | .6847 |
| 26.00 | .5131 | 1.3338 | 1.4613 | 1.9491 | .7497 | .6843 |
| 26.50 | .5128 | 1.3338 | 1.4621 | 1.9501 | .7498 | .6840 |
| 27.00 | .5126 | 1.3338 | 1.4628 | 1.9510 | .7498 | .6836 |
| 27.50 | .5123 | 1.3337 | 1.4635 | 1.9519 | .7498 | .6833 |
| 28.00 | .5121 | 1.3337 | 1.4641 | 1.9527 | .7498 | .6830 |
| 28.50 | .5119 | 1.3337 | 1.4647 | 1.9535 | .7498 | .6827 |
| 29.00 | .5117 | 1.3337 | 1.4654 | 1.9543 | .7498 | .6824 |
| 29.50 | .5115 | 1.3337 | 1.4659 | 1.9551 | .7498 | .6822 |
| 30.00 | .5113 | 1.3337 | 1.4665 | 1.9559 | .7498 | .6819 |
| 30.50 | .5111 | 1.3337 | 1.4671 | 1.9566 | .7498 | .6816 |
| 31.00 | .5109 | 1.3337 | 1.4676 | 1.9573 | .7498 | .6814 |
| 31.50 | .5107 | 1.3336 | 1.4681 | 1.9579 | .7498 | .6811 |
| 32.00 | .5106 | 1.3336 | 1.4686 | 1.9586 | .7498 | .6809 |

Even-order CPCs all have a magnitude ripple of about 3dB, just like their two-way counterparts. The third-order CPC magnitude ripple is about 3dB at a two-octave crossover frequency spread and is still well over 1dB with a three-octave spread.

**LOSSES, SENSITIVITY & $R_A$.** Just as with the low-pass and high-pass sections, the resistances of the source and series inductors cause a flat loss and a shift in corner frequencies in the bandpass section. Most of the time, this is not a problem because an amplifier with a high damping factor is used and the bandpass series inductors are relatively small. But when the lower crossover frequency ($f_L$) is less than 300Hz or so, the inductors can be large, and it is then worthwhile to try to account for the flat loss they cause. You must live with the frequency shift because extremely sophisticated techniques are needed to account for it.

The easiest way to deal with the inductor losses is to design the bandpass circuit with $R_A$ deleted—i.e., with $R_O$ equal to $R_M$. This in itself might more than account for the losses caused by

TABLE 5

THIRD-ORDER BANDPASS NORMALIZED COMPONENT VALUES
POSITIVE-POLARITY BANDPASS

| S | C21 | L22 | C23 | L24 | C25 | L26 | RA |
|---|---|---|---|---|---|---|---|
| 2.00 | 3.4893 | 1.1428 | .9242 | .3825 | 2.2557 | .3145 | .3048 |
| 2.50 | 3.7805 | 1.2465 | 1.0450 | .3358 | 1.5993 | .3782 | .2503 |
| 3.00 | 4.0495 | 1.3462 | 1.1594 | .3024 | 1.2722 | .4113 | .2216 |
| 3.50 | 4.3000 | 1.4412 | 1.2651 | .2773 | 1.0775 | .4269 | .2024 |
| 4.00 | 4.5352 | 1.5316 | 1.3626 | .2576 | .9476 | .4329 | .1876 |
| 4.50 | 4.7576 | 1.6179 | 1.4530 | .2416 | .8538 | .4335 | .1753 |
| 5.00 | 4.9691 | 1.7003 | 1.5372 | .2283 | .7825 | .4311 | .1648 |
| 5.50 | 5.1712 | 1.7793 | 1.6162 | .2170 | .7260 | .4270 | .1555 |
| 6.00 | 5.3650 | 1.8552 | 1.6907 | .2072 | .6798 | .4218 | .1473 |
| 6.50 | 5.5516 | 1.9283 | 1.7615 | .1987 | .6413 | .4162 | .1398 |
| 7.00 | 5.7318 | 1.9989 | 1.8290 | .1911 | .6085 | .4103 | .1331 |
| 7.50 | 5.9061 | 2.0673 | 1.8935 | .1844 | .5802 | .4042 | .1270 |
| 8.00 | 6.0752 | 2.1335 | 1.9556 | .1784 | .5554 | .3983 | .1214 |
| 8.50 | 6.2395 | 2.1978 | 2.0153 | .1729 | .5335 | .3923 | .1163 |
| 9.00 | 6.3994 | 2.2604 | 2.0731 | .1679 | .5139 | .3865 | .1115 |
| 9.50 | 6.5552 | 2.3213 | 2.1290 | .1633 | .4963 | .3809 | .1072 |
| 10.00 | 6.7073 | 2.3807 | 2.1832 | .1591 | .4804 | .3754 | .1031 |
| 10.50 | 6.8559 | 2.4386 | 2.2360 | .1551 | .4659 | .3701 | .0994 |
| 11.00 | 7.0013 | 2.4953 | 2.2873 | .1515 | .4526 | .3650 | .0959 |
| 11.50 | 7.1436 | 2.5508 | 2.3374 | .1481 | .4403 | .3600 | .0926 |
| 12.00 | 7.2831 | 2.6050 | 2.3862 | .1449 | .4290 | .3552 | .0895 |
| 12.50 | 7.4199 | 2.6582 | 2.4340 | .1420 | .4185 | .3506 | .0867 |
| 13.00 | 7.5541 | 2.7104 | 2.4807 | .1392 | .4088 | .3461 | .0840 |
| 13.50 | 7.6860 | 2.7616 | 2.5265 | .1365 | .3996 | .3417 | .0815 |
| 14.00 | 7.8156 | 2.8119 | 2.5714 | .1340 | .3911 | .3376 | .0791 |
| 14.50 | 7.9430 | 2.8613 | 2.6155 | .1317 | .3831 | .3335 | .0768 |
| 15.00 | 8.0684 | 2.9098 | 2.6587 | .1295 | .3755 | .3296 | .0747 |
| 15.50 | 8.1919 | 2.9576 | 2.7012 | .1273 | .3684 | .3258 | .0727 |
| 16.00 | 8.3135 | 3.0047 | 2.7430 | .1253 | .3616 | .3221 | .0708 |
| 16.50 | 8.4333 | 3.0510 | 2.7841 | .1234 | .3552 | .3185 | .0690 |
| 17.00 | 8.5514 | 3.0966 | 2.8245 | .1215 | .3492 | .3151 | .0672 |
| 17.50 | 8.6679 | 3.1416 | 2.8643 | .1198 | .3434 | .3117 | .0656 |
| 18.00 | 8.7828 | 3.1859 | 2.9036 | .1181 | .3379 | .3085 | .0640 |
| 18.50 | 8.8962 | 3.2297 | 2.9423 | .1165 | .3326 | .3053 | .0625 |
| 19.00 | 9.0082 | 3.2728 | 2.9805 | .1149 | .3276 | .3023 | .0611 |
| 19.50 | 9.1188 | 3.3154 | 3.0181 | .1134 | .3228 | .2993 | .0598 |
| 20.00 | 9.2281 | 3.3575 | 3.0553 | .1120 | .3183 | .2964 | .0585 |
| 20.50 | 9.3360 | 3.3990 | 3.0920 | .1106 | .3139 | .2936 | .0572 |
| 21.00 | 9.4427 | 3.4401 | 3.1282 | .1093 | .3096 | .2909 | .0560 |
| 21.50 | 9.5483 | 3.4807 | 3.1640 | .1080 | .3056 | .2882 | .0549 |
| 22.00 | 9.6526 | 3.5208 | 3.1994 | .1067 | .3017 | .2856 | .0538 |
| 22.50 | 9.7558 | 3.5604 | 3.2343 | .1055 | .2979 | .2831 | .0527 |
| 23.00 | 9.8580 | 3.5997 | 3.2689 | .1044 | .2943 | .2806 | .0517 |
| 23.50 | 9.9591 | 3.6385 | 3.3031 | .1033 | .2908 | .2782 | .0507 |
| 24.00 | 10.0591 | 3.6769 | 3.3370 | .1022 | .2874 | .2759 | .0498 |
| 24.50 | 10.1582 | 3.7149 | 3.3705 | .1011 | .2841 | .2736 | .0489 |
| 25.00 | 10.2563 | 3.7525 | 3.4036 | .1001 | .2810 | .2714 | .0480 |
| 25.50 | 10.3535 | 3.7897 | 3.4364 | .0991 | .2779 | .2692 | .0472 |
| 26.00 | 10.4498 | 3.8266 | 3.4689 | .0982 | .2750 | .2671 | .0463 |
| 26.50 | 10.5451 | 3.8631 | 3.5011 | .0972 | .2721 | .2650 | .0455 |
| 27.00 | 10.6397 | 3.8993 | 3.5329 | .0963 | .2694 | .2630 | .0448 |
| 27.50 | 10.7333 | 3.9352 | 3.5645 | .0954 | .2667 | .2610 | .0440 |
| 28.00 | 10.8262 | 3.9707 | 3.5958 | .0946 | .2640 | .2591 | .0433 |
| 28.50 | 10.9183 | 4.0060 | 3.6268 | .0937 | .2615 | .2572 | .0426 |
| 29.00 | 11.0096 | 4.0409 | 3.6576 | .0929 | .2590 | .2553 | .0420 |
| 29.50 | 11.1001 | 4.0755 | 3.6880 | .0921 | .2566 | .2535 | .0413 |
| 30.00 | 11.1900 | 4.1098 | 3.7183 | .0914 | .2543 | .2517 | .0407 |
| 30.50 | 11.2791 | 4.1439 | 3.7482 | .0906 | .2520 | .2500 | .0401 |
| 31.00 | 11.3675 | 4.1776 | 3.7780 | .0899 | .2498 | .2483 | .0395 |
| 31.50 | 11.4552 | 4.2111 | 3.8075 | .0891 | .2477 | .2466 | .0389 |
| 32.00 | 11.5422 | 4.2444 | 3.8367 | .0884 | .2456 | .2450 | .0384 |

the series inductors because leaving out $R_A$ produces an excess gain (EG) in the amount determined by the following equation:

$$EG = 20\log\left(\frac{R_M+R_A}{R_M}\right) \tag{32}$$

The inductor-source loss (LG) can be calculated as follows:

$$LG = 20\log\left(\frac{R_M+R_S}{R_M}\right) \tag{33}$$

where $R_S$ is the sum of the source and inductor resistances. Thus, if SN is the sensitivity of the midrange driver (in decibels), its effective sensitivity (SNE) when driven by the bandpass filter with $R_A$ equal to zero is as follows:

$$SNE = SN + EG - LG \tag{34}$$

You can then use this figure to match sensitivities with the woofer and tweeter. If attenuation is necessary for matching, use an attenuator circuit that maintains the bandpass load at the value $R_M$ so that the filter sees the proper load.

By now you may have realized that this excess bandpass gain might be useful even when the source and inductor losses are negligible—i.e., when LG equals zero. Then there is an overall improvement in midrange sensitivity, which allows the possibility of matching a midrange to a woofer and tweeter, even when it is less sensitive than the woofer and tweeter, without having to attenuate the woofer. For example, if EG equals 2dB and the woofer-tweeter sensitivity is 92dB, you may use a midrange driver with a nominal sensitivity of 90dB without using any attenuating circuitry.

If you remember that the $R_A$,$R_M$ pair is just a voltage divider (since the signal is taken from $R_M$), you can change $R_A$ to attenuate more or less to help match sensitivities. If you use it this way, however, each time you change $R_A$, you must recompute the bandpass LC components because you are now using a new value of $R_O$. I have included an option in the CAD program that calculates the bandpass circuit values with $R_A$ equal to zero and the value of EG and LG. In terms of the circuit design parameters of *Figs. 7–10,* EG can be calculated as follows:

$$EG = 20\log\frac{K}{H} \tag{35}$$

**DRIVER PHASE & OFFSET.** The on-axis magnitude response of a multiple-driver loudspeaker system can be altered significantly by the individual loudspeaker phase responses and by horizontal offset between adjacent driver acoustic centers. I have shown$^5$ that two-way, even-order crossovers are especially insensitive to these phase and geometry influences. I expect the new even-order, three-way crossovers to possess the same type of insensitivity, although its degree will probably vary with the spread between the two crossover frequencies.

If the spread is large, the woofer-midrange and midrange-tweeter pairs can be considered independently and the two-way sensitivity analysis of reference 5 should carry over without complication. On the other hand, if the crossover frequencies are close, there might be enough three-channel interaction to complicate the argument. Even then, I expect that an even-order network would still be less sensitive to driver phase and offset than an odd-order network.

Regardless of the crossover order, you can minimize phase and offset effects by keeping the crossover frequencies as far apart as possible. Also, it is important to keep the fundamental midrange resonance well below

## TABLE 6

### THIRD-ORDER LOW AND HIGH-PASS NORMALIZED COMPONENT VALUES NEGATIVE-POLARITY BANDPASS

| | LOW-PASS VALUES | | | HIGH-PASS VALUES | | |
|---|---|---|---|---|---|---|
| S | L11 | C12 | L13 | C31 | L32 | C33 |
| 3.00 | .3737 | 1.3795 | 1.9395 | 2.6756 | .7249 | .5156 |
| 3.50 | .4029 | 1.3599 | 1.8251 | 2.4820 | .7353 | .5479 |
| 4.00 | .4181 | 1.3520 | 1.7691 | 2.3919 | .7396 | .5653 |
| 4.50 | .4283 | 1.3475 | 1.7325 | 2.3346 | .7421 | .5772 |
| 5.00 | .4360 | 1.3446 | 1.7058 | 2.2937 | .7437 | .5862 |
| 5.50 | .4420 | 1.3426 | 1.6852 | 2.2625 | .7448 | .5934 |
| 6.00 | .4469 | 1.3410 | 1.6686 | 2.2377 | .7457 | .5993 |
| 6.50 | .4510 | 1.3399 | 1.6549 | 2.2174 | .7463 | .6043 |
| 7.00 | .4545 | 1.3390 | 1.6433 | 2.2004 | .7468 | .6085 |
| 7.50 | .4575 | 1.3382 | 1.6335 | 2.1860 | .7472 | .6122 |
| 8.00 | .4601 | 1.3377 | 1.6249 | 2.1736 | .7476 | .6154 |
| 8.50 | .4624 | 1.3372 | 1.6174 | 2.1627 | .7478 | .6183 |
| 9.00 | .4644 | 1.3368 | 1.6108 | 2.1532 | .7481 | .6208 |
| 9.50 | .4663 | 1.3364 | 1.6049 | 2.1447 | .7483 | .6231 |
| 10.00 | .4679 | 1.3361 | 1.5995 | 2.1372 | .7484 | .6252 |
| 10.50 | .4694 | 1.3359 | 1.5948 | 2.1304 | .7486 | .6271 |
| 11.00 | .4708 | 1.3356 | 1.5904 | 2.1242 | .7487 | .6288 |
| 11.50 | .4720 | 1.3354 | 1.5865 | 2.1187 | .7488 | .6303 |
| 12.00 | .4731 | 1.3353 | 1.5829 | 2.1136 | .7489 | .6318 |
| 12.50 | .4742 | 1.3351 | 1.5795 | 2.1089 | .7490 | .6331 |
| 13.00 | .4752 | 1.3350 | 1.5765 | 2.1046 | .7491 | .6343 |
| 13.50 | .4761 | 1.3349 | 1.5736 | 2.1006 | .7491 | .6355 |
| 14.00 | .4769 | 1.3348 | 1.5710 | 2.0969 | .7492 | .6365 |
| 14.50 | .4777 | 1.3347 | 1.5685 | 2.0935 | .7492 | .6375 |
| 15.00 | .4784 | 1.3346 | 1.5663 | 2.0903 | .7493 | .6385 |
| 15.50 | .4791 | 1.3345 | 1.5641 | 2.0873 | .7493 | .6393 |
| 16.00 | .4797 | 1.3344 | 1.5621 | 2.0846 | .7494 | .6402 |
| 16.50 | .4803 | 1.3344 | 1.5602 | 2.0820 | .7494 | .6409 |
| 17.00 | .4809 | 1.3343 | 1.5585 | 2.0795 | .7494 | .6417 |
| 17.50 | .4814 | 1.3343 | 1.5568 | 2.0772 | .7495 | .6423 |
| 18.00 | .4819 | 1.3342 | 1.5552 | 2.0750 | .7495 | .6430 |
| 18.50 | .4824 | 1.3342 | 1.5537 | 2.0730 | .7495 | .6436 |
| 19.00 | .4829 | 1.3341 | 1.5523 | 2.0710 | .7496 | .6442 |
| 19.50 | .4833 | 1.3341 | 1.5510 | 2.0692 | .7496 | .6447 |
| 20.00 | .4837 | 1.3340 | 1.5497 | 2.0674 | .7496 | .6453 |
| 20.50 | .4841 | 1.3340 | 1.5485 | 2.0657 | .7496 | .6458 |
| 21.00 | .4845 | 1.3340 | 1.5474 | 2.0641 | .7496 | .6463 |
| 21.50 | .4848 | 1.3340 | 1.5463 | 2.0626 | .7497 | .6467 |
| 22.00 | .4852 | 1.3339 | 1.5452 | 2.0612 | .7497 | .6472 |
| 22.50 | .4855 | 1.3339 | 1.5442 | 2.0598 | .7497 | .6476 |
| 23.00 | .4858 | 1.3339 | 1.5433 | 2.0585 | .7497 | .6480 |
| 23.50 | .4861 | 1.3339 | 1.5423 | 2.0572 | .7497 | .6484 |
| 24.00 | .4864 | 1.3338 | 1.5415 | 2.0560 | .7497 | .6487 |
| 24.50 | .4866 | 1.3338 | 1.5406 | 2.0549 | .7497 | .6491 |
| 25.00 | .4869 | 1.3338 | 1.5398 | 2.0538 | .7497 | .6494 |
| 25.50 | .4872 | 1.3338 | 1.5390 | 2.0527 | .7498 | .6498 |
| 26.00 | .4874 | 1.3338 | 1.5383 | 2.0517 | .7498 | .6501 |
| 26.50 | .4876 | 1.3337 | 1.5376 | 2.0507 | .7498 | .6504 |
| 27.00 | .4879 | 1.3337 | 1.5369 | 2.0498 | .7498 | .6507 |
| 27.50 | .4881 | 1.3337 | 1.5362 | 2.0488 | .7498 | .6510 |
| 28.00 | .4883 | 1.3337 | 1.5356 | 2.0480 | .7498 | .6512 |
| 28.50 | .4885 | 1.3337 | 1.5349 | 2.0471 | .7498 | .6515 |
| 29.00 | .4887 | 1.3337 | 1.5343 | 2.0463 | .7498 | .6518 |
| 29.50 | .4889 | 1.3337 | 1.5337 | 2.0455 | .7498 | .6520 |
| 30.00 | .4891 | 1.3337 | 1.5332 | 2.0447 | .7498 | .6522 |
| 30.50 | .4892 | 1.3336 | 1.5326 | 2.0440 | .7498 | .6525 |
| 31.00 | .4894 | 1.3336 | 1.5321 | 2.0433 | .7498 | .6527 |
| 31.50 | .4896 | 1.3336 | 1.5316 | 2.0426 | .7498 | .6529 |
| 32.00 | .4897 | 1.3336 | 1.5311 | 2.0419 | .7498 | .6531 |

## TABLE 7

### THIRD-ORDER BANDPASS NORMALIZED COMPONENT VALUES NEGATIVE-POLARITY BANDPASS

| S | C21 | L22 | C23 | L24 | C25 | L26 | RA |
|---|---|---|---|---|---|---|---|
| 3.00 | 5.5514 | 2.0223 | 1.2436 | .1977 | .7063 | .5129 | .9747 |
| 3.50 | 5.4949 | 2.0116 | 1.2658 | .2001 | .7034 | .5078 | .8555 |
| 4.00 | 5.5703 | 2.0472 | 1.3111 | .1968 | .6751 | .5035 | .7232 |
| 4.50 | 5.6844 | 2.0955 | 1.3635 | .1920 | .6434 | .4983 | .6155 |
| 5.00 | 5.8150 | 2.1489 | 1.4187 | .1869 | .6131 | .4922 | .5306 |
| 5.50 | 5.9534 | 2.2043 | 1.4753 | .1818 | .5854 | .4853 | .4634 |
| 6.00 | 6.0954 | 2.2604 | 1.5321 | .1769 | .5603 | .4779 | .4096 |
| 6.50 | 6.2387 | 2.3166 | 1.5888 | .1722 | .5378 | .4702 | .3659 |
| 7.00 | 6.3820 | 2.3723 | 1.6449 | .1678 | .5175 | .4624 | .3298 |
| 7.50 | 6.5244 | 2.4275 | 1.7004 | .1636 | .4992 | .4546 | .2996 |
| 8.00 | 6.6657 | 2.4820 | 1.7551 | .1597 | .4826 | .4469 | .2741 |
| 8.50 | 6.8053 | 2.5357 | 1.8090 | .1560 | .4675 | .4393 | .2522 |
| 9.00 | 6.9433 | 2.5886 | 1.8620 | .1525 | .4537 | .4318 | .2334 |
| 9.50 | 7.0794 | 2.6407 | 1.9141 | .1492 | .4410 | .4246 | .2170 |
| 10.00 | 7.2137 | 2.6920 | 1.9653 | .1462 | .4293 | .4176 | .2026 |
| 10.50 | 7.3461 | 2.7425 | 2.0156 | .1432 | .4185 | .4108 | .1899 |
| 11.00 | 7.4767 | 2.7922 | 2.0651 | .1405 | .4084 | .4043 | .1786 |
| 11.50 | 7.6054 | 2.8411 | 2.1138 | .1379 | .3991 | .3980 | .1685 |
| 12.00 | 7.7323 | 2.8893 | 2.1616 | .1354 | .3903 | .3919 | .1595 |
| 12.50 | 7.8575 | 2.9368 | 2.2087 | .1330 | .3821 | .3860 | .1513 |
| 13.00 | 7.9809 | 2.9836 | 2.2550 | .1308 | .3744 | .3803 | .1438 |
| 13.50 | 8.1027 | 3.0298 | 2.3006 | .1287 | .3671 | .3749 | .1371 |
| 14.00 | 8.2229 | 3.0753 | 2.3454 | .1266 | .3603 | .3696 | .1309 |
| 14.50 | 8.3415 | 3.1201 | 2.3896 | .1247 | .3538 | .3645 | .1252 |
| 15.00 | 8.4587 | 3.1644 | 2.4332 | .1228 | .3477 | .3596 | .1200 |
| 15.50 | 8.5743 | 3.2081 | 2.4761 | .1210 | .3418 | .3549 | .1151 |
| 16.00 | 8.6885 | 3.2513 | 2.5184 | .1193 | .3363 | .3503 | .1107 |
| 16.50 | 8.8014 | 3.2939 | 2.5601 | .1177 | .3310 | .3459 | .1065 |
| 17.00 | 8.9129 | 3.3359 | 2.6012 | .1161 | .3260 | .3416 | .1027 |
| 17.50 | 9.0231 | 3.3775 | 2.6418 | .1146 | .3212 | .3375 | .0991 |
| 18.00 | 9.1320 | 3.4186 | 2.6818 | .1131 | .3166 | .3335 | .0957 |
| 18.50 | 9.2398 | 3.4592 | 2.7214 | .1117 | .3122 | .3297 | .0926 |
| 19.00 | 9.3463 | 3.4994 | 2.7604 | .1104 | .3079 | .3259 | .0896 |
| 19.50 | 9.4517 | 3.5391 | 2.7990 | .1091 | .3039 | .3223 | .0868 |
| 20.00 | 9.5560 | 3.5784 | 2.8370 | .1078 | .3000 | .3188 | .0842 |
| 20.50 | 9.6592 | 3.6173 | 2.8747 | .1066 | .2962 | .3154 | .0818 |
| 21.00 | 9.7614 | 3.6558 | 2.9119 | .1054 | .2926 | .3121 | .0794 |
| 21.50 | 9.8626 | 3.6939 | 2.9487 | .1043 | .2891 | .3089 | .0772 |
| 22.00 | 9.9627 | 3.7316 | 2.9851 | .1031 | .2857 | .3057 | .0751 |
| 22.50 | 10.0619 | 3.7689 | 3.0210 | .1021 | .2825 | .3027 | .0731 |
| 23.00 | 10.1602 | 3.8059 | 3.0566 | .1010 | .2793 | .2998 | .0713 |
| 23.50 | 10.2575 | 3.8425 | 3.0919 | .1000 | .2763 | .2969 | .0695 |
| 24.00 | 10.3540 | 3.8788 | 3.1267 | .0990 | .2734 | .2941 | .0678 |
| 24.50 | 10.4496 | 3.9148 | 3.1612 | .0981 | .2705 | .2914 | .0661 |
| 25.00 | 10.5443 | 3.9504 | 3.1954 | .0972 | .2678 | .2888 | .0646 |
| 25.50 | 10.6382 | 3.9857 | 3.2292 | .0963 | .2651 | .2862 | .0631 |
| 26.00 | 10.7314 | 4.0208 | 3.2627 | .0954 | .2625 | .2837 | .0617 |
| 26.50 | 10.8237 | 4.0555 | 3.2959 | .0945 | .2600 | .2812 | .0603 |
| 27.00 | 10.9153 | 4.0899 | 3.3288 | .0937 | .2575 | .2788 | .0590 |
| 27.50 | 11.0061 | 4.1241 | 3.3613 | .0929 | .2551 | .2765 | .0578 |
| 28.00 | 11.0962 | 4.1579 | 3.3936 | .0921 | .2528 | .2742 | .0566 |
| 28.50 | 11.1856 | 4.1915 | 3.4256 | .0913 | .2506 | .2720 | .0555 |
| 29.00 | 11.2743 | 4.2249 | 3.4573 | .0906 | .2484 | .2699 | .0544 |
| 29.50 | 11.3623 | 4.2579 | 3.4888 | .0899 | .2462 | .2677 | .0533 |
| 30.00 | 11.4496 | 4.2908 | 3.5200 | .0892 | .2442 | .2657 | .0523 |
| 30.50 | 11.5363 | 4.3233 | 3.5509 | .0885 | .2421 | .2636 | .0513 |
| 31.00 | 11.6224 | 4.3557 | 3.5816 | .0878 | .2401 | .2617 | .0503 |
| 31.50 | 11.7078 | 4.3878 | 3.6120 | .0871 | .2382 | .2597 | .0494 |
| 32.00 | 11.7926 | 4.4196 | 3.6422 | .0865 | .2363 | .2578 | .0486 |

the low crossover frequency and the fundamental tweeter resonance well below the higher crossover frequency. You should, of course, make some attempt to align the driver acoustic centers.

**RADIATION PATTERNS.** In a two-way loudspeaker system, the vertical radiation pattern changes from one caused by a single source to one caused by two interacting sources at any frequency where both drivers are active. The result is a lobing in the vertical radiation pattern, which is obviously most pronounced at the crossover frequency, but persists for some range of frequencies surrounding it. The exact geometry of the pattern depends on the type of crossover used and how its channel phases affect the air-path delays from the sources to the off-axis listening positions. We have seen that the even-order networks described in Part I cause a lobing pattern that is symmetric about the main listening axis, while the odd-order networks yield an asymmetric pattern.

The same phenomenon occurs in three-way systems, but its analysis is more complicated because there are now two different crossover frequencies where two drivers are active. Further, if the crossover frequencies are too close together, it is possible that three drivers are contributing significantly to the total response at the midrange center frequency. To obtain adequate insight into three-way patterns, you should examine them at the frequencies $f_L$, $f_M$ and $f_H$ for different crossover frequency spacings.

*Figures 13* and *14* show patterns for a new three-way, second-order APC at crossover frequency spreads of S=4 and S=9, respectively. *Figures 15* and *16* are third-order patterns for the same spreads. The second-order graphs are not symmetric about the listening axis as we would expect, but this is due to the placement of the main axis and not to any new behavior. The model I used is shown in *Fig. 12,* where you will note that the reference axis is taken as the midrange principal axis. If I had placed the reference axis midway between the woofer and tweeter, the expected symmetry would have materialized. Using the midrange principal axis as

### TABLE 8

### FOURTH-ORDER LOW & HIGH-PASS NORMALIZED COMPONENT VALUES

| | LOW-PASS VALUES | | | | HIGH-PASS VALUES | | | |
|---|---|---|---|---|---|---|---|---|
| S | C11 | L12 | C13 | L14 | L31 | C32 | L33 | C34 |
| 2.0 | .4095 | .9294 | 1.4526 | 1.8087 | 2.4419 | 1.0760 | .6884 | .5529 |
| 2.5 | .3914 | .9461 | 1.4985 | 1.8019 | 2.5548 | 1.0569 | .6673 | .5550 |
| 3.0 | .3808 | .9483 | 1.5245 | 1.8166 | 2.6262 | 1.0545 | .6559 | .5505 |
| 3.5 | .3740 | .9479 | 1.5409 | 1.8305 | 2.6737 | 1.0549 | .6490 | .5463 |
| 4.0 | .3695 | .9472 | 1.5519 | 1.8413 | 2.7066 | 1.0558 | .6444 | .5431 |
| 4.5 | .3663 | .9464 | 1.5597 | 1.8496 | 2.7304 | 1.0566 | .6411 | .5407 |
| 5.0 | .3639 | .9458 | 1.5654 | 1.8559 | 2.7479 | 1.0573 | .6388 | .5388 |
| 5.5 | .3622 | .9454 | 1.5697 | 1.8607 | 2.7612 | 1.0578 | .6371 | .5374 |
| 6.0 | .3608 | .9450 | 1.5730 | 1.8645 | 2.7715 | 1.0582 | .6357 | .5363 |
| 6.5 | .3598 | .9447 | 1.5756 | 1.8675 | 2.7797 | 1.0586 | .6347 | .5355 |
| 7.0 | .3589 | .9444 | 1.5777 | 1.8699 | 2.7862 | 1.0589 | .6338 | .5348 |
| 7.5 | .3582 | .9442 | 1.5794 | 1.8719 | 2.7915 | 1.0591 | .6332 | .5342 |
| 8.0 | .3577 | .9440 | 1.5808 | 1.8735 | 2.7959 | 1.0593 | .6326 | .5338 |
| 8.5 | .3572 | .9439 | 1.5819 | 1.8749 | 2.7995 | 1.0594 | .6321 | .5334 |
| 9.0 | .3568 | .9438 | 1.5829 | 1.8760 | 2.8026 | 1.0596 | .6318 | .5330 |
| 9.5 | .3565 | .9437 | 1.5837 | 1.8770 | 2.8052 | 1.0597 | .6314 | .5328 |
| 10.0 | .3562 | .9436 | 1.5844 | 1.8778 | 2.8075 | 1.0598 | .6311 | .5325 |
| 10.5 | .3560 | .9435 | 1.5850 | 1.8785 | 2.8094 | 1.0599 | .6309 | .5323 |
| 11.0 | .3557 | .9435 | 1.5855 | 1.8792 | 2.8111 | 1.0599 | .6307 | .5322 |
| 11.5 | .3556 | .9434 | 1.5860 | 1.8797 | 2.8125 | 1.0600 | .6305 | .5320 |
| 12.0 | .3554 | .9434 | 1.5864 | 1.8802 | 2.8138 | 1.0600 | .6304 | .5319 |
| 12.5 | .3552 | .9433 | 1.5868 | 1.8806 | 2.8149 | 1.0601 | .6302 | .5317 |
| 13.0 | .3551 | .9433 | 1.5871 | 1.8810 | 2.8160 | 1.0601 | .6301 | .5316 |
| 13.5 | .3550 | .9432 | 1.5874 | 1.8813 | 2.8169 | 1.0602 | .6300 | .5315 |
| 14.0 | .3549 | .9432 | 1.5876 | 1.8816 | 2.8177 | 1.0602 | .6299 | .5315 |
| 14.5 | .3548 | .9432 | 1.5878 | 1.8819 | 2.8184 | 1.0602 | .6298 | .5314 |
| 15.0 | .3547 | .9432 | 1.5881 | 1.8821 | 2.8190 | 1.0603 | .6297 | .5313 |
| 15.5 | .3547 | .9431 | 1.5882 | 1.8824 | 2.8196 | 1.0603 | .6296 | .5312 |
| 16.0 | .3546 | .9431 | 1.5884 | 1.8826 | 2.8202 | 1.0603 | .6296 | .5312 |
| 16.5 | .3545 | .9431 | 1.5886 | 1.8827 | 2.8207 | 1.0603 | .6295 | .5311 |
| 17.0 | .3545 | .9431 | 1.5887 | 1.8829 | 2.8211 | 1.0604 | .6294 | .5311 |
| 17.5 | .3544 | .9431 | 1.5888 | 1.8831 | 2.8215 | 1.0604 | .6294 | .5311 |
| 18.0 | .3544 | .9431 | 1.5889 | 1.8832 | 2.8219 | 1.0604 | .6293 | .5310 |
| 18.5 | .3543 | .9430 | 1.5891 | 1.8833 | 2.8222 | 1.0604 | .6293 | .5310 |
| 19.0 | .3543 | .9430 | 1.5892 | 1.8834 | 2.8226 | 1.0604 | .6293 | .5309 |
| 19.5 | .3543 | .9430 | 1.5892 | 1.8836 | 2.8229 | 1.0604 | .6292 | .5309 |
| 20.0 | .3542 | .9430 | 1.5893 | 1.8837 | 2.8231 | 1.0604 | .6292 | .5309 |
| 20.5 | .3542 | .9430 | 1.5894 | 1.8838 | 2.8234 | 1.0604 | .6292 | .5309 |
| 21.0 | .3542 | .9430 | 1.5895 | 1.8838 | 2.8236 | 1.0605 | .6291 | .5308 |
| 21.5 | .3541 | .9430 | 1.5896 | 1.8839 | 2.8238 | 1.0605 | .6291 | .5308 |
| 22.0 | .3541 | .9430 | 1.5896 | 1.8840 | 2.8241 | 1.0605 | .6291 | .5308 |
| 22.5 | .3541 | .9430 | 1.5897 | 1.8841 | 2.8242 | 1.0605 | .6291 | .5308 |
| 23.0 | .3541 | .9430 | 1.5897 | 1.8841 | 2.8244 | 1.0605 | .6290 | .5307 |
| 23.5 | .3540 | .9430 | 1.5898 | 1.8842 | 2.8246 | 1.0605 | .6290 | .5307 |
| 24.0 | .3540 | .9429 | 1.5898 | 1.8843 | 2.8248 | 1.0605 | .6290 | .5307 |
| 24.5 | .3540 | .9429 | 1.5899 | 1.8843 | 2.8249 | 1.0605 | .6290 | .5307 |
| 25.0 | .3540 | .9429 | 1.5899 | 1.8844 | 2.8250 | 1.0605 | .6290 | .5307 |
| 25.5 | .3540 | .9429 | 1.5900 | 1.8844 | 2.8252 | 1.0605 | .6289 | .5307 |
| 26.0 | .3539 | .9429 | 1.5900 | 1.8845 | 2.8253 | 1.0605 | .6289 | .5307 |
| 26.5 | .3539 | .9429 | 1.5900 | 1.8845 | 2.8254 | 1.0605 | .6289 | .5306 |
| 27.0 | .3539 | .9429 | 1.5901 | 1.8845 | 2.8255 | 1.0605 | .6289 | .5306 |
| 27.5 | .3539 | .9429 | 1.5901 | 1.8846 | 2.8256 | 1.0605 | .6289 | .5306 |
| 28.0 | .3539 | .9429 | 1.5901 | 1.8846 | 2.8257 | 1.0605 | .6289 | .5306 |
| 28.5 | .3539 | .9429 | 1.5902 | 1.8847 | 2.8258 | 1.0606 | .6289 | .5306 |
| 29.0 | .3539 | .9429 | 1.5902 | 1.8847 | 2.8259 | 1.0606 | .6289 | .5306 |
| 29.5 | .3539 | .9429 | 1.5902 | 1.8847 | 2.8260 | 1.0606 | .6288 | .5306 |
| 30.0 | .3538 | .9429 | 1.5903 | 1.8847 | 2.8261 | 1.0606 | .6288 | .5306 |
| 30.5 | .3538 | .9429 | 1.5903 | 1.8848 | 2.8261 | 1.0606 | .6288 | .5306 |
| 31.0 | .3538 | .9429 | 1.5903 | 1.8848 | 2.8262 | 1.0606 | .6288 | .5306 |
| 31.5 | .3538 | .9429 | 1.5903 | 1.8848 | 2.8263 | 1.0606 | .6288 | .5306 |
| 32.0 | .3538 | .9429 | 1.5903 | 1.8849 | 2.8264 | 1.0606 | .6288 | .5305 |

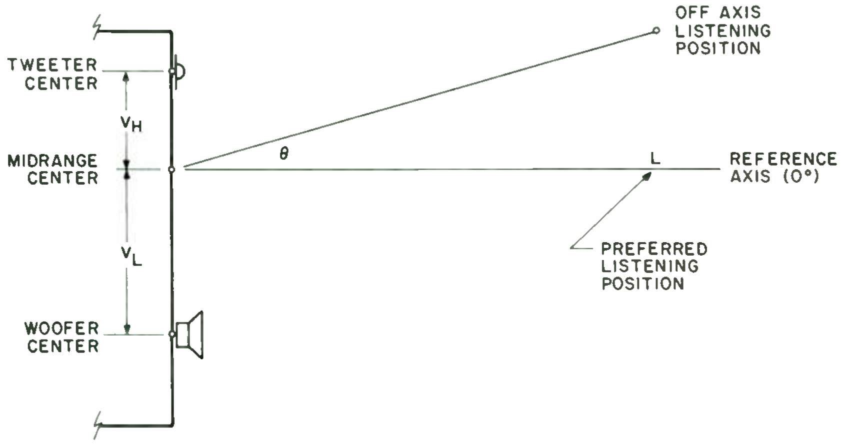


**FIGURE 12: Three-way loudspeaker system model used to construct vertical radiation patterns. L is the reference level position, θ is the polar angle relative to the midrange, $v_L$ equals 1 foot, and $v_H$ equals 6 inches.**

the reference, however, makes the mathematics easier. It might also be a good reference to use in practice because it corresponds to an easily recognized physical position on a loudspeaker system baffle.

In the figures, I assume $v_L$ (the distance between the mid and low-frequency driver centers) equals 1 foot, $v_H$ (the distance between the mid and high-frequency driver centers) equals 6 inches, and the listening distance is large compared to $v_L$. I keep $f_H$ equal to 2,700Hz in all cases, so when S equals 4, $f_L$ equals 675Hz and $f_M$ equals 1,350Hz; when S equals 9, $f_L$ equals 300Hz and $f_M$ equals 900Hz. The reference position L in *Fig. 12* corresponds to L in *Figs. 4–16*, and the θ of *Fig. 12* is the polar angle in all the graphs.

The second-order patterns are symmetric for all practical purposes. The differences between *Fig. 13* (S=4) and *Fig. 14* (S=9) show that off-axis response variations are more pronounced overall when the crossover frequencies are close (S=4)—i.e., when there are three significantly active sources. The third-order patterns bear this out. That is another reason to keep the crossover frequencies as widely spaced as possible.

The fourth-order patterns should be similar, but both the S=4 and S=9 patterns should resemble the second-order S=9 pattern more because there is a smaller frequency range in which three drivers can be active.

Again, the third-order patterns display noticeable asymmetry, as expected from the two-way case. The lobing is at its worst at the crossover frequencies, but is not too bad at $f_M$, even when S=4. All other things being equal, I still prefer the even-order patterns. The lobing in first-order networks should be similar to the third, but both the S=4 and S=9 patterns should resemble *Fig. 15* more closely, as there is a wider range in which three drivers are active.

The D'Appolito configuration described in Part I could be applied to three-way systems, which would produce symmetric, nonlobing radiation patterns using an odd-order network. Such a system would require two woofers and two midranges and would be tall, top-heavy and expensive. Even so, it might be worth trying.

**EXAMPLES.** I am going to finish up by looking at two design examples, one each for orders two and three.

## TABLE 9

### FOURTH-ORDER BANDPASS NORMALIZED COMPONENT VALUES

| S | C21 | L22 | C23 | L24 | L25 | C26 | L27 | C28 | RA |
|---|---|---|---|---|---|---|---|---|---|
| 2.0 | .1786 | .5070 | .8245 | 1.1063 | 3.9857 | 2.1941 | .3329 | 4.1584 | 1.3693 |
| 2.5 | .1678 | .4769 | .7745 | 1.0381 | 4.4458 | 2.2898 | .4438 | 3.4417 | 1.2985 |
| 3.0 | .1586 | .4495 | .7290 | .9741 | 4.8814 | 2.3982 | .5582 | 3.0227 | 1.1284 |
| 3.5 | .1509 | .4260 | .6903 | .9200 | 5.2810 | 2.5070 | .6660 | 2.7778 | .9728 |
| 4.0 | .1443 | .4058 | .6575 | .8739 | 5.6506 | 2.6130 | .7666 | 2.6257 | .8456 |
| 4.5 | .1385 | .3883 | .6292 | .8342 | 5.9960 | 2.7156 | .8608 | 2.5273 | .7436 |
| 5.0 | .1334 | .3728 | .6045 | .7994 | 6.3216 | 2.8148 | .9494 | 2.4625 | .6611 |
| 5.5 | .1289 | .3591 | .5826 | .7685 | 6.6306 | 2.9107 | 1.0332 | 2.4198 | .5936 |
| 6.0 | .1248 | .3468 | .5631 | .7409 | 6.9256 | 3.0036 | 1.1128 | 2.3927 | .5377 |
| 6.5 | .1211 | .3356 | .5455 | .7160 | 7.2084 | 3.0938 | 1.1887 | 2.3767 | .4908 |
| 7.0 | .1177 | .3255 | .5296 | .6933 | 7.4804 | 3.1816 | 1.2614 | 2.3689 | .4510 |
| 7.5 | .1145 | .3163 | .5150 | .6725 | 7.7428 | 3.2670 | 1.3310 | 2.3674 | .4169 |
| 8.0 | .1116 | .3078 | .5016 | .6535 | 7.9966 | 3.3504 | 1.3980 | 2.3706 | .3873 |
| 8.5 | .1090 | .2999 | .4893 | .6359 | 8.2426 | 3.4318 | 1.4625 | 2.3777 | .3614 |
| 9.0 | .1065 | .2926 | .4778 | .6196 | 8.4815 | 3.5113 | 1.5249 | 2.3877 | .3387 |
| 9.5 | .1041 | .2858 | .4672 | .6044 | 8.7138 | 3.5892 | 1.5852 | 2.4001 | .3185 |
| 10.0 | .1019 | .2795 | .4572 | .5903 | 8.9402 | 3.6655 | 1.6437 | 2.4144 | .3005 |
| 10.5 | .0999 | .2736 | .4479 | .5770 | 9.1610 | 3.7403 | 1.7005 | 2.4303 | .2844 |
| 11.0 | .0980 | .2680 | .4391 | .5646 | 9.3766 | 3.8136 | 1.7556 | 2.4475 | .2698 |
| 11.5 | .0961 | .2628 | .4309 | .5529 | 9.5874 | 3.8857 | 1.8093 | 2.4657 | .2567 |
| 12.0 | .0944 | .2578 | .4231 | .5419 | 9.7936 | 3.9564 | 1.8616 | 2.4847 | .2447 |
| 12.5 | .0928 | .2531 | .4157 | .5315 | 9.9957 | 4.0260 | 1.9127 | 2.5044 | .2337 |
| 13.0 | .0912 | .2487 | .4087 | .5216 | 10.1937 | 4.0944 | 1.9625 | 2.5248 | .2237 |
| 13.5 | .0897 | .2445 | .4020 | .5123 | 10.3880 | 4.1618 | 2.0112 | 2.5455 | .2145 |
| 14.0 | .0883 | .2405 | .3957 | .5034 | 10.5787 | 4.2281 | 2.0589 | 2.5667 | .2060 |
| 14.5 | .0870 | .2367 | .3896 | .4950 | 10.7661 | 4.2934 | 2.1056 | 2.5882 | .1981 |
| 15.0 | .0857 | .2330 | .3839 | .4869 | 10.9502 | 4.3577 | 2.1513 | 2.6099 | .1908 |
| 15.5 | .0845 | .2296 | .3783 | .4792 | 11.1314 | 4.4212 | 2.1961 | 2.6318 | .1840 |
| 16.0 | .0833 | .2262 | .3731 | .4719 | 11.3096 | 4.4838 | 2.2401 | 2.6539 | .1776 |
| 16.5 | .0821 | .2231 | .3680 | .4649 | 11.4851 | 4.5455 | 2.2833 | 2.6761 | .1717 |
| 17.0 | .0811 | .2200 | .3631 | .4582 | 11.6579 | 4.6064 | 2.3257 | 2.6984 | .1661 |
| 17.5 | .0800 | .2171 | .3585 | .4517 | 11.8282 | 4.6666 | 2.3674 | 2.7207 | .1609 |
| 18.0 | .0790 | .2143 | .3540 | .4455 | 11.9961 | 4.7260 | 2.4084 | 2.7431 | .1560 |
| 18.5 | .0780 | .2116 | .3496 | .4396 | 12.1617 | 4.7847 | 2.4488 | 2.7655 | .1514 |
| 19.0 | .0771 | .2089 | .3455 | .4339 | 12.3251 | 4.8427 | 2.4885 | 2.7879 | .1471 |
| 19.5 | .0762 | .2064 | .3414 | .4284 | 12.4863 | 4.9000 | 2.5276 | 2.8103 | .1429 |
| 20.0 | .0753 | .2040 | .3376 | .4230 | 12.6455 | 4.9567 | 2.5662 | 2.8326 | .1390 |
| 20.5 | .0745 | .2017 | .3338 | .4179 | 12.8027 | 5.0128 | 2.6042 | 2.8549 | .1354 |
| 21.0 | .0737 | .1994 | .3302 | .4130 | 12.9579 | 5.0682 | 2.6417 | 2.8771 | .1319 |
| 21.5 | .0729 | .1972 | .3267 | .4082 | 13.1114 | 5.1231 | 2.6786 | 2.8993 | .1285 |
| 22.0 | .0721 | .1951 | .3232 | .4036 | 13.2631 | 5.1774 | 2.7151 | 2.9215 | .1254 |
| 22.5 | .0714 | .1930 | .3199 | .3991 | 13.4130 | 5.2311 | 2.7511 | 2.9435 | .1223 |
| 23.0 | .0707 | .1910 | .3167 | .3948 | 13.5614 | 5.2843 | 2.7866 | 2.9655 | .1195 |
| 23.5 | .0700 | .1891 | .3136 | .3906 | 13.7081 | 5.3370 | 2.8217 | 2.9874 | .1167 |
| 24.0 | .0693 | .1872 | .3106 | .3866 | 13.8532 | 5.3892 | 2.8564 | 3.0092 | .1141 |
| 24.5 | .0687 | .1854 | .3077 | .3826 | 13.9969 | 5.4408 | 2.8907 | 3.0309 | .1116 |
| 25.0 | .0680 | .1836 | .3048 | .3788 | 14.1390 | 5.4920 | 2.9246 | 3.0526 | .1092 |
| 25.5 | .0674 | .1819 | .3021 | .3751 | 14.2798 | 5.5428 | 2.9581 | 3.0741 | .1069 |
| 26.0 | .0668 | .1803 | .2994 | .3715 | 14.4192 | 5.5931 | 2.9912 | 3.0956 | .1047 |
| 26.5 | .0662 | .1786 | .2968 | .3680 | 14.5573 | 5.6429 | 3.0240 | 3.1170 | .1026 |
| 27.0 | .0656 | .1771 | .2942 | .3646 | 14.6941 | 5.6923 | 3.0564 | 3.1382 | .1005 |
| 27.5 | .0651 | .1755 | .2917 | .3612 | 14.8296 | 5.7413 | 3.0885 | 3.1594 | .0986 |
| 28.0 | .0645 | .1740 | .2893 | .3580 | 14.9638 | 5.7899 | 3.1202 | 3.1805 | .0967 |
| 28.5 | .0640 | .1726 | .2869 | .3549 | 15.0969 | 5.8381 | 3.1517 | 3.2014 | .0949 |
| 29.0 | .0635 | .1711 | .2846 | .3518 | 15.2288 | 5.8859 | 3.1828 | 3.2223 | .0931 |
| 29.5 | .0630 | .1697 | .2823 | .3488 | 15.3596 | 5.9333 | 3.2137 | 3.2431 | .0914 |
| 30.0 | .0625 | .1684 | .2801 | .3459 | 15.4893 | 5.9804 | 3.2442 | 3.2638 | .0898 |
| 30.5 | .0620 | .1671 | .2780 | .3431 | 15.6179 | 6.0270 | 3.2745 | 3.2844 | .0882 |
| 31.0 | .0615 | .1658 | .2759 | .3403 | 15.7455 | 6.0734 | 3.3045 | 3.3048 | .0867 |
| 31.5 | .0611 | .1645 | .2738 | .3376 | 15.8720 | 6.1194 | 3.3342 | 3.3252 | .0853 |
| 32.0 | .0606 | .1633 | .2718 | .3349 | 15.9975 | 6.1650 | 3.3637 | 3.3455 | .0838 |

They both have the crossover frequencies $f_L = 400\text{Hz}$ and $f_H = 2{,}400\text{Hz}$, and the loads $R_L = 7\Omega$, $R_M = 6\Omega$ and $R_H = 6\Omega$. Thus, $f_M = \sqrt{400 \times 2{,}400} = 980\text{Hz}$; $W1 = 2{,}513$; $W2 = 6{,}156$; $W3 = 15{,}080$; $S = 6$; and $R = 2.450$ from formulas (3) through (8), respectively. I have rounded all values to four significant figures.

*1. Second-order APC by formulas.* From equations (12) and (13), $a = 2.041$ and ~~b~~H$= 6.667$. From equations (16) and (17), $A = 5.833$ and $B = 10.33$.

The design formulas in *Fig. 8* give us the following values:

$C11 = 27.85\mu F$
$L12 = 5.685\text{mH}$
$K = 9.333$
$E = 5.208$
$R_A = 2.4\Omega$
$R_O = 8.4\Omega$
$C21 = 3.315\mu F$
$L22 = 0.8528\text{mH}$
$L23 = 7.107\text{mH}$
$C24 = 34.65\mu F$
$L31 = 0.8122\text{mH}$
$C32 = 5.415\mu F$

This is also *Sample Run 1.*

From formula (35), the potential excess gain (EG) of the bandpass is as follows:

$$EG = 20\log\frac{K}{H} = 2.9\text{dB}.$$

Suppose L22 has a resistance of 0.3Ω and the source has a resistance of 0.1Ω. Then the flat loss is as follows:

$$LG = 20\log\frac{6.5}{6} = 0.6\text{dB}.$$

```
XOVER FREQUENCIES FL.FH?400.2400
LOADS RL.RM.RH? 7.0.6.0.6.0
CROSSOVER TYPE(1=APC.2=CPC)? 1
CROSSOVER ORDER(1.2.3.4)? 2

LABELS REFER TO FIG. 8
C11= 27.8463 UF
L12=  5.6853 MH
 RA=  2.4000 OHMS
C21=  3.3150 UF
L22=   .8528 MH
L23=  7.1066 MH
C24= 34.6532 UF
L31=   .8122 MH
C32=  5.4146 UF

DO YOU WANT RA=0 CIRCUIT VALUES?
(1=YES.0=NO) - 0
```

**SAMPLE RUN 1: Second-order APC values from CAD program.**

```
XOVER FREQUENCIES FL.FH?300.2400
LOADS RL.RM,RH? 7.0.6.0.6.0
CROSSOVER TYPE(1=APC.2=CPC)? 1
CROSSOVER ORDER(1.2,3,4)? 3

BP. POLARITY(1OR-1)?  1
LABELS REFER TO FIG. 9
L11=  2.0190 MH
C12=101.4323 UF
L13=  5.1037 MH
 RA=   .7284 OHMS
C21=169.3584 UF
L22=  2.6925 MH
C23= 54.5154 UF
L24=   .2251 MH
C25= 15.4828 UF
L26=   .5026 MH
C31= 20.3294 UF
L32=   .2973 MH
C33=  8.0420 UF

DO YOU WANT RA=0 CIRCUIT VALUES?
(1=YES.0=NO) - 1

LABELS REFER TO FIG. 9
L11=  2.0190 MH
C12=101.4323 UF
L13=  5.1037 MH
 RA=   .0000 OHMS
C21=189.9177 UF
L22=  2.4010 MH
C23= 61.1333 UF
L24=   .2007 MH
C25= 17.3624 UF
L26=   .4482 MH
C31= 20.3294 UF
L32=   .2973 MH
C33=  8.0420 UF

EXCESS GAIN IS EG= 1.00 DB.

IND-SOURCE LOSSES(0 IF NONE)?.50

DRIVER SENSITIVITY INCREASE IS
  EG-LG=   .30 DB.
```

**SAMPLE RUN 2: Third-order, negative-polarity APC values from CAD program.**

```
XOVER FREQUENCIES FL,FH?300.2400
LOADS RL,RM,RH? 7.0.6.0,6.0
CROSSOVER TYPE(1=APC.2=CPC)? 1
CROSSOVER ORDER(1,2.3,4)? 3

BP. POLARITY(1OR-1)? -1
LABELS REFER TO FIG. 9
L11=  1.7085 MH
C12=101.3785 UF
L13=  6.0342 MH
 RA=  1.6444 OHMS
C21=163.5519 UF
L22=  3.5588 MH
C23= 43.0644 UF
L24=   .2289 MH
C25= 11.8423 UF
L26=   .6407 MH
C31= 24.0231 UF
L32=   .2975 MH
C33=  6.8019 UF

DO YOU WANT RA=0 CIRCUIT VALUES?
(1=YES,0=NO) - 1

LABELS REFER TO FIG. 9
L11=  1.7085 MH
C12=101.3785 UF
L13=  6.0342 MH
 RA=   .0000 OHMS
C21=208.3752 UF
L22=  2.7933 MH
C23= 54.8667 UF
L24=   .1797 MH
C25= 15.0878 UF
L26=   .5029 MH
C31= 24.0231 UF
L32=   .2975 MH
C33=  6.8019 UF

EXCESS GAIN IS EG= 2.10 DB.

IND-SOURCE LOSSES(0 IF NONE)?.50

DRIVER SENSITIVITY INCREASE IS
  EG-LG=  1.41 DB.
```

**SAMPLE RUN 3: Third-order, positive-polarity APC values from CAD program.**

```
XOVER FREQUENCIES FL.FH?300.1500
LOADS RL,RM,RH? 7.0,6.0.6.0
CROSSOVER TYPE(1=APC,2=CPC)? 1
CROSSOVER ORDER(1.2.3.4)? 4

LABELS REFER TO FIG. 10
C11= 27.5802 UF
L12=  3.5125 MH
C13=118.6407 UF
L14=  6.8921 MH
 RA=  3.9664 OHMS
C21=  3.1767 UF
L22=   .8815 MH
C23= 14.3895 UF
L24=  1.8902 MH
L25= 14.9478 MH
C26= 67.0061 UF
L27=  2.2449 MH
C28= 58.6194 UF
L31=  1.7494 MH
C32= 18.6965 UF
L33=   .4067 MH
C34=  9.5285 UF

DO YOU WANT RA=0 CIRCUIT VALUES?
(1=YES,0=NO) - 1

LABELS REFER TO FIG. 10
C11= 27.5802 UF
L12=  3.5125 MH
C13=118.6407 UF
L14=  6.8921 MH
 RA=   .0000 OHMS
C21=  5.2767 UF
L22=   .5307 MH
C23= 23.9020 UF
L24=  1.1380 MH
L25=  8.9989 MH
C26=111.3021 UF
L27=  1.3515 MH
C28= 97.3712 UF
L31=  1.7494 MH
C32= 18.6965 UF
L33=   .4067 MH
C34=  9.5285 UF

EXCESS GAIN IS EG= 4.41 DB.

IND-SOURCE LOSSES(0 IF NONE)?.50

DRIVER SENSITIVITY INCREASE IS
  EG-LG=  3.71 DB.
```

**SAMPLE RUN 5: Fourth-order APC values from CAD program, with crossover frequencies at 300 and 1,500Hz.**

```
XOVER FREQUENCIES FL,FH?300.2400
LOADS RL,RM.RH? 7.0,6.0.6.0
CROSSOVER TYPE(1=APC.2=CPC)? 1
CROSSOVER ORDER(1,2.3,4)? 4

LABELS REFER TO FIG. 10
C11= 27.1070 UF
L12=  3.5058 MH
C13=119.8030 UF
L14=  6.9576 MH
 RA=  2.3236 OHMS
C21=  2.5156 UF
L22=   .4805 MH
C23= 11.3041 UF
L24=  1.0202 MH
L25= 12.4845 MH
C26= 75.4979 UF
L27=  2.1826 MH
C28= 53.4203 UF
L31=  1.1124 MH
C32= 11.7075 UF
L33=   .2517 MH
C34=  5.8993 UF

DO YOU WANT RA=0 CIRCUIT VALUES?
(1=YES.0=NO) - 1

LABELS REFER TO FIG. 10
C11= 27.1070 UF
L12=  3.5058 MH
C13=119.8030 UF
L14=  6.9576 MH
 RA=   .0000 OHMS
C21=  3.4898 UF
L22=   .3463 MH
C23= 15.6819 UF
L24=   .7354 MH
L25=  8.9993 MH
C26=104.7363 UF
L27=  1.5733 MH
C28= 74.1085 UF
L31=  1.1124 MH
C32= 11.7075 UF
L33=   .2517 MH
C34=  5.8993 UF

EXCESS GAIN IS EG= 2.84 DB.

IND-SOURCE LOSSES(0 IF NONE)? .50

DRIVER SENSITIVITY INCREASE IS
  EG-LG=  2.15 DB.
```

**SAMPLE RUN 4: Fourth-order APC values from CAD program, with crossover frequencies at 300 and 2,400Hz.**

Thus, if $R_A$ is left out, the effective sensitivity of the midrange driver will be 2.9 minus 0.6, or 2.3dB, more than its nominal sensitivity. In this case, though, you must recompute the LC component values with $R_O=R_M$. You can obtain the LC values directly from the values already computed above by multiplying each L by $R_M/(R_A+R_M)$, or 0.7143, and each C by $(R_A+R_M)/R_M$, or 1.4.

2. *Third-order, positive-polarity APC by tables.* The S=6 row of *Tables 4* and 5 gives the normalized values for the circuit in *Fig. 9.* The low-pass denormalizing constants are $1{,}000R_L/W1$, or 2.786, for inductors, and $1{,}000{,}000/R_L/W1$, or 56.85, for capacitors. The high-pass constants are 0.3979 for inductors and 11.05 for capacitors.

From *Table 4,* you can find the following values:

L11 = 2.019mH
C12 = 101.4μF
L13 = 5.104mH
C31 = 20.33μF
L32 = 0.2973mH
C33 = 8.042μF

Multiplying the last entry of *Table 5,* row S=6, by $R_M$ (6) gives you the value of $R_A$—0.7284. Therefore, $R_O$ equals 6.728. The inductor denormalizing constant is $1{,}000R_O/6{,}156$, which equals 1.09292, and the capacitor constant is $1{,}000{,}000/R_O/6{,}156$, which equals 24.14.

The bandpass values are as follows:

C21 = 169.4μF
L22 = 2.693mH
C23 = 54.51μF
L24 = 0.2251mH
C25 = 15.48μF
L26 = 0.5027mH

Note that this example is the same as *Sample Run 3.*

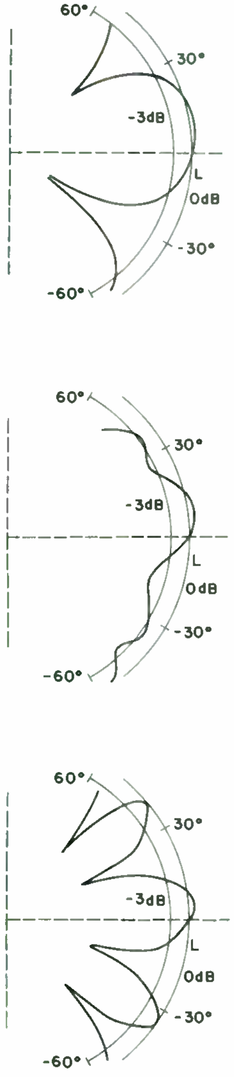


**FIGURE 13:** Radiation patterns for the new second-order APC with S equal to 4. From the top down, the patterns are taken at $f_L$ = 675Hz; $f_M$ = 1,350Hz; and $f_H$ = 2,700Hz, respectively.

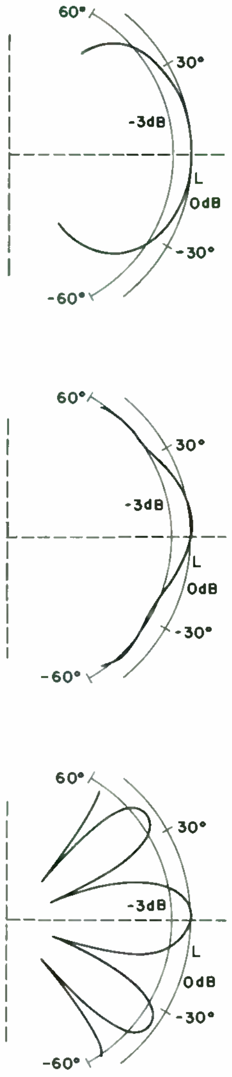


**FIGURE 14:** Radiation patterns for the new second-order APC with S equal to 9. From the top down, the patterns are taken at $f_L$ = 300Hz; $f_M$ = 900Hz; and $f_H$ = 2,700Hz, respectively.

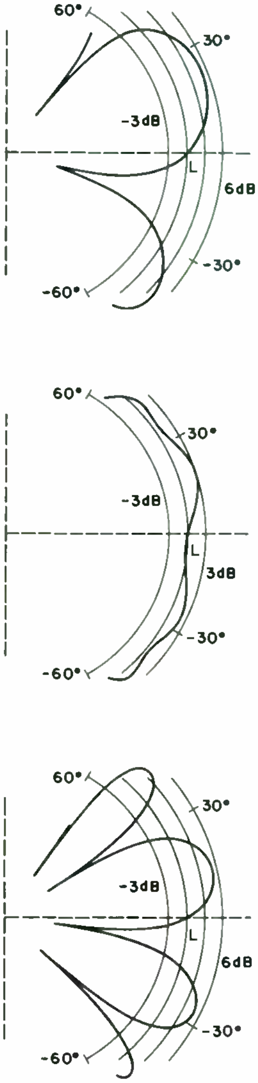


**FIGURE 15:** Radiation patterns for the new third-order, positive-polarity bandpass APC with S equal to 4. From the top down, the patterns are taken at $f_L$ = 675Hz; $f_M$ = 1,350Hz; and $f_H$ = 2,700Hz, respectively.

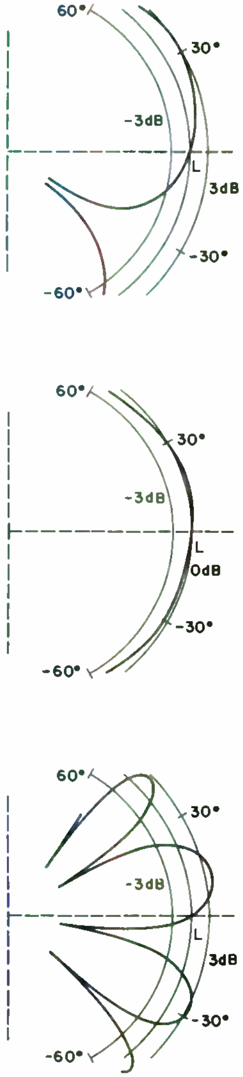


**FIGURE 16:** Radiation patterns for the new third-order, positive-polarity bandpass APC with S equal to 9. From the top down, the patterns are taken at $f_L$ = 300Hz; $f_M$ = 900Hz; and $f_H$ = 2,700Hz, respectively.

**COMMENTS.** The most interesting examples are *Sample Runs 4* and *5*. In particular, the bandpass component L25 is well in excess of 10mH in both cases. Even when $f_L$ is increased to 500 and S to 8, both of which serve to decrease L25, it is still about 7mH. This is a parallel component, so its resistance does not affect the flat loss, but it can change the filter shape significantly, and there is nothing you can do about it. A low DCR inductor of this size is probably quite expensive, so a fourth-order network may be more than twice as expensive as a second-order network if shape distortion is to be minimized.

It is also interesting that the negative-polarity, third-order network has a larger excess gain (2.1dB) than the positive-polarity network (1.0dB). These are *Sample Runs 2* and *3*, respectively. This would argue in favor of the former when a low-sensitivity midrange is used.

*As usual, if you have any questions, please send them to me, along with a self-addressed, stamped envelope, care of Speaker Builder, PO Box 494, Peterborough, NH 03458. In the next installment, I will talk about how you can actively realize the crossover networks I have described.*

## *IF YOU SHOULD HAVE A* TECHNICAL QUERY...

...please drop us a note explaining precisely what information you need. We will answer your question ourselves or forward your letter to someone with expertise in that area. Make sure to enclose a self-addressed, stamped envelope for our reply, and address your letter to: *Speaker Builder*, Technical Dept., PO Box 494, Peterborough, NH 03458.

Help us out by *not* calling in your question. We have neither the staff nor the time to respond to each query over the phone.

# Kit Report

## Weighing Woofer Performance

Since my article on transmission-line loudspeakers first appeared in *SB* (1/82, p. 7; 2/82, p. 24), I have evaluated two new 10-inch woofers in my TL-10 loudspeakers—the Madisound M1054 and the Meniscus Eclipse W1032R—along with my original driver, the Audax HD24B45. *Table 1* lists the manufacturers' specifications on the drivers. More detailed information is available from Madisound (8982 Table Bluff Rd., Box 4283, Madison, WI 53711) and Meniscus (3275 Gladiola Ave., Wyoming, MI 49509), both of which also sell the Audax unit.

The Audax is a Bextrene-cone driver with a polyvinyl chloride (PVC) surround. It costs about $45, and Audax specifies a free-air resonance of 23Hz. Madisound's woofer has a black polypropylene cone and a foam surround. Free-air resonance is specified as 22Hz, and the price is $32. The Meniscus Systems design is the newest of the three. It has a clear polypropylene cone and a butyl rubber surround. Finding rubber surrounds on polypropylene cones was virtually impossible in the past because of the difficulty in obtaining a suitable bonding material. Meniscus has apparently overcome the gluing problem. This unit's free-air resonance is specified as 23Hz, and it sells for $31.

### Objective Data

I made my frequency-response measurements with the drivers mounted in the TL-10 enclosure and at a 1W power level. I used a Neumann KM-86 condenser microphone, taking the mike's response curve into account when I drew the graphs. Using the near-field technique, I measured up to 700Hz, the crossover frequency for the TL-10 woofer. This is about as high as I would operate any 10-inch driver to preserve midrange accuracy.

Of the three, the Audax driver had the poorest low-end response *(Fig. 1)*. Both units had a free-air resonance considerably higher than specified—about 34Hz.

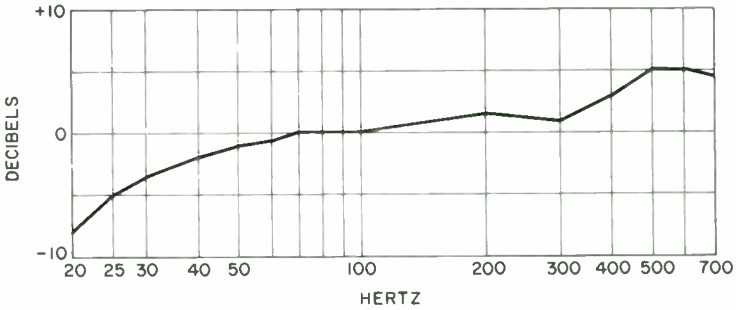


**FIGURE 1:** Near-field measurement of the Audax HD24B45 10-inch Bextrene woofer's frequency response in the TL-10 enclosure.

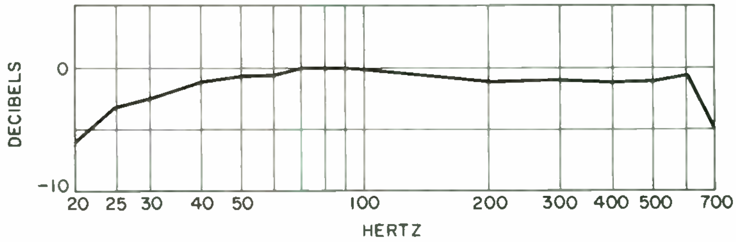


**FIGURE 2:** Near-field measurement of the Madisound M1054 10-inch polypropylene woofer's frequency response in the TL-10 enclosure.

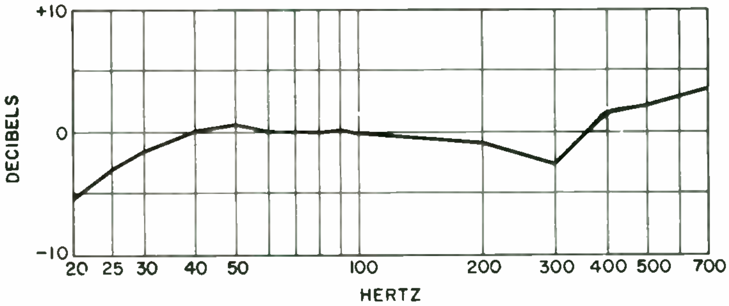


**FIGURE 3:** Near-field measurement of the Meniscus Eclipse W1032R 10-inch polypropylene woofer's frequency response in the TL-10 enclosure.

(This was after nearly two years of operation. They measured 39Hz when they were new.) Their response above 300Hz was also not as smooth as the other drivers'. I did not attempt to verify the manufacturer's power rating of 50W.

Measured response of the Madisound and Meniscus drivers is shown in *Figs. 2* and *3*. Below 100Hz, there was little difference between these drivers, and both had considerably greater output in the 25 to 40Hz region than the Audax. Free-air resonance of the Madisound measured 24Hz in both samples, which is very close to the manufacturer's specifications (±2Hz is a reasonable tolerance). The Meniscus units measured higher than specified, with one measuring 31Hz and the other 33Hz. This did not, however, seem to have a detrimental effect on the low-frequency output.

The cone motion of the Meniscus driver was quite well controlled at resonance. I measured a maximum free-air impedance of 43Ω, and the peak was quite broad. Maximum free-air impedance for the Audax and Madisound drivers measured 42Ω and 92Ω, respectively. Incidentally, Meniscus has informed me that early versions of this driver have an overly stiff suspension. They have corrected this problem in newer units, which should have a lower resonant frequency than my samples.

Above 100Hz, the Madisound woofer had the smoothest response, but the Meniscus still measured somewhat better than the Audax. Both Madisound and Meniscus report very high power handling (125 and 100W, respectively). I did not attempt to verify these claims.

All three drivers exhibited impedance rises at the upper end of the operating range. This is due to the inductive reactance of the voice coils. At 700Hz, the Audax, Madisound and Meniscus drivers measured 8.5Ω, 14.5Ω and 11.5Ω, respectively. If you use a passive crossover, a compensation network is required to maintain a constant 8Ω impedance. This network is shown in *Fig. 4*. *Table 2* lists the required values of R and C. (R is always equal to the driver's rated impedance.) I have also shown the values required for three 8-inch drivers I have tested. I hope this information will be useful.

## Subjective Evaluation

Both the Madisound and Meniscus woofers are extremely well constructed, making them visually impressive. While construction of the Audax is certainly acceptable, it is not nearly as impressive. After about 1½ years of use, the PVC surround on both of my Audax units began to separate from the frame and had to be reglued.

The most important consideration, however, is not how they look but how

TABLE 1

MANUFACTURERS' SPECIFICATIONS

| | Audax<br>HD24B45 | Madisound<br>W1054 | Meniscus Eclipse<br>W1032R |
|---|---|---|---|
| **Price** | $45 | $32 | $31 |
| **Impedance** | 8Ω | 8Ω | 8Ω |
| **Free-Air Resonance** | 23Hz | 22Hz | 23Hz |
| **Mechanical "Q" ($Q_{MS}$)** | 4.05 | 4.34 | 2.49 |
| **Electrical "Q" ($Q_{ES}$)** | 0.33 | 0.28 | 0.40 |
| **Total "Q" ($Q_{TS}$)** | 0.31 | 0.27 | 0.345 |
| **Efficiency, 1W, 1 meter** | 92.6dB | 91.7dB | 90dB |
| **Magnet Weight** | 31 oz. | 30 oz. | 32 oz. |
| **Power Handling** | 50W | 125W | 100W |

### TABLE 2

### IMPEDANCE-COMPENSATION NETWORK COMPONENT VALUES

| | R | C |
|---|---|---|
| **10-inch Woofers** | | |
| Madisound M1054 Polypropylene | 8Ω | 25μF |
| Meniscus Eclipse | | |
| W1032R Polypropylene | 8Ω | 20μF |
| Audax HD24B45 Bextrene | 8Ω | 10μF |
| **8-inch Woofers** | | |
| Madisound M8154 Polypropylene | 8Ω | 27μF |
| Audax HD20B25H-4C12 Bextrene | 8Ω | 20μF |
| Audax HD21B37R-2C12 Bextrene | 8Ω | 15μF |

they sound. For several years, the Audax driver has been considered one of the choice woofers for transmission-line applications. In my opinion, it is no longer in the running, especially in view of its higher price. It is audibly weaker at extreme low frequencies than the other two drivers. Bass transient response is far better (i.e., faster) with the Madisound and Meniscus woofers. Sharp attacks, such as bass drum and tympani, are more clearly defined on the Madisound and Meniscus woofers. On very loud bass passages, the Audax units seem starved in terms of their power-handling capability. Although I did not conduct any power-handling measurements, the Audax is *audibly* inferior in this respect.

In the lower midrange region, the Audax woofers are not as well defined as the Meniscus and Madisound drivers. I have become increasingly dissatisfied with the midrange performance of Bextrene drivers in general. They exhibit a harshness or stridency at mid-frequencies, which I find offensive. This is most evident in two-way systems where the woofer must operate as high as 2 or 3kHz. In my three-way TL-10, with the woofer operating only to 700Hz, the clarity and definition of the Audax Bextrenes still falls short of the other two drivers.

At this point, I should mention that I do not, as a rule, recommend using 10-inch drivers in two-way systems. An 8-inch woofer will invariably have more accurate midrange performance than a 10-inch driver of similar construction. Some compromise is always necessary in a two-way system, but I think it is preferable to sacrifice some low-end response rather than midrange accuracy.

Comparisons between the Madisound and Meniscus woofers are extremely difficult, as these drivers are very similar in their audible performance. I will say that, so far, they are the best 10-inch woofers I have encountered, and at $32 each, they are an outstanding value. Unlike Audax products, which are made in France, Madisound and Meniscus products are manufactured in the US, which saves you a great deal in shipping charges.

I have been doing business with Madisound for several years. They are a pleasure to deal with, providing fast service and attention to individual needs. Madisound also manufactures an 8-inch polypropylene woofer that I have used with excellent results. In the short time I have dealt with Meniscus, I have been equally impressed with their service.

Gary Galo
Potsdam, NY 13676

*Meniscus Systems comments:*

*We wish to thank Mr. Galo for his review of the Eclipse W1032R woofer. We, too, find this driver well suited for transmission-line, as well as sealed-box, use.*

*Note that the W1032R will have a resonance of 26 to 28Hz and that the components in* Fig. 4 *are now included in the price of the driver. We also have a dual-voice-coil version of the W1032R with a resonance of 23Hz.*

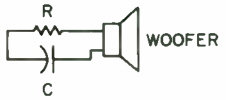


**FIGURE 4: If you use a passive crossover, an impedance-compensation network can help you maintain a constant 8Ω impedance. See Table 2 for component values.**

## SOMETHING NEW

Lots of magazines—most of them, in fact—offer readers special information services for products mentioned in news columns and advertisements. Usually only large magazines offer such services. We think we are one of the first small publishers to do so—and on our own computer.

But we need your help to make it all work. Remember to write your subscriber number (what we are calling your "magic number") on the **FAST REPLY** cards you mail in—and on any other correspondence about your subscription or orders for other items. That "magic number" is actually your record number on our computer. We have designed our little system to use that number in addition to the number of the vendor or vendors from which you wish to hear. Our clerk will enter only the numbers from your returned card, and our computer will do the rest.

If you have a friend who wishes to use the second **FAST REPLY** card, that's fine with us, even though your friend is not a subscriber. Just ask the person to check the non-subscriber box at the top, and we will take care of the rest.

# Tools, Tips & Techniques

## Speaker Stack Saves Space

If floor space is a problem in your listening/living room, perhaps this suggestion can help.

Some years ago, Radio Shack made the T-100 "tower" speaker system featuring two 8-inch woofers and a cone tweeter. I always believed the idea had potential given a better selection of drivers (as Infinity and ADS have proved). I chose not to be quite that extravagant, however, and instead selected my drivers and filter from the McGee catalog (1901 McGee, Kansas City, MO 64108-1891). I chose a Peerless dome mid-tweeter (catalog #PMT 30V), a 16Ω, 8-inch woofer (catalog #CL8BI) and the McGee 1,500Hz, two-way, 12dB/octave crossover (catalog #2W1). Don't be alarmed by the difference in sensitivity ratings. Sometimes manufacturers rate their products differently, but in actual use, the difference is not apparent.

One and a half sheets of ⅝-inch particle board will be enough to build a pair of 36-inch-tall, 3-cubic-foot cabinets, which will take up only 1 square foot of floor space each. Before mounting the crossover and tweeter on top of the cabinet *(Fig. 1)*, I mounted the tweeter in a wooden L-bracket. This allowed me to experiment with time/phase alignment before fastening it permanently. I have also found an inexpensive source of fiberglass batting at the lumberyard. I pay only 75 cents for torn or loose bundles of 24 by 48 by 4 inch batting panels. I then split them into 2-inch-thick sheets, producing 16 square feet of usable material.

The end result is a smooth-sounding stage front. I never feel as though I am listening to speakers, just music. I use a ten-octave band equalizer to sweeten the extreme top and bottom ends of the spectrum, more for my personal taste (and aging ears) than for the speakers. I use the equalizer mostly to adjust tonal balance in program material. I finished the speaker cabinets in ultra-flat black paint and used a light gray double-knit for the grille cloths. Total cost for the pair was about $125.

Clifford L. Dunning
Portsmouth, NH 03801

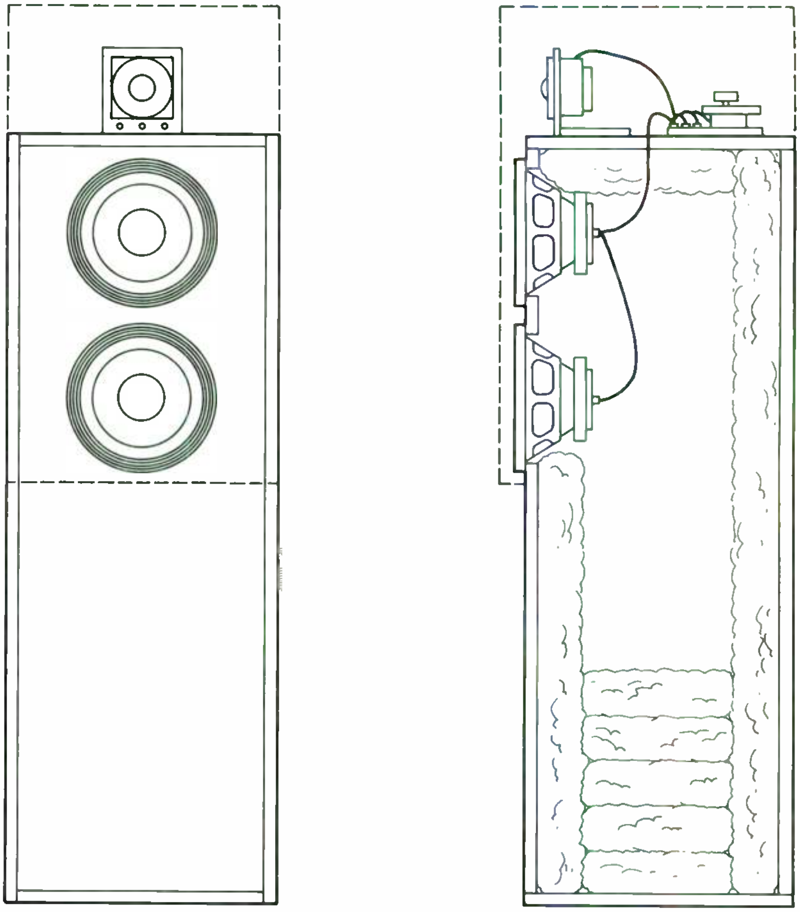


**FIGURE 1: Mr. Dunning's tweeter is mounted on top of his cabinet (left), which is stuffed with fiberglass batting (right).**

## Sonotube Speaker Cabinet

When I assessed my system's performance with my new pink-noise analyzer, it became apparent that I needed to rearrange my listening room. After finding the ideal locations for my speakers and settling in for a spell of great satisfaction, I noticed that the old speaker cabinets looked awfully big and boxy in their new locations. What I needed was round enclosures of approximately the same volume. This seemed to be an insurmountable problem until I ran across a product that is an ideal basis for round enclosures.

The Sonotube is a super-heavy-duty cardboard tube that is usually used as a form for poured concrete on highway bridges. Sonotubes are available in 1-inch increments up to 10 inches in diameter and in 2-inch increments up to 48 or more inches in diameter. They are cut to any length at the time of sale. A single Sonotube is not sturdy enough and exhibits a mid-bass resonance. If two concentric tubes have the space between them filled with sand, however, they make the most nonresonant cabinet I have ever seen. The 2-inch increment between sizes provides the correct space for an appropriate amount of sand. The round shape produces minimal cabinet diffraction and is visually pleasing.

For my speakers, I was able to use another excellent material that is rock solid and inexpensive. Local lumberyards and discount stores sell 1⅛-inch-thick particle board in 30-by-60-inch sheets for around $5. Normally used for workbench tops, this material complements the sand-filled Sonotube to make a structure so solid and dead that my audiophile friends never stop knocking on the cabinets in amazement.

*Figure 1* shows some suggested configurations. The cabinets should be glued with a resilient glue such as Liquid Nails. This is a construction adhesive that makes tearing something apart impossible. I have used it a number of years for speaker cabinets and have never had a rattle or buzz. I plan to cover the cabinets with hardwood veneer, but they could just as well be painted.

Sonotubes are available from industrial construction and concrete supply houses. My local supplier was helpful in cutting them precisely to length, and I had no problem ordering small quantities. If you cannot find a local distributor, write to Sonoco Products, State Highway 19 South, Akron, IN 46910.

Bernhard F. Muller
Milan, MI 48160

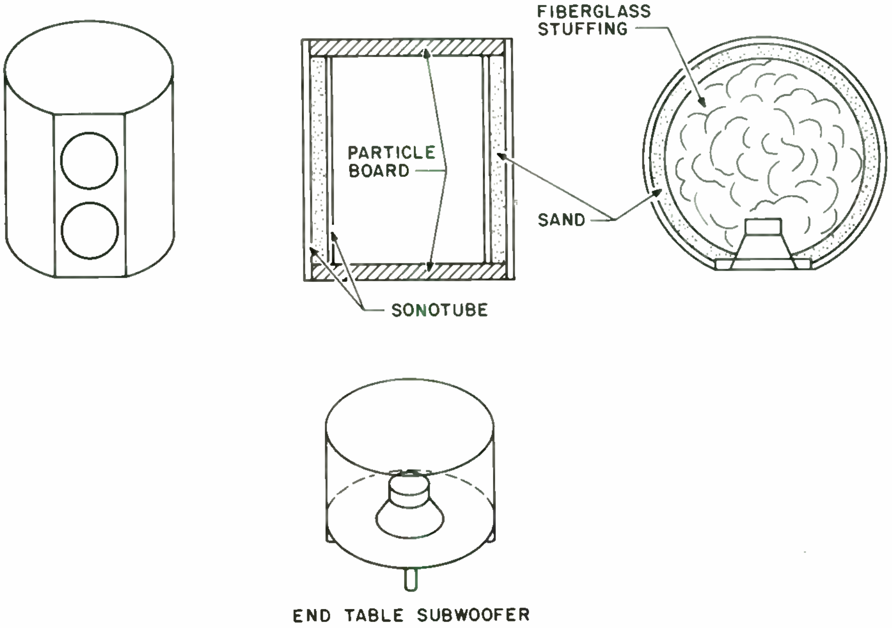


**FIGURE 1: Suggested cabinet configurations. Volume equals $\pi r^2h$, where r is the radius of the base and h is the height. You can usually ignore the volume loss of the flat side, as the formula is too complex to mess with.**

## Driver Mounting Details

In the past few years, I have seen many letters and articles dealing with different methods of mounting drivers on a baffle. Most seem to favor decoupling the driver from the baffle, usually by mounting the driver with silicone rubber sealant instead of screws. The idea is that driver vibrations will not be passed to the enclosure's panels, thereby eliminating panel resonances and producing a less boxy sound and a better stereo image. I used this technique on several projects, and the speakers always sounded fine.

As I examined more and more top-quality speakers, however, I noticed that none of them had decoupled drivers. In fact, I discovered that many manufacturers believe that it is of the utmost importance to ensure that the driver is held firmly in place so that it will not vibrate. The idea, in simplified terms, is that when the cone is thrust forward, there is also a tendency for the basket to move backward, robbing transients of their leading edges. The movement of the driver's frame adds distortion and colorations and also results in what has been called a loss of information.

I had never tried mounting the drivers with screws, so I bought some bolts and T-nuts and mounted the drivers with them, using Mortite as a gasket. I tightened the bolts as much as I could, even to the point of blistering my hands. (With some drivers, the surround overlaps the screw hole in the frame. In this case, use a clip to hold the driver and mount the clip on the baffle. Otherwise, you can ruin the surround.)

When I turned on my speakers, the top end was less harsh, and notes were more separate. Especially in the treble, there was an absence of the sizzle to which I had grown accustomed. It is now much easier to listen to the speakers for extended periods of time. The image is a little boxy, but I think the way to avoid boxiness is not through loose mounting, but in the initial design. None of the commercial designs that image well are conventional boxes. They all have special shapes for dealing with diffraction, time alignment and internal standing waves. The best cabinets are acoustically dead, either because of the use of exotic materials or massive internal bracing. Try both mounting methods and use whichever gives you the most pleasure.

David G. Baldwin
Lake Bluff, IL 60044

## No Free Lunch

In *SB* 2/84 (p. 32), David J. Meraner suggests that coupling two identical drivers through a sealed chamber will reduce $V_{AS}$ by one-half. This proposition—an easy answer to box size constraints—seems too good to be true. And sure enough, it is.

I tested the proposition by measuring the $V_{AS}$ of two 18-inch woofers mounted in a 22-foot enclosure. What I actually did was to mount a second 18-inch woofer face-to-face with the one already resident in my subwoofer, plug the vents and measure the new resonance. The woofers (both with a free-air resonance of 16Hz and a $Q_T$ of 0.6) had known $V_{AS}$ values of 32 cubic feet and 64 cubic feet respectively. Measured together, the $V_{AS}$ was 23 cubic feet as predicted.

So far so good. But as the saying goes, there's no such thing as a free lunch. The catch is that this setup essentially adds the cone masses together. This will reduce $V_{AS}$, but will also *increase* $Q_E$, $Q_M$ and $Q_T$ by a factor of two. In my case, this technique would cause the 5dB ripple at 32Hz to increase by another 6dB. This initial peak occurs because the 22-cubic-foot box is too small. Although reducing $V_{AS}$ would help compensate for ripple, doubling the driver Q would cause other problems.

This technique could help some sealed-box alignments. For example, theoretically, I could convert my system to a sealed box and move the peak down to 23Hz. This sounds interesting, but I would have to forego the advantages of my bass-reflex design. Because my reflex system ripple is easily compensated with a single op-amp equalizer, there seems to be little reason to seal my ports.

Tom Nousaine
Chicago, IL 60606

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# SB *Mailbox*

## CORRECTION: INVERSE RELATION

Regarding the article "Loudspeakers From A to Z" (*SB* 3/84, p. 4A), one error has come to my attention. The equation for the increase in bass resonance from the free-air condition ($f_o$) to that in the finished cabinet is incorrect. As given, the increase should be proportional to the square root of the increase in stiffness, *not* to the inverse, as stated. In my original manuscript, which was taken from a much more thorough work done years back, I inadvertently stated the relationship in terms of compliance, which is the inverse of stiffness.

William R. Hoffman
Reno, NV 89502

## CROSSOVER CORRECTION

David J. Meraner reports an error in *Fig. 18* of Robert Bullock's article on passive crossover networks (*SB* 1/85, p. 18). The formula for E should read as follows:

$$E = A(1-1/D).$$

We apologize for any inconvenience this might have caused.—Ed.

## UNFAIR ASSESSMENT

Timothy Palmer-Benson's review of Audio Concepts' JCRS speaker system in *SB* 4/84 (p. 30) accurately reflects the essence of the system's superb sound and quality design and workmanship. On both a business and a personal level, I have come to appreciate the high caliber of the service and products Mike Dzurko and his associates at Audio Concepts offer. I do feel, however, that the Shadow Engineering MKIVF electronic crossover was neither accurately nor fairly represented in the article.

In the review, Mr. Palmer-Benson states that the "Shadow Engineering electronic crossover board was somewhat of a disaster" and that he "had to resolder just about every connection." He also implies that some ambiguity existed about the slope and frequency of the crossover, and he complains that the component leads on the circuit board had been cut too short. In addition, he incorrectly describes how the different types of capacitor are used. I would like to correct these errors and any misconceptions his comments might have caused.

The MKIVF is sold as a kit, but the stuffed circuit board and other major components are available separately. Audio Concepts has chosen to make the unit an integral part of its phenomenal Jack Caldwell Ribbon System. The standard MKIVF crossover configuration is an 18dB/octave slope at the cutoff frequency, but it may be alternately supplied or retrofitted with 6dB/octave slopes or an asymmetrical combination. The boards use plug-in modules, whereby you may change the frequency at your discretion. The dealer supplies these modules to the purchaser's specified frequency. One module is supplied with each kit or board purchased. The module supplied by Audio Concepts was for the frequency they determined to be optimum for the JCRS, as was the 6dB/octave slope. Since the 18dB and the 6dB boards are nearly identical, the 6dB boards are hand-marked to denote that option. Every board is hand-built.

Contrary to the article, power supply caps are used for the filtering functions. The unit is otherwise direct coupled. Each solder joint is carefully made and reinspected after assembly. Leads are clipped close to the board after soldering, as that is the customary practice in any good electronic assembly. Because of that care in design and assembly, we have never experienced a warranty claim. During the three years the MKIVF has been in production, the board layout, frequency-selection provision and chassis have all been redesigned to enhance performance and value, at only a nominal price increase. Therefore, we find it hard to understand Mr. Palmer-Benson's criticisms.

Bob Bullock comments on the MKIVF's high-quality construction in his review of the crossover (*SB* 1/85, p. 36). His review unit came from Audio Concepts' inventory and was in no way specially tweaked or assembled. No unit we ship is any less well-constructed than was the Bullock crossover.

The JCRS review and our crossover's contribution to that unit's sound tell the whole story. Thanks for the opportunity to comment.

Neil Shattles, Owner
Shadow Engineering
Lilburn, GA 30247

## D'APPOLITO ADVICE

I appreciated Joseph D'Appolito's high-power satellite article (*SB* 4/84, p. 7) very much. It is an elegant exposition of a rationale for speaker-system design that will benefit many speaker builders.

I have tried to apply Mr. D'Appolito's principles for the elimination of lobing errors as set forth in his AES article (*Preprint No. 2000*, October 1983). Mine is a full-range system with 6½-inch woofers (Audax HD17B25H4C12) and a Peerless mid-tweeter (PMT30V). The voice coils are in mechanical alignment, but my acoustic measurements tell me that I have not yet "arrived." I suspect that the problem is an acoustic interdriver phase difference.

This brings me to my first two questions. First, Mr. D'Appolito seems to be very successful in making 1-meter acoustic measurements. What setup and instruments does he use?

Second, Mr. D'Appolito does not seem to deal with the problem of interdriver acoustic phase differences. Why isn't the acoustic output the same, independent of speaker phasing, as it should be for an odd-order network? Mr. D'Appolito mentions a "small, uncompensated delay." Is this a voice-coil offset problem only? He does not say whether he strove for voice-coil alignment. Does his design require this? If you measure at 1 meter and the voice coils are aligned, the distance from the voice coils to the mike cannot be the same, so a frequency-dependent phase shift will result. How do you deal with that?

I have another question concerning the D-28 and Mr. D'Appolito's selection of 2kHz as the crossover frequency. While I cannot question his results, I wonder how he can break the old design rule that says you must have an overlap on the crossover frequency. I believe the overlap rule gives some assurance that the driver will exhibit minimum phase behavior over its intended frequency range (as amplitude falls, phase behavior might deviate from minimum).

Finally, I have a question concerning "phase coherence" (can it pass a square wave?), constant power versus constant pressure, and lobing error. Most designers seem convinced that you cannot hear phase incoherence and that in a semi-reverberant room, constant power is not necessary. These conclusions are based on subjective perceptions, yet lobing errors are regarded as intolerable, based on *analytical* considerations alone. Has anyone attempted to establish whether or not lobing errors are subjectively perceptible?

David J. Meraner
Scotia, NY 12302

*Mr. D'Appolito replies:*

*I was glad to hear that Mr. Meraner is trying my three-driver, two-way geometry in a full-range system design. His choice of drivers seems reasonable, and he should be able to make them work. Response irregularities around the crossover region might be due to interdriver phase difference. When mounted on a common baffle, tweeters and woofers are rarely in phase.*

*With regard to Mr. Meraner's first question, I have a large, open area in my basement, approximately 26 by 40 by 10 feet, devoted to loudspeaker testing. One wall and a contiguous portion of the floor are covered with acoustic foam and sculptured foam rug pad to damp near-floor and wall reflections. I can position the speaker under test near reflecting or nonreflecting surfaces, in the open, or near walls or corners to simulate a range of actual listening environments. I use inexpensive omnidirectional electric microphones. These microphones have been individually calibrated to within ± 1dB using the principle of acoustic reciprocity, a self-consistent procedure that does not require an accurately calibrated reference microphone or acoustic source. The theory behind this technique is covered in many elementary texts on acoustics, including Kinsler and Frey's* Fundamentals of Acoustics.

*I have signal generators that produce ⅓-octave warble tones, ⅓-octave band-limited tone bursts and repetitive band-limited impulses for testing. The ⅓-octave warble tones are most useful for obtaining average room responses. The tone bursts yield anechoic response when properly gated. The band-limited impulses help in "time aligning" drivers. The impulses are haversines, with an independently set width and a digitally selected repetition rate. I can set the upper frequency of the impulse spectrum anywhere between 100Hz and 20kHz and can vary the bandwidth from 2 to 16 octaves below the upper limit.*

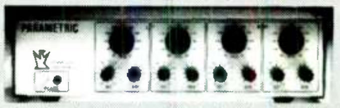
*With regard to Mr. Meraner's second question, I will first say that physical alignment of voice coils does not time align the tweeter and mid-bass drivers. The effective acoustic position of any driver is a complex function of its frequency and phase response, including diaphragm contouring. In general, the acoustic position of a driver varies with frequency, so interdriver separation cannot be characterized by a single delay valid for all frequencies. In a narrow band of frequencies around crossover, however, you can find a representative interdriver delay with band-limited impulse testing (and other techniques). When mounted as suggested in my article, the D-28 is ahead of the B110s by 0.2msec, which is equivalent to an acoustic path length difference of 6.8cm or an electrical phase lead of 145 degrees at 2kHz.*

*As Linkwitz points out in his SB articles (2/80, 3/80, 4/80), the best way to compensate for this delay is electrically with active all-pass delay approximations. Offsetting the drivers physically by 6.8cm corrects the delay on-axis, but produces off-axis response errors.*

*Because I restricted my design to passive crossovers, proper electrical delay compensation was not practical. Furthermore, because the third-order Butterworth crossover does not sum to a minimum-phase response, the best you can do is to obtain a flat frequency response by minimum-phase contouring of the electrical portion of the crossover to account for interdriver delay around 2kHz. If the drivers were exactly 90 degrees out of phase, as they should be with a third-order Butterworth crossover, reversing tweeter polarity would not change the frequency response at 2kHz. Because of the extra 145-degree phase lead, however, response is either up 2dB or down 4dB, depending on tweeter polarity. If you examine Fig. 7 of my article, you will see that at the crossover frequency, the mid-bass pair and the tweeter are each down by 5dB rather than 3dB. The extra 2dB brings the overall summed response to flat. This is accomplished by moving the tweeter's 3dB-down point to about 2,300Hz.*

*Concerning Mr. Meraner's question on overlap, the D-28's mechanical resonance is at 600Hz, which is well below the crossover frequency. Although the low Q of this tweeter causes its acoustic output to fall below 2kHz, the response is still minimum phase. As I stressed in my article, you must carefully combine crossover electrical response with driver electro-acoustic response to obtain the desired overall acoustic response. As Linkwitz and others have shown, with this approach, you can often extend the useful range of a tweeter down to its fundamental resonance.*

*Finally, you can hear lobing errors easily. Loudspeakers are traditionally designed for flat frequency response on-axis. I am sure*



*you have heard changes in frequency response as you walk to the left or right or change from a standing to a sitting position. Many of these location-dependent response irregularities are the consequence of lobing error.*

Figure 1a, *which is taken from my 1983 AES paper, gives an example of lobing error. It shows the polar response pattern at the crossover frequency of a woofer/tweeter combination when using an 18dB/octave Butterworth crossover. Notice that response is flat on-axis, but peaks +3dB at −15 degrees off-axis. Figure* 1b *shows the complete frequency response for this simple but typical system both on-axis and −15 degrees off-axis. The broad off-axis response peak extends an octave above and below the crossover frequency* $\omega_c$*. This response error should be subjectively obvious relative to the on-axis response. The response at +15 degrees will show a broad dip also extending from 0.5 to 2* $\omega_c$*, which you can also hear easily. Notice that even with an 18dB/octave crossover, driver interaction extends well above and below* $\omega_c$*.*

## SPL CONFUSION

I have just read Joseph D'Appolito's satellite speaker article (*SB* 4/84, p. 7) and am confused about the sound-pressure level (SPL) calculations. I have always understood SPL to be a power, not a voltage, calculation. In other words, a unit with an impedance of 8Ω and a sensitivity of 90dB/watt/meter would, with its stereo twin, put out 93dB SPL at 1W for each channel.

If you parallel two identical 8Ω units, 2.83V would provide 1W for each and double the current for 2W from the amplifier. Again, you get 93dB SPL as an acoustic sum, the same as with a stereo pair. In series, the same voltage is halved, the power is quartered, each driver loses 6dB, and you add 3dB in the acoustic sum, for a net loss of 3dB in SPL, or 87dB out. Mr. D'Appolito adds 6dB in parallel and has no gain or loss in series. Please explain.

Ken Kern
Minneapolis, MN 55412

*Mr. D'Appolito replies:*

*I do not blame Mr. Kern for being confused. Loudspeaker sensitivity is a tricky topic.*

*I want to make one point clear: computing the SPL from a single loudspeaker or multiple combinations of loudspeakers is not inherently a power calculation. The sound pressure produced by a direct-radiator loudspeaker operating in the so-called "mass-controlled" region above its resonant frequency is directly proportional to its voice-coil current, which in turn is directly proportional to the applied voice-coil voltage. (See Linkwitz, SB 4/84, p. 24, for more details.) Stated another way, the relationship between SPL and voice-coil current or voltage is linear. Since power is proportional to current or voltage squared, the relationship between pressure and power is nonlinear. This is one reason why power sensitivities for multiple speakers are difficult to determine.*

*Loudspeaker systems are designed for flat voltage response. For example, when making a frequency-response curve on an 8Ω speaker, the amplifier output voltage is held constant (typically at 2.83V) as frequency is varied from 20Hz to 20kHz. The result is a constant-voltage response measured or controlled in this response test. The input power varies with loudspeaker impedance and is generally not constant. The quoted power sensitivities are really voltage sensitivities that have been converted to pseudo-power equivalents by assuming the loudspeaker impedance is a pure constant resistance of 4 or 8Ω.*

*Even though loudspeakers are designed for flat voltage response, it has been traditional to rate them in terms of power sensitivity. This works well with vacuum-tube amplifiers where impedance taps provided on the output transformer keep output power relatively constant with changing loudspeaker impedance. Modern solid-state amplifiers, however, are constant-voltage sources, and output power varies with load impedance. When using these amps, loudspeaker voltage and sensitivity may be a more useful loudspeaker specification.*

*An example might make this point clear. Suppose you have 4Ω and 8Ω loudspeakers with identical power sensitivities, say 90dB/watt/meter. The 8Ω speaker will require 2.83V to produce 90dB, while the 4Ω speaker will need only 2V for the same SPL. If the output of a solid-state amp is switched*

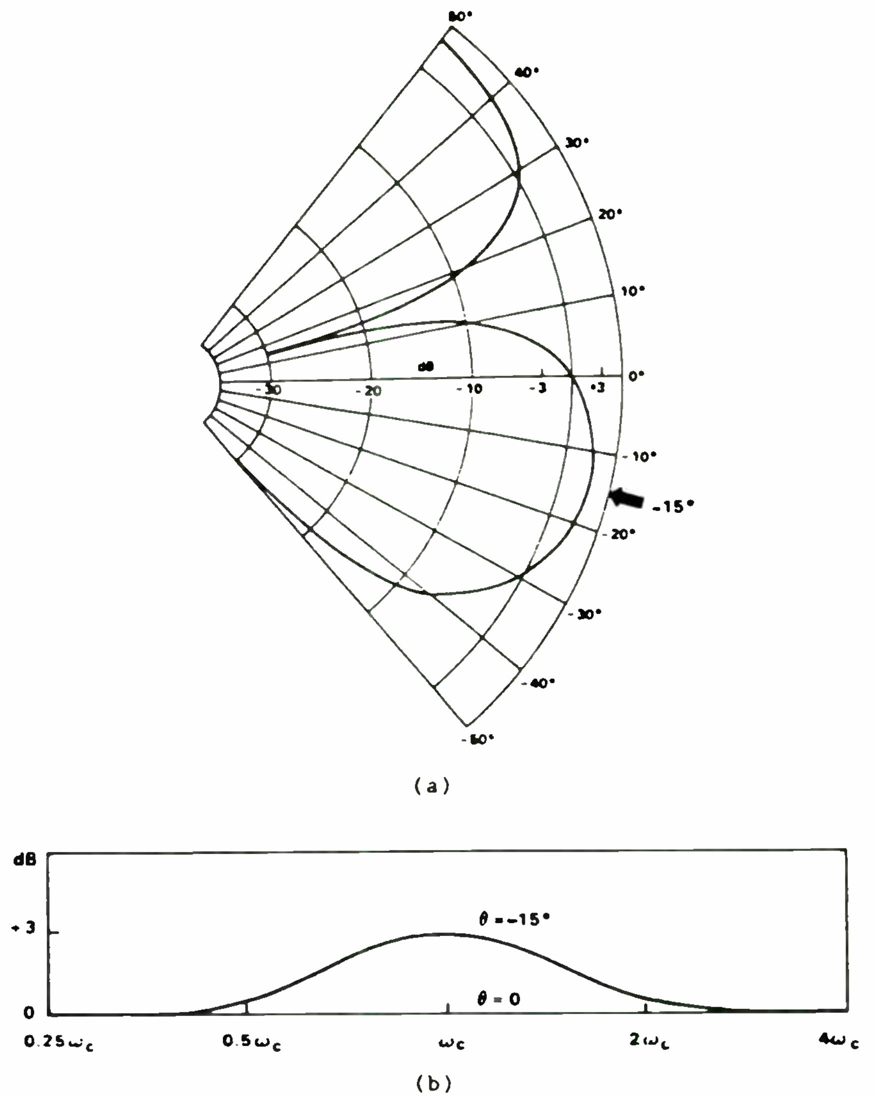


**FIGURE 1: The polar response at crossover frequency (a) and frequency response (b) for a two-way, two-driver speaker with a third-order Butterworth crossover.**

*from the 8Ω to the 4Ω speaker without adjusting the volume control, the 4Ω speaker will sound louder by 3dB [20log(2.83/2)], so you would tend to call the 4Ω speaker more "sensitive." The 4Ω speaker does have a 3dB higher voltage sensitivity. With solid-state amplifiers, power sensitivities can be compared only when speaker impedances are equal. To sound as loud as the 4Ω speaker, the 8Ω speaker must have the same voltage sensitivity or, equivalently, a 3dB higher power sensitivity.*

*Let's look at Mr. Kern's 8Ω stereo speaker pair. Whether we get a 3dB or a 6dB increase in SPL over one speaker depends on how the pair is driven. Let's stand on the centerline between the two speakers. Assume each speaker is driven at the same voltage and pseudo-power level (2.83V and 1W). Each speaker produces the same acoustic pressure (P) at our listening locations, say 90dB. If the two speakers are driven in phase (i.e., monaurally), the individual pressures will add directly to produce 2P, which is an increase of 6dB over one speaker. Since a 2W total input produces 96dB, 1W will produce 93dB (93dB/watt), which is an increase of 3dB in power sensitivity over that of a single speaker. (Remember—doubling or halving applied voltage causes a 6dB change in SPL, while doubling or halving power produces only a 3dB change in SPL.)*

*Suppose the speakers are now driven with stereo program material. In stereo, the phase of one channel relative to the other is highly random (as it must be for good stereo), with an average value of 90 degrees. The equal sound pressures from each speaker no longer add directly because they are 90 degrees out of phase. They now combine according to the right triangle rule for a total pressure of √2P, or a 3dB higher SPL than that of a single speaker. Since 2W produces 93dB, our combined stereo pair has an average power sensitivity of 90dB/watt—the same as that of a single speaker. Mr. Kern's example is correct for stereo operation.*

*In my satellite speakers, the two mid-bass drivers are driven in phase so that the sound pressures they produce add directly. Furthermore, the voice coils are connected in parallel. If 2.83V is applied to one KEF B110, you get 84dB at 1 meter. When a second driver is connected in parallel to the first, each voice coil sees 2.83V, and you obtain twice the sound pressure (90dB) for a voltage sensitivity of 90dB/2.83V at 1 meter. Since the nominal input power is 2W, the power sensitivity of the pair is 87dB/watt/meter, which is 3dB higher than a single KEF. (Note that two KEFs in parallel are equivalent to one 4Ω driver.)*

*The tweeter in my satellites has a nominal impedance of 8Ω. As you saw earlier, when the driver impedances are different, you must match voltage sensitivities or find a tweeter with a 3dB greater power sensitivity. My tweeter must have a voltage sensitivity of at least 90dB/2.83V or a power sensitivity of 90dB/watt to match the mid-bass pair.*

*Suppose we had connected the two mid-bass driver voice coils in series. The two drivers would still be driven in phase. Each driver would, however, receive only half the voltage (and half the current) and put out only half the sound pressure, or P/2. But each output would still add directly to produce (2×P/2), or P. Therefore, with the voice coils connected in series, you get 84dB/2.83V—the same voltage sensitivity as that of a single driver—but the input power is halved. One-half watt produces 84dB, and the power sensitivity is 87dB/watt/meter, which is 3dB higher than a single driver and equal to the parallel connection. The power sensitivity is doubled with either connection, but the voltage sensitivity of the pair depends on the type of connection used. Paralleling like drivers is a good way to improve loudspeaker system efficiency because both voltage and power sensitivity are doubled.*

*The above examples show that the combined sensitivity of multiple drivers is a complicated topic. To arrive at the correct sensitivities, you must keep careful track of what is happening both on the acoustic output side and the electrical input end of multiple driver combinations. When dealing with drivers of differing nominal impedances driven by solid-state amplifiers, it is often easier to keep track of voltage (or current) sensitivity than power sensitivity.*

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## SATELLITE SYMPOSIUM

I have a couple of questions about Joseph D'Appolito's satellite system in *SB* 4/84 (p. 7). My first question is really a comment on his choice of tweeter. Here is his selection procedure, as I see it:

1. Use the D-28 tweeter. It will cost more than some tweeters because of its extra sensitivity.
2. Even though it adds more cost and complexity to the system, destroy 4dB of tweeter sensitivity by placing a resistor in series with the tweeter voice coil.
3. Neutralize the effects of the more expensive horn loading by placing a capacitor in parallel with the resistor. This will pull up the 6dB droop at the high end. With luck, you will not notice the phase shift caused by this capacitor.
4. When you are finished, you will have a very nice dome tweeter with a sensitivity of 90dB sound-pressure level (SPL).

Four or five years ago, the D-28 might have been the only tweeter to produce a 2kHz tone at 110dB SPL, but that is not so today. Why not give us a simpler, more sensible design using one of the quality dome tweeters now available?

Even if I sound critical of the tweeter, I will probably build the system as Mr. D'Appolito describes it. Because my living room is larger than 3,000 cubic feet, I am considering using one pair of satellites per channel. (I have an amplifier that can handle the 2Ω load.) Perhaps Mr. D'Appolito can advise me about which physical arrangement of paralleled satellites (*Fig. 1*) is

likely to produce the better stereo imaging. In either case, the systems are shown on a flat wall, about 8 feet apart and 36 inches off the floor.

I enjoyed the article very much and appreciate any help he can offer.

Kenneth P. Miller
Mexico, MO 65265

*Mr. D'Appolito replies:*

*I agree with the fourth comment in Mr. Miller's letter, although I would put it more positively. I believe my crossover design makes a fine tweeter sound even better. I also agree that my satellite speaker design, as it appeared in SB, is already a little out of date. SB readers should realize, however, that there is usually a very long lead time between the start of a project and its appearance in the magazine. As I indicated in my article, the satellite design evolved over a period of two years. When I and my good friends were happy with the satellites, we built eight more copies just to make sure the design was reproducible. Finally, there was another full year's delay between preparation of the manuscript and its ultimate publication—a total of 3½ years from the start of the project. Of course, any project can be improved, but the design must be frozen at some point in time if an article is ever to come to life.*

*In the year between preparation and publication of my article, I have tested several other drivers. I have not found a satisfactory substitute for the D-28. Most so-called high-power dome tweeters still cannot produce the required SPL at 2kHz with acceptable distortion levels. The flat flange versions of both the Dynaudio and Morel tweeters can handle the power, but they still do not work well. Although these 90dB tweeters are flat ±2dB from 2kHz to 20kHz, their departure from flat response is in the form of a broad dip of almost 4dB in the octave between 4 and 8kHz. This dip is difficult to correct passively. It can be done only by "destroying" 4dB of sensitivity, which makes it too low for my satellites. On the other hand, the response deficiencies of the horn version are easily corrected with a simple RC network.*

*I do not consider the D-28 expensive in light of its capabilities. If cost is Mr. Miller's concern, I am surprised that he did not object to the B110s, which despite the sad state of the British pound, are perhaps the most expensive 110mm Bextrene drivers available. I have successfully adapted the new dual-voice Focal 5N402DBs to my satellite design and now recommend them instead of the B110s. The Focals are about $15 less per unit than the B110s and are sonically superior to them in this application. I hope to explain this mod in detail in a later letter to SB.*

*I must disagree with Mr. Miller's third comment. The capacitor in my crossover does not add phase shift: it corrects for it. The drooping high-frequency response of the D-28 also causes an increasing phase lag with frequency. The RC network in my crossover supplies a correcting rise in drive voltage and an increasing phase lead with frequency, both of which restore the D-28 to overall flat frequency and phase response.*

*With regard to Mr. Miller's question about multiple satellites, I am not convinced he needs them. A single satellite pair produces 115dB SPL peaks with a 300W/channel amp in my 6,000-cubic-foot living room. I would try a single pair before taking other steps. The major problem is not with the D-28s, which can put out 127dB if you have the power, but with the mid-bass drivers in the bottom octave or so. By mounting your system on a wall, you can avoid the diffraction loss problem and increase low-frequency output capability.*

*If you still feel you require more output, multiple satellites might not be the best solution. Mr. Miller's Arrangement B is better, but both arrangements will display frequency-dependent nulls in the horizontal polar response, which will compromise imaging. I think the best way to get more output capability is to go to 6½-inch mid-bass drivers. I am currently experimenting with the Dynaudio 17W-75s, which are far superior to the B110s in linearity and pulse power handling ability. They are also less expensive. Satellite sensitivity with these drivers is about 93dB, and a pair produce peak SPLs of 119dB with my amp. The system, however, is still under development at this time, and I do not have a final circuit recommendation.*

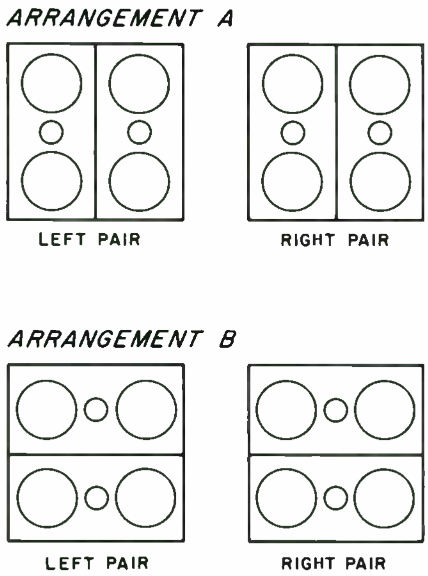

**FIGURE 1: Mr. Miller proposes these two options for a paralleled satellite setup.**

# SPEAKER SPEC GUARANTEE?

I have two items I would like to share with my fellow speaker builders. The first concerns stiffening and/or damping of speaker panels. Why do most builders go to great lengths to stiffen and/or apply damping materials to the solid top, bottom, side and rear panels of speaker enclosures, but do nothing for the front panel, which has been severely weakened by the holes used to mount the drivers?

The second item concerns published versus actual speaker specifications and is a bit more involved. I have looked at a number of units, with the following results:

- HIF13J2C12 (Audax): My $f_S$ and $Q_T$ measurements corresponded to the published values reasonably well.
- HD17B25H2C12 and H4C12 (Audax): My measurements showed $f_S$ to be 46 and 33 percent higher than published, respectively, and $Q_T$ to be 47 and 63 percent high, respectively.
- HIF17ES and HD20B25J2C9 (Audax): The impedance curves on these units are among the few that have not been cut off near their upper extremes. Consequently, it is possible to calculate $Q_T$ from Audax's own data and to compare it to the published value. For the first model number, I calculated a $Q_T$ of 1.06 versus the published value of 0.7; for the second, I calculated a $Q_T$ of 0.9 versus the published value of 0.57.

On the face of it, such discrepancies must be quite discouraging to speaker builders. Yet there is some evidence that things might not be so bad after all. In his 1977 AES paper, "Simple Formulas and Graphs for Design of Vented Loudspeaker Systems," Patrick Snyder implies that although a production run of a loudspeaker model might show substantial variations in $f_S$, $Q_T$ and $V_{AS}$, the ratio $f_S/Q_T$ and the product $V_{AS}f_S^2$ will tend to show relatively little variance. It will also show correspondingly minor performance variations when placed in a box of constant volume, if tuned to a frequency equal to 0.39 $(f_S/Q_T)$. The two design formulas are as follows:

$$f_3 = f_S \sqrt{\frac{V_{AS}}{V_B}}$$

$$f_B = 0.39 \frac{f_S}{Q_T}$$

An example might illustrate his point more effectively. A manufacturer might list the Thiele/Small parameters as follows: $f_S = 42$; $Q_T = 0.42$; $V_{AS} = 0.75$ cubic feet. Mr. Snyder is saying that although these three parameters might fluctuate considerably from one "identical" speaker to another, the critical ratio $(f_S/Q_T)$ and product $(V_{AS}\ f_S^2)$ will not. Consequently, neither will performance. Using Mr. Snyder's design formulas, the Thiele/Small parameters listed previously and an arbitrarily selected box volume of 1 cubic foot, we find the following values:

$$f_3 = 42\sqrt{\frac{0.75}{1}} = 36.4\text{Hz}$$

$$f_B = 0.39\left(\frac{42}{0.42}\right) = 39\text{Hz}$$

Another copy of the same speaker might have different parameter values but the same critical ratio and product. Thus, if $f_S$ equals 52, $Q_T$ would equal 0.52 and $V_{AS}$ would equal 0.489. These new values, plugged into the formulas for $f_3$ and $f_B$, will result in values for $f_3$ and $f_B$ identical to the original values.

Instead of using the above formulas, let's use J.B. Keele's formulas, as outlined in David Weems's book *Designing, Testing and Building Your Own Speaker System*. For a 1-cubic-foot box, the first set of parameters will result in an $f_3$ of 36.4Hz and an $f_B$ of 38.3Hz, while the second set of parameters will result in an $f_3$ of 36.4Hz and an $f_B$ of 41.4Hz. (Mr. Snyder's estimate for $f_B$ is based on an average calculated from the Thiele/Small alignments, whereas Mr. Keele's formulas are based on a curve fit of equivalent data. Therefore, the latter can be expected to be more accurate. For utmost accuracy, consult Bob Bullock's tables in *SB* 1/82, pp. 22–23.)

This discussion suggests that it is reasonable for speaker users to expect that published Thiele/Small parameters be guaranteed, with tolerance, but that the parameters subject to guarantee should not be the traditional $f_S$, $Q_T$ and $V_{AS}$ values, but the ratio $f_S/Q_T$ and the product $V_{AS}\,f_S^2$.

David J. Meraner
Scotia, NY 12302

## RMS QUERY & PANEL TIP

As a new subscriber to *SB*, I have a question and a tip. First, if a three-way speaker is designed for 100W RMS, is there a rule of thumb for what portion of the 100W is expected to be used by the woofer, midrange and tweeter? When a midrange is advertised at 100W RMS, does that mean it can handle that portion of the total 100W that usually gets through the crossover to the midrange driver? Or does it really mean that the driver can handle a full 100W RMS itself?

As for the tip, I have very good luck lining my enclosures with 24-by-48-inch ceiling panels. I use vinyl-faced panels over a 1-inch-thick batt of semirigid, yellow fiberglass insulation, which you can cut to close dimensions with a razor blade or X-acto knife. You can smear glue on the vinyl face to hold the pieces in place, but I find that they force-fit adequately.

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RTR's finest electronic amps, $75; Singer spectrum analyzer MF-5, $195; WE volume indicator, $30; Ampex R/R AG440 deck, servo capstan, multispeed, ¼″, multitrack ES100 electronic, $895; new Altec tube line amps, $25; Haeco power transformers, 60V ct, $20 each. J.R. Stephens, 41285 Crest Dr., Hemet, CA 92344.

KEF B39 woofers, $150 pair; KEF B110 midranges, $75 pair; KEF T27 tweeters, $50 pair; Falcon crossovers (for above), $75 pair; JVC ribbon tweeters and 10kHz, 12dB crossovers, $50 pair; four JBL LE-10H woofers, $150 pair. All items new, in boxes. L. Cartwright, 2723 Darlington Rd., Beaver Falls, PA 15010.

Acoustat Model 2, $1,400, Canadian, OBO. Lee Ettinger, 119 Walker Rd., Edmonton, Alberta, Canada, T5T 4C2, (403) 487-8032.

Builder designed cabinets for KEF B110s/T27s. Professionally built by cabinetmaker with ¾″ particle board. Rosewood formica, removable front baffle, speaker holes countersunk to KEF specs. T-nuts installed, banana plug terminals, corner braced, black polyacoustic foam grilles. 12″ x 8″ x 8″, $125 plus half shipping and insurance. Walt Fleming, RFD 7, Norwich, CT 06360, (203) 889-1937.

Strathearn ribbon with transformer, $230 pair; Panasonic modified leaf tweeter, $55 pair; SEAS P21REX 8″ polypropylene woofer, $35 pair; New York Acoustics passive crossover for above combination, $50 pair. All in virtually new condition. Eric Pitschmann, 6308 Sunset Ave., Independence, OH 44131, (216) 524-6684.

Pair 15″ woofers for Realistic Mach One system, new, $80 pair. Joseph D'Airo, 201 N. Richmond Ave., Massapequa, NY 11758.

Dynaco FM-3 tuner. Excellent condition. $100 includes shipping in continental US. Call Terry at (212) 697-7660 days.

Four Alps 21-step stereo pots, 100k with film resistors, silver contacts, new, $15 each. Four mono 100k, $12 each. D. Jensen, 12655 W. Brookview Dr. Circle, Grass Valley, CA 95945, (916) 273-6738.

# Advertising Index

Pioneer series 20 D23 multiamp electronic crossover, $450; Strathearn ribbons with extras, two pairs, $500; Pyramid T1 ribbon tweeters, $500; Dynaudio 21W54MPS, $75 pair; D54, $75 pair; D28, $30 pair; Bryston 4B, $700; Bedini 25DE, $375; Belles A, $775; Magnepan arm, $110; ProAC Studio 3, $1,750. James P. White, 4750 Bedford Ave., Brooklyn, NY 11235, (718) 648-6157.

Exotic Zebrawood veneer cabinets, sloped sides and blank, veneered front, solid walnut trim, high-density MDF, interior baffles, 2 cu. ft., $120 invested, asking $150 pair; Peerless 10″ three-way system with ribbon tweeters, uniquely styled, very nice oak cabinet, asking $360 pair. Pictures available. David Tryon, 3202 Bellevue, #27, Tucson, AZ 85716.

ReVox A-700 recorder, $1,400; Pyramid T-1 tweeter, $500. Douglas S. Robinson, 104 Lincoln Ave., Waterloo, NE 68069, (402) 779-2589.

Carver C-9, $150; Dynavector 23RS, new, $175; pair Altec Lansing 208-B loudspeakers, $100; Sansui TU-S7 tuner, rackmount, $135; Sansui CA-F1 preamp, rackmount, as is, $100; pair SEAS 403 speaker kits with Audax 100 D-25 tweeters, $125. James Lee, (803) 248-4316, (803) 248-2672 EST.

dbx 224, mint, $150; dbx switching box, $20; digital-dbx disks, $11 each; excellent-sounding phono preamp (see *TAA* 5/83), $100; Nitty Gritty Record Survival Kit (unused), $25; Maxell UDXL35-90B reel-to-reel tapes, $4 each; subwoofer, $80; electronic crossover, $50; peak-reading power meters, $30. Call Bill, (415) 321-4857.

# WANTED

Marantz power amp 170DC or 300DC. Please write Dave King, 1005 Hurstdale, Cardiff, CA 92007

Will trade Sanyo Plus 75 receiver in excellent condition (75W/side) for equal value basic power amplifier. Prefer Hafler DH-220 or 200, but will consider any unit 100W/side or more in good condition. R. H. Harlan, 3320 Park St., Jacksonville, FL 32205.

VTC transformers—LS6, LS7, LS6L4, LS58. A. Fisher, 239 Georgina, Santa Monica, CA 90402, (213) 395-0355 evenings.

MC225, Bryston 2B, ⅓-octave equalizer, LS3/5a's. Steve Hluchan, (203) 397-4965 EST.

JBL's last issue of their speaker cabinet design, construction and theory guidebook. Prefer actual booklet, but a clean copy will do. Also need source near East Coast for two-part polyurethane foam damping material used to treat curved horn flares. Contact Tom Young, PO Box 436, Naugatuck, CT 06770.

# COMPUTER SMYTH

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**Announcing publication** of a brand new magazine for the technically sophisticated microcomputer enthusiast who likes to build, customize and explore micro hardware at the chip and board level.

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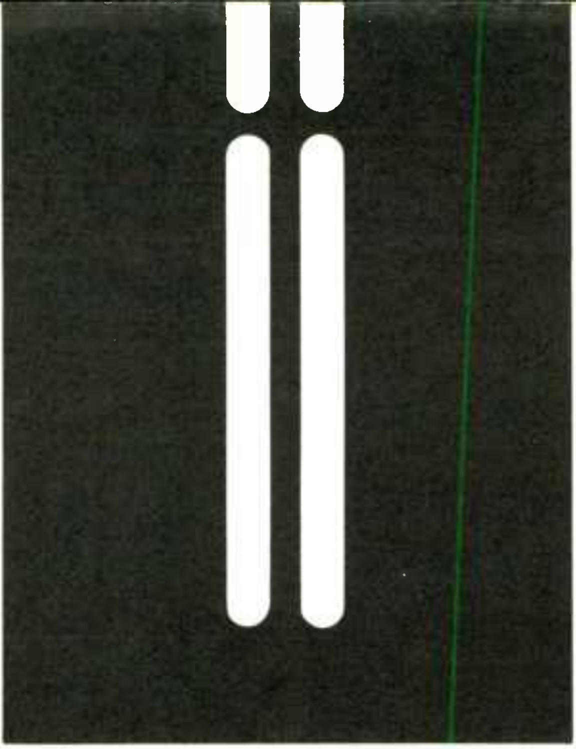

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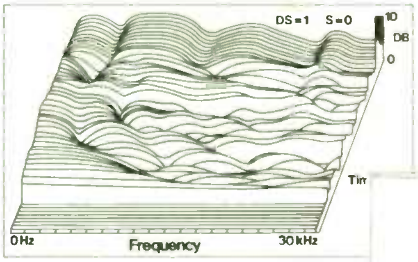

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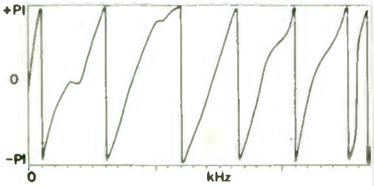

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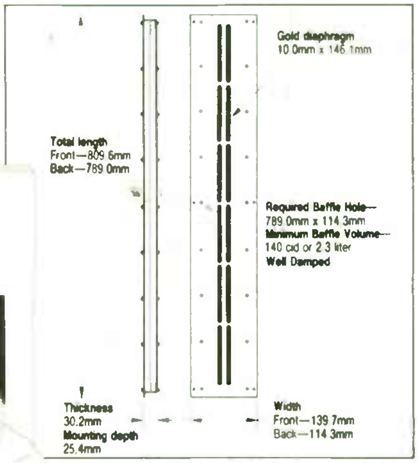

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