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World Radio History

Good News

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B&W Loudspeakers has introduced the new Nautilus™ SCM1 On-Wall Mounting Loudspeaker for applications that require an on-wall, low-profile speaker. You can use the SCM1, at only 4½″ deep, to complete a surround system or as rear-channel speakers, and other applications. The SCM1 uses the company's Nautilus tweeter and bass/midrange driver housed in a low-profile cabinet enclosure in your choice of finishes—black ash, natural cherrywood, or red cherrywood.

■ SONANCE SYMPHONY

Sonance has introduced a line of rectangular in-wall and round in-ceiling sound systems. These 6½″ speakers feature dome tweeters, two-piece baffles to reduce unwanted resonance, glass-reinforced vented ABS baskets, high-end cosmetics, rear-mounted drivers, and improved crossover networks, for a smooth on- and off-axis response. For more information, contact Sonance, 212 Avenida Fabricante, San Clemente, CA 92672-7531, 800-582-7777, FAX 800-538-5151, www.sonance.com.

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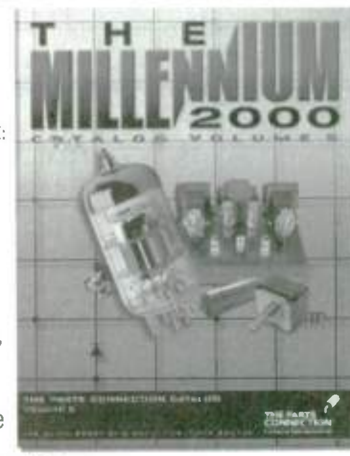

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About This Issue

What happens when one audiophile (**Ray Alden**) sets out to build the speaker system of his dreams? With a little help from his friend (**Joe D'Appolito**), the result is an excellent research, design, and construction project by noted experts ("The Bella Voce, Pt. 1," p. 8).

For another expert viewpoint, consider **G. L. Augspurger's** third part of his work on transmission lines. He demonstrates how to deliver greater efficiency to your system with alternate pipe geometries ("Transmission Lines Updated," p. 24).

The design of your listening room greatly affects how your loudspeaker will sound. To help you get a handle on the bounces that standing waves take, **John Sehring** provides some help in determining room size and room dimension ratio ("Optimum Room-Dimension Ratios," p. 20).

What do you do when the woofers are shot in a classic loudspeaker such as the Advent? No need to deep-six the unit. You can bring these beauties back to life, as **Tom Yeago** shows you in "Refurbishing the Advent 10" Woofer" (p. 30).

Justus V. Verhagen presents an unusual construction solution to address diffraction, resonances, and through-the-wall transmissions. His spherical speaker design uses a Dynaudio woofer ("A Novel Cabinet Construction Method," p. 34).

Jesse W. Knight reviews a new product from Audio Specialties. This company's multipurpose, portable loudspeaker meter determines T/S parameters ("Product Review," p. 40).

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

JOHN STUART MILL

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Speaker Builder (US USSN 0199-7920) is published every six weeks (eight times a year), at **$32** per year, **$58** for two years; Canada add $8 per year; overseas rates **$52** one year, **$93** two years; by Audio Amateur Corporation, Edward T. Dell, Jr., President, at 305 Union Street, PO Box 876, Peterborough, NH 03458-0876. Periodicals postage paid at Peterborough, NH and an additional mailing office.

POSTMASTER:
Send address change to:
Speaker Builder, 305 Union St.
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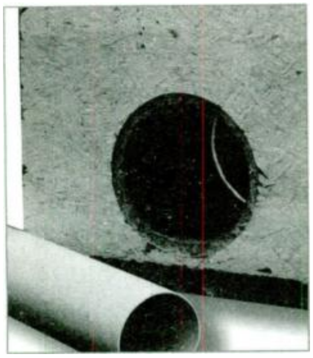
THE LOUDSPEAKER JOURNAL

VOLUME 21 NUMBER 4 JUNE 2000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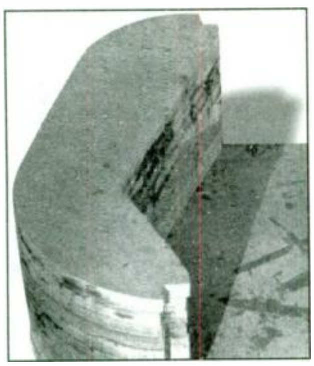
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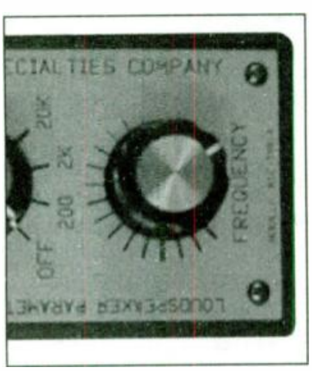

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DEPARTMENTS

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World Radio History

Set sail on the first of this two-part adventure with noted experts in the areas of speaker-building design, measurement, and construction. The goal is to produce a top-quality speaker.

Part 1

The Bella Voce

By Ray Alden and Joseph D'Appolito

"Ships at a distance have every man's wish on board. For some they come in with the tide. For others they sail forever on the horizon, never out of sight, never landing until the Watcher turns his eyes away in resignation, his dreams mocked to death by Time." From *Their Eyes Were Watching God*, by Zora Neale Hurston

I heard this passage from a cassette reading of Ms. Hurston's book while driving up to Joe D'Appolito's house in New Hampshire. In the van with me was the prototype of a speaker design I had named the "Bella Voce," which means "beautiful voice" in Italian. This prototype (*Photo 1*) contained my dreams for a singularly designed speaker *par excellence*.

For years I had harbored dreams, as do many speaker builders, of constructing a speaker to rival those costing several thousand dollars. Over the years I had built many speaker designs, but always used the best low-cost drivers I could locate. I imagine that, in so doing, many of us doom ourselves to never achieving our personal Holy Grail of sound, suffering this ship containing our dreams to remain only a vision on the horizon. Something in me sensed that this was the time to have my ship come in with the tide.

ABOUT THE AUTHORS

Ray Alden is the author of the book *Advanced Speaker Systems*. He studied at NYU's Courant Institute of Mathematics. He wrote "Building Speakers at Stuyvesant" (*SB* 1/91, p. 10), based on 11 years of experience teaching speaker design and building at New York's Stuyvesant High School. He currently runs the Chubby Dragon Compact Disc label, is a music coordinator for Clearwater's Hudson River Revival, and plays square dances and concerts. You can find parts of his book and samples of his CDs on www.bestweb.net/~rgamusic/.

Joseph D'Appolito, *SB* regular contributor and author of many papers on loudspeaker-system design, holds four degrees in electrical and systems engineering, including a Ph.D. Previously, he developed acoustic propagation models and advanced sonar signal-processing techniques at an analytical services company. He now runs his own consulting firm specializing in audio, acoustics, and loudspeaker system design. A long-time audio enthusiast, he now designs loudspeaker systems for several small companies in the US and Europe.

COMPLEMENTARY SKILLS

Perhaps confidence in completing a difficult task comes of knowing both your abilities and the forces you can muster to support areas that are lacking. This trip to Joe in the Spring of 1998 came as he was in the middle of writing his book, *Testing Loudspeakers*, a field in which I am inexperienced, but in which Joe excels. I was fortunate to come to know him in 1994, when he served as technical advisor for my book, *Advanced Speaker Systems* (Prompt Books).

My desire for high-quality speakers arose from musical interests, leading me to speaker building in the mid-1970s. I currently am proprietor of a small CD label on which I record traditional American music, ranging from Appalachian string-band, blues, and ethnic music to Cajun and Zydeco. After recording on an 8-track digital ADAT recorder, I then mix the eight channels down to 2-track stereo format on a DAT machine.

This process involves many decisions of equalization, panning, and adjusting vocal and instrumental balances while listening carefully through a set of speakers. I use headphones only occasionally to check for low-level distortions, knowing it is primarily through speakers that the world will hear these recordings. It is obviously critical that the set of speakers I use to monitor these recordings be accurate. However, more than just a super-analytical near-field monitor, I also need in my listening room a speaker that is musical.

PHOTO 1: Prototype of the Bella Voce.

Aside from mixing recordings, I simply wished to enjoy a full range of music, from jazz to classical to occasional pop. From a recording-studio point of view, I found myself trying to design a set of speakers with first-class resolution and clarity, excellent pinpoint imaging, and a relatively flat, full-frequency spectrum. This implied that I needed the first arrival of the sound spectrum to be relatively

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free of room reflections. On the other hand, from a musical point of view, I wished to avoid a speaker design so dry as to be stripped of any possible sonic benefits from the room's natural reverberant field. Could I design a balance through some sort of compromise, or was I, in fact, trying to have my cake and eat it too?

DRIVER CHOICES

Although willing to purchase relatively expensive drivers, I avoided being swept into a money-is-no-object delirium, restricting myself to individual drivers costing no more than $250. This limitation allowed me to use two of the same drivers per speaker, knowing this could increase sensitivity, more easily control acoustic radiation patterns, and often provide a distortion rating below that of a single more expensive driver.

I hoped that a persistent search might be rewarded. It was necessary to start somewhere, but simply looking at frequency-response graphs on specification sheets was not going to do it. Luckily, I had an experience that gave me a starting point. I occasionally visit the Zalytron store in Mineola, New York, to pick up speaker supplies from Elliot Zalayet. Elliot almost always has newly constructed speaker systems hooked up, often composites commissioned by Kimon Bellas of Orca Design, using crossovers designed by Joe D'Appolito.

On one visit, I heard an MTM (midrange-tweeter-midrange) speaker using a Raven R1 ribbon tweeter nestled between two white-coned Cabasse midbass drivers. Initially, I was stunned by the sound, but the more I listened something chafed, preventing nearly ideal sound. I make no claims of having a "golden ear," but perhaps when something approaches that level of excellence, irregularities stand out.

I sensed that the otherwise excellent Cabasse drivers were beginning to run out of steam in the upper midrange. However, the higher frequencies covered by the Raven tweeter reminded me of the same kind of phenomenal clarity that the original Quad electrostatics gave to the midrange. I concluded that the Raven R1 ribbon tweeter was to be the starting point in my driver selection.

QUOTH THE RAVEN

The Raven R1 is a very high-efficiency ribbon design, obtaining 95dB/1W/1m using the 6Ω transformer tap. This high efficiency results from using a pure conductive ribbon of incredibly low moving mass (.0061 grams), lightly suspended and immersed in the powerful field of an NeFeB magnet.

There are four generations of the Raven R1. The first had a separate transformer with two taps, a 6Ω and a 12Ω. The second integrated the transformer with the body of the tweeter and provided one 6Ω tap. The third and fourth generations use a brass piece to strengthen the coupling between the tweeter body and the transformer. The last two designs have increased sensitivity, albeit achieved by lowering impedance.

The Raven R1 units I purchased were second generation. At home, I was startled by the R1 suspension system. When I held the Raven up for a closer look, my breath actually set the ribbon into motion! Everything about this tweeter seemed to say, "I challenge you to find a midrange counterpart to match my efficiency, clarity, and transient response."

Finding an exceptionally fast 4″ or 5″ driver required searching for one with a low moving mass, and probably a strong magnet as well. Furthermore, I needed either a woofer or separate subwoofer to relieve this small, quick midrange from the necessity to perform large excursions stemming from bass duty. The Eton 4-300/25Hex, a 4″ bass-midrange unit made in Germany, caught my attention.

The Eton's cone, made of a proprietary "hexacone" material, has a moving mass (including the pushed air) of 5g. It is fashioned from two thin outer layers of Kevlar® placed over a honeycomb structure of Nomex. This fusion of materials provides both a high degree of stiffness and excellent internal damping. When compared to conventional materials such as treated paper or bextrene, this amalgam reduces mass up to 30%, while increasing rigidity by 70%.

Furthermore, the Eton 4-300/25Hex spec sheet shows a smooth frequency response up to 5kHz. I intended to set the upper-frequency crossover point at 3kHz, which would give a crossover optimizer nearly an octave of usable response to achieve an appropriate filter shape. Further advantages of using a 4″ unit will become clear as I pursue an analysis prescribed by Siegfried Linkwitz and Joe D'Appolito.

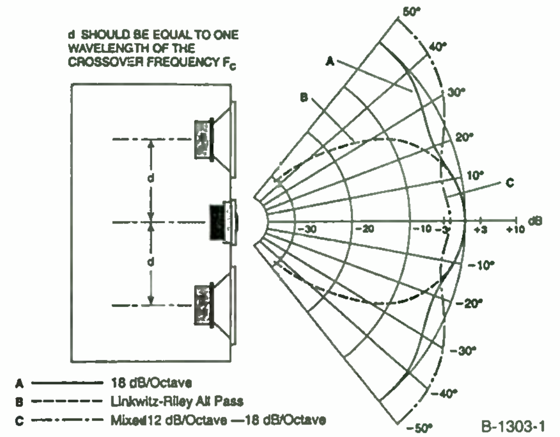

FIGURE 1: Three vertical acoustic radiation patterns (A, B, and C) resulting from an MTM-configured speaker combined with three different filter shapes.

D'APPOLITO CONFIGURATION

As you probably well know, Joe D'Appolito made a major contribution to the field of speaker engineering by describing a method that could control and shape the vertical lobing pattern of a speaker's acoustic radiation (*Fig. 1*). While he calls this the 3/2 geometry (three drivers in a two-way system) or sometimes MTM, speaker manufacturers informally use the term "D'Appolito configuration."

This symmetrical driver placement offers stability to the speaker's vertical polar-response pattern, providing a defense against image-damaging frequency-contingent shifts attributable to interdriver phase differences and crossover characteristics. Joe's system emerged after he scrutinized Siegfried Linkwitz's 1978 efforts to control acoustic radiation patterns through a combination of crossover order, cone diameter, driver placement, and box proportions.

As Linkwitz observed, "Wide dispersion can only be obtained from a small drive unit which will also have higher distortion than a larger unit. It appears that psychoacoustically the increased distortion is outweighed by an improved sound perspective which gives a greater sense of realism."[1] By using two Eton 4″ units in the MTM configuration, distortion is reduced.

Linkwitz specified that the ratio of piston diameter to crossover-frequency wavelength should be less than or equal to 1 for wide dispersion. The Eton units fall within this range since, with piston diameter D = 8.368cm and at my planned 3kHz crossover frequency, wavelength (γ) = 11.433cm, giving the ratio $D/\gamma = .73$.

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FINDING THE FREQUENCY

For use in his original Swan satellite speakers, Joe D'Appolito specified an exact horizontal polar response that falls –3dB at the end points of a 90° horizontal beamwidth (*Fig. 2*).[2] This state exists at a certain drive frequency f (Hz) only when the driver's piston circumference is twice the wavelength of this frequency. This places the D/γ ratio close to .64 and, using the following formula, you can find the frequency that corresponds to this ratio for a driver of given diameter D:

$$f = \frac{68600}{\pi D}, \quad [1]$$

where 68,600 equals twice the speed of sound in cm/s. The Eton midrange, with an effective piston D = 8.368cm, falls short of my cited crossover frequency, since, after substituting, f = 2609.5Hz.

The Raven R1 tweeter will fill in some missing off-axis response, but in using a 24dB/octave crossover, I could expect perhaps only 12% more at best. This brings the frequency up to 2922.6Hz for a horizontal –3dB beamwidth of 90°, close enough to my crossover point. There is one last consideration. The Raven R1 is capable of 105dB (with a long-term power burst of 10W RMS producing less than 1% distortion), but can a pair of 4″ Eton units reach that SPL level at the intended low-frequency crossover of 250Hz? The following approximation formula applies:

$$SPL = -86 + 40\log f_{req} + 40\log D_{iam} + 20\log A_{pp}. \quad [2]$$

For one Eton 4″ 4-300/25Hex unit, D_{iam} = piston diameter = 83.68mm; A_{pp} = pk-pk excursion = 4mm; and f_{req} = crossover frequency = 250Hz. This yields SPL = –86 + 184.86 = 98.86dB. However, using two Eton 4″ units in parallel gives a combined increase of +6dB, or, in this case, SPL = 104.86dB. Combining all these considerations, and seeing a step-response graph from an Eton brochure forecasting excellent transient response, I purchased four units.

WOOFER CHOICE

Finally, I selected the SEAS P21 RF/P 8″ polypropylene-cone woofer with an injection-molded magnesium frame. It has a smooth frequency response, even 60° off-axis, up to 1.5kHz. This was important to my design for, as you shall see, I intended to use the woofer off-axis.

The P21 RF/P is not a well-known woofer, but a more recent development of SEAS's classic P21 REX. It has a 2″ voice coil, a bullet-shaped phase plug, a high-loss rubber surround, and a low Q that is suitable for bass-reflex designs. The magnet system attempts to lower distortion through use of optimal magnetic-field symmetry, simultaneously using a progressive suspension stiffness to reduce the delayed excursions occurring in bass-reflex designs.

However, nothing in all this technical talk is quite as satisfying to me as hooking up a raw driver and simply playing some music and vocals through it. I was particularly impressed with the clarity of the human voice heard through the Eton 4″ driver, and hoped this was a precursor of good things to come. However, it was necessary to delay the satisfaction of hearing the complete speaker design until a much later time.

SPEAKER GEOMETRY

The Raven R1 has a sensitivity of 95dB/2.83V/1m. The Eton and SEAS units both have a rated sensitivity of 88dB/2.83V/1m. Rather than use larger resistors to bring down the sensitivity of the Raven, it clearly makes sense to raise the midrange sensitivity by using two drivers in parallel. As I have already mentioned, using two Eton midrange units wired in parallel will raise the sensitivity of each by +3dB, so that the pair sums to a value just 1dB below that of the Raven R1. One Eton unit is placed above the Raven, and the other directly below.

In addition to increased sensitivity, the frequencies above 250Hz benefit from having a controlled acoustic-radiation pattern by using the MTM geometry with the appropriate crossover filter. Since my intent was to achieve a 24dB/octave acoustic filter rate at the 3kHz crossover between the Raven R1 and the two Eton midrange units, I hoped to obtain the vertical acoustic-radiation pattern labeled B in *Fig. 1*. By reducing off-axis SPLs, this crossover promises a first signal arrival largely free of room reflections.

Ken Kantor[3] identified three important features for a loudspeaker: "First and foremost, you need a flat first-arrival signal. This relates to a good anechoic-chamber response. The second thing is a speaker design that preserves the flat response...that is, a speaker that minimizes room reflections. Third, you need a sensible way of dealing with the long-term reverberant field in the listening room."

I planned to use the rear waves of the

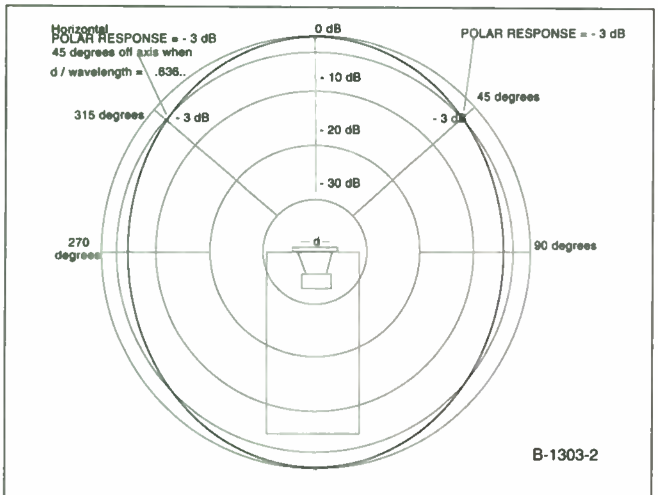

FIGURE 2: The conditions required for a horizontal polar response to fall –3dB at the endpoints of a 90° beam width.

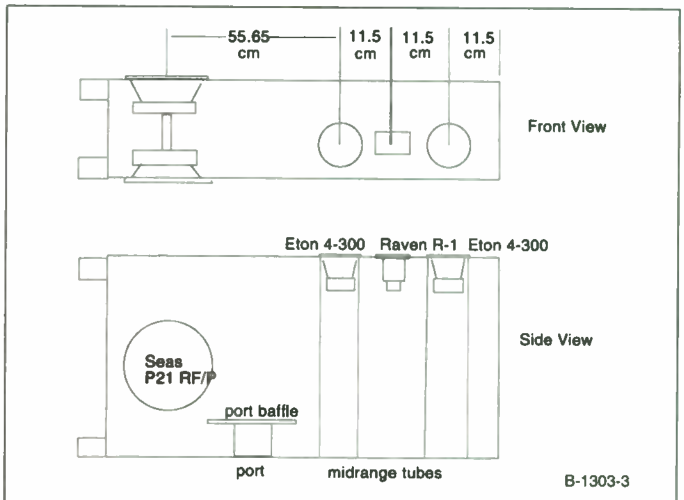

FIGURE 3: Layout and proportions of the Bella Voce speaker.

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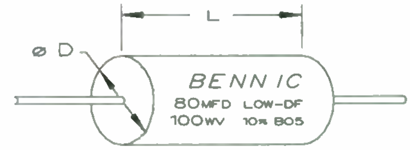

Radial

Value mfd	D / L mm	Price Each	Value mfd	D / L mm	Price Each
12	12 / 31	$0.75	140	22 / 45	$2.95
22	12 / 31	$0.95	165	16 / 42	$2.80
31	16 / 34	$1.10	180	22 / 45	$2.90
40	16 / 34	$1.30	200	16 / 42	$3.10
50	16 / 34	$1.45	250	18 / 42	$3.80
65	16 / 34	$1.60	280	22 / 45	$4.25
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4 μfd: 18 D, 33 L	15 μfd: 28 D, 45 L	60 μfd: 39 D, 84 L	120 μfd:54 D, 83 L
8 μfd: 21 D, 45 L	25 μfd: 34 D, 53 L	70 μfd: 43 D, 84 L	150 μfd:60 D, 83 L
	35 μfd: 35 D, 65 L	80 μfd: 49 D, 70 L	200 μfd:60 D, 110 L

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3.0	1.95	7.0	2.95	30.0	8.65	120.0	29.35
3.3	2.00	8.0	3.55	35.0	9.85	150.0	34.90
4.0	2.20	10.0	3.80	40.0	10.65	200.0	44.95
4.7	2.35	12.0	4.40	45.0	11.70		
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Eton 4″ midrange units to produce a more balanced reverberant field response. Hidden behind the Bella Voce are the openings of three 4″ PVC tubes. Two of the three, shown schematically in the side view of the Bella Voce in *Fig. 3*, exist to vent the rear waves of the two midranges. One such tube is shown at the bottom of the prototype in *Photo 1*.

UNENCLOSED MIDRANGES

Some of my reasons for doing this stem from hearing the first Dahlquist speaker, the DQ-10, well known in the 1970s. This speaker, with unenclosed midranges, and tweeters mounted on small flat panels, each in a different plane, had a refreshingly clear sound despite the use of an inexpensive piezoelectric super tweeter and a 10″ sealed woofer that provided bantamweight bass. I suspected this clarity was due to reduced midrange colorations resulting from a lack of enclosure reflections, rather than company emphasis on the "time-domain" coherence of the signal.

Ralph Gonzalez, in fashioning his BR1 speaker, was also attempting to deal with Kantor's third point. The three-way BR1 had a large baffle at the top housing the higher frequency units. The midrange units were not enclosed. In his *Speaker Builder* article,[4] Gonzalez said, "When a box speaker with a flat axial response is reproducing the music, the frequency balance of the in-room reverberant response is usually very different from that of the original venue. I believe this makes a you-are-there soundstage very difficult to achieve. A near-omnidirectional speaker would appear to be a much better compromise than a conventional forward-firing one."

I would need to stuff each midrange tube of the Bella Voce to damp pipe resonances. Therefore, the SPLs of these rear waves will be attenuated. Nonetheless, these rear waves will contribute to making a "somewhat" omnidirectional speaker in the 250Hz–3kHz range. Since the rear wave is 180° out of phase with the front wave, I must be concerned with cancellations occurring at the lowest wavelength. At 250Hz,

$$\text{wavelength} = \frac{\text{velocity}}{\text{frequency}} = \frac{13{,}503''/\text{s}}{250\text{Hz}} = 54''. \qquad [3]$$

Measuring, I found the minimum path length that the midrange rear signal must travel to reach the front of the midrange was approximately 52″. If the 4″ PVC tubes are stuffed with dacron material, which both slows and attenuates the rear signal, cancellation should be marginal.

While I would address the first two of Kantor's three speaker virtues head-on through the crossover and driver placement, I hoped the midrange venting would qualify as an economical leverage towards the third point. At the very least, the midrange would not have a rear pressure wave reflecting back to cause cone perturbations.

RAISING SENSITIVITY

You can also raise the sensitivity of the woofer section by using a pair of SEAS P21 RF/P woofers wired in parallel. Using this combination for each speaker raises the sensitivity to a value of 94dB/1W/1m. In my design geometry, I decided to use one on each side, placed near the floor.

TABLE 1

PARAMETERS	ONE SEAS P21RF/P	TWO IN PARALLEL
Resonant frequency (Hz)	40.9	40.9
Electrical Q	0.41	0.41
Mechanical Q	2.04	2.04
V_{AS} (liters)	41.5	83
DC resistance (ohms)	6.61	3.3
Voice-coil inductance (mH)	0.52	0.26
Power rating (watts)	50	100
X_{MAX} (mm)	4	4
Piston area (Sd) (cm^2)	194	388

Placing the Bella Voce near a wall will provide a more favorable air load to the woofers. Roy Allison[5] observed that considerable improvement in the low-frequency power output of a speaker occurs when you place one woofer close to two intersecting boundaries (each of substantial size with respect to the wavelength of the drive frequency) and several feet from the other. Located at the bottom and placed near a wall, all four of my woofers would be close to the floor and wall, and far from the ceiling. Finally, I hoped that a brace placed between the reverse-facing woofers would cancel symmetrically opposing forces of voice-coil motion. The precise driver placement of this multidriver three-way system is shown in *Fig. 3*.

Upon arrival with the prototype to Joe D'Appolito's house, I was quickly disabused of any notion that the speaker had a singular three-way geometry. After one look at the prototype, Joe said, "Oh yes, similar to a model that AR had; I think it was called the AR-9." While I did not intend to reinvent the wheel, I hoped this combination of carefully selected drivers, crossover, and cabinet dimensions would at least assemble into a clear, cohesive, and musical-sounding speaker system.

MODELING THE SPEAKER CABINET

After making your driver choices, the next order of business is to minister to the low end of the loudspeaker spectrum through box design. While this has become an increasingly prosaic part of speaker building, it nonetheless determines to what degree the selected woofers can provide a deep, visceral bass impact.

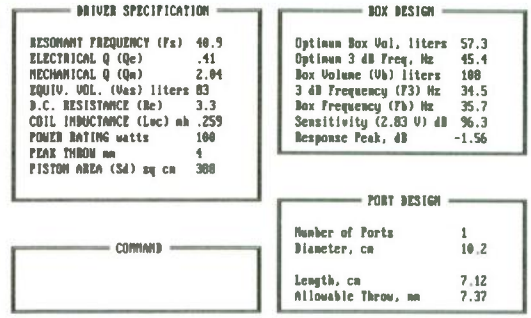

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FIGURE 4: The box-design dialog window appearing in the TOP-BOX modeling program.

The equations with which you can calculate bass-reflex box volume, low-end cutoff F_3, and tuning frequency F_b are well known. Alternatively, any number of software programs can predict the optimum box volume that provides the flattest bass response for a given set of woofer parameters. These same programs can also predict another bass response if you choose to use a custom cabinet volume.

After you have made these determinations, virtually any of these programs will also calculate the port length. More than any other variable, port length seems typically to vary from one software program to another. Sometimes, to exploit each program's strength, it is helpful to use one program for certain parts of the design, and another for other portions, as I have done in this case.

I prefer to begin cabinet design by measuring woofer parameters, using Brian Smith's Woofer Tester rather than relying on generalized specification sheets. The Woofer Tester consists of a software program coupled with an out-

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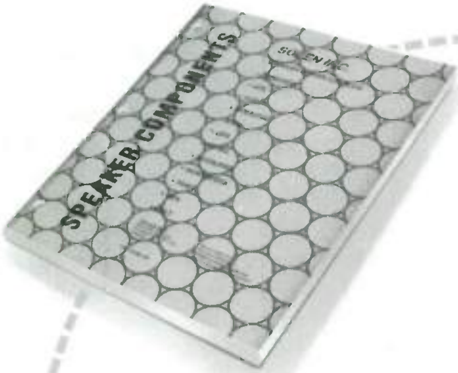

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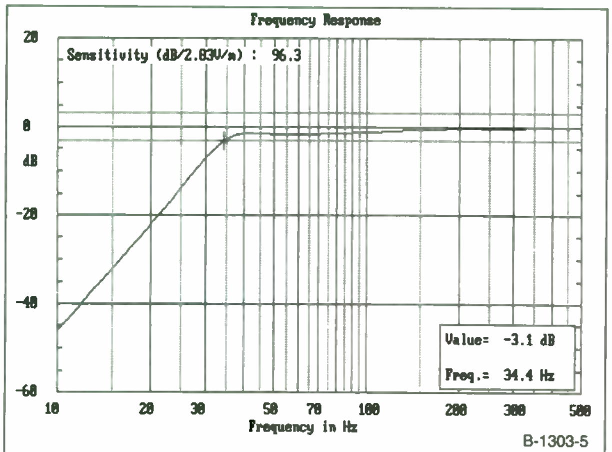

FIGURE 5: TOPBOX's prediction of the low-frequency response. (The 96.3dB/2.83V/m on top gives a referential measure to the 0dB midband efficiency line on the graph.)

under Windows 3.1 (the current version of BassBox runs under Windows 95 and 98). One of its wonderful features is the ability to account for the many parts ("sub-volumes") that exist in a speaker cabinet. BassBox 5.1 can calculate each of these and then subtract them from a proposed cabinet.

For example, subtracting all sub-volumes in *Fig. 6* shows that interior dimensions of 40″ × 20″ × 9.5″ (i.e., a 4.4ft³ internal cabinet volume) are needed to provide the actual 3.8ft³ volume of

board box, from which wires are then connected to the woofer in question. Based upon use of this device, the parameters for one SEAS P21RF/P and two wired in parallel are listed in *Table 1*.

TOPBOX VIRTUES

The numbers in the second column of *Table 1* follow well-known precepts (voice-coil inductance and DC resistance are halved, V_{AS} and piston area are doubled) for a pair of identical drivers wired in parallel. For the pair of SEAS P21RF/Ps in the Bella Voce, I use the numbers in the second column for box-modeling. *Figure 4* shows these numbers placed in the driver-specification dialog window of TOPBOX, a DOS-based loudspeaker-box-modeling program.

The first two lines of the box-design window in the upper-right corner show TOPBOX's optimum box suggestion of 57 ltr. Since I opt instead for a 108-ltr cabinet, TOPBOX predicts this will give a lower F_3 of 34.5Hz, at the slight expense of a 1.6dB dip below the midband reference sensitivity (*Fig. 5*).

Although the PC version works exclusively in the metric system, TOPBOX has several excellent features, one of which is the calculation of voltage sensitivity, which also appears in the box-design dialog window. The port-design feature, among the most accurate of all box-design programs, incorporates calculations of the interior and exterior air-mass load on the system. Converting from metric units, TOPBOX specifies that a 2.8″-long, 4″-diameter port will tune a 3.8ft³ box to the required 36Hz.

I then switched to HarrisTech's BassBox 5.1 to refine box size. While TOPBOX runs under DOS, BassBox 5.1 runs

air required to produce the predicted low-frequency curve. The two midrange tubes, the crossover, ports, braces, the pair of woofers, and the Raven tweeter are all treated as sub-volumes, and subtracting all of these from 4.4ft³ demonstrates that you will indeed have 3.8ft³ of actual air enclosed.

CROSSOVER CHOICE

I desired a crossover topology that would permit the direct sound field to arrive relatively free from room reflections and, at the same time, protect the Raven R1 from potentially damaging low frequencies. Room reflections can be confusing in a critical "mix-down" session, causing unevenness in both frequency response and imaging.

In order to realize both of these goals, my design called for a Linkwitz-Riley 24dB/octave final acoustic rolloff at the upper 3kHz crossover. This produces an on-axis forward-focused "balloon"-shaped lobing pattern (curve B, *Fig. 1*), which, unlike the "quasispherical" shape (curve A, *Fig. 1*) of the 18dB/octave odd-order Butterworth crossover, greatly attenuates vertical off-axis sound-pressure levels and hence many room reflections.

In addition, the sharper filtering action of the fourth-order crossover offers the Raven R1 increased protection from low frequencies. I hoped to achieve the design of the electrical crossover using "state-of-the-art" techniques.

Some words regarding "state-of-the-art" crossover design might be in order for new subscribers to *Speaker Builder*. Some readers may be unfamiliar with the older articles and letters probing and advancing this difficult area of design. Crossover design has been a *bête noire*

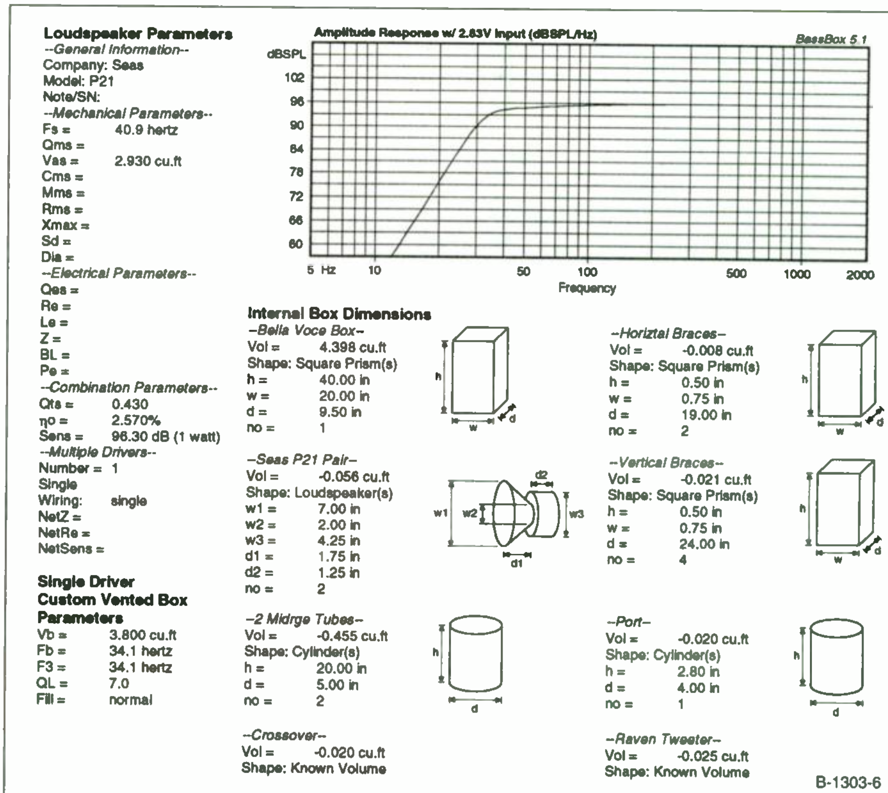

FIGURE 6: The ability of BassBox software to subtract (or add) the sub-volumes that occupy space within a speaker in order to find the actual box volume required.

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in the speaker infrastructure for amateurs not privy to the equipment of professional designers and builders.

Many of us who began building speakers in the 1970s first used store-bought "one-size-fits-all" crossovers. In most cases, this was due to a lack of information about formulas and parts to construct filters. When authors such as David Weems[6] informed us of first- and second-order filter formulas, we were finally free to build our own. As information became available, we were treated to formulas for higher-order crossovers, series notch filters, impedance compensation, and attenuation networks.

Sophisticated mathematical treatment of crossovers followed, such as that by Robert Bullock, taking numerous factors into account. For example, made aware of several filters with low input impedance, Dr. Bullock informed us of corrective ladder-topology bandpass circuits[7] (i.e., transformation-bandpass filters) to replace ordinary cascade-bandpass filters. *Figure 7* shows this type of filter, taken from Dr. Bullock's PXO software and used to obtain a midrange bandpass section.

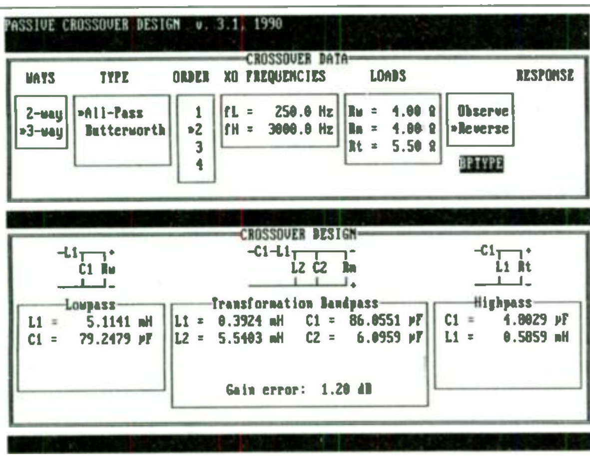

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FIGURE 7: The crossover-design dialog box in PXO software. Notice that the midrange section of this 3-way second-order crossover uses a "transformation-bandpass" section instead of a cascade bandpass.

You may notice that a second-order crossover was selected, but recall that I required fourth-order results. Often an electrical second-order filter gives fourth-order acoustic results, an appropriate result when a driver's natural acoustic rolloff is taken into account.

LINKWITZ'S REALIZATION

As far back as 1978, Siegried Linkwitz[8] realized that to achieve a final acoustic crossover slope of 24dB/octave, he needed to take into account driver Q, frequency-response rolloff, and crossover phase shift. He correctly realized that blindly applying the formula for an electrical 24dB/octave filter could lead to final acoustic rolloffs as sharp as 36db/octave. In his case, he used a 12dB/octave electrical filter, giving his tweeter the desired 24dB/octave acoustic rolloff.

Over the years, several articles dealing with "real world" crossover problems have appeared. Techniques range from making variations in the Q in second-order crossovers[9] to accounting for phase shifts arising from driver offset.[10] Each sophistication approaches inch-by-inch the building of superior filters, but real-world-driver frequency response, impedance variations, and complex phase changes all add up to prevent theoretical formulas from

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producing state-of-the-art crossovers.

Early rescue ships that came to offer us deliverance from rough seas were Ted Telesky's Computer Aided Crossover Design (CACD) and Peter Schuck's XOPT crossover-optimization software. These were the first affordable programs obtainable. CACD, demonstrated in *Audio* magazine[11] by speaker designer Ken Kantor of NHT, became my choice in the later 1980s.

Into this program you could enter the impedance, Thiele/Small parameters, and frequency-response data. CACD then generated an electrical circuit devised to be an "equivalent impedance model" of the driver itself. When a crossover network with given starting values was combined with the equivalent impedance model's circuit, the program could predict the driver's final acoustic response.

Optimization was a routine in which you could calculate a best-case final result after selecting a target response (e.g., an ideal 24dB/octave high pass at a specified sensitivity rating). The software would repeatedly change the beginning crossover values, then calculate the resulting driver's response and compare it with the target response until they closely matched.

After the error between calculated and ideal responses was significantly reduced, the program was said to have optimized the crossover values. While optimization software such as CALSOD and LEAP are currently available, CACD and XOPT are no longer sold or supported.

UNDERPINNINGS FOR A STATE-OF-THE-ART CROSSOVER

While I still use CACD, I realized that it was not suited to give a state-of-the-art crossover for the complex three-way geometry of the Bella Voce. CACD does not incorporate phase or driver offset, nor does it do an optimization of the crossover simultaneously using all drivers. Hence, you cannot realize a frequency-response summation at the system level, which means, for example, that CACD can optimize a bandpass network, but without regard to how the associated parallel high-pass and low-pass networks impact on input impedance.

You might try to mitigate these effects by using starting values in a standard CACD crossover circuit obtained from Robert Bullock's PXO software (*Fig. 7*), which does take these effects into account. Or, you could use Ralph Gonzalez's LMP software to include driver offset and diffraction loss.

Even so, aspiring to a state-of-the-art crossover system this way is a gamble if not plain impracticable. XOPT, one of the programs Joe D'Appolito uses, can perform a complete system optimization. Unlike CACD, it does not generate a driver model, but rather works from the driver data directly. XOPT accepts five columns of data:

1. frequency (Hz);
2. driver impedance (ohms);
3. phase angle of impedance (degrees);
4. acoustic output (dB); and
5. weight applied to this point (usually left as 1.0).

Also important in producing a state-of-the-art crossover, you should gather data with drivers mounted on a prototype that closely mimics the final cabinet proportions. Measured in this enclosure, the impedance and frequency response of the drivers will accurately reflect those finally interacting with the crossover.

Using an extremely accurate microphone and loudspeaker-measurement software such as MLSSA and CLIO, Joe D'Appolito gathers data that forms a true image of the eventual speaker. Subtle issues such as diffraction losses, driver offset, and the additional interdriver phase difference that complicates crossover design can all be accounted for. For these reasons, Joe recommends that measurements be taken on a prototype built for this purpose. "It doesn't have to be built like a battleship," Joe said in the months before my planned visit.

Once I arrived, the difficulty of taking these measurements accurately was soon revealed. The time it took for data collection was significantly longer than entering all the data into XOPT and performing a system-level optimization. The next five sections comprise Joe's description of the measurements made on the prototype.

DRIVER MEASUREMENTS

The reverberant field is a function of driver polar response, room geometry, and system placement in the room. This article has already dealt with reverberant response by selecting the drivers for acceptable polar coverage. The goal in the crossover-design process is to obtain the flattest possible first-arrival response within the limitations imposed by the selected drivers. To do this, it is necessary to have the following data for each driver:

- on-axis, anechoic frequency and phase response;
- acoustic phase center; and
- impedance magnitude and phase.

Since baffle geometry and enclosure loading strongly influence driver response and impedance, you must acquire this data with the drivers mounted in the final enclosure or a prototype enclosure that closely approximates the final design. I acquired the data with a prototype enclosure and the PC-based MLSSA and CLIO acoustic data-acquisi-

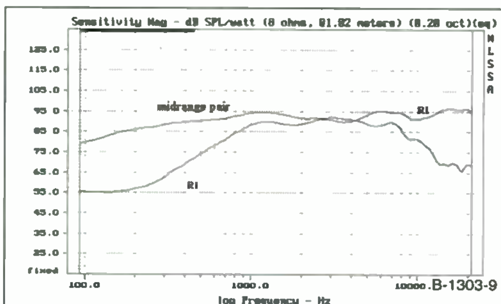

FIGURE 9: R1 tweeter and midrange-pair frequency responses.

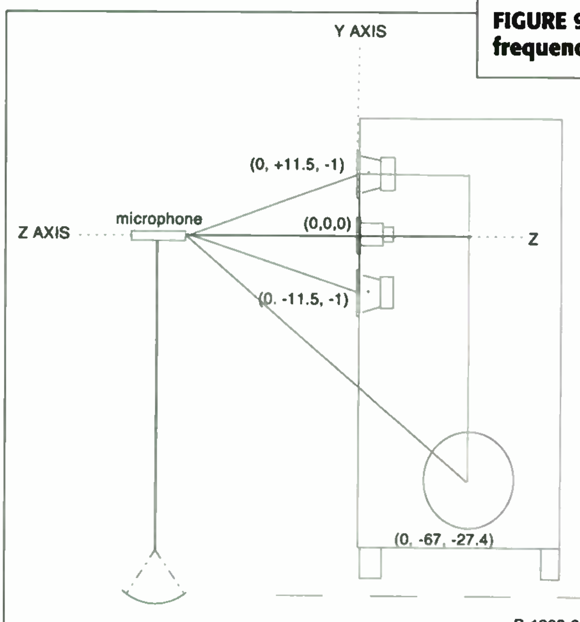

FIGURE 8: A side view of the Bella Voce with microphone measuring frequency response at a distance of 1m. In this three-dimensional scheme, the X-axis is not visible to inhabitants of Flatland, since it comes out of the plane of the page at right angles through the origin.

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tion and analysis systems.

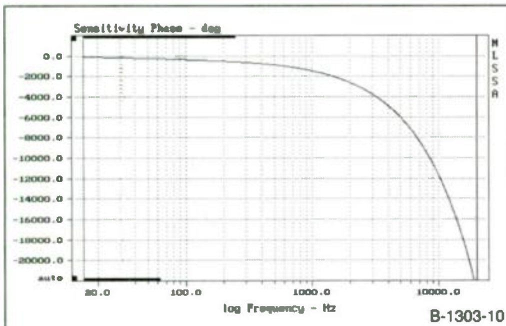

FIGURE 10: Midrange total phase response.

FIGURE 11: Midrange driver-pair minimum phase response.

MIDRANGE & TWEETER FREQUENCY-RESPONSE MEASUREMENTS

The basic acoustic measurement performed by MLSSA or CLIO is the loudspeaker impulse response, a time-domain measurement. Frequency response is computed from the impulse response via the Fast Fourier Transform (FFT).

Because these systems work in the time domain, you can accurately synchronize the measured impulse response to the test stimulus, enabling measurement of both frequency and phase response. A further advantage of working in the time domain is that late-arriving reflections from the floor, ceiling, and walls can be windowed out of the impulse-response measurement.

Since the windowed impulse response is free of almost all reflections, its FFT produces a response that is nearly anechoic. For this reason, it is called the quasi-anechoic response. You can find a detailed description of the theory of operation of these systems, together with many real-life examples, in my book, *Testing Loudspeakers*.[12]

The test setup used to measure midrange and tweeter driver responses is shown in *Fig. 8*. I placed the microphone on the tweeter centerline at a distance of 1m. *Figure 9* shows the measured frequency responses of the midrange pair and the ribbon tweeter. The responses overlap between 1 and 7kHz, which is more than one octave on either side of the desired 3kHz crossover frequency. This overlap is more than adequate with 24dB/octave acoustic crossover slopes. Note that the measured midrange response represents the sum of two electrically paralleled drivers. The response of each midrange driver is 6dB below the measured level.

MIDRANGE AND TWEETER PHASE RESPONSE AND ACOUSTIC-CENTER MEASUREMENTS

The processes of determining a driver's phase response and acoustic-phase center are intimately connected. The measured phase response consists of two components: the driver phase response, and the additional buildup in phase caused by the time it takes for the driver output to reach the microphone. Fortunately, the two components have very different characters, so you can easily separate them with the appropriate post-processing algorithms.

Driver response is minimum phase, at least over the frequency range of concern here. For minimum-phase systems, phase response is related to frequency response by a mathematical operation called the Hilbert Transform.[13] Time delay, on the other hand, produces a phase response that builds up linearly with frequency.[14]

When plotted on a linear frequency scale, time-delay-induced phase is a straight line with a constant negative slope proportional to the time delay. (Frequency response and phase data are normally plotted on logarithmic frequency scales.) This is what is meant by the term "linear phase." Minimum-phase systems are not linear phase, and a pure time delay is never minimum phase.

With that brief explanation, the process of determining driver acoustic center and phase response with MLSSA goes something like this. First, the program uses the Hilbert Transform to compute the minimum-phase response associated with the measured frequency response. This phase response is then subtracted from the total measured phase. What is left is the excess phase due to the signal fly time.

A central frequency region exists where the excess phase plot is linear; that is, the excess phase angle is a straight line with negative slope when plotted on a linear frequency scale. The phase slope in this region is used to compute the fly time, which is then used together with the speed of sound to compute a distance from the microphone to the driver's acoustic center. Finally, the FFT of the impulse response is recalculated with the fly time zeroed out to obtain the correct driver phase response.

FIGURE 12: Midrange driver-pair excess phase.

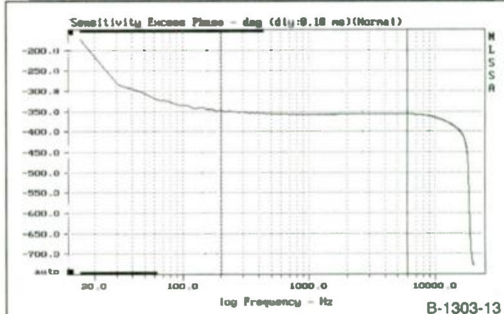

FIGURE 13: Determining midrange acoustic phase center.

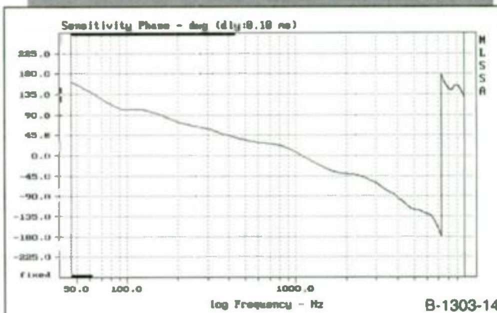

FIGURE 14: Midrange driver-pair phase response.

This last step is necessary for two reasons. First, because of cone breakup, drivers often are not minimum phase over the full frequency range of the

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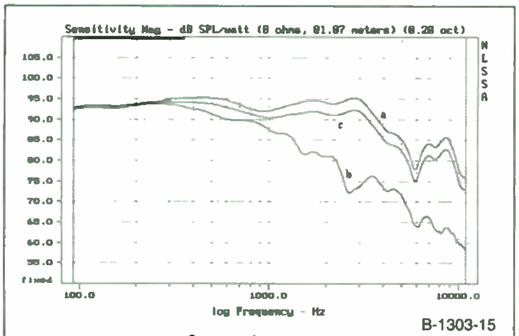

FIGURE 15: Woofer-pair responses: (a) ground plane, (b) on tweeter axis, (c) average of both.

measurement. The second reason requires a bit more explanation. MLSSA (and CLIO) will accept reference files that are used to correct errors in the measurement chain. Typical reference files contain the frequency and phase response of the test amplifier, the measurement microphone, and the antialiasing filters in the system. These are all minimum-phase devices.

However, to achieve the most accurate measure of excess phase, and thus the fly time, MLSSA ignores the reference files when computing minimum phase. The computation includes the minimum-phase response of all components in the measurement chain. Once the fly time has been determined, the reference files are used to correct the computed frequency and phase responses for all known magnitude and phase errors in the measurement chain.

Determining the acoustic center and phase response of the midrange driver pair is illustrated in *Figs. 10–14*. *Figure 10* is a plot of the total measured phase response of the midrange pair on a logarithmic frequency scale. The total phase shift exceeds 20,000° at 20kHz.

The minimum-phase response corresponding to the measured midrange frequency response is shown in *Fig. 11*. The total minimum phase at 20kHz is roughly 356°, but this includes phase shift from the test amplifier, microphone, and other elements of the signal-processing chain. The minimum-phase plot is now subtracted from the total-phase plot to get the excess phase, which appears in *Fig. 12* on a linear frequency scale. You can see that the plot is a straight line with negative slope.

From the slope, MLSSA calculates a fly time of 3.091ms over the frequency range of 200Hz–6kHz. This places the midrange acoustic centers at 105.8cm from the microphone. With the fly time removed, excess phase is now essentially zeroed in this frequency range. This is shown in *Fig. 13*. (The excess-phase plot shows a value of −360° in this frequency range, but this is the same as 0°.)

Notice that excess phase builds up again beyond 10kHz. This indicates a shift in the driver's acoustic-phase center, probably because of apex decoupling. With the fly time removed and the reference files included, the true phase response of the midrange pair is shown in *Fig. 14*.

DETERMINING ACOUSTIC-CENTER OFFSETS

The crossover optimization software needs the acoustic-center offset of each driver relative to a reference plane. A plane passing through the tweeter acoustic phase center and parallel to the front baffle is chosen as the reference plane for the design. This sets the tweeter's phase center to zero. All other driver offsets are then relative to the tweeter location.

Distances from the microphone to the acoustic centers of all of the other drivers were measured using MLSSA. Each distance represents the hypotenuse of a right triangle, with the height of each one simply the known vertical distance between a driver and the tweeter. The base of each triangle represents the horizontal distance from the microphone to the driver acoustic center. This distance is easily computed and then subtracted from the tweeter distance to get the driver offset relative to the reference tweeter location. Details of this computation are given in my book.[15]

WOOFER FREQUENCY RESPONSE

At this point you have the on-axis response data and acoustic-center locations relative to the microphone for the midrange and tweeter drivers, for which the on-axis response is representative of the first-arrival response. With side-mounted woofers, there is the question of what data should be used in the design process.

Figure 15 shows the woofer response for two microphone locations. Curve (b) is the woofer-pair response at the original microphone location, 1m out along the tweeter axis. For the second measurement, curve (a), the microphone location was on the floor, aligned with the vertical plane passing through a woofer centerline. This is a ground-plane measurement.[16] Both measurements on the plot are referenced to 1m for direct comparison. Microphone locations for these measurements are shown in *Fig. 16*.

Notice that the woofer responses for both locations are identical up to about 300Hz. Thus, the woofers are essentially omnidirectional up to this frequency. Above 300Hz, however, more high-frequency energy is radiated to the sides than to the front of the enclosure. Using curve (b) rolls off high frequencies on the design axis too quickly. If you use curve (a), the opposite will be true. For the purpose of crossover design, the decision was to use curve (c), which is the average of the two response curves. [*The D'Appolito section ends here. –Ed.*]

DRIVER OFFSET

After XOPT optimizes each section of the crossover network, it then allows you to enter more information so it can perform a complete system optimization. Coordinates (x,y,z) are used to specify the location of each driver in three-dimensional space (*Figure 8*). The tweeter is set at the origin (0,0,0), and each of the other driver's coordinates is referenced relative to the tweeter's position. While the X, Y and Z axes are all mutually perpendicular lines, only the X and Y axes are located on the plane containing the speaker's front baffle.

The microphone is placed on the Z axis, 1m away from the tweeter. The Y

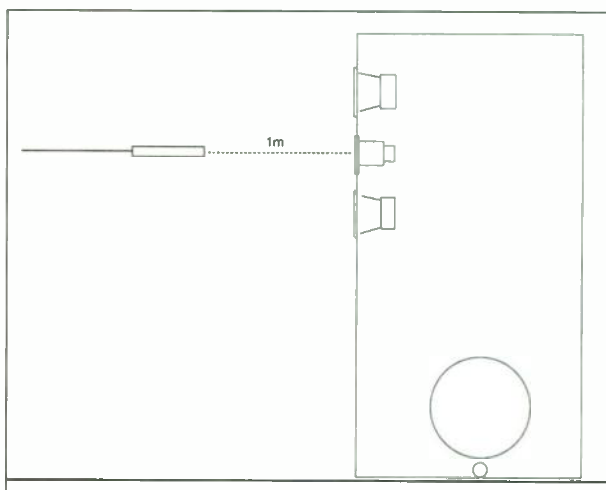

FIGURE 16: The location of the microphone used to make a ground-plane measurement of the woofer's low-end frequency response.

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axis goes through the center axis of the MTM, as shown in *Fig. 8*. The X axis comes out of the page (perpendicular to it) and, as with the Z axis, passes through the origin. One of MLSSA's specialties is location of the driver's acoustic center, which is used to determine each driver's "offset" from the tweeter's acoustic center. For example, in *Fig. 8*, notice the upper midrange's coordinates (0, +11.5, −1). The z coordinate (−1) means the midrange's acoustic center is located 1cm behind the tweeter, whereas the x coordinate (0) means it is neither right nor left of the tweeter. The y coordinate (+11.5) means the midrange's center is 11.5cm above the tweeter's center.

PORTS, BRACES, AND OTHER PROBLEMS

All did not go smoothly with bass measurements on the prototype. I had perhaps taken Joe's caveat, "You don't need to build it like a battleship," a bit too loosely. Although I used ¾" particleboard for several sides of the prototype, I had used two ½"-thick wafer-boards to construct the large 40" × 20" side panels. On each of these side panels I mounted one of the two 8" SEAS P21 woofers. In addition, there was no internal bracing. Also, as shown on the prototype's front panel in *Photo 1*, I had used four small 1"-diameter ports instead of one large 4" port.

When Joe used CLIO to measure the impedance of the two woofers (both wired in parallel and screwed into the vented cabinet), he said, "We're not getting bass-reflex action." We tried placing clay-like Mortite around the woofers and midrange tubes, trying to seal any leaks, but when Joe ran the impedance curves again, they still lacked a deep impedance notch at the 34Hz tuning frequency.

We considered several possibilities: air leaks from the space around the bullet-nosed phase plug; or maybe the small-diameter ports had too much resistance to allow free air flow. In addition, there was a slight but bizarre wiggle in the impedance curve of the mounted speakers, a wiggle that did not appear in the free-air impedance measurement of the woofer.

In his book, *Testing Loudspeakers*,[12] Joe writes about "anomalous impedance" occurrences: "Acoustical or mechanical energy coupled from a driver into the enclosure walls or the enclosed volume can produce cabinet-wall vibrations, internal reflections, and internal standing waves...all mechanical and acoustical loading on a driver will be reflected back to its impedance data." There were several lessons I would take from the possible meanings of these measurements, and these, in addition to Joe's cautions regarding the final speaker, led me to consider the following:

1. Build the cabinet to successfully withstand cabinet-wall vibrations through use of thick nonresonant walls and appropriate bracing.
2. Use "egg-crate" foam to provide some damping material to attenuate internal reflections and standing waves, but not so much as to block port air motion that permits the bass reflex action.
3. Use as large a diameter pipe as a reasonable length permits instead of using several smaller diameter ports that may restrict air flow.
4. Set the axis of the front MTM driver section so it is not in the center of the panel. This will suppress maximum interference to the original wave caused by edge-diffraction waves. Offsetting the entire MTM axis avoids two identical out-of-phase waves created at each edge. Edge diffraction waves result when the original surface wave encounters a pressure drop at the edges.
5. In order to ensure the best possible working of the port, create a reasonably sized baffle for the inside port edge to match the baffle surrounding the port's outside edge. (This interior baffle is shown in *Fig. 3*, which incorporates several of the foregoing ideas.)

I also realized, after Joe mentioned some examples, that the type of bracing used inside a bass-reflex speaker could be of particular concern. For example, look at the common commercial bracing technique shown on page 80 of Vance Dickason's *The Loudspeaker Design Cookbook*. The brace is a solid panel with large cutouts connecting four sides of the speaker. It is possible that hole cutouts, particularly if you use an unfortunate diameter, would actually form a double-tuned bass-reflex enclosure.

I would need to think carefully about how to have effective bracing, maintaining free air flow, yet not resulting in a second tuned bass-reflex action inside the final speaker. With all these thoughts in mind and some trepidation, I went home to work on modifications to the final speaker design. Part 2 of this article will conclude with the final design. I had called my ship into port and, before deciding to again put out on a sometimes cruel sea, I meant to prevent the Bella Voce from becoming an *Andrea Doria*.

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15. D'Appolito, op. cit., Section 7.6.
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With standing waves bouncing 'round the room, it's not easy to determine what's happening. This author shows how to get a handle on room size and shape that gives best sound.

Optimum Room-Dimension Ratios

By John Sehring

There is no doubt that standing waves are strong determinants of how a loudspeaker will sound to a listener in a given room. It is astonishing how long ago this was known—as early as 1930.[1] It's important to know that in rooms, at low frequencies, both sound produced (dependent on loudspeaker location) and sound perceived (dependent on listener location) are strongly affected by these waves.

STANDING-WAVE GEOMETRY

Briefly, standing waves are set up by sound energy bouncing back and forth between the various surfaces of a room. The collection of standing waves is called a "room mode."

The most basic bounce geometry involves two parallel surfaces, e.g., opposite walls of a room. In a rectangular room there are three sets of such surfaces, including ceiling and floor. The distance between those surfaces is described by the length, width, and height dimensions of the room. (This discussion is confined to rectangular rooms. I am not aware of room-mode theory being routinely applied to describe the modal behavior of other shapes of rooms.)

The lowest-frequency standing wave in a room involves a half-wavelength of sound energy bouncing back and forth between the opposite walls that are farthest apart. To obtain the size of a half-wavelength, you can use this formula:

$$\text{Half-wavelength [feet]} = 565 \div \text{frequency [Hz]} \qquad [1]$$

This shows, for example, that a half-wavelength standing wave with a frequency of 30Hz could be supported by a room dimension of 18.8′. The larger the room dimension, the lower the frequency of the standing waves associated with it.

This particular room would boost loudness at (and around) this mode frequency of 30Hz. And because of harmonics, it would also increase loudness at frequencies of twice, three times, four times, and so on, the fundamental 30Hz frequency, (i.e., 60, 90, and 120Hz). Since there are two other pairs of parallel walls, these add their own set of modal frequencies, once again based on their distance from one another.

Sound is squirrely stuff. It can bounce off walls at angles other than 90°. So four walls of a room can be involved, the sound going around in a complete circuit like a ball on a pool table that hits all four surfaces. The same is true for bounces off the floor, ceiling, and end walls. Furthermore, sound-wave bounces can involve all six surfaces of the room, taking a really complex trip!

The combinations of all these different kinds of room modes and their harmonics quickly complicates the standing-wave geometry of a room.

ROOM-MODE FREQUENCIES

You can use the following formula to calculate the frequency of each individual room mode:

$$\text{Mode frequency [Hz]} = 565 \times \sqrt{(L \times i)^2 + (W \times j)^2 + (H \times k)^2} \qquad [2].$$

Where L, W, and H are the room's length, width, and height, measured in feet. The integers i, j, and k (zero or positive) are associated, respectively, with the length, width, and height dimensions.

To get all the modes in a room, set the values i, j, and k separately to all permutations and combinations of integers from zero up to some maximum value. For example, you might calculate the room-mode frequency associated with 0,0,1; 1,2,0; 3,3,1; and so on. This is obviously very tedious to do by hand, so a computer is needed to calculate all the modes (*Table 1*).

A lot of data for a room is generated by all this arithmetic. The most important question for an audiophile is what to do with it?

Room-mode information will certainly tell you at what frequencies the room will boost loudness. Also, examining standing-wave geometry will tell you which loudspeaker and listener locations will give the most and least amount of room-mode boost.

Briefly, a loudspeaker (or listener) located at a room mode's peak will produce more sound (or will hear a louder sound) at and around that mode's frequency. When a loudspeaker (or listener) is located at a mode's null, it's much harder to generate (or hear) loud sound at and around that mode's frequency. So, moving either the loudspeaker or listener (or both) in a room will have a large effect on perceived low-frequency loudness.

It's important to know that low-frequency room reinforcement does not cease below the lowest-frequency room mode. Room-mode standing-wave effects essentially cease at about one-half the frequency of a room's lowest-frequency mode. So-called "boundary effects,"

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brought to popular attention by Roy Allison[2], provide increased boost as the frequency goes down to almost 0Hz.

ROOM-DIMENSION RATIOS

There are many opinions about which dimensions and ratios of dimensions provide for an "optimum" listening room. Since room modes so strongly affect the low-frequency behavior of a room, it makes sense to look at them for some guidance.

Since there are an infinite number of different combinations of loudspeaker and listener locations in a room, how can you use room-mode data to help design the best room? It would require plowing through an infinity of room-mode data to even begin to answer that question.

An interesting way of evaluating room size and dimension ratios based on low-frequency room modes was described by Oscar Bonello about 20 years ago.[3] Being relatively simple in concept and intuitive in its logic, his idea is to make both a room's size and ratios of its dimensions such that its mode frequencies are properly distributed.

TABLE 1
ROOM MODE FREQUENCIES

Room size: L = 134.4″ W = 182.4″ H = 96″
Room volume: 1362 ft³
Schroeder frequency = 214Hz
Average room damping = −3dB Mode bandwidth = 5Hz
Fundamental axial modes (i, j, k): 1,0,0 = 50Hz; 0,1,0 = 37Hz; 0,0,1 = 71Hz
Maximum mode indexes (i, j, k) used for L, W, and H: 4, 5, 3
Total number of modes used: 62

I	J	K	FREQ [HZ]	I	J	K	FREQ [HZ]
0	1	0	37**	1	0	0	50**
1	1	0	63*	0	0	1	71**
0	2	0	+74**	0	1	1	80*
1	0	1	87*	1	2	0	+90*
1	1	1	+94	2	0	0	101**
0	2	1	+103*	2	1	0	+108*
0	3	0	+112**	1	2	1	+114
1	3	0	122*	2	0	1	+123*
2	2	0	+125*	2	1	1	+129
0	3	1	+132*	0	0	2	141**
1	3	1	+141	2	2	1	+144
0	1	2	+146*	0	4	0	+149**
1	0	2	+150*	2	3	0	+150*
3	0	0	+151**	1	1	2	+155
3	1	0	+156*	1	4	0	+157*
0	2	2	+160*	0	4	1	+165*
2	3	1	+166	3	0	1	+167*
1	2	2	+167	3	2	0	+169*
3	1	1	+171	1	4	1	+172
2	0	2	+174*	2	1	2	+178
2	4	0	+180*	0	3	2	+180*
3	2	1	+183	0	5	0	+186**
1	3	2	+187	3	3	0	+188*
2	2	2	+189	1	5	0	+193*
2	4	1	+193	0	5	1	199*
3	3	1	+201	4	0	0	+202 **
0	4	2	+205*	1	5	1	+205
4	1	0	+205*	2	3	2	+206
3	0	2	+207*	3	1	2	+210
1	4	2	+211	2	5	0	+211*
0	0	3	+212**	3	4	0	212*

Notes: + = Adjacent modes are less than or equal to 5Hz apart.
** = axial, * = tangential modes; remainder are oblique.

Bonello's important conclusion is that the optimum room-dimension ratios of length to width to height depend on the room's volume. So there is no single best dimension ratio for listening rooms—it depends on their volumes.

I find an interesting similarity of room-volume dependence in another area of room acoustic theory. It comes from calculating a room's "Schroeder frequency,"[4] which depends on a room's volume (and its reverberation time, T_{60}):

$$\text{Schroeder frequency [Hz]} = 11844 \times \sqrt{T_{60}\ \text{[seconds]} \div \text{Volume of Room [cu. ft.]}} \qquad [3]$$

The Schroeder frequency marks the dividing line in room acoustic theory between wave and statistical mathematical modeling. Below this frequency, discrete room modes (or equivalent wave models)[5] accurately describe a room's steady-state acoustic behavior (but they do not describe early-time boundary effects).

Above this frequency, statistical methods are used. The higher-frequency room modes become so densely overlapped that they form a continuum. The effects of individual modes are then no longer discernible.

The Schroeder frequency is useful since it tells you how high you must take the values of i, j, and k in equation (2) when calculating room modes. Only those modes with frequency below the Schroeder frequency need be considered for a particular room's modal analysis, because here you are interested only in the effects of discrete room modes.

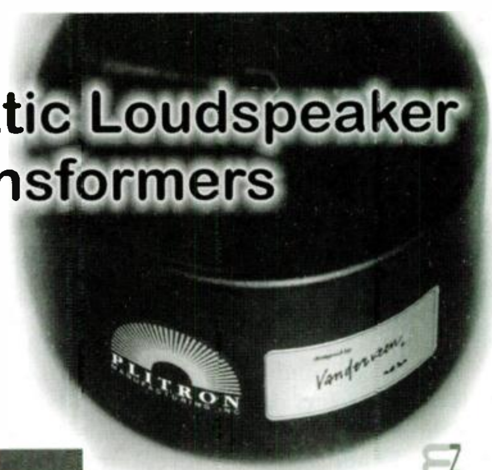
REVERBERATION TIME AND DAMPING

T_{60} in equation [3], often defined as the

TABLE 2
REVERBERATION TIME (T_{60}) VS. MODAL FREQUENCY BANDWIDTH (AT −3DB POINTS)

ROOM DAMPING	T_{60} (SECONDS)	BANDWIDTH (HZ)
Light	0.73	3
Average	0.43	5
Heavy	0.31	7
Very heavy	0.24	9

Electrostatic Loudspeaker Transformers



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Specifications

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Input, Nominal Power	4 ohms	4 ohms
Secondary Inductance	719 H	1600 H
Effective Sec. Leakage Induct.	15 mH	22 mH
Primary DC Resistance	0.1 ohms	0.1 ohms
Secondary DC Resistance	190 ohms	273 ohms
Eff. Sec. Internal Capacitance	700 pF	800 pF
-3dB Power Bandwidth, Start	35.35 Hz	35.35 Hz
w/ Rep in-series	1.051 Hz	0.515 Hz
Pri. Imped. W/Rep, 10Hz	18.26 ohms	18.10 ohms
Electrostatic Speaker Cap.	1 nF	1 nF
Resonance Freq., 2nd order	31.52 kHz	25.29 kHz
Q factor	0.601	0.642
-3db Hi Freq. Bandwidth	26.14 kHz	22.74 kHz
Eff. Pri. Impedance @ 20kHz	2.272 ohms	1.013ohms
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"reverberation time," is the time required for a sound to fade to –60dB (one-millionth) of its original strength. This discussion assumes T_{60} to be constant with frequency, which is not strictly true in actual rooms.

Room "damping" describes how fast a room soaks up sound energy. (Those familiar with electronic-circuit theory may recognize that damping is the inverse of Q.) The heavier a room's damping, the faster sound energy is absorbed and the more quickly a sound dies away. In such a room, the reverberation time, T_{60}, will be shorter. Conversely, a room with lighter damping soaks up energy more slowly, so sounds last longer before dying away and T_{60} is longer.

To give you a sense for this, T_{60} for a room of average damping is about 0.43 second. See the first two columns of *Table 2* for more on this.

FREQUENCY/TIME EQUIVALENCE

Room modes are described in terms of frequency, but damping and the resulting reverberation time are described in terms of time, so you must relate one to the other to discuss them both.

You can describe a room mode's response by specifying how wide a range of frequencies around its center frequency that mode affects. This is done by giving the plus-to-minus frequency range (bandwidth) at which the mode's response drops by 3dB (half-peak response) above and below its center frequency. *Table 2* shows the relationship between reverberation time and modal bandwidth for rooms of different damping.[6]

In a room of average damping, which has a T_{60} of 0.43s, the room modes will have a bandwidth of 5Hz or ±2.5Hz around their center frequency. Heavier damping gives shorter T_{60} times and wider room-mode bandwidths. The converse is true for lighter damping. The reason for this is that heavier damping dissipates sound energy faster, preventing room modes from building up very much. Damping flattens out the peak and widens the skirts of the response of each mode, which then affects a wider band of frequencies.

This time-frequency equivalence means you can discover a room's damping by measuring either its reverberation time or the bandwidth of its modes. In the frequency domain, modal bandwidths are easier to measure for the lowest frequency modes of the room. These three fundamental axial modes have values for i,j,k of 1,0,0; 0,1,0; and 0,0,1.

TABLE 3
ROOM MODE THIRD-OCTAVE STATISTICS

⅓-OCTAVE

CENTER FREQ.	BAND (HZ)	# MODES PER BAND
32.0	28.3–35.7	0
40.3	35.7–45.0	1
50.8	45.0–56.7	1 #
64.0	56.7–71.4	+2
80.6	71.4–90.0	+4
101.6	90.0–113.4	5
128.0	113.4–142.8	8
161.3	142.8–179.9	20
203.2	179.9–226.7	21

Notes: ## = decline or, # = no increase, in number of modes from previous band.
+ = 2 to 4 modes in this ⅓-octave band. Check for double modes less than ≈5Hz apart.

ROOM OPTIMIZATION

Bonello's work is based on looking at the number and distribution (with frequency) of a room's low-frequency modes. Using room-mode theory as described by equation [2], he calculates and plots the number of modes that fall into each third-octave band, up to the room's Schroeder frequency.

He uses two criteria to evaluate these results for gauging listening-room performance: First, the number of modes in each third-octave frequency band should increase monotonically, or, less ideally, have at least as many modes as the preceding one, as frequency increases (thus ensuring there are enough modes in each band).

Second, there should be no double modes, i.e., modes having the same or close frequencies in any band. Or, at most, double modes should be tolerated only in third-octave bands where there are at least a total of five modes present. (This ensures there won't be an excess of closely spaced modes in any one band.)

Bonello's basic assumption is that it is the amount of sound energy within a frequency band—rather than frequency spacing—which makes his criterion plausible. Note that Bonello makes no distinction among types of room modes (axial, tangential, and oblique) for his analysis.

He chooses to use third-octave frequency bands since they "... use a relative bandwidth, not an absolute one, taking into account the logarithmic characteristic of auditory perception and the ear's response to musical intervals" and "we are also influenced by the electroacoustical experience that indicates the usefulness of one-third octave as a minimum unit of bandwidth."[7]

From his first criterion, if low-frequency room modes are too widely spaced, you'll get holes in the room's modal frequency response. From his second criterion, if you have too many room modes that are close together (double modes), you'll get peaks in the room's response. Both effects may occur simultaneously, which is especially undesirable.

Double modes are those whose frequencies differ by less than their bandwidth, i.e. they are too close together to act as separate modes. The two closely spaced modes then combine into a "super mode," which gives excess boost at one frequency—not at all what you intend. The minimum allowable frequency spacing between two modes depends on the room damping, which affects the modal bandwidth, as *Table 2* shows.

For a room of average damping, modal bandwidths are 5Hz. So two modes whose frequencies differ by 5Hz or less will combine their effects in such a room. Altering room damping will change the modal bandwidths, and therefore how close in frequency modes must be to act as double modes. This may alter a room's Bonello statistics.

The goal is to have the right number of properly distributed room-mode frequencies to produce the smoothest possible room-mode frequency response.

EXAMPLES

Among examples of room designs, Bonello notes the work of Knudsen and Harris, where the ratio of 1:1.5:2.4 is recommended for a "large" studio.[8] For a room volume of 60m³, this ratio is not acceptable by Bonello's criteria, but for 2000m³, he describes it as "satisfactory."

Another of Knudsen's suggested ratios, 1:1.45:3.27, is acceptable for neither 60 nor 2000m³. Bonello writes, "Nevertheless, and rather unexpectedly, if dimensions are increased to 4850m³, which corresponds exactly to the studio described by Knudsen, those dimensions become the best." (Bonello reports on the analysis of 23 different rooms in his article.)

Using Bonello's concept, I analyzed the room size and shape recommended by Louden as quoted by Weinberg and Ferstler[9], which is 8′ × 11.2′ × 15.2′, giving a dimensional ratio of 1:1.4:1.9.

To do this more easily, I incorporated Bonello's ideas into a computer program that does all the hard work, computing, counting, and displaying room modes. This freeware program is available for download at no charge only at Old Colony's web site in the demo area,

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www.audioXpress.com. I wrote this MS-DOS-based program to run on virtually any PC running MS-DOS 2.1 or later, including the very oldest computers. It's based on work described in an *Audio* article of mine.[10]

(I'm sad to relate that this reference has an important error of omission of which I was not aware when I wrote it: it neither describes nor accounts for important low-frequency room "boundary effects," well described by Allison.[2])

When all modes were calculated for this room and sorted into third-octave frequency bands, I obtained the following statistics with the help of the computer program. It shows the number of modes in each successively higher-frequency, third-octave band:

0, 1, 1, 2, 4, 5, 8, 20, 21
———> frequency ———>

According to Bonello's criteria, this room is quite good, but not perfect, since there is a double mode in the fifth third-octave band that contains a total of only four modes. This violates the second criterion. *Table 3* shows a printout of the computer-program results that provide more detail for this room.

REVIEW RESULTS

I've previously referred to the computer printout in *Table 1*, the actual mode frequencies for this room. Specifically, there are two modes in the third-octave band centered on 80.6Hz that are only 3Hz apart. This is less than the modal bandwidth of 5Hz for this room with average damping, so they qualify as double modes and violate Bonello's second criterion.

Note that even with computer assistance, you need to review the results carefully to pick out all potential problems. As they may not get counted together in the same band, it's important to look for modes that are too close together in frequency, but are located in adjacent third-octave bands.

There is nothing sacred about the third-octave center frequencies used here—they are arbitrary. Choosing a different set of third-octave center frequencies will occasionally give slightly different third-octave-band mode counts for the same room.

It's useful to see a room shape that's dreadful from an acoustic point of view. I computed the stats of a room having exactly the same volume as that described before, but with equal dimensions of length, width, and height—a perfect cube shape, 133″ on each side. Room-mode theory strongly hints that this should be a terrible-sounding room, since too many modes are going to wind up at the same frequencies!

The third-octave mode counts are:

0, 3, 0, 4, 3, 9, 19, 24
———> frequency ———>

You can see that criterion 1 is repeatedly and strongly violated in the third and fifth bands. Also, all of the room's axial modes gang up to produce triple modes with exactly the same frequencies in the second, fourth, and fifth bands, thus violating criterion 2. Remember, having all room dimensions equal means that the mode frequencies are not spread out, so many fall at exactly the same frequencies, giving both deep holes and high peaks in this room's response. Bad!

CONCLUSION

I believe that looking at listening-room design using Bonello's concept and criteria gives fundamental insight beyond the modal frequency versus amplitude response of a listening room. The latter is always specific to a particular loudspeaker and listener location, and so cannot easily provide information on the room's performance as a whole.

Download the freeware program and try exploring this for yourself!

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Reader Service #12

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How to improve transmission-line efficiency with a configuration other than a simple straight pipe.

Part 3: Pipe Geometry and Optimized Alignments

Transmission Lines Updated

By G. L. Augspurger

After I was satisfied that my computer analog could match real-world test results, I used it to experiment with all sorts of modifications to the basic stuffed pipe. Five of these seemed to deliver greater efficiency without sacrificing traditional transmission-line performance. *Figure 13* shows these designs:

1. Tapering the pipe lowers the fundamental resonance with almost no effect on upper harmonics; it also broadens the frequency range of constructive pipe output.
2. A constricted exit effectively increases air mass, which again lowers the fundamental resonance with less effect on upper harmonics.
3. A coupling chamber between the driver and the pipe throat not only lowers the fundamental resonance, but also serves to increase the pipe's high-frequency attenuation.
4. A sudden reduction in cross-sectional area at ⅓ of the total pipe length produces a secondary reflection that tends to cancel the first-passband response dip.
5. Mounting the driver at ⅕ the length of the pipe is even more effective in reducing the first-passband dip.

I decided that the tapered pipe, coupling chamber, and offset speaker showed the most promise, so I subjected these to additional computer analysis. I built and tested at least one example of each.

Tapered Pipe

A pipe of gradually decreasing cross section (reverse flare) is a common transmission-line variant. It may have been borrowed from experiments with undamped pipes in the 1950s. The theory usually given is that since internal energy gradually decreases from loudspeaker to exit, you can make the pipe correspondingly smaller with no change in performance.

In fact, there is a dramatic change. The fundamental resonance moves down in frequency, while the upper harmonics are almost unchanged. As a result, pipe output reinforces cone output over a broader frequency range, and less damping is required for given passband ripple. (According to some loudspeaker advertisements, the nonparallel sides of a tapered pipe should "eliminate standing waves." However, this is true neither in listening rooms nor loudspeaker enclosures.)

A reduction in area between 1:3 and 1:4 seems to work best. If the exit is too small, then excessive air turbulence may result. The taper can be linear, or conic, or approximated by straight sections. These variations slightly affect pipe output, but not enough to change overall system response. Stuffing density should be the same from one end to the other.

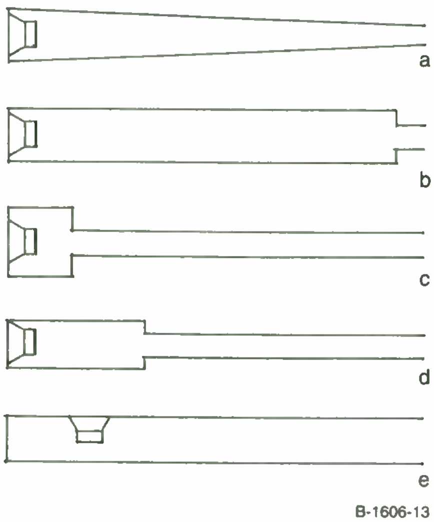

FIGURE 13: Alternate pipe geometries (top to bottom): tapered, vented, chamber, stepped, offset speaker.

Figure 14 shows the performance of a 4:1 tapered line normalized to a low-frequency cutoff of 100Hz. This scaling makes it easy to visualize what would happen with any other cutoff frequency. For example, if you wish to design a 40Hz system, then multiply everything by 0.4; response will be down 10dB at about 24Hz, and the first passband dip will be centered at 160Hz. In this particular alignment, the cutoff frequency f_3 is 0.8 times f_p.

Pipe with Coupling Chamber

Many successful transmission-line designs have also used coupling chambers. Technical explanations range from better impedance matching to suppression of pipe resonances. However, what really happens is not hard to understand. At mid and high frequencies the acoustic impedance of a damped pipe is resistive. Since the speaker cone is coupled to the pipe by the chamber's air springiness, the resulting R/C lowpass filter adds another 6dB per octave of high-frequency rolloff. You can clearly see this in *Fig. 15*.

Again, less damping is required to control passband ripple. However, for the system to work as described, there must be a clear demarcation between pipe and chamber, and the chamber must be boxy in shape. If the chamber is too small, then it is more like a stepped pipe. If you use a large chamber, then you have re-

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stored the resonant cavity that the transmission line was supposed to eliminate. A safe rule is to make chamber volume ⅓ of the total volume, as in *Fig. 15*.

You might think that any damping material in the chamber would interfere with its role as pure acoustic capacitance. However, computer simulations and actual measurements confirm that the pipe and chamber should both be stuffed. Low-frequency performance is not affected one way or the other, but mid-range response is smoother when the chamber is damped.

Offset Speaker

In Voigt's original corner horn, the back of the driver was loaded by a flared pipe driven at ⅓ its length. He did this to suppress the resonance at three times the fundamental frequency. The idea was picked up by Ralph West in a 1949 corner-speaker design for the Decca Record Company. West pointedly contrasted his cut-down horn against a damped pipe: "The very wide-open end damps the system by turning energy into sound. This is better than merely wasting the energy with layers of felt."[12]

With a properly matched loudspeaker, the Decca enclosure is able to deliver smooth bass response up to about four times its fundamental resonance. As with all undamped pipes, however, midband response is a series of abrupt peaks and dips.

The reason for this digression is that you can also improve the performance of a damped pipe by mounting the driver some distance away from the closed end. In this case, you should center the driver at ⅕ the length of the pipe to smooth out the first-passband dip. Unlike the other systems described, f_3 is set about 20% higher than f_p for flattest low-frequency response.

Figure 16 shows the response of such a transmission line. The system has the same pipe volume, the same stuffing density, and the same cutoff frequency as *Figs. 14* and *15*, but the pipe is longer and thinner.

Combinations

It is possible to combine various pipe geometries, but any additional benefits range from slight to nonexistent. For example, adding a coupling chamber to an offset speaker largely negates the value of either one used alone.

The combination of a coupling chamber and tapered pipe has often been used in successful transmission-line designs, but a straight pipe is more efficient. In this case, the taper gives no reduction in pipe volume and actually degrades low-frequency performance.

You can taper a pipe driven by an offset driver, with perhaps a tiny extension of low-frequency bandwidth, but this is accompanied by greater cone excursion. The net result is a decrease in maximum low-frequency output.

To summarize, all three geometries I've described are capable of comparable performance and can be specified by simple system alignments. Hybrids are not recommended.

OPTIMIZED ALIGNMENTS

You can scale the performance graphed in *Figs. 14*, *15*, and *16* to any desired frequency and any reasonable efficiency by establishing appropriate relationships be-

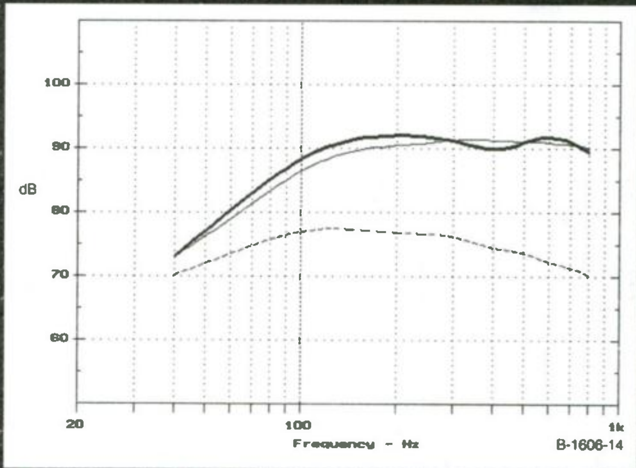

FIGURE 14: Tapered pipe optimized alignment response: cone output, pipe output, and system response (bold).

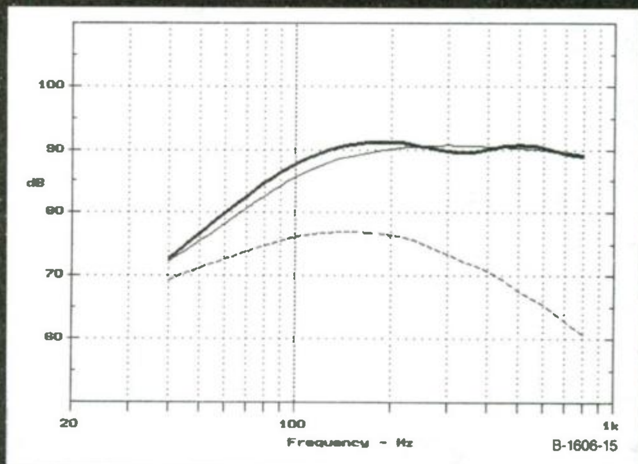

FIGURE 15: Coupling chamber optimized alignment response: cone output, pipe output, and system response (bold).

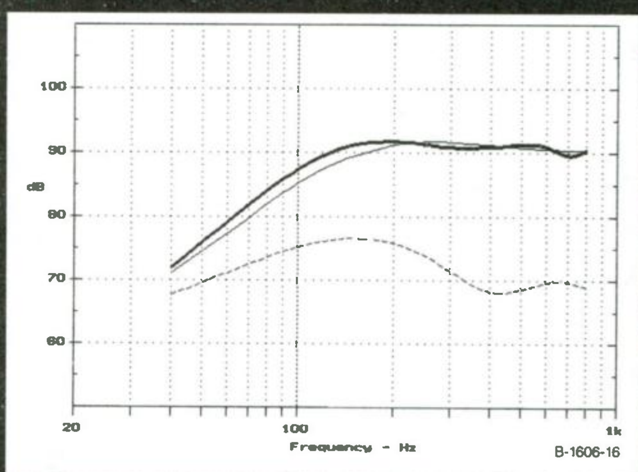

FIGURE 16: Offset speaker optimized alignment response: cone output, pipe output, and system response (bold).

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TABLE 1
PACKING DENSITY IN LB/FT^3 VS PIPE LENGTH FOR TAPERED, OFFSET, AND COUPLING-CHAMBER ALIGNMENTS.

LENGTH INCHES	F_P HZ	ACOUSTA-STUF®	POLYESTER	FIBERGLASS	MICROFIBER
24	140	1.70	1.8	0.90	0.65
36	94	1.30	1.40	0.70	0.55
48	71	1.00	1.10	0.60	0.45
72	48	0.75	0.85	-	0.35
96	36	0.50	0.65	-	0.27

tween pipe geometry, stuffing characteristics, and driver parameters. This is shown in *Tables 1* and *2*.

Table 1 is a cross-reference of stuffing densities versus pipe length. It is appropriate for all three geometries presented here, but not for simple, straight pipes. The values listed are derived from several sets of measurements for each material. I have a high degree of confidence in the listings for fiberglass, Acousta-Stuf®, and polyester. I made fewer tests with microfiber, and a fair amount of interpolation is included. Also, tests made with low packing densities show appreciable deviations from the norm.

Table 2 sets forth relationships between driver parameters and pipe geometry. I have shown three sets of values for each design to provide a practical spread of driver choices. In reality, all three alternatives describe the same speaker mechanism with different cone-suspension compliances.

First, look at the optimized alignments referenced as a, b, and c. I have restricted Q_{TS} to values less than 0.6 and, as a result, f_3 is always higher than f_S. Note also that f_3 is set at $0.8f_P$ for the tapered pipe and coupling chamber,

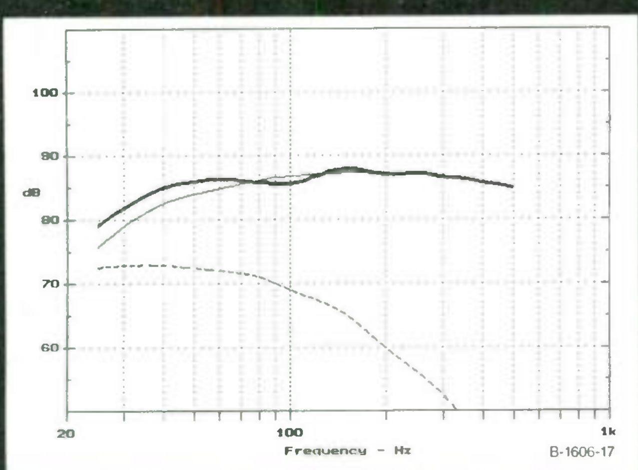

FIGURE 17: Bailey's 1972 transmission-line simulation: cone output, pipe output, and system response (bold).

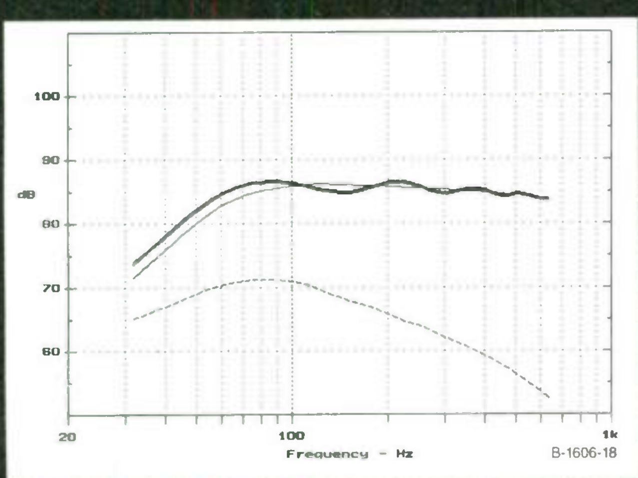

FIGURE 18: High-Q woofer on 43Hz tapered pipe: cone output, pipe output, and system response (bold).

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and at $1.2f_P$ for the offset speaker. There is nothing magic about these numbers, but they make efficient use of pipe volume without requiring unrealistic driver parameters. Even so, it is a little discouraging to see that f_3 is 30% higher than f_S at best, and this ratio requires Q_{TS} to be at least 0.5.

In many cases you might be willing to increase pipe volume in exchange for a lower cutoff frequency. This is what I have done in the corresponding "extended" alignments referenced as d, e, and f. For the tapered pipe and offset driver, I simply doubled pipe volume and then adjusted Q_{TS} until I achieved the desired response. However, the coupling-chamber alignments did not respond well to this technique. For these, I repeated the values for Q_{TS} and then adjusted other relationships as needed.

For a given driver, the extended alignments push f_3 down by about ⅙ octave for the coupling chamber, and by more than ⅓ octave for the tapered and offset designs. For both sets of alignments, packing density can vary by ±15% with only a small change in system response. The tapered line is slightly less sensitive to changes in damping than the other two designs. When in doubt, a little too much stuffing is better than too little.

GENERAL COMMENTS

The optimized alignments listed above are characterized by second-order low-frequency rolloff, with nominal ±1dB passband ripple. The efficiency matches that of an equivalent closed-box system; however, pipe output contributes 2–3dB in the low-frequency range. Since loudspeakers are displacement-limited at low frequencies, the net result is a corresponding increase in maximum output.

As a point of interest, it is possible to design a transmission-line system in which f_S, f_P, and f_3 are all equal. Bailey's 1972 design (*Fig. 17*) is inefficient, but delivers very good performance.

(His design was available in kit form and was tested by Letts as part of his thesis project.[13] Using this information, the frequency response graphed in *Fig. 17* is a best-fit computer simulation. Q_{TS} is 0.6, and V_{AS} is about 2ft³; f_S, f_P, and f_3 are all 35Hz.

The 8′ folded line consisted of three sections approximating a 2.3:1 taper. V_P was close to 3.3ft³. The line was stuffed with long-fiber acetate at a density of 1 lb/ft³, which seems to be roughly equivalent to Acousta-Stuf at 0.5-lb density.)

By using a driver with Q_{TS} greater than 0.707, it is also possible to extend low-frequency response below f_3, as in *Fig. 18*. This automotive woofer has a 63Hz free-air resonance; $Q_{TS} = 0.95$, and $V_{AS} = 0.4ft^3$.

PRACTICAL EXAMPLE

As a practical test, I decided to design a transmission-line enclosure for the Vifa P17WJ. This popular driver is intended for use in vented boxes, but is also a favorite with transmission-line builders. Its cone resonance is listed as 37Hz, $Q_{TS} = 0.35$, $V_{AS} = 1.23ft^3$, and its rated sensitivity is 88dB (1W/1m).

Looking first at the optimized alignments and doing a little rough interpolation, it appears that f_3 must be at least 67Hz. The latter figure is achieved with a coupling-chamber design having a total volume of about 0.7ft³.

I had hoped for something nearer to 55Hz, which suggests that one of the extended alignments would be a better choice. Tapered alignment (e) is close enough to use without interpolation. Using this, f_3 works out to be 59Hz, with

TABLE 2
ALIGNMENTS FOR SIX PRACTICAL SYSTEMS

Design		f_3/f_S	f_3/f_P	f_S/f_P	V_{AS}/V_P	Q_{TS}
Optimized System Alignments						
Tapered (Nom. 4:1)	a)	2.0	0.8	0.40	3.10	0.36
	b)	1.6	0.8	0.50	2.00	0.46
	c)	1.3	0.8	0.63	1.20	0.58
Coupling Chamber	a)	2.0	0.8	0.40	2.14	0.31
	b)	1.6	0.8	0.50	1.35	0.39
	c)	1.3	0.8	0.63	0.84	0.50
Offset Speaker	a)	2.0	1.2	0.60	3.10	0.36
	b)	1.6	1.2	0.74	2.00	0.46
	c)	1.3	1.2	0.94	1.20	0.58
Extended System Alignments						
Tapered (Nom. 4:1)	d)	2.0	0.8	0.40	1.50	0.25
	e)	1.6	0.8	0.50	1.00	0.33
	f)	1.3	0.8	0.63	0.60	0.41
Coupling Chamber	d)	1.75	0.7	0.40	1.10	0.31
	e)	1.40	0.7	0.50	0.68	0.39
	f)	1.10	0.7	0.63	0.42	0.50
Offset Speaker	d)	2.0	1.2	0.60	1.50	0.25
	e)	1.6	1.2	0.74	1.00	0.33
	f)	1.3	1.2	0.94	0.60	0.41

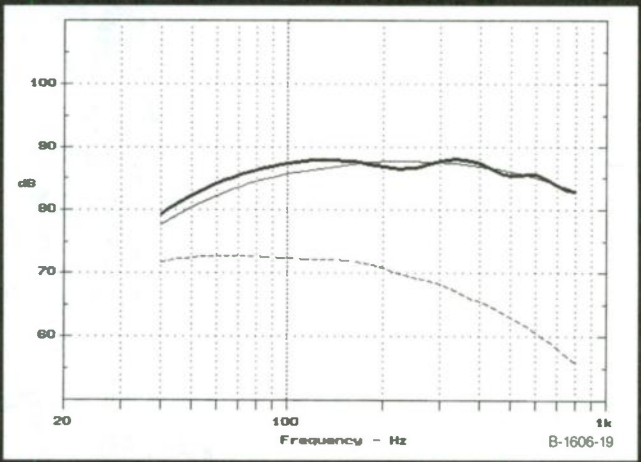

FIGURE 19: Vifa P17WJ on 74Hz tapered pipe: cone output, pipe output, and system response (bold).

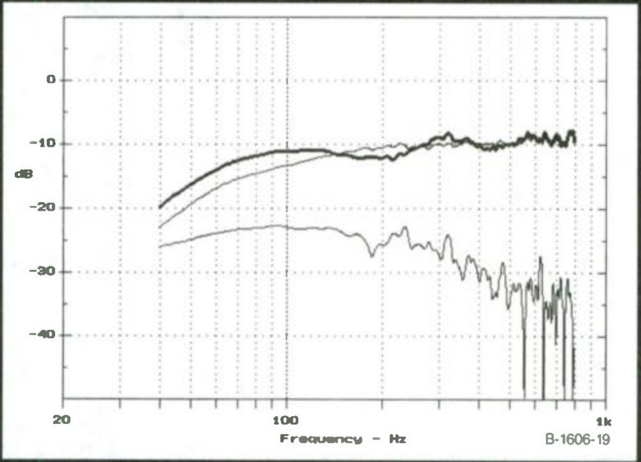

FIGURE 20: Vifa P17WJ on tapered test pipe: cone output, pipe output, and system response (bold).

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$V_P = 1.23ft^3$, and $f_P = 74Hz$. These figures seem reasonable. *Figure 19* shows the predicted response with 0.5 lb of Acousta-Stuf.

At this point, I was ready to construct and test the system, but Murphy's Law intervened. The cone resonance of my recently acquired P17WJ was closer to 50Hz than 37Hz. Even after a strenuous break-in period, f_S settled in at 48Hz.

This is not an unusual situation. To keep the Sales Department happy, a new loudspeaker prototype was built with a very floppy suspension and correspondingly low cone resonance. Once in production however, it became obvious that it needed a stiffer centering spider to keep the voice coil from rubbing and the cone from bottoming out. The infinite-baffle response is about the same, and the buyer is really getting a more rugged loudspeaker, right?

What the higher resonance implied was that Q_{TS} was actually about 0.4, and V_{AS} had decreased to $0.75ft^3$. If I had built a vented box for the P17WJ, I would have been very upset, but transmission lines are much more forgiving. In this case, the best-fit tapered alignment simply moved from (e) to (f). Pipe dimensions and passband performance were the same.

Figure 19 is a computer curve, but you can compare it directly with the measured response of *Fig. 20*. Below 500Hz, the system-response curves track within 0.5dB. The correspondence is even more impressive when I confess that I did not build the pipe described. Instead, I used one of my existing test pipes: f_P was 68Hz instead of 74Hz, V_P was 1.0 instead of $1.23ft^3$, and the taper was only 2.5:1.

SUMMARY

I restricted this project to a particular class of drivers on damped pipes, stuffed with tangled, fibrous material of uniform density. The damping is sufficient to control passband ripple, yet it allows useful reinforcement of cone output at low frequencies.

- With practical damping materials, the result is a nonresonant system, not a tuned pipe.
- For a pipe of given length, different materials require different packing densities to achieve desired damping. Once this is done, system performance is essentially the same for any of the materials tested.
- Pipe length establishes a usable range of cutoff frequencies, typically a one-octave band centered at f_P.
- Within that range, f_3 is controlled by driver parameters in relation to pipe length and volume. Damping remains unchanged.
- Systems can be scaled to any cutoff frequency and any practical efficiency by using simple alignment tables.
- In contrast to a basic cylindrical pipe, at least four alternate geometries allow lighter damping, which results in higher efficiency.
- Allowing for ±1dB passband ripple, optimized alignments approximate the response of an equal-volume closed box, but with reduced cone excursion.

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Reader Service #4

World Radio History

This author's hands-on approach to remodeling the Advent woofer provides us a deep inside look at this classic unit.

Refurbishing the Advent 10″ Woofer

By Tom Yeago

A friend approached me with some old Advents having the usual malady, i.e., foam rot. Fix it? "Sure, an easy little chore, happy to do it for the cost of materials," say I. Besides, I'd never really examined this important speaker, and this would satisfy my curiosity. So I pulled out the woofers, scoped out the box, and went to work. For an appreciation and diluted technical analysis, go to the sidebar. For the blow-by-blow, read on.

PHOTO 1 ◄: The Advent woofer with new surround and dust cap removed, ready for work to begin.

PHOTO 2 ►: The aluminum insert held in place with a foam plug. Arrayed to the rear are a doped dust cap, another doped dust cap with felt "donut" in place, and—barely visible because of the overexposure—another prepared aluminum strip.

In *Table 1*, you will see separate "stock" and "modified" line entries. From this you may rightly assume I was unable to restrain my impulses to modify. It's true that I've never encountered a woofer that didn't make me grouse and mutter, "Why in the world did they do *that*?"

I did manage to control myself here. None of the wholesale redesign suffered by the AR 12″ woofers (see "Rebuilding the AR-3*a*," *SB* 6/97 to 3/98) for these Advents. After all, they didn't belong to me. So the changes I made were modest, for simplicity's sake and also because I was reluctant to pull the cone and suspension out of the frame. We're talking low octane here, small and tentative steps down the wide and easy path that leads to wholesale modification.

STRUCTURAL CHANGES

First, I replaced the surrounds with new ones from a kit. I customarily give foam surrounds a couple of coats of black RTV silicone on both sides. This seals any leaks, adds to the structural integrity of the surround (which ought to help marginally with keeping the noise inside the box from leaking out through the surround), and presumably helps the surround resist whatever it is that causes foam rot. This means using RTV to glue the surround, but that's okay. I also caulked the underside of the masonite reducer ring and frame flange with DAP Alex Plus. Advent didn't do a very thorough job here, so I fixed it.

All my structural changes were made with the goal of stiffening the former-cone joint, and modestly stiffening the center of the cone. Henry Kloss went the porous-dust-cap route with this unit. That is, the dust cap serves no structural purpose but to bleed the pesky air-pressure buildup between it and the top of the pole piece (neglecting leakage from

TABLE 1
DATA AND CALCULATED PARAMETERS

	M_{ms}[1]	C_{ms}[2]	f_S	V_{AS}	R_e	Bl	Q_e
Stock	50g	1.4mm/N	19Hz	240 ltr	4.5–5Ω	6.7–7.5Tm	0.53–0.6
Modified	55g	1.4mm/N	18Hz	240 ltr	4.5–5Ω	8.3–8.6Tm	0.4–0.44

	Q_m[3]	Q_{ts}[4]	V_{box}	Q_{cb}	f_{cb}	X_{MAX}	SENS.[5]
Stock	4.0	0.47–0.52	66 ltr	1.0–1.1	41Hz	±4mm	88–89dB
Modified	3.9	0.36–0.39	66 ltr	0.77–0.84	38Hz	±4mm	88.5–89.5dB

1. As noted in the text, I didn't disassemble and weigh the assembly. This is an educated guess, based on my experience with similar woofers.
2. As with my 3*a* project, I get this figure by weighting the cone and measuring deflection—not the usual procedure.
3. This is another educated guess, but Q_m isn't a critical factor.
4. This figure is calculated from formula, not measured, but it's much as I expected.
5. Assuming half-space radiation and that the amplifier sees the woofers as 5–5.5Ω loads.

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the inside of the box through the magnetic gap). I took pains to gently tease and cut the dust cap and flange free from the cone with minimal damage. See *Photo 1* for a look down the throat.

I think dust caps are an excellent opportunity to increase the structural integrity of the motor/cone joint. My idea was to use a stiff dust cap to add essentially another glue joint between the motor former and the cone. So I stiffened and sealed the dust cap by cleaning it with a pencil eraser and then working some epoxy into the fabric on the underside. Don't dope the flange, just the dome part, and concentrate on the periphery, since that's what counts here.

Apply two coats, and when the second coat is starting to set, press a "donut" of felt (2″ diameter, 1″ hole) onto the tacky epoxy. Don't put any epoxy on the felt; just let the tacky epoxy hold it to the underside of the dome. It's a good practice to cut this felt "donut" a little large, then trim it flush with the flange after this epoxy sets. I stiffened this felt with epoxy later. *Photo 2* shows a doped dust cap and one with a felt "donut" attached sitting on the masonite ring at the rear.

PHOTO 3: Insert glued in place. Also visible are the tabs bent in at the rim, and two of the four vent holes.

THE MOTOR FORMER

I next turned my attention to the motor former. On this woofer, it's made of a cuprous alloy (phosphor bronze?) and is unusually long. I've never seen another woofer with so much former showing between the suspension and the cone/former joint. I wished to beef this up and extend it forward: beef it up so I could file venting holes in it, and extend it so as to glue it to the underside of the stiffened dust cap. I did this using a strip of aluminum from a soda can, which I scrubbed free of ink using isopropyl alcohol and Bon Ami.

First trim the strip so it fits snugly against the inside of the former with a gap of about 2mm. Start with a strip 4.77″ long by 1.25″ wide. To hold this snug against the Advent former as you fit it, use a foam plug as in *Photo 2*, or,

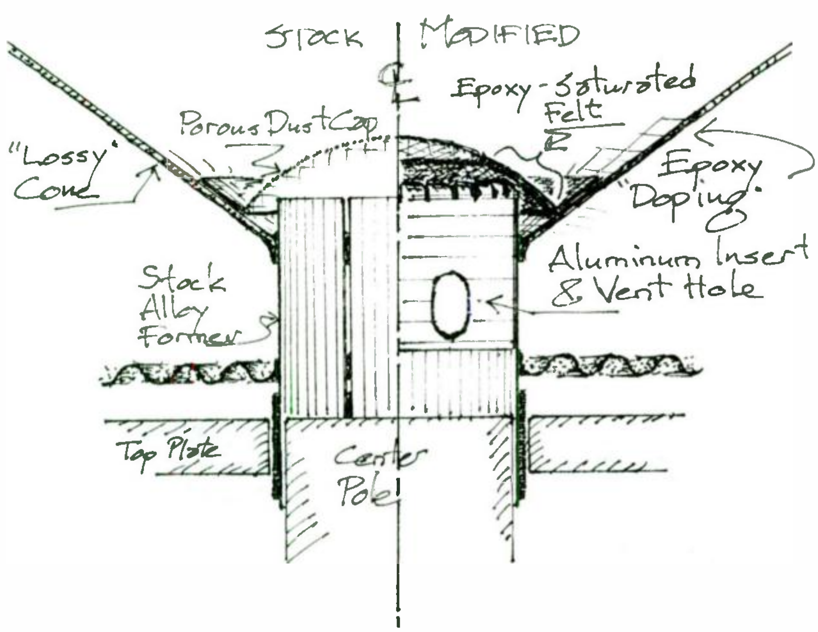

FIGURE 1: Before and after, all in one figure. The idea is to drive the cone through the beefed-up dust cap as well as the former/cone joint. Stiffening the central cone area by doping it with epoxy adds yet more rigidity. Not as good as a 3″ motor, but it sure beats the stock arrangement for strength, with only a 5g penalty. The dust cap is sealed with coats of epoxy, making necessary the oblong vent holes.

SECOND-GUESSING HENRY KLOSS

Advent was Henry Kloss' third company, and looking back, it's clear the Advent loudspeaker's direct ancestors were the KLH 6 and AR-2. I didn't even trace out the crossover, so I can't comment on the design in its entirety. But I know the woofer pretty well now, and some of the decisions Mr. Kloss made are interesting, even instructive.

First, some context: Mr. Kloss had been there at the beginning of AR and carried on with more high-value air suspension designs at KLH. He's reported to dislike three-way speakers as needlessly complicated, so it should surprise no one that the first, and for years, only product of his new company was a two-way air suspension loudspeaker whose chief calling card was great bass for the money.

Today it's interesting to note that Mr. Kloss maintained at the time (the early '70s) that it just didn't make sense to build a more expensive speaker. He advised customers who insisted on spending more to buy another pair of Advents and stack them up, tweeter-to-tweeter. Anticipating D'Appolito and Dunlavy? Maybe. After all, this is the same guy who prodded Ray Dolby into devising a simplified noise-reduction circuit for consumer use (Dolby B) and otherwise made the cassette a viable, pretty-hi-fi format.

His successor and long-time associate, Andy Kotsatos, produced a bi-amped loudspeaker (the Powered Advent) long before anyone else considered that a rational approach. Henry Kloss has a long history of being ahead of his time, and he's still knocking around, kicking ideas to see what precipitates.

ADVENT DETAILS

But I digress. The Advent loudspeaker is a two-way design with a 10″ woofer mounted in a 12″ frame and mated to a big, sealed, stuffed box. The tweeter's one of those neither-fish-nor-fowl deals with a 0.75″ motor driving a hard-paper-dome and curvilinear cone that sweeps back to attach rigidly to the frame. The diameter of the moving surface is 1 to 2″, depending on where it flexes, which depends on frequency.

Why mount the woofer in an oversize frame? At first I thought maybe it was to accommodate the cone, which is unusually deep. I was half right. It also allows the use of a large-diameter, unusually compliant spider. This spider, or suspension, is slightly more compliant than the one AR used with their 12″

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woofer (1.4mm/N versus 1.3mm/N; typical). Also interesting is that this box is considerably larger than AR used with their 12″ woofer (55 ltr versus 40 ltr). Throw in the usual 20% fudge-factor to account for stuffing, and the woofer's looking at 66 ltr.

Now recall that the 10″ woofer will have a smaller V_{AS} (about 240 ltr), and you begin to see what Mr. Kloss was up to. Instead of a bigger woofer in a smaller box, where the pneumatic spring will push up the woofer's resonance considerably (from about 15Hz to about 45Hz in the 12″ ARs), he went the other way. He used a larger box and a smaller woofer, so the pneumatic component of the spring is considerably more compliant, barely above infinite-baffle territory. Resonance rises from about 19Hz to about 41Hz—just over double.

Mr. Kloss, like AR, seems to prefer a system Q of about 1.0. With his new loudspeaker, he outperformed the best AR had to offer by a handful of hertz, so it's no wonder he made such an impression on listeners. He had the extension, but AR had him beat when it came to output. An AR 12″ woofer can displace almost exactly twice as much as the Advent 10″ unit before the motors go nonlinear, giving the bigger woofer a 6dB advantage.

FURTHER WOOFER FEATURES

Other features of the woofer hark back to precedents. The cone itself is interesting. It's one of those thick felt jobs that were something of a Kloss specialty. But the angle is unusually steep; the included angle is about 105°, which gives a deeper, stronger cone than the approximately 120° that's typical. Another Kloss hallmark is the flat flange at the rim, where the surround attaches. Throw in the ribs to discourage bell modes, and you're looking at a stiff unit—which is exactly what's needed if you intend to use it well past 1kHz. Heavy? Sure. But that's an asset in a sealed-box design.

The only problem is the depth of the cone, which will lead to cavity effects; but I'm sure they did their homework there, too. Remember what I said about precedents? This cone looks very like the one in a KLH 6. The only real difference is the textile half-roll surround, which doesn't seem to deteriorate and probably contributes to a lower Q_m for that woofer.

Another very clever thing about this speaker is that Henry Kloss beat Dahlquist to the punch on the diffraction question. The frame for the grille cloth isn't a frame at all. It's a solid panel except for a small hole just big enough for the tweeter screen, and, of course, a bigger hole to match the woofer. This panel is attached with velcro to blocks that hold it flush with the front trim. The tweeter itself is designed to stand proud, protruding flush with the front of the grille panel. There you have it: diffraction control in the early '70s. But that's Henry Kloss' history: always thinking.

The Advent loudspeaker's an important, interesting, and in many ways remarkable example of intelligent speaker building. You could do worse for subwoofers. And since the going yard-sale price seems to be in the $40 range, it's hard to see how you could do much better for the buck. —TY

even better, lids from plastic 35mm film canisters shimmed out with about eight turns of masking tape.

Once you have the length right, cut the edge of the strip into little tabs about ⅛″ wide and about 2mm deep, with 1mm gaps between them, as shown in *Photos 2* and *3* and less clearly in *Fig. 1*. These tabs, thanks to the 1mm gaps, will bend inward to conform to the bottom of the now fortified dust cap, forming a strong joint when you eventually glue it all up.

Now fit for width, i.e., how far down into the stock former the addition will reach. It should go down as far as the point where the suspension (or spider) is attached, but no further. First, immobilize the cone by inserting some shims into the magnetic gap between the pole piece and former. Then insert the aluminum strip, held snugly against the stock former with a foam plug or plastic lids.

Bend those little tabs at the edge to about a 45° angle. Now press the aluminum addition to proper depth using the dust cap. The tabs will press against the felt on the cap, showing you have full contact. With a fine-point marker, put a dot on the aluminum addition through the gap in the stock former, just above the suspension joint. Now take everything apart and cut the strip to the width indicated by the dot.

PHOTO 4: Structural modifications complete. The cone has a good coat of epoxy at the apex, and the hard, nonporous dust cap is securely glued, making for a much stiffened assembly.

GLUING THE ADDITION

Now it's time to glue the former addition to the stock motor former. Clean and degrease it, then slip it into place, pressing it snug against the stock motor former with foam or film-canister lids. Then tamp the addition to proper depth, using the dust cap as before. I tried using epoxy for this joint, but it wouldn't take to the copper alloy. So I used a cyano-type "instant" glue, which actually is better for this application. It'll withstand 300°F plus, which is fine here, but more important, it's a thin glue, so capillary action pulls it down between the two pieces.

Apply glue around the top and through the former gap in the side. Let it set a couple of hours for good measure, then remove the foam or lids and dab a little glue on the joint at the bottom and through the aluminum's gap, again letting capillary action pull it up inside the joint. Replace the foam or lids, and let it set overnight.

TRAPPED AIR

Now address the problem of the air trapped in this chamber formed by the now impermeable dust cap, motor former, and pole piece. Drilling a hole the length of the pole would have helped, but that is a truly foolhardy undertaking with the cone still in place. Even I would not try that on my own speakers, which these weren't, so I contented myself with filing oblong holes (approximately ¼″ × ½″) using needle files.

This is a fairly ticklish operation. I filed four of these holes, starting them by twisting the tip of a round needle file against the former until it burrowed its way through. Then I slowly filed away

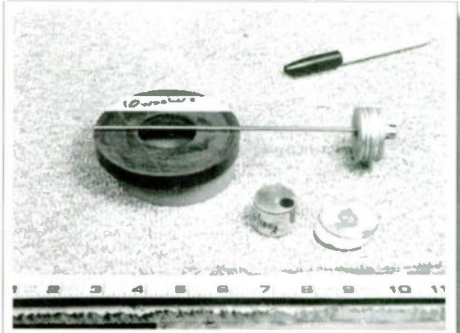

PHOTO 5: It looks silly, but this is how I determine the relative strength of same-size magnets. I just slide on the washers until the rod trips. See text.

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until I'd enlarged the vent holes to my intended dimensions. I also sealed off the magnetic gap with a piece of mortite, even though no ferrous metal is involved, so there's no danger of bits falling into the gap. It takes some patience to produce decent-looking holes without distorting the metal, so take your time.

When you're finished, clear out any debris using a vacuum nozzle and masking tape; then daub some instant glue on the edges of the holes, again taking advantage of capillary action to draw the adhesive in. *Photo 3* is a view down the bore at this stage. I blackened the aluminum with a "Sharpie" marker to help it radiate heat more efficiently; or that's the theory, anyway. Actually, I blackened pretty much everything I could get to. Couldn't hurt.

FINAL GLUING

For final gluing, I mixed up some epoxy and used it to dope the cone about halfway to the ribs—a purely arbitrary distance. Then I daubed some on the aluminum tabs, saturated the epoxy into the felt on the bottom of the dust cap, and then into the dust-cap flange. I carefully positioned the cap exactly where it belonged, with the motor-coil wires in their original grooves, and held it in place with a 2″-diameter can that fitted nicely into the crease.

As the epoxy became tacky, I began pressing the flange against the cone until it stayed tolerably flush. Later, I filled in any remaining gaps with more epoxy. *Photo 4* shows the completed woofer, looking completely stock except for the glossy patch at the cone's apex and the rubber-like appearance of the surround.

Finally, since the four new vent holes allow contamination of the gap with dust, motes of fiberglass, and other offensive particles, I cut some pieces of polyester batting into large rectangles and pasted them over the woofer-frame cutouts with DAP caulk. This should adequately keep debris at bay, along with the canvas lining Advent included in its boxes between the woofer and the fiberglass stuffing.

I generally weigh the cone assembly to determine moving mass (M_{ms}) but since I had never taken these units apart, I made an educated guess. I peg M_{ms} at about 50g, and figure the above changes added 5g at the very most. Not a bad tariff, considering the structural improvements.

MOTOR CHANGES

A pretty modest effort here, all things considered. See *Table 1* for the summary. Improvements in the Bl figure came entirely from adding backing (or bucking) magnets to the back plate to stifle flux leakage. From the Bl figures on the stock units, I decided to try bringing the two woofers into closer tolerance by applying more and stronger magnets to the weaker motor. It wasn't a complete success, but it brought the two units within about 5%, which is about ½dB, all things being equal.

PHOTO 6: Backsides of the two woofers, complete except for the filters pasted over the frame cutouts. Note the more extensive bucking magnet coverage on the right, used to equalize motor strength. And you thought *your* workbench was cluttered?

As a curiosity, *Photo 5* shows my method of determining the relative strength of two magnets of the same size. I lay a steel rod with a stop at its far end across the magnet, and keep adding weights (washers in this case) to the end of the rod until it pulls free. This particular magnet will support ten washers, but one more will trip it. This quaint little exercise yields only relative figures, and only for magnets with the same diameter and (to a lesser extent) hole size. But it's better than nothing.

Photo 6 shows the backsides of the two woofers, barely discernible against the clutter of the workbench. The woofer on the right has the stronger backing (or bucking) magnet, plus odd chunks I broke to cover more of the square back plate and, I hope, stifle more stray flux. For more on this technique, see "Tour de Magnetic Force," by Richard Pierce (*SB* 4/90, p. 68), and "Adjusting Woofers for High Performance," by Brian Smith (*SB* 6/89, p. 22).

Also in this photo, but barely visible, is the nylon twine saturated with glue (Titebond) that I wound into the crevice between the front plate of the magnet structure and the stamped frame—another marginal structural improvement.

END OF STORY

With a little fresh mortite and careful tightening of the four woodscrews, each woofer was back home. Another pair of veteran loudspeakers is returned to service. I figure they're good for at least another 20 years, or until something goes wrong with the tweeters, or the electrolytic crossover caps dry up.

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Reader Service #73

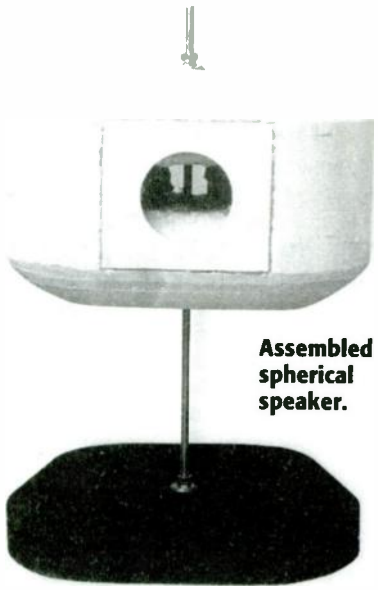
World Radio History

This article presents a new way of making loudspeaker cabinets of any desired shape. It can be used to minimize various problems that tend to plague speaker cabinets.

A Novel Cabinet Construction Method

By Justus V. Verhagen

In my experience, both planar-type and dynamic speakers have problems associated with the low-frequency part of the audio spectrum. The planars' bass (including such types as electrostats, magnetostats, and ribbons) seems too shallow to me and has several audible resonance modes (I own Apogee Duettas). They usually tend to bundle their higher-frequency energy, and require quite a large surface area (at the extreme are the multipanel Magnepans).



Assembled spherical speaker.

The dynamic systems (woofers) are usually installed in cabinets (although not necessarily so). That's where I think part of the trouble starts: diffraction, resonances (produced by the three pairs of usually parallel sides), and noise appearing through the cabinets' walls all contribute to degeneration of the quality of speaker performance.

DESIGN APPROACHES

My design addresses all three problems to a large extent, allowing you to design a woofer cabinet of the shape you wish, both inside and out, with few constraints. It is done by individually stacking cut plates of medium-density fiberboard (MDF).

Harry Olson[1] showed that in order to minimize diffraction where the sound wave interacts with the cabinets' shape, the cabinet should approach a spherical shape. Rion Dudley[2] came up with a novel solution for fabricating a cabinet of such shape. The egg-shaped cabinet's construction resembles the slices of an orange glued together. It seems to me, however, that this construction is somewhat problematic, since it requires special tools (especially a band saw), a high degree of accuracy, and may not allow for much freedom in the design. But it probably did solve the problem Olson pointed out.

Currently there is a commercial speaker designed by David Gallo that seems to have taken the diffraction into account. However, Gallo's speaker cabinets are aluminum spheres, which you should generally avoid because of their dominant radial-mode standing waves.[3]

You can make cabinet-enclosure resonances less audible by bracing or by using golden-ratio proportions or nonperpendicular shapes. This last is by no means easy, especially in combination with a rounded exterior. Also, by using thick, high-damping materials such as MDF, bitumen/asphalt plates, concrete, sand, aluminum sandwiches, and so on, builders have tried to make the cabinets more acoustically dead.

A NEW DESIGN

To my knowledge there are no designs published that take care of all three problems I have mentioned: diffraction, resonance, and through-the-wall-transmission. I believe the design I describe here does take care of the better part of these. Ever seen a 3-D puzzle? You stack plates of certain shapes on top of each other, thereby forming a face, or other shape. That's how this works, but you'll be its

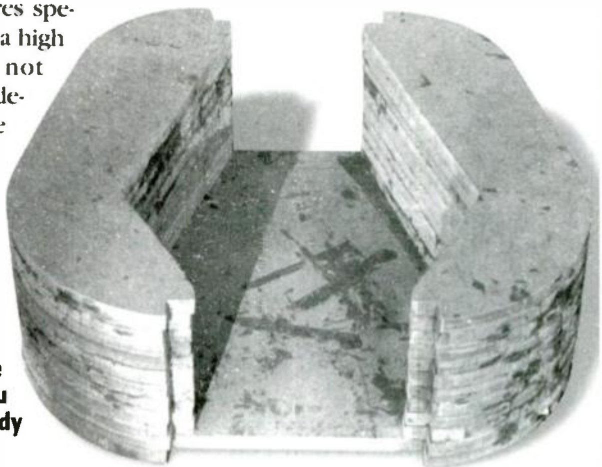


PHOTO 1: The side plates glued stackwise to the bottom plate (front, top view); make sure you have the front and back plate handy while gluing.

ABOUT THE AUTHOR

Justus Verhagen, 28, is Dutch and has been working on speakers since high school. He hopes to get his Ph.D. in neuroscience this year. He has made amplifier modifications, an active crossover, and several dynamic and planar-type speakers (including ribbons), but finds the planar ones less useful than dynamic speakers for low-frequency systems.

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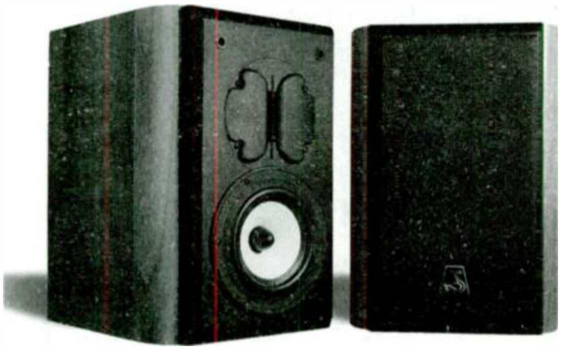
Swans M1 kit



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The step beyond the limits

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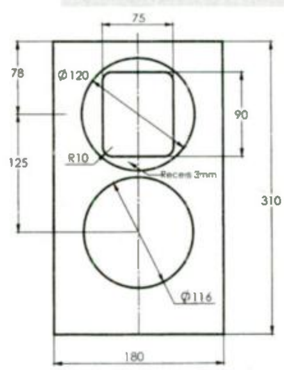
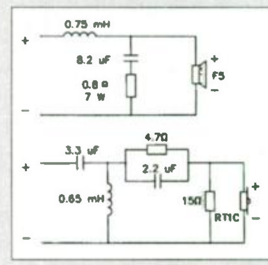
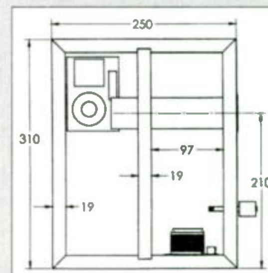
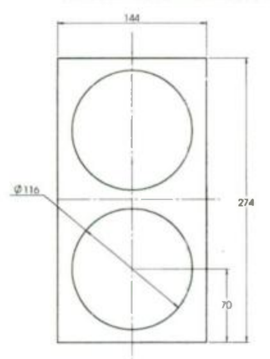


Front view





Right view of the cabinet with accessories(right side panel removed)



Internal panel

Great news from Swans!

New beautifully cabinets for Swans M1 kits are available in three finishes: piano black, solid walnut and rosewood veneer. Totally irresistible!

The Swans M1 speaker system is a two-way bass-reflex design. The front baffle is very narrow with rounded edges to reduce cabinet diffraction for better clarity and imaging. The internal panel and comer reinforcement substantially reduce unwanted cabinet vibrations. A flared port is mounted on the rear baffle for smooth transition from the port to cabinet boundaries. This provides linear bass performance and absence of port noise. The heavy-duty gold plated binding posts are mounted directly on the rear panel to enable easy cable connection.

The 5-inch paper/Kevlar cone woofer has a rubber surround, cast aluminum frame and a magnetically shielded motor system. This driver utilizes a central phase plug to avoid air compression, improving frequency response and dispersion. These key features greatly contribute to the M1 s clear transparent sound and effortless dynamic performance.

The tweeter is a high-tech planar isodynamic design that employs Neodymium magnets and extremely light Kapton film, with flat aluminum conductors.

This unit provides an immediate and precise response to any transients in original signal, and gives the M1 an exceptional ability to reveal the true dynamics of instruments with a complex high frequency spectrum.

The crossover is a second order Linkwitz-Riley type resulting in an in-phase connection of the drive units. The crossover frequency between the two drivers is 3.3 kHz and only high quality polypropylene capacitors are used. Each filter has it s own dedicated board mounted on a special rubber interface to reduce vibrations and microphonic phenomenon. The filter boards are spaced inside the loudspeaker with the inductors positioned at right angles to minimize the interaction.

Swans M1 kit includes:
- 2x F5 paper/Kevlar bass-midrange drivers,
- 2x RT1C isodynamic tweeters with sealing gaskets,
- 2x dedicated tweeter crossovers,
- 2x dedicated base-midrange crossovers,
- two flared ports,
- two pairs of heavy duty gold plated terminals.

The drawings of the cabinet shown here represent general dimensions required for optimum bass performance. Rounded corners are advisable as they improve imaging and clarity. Actual finish and appearance is a matter of personal taste

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Frequency response (1m,half space)	60Hz-35kHz,±2dB 55Hz-40kHz,-3dB
Sensitivity,1W/1m (100Hz-8kHz averaged)	86 dB
Nominal impedance (7.2 ohms minimum at 250 Hz)	8 ohms
Power handling	50W nominal, 90W music
Dimensions,HxWxD	310x180x250 mm

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Reader Service #89

World Radio History

designer: you control the outside and inside contours by cutting out each plate in whatever shape works for you.

I designed what I thought would be an acoustically favorable inside and outside shape for a Dynaudio 17W75ext speaker. I chose these woofers because I think of them as among the most uncolored-sounding speakers I know. (I'm a Dynaudio-freak and am especially impressed with their Geminis.) I also expected them to blend well with my projected ribbon speakers because of their well-known good transient behavior.

I decided on a closed cabinet, again for its good transient behavior. I needed the system's Q to be about 0.9–1, a compromise between bass response and impulse behavior. My design programs indicated a volume of about 1ft^3. To further improve the transient behavior, I decided to add a Dynaudio variovent (aperiodic damping), and I also added a simple R-C impedance-compensation network.

To minimize diffraction, I decided to make a spherical-like outside shape, and to reduce the chances of standing waves, I decided on nonparallel interior walls, except for the top and bottom. To reduce the noise radiating from the inside to the outside of the enclosure, I decided on a very thick cabinet (4–5″ on average). Finally, I designed this speaker to rest on an integrated, acoustically transparent, adjustable-height stand.

I must warn you that this project takes a lot of wood (hence becoming very heavy and somewhat pricey), and it takes a lot of cutting (this is the ultimate test of your jigsaw).

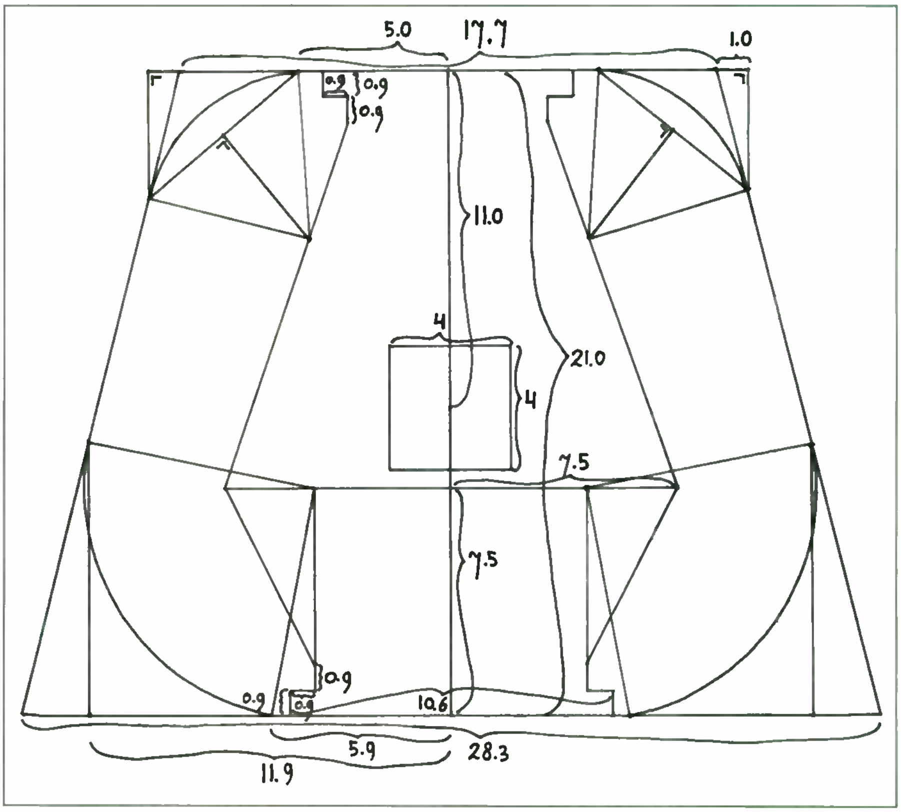

FIGURE 1: Top view and dimensions of the plates needed. Indicated are the outer roundings, the inner borders of the side plates, and the square to be cut out of the speaker stand's lowest two plates. Note how the centers of the circles that outline the roundings of the corners are defined.

CONSTRUCTION

The construction consists of making the cabinet, the integrated stand, and the front and back panels (to hold the woofer, variovent, and binding posts). In addition, you need to round off the top and bottom of the cabinet, smooth it, and mount the woofer, cables, variovent, binding post, and impedance network.

For two complete speakers, you will need to cut out 72 pieces. This requires a good jigsaw and a bunch of fast, sharp blades, which will make somewhat rough edges, but you'll see that accuracy is not critical at all with this project. *Table 1* is the parts list.

THE CABINET

These instructions are for one cabinet only. Each consists basically of an approximately cylindrical body with rounded top and bottom. Start by cutting out a base plate, as shown in *Photo 1*, 20 side plates, and one top plate (¾″ thick; see

TABLE 1
PARTS LIST FOR ONE SPEAKER CABINET

ITEM	NUMBER NEEDED PER SPEAKER	TOTAL COST
4′ × 8′ MDF, ¾″ thick	4	$60
Dynaudio 17W75ext 4Ω	1	$100
Dynaudio variovent	1	$5
15μF polypropylene capacitor	1	$5
10Ω resistor 10W	2	$1
Elmer's wood glue	1 gallon	$10
Binding posts, damping materials	2	$10
Cardboard sheets for drawings	4	$2
½″-thick, threaded iron rods 2′ long; washers and nuts	1, 4, and 8, respectively	$6
Silicone caulk	1 tube	$3
Primer, paint		
P.U. foam, wood putty	1 can, 1 pint, respectively	$3
½″ wood drill; ¾″ wood drill		
		$200 per speaker

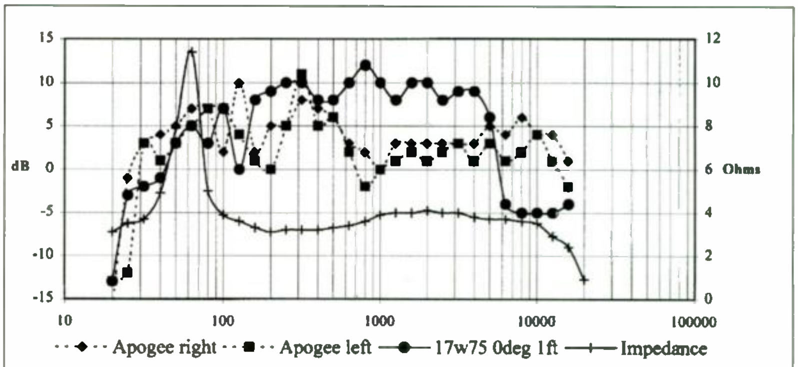

FIGURE 2: SPL plot of my Apogee Duetta IIs (20° off-axis; dotted lines) and the mounted Dynaudio speaker (on-axis; solid line with solid circles). Note the consistency between the two Apogee measurements. The impedance of the Dynaudio is also plotted (plus symbols); in-room measurements.

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Table 1). *Figure 1* shows the dimensions of the plates. Because of the repetitiveness, I drew the shapes on cardboard, cut them out, and used them as templates to trace the shapes on the wood. Then, when cutting, you don't need to be very accurate; just follow the tracings.

I did this over several days, since it's quite fatiguing. I found that vibration control on my jigsaw, together with a slightly angling "bite" at each cutting-cycle (here the lower part of the blade moves slightly forward) hastened the work a lot. Note that both the front and back of each plate is notched where the back and front plates will be fitted and glued. Lightly sand the plates and dust them off.

Spread an even, thin coat of (Elmer's) wood glue on two of the side plates and carefully place them on the base. Stack all of the remaining plates using a little glue in between them (the glue should hardly ooze from between the plates). This amounts to ten plates on each side of the cabinet. Do not yet glue the top plate on the top side plates, just place it there. Put something really heavy on top of the top plate.

The side plates have a tendency to move a bit, so keep track of the front and back notches and the inner alignment by using a set square or other rigid L-shaped object; the plates should be reasonably well lined up. Make sure the front and back plates will fit. After about half an hour, the plates will become immobile. I found this stacking and gluing the most stressful and critical part of the whole process, so be well prepared. *[Perhaps two short finishing nails would stabilize each added plate. – Ed.]*

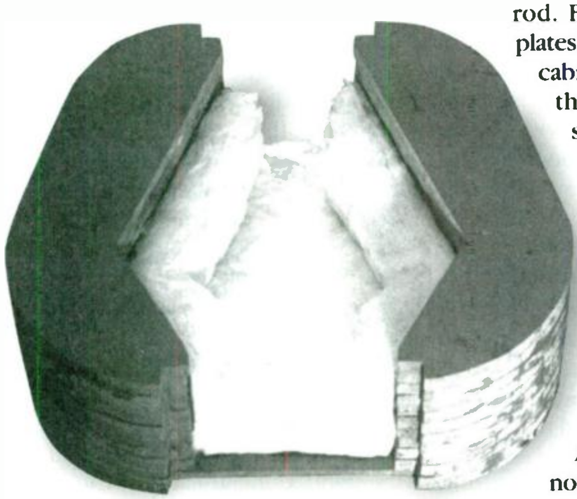

PHOTO 2: Lining the bottom and sides with fiberglass. Keep the path between front and back open.

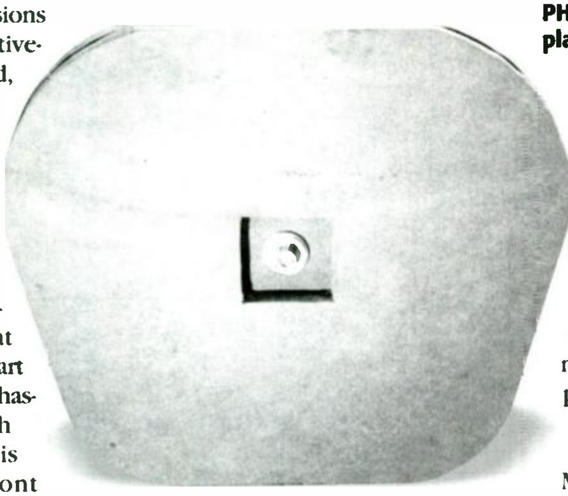

PHOTO 3: Underside of the stand's bottom plate. Note the two nuts and washers.

After an overnight drying period, line the speaker with acoustically absorbent material (*Photo 2*). Fill the cabinet to about 50–75%, keeping the path between woofer and variovent unobstructed. Note, by the way, that the opposite inner sides of the speaker are not parallel. Start with cutting out the material (I used fiberglass) for the top and bottom. Cut some away to leave enough breathing space for the woofer.

Now put a lot of hot glue on the bottom plate and press the fiberglass against it. Next cut and glue fiberglass for the sides, leaving space for the top layer of fiberglass. Finally, glue the top plate to the rest of the cabinet overnight and attach the fiberglass (cut some of it away from the woofer location). The total volume of the cabinet is 0.9ft^3 (25 ltr) before adding the damping material.

THE STAND

The stand consists of a base plate to which you screw a thick, threaded iron rod. For this base plate, cut out four plates of the same shape and size as the cabinet's top and bottom plate. From the two lowest of these, cut out a square piece about 4″ × 4″ to allow for the nuts and rod (see *Photo 3* and *Fig. 1* for the location). Sand and glue the plates and let them dry overnight. Then prime and paint. Firmly attach the bar to the base plate using large washers and two nuts on each side (*Photo 4*).

ROUNDING UP

At this point, your "cylinder" does not exactly appear rounded, so next you'll cut out the plates necessary for making the cabinet more so. You add four plates of decreasing size to the top, and four to the bottom. These also constitute the top and bottom panels (which *do* happen to be parallel) and make them much thicker.

First, cut out cardboard templates that are 0.35, 1.06, 2.12, and 3.54 inches smaller than the top and bottom plates, allowing you to trace them onto the MDF. Note, however, that none of these plates have the notches cut out for the front and back plates: they will enclose those plates at the top and bottom (*Photo 5*, right side). Next, for each size, saw two MDF plates, one for the top and one for the bottom. After you've cut and sanded all eight plates, stack the smaller ones on top of the larger ones with a little glue in between (*Photo 5*). I did one side a day.

Now you need to drill a ¾″ hole through the top and bottom plates of the cabinet for the stand's rod to pass through (*Photo 4* and *Fig. 1*). Make sure this hole is quite a bit larger than the diameter of the rod of the stand. I decided the location (front-back) by placing the cabinet on the bar in horizontal position and getting a sense for the mid-point of

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its mass. (This is the basis for the 11″ distance in *Fig. 1*.)

Because of the heavy weight of the speaker, which I'm sure you've noticed by now, this step is quite crucial. Mark the sides of the cabinet, and drill as perpendicularly as you can. Remove woodchips and dust from the cabinet.

FRONT AND BACK PLATES

The front plate will hold the woofer and the backplate the variovent and binding posts. Cut out the front (10¼″ × 9 1/32″) and back (9 × 7⅞″) plates. In the center of the front plate cut out a circular hole with a diameter of 5 19/32″ (radius = 2 13/16″). In the center of the back plate cut one with a diameter of 4 13/32″.

Drill the holes for the screws that will clamp your woofer to the front plate, and drill those for the binding posts (I prefer the simple bolt-type); now would be a good time to mount them on the back plate. Make sure that the variovent fits well in the back plate; if not, sand away the obstacles.

Now mount the front and back plates with silicone caulk. The advantages are that with silicone the contact areas do not need to be smooth (hence you don't need to work very accurately), and it will decouple the woofer from the cabinet to some extent, with positive acoustical effects.

With the cabinet lying on its back, deposit two lines of silicone next to each other on the MDF that will hold the front plate (the edge that is now horizontal). Put another line on top and in the middle of the other two. Lay the plate on the silicone, but do not push. Next, fill all gaps with silicone until everything is flush. Mount the back plate in the same manner after the front has hardened overnight.

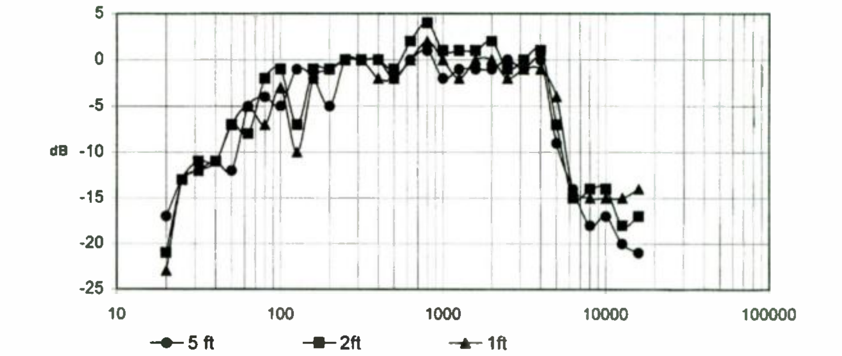

FIGURE 3: Shows little effect of distance (between the Dynaudio speaker and the back wall) on the frequency response (on-axis); note dip at 126Hz; in-room measurements.

PHOTO 4: Frontal view of the unpainted speaker on its stand. The stand's rod penetrating the top and bottom of the cabinet is clearly visible. The front plate has been mounted. On another stand, the cabinet can easily be mounted in a 90° rotated fashion, as well.

SMOOTHING THE CABINET

For this step you'd best mount the cabinet on the stand since you'll need to reach all around. It's advisable to have someone help you lift the cabinet. Make sure not to lift it by the holes in the front and back plates.

As you see, there's quite a bit of space to be filled for the cabinet to be rounded. If you have a cost-effective material for it, go right ahead and use it. Dick Crawford[4] used Sculptamold (plaster and papier-mâché; American Art Modeling Clay Co.) for his dome horn, which may be the best way to go. I simply bought two cans of polyurethane foam to start filling the large gaps, and three pints of wood putty to apply on top of the foam.

The foam is somewhat tricky to work with (it's very sticky). After applying the foam to the ridges of the top and base plates, cut away the surplus after it has hardened. I used a long sharp cook's knife for this (just rest it on the two edges of the plates you wish to smooth off, and cut away any foam that sticks out). Fill in the holes with wood putty (several layers will be needed). After all has dried, sand the cabinet with rough paper and apply a primer. Next, paint as you wish.

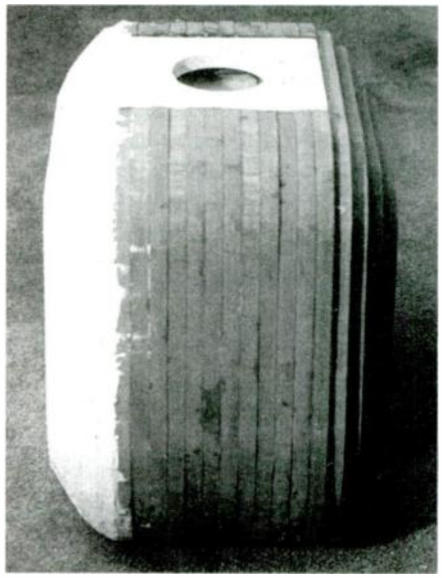

PHOTO 5: Side/bottom view of a nearly finished cabinet. Only the top plates' gaps have been filled with P.U. foam and wood putty. The back plate has been mounted.

FINAL ASSEMBLY

Mount the woofer to the front plate after connecting it with speaker cable. After mounting the binding posts, put the resistor—in series with the capacitor—parallel over the two binding posts. These will smooth out the impedance rise at higher frequencies (2kHz and up for the 4Ω version [5Ω and 15μF], 500Hz and up for the 8Ω version [7Ω and 20μF]), but may be over the top, depending on your crossover.

Finally, mount the variovent and add some silicone if there are leaks. To prevent other air leaks, add cut-out rubber-sheet rings in between the washers and nuts of the stand. Congratulations; you're finished with one of them! If you wish, you can add wheels to the stand, which greatly improves maneuverability.

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IS IT WORTH THE TROUBLE?

I think these units sound very good. They were designed to blend well with the ribbons, and they sound very neutral. I also listened to them positioned behind the woofer of the Apogee Duetta II. The Dynaudios covered the spectrum below 500Hz, and the Apogee ribbons the rest.

The largest apparent difference may derive from the monopolar character of these woofers as compared to the dipolar of the ribbons (a different "spaciousness"). The bass was very tight and certainly deep enough for me. Of course this setup does not do justice to the cabinets' shape, but it's all I can do for now.

Figure 2 shows the in-room responses of both my Apogee Dueta IIs and the Dynaudio speaker. I located the Apogees in their normal listening position (2.5′ from the back wall; 1′ from a side wall [right speaker only]). The Dynaudio I placed 1′ from the back wall. The measuring mike (a Radio Shack analog SPL meter with responses corrected for its sensitivity) was placed at a distance of 10′ (1′ from my normal listening position), and the test tones were ⅓-octave pink noise. The units (all 4Ω) were driven by 2V.

My active crossover (at 500Hz) obviously pumped a bit more lows than highs (relevant for Apogees only). The sensitivity of the Dynaudio is 86dB/W/m at 315Hz. The Dynaudio's −3dB points are at approximately 60Hz and 4kHz, close to what Dynaudio published for this unit in a 0.5ft^3 closed cabinet. There's a gradual 6dB/octave falloff below 80–100Hz, and a steep one (30dB/octave) above 4kHz.

I designed this system to have a total system Q of 0.9 to 1.0, but it seems smoother than that, which may be due to the variovent. There are clear troughs in the 100–300Hz region. Since these measurements were not done in the open-field, these troughs are to be expected (fluctuations of 10–15dB are quite normal for indoor measurements). These troughs likely have to do with my room acoustics, and may need some work. The impedance peaks at around 60Hz (11Ω) and otherwise fluctuates smoothly around 3–4Ω.

Figure 3 shows the effect of distance to the back wall on the Dynaudio's frequency response. As you can see, the differences tend to be small. At both 1′ and 2′ the response at 50Hz is about 5dB higher than that at 5′. The dip at around 126Hz tends to increase with decreasing distance. Overall, as far as I have determined, these units do not seem very position-critical. Not shown in *Fig. 3* is that measuring 25° off-axis decreased amplitude only from about 4kHz onward.

FINAL SUGGESTIONS

You can easily mount the cabinets while rotated 90° if you make another stand, so that now the cabinets' two holes through which the stand's bar passes lie in a horizontal plane. The advantage is the smaller cabinet width and vertical-axis adjustability. A disadvantage could be that the stand may have a larger influence on the sound. Experiment with it; I haven't yet. I'm curious to hear what you find.

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3. Martin Colloms, *High Performance Loudspeakers*, 4th ed., Pentech Press Limited, London, 1991.
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Reader Service #43

Product Review

ASC LOUDSPEAKER PARAMETER METER

Reviewed by Jesse W. Knight

Audio Specialties Company, 2230 East State St., Hermitage, PA 16148. Model ASC-588-B, $89.

The ASC 588 is probably the smallest tester (6″ × 2.75″ × 2.625″) for determining T/S parameters you are likely to see for some time. Powered by a 9V battery, it is very portable. Controls are minimal: a range switch for frequency, a frequency control, and a slide switch for selecting the function (Z or Hz) to be displayed on your digital meter. Ideally, you should use the tester with a meter that reads down to 0.1mV, but it will work with reduced accuracy with 1mV resolution meters. Its simplicity will appeal to the beginner and to the pro who prefers to travel lightly.

In the interest of keeping the price low, the signal generator in this unit is designed to produce a 16-step synthesized sine wave. This results in high-order harmonics that can cause errors in impedance readings when measuring drivers at high frequencies. Fortunately, the effects at frequencies used for T/S tests are small in general. The designer suggests using the tester to design the Zobel network and then do the T/S measurements.

Once the upper response of the driver has been leveled for impedance (Z) with a Zobel, the harmonics have little effect on Z readings. Limited tests suggest this is true. One fact is clear: Even if this precaution is not followed, the data obtained will be much better than a driver manufacturer's spec sheet. I did extensive tests without zobels on a Madisound 10207 DVC woofer, Focal 4V3211 and Vifa D75MX-31-08 midranges, and a Peerless 811815 tweeter.

If you are working with large woofers with an Fs below 20Hz (as I do), you will not be able to measure F low or F res.

PHOTO 1: ASC Loudspeaker Parameter Meter.

With woofers with an Fs of 20Hz or more, you can calculate F low without measuring it and obtain reasonable results. If you choose to measure box quality, frequencies will be higher. However, this is not a problem, since most people are working with 8″ and smaller woofers with higher free air resonance. Large musical instrument speakers are stiff enough that you will not need to measure them at less than 20Hz.

ACCURACY

I spent most of my review time designing a switching circuit that would allow rapid switching between the ASC tester and my test bench. Impedance measurement in the presence of strong radio signals is not a simple matter. In this regard, the ASC is more immune to interference than my bench because it can be used without any connection to AC power. For the novice, this gain in stability offsets errors due to the 16-step waveform.

Frequency readings were very accurate (1%), and I soon concentrated on the impedance readings. With care, I obtained an accuracy of 3% without undue difficulty in the T/S frequency range with Zobelled woofers, mids, and tweeters. Removing the Zobel caused the F high to read about 5 to 6% high in impedance. This would not harm the design of air-suspension systems and thus is not a

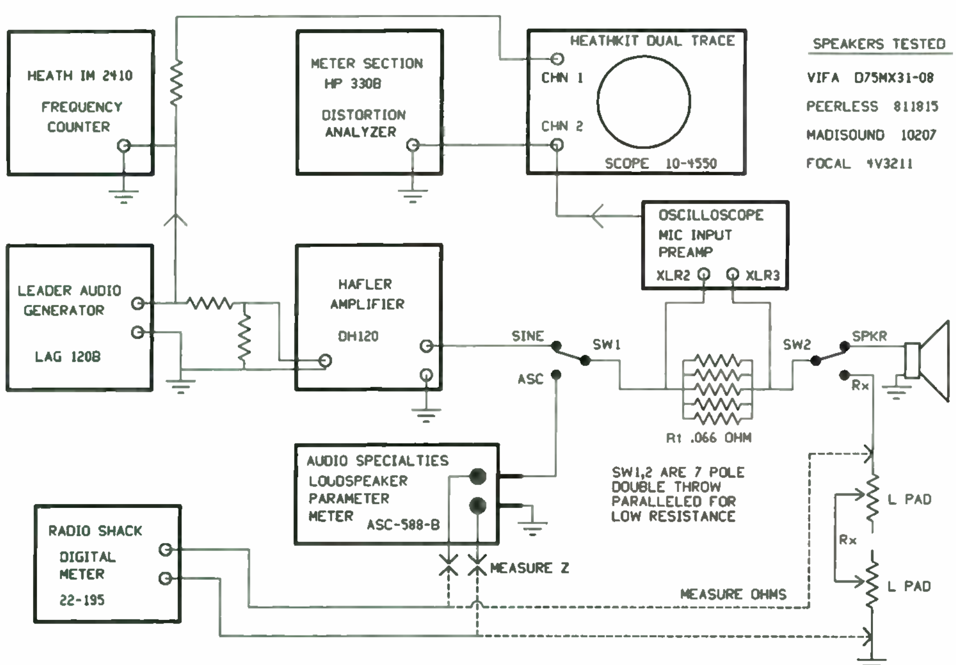

FIGURE 1: Test setup.

B-1631-1

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TEST SETUP

Step 1. Set signal generator and ASC to the same frequency using the frequency counter and oscilloscope as verification. Set SW2 to SPKR and SW1 to ASC.

Step 2. Set output of DH-120 amplifier to match the current output level of the ASC as defined by the HP 330B RMS meter. Only the meter section is used in this test. SW1 is switched many times to be sure levels are matched. Occasionally the scope should be used to check the frequency match of the ASC and LAG 120 generator, but the ASC is never off by more than 1% in frequency, so an occasional check is all that is needed. The strong harmonics confuse the frequency counter if it is connected to the ASC.

Step 3. With SW1 on "sine," adjust RX so the HP meter does not change when SW2 is switched between SPKR and RX. RX is now the same resistance and impedance as the speaker.

Step 4. Set SW1 to ASC and SW2 to SPKR and use ASC per ASC instructions. Record Z reading.

Step 5. Measure RX while SW2 is set to SPKR and record reading in ohms.

Step 6. Compare readings. Error is the difference.

This test procedure is self-calibrating: Error in the VTVM cancels out as we are only using it to compare voltage drops across R1. R1 is not critical, as it is also common to all tests.

SW1 and 2 are made up of parallel sections of two seven-pole rotary switches for low resistance. Single contact pairs are not to be trusted. The ohmmeter is checked with 1% resistors. The sine signal is very clean, 0.07% THD max.

Errors from the transformer are much smaller than those caused by radio interference that results from putting R1 in the ground line. At worse, this could result in a slight change in actual level as SW1 is switched. SW1 is not switched while adjusting RX so the only concern is parameter shift in the speaker because of a small level shift. This is unlikely to be significant. Phase was not used in these tests.—JK

concern for the beginner. I think that by the time you are ready to do a ported system, you will not have any problem with designing the Zobel first.

The key to good results is to change the frequency setting very slowly when finding points of maximum and minimum impedance. A digital meter has a longer settling time than analog meters. In the past I have always relied on the instant response of an oscilloscope, which also gives you phase information leading to greater accuracy than any meter-based measurements, provided you include interference traps. Otherwise, the trace can be so fuzzy as to be unreadable. Poorly designed traps will reduce accuracy. Scope techniques are thus quite fallible at times.

MEASURING CAPACITORS AND INDUCTORS

When testing capacitors and inductors it is best to use the resonant frequency method. I like to have one inductor of around 1 to 5mH to use as a reference. Ideally this would be an air core unit with a 1% accuracy. From this a standard capacitor can be measured by finding its resonance with the inductor. To avoid confusion from small false peaks that result from the tester, start at a frequency well above the predicted resonance and work downward in frequency. The first impedance peak will be the real one. It is not hard to achieve 2% accuracy.

CONCLUSION

Many fieldwork situations require an easy-to-set-up speaker tester. For example, if you need to know the impedance of a complex speaker array that has a transformer in the line, how do you know if a low-resistance ohmmeter reading is the transformer or a short? The ASC will quickly answer this question.

We are entering a time when many speaker builders may not buy an oscilloscope and signal generator right away. Many may share my belief that time spent trying to build amplifiers and preamps is time better spent on speakers, considering that amplifiers are seldom the weak link today and cost as much to build in many cases as to buy. Speakers keep me as busy as I care to be. In this light, the ASC tester is a nice addition to a basic tool kit.

Manufacturer's response:

The LPM is available in kit form ($89—postal money order) by writing to Audio Specialties. Please look for Martin Sound Products advertisement to purchase an assembled and tested instrument. I know the LPM will increase your ability to design and build excellent speakers by providing the necessary electronics affordably.

Jim Mitchell
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Reader Service #90

World Radio History

SB *Mailbox*

ESOTERIC WALLFLOWER

The end of the century has brought forth a very interesting set of articles in *SB* about the TL as well as lively discussions in *SB* Mailbox. I would like to add to this cornucopia with a mention of the work of Bernd Timmermanns, formerly of the magazine *Klang & Ton* and now of *Hobbie HIFI*, where he has published two SOTA designs using Helmholtz cavities to control the TL's low-frequency response.

Closer to home is the interesting letter from G.L. Augspurger (*SB* 8/99, p. 52), with an indication of a series of articles to come (*SB* 2/00–4/00). The TL has been an esoteric wallflower, and I hope that this notoriety does not do it in. However, my interest is in the data shown in Fig. 1 (p. 52), and the following points that G. L. Augspurger develops.

The frequency response shown by Bailey himself in "A Non-Resonant Loudspeaker Enclosure Design" (*Wireless World*, October 1965, p. 4, Fig. 9) is very different from the figure that is given by Mr. Augspurger. What is not apparent in Fig. 1 is the low-frequency slope 30–10Hz, which illustrates very well the gain of the line at the line-resonant frequency of 30Hz. Thus the implication, as I read it, that Fig. 1 is representative of the TL's response is misleading.

The TL's optimized response would be defined by response at 30Hz and below. The response 60Hz and above would be primarily defined by the drivers' T/S response as loaded by the TL's line loading and not by fiber effects. This leads to the apparent reliance on modeling data to define the TL's characteristics.

While Mr. Augspurger may have developed an excellent theoretical model, that has to be proven, and to quote Richard P. Feynman, "the principle of science, the definition, almost, is the following: The test of all knowledge is experiment." Thus instead of giving us the results of a simulation, Mr. Augspurger should have given us a measured response and compared it to the simulation of Fig. 1.

The second point concerns his statement, "In terms of sound speed, it also turns out that there is no magic stuffing material for transmission lines...Once packing density has been set for acceptable passband ripple, sound speed pretty much takes care of itself." What I find very nebulous about this principle is the question it raises: What, then, is the definition of an optimum design for the TL? This in my opinion is the crucial question, and a clear definition is required. If this is not to be a subjective opinion, then Mr. Augspurger must provide a definitive answer that needs to pass the scrutiny of experimental data.

E. Jakulis
Avon, MA

G.L. Augspurger responds:

Most of Mr. Jakulis' concerns are addressed in my transmission-line article, which includes tables of 18 practical system alignments. There will be plenty of time for discussion after publication. However, the issue of computer simulation versus measured response deserves clarification.

As I stated, the computer curves were based on measurements made by Geoffrey Letts. A copy of Letts' thesis was made available to me through the courtesy of Dr. Richard Small (yes, *the* Richard Small). As part of an exhaustive examination of transmission-line behavior, Letts tested several commercial systems, one of which was Bailey's 1972 design as furnished in kit form.

This was a folded, tapered pipe in which the taper was approximated by three linear sections. Pipe length was about 8′, and internal volume was about 3.25ft^3. The pipe was stuffed with 3 lb of "Wonder Wool," a long-fiber nylon product. The line was driven by a KEF B139 woofer.

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Letts measured cone output, pipe output, and combined system response simultaneously using two nearfield microphones. His results are probably accurate up to 200Hz or so. Moreover, he made tests with two different stuffing densities as well as with no stuffing. As a result, I was able to compare my computer analog with measured performance for three different test conditions.

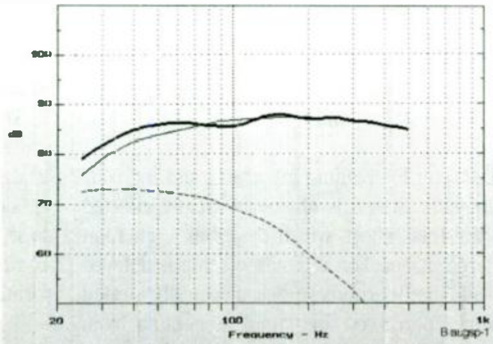

FIGURE 1: Computer simulation used for sound-speed comparisons.

Figure 1 is the basis for my earlier sound-speed comparison. This computer simulation is fairly close to measured response. It uses characteristics of known stuffing materials as derived from my own tests. Relative sound speed through the pipe is set at 0.8 independent of frequency. The graph shows cone output, pipe output, and combined system response (bold).

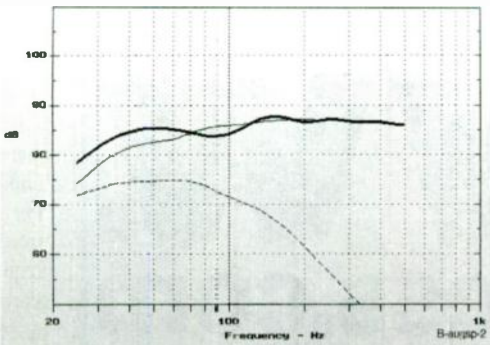

FIGURE 2: Improved analog derived from Letts' data and tests.

Figure 2 shows a more careful attempt to replicate Letts' test results, yet without assigning unrealistic damping characteristics to Wonder Wool. Pipe attenuation above 50Hz is steeper than with polyester or fiberglass. Also, the simulation varies relative sound speed from 0.6 at 20Hz to 0.8 at 200Hz.

From 30 to 200Hz the computer simulation closely matches measured cone output, pipe output, and system response. However, Letts' curves show pipe output to be about 2dB higher in the 50Hz region and system response to dip about 1dB lower at 90Hz. These discrepancies are not surprising. In contrast to idealized computer curves, real-world stuffing materials always generate somewhat lumpy and unpredictable response curves.

Mr. Jakulis is interested in the difference between cone output and system response (pipe gain) at frequencies below cutoff. Below 35Hz my computer simulation is overly optimistic. Letts' curves indicate more rapid low-frequency rolloff, with only 2dB of pipe gain at 20Hz. The computer analog predicts 4dB at this frequency.

To be truly nonresonant, this system obviously needs more damping. Passband ripple is excessive and pipe resonances are apparent in both cone output and pipe output. If enough stuffing is added to keep passband ripple within ±1dB, then the computer analog predicts that maximum pipe gain will be around 3dB, which agrees with my own tests of damped, tapered pipes.

CRUISIN'

Kudos to Mr. Raczynski on his "Auto Passenger Space As a Listening Room" article (*SB* 1/00, p. 20).

I work in the auto-sound industry, and we have innumerable discussions of this type, though generally without the complex math. Let me also mention that some of us are actually interested in the quality of the sound, not merely the quantity!

While the modeling in the article does address the issue of speaker location, consider the following. The single largest problem with auto sound is speaker location, the second being the variety of absorptive and reflective materials and surfaces. Since we have limited control—within most budgets, that is—over the materials and layout of the interior, I will address speaker location.

Most OEM speaker locations produce unequal path lengths. This is due to the proximity of the speaker locations and the fact that passengers rarely sit in the middle of the car, equidistant from the left and right speakers. The resulting unequal arrival times inhibit our brains from re-creating the stereo image on the recording. The starting point is equalization of the path lengths. While equal left and right paths are nearly impossible, alternate speaker locations can even things up greatly over the stock-type locations.

Probably the most popular location over the last several years is the kick-

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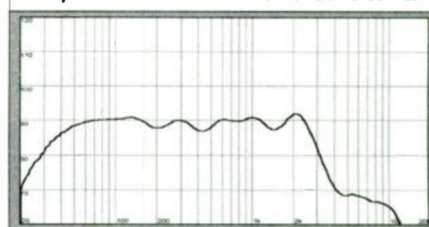
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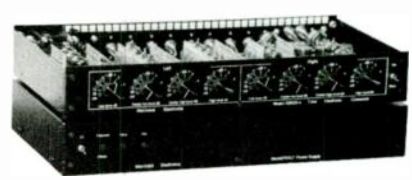
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panel or the immediate surrounding area. While this is not the panacea that some believe it to be, it does provide a solid base from which to start.

While my suggestions may seem oversimplified, they can yield great results in a timely fashion. My last installation of kick-panel-mounted speakers in my own vehicle took about one hour, with a couple of additional hours of tweaking to suit my taste. The foundation provided by the alternate speaker locations removed one of the most basic obstacles in auto sound.

A sincere thanks for the fine periodical!

Jeff Triplett
Technical Services Manager
Memphis Car Audio

Mr. Raczynski responds:

Thank you for reading my article and for your comments. Stereo is obviously greatly affected by the Haas Effect, which describes a situation where one speaker in a stereo setup is delayed by 5–25 milliseconds so that a centrally located listener perceives the sound as coming from the undelayed speaker. The delayed speaker needs to have its level increased by 8–10dB in order to return the "sound image" to its central position. The same effect is produced when the listener sits closer to one of the speakers, which is the situation most often encountered in car audio.

The kick-panel location has been used because it seems to minimize the path difference or delay, from the left and right front-mounted speakers to the driver's position in many cars, so it may be seen as preferable for the frequency range which carries stereophonic/imaging information (e.g., above 200–300Hz).

To improve imaging, companies such as Chrysler, Nissan, Mercedes, and Saab adopted a center-channel loudspeaker located in the dashboard close to the rear-view mirror. The speaker, which is fed L+R signals, typically is a midrange/tweeter, since this is the frequency range that most affects the imaging. Now each front-seat passenger gets his/her own center image.

My article is concerned with the lowest end of frequency range (e.g., below 200Hz). Low-frequency source tends to be nearly impossible to pinpoint because there is a little difference in either phase (delay) or intensity for the hearing process to pick up. Also, you can add the low-frequency content of left and right channels and reproduce them through one speaker with no (or very little) loss of stereo image. The whole concept of the subwoofer-satellite system is based on this phenomenon. The lower the frequency, the less phase difference is produced due to the different path lengths from speakers in the car cabin.

I will skip the numerical examples of the above for the sake of emphasizing that, for the low end of the audio range, self-resonance of the passenger compartment will play a dominant role in the sound-pressure distribution within the compartment. The aim of the article is therefore to provide a somewhat simplified view of this problem using available FEM techniques.

I chose the location of sound sources and microphones only as examples, and they are far from being optimal for the FEM mesh (e.g., car) used in my example.

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amp does not afford the good damping required in a ported speaker. The air spring of a closed box does a much better job of this. Although the port action itself is supposed to accomplish speaker damping, it seems that the amp has a share in this.

Some solid-state amps with little or no negative (loop) feedback may also qualify. Using amps with high damping factors, the vent(s) should be left open. However, since ported speaker drivers usually have shorter excursion capabilities, closing off the ports may not be recommended, if the bass driver is normally played at higher volumes.

Some amps with two sets of speaker switching allow four speakers to play at the same time. Most amps connect these sets in parallel, which retains good damping. Some, however, connect the sets in series, which destroys the amp's damping ability. In this case I've found that closing off the ports will improve the bass. To determine whether the amp connects in a series fashion, the speaker volumes will decrease when switched in as pairs.

Some speakers have two ports; in these cases, close both. Stuffing towels in the ports or taping the ports closed will not qualify. Use something solid that fits snugly.

Roger Floth
Waterloo, IA

Dick Pierce responds:

While it might seem like a good idea, and your reasons are sound, there are some misconceptions about what is "damping" and what is being "damped" in the speakers.

First, despite the prevalent myth to the contrary, higher output impedance of tube amplifiers does not change the damping of speaker systems in a significant way, with very few exceptions. Despite its pervasive use, "damping factor" really is anything but. The electrical damping of the woofer is dependent on the entire source resistance the voice coil experiences; that includes the amplifier, the speaker cables, the crossover components, and the voice coil itself.

Of all these, the amplifier's output impedance is among the most significant contributor to that series resistance. The largest contributor by far is the very DC resistance of the voice coil itself. Unless the output impedance of the amplifier starts to approach that of the voice-coil resistance, increased amplifier-output impedance will not materially affect damping.

In one sense, the so-called damping factor is a useful figure, but one that is somewhat misnamed. What the damping factor number tells you is not what the contribution of the amplifier to system damping is, but how much more important the voice-coil resistance is when compared to the amplifier. Another way to look at it is the higher the damping factor, the less the amplifier influences the damping of the system. An amplifier advertised as having a damping factor of 100 shows clearly that the voice-coil resistance is 100 times more significant in damping the speaker than the amplifier.

The amplifier's contribution to damping is less than 1% that of the voice coil. If it had a damping factor of 10,000, less than 0.01% of the damping would be contributed by the amplifier. Unfortunately, it may seem counterintuitive, but we've been led by advertising and marketing to believe that damping factor means something very different than what it really is.

Another incorrect assumption is that the port is "damping" the speaker. Damping is a very specific mechanism: it is the removal of energy from a resonant system so that it can no longer participate in the resonance. That is not what a port is doing. The port itself, along with the volume of air in the enclosure, makes up a resonant system of its own.

At the resonant frequency of the enclosure/port system, the load provided to the driver is such that the driver can very easily couple energy to it. At that point, the port takes over the

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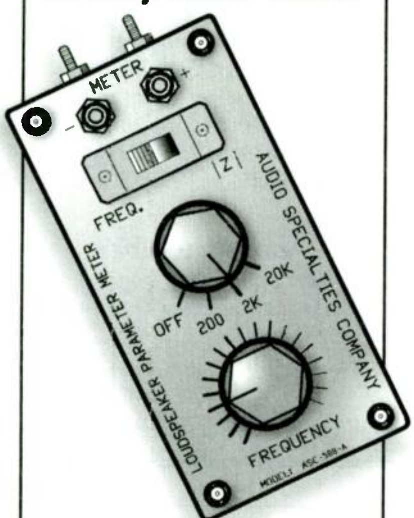

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job of radiating sound via the port and out into the room. Because the enclosure is easier to drive (since it is resonant at that frequency), the excursion of the cone is substantially reduced as well. But it is most definitely not "damped."

A third incorrect assumption is that drivers for vented enclosures generally have reduced excursion capability. This may be true for very specific examples, but there is no general rule that says that drivers used in vented systems have reduced excursion capabilities. The excursion limits of drivers are determined by several factors: relative size of magnet gap-to-voice coil winding length and the linearity limits of the suspension and centering spider. There is no inherent property of drivers for vented enclosure that would require that these factors be different.

So, in the face of all this you still claim that plugging the ports makes a difference in the sound, a difference that you believe is positive. I am not surprised in the least that it does make a difference, but it's not for the reasons you might think.

Obviously, plugging the ports will dramatically change the low-end frequency response of any vented loudspeaker system, maybe for the better, maybe not. In general, woofers for vented enclosure have larger magnet assemblies because a vented driver requires a lower Q_{TS} than a driver intended for sealed or acoustic-suspension systems. Sealing the ports eliminates the enclosure resonance, and the enclosure compliance and suspension compliance will now work together as a single-system compliance. If you're either lucky, or the system designer was sufficiently clever or competent, you could end up with a sealed box system that has a reasonable low-end frequency response.

But that still, in and of itself, doesn't account for your observation that it makes a substantial contributive difference, when using a tube amplifier. There is another amplifier-dependent mechanism that we haven't explored. Assume, for the moment, that the output impedance of the amplifier is substantial, let's say around 1Ω (a damping factor of 8). Also let's assume that our vented speaker system has a typical vented-speaker system impedance curve showing two substantial peaks in the bass spaced (roughly) even on either side of the system's driver resonance. The impedance at the peaks could easily reach 30, 40Ω, or more. And between the two, the impedance could easily drop to near the DC resistance of the voice coil.

The result, not surprisingly, is a frequency-dependent attenuator (an accidental equalizer?) whose attenuation is a complex function of the impedance. When the speaker impedance is very high, the resulting attenuation is low, and vice versa. In the present example, at the impedance peaks of, say, 40Ω, the output impedance of the amplifier would provide only a tiny attenuation, about 0.2dB. But at the lower impedance, say 8Ω, the attenuation is higher, more than 1dB. And it's also important to consider that the effective output impedance of transformer-coupled tube amplifiers is different at low frequencies, which could well exacerbate the problem.

By plugging the ports in the speaker, you have changed the impedance curve dramatically. No longer are there two large impedance peaks in the bass, but one broader peak, roughly halfway between where the original two were (the exact point depends upon the actual driver and enclosure, of course). In addition to the changes you've made to the acoustical frequency response by changing the tuning of the system, you've also changed even further the frequency-dependent attenuation electrically.

I have no doubt that these effects can be heard, but the reasons above explain the differences. Whether the improvement you heard is universally applicable to all situations of this type is doubtful: it's really going to depend upon the specific speaker system itself.

I can imagine, for example, in a speaker such as KEF's RS-104.2, where the designer has gone to great lengths to linearize the impedance, the amplifier sees an almost pure resistance with little or no frequency dependence, and the effect could be negligible. Some systems might end up

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as a high-Q sealed box, and the effect of your change could be to make the system sound underdamped and loose.

As to your comment about the fact that some amplifiers connect multiple speakers in series, this is almost always a sign that the designer of the amplifier knew very clearly that the amplifier had very poor low-impedance capability and severely limited output capability. It's been an unfortunate trend in the last decade or so that many amplifiers and receivers have this inherent design fault. It's the result of skimpy power supplies and inadequate output-device capability.

Sorry to say, but port-stuffing in this context is merely applying a band-aid to a much larger problem. I would rather see the problem itself dealt with. The only real way to do this is for consumers to become educated and vote with their checkbooks. If there's enough of a negative impact in the sales of these defectively designed receivers, maybe the manufacturers will get the message.

PIPE DREAM

I have recently read through some of my back issues of *Speaker Builder* in order to find a design idea for a subwoofer project using my four Dynaudio 30W54s. In two of these issues (5/89, p. 51, and 3/91, p. 28), Scott Wolf wrote articles in which he mounted his woofers at the end of an unstuffed tube. He also mentioned that he believed his Dynaudio 30W54s should sound breathtaking in 12″ diameter, 17′ long pipes.

I do not quite understand how he came up with these dimensions, and I have tried unsuccessfully to find more information regarding his design.

Thomas Gillin
Palm Coast, FL

Scott Wolf responds:

When I actually took a 30W54 to a supply house for large-diameter PVC, the 10″ pipe was a better match. I planned to use soft plastic that when heated in a conventional oven can be machined and affixed to the PVC end with epoxy to hold the woofers in very rigid structures.

I must agree with the single-ended waveguide explanation, as it comes closest to what I've experienced. Please note that my waveguides are partially filled with Acousta-Stuf. Experiment to suit your tastes. I used my Stax Mk-III Ear speakers and a tube amp for a reference.

The equation I used is from *University Physics*, p. 428, Fundamental = C/4L. I actually planned to use greater lengths than 17′. The problem was cost.

In 1989 at the yard that sold me PVC, the 90° elbows would have cost $800. Expensive, yet when you look at the cost of the new Planar magnetics and two twelves at the retail level, not too bad. Two years later, the cost at the yard was $169 per 10″ 90° elbow.

I won't pay this amount, and recently began playing with other materials because I could live with my 30W54s loaded in 26′ single-ended waveguides. My Morel MW16Hs are loaded in 11.5′, 6″ ID PVC. My Langs biased at 4As with a large filter reservoir in the output stages, and I'd benefit from deeper bass energy.

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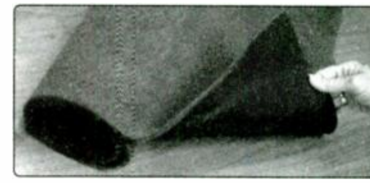

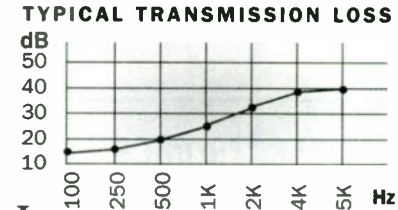

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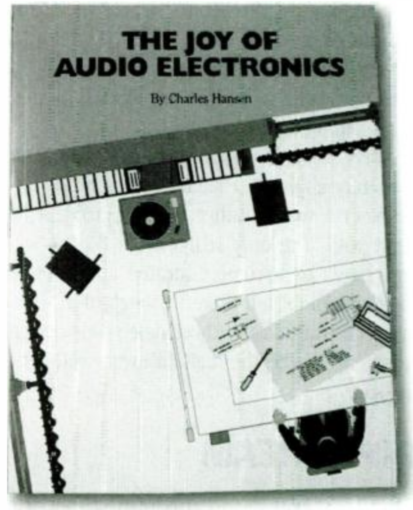
Book Review

THE JOY OF AUDIO ELECTRONICS

Reviewed by Bill Chater

The Joy of Audio Electronics, *by Charles Hansen. Available from Old Colony Sound Lab, PO Box 876, Peterborough, NH 03458, (603) 924-6371, FAX (603) 924-9467, E-mail custserv@audioXpress.com.*



When it comes to hobbies, there can be few that combine such an interesting pair of enterprises as does an interest in audio, because it fuses the very technical with the very artistic–something about right-brain/left-brain comes to mind in this. Certainly there is great satisfaction in building with your hands an instrument that is to a certain extent unique–and thus not trivial–and at the same time you can get another level of satisfaction, for the instrument makes it possible to enjoy your favorite music, whatever form that might take. Thus you can feel you're a craftsperson as well as artistic.

If that is the basis of your interest in audio electronics, to the uninitiated it can be discouraging. Like a lot of other pastimes, it needs a certain level of understanding before you can play the game, and this is where you can appreciate the book Mr. Hansen has written. The fact that there are so many books "for dummies" tells us that there is a large audience in need of help in many subjects.

But this book is not for "dummies," even though it is pitched to the beginner. If you have ever wished to try your hand at the actual construction of something electronic, audio is a good place to start. It is presumed at the outset that you have some knowledge you may not even know you have, for by now many have experienced the challenges of coming up to speed with the modern computer, and have needed to learn a few things electrical, such as voltage and current, power and speed in an electronic sense, and many other words that have

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become part of the modern vernacular. In this book, concepts like these are used and described in context.

FIRST PROJECT

For some hands-on learning, start with Chapter One, which contains a simple, build-it-yourself project of practical utility, fully described with a lot of emphasis on the basics that a beginner might encounter. At some point in the text, though, the author has fallen into a trap of his own making, since there are some things that in my opinion might be in need of explanation first. It is harder than you might think to introduce a new—or nearly new—subject like this from the very basic. In the manner of many tale-tellers, it is easy to forget that some item of importance to the tale has been left until later for description. This is a familiar trouble, like the person who spills the punch line in a joke before telling the first part.

Therefore it might be desirable to look over Chapter Four first to see what you are getting into, and how to actually build the Chapter One project. And maybe even before that, it is probably necessary to delve into Chapter Six's look at theory to find the descriptions of several electrical terms used in Chapter One. A glossary of terms in a prominent place would have been nice for the beginner to refer to as part of the rest of the text. This would have saved the reader from having to make a list along the way. For example, what is actually meant by the terms Q, CR, npn, LED? Or oscillation, or "hum"? These are basic terms, and demand an understanding (or a skip-over until later).

Mr. Hansen has managed a way through these small minefields, and of course many readers might take all this in stride. Beginners will have a chance to work it out as they go.

SECOND PROJECT

Once you get past these hurdles, Chapter Two opens up the subject of constructing a more complete and functional project, the so-called "Quadpod." Here we find an almost Heathkit-like thoroughness in how-to detail. Heathkit is a name many remember fondly as their own introduction to electronic kits. Newer readers will have to do without this now-historic experience, but will probably get the same results here in Chapter Two. I hope Mr. Hansen is flattered by the association. He is meant to be.

The Quadpod project provides the reader with a 32-page description of the construction of a piece of electronic equipment that brings together several hands-on projects. First, there is the mechanical construction of a chassis box to house the unit and make it attractive and useful in operation. Then, there is the assembly of the printed circuit board (not provided; however, it is available from the publisher). This procedure introduces the builder to the physical nature of electronic parts, as well as soldering them in place. There is that moment-of-truth experience when you get to turn it on for the first time, and in a sense get your examination grade for your work. By the time you are through with this business, you will very well be able to realize what goes on inside all electronic equipment, and you may wonder how it is that so much high-tech equipment can actually be sold for so little. There is a lot of work and knowledge in it.

The rest of *The Joy of Audio Electronics* supplies a wealth of information, exhaustively compiled, about parts, retailers, and reference materials. This part of the book alone took a lot of Mr. Hansen's attention, and will ensure the book a place on your shelf for regular reference.

And last, and maybe also least, I did find a few confusing typos—equation 6.34 on page 108 leaves us a little in error (the gain is correctly calculated only for the part of the circuit following resistor R4, and the input resistance is not R2 for the circuit shown). Page 7 uses the capital omega for ohms, where instead the text must have meant a capital W for watts, while on page 9 the capital omega for ohms is needed instead of the W (two places). These small items can be easily corrected, except for the possible turmoil they might cause in the mind of a beginner.

I wonder if Mr. Hansen has any more up his sleeve? Maybe there is an interest in "Project Three"? We can hope for a second edition.

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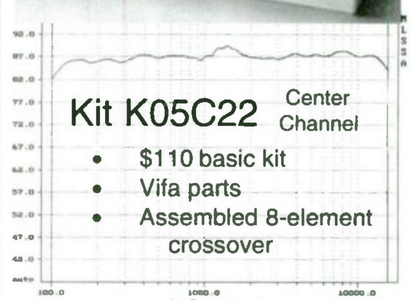
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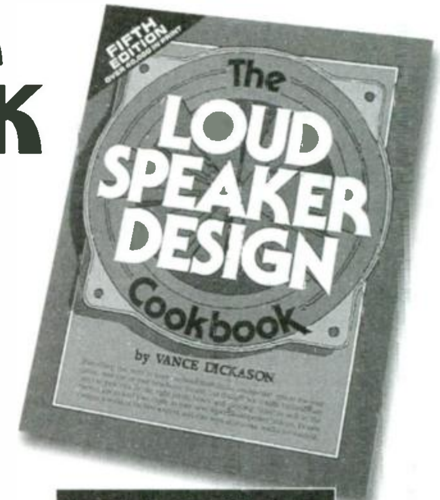

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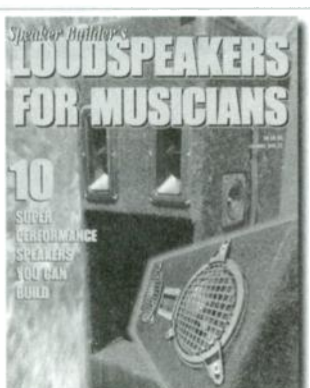

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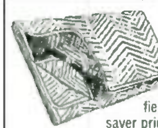

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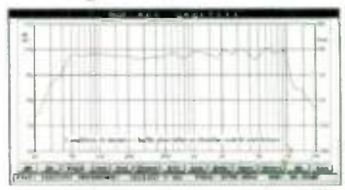

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Tools, Tips & Techniques

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by Rick Oakley

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I joined the cabinet sides, top, and bottom using nominal ¾″ square cleats and liberal quantities of sheetrock screws. I think you'll agree the appearance of this cabinet belies its QDC2W, which stands for "quick (and) dirty cheapie dual woofer," designation. With my radial-arm saw buried in the shed, the only power tools I used were a ¼″ hand drill and a saber saw.

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

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

Thiel-Small Parameters

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

TITANIC Subwoofer Cabinet

ONLY $119.80 ASK FOR #300-729

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

250 Watt Class D Subwoofer Amplifier

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

ONLY $249.80 ASK FOR #300-795

All subwoofer amps are not created equal!

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

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