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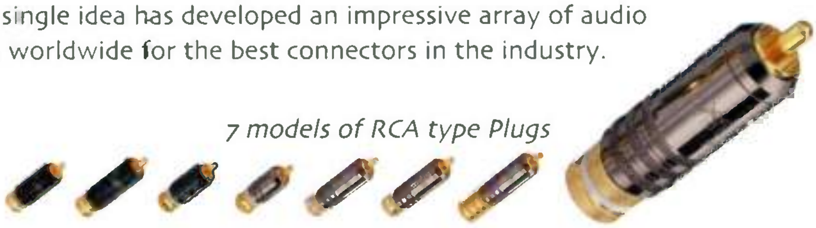

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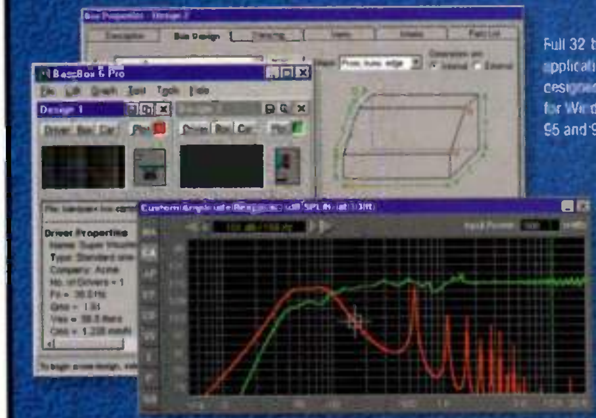

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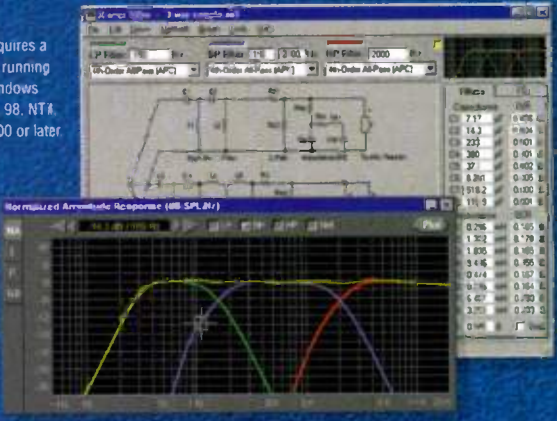

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- Includes a full online manual with tutorials for beginners and step-by-step sample designs. (A Design Wizard & printed manual are not included.)
- Driver data can be saved in design files and re-used later. (The driver database is not supported.)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

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Reader Service #3

Good News

NEW CLASSIC SPEAKERS

Cambridge SoundWorks® announces the availability of SoundWorks Digital, a newly enhanced version of its three-piece multimedia speaker system. Based on the FourPointSurround FPS2000 Digital design, this digitally enhanced speaker system includes an improved wooden subwoofer and a S/PDIF digital audio input. Using custom-designed amplifiers with 22W of power to the subwoofer and 16W to the stereo satellite cubes, this speaker system features digital input that connects easily to high-performance PC sound cards, as well as to home and portable components including compact disk (CD) and MiniDisc (MD) players. The new system incorporates two stereo analog inputs, providing a convenient, permanent connection for analog-only computer audio, plus a second connector for portable devices including CD or MD units, or an MP3 pocket-player. Cambridge SoundWorks, 311 Needham St., Newton, MA 02164, (800) 367-4434, (617) 332-5936, FAX (617) 244-3743, Website www.hifi.com.

Reader Service #135

MONSTER® SELECTORS AND VOLUME CONTROL

Monster Cable Products, Inc. has unveiled three new products—Monster Multi-Speaker Selector MSS–6, Multi-Speaker Selector MSS–4, and Stereo Volume Control (SVC–75). MSS–6 allows control of up to six speaker pairs, while MSS–4 allows up to four pairs throughout the home or office. They provide the convenience and flexibility of listening to one speaker pair or several pairs at a time, in any location of the house or backyard. MSS–6 and MSS–4 feature high Current Amplifier Protection Circuitry, Monster's impedance-matched circuitry that allows you to safely use multiple speaker pairs simultaneously without overloading your amplifier. Audiophile-grade resistors deliver maximum power from systems using power-hungry amplifiers—up to 150W per channel. Monster's Multi-Speaker Selectors not only offer the flexibility to enjoy music anywhere in the house, but protects the amplifier from overloading, thereby maximizing the performance of the entire music system. MSS–6 and MSS–4 are internally wired with high-performance Monster Cable. SVC–75 enables separate volume control for one additional speaker pair anywhere in your home or office. This is the companion product to the speaker selectors because volume can then be adjusted room-by-room as desired. Monster Cable, 455 Valley Dr., Brisbane, CA 94005, (415) 840-2000, FAX (415) 468-0204, Website www.monstercable.com.

Reader Service #138

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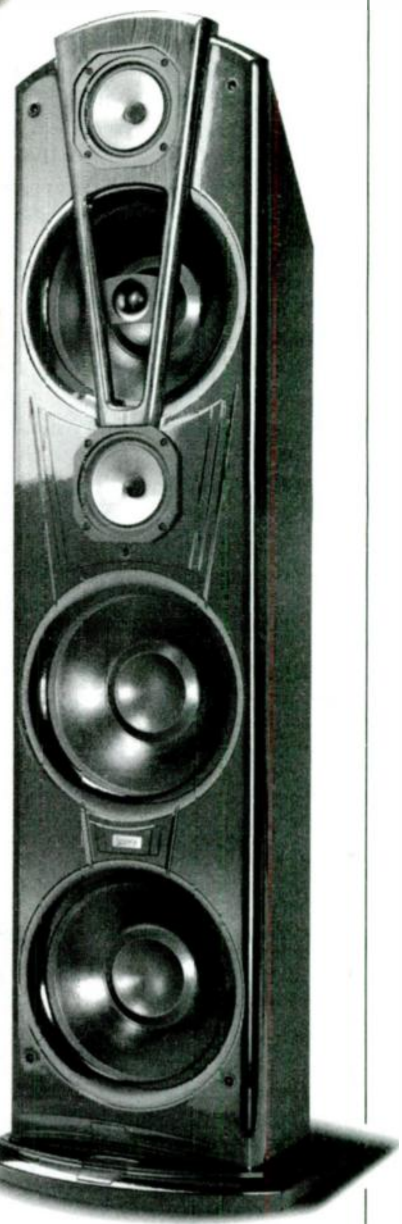

A new material called KEVLITE-Ti™ (composed of KEVLAR™, graphite, and titanium) has been developed for the 5.25″ drivers to enhance vocals and impart rich luster to the glow of brass, according to the company. A special magnetic material called neodymium lends clarity to the NEOdome™ tweeter. EMPIRE's baffle and base are machined from 1.5″ thick Ultra-LITE. Legacy Audio, Inc., 3023 E. Sangamon Ave., Springfield, IL 62702, (800) 283-4644, FAX (217) 544-1483, Website www.legacy-audio.com.

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ANALYSIS SOFTWARE FOR WINDOWS

HpW announces V2.70 of the FFT-based analysis software HpW Works. The new release includes an improved lookout and several new display options—THD, THD+ N, dynamic range (DR), SNR, and level calculations. The analysis data showing more detailed information is presented on a separate data window. Using dual channels, the phase relationship is also shown. Analyzing signals, in the labor, development, or music studio is the target use of HpW Works. The full system includes an FFT-software plus signal generator, operating with any PC sound or digital I/O hardware. The FFT analyzer uses 64-bit resolution internally and supports up to one million sample points. The wave generator delivers various signals: sine, sweep, various harmonics (1–24), multiwaves (1–44), static signal (DC), IM signals, d-jitter test signal (fs/4 or fs/8 with LSB toggle), test sequences, and various noise signals. Hanspeter Widmer, E-mail hpwidmer@hpw-works.com, Website www.hpw-works.com.

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Reader Service #139

HIGH-END LOUDSPEAKER

Norwex B–2 Nisse is designed to be placed on a bookshelf or in a wall unit, since its dimensions are only 9″ × 7″ × 9″. Custom-made floor stands are also available. The bass-reflex design uses a 4½″ woofer and a 1″ soft-dome tweeter. Frequency response is 53Hz–20kHz, impedance 8Ω, and sensitivity 84.5dB/1m/1W. Well suited for stereo music and home theater front or rear channels. Norwex, PO Box 86, Palmyra, VA 22963, (804) 589-8043, E-mail norwex@cfw.com.

Reader Service #137

About This Issue

As we enter the third decade of publishing *Speaker Builder*, we'd like to thank the speaker building community for its continuing support and interest over the years. In appreciation, we've redoubled our commitment to bringing you the best in design, theory, and construction coverage in the coming issues. Stay tuned.

We kick off this issue with the first of a three-part series by veteran speaker builder **Jim Moriyasu**, who shows us that big sound can come from a small package. His compact design features a vented subwoofer and a satellite with a Morel mid-range and Scan-Speak tweeter ("The Menehune MX-1," p. 10). Part 1 includes many simulations of system performance.

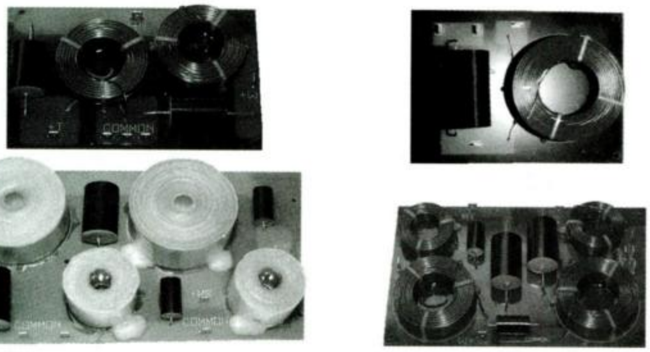
Car acoustics is a topic that concerns everyone who spends any time on the road. Its quality depends on several considerations, primarily speaker placement. In the passenger compartment, your options are limited. **Bohdan Raczynski**'s modeling method shows the optimum location to mount your car speakers ("Auto Passenger Space As a Listening Room," p. 20).

The use of fiber stuffing is critical in transmission-line performance. In the concluding article in his series, **A. Monk** investigates how fiber characteristics and selection for your design will affect system optimization ("Transmission Lines: The Real Story," p. 24).

When designing your speaker system, you need to know the difference between the acoustic centers of drivers. **David L. Ralph** shows how to find relative acoustic offsets with the right software and a good measurement system (p. 36).

Talk about flexibility! **Kim Girardin**'s article ("A Breadboard for Passive Crossovers," p. 40) shows you how to build and set up a breadboard to easily connect—and change—crossover components for testing.

In this issue's guest editorial (p. 8), regular contributor **Gary Galo** reports on the latest AES convention and uncovers a couple of encouraging trends.



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those who dissent from the opinion,
still more than those who hold it.
JOHN STUART MILL

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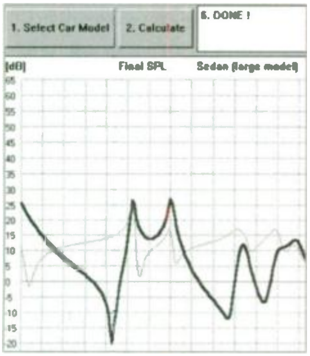

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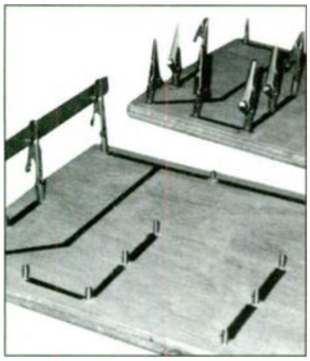

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Guest Editorial

THE HIGH-END AT AES

By Gary A. Galo

THE AUDIO ENGINEERING SOCIETY held its 107th convention at the Javits Convention Center in New York City, September 24–27, 1999. Particularly striking was the extremely high quality of the audio demonstrations offered by several manufacturers, which certainly reflected the convention theme "Advancing the Art of Sound."

For audiophiles, the AES convention has not traditionally been the event of choice for high-quality sound reproduction. I began attending New York AES conventions over 20 years ago, when they were held at the Waldorf-Astoria Hotel. For many years, I was appalled at the audio demonstrations.

In the late 1970s through the early 1980s, many manufacturers used a particular line of large coaxial "studio monitor" loudspeakers in their demonstration rooms. The colorful horn tweeters in the center of these drivers sounded like bacon frying. I walked out of many sonic sizzlers in those days, unable to bear the screeching treble. Most audiophiles would never tolerate such sound in their living rooms.

I recall Harvey Rosenberg of New York Audio Labs demonstrating in the early 1980s his company's output-transformerless tube amplifiers using 30ips master tapes played on a modified Studer A-80. When I asked Mr. Rosenberg why he was using one of the popular studio monitor loudspeakers to demonstrate high-end amplifiers and source material, he conceded that the AES market was quite different from the audiophile one.

IMPROVED EQUIPMENT

In recent years, those grossly inaccurate loudspeakers have become a small minority at AES. Since the early 1980s, the quality of "studio monitor" loudspeakers has improved by several orders of magnitude, with manufacturers such as B&W (whose excellent loudspeakers have gained acceptance in high-end listening rooms and recording studios alike) leading the way. I believe *Speaker Builder* has also had a significant positive influence on the science of loudspeaker design and the desire for higher-accuracy reproduction in professional monitoring applications. Back in the 1980s several *SB* authors, including Bob Bullock and Joe D'Appolito, regularly presented papers at AES conventions.

The vast improvement in professional studio loudspeakers is only part of the story, at least in my view. What has also been striking at recent AES conventions is the increasing presence of high-end consumer audio equipment, including preamps, amplifiers, and even cables. The AES made a serious attempt to discredit the high-end in 1991, with the New York convention theme "Audio Fact and Fantasy—Reckoning With the Realities" (see my report in *TAA* 1/92, and letters in 3/92).

Yet despite the continued insistence of a large contingent in the AES, many mainstream audio manufacturers aren't buying the view that all amplifiers and cables sound alike. This was most evident in the demonstration rooms of three of the leading manufacturers in the professional audio industry.

DEMOS

Cirrus Logic demonstrated the Crystal CS4396 D/A converter, capable of up to 192kHz/24-bit performance. A Pioneer DV-525 DVD player was used as a transport for a 96kHz/24-bit demonstration CD, feeding a CS4396 evaluation prototype board. Bryston's SP-20 preamp and 4B power amplifier fed a pair of PMC LB-1 loudspeakers. Interconnects were Kimber, and the loudspeaker cables were Nordost Blue Heaven. Cirrus Logic's Fred Valenzuela noted that they did not wish to color the superb resolution of the CS4396 DAC with inferior equipment.

The JVC demonstration room featured their Digital K2 professional clock-jitter suppressor, intended for digital production and mastering applications. All electronics were from Mark Levinson, including the No. 37 CD transport, 36s digital processor, 38s preamplifier, and 332 stereo power amp. Madrigal and Harmonics interconnects were used for the low-level connections, along with loudspeaker cables and power cords by MIT. The loudspeakers were WATT Puppies.

Digital K2 could also be auditioned with Grado RS-1 headphones powered by a custom-built Holmes-Powell tube amplifier. Only three of these headphone amps exist, selling for around $3,000.

It goes without saying that the improvements rendered by Digital K2 were readily audible on this high-resolution equipment. JVC's representative noted that expensive equipment isn't needed to hear improvements effected by Digital K2, but high-end equipment is necessary to show the maximum performance capabilities of the K2 system.

Sony demonstrated its Super Audio Compact Disc (SACD), a format offering up to six channels of high-definition digital audio, with a sampling rate of 2.8MHz. Their five-channel demonstration was, without a doubt, the finest sound I have ever heard at an AES convention. The loudspeakers were Sony SS-M9ED, designed in the US, manufactured in Park Ridge, NJ, and retailing for around $16,000 per pair. They were powered by Pass X600 Class-A mono amplifiers, and all interconnect and loudspeaker cables were manufactured by Straightwire.

The demonstration room was treated with panels made by RRG. Sony's David Kawakami noted that although the superiority of the SACD system will be audible on normal consumer equipment, the high-end equipment used in this demonstration was selected to reveal the full capabilities of the format.

Sony also held a special presentation on the SACD, featuring several distinguished panelists including recording engineer Tom Jung of DMP. Jung's endorsement of SACD was most enthusiastic. He believes that the SACD system yields recordings closer to the direct feed from the mixing console than anything he has previously heard, noting that he has ob-

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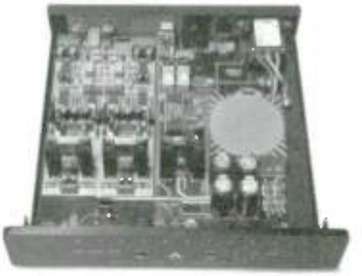

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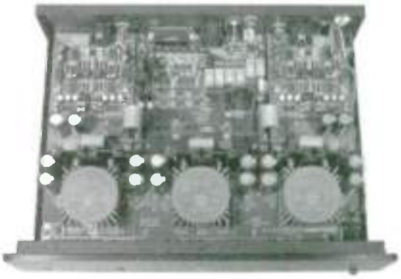

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World Radio History

A unique feature of this author's design—a rumble filter—allows this satellite/sub combo to pack plenty of wallop.

Part 1

The Menehune* MX-1

A Compact Satellite/Subwoofer System

By Jim Moriyasu

This design attempts to maximize sound output and quality from relatively small enclosures. Since low-frequency output is limited by the woofer's infrasonic cone excursions in a passive design, this speaker system uses a rumble filter in conjunction with an active crossover optimized to minimize low-frequency cone excursions and provide some low-end boost. The satellite uses a mid-bass driver with a large voice coil to minimize thermal output limitations caused by voice-coil heating.

The popularity of vented woofer designs requiring high output stems, according to Dickason,[1] from their 3dB higher efficiency and lower cone excursion at or in the vicinity of the box resonance frequency (f_C). However, vented designs have greater cone-excursion potential below the f_C.

To compensate for this problem in the design, I used LEAP software (Loudspeaker Enclosure Analysis Program), a sophisticated loudspeaker-modeling program from LinearX, to design an optimized sixth-order vented enclosure.

This was accomplished with active filter modeling, which determined the optimum low-frequency crossover point and filter Q for a second-order high-pass (or "rumble") filter. (For those who don't know what "rumble" refers to, it's the unwanted 5Hz to 10Hz signal generated from warped LP records.) With this active equalization in place, the woofer's maximum cone excursion (X_{MAX}) is the same both below and above the box-tuning frequency. Thus, the woofer's output isn't limited by undue driver excursions caused by unwanted or unplayable in-

PHOTO 1: ScanSpeak D2905/9300 Morel MW142 and VIFA M22WR ready for SPL testing.

ABOUT THE AUTHOR
Jim Moriyasu has been an avid speaker enthusiast for over 20 years. Despite a B.S. in biochemistry, he has been a financial advisor (stockbroker) with Morgan Stanley Dean Witter for the past 21 years. He has been using Loudspeaker Enclosure Analysis Program (LEAP) and Loudspeaker Measurement System (LMS) for the past four years, and Liberty Audiosuite (Laud) since last summer.

*The Menehune (may-nay-who-nay) are mythical Hawaiian forest-dwelling beings who are not only diminutive, hard-working, and playful, but also shy and furtive. According to legend, the Menehune were credited as master builders capable of completing major projects in a single night! They worked at night so as to go unnoticed.

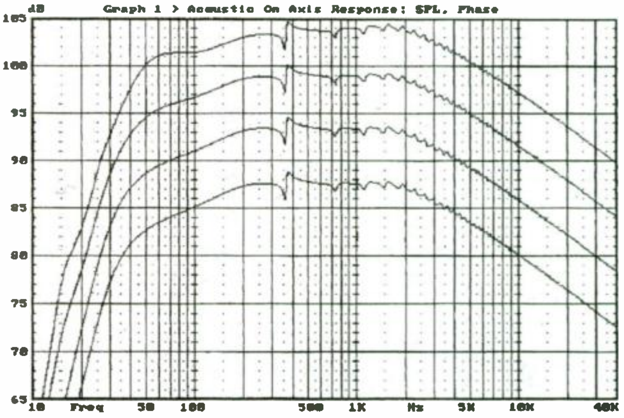

FIGURE 1: Low-frequency SPL simulation of the Vifa M22WR in the Woodstyle WS803 cabinet at 1, 4, 16, and 64W.

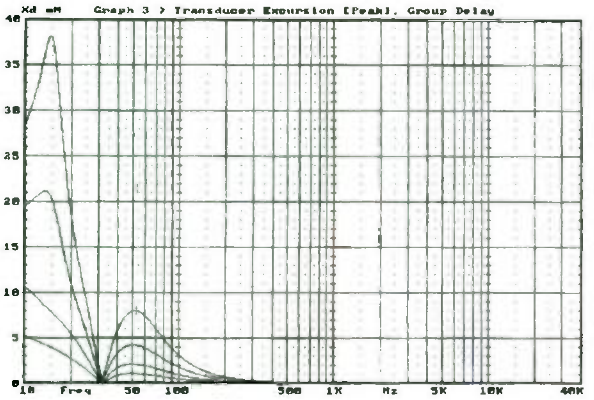

FIGURE 2: Low-frequency cone-excursion simulation of the Vifa M22WR at 1, 4, 16, and 64W, with 32.5Hz port tuning.

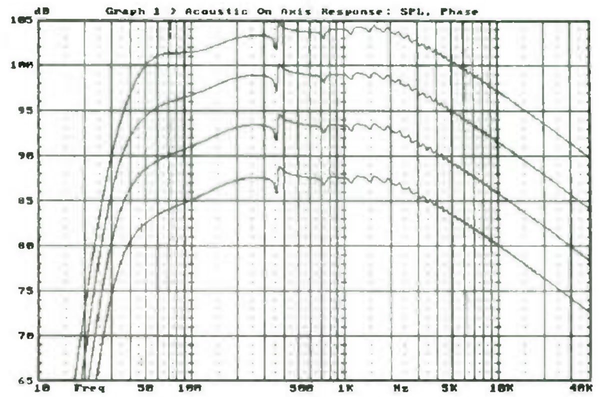

FIGURE 3: Low-frequency SPL simulation of the M22WR with a standard third-order Butterworth rumble filter at 1, 4, 16, and 64W.

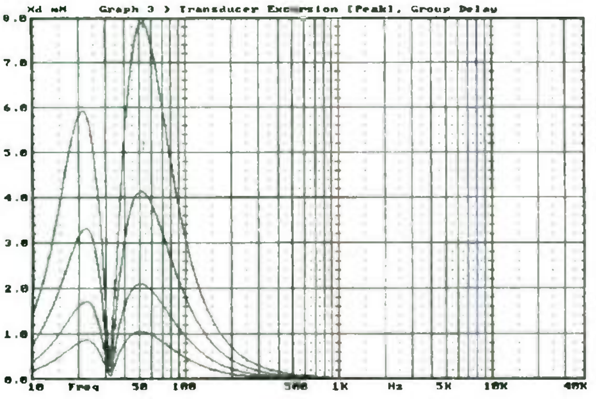

FIGURE 4: Low-frequency cone-excursion simulation of the M22WR with the Butterworth rumble filter at 1, 4, 16, and 64W.

TABLE 1
PARTS LIST

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

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

ELECTRONIC CROSSOVER

XVR-1, from Audio Arts

MEASUREMENT EQUIPMENT AND CAD SOFTWARE

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

frasonic signals. LEAP simulations indicate this alignment will enable the woofer to play 12.5dB louder than the unfiltered, fourth-order version.

WOOFER DESIGN AND SIMULATIONS

I've chosen the Vifa M22WR for this design, since I've had several years of experience with it after seeing it in a design by Vance Dickason in the *Loudspeaker Design Cookbook*. It has a large vented magnet, damped paper cone, cast frame, and an X_{MAX} of 6.5mm, which is about the maximum for a woofer of this size. It was designed for subwoofer use with a resonant frequency of 28Hz. With its 40mm voice coil, it is rated at 150W.

While an optimum-sized cabinet would be in the 1.2–1.4ft^3 range, I decided to limit the subwoofer cabinet to 1ft^3 or less, since a compact size would have a higher spousal acceptance factor.

Even though I have a workshop and built the prototype cabinets myself, I used the Woodstyle WS803 cabinet units from Madisound for the subwoofer enclosures. These cabinets, nicely finished in oak with rounded hardwood corners, come with a blank front baffle, but have a rear cutout for an input panel, and are complete with black-fabric-covered grilles and male/female grille fasteners.

The WS803 has an internal volume of .88ft^3. For the simulations, I assumed a volume of .80ft^3 with approximately .08ft^3 occupied by vent, bracing, and woofer. I made all the simulations with output in an anechoic environment, instead of half-space, and at one meter. The finished unit is shown in *Photo 1*.

Figure 1 shows the simulated sound pressure level (SPL) response curves of

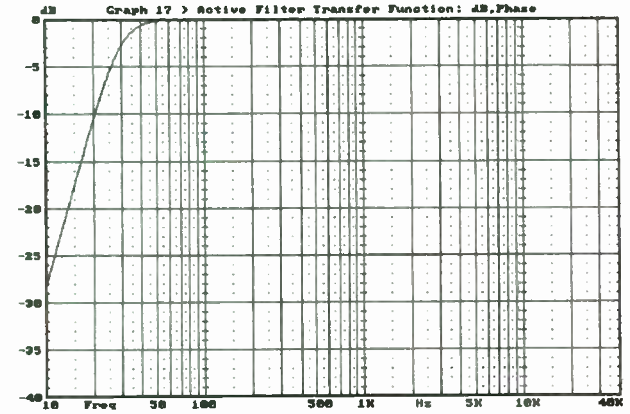

FIGURE 5: Active filter-transfer function for the standard third-order Butterworth rumble filter.

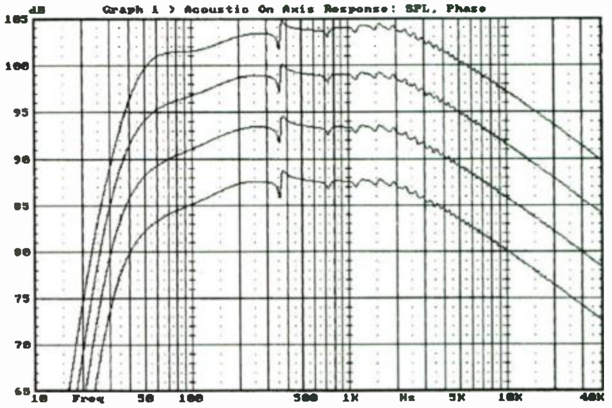

FIGURE 6: Low-frequency SPL simulation of the M22WR with an optimized Bessel rumble filter at 1, 4, 16, and 64W.

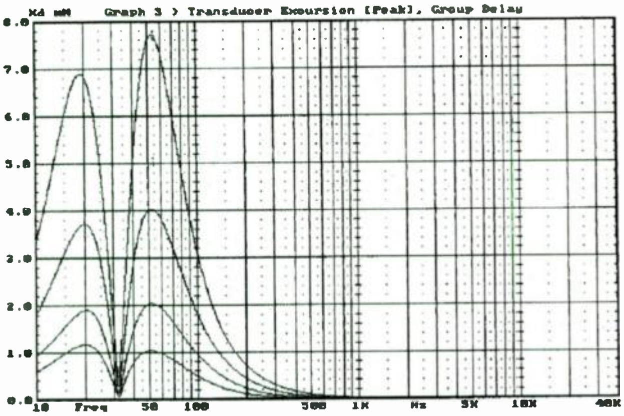

FIGURE 7: Low-frequency cone-excursion simulation of the M22WR with the Bessel rumble filter at 1, 4, 16, and 64W.

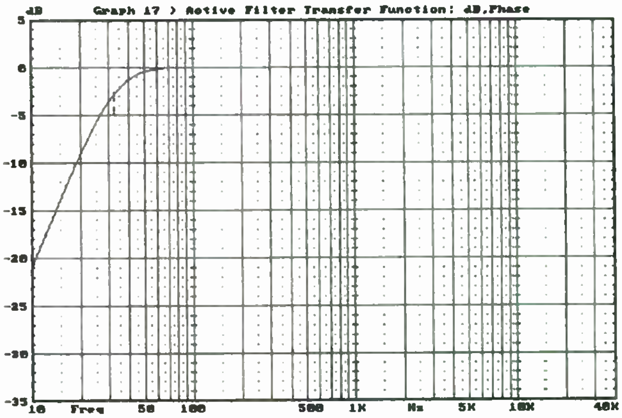

FIGURE 8: Active filter-transfer function for the optimized Bessel rumble filter.

the M22WR, with a box tuning or resonance of 32.5Hz and with no rumble filter in place. The cutoff frequency (f_3) is at 45.10Hz relative to the 100Hz level at 1W, due to the Bessel-shaped rolloff. The curves represent simulated output for 1, 4, 16, and 64W.

TRANSDUCER EXCURSION CURVES

Figure 2 shows the transducer (woofer) excursion curves. At 53Hz, the woofer's cone reaches its first rise in excursion, but then declines with frequency as the port begins to produce most of the output. Below the port tuning, the transducer excursion begins to rise rapidly, quickly exceeding X_{MAX}. Since the M22WR has an X_{MAX} of 6.5mm, adding 15 percent gives 7.5mm, which is suggested as the maximum excursion level before the onset of audible distortion.[2]

Judging by the excursion curve for 64W, it appears that the woofer will play cleanly to 102dB at 100Hz as long as there is no program content below 28Hz. Only at the 1W level will the cone excursion be within 7.5mm at all frequencies. Actually, while not shown, 2W will still be within 7.5mm at all frequencies, with an output at 100Hz of 88dB.

A simulation of a sealed-box woofer would show X_{MAX} leveling off or rising less dramatically below the f_3.[3] So it seems the only way to bring a vented box's transducer excursion curve up to parity with a sealed box would be to filter or limit the signal below the box resonance.

Figure 3 shows the SPL response for the same woofer and box and tuning, except with a standard third-order Butterworth rumble filter inserted. The filter has a corner frequency of 30Hz and attenuates the signal at 18dB per octave. The corner frequency is the point at which the filter's transfer function is down by 3dB in the case of a Butterworth alignment.

Figure 4 shows the excursion curves and the attenuation due to the filter. At the 64W level, the transducer excursion reaches 7.90mm. Note how excursion declines with frequency, nearing zero at the box-tuning frequency at 32Hz. As the frequency declines further, the excursion rises, peaking at 12Hz. However, the excursion is 5.95mm, which means the transducer could have another 2mm of excursion to match the right-side peak.

While the filter has reduced the excursion, it has also reduced output enough to raise the f_3 to 47.00Hz relative to the 100Hz level at 1W, as seen in *Fig. 3*. Evidently, the standard Butterworth rumble filter helps minimize transducer excursion, but doesn't maximize f_3. *Figure 5* is the active filter-transfer function, showing the 18dB per octave slope.

Madisound is pleased to introduce the latest drivers in Scan-speak's line of premium drive units. In the past few years, Scan-speak has developed new drivers that have quickly become industry favorites. Drivers like the Carbon-paper cone 18W/8545 and the Revelator D2905/9900 can be seen in super high end loudspeakers throughout the world. The Scan-speak engineers are consistently producing new products that meet the ever demanding requirements of today's audiophiles.

These three new Scan-speak drivers have all been carefully engineered and are already causing excitement in the speaker building community. If you are interested in using these speakers in your next speaker project, please consider our Leap design services to assist you. We are happy to answer any further questions regarding all Scan-speak products.

D2904/6000-01	$149.00 each
D2904/9800-00	$198.00 each
15W/8530K-01	$175.00 each

All other versions of these drivers are currently not available for retail sale.

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MADISON, WI 53744-4283 U.S.A.
TEL: 608-831-3433 FAX: 608-831-3771
e-mail: info@madisound.com
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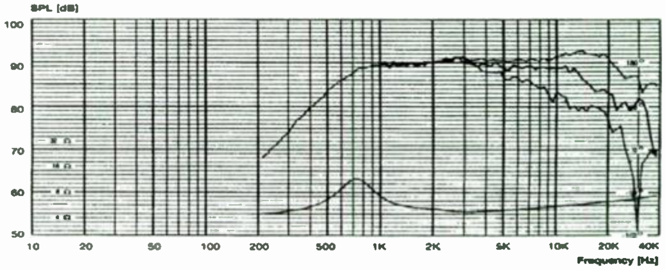
D2904/6000-01

The D2904/6000-01 tweeter has a 1" coated textile dome and a neodymium magnet system. This speaker uses a compact self shielding Symmetric Drive magnet system, utilizing three powerful neodymium magnets. The cavity under the voice coil is coupled to the chamber through eight holes in the top plate. Pure cotton is used as damping material. The textile diaphragm is carefully hand coated. The reproduction is very dynamic and open, with low levels of compression. Perfect for home, A/V or automotive use.

TECHNICAL DATA:

Characteristic sensitivity	90.5dB	Lin. & max. excur.	±0.25 / ±1.3mm
Free air resonance Fs	750 Hz	Air gap flux density	-
DC resistance	3.5 ohm	Force factor BL	2.7 Tm
V.C. inductance	0.02 mH	Moving mass	0.4 g
Power 12dB@Hz	150W@2.7K	Net weight	0.13 kg
Effective cone area	8 cm^2	Vas	-
V.C. diameter	28 mm	Qms	-
V.C. height	-	Qes	-
Air gap height	-	Qts	-

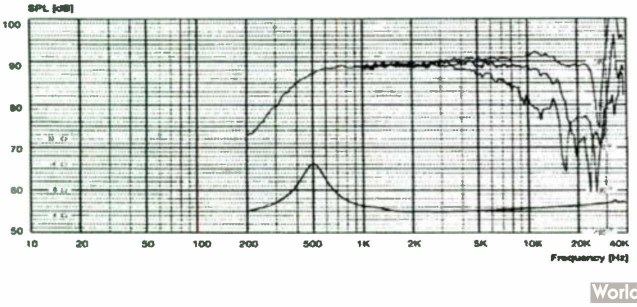


D2904/9800

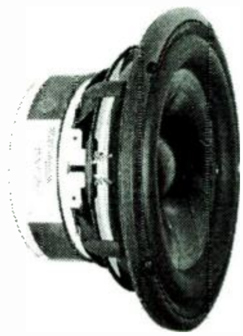
The D2904/9800 is a high-end 1" aluminum dome tweeter. The magnet system uses the Symmetric Drive technology that almost eliminates electrical phase shift. The specially designed chamber reduces air noise and compression. The geometry of the dome causes the characteristic "break-up" to appear beyond the audible range. A specially designed diffusor is used to equalize the response in the upper octave. The tweeter has a very clear and open sound. The detailing is brilliant.

TECHNICAL DATA:

Characteristic sensitivity	90dB 1W/1m	Lin. & max. excur.	±0.1 / ±1.5 mm
Free air resonance Fs	500 Hz	Air gap flux density	-
DC resistance	3.5 ohm	Force factor BL	2.8 Tm
V.C. inductance	0.01 mH	Moving mass	0.50 g
Power 12dB@Hz	160W@2.8K	Net weight	0.7 kg
Effective cone area	8.5 cm^2	Vas	-
V.C. diameter	28 mm	Qms	-
V.C. height	-	Qes	-
Air gap height	-	Qts	-



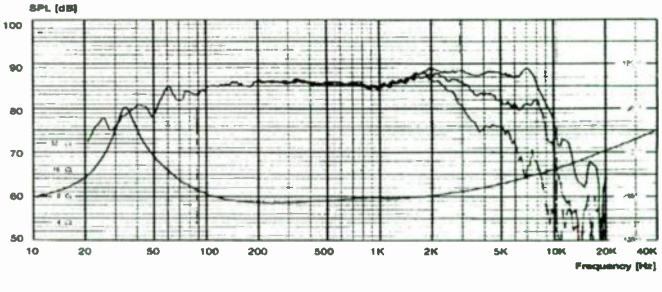
15W/8530K-01



The 15W/8530K-01 is a 5 ½" reference mid/woofer. It features a non-resonant cone and dust cap structure, dynamic linear suspension, SD-1 magnet system, "Grasshopper" cast chassis with maximized air flow and resonance terminating mounting system. Less resonance in all structures, lower compression and higher linearity, faster termination of excess energy and higher sound pressure capability make the 15W have more musical and dynamic capability than any other 5 ½" we know of. Wonderful bass in a small box!

TECHNICAL DATA:

Characteristic sensitivity	84.5dB 1W/1m	Lin. & max. excur.	±6.5 / ±9mm
Free air resonance Fs	30 Hz	Air gap flux density	-
DC resistance	5.8 ohm	Force factor BL	6.1 Tm
V.C. inductance	0.35 mH	Moving mass	13 g
Power 12dB@Hz	60W	Net weight	1.1 kg
Effective cone area	95 cm^2	Vas	28 ltrs
V.C. diameter	38 mm	Qms	4.9
V.C. height		Qes	0.38
Air gap height	-	Qts	0.35



BACK TO LEAP

Well, back to the drawing board, or, actually, back to LEAP. Since the nonfiltered woofer-response curve approximates a Bessel response, I used LEAP's Design Graph Library Corrective Filter System (DGLCFS) to produce a sixth-order Bessel curve at 32Hz, using it as a target to optimize the active crossover. The LEAP Reference Manual has filter-alignment tables that tell you what parameters to use in forming a specific order alignment.

The SPL response curves in *Fig. 6* show that the f_3 is about the same as with the unfiltered woofer at 49.915Hz relative to the 100Hz level at 1W.

The excursion curves in *Fig. 7* show that some excursion is still available below the box tuning at the 64W level. So, again it seems that optimal results are not yet achieved in terms of low-frequency extension and management of the woofer's excursion potential. *Figure 8* shows the active filter-transfer function, which is the result of setting the second-order high-pass filter at 33.90Hz with a Q of .747.

So it occurred to me that an optimal rumble filter would produce an excursion curve shaped like the letter M. The right side of the M is the excursion above resonance, and nothing can or should be done to limit it. The left side of the M is the excursion below resonance, and the design goal would be to have it reach the same level as the right side. To do this, I used LEAP's DGLCFS to produce a sixth-order Butterworth target alignment with f_3 at 35Hz. Then I set up a second-order high-pass filter in LEAP's active crossover file. Next I had LEAP optimize the active second-order high-pass filter with the woofer so that it would match the sixth-order target. In essence, I've designed a sixth-order Butterworth vented alignment.

T/S ALIGNMENT TABLE

Having gone through this design process, it dawned on me that a Thiele/Small alignment table might have been an easier approach. LEAP has a Quick Cabinet utility to provide starting parameters for low-frequency simulations, but it doesn't provide for sixth-order alignments. So, while I "reinvented the wheel," so to speak, at least I refined it by optimizing the shape of the excursion curve and, I hope, increased power handling and output.

Figure 9 shows the SPL response curves of the sixth-order design with the M-shaped excursion curve. The f_3 of the system is now 37.519Hz relative to the 100Hz level at 1W, and the response curve has a Butterworth shape.

Figure 10 shows the transducer excursion curves, with 7.5mm being reached at 38W instead of 64W because of the filter's modest boost. Note, however, that the cone's excursion below the box resonance, at 32.5Hz, never exceeds the excursion at 50Hz.

Figure 11 is the active filter-transfer function, which you accomplish by setting the second-order active filter to a crossover point at 32.5 and a Q of 1.176. Since the Q is above .707, the filter has a modest response peak that boosts low-frequency SPL by up to 2.27dB between 30Hz and 150Hz.

LOUD MUSIC

From an output-versus-excursion standpoint it is important to note that the SPL reaches 100.5dB relative to 100Hz, with an excursion of less than 7.5mm at all frequencies. This is 12.5dB above the unfiltered system, which means that this design should be able to play—with acceptable levels of distortion—all types of music four times louder than the unfiltered system.

In a real listening situation, maximum SPL would rise to 106.5dB with two subwoofers. At four meters this would drop to 94.5dB, which might still be relatively loud for most listeners. As it turns out, according to Dickason, this design is categorized as a Class II sixth-order alignment.[4]

While an f_3 of 35Hz is quite good for an 8″ woofer in a .80ft^3 enclosure, to see how much more I could get from a sixth-order alignment, I tuned the box to 30Hz and increased the filter's boost. *Figure 12* shows output at 1, 4, and 22W, with an f_3 of 30.60Hz relative to the 100Hz level at 1W.

Figure 13 shows the transducer excursion curves, with 7.5mm being reached at 22W instead of 64W because of the boost of the filter. Again, note that the curves have an M shape.

Figure 14 shows the filter puts out 5.42dB of boost. It has a crossover frequency at 30.5Hz and a very high Q of 1.794. Output at X_{MAX} plus 15%, though, is down 2.5dB to 98dB at 100Hz. As ex-

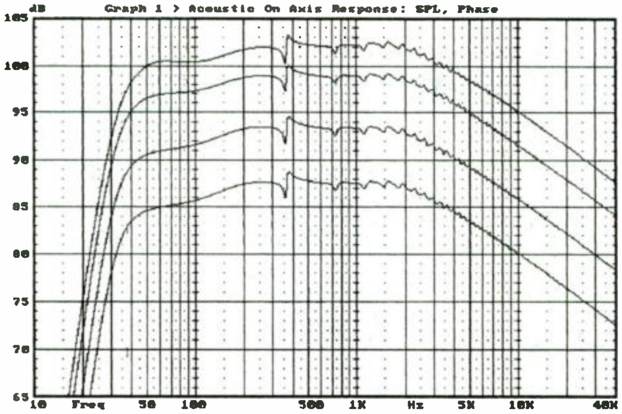


FIGURE 9: Low-frequency SPL simulation of the M22WR with the Butterworth rumble filter with M-shaped excursion curve at 1, 4, 16, and 64W.

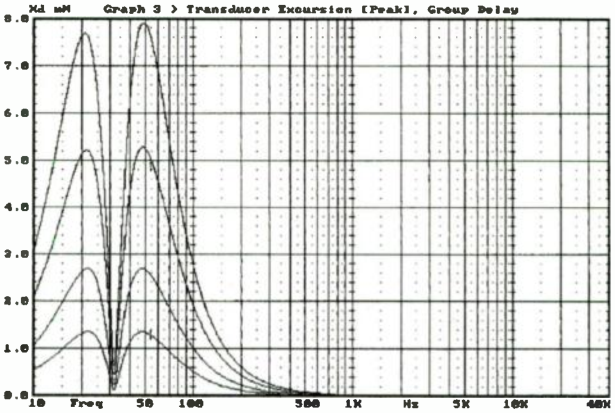


FIGURE 10: Low-frequency cone-excursion simulation of the M22WR with optimized Butterworth rumble filter with M-shaped excursion curve at 1, 4, 16, and 64W.

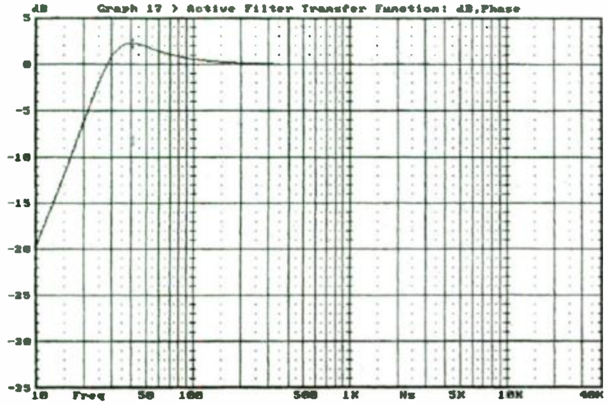


FIGURE 11: Active filter-transfer function for optimized M-shaped cone-excursion curve with crossover at 32.5Hz and Q of 1.176.

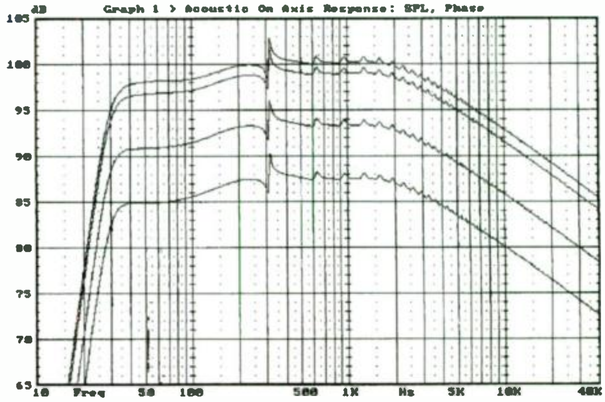


FIGURE 12: Low-frequency SPL simulation of 30Hz Class I sixth-order alignment with M-shaped excursion curve at 1, 4, 16, and 64W.

pected, there's no free lunch when it comes to low-frequency design. Output is traded off for low-frequency extension. And this alignment requires a 19″ vent, which would then entail redesigning the cabinet. And as it turns out, this design is categorized as a Class I sixth-order alignment.[4]

SATELLITE MIDBASS DESIGN AND SIMULATIONS

Madisound also offers several enclosures suitable for use as satellites or minispeakers. I used the WS602, which has a volume of .189ft^3. Like the subwoofer enclosure, it is finished in oak, has rounded corners, and comes complete with grille and fasteners installed.

My satellite prototype used a Vifa P13WH mid-woofer, while the final design uses a Morel MW142. While sonically excellent, the P13WH had two drawbacks: first, it uses a 1″ voice coil, so its power handling is much less than the Morel MW142, which has a 3″ voice coil. The Vifa is rated at 40W, while the Morel has a 150W rating.

Figures 15, 16, 17, and *18* show SPL and transducer excursion for the Vifa and Morel drivers hooked up to optimized second-order Linkwitz-Riley highpass active filters at 150Hz, with 1, 4, 16, and 64W of input. Thanks to the crossover, they stay within X_{MAX} at all power levels, so excursion is not a problem. However, as shown in *Fig. 15*, the effect of voice-coil heating shows up at 16W for the Vifa, where SPL has increased by 4dB instead of 6dB. At 64W, the Vifa increases SPL by only 1 to 2dB over the 16W input. The Morel shows no compression until 64W, where it increases 4dB instead of 6dB over the 16W input level.

I also ran a test to show how voice-coil heating would reduce SPL output. I performed a sine-wave sweep of the drivers at 1, 4, 16, and 64W without a crossover to examine the effects of voice-coil heating on output. The P13WH was in a .25ft^3 cabinet stuffed with Acousta-Stuf®, while the MW142 was in a Woodstyle WS602 cabinet similarly stuffed.

Figures 19 and *20* show that as the power is increased from 1 to 4W, the output increases by 6dB for both drivers. Between 4 and 16W, the output again increases by 6dB for both drivers, but as the power is increased to 64dB, the P13WH shows the effects of compression by increasing its output by 4dB or less, while the MW142 shows an increase of 4.5 to 5dB.

While the measured responses don't show as much compression in output as

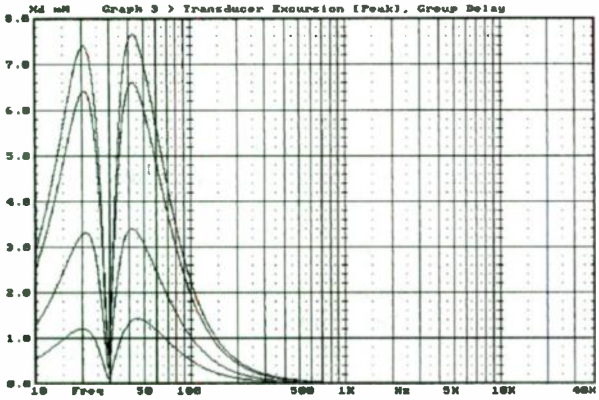


FIGURE 13: Low-frequency cone-excursion simulation of 30Hz Class I sixth-order alignment at 1, 4, 16, and 64W.

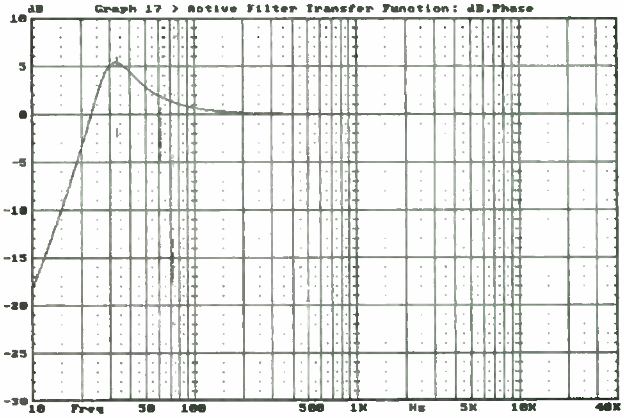


FIGURE 14: Active filter-transfer function for optimized M-shaped cone-excursion curve of Class I sixth-order alignment with crossover at 30.5Hz, Q of 1.794, and 5.42dB boost.

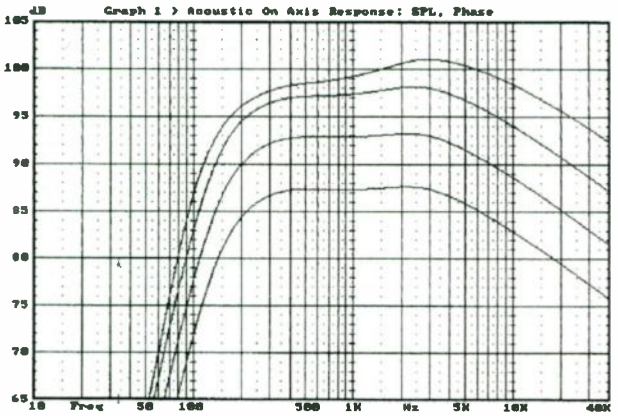


FIGURE 15: SPL simulation of the Vifa P13WH in 0.19ft^3 enclosure with 150Hz second-order high-pass filter at 1, 4, 16, and 64W.

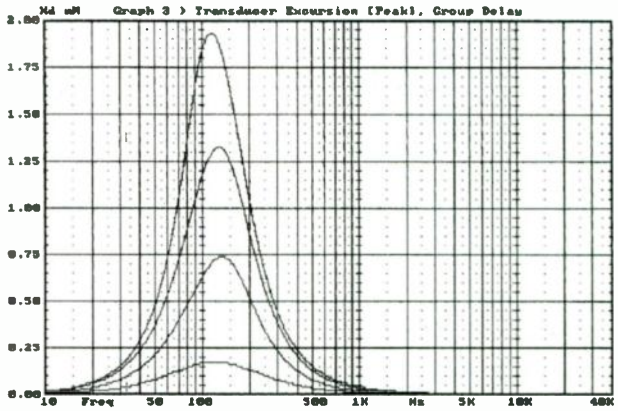


FIGURE 16: Cone-excursion simulation of the P13WH with 150Hz second-order high-pass filter at 1, 4, 16, and 64W.

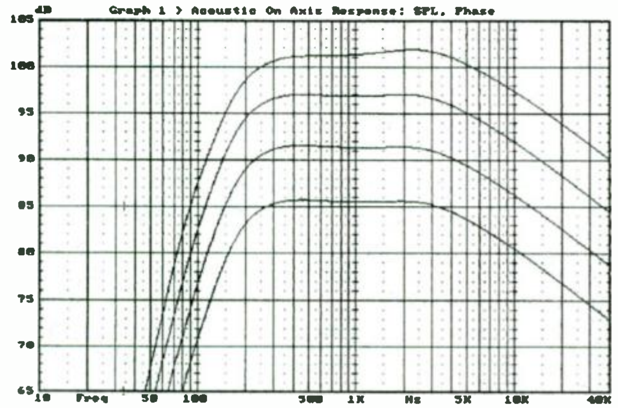


FIGURE 17: SPL simulation of the Morel MW142 in 0.19ft^3 enclosure with 150Hz second-order high-pass filter at 1, 4, 16, and 64W.

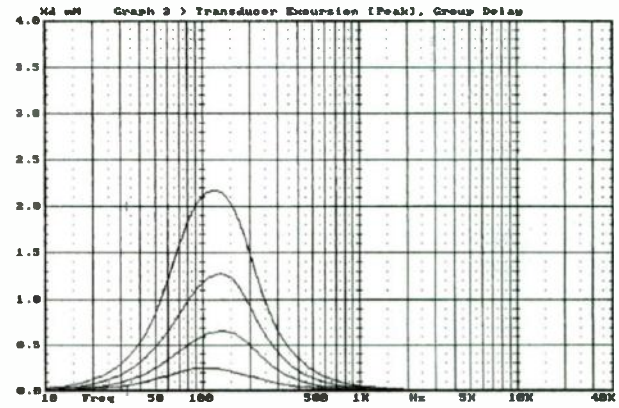


FIGURE 18: Cone-excursion simulation of the MW142 with 150Hz second-order high-pass filter at 1, 4, 16, and 64W.

the simulations, I still think the simulations are valid, since a sine-wave sweep probably doesn't heat up the voice coil as much as assumed in the simulation or as much as it would if the speaker were played with music.

The second drawback of the Vifa P13WH can be seen in *Fig. 19*, which shows that the Morel MW142 has more output between 100Hz to 200Hz, thus making possible a lower crossover to the subwoofer. There might be some subjective benefits to having the midbass driver handle more of the signal in that region.

The Morel MW142 is also better suited for the enclosure in another way, since the Q of the simulated impedance curve is .692, which is very close to the Q of .707 for a Butterworth sealed box. The Vifa P13 comes in at .600, which is a little more damped.

TWEETER SELECTION

For the tweeter, I've chosen the Scan-Speak D2905/9300 for its excellent reputation and because of the satisfying experience I've had with it in another design. Initially, I used the Morel MDT30 because it came highly endorsed. Together with the Vifa P13, the Morel sounded very good, but to discover what might be better, I tried the Morel MW142 and the Scan-Speak and found I preferred the new combination.

DRIVER SPL MEASUREMENTS

I installed the drivers into their cabinets with #8 1″ screws for the woofer and #6 ¾″ screws for the midbass and tweeter. I used a standard 16-gauge wire from Parts Express that has red and black plastic insulation, and I soldered all connections to the drivers and the input panels. For testing purposes, I built a dual-pair input panel for the satellite enclosure so the tweeter and midbass could be measured separately.

Using LinearX's Loudspeaker Measurement System (LMS), its standard M31 mike, an NAD2140 40W power amp, and a "duct lift," I measured the Scan-Speak tweeter and the Morel midbass using the gated-sine-wave method,[5] which produces a quasi-anechoic, free-field SPL measurement down to about 300Hz.

Since the driver under test was more than 7′ off the ground, the gating software effectively windowed out reflections. However, the measurement was limited to about 250Hz because as frequency decreases, the wavelengths become longer. I measured the drivers with the satellite cabinets stacked on top of the subwoofer cabinets, and with grille frames not in place.


RT1C


RT2


F6


TN28


TM1


W12

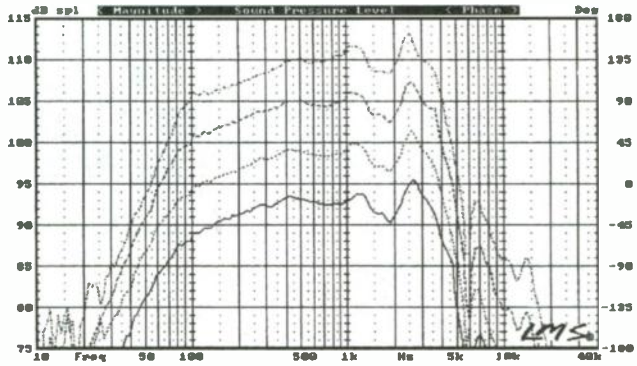


FIGURE 19: Actual SPL measurement of Morel MW142 in 0.19ft³ enclosure at 1, 4, 16, and 64W.

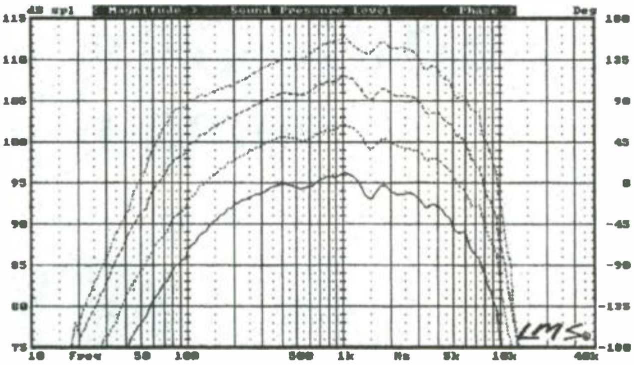


FIGURE 20: Actual SPL measurement of Vifa P13WH in 0.25ft³ enclosure at 1, 4, 16, and 64W.

I made all gated measurements with the microphone 2m from the tweeter and on-axis with it. To reference the measurements to the standard 1m at 1W, I set the output from LMS to generate 4W from the power amp, or twice the voltage as at 1W. While I could measure the satellite at 1m, when it was stacked and combined with the subwoofer, the largest dimension was 31″. So it needed to be measured at more than 1m for the measurement to be in the far field,[6] generally considered to be two to three times the largest dimension of the speaker cabinet.

GROUND-PLANE MEASUREMENT

I then measured the MW22 woofer and the MW142 using the ground-plane[7] method to determine their SPL response from 10Hz to 1kHz. The ground-plane measurement for the MW142 is spliced to its gated measurement at 250Hz to produce a full-range response. The tweeter's response drops rapidly below 500Hz, and since it is crossed over above 2kHz, a ground-plane measurement was not necessary. The LMS software allows you to "tail correct" the tweeter's response below 500Hz.

I performed the ground-plane measurements with a 1W sine-wave signal measured from 2m. Normally, you would measure with 4W at 2m to get results comparable to measurements at 1m and 1W. However, since the ground-plane measurement would be 6dB higher than a gated or anechoic measurement, you would need to "scale down" the measurement by 6dB in order to splice it to a gated measurement. Since I like to save a step or two whenever possible, I just measure at 1W at 2m for ground-plane measurements.

I took impedance measurements using the current-shunt or constant-voltage method. Using LinearX's VI box, I measured all the drivers from 10Hz–40kHz at 4W. I have compared the constant-voltage method, which uses a relatively low output, to the current-shunt procedure and have found differences that are due to port losses or damping material. Generally, I think it is best to measure loudspeakers at levels that approximate those in the

REFERENCES

1. Dickason, V., *The Loudspeaker Design Cookbook*, Fifth Edition, 1995, Audio Amateur Press, p. 43.
2. Dickason, V., ibid, p. 19.
3. Dickason, V., ibid, p. 13, Fig. 1.3.
4. Dickason, V., ibid, p. 62.
5. Dickason, V., ibid, p. 136.
6. D'Appolito, J., *Testing Loudspeakers*, First Edition, 1998, Audio Amateur Press, p. 61.
7. Dickason, V., ibid, p. 136.

"real world." Four watts is pretty loud, but I suppose if I were designing for very high levels, I could always measure at 16W or 64W with the VI box.

TAIL CORRECTING

The SPL and impedance measurements still required some post-measurement work. First, the SPL measurements were "tail corrected" where necessary. This is done at either end of the 10Hz–40kHz spectrum whenever the measurement drops so far down in level that all you see is random noise.

Since you must generate phase off of the measurement, it is critical to correct the responses as if they were rolling off or rising at 12dB per octave. With the Vifa M22WR and Morel MW142, these "corrections" were made at 15Hz and 31Hz, respectively. With the Scan-Speak tweeter, I made tail corrections at 350Hz and 35kHz. The driver's absolute phase is then generated by the LMS software, which uses the Hilbert method.

Finally, it is important to measure the time delay between the drivers, which is caused by unequal path lengths from the drivers to the microphone. This is important for crossover design, since the drivers' time delay causes dips and peaks in the crossover region. This problem occurs as the difference in driver path length becomes close to the wavelength in the crossover region. Since sound from a driver originates in the plane of the voice coil, each driver has a different time delay or path length to the microphone because of the depth of the cone or driver frames.

To measure the time delay relative to the tweeter, I measured the system with the satellite on top of the woofer, and the microphone 3m from, and on-axis with, the tweeter. By comparing the tops of the impulses, I found the MW142 midbass impulse to be 63μs behind the tweeter, and the Vifa M22WR woofer to be 187μs behind the tweeter. This information is set up in the LEAP crossover-modeling and optimization software. The SPL and impedance measurements were then imported into LEAP for crossover optimization.

Part 2 will describe the various crossover and active-filter designs.

SOURCES

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

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

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

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

Mahogany Sound
334-633-2054

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

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

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

No crash-test dummies are needed here to determine car acoustics. This author has developed a modeling method that shows the most effective speaker placement.

Auto Passenger Space As a Listening Room

By Bohdan Raczynski

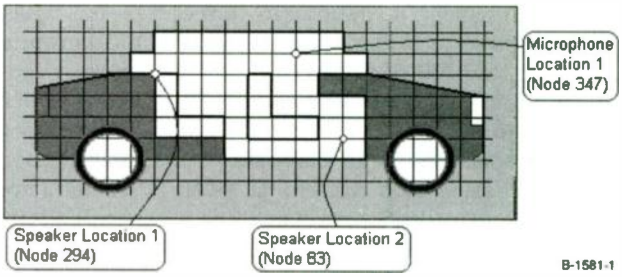


FIGURE 1: "Brick" element approximation of the passenger compartment.

As a listening environment, the passenger space of a car leaves a lot to be desired. The space is rather limited, so you can mount the loudspeakers only where there is some available room, and where the sound is not muffled or obstructed. Often, this is in door panels, or in the rear deck under the window, so you can use the interior of the trunk as a closed box.

To model harmonic acoustic behavior of an enclosed space with a sound source, the following equation is sufficient:

$$(K[][] - k^2M[][] + j\omega C[][])p[] = j\rho_0 \omega v[],$$

where $k = \omega/c$; $\omega = 2\pi f$; $j=\sqrt{-1}$; K[][] is the acoustic-stiffness matrix; M[][] is the acoustic-mass matrix; C[][] is the system damping; p[] is the sound-pressure vector; v[] is the excitation vector (in cubic meters per second); f is the test frequency; and c is the speed of sound.

SOUND SOURCE

For the source of the sound, I assume a point source, which is convenient, since you can locate it in any of the mesh nodes in my Finite Element Method analysis.[1] Larger sources would need to be part of the room boundary. Mathematically, the problem now reduces to assembling the K[][], M[][], and C[][] matrixes and inverting the expressions in the brackets. In this way, you can find vector p[] for any frequency and location of the sound source represented by excitation vector v[].

Vibration of the compartment surfaces can alter the sound generated by the loudspeakers in varying degrees. The low-quality vibrating doors can actually resonate to the point where the door panel behaves like a diaphragmatic absorber. This effect can quite significantly alter the cabin's resonant modes and pressure distribution. Taken to an extreme, the space could maintain ¼-wave resonance.

Proper mathematical treatment of this type of problem would involve "fluid-structure coupled systems," where the air trapped in the interior of the space (fluid) influences panel resonances (structure), and vice-versa. The issue is quite complex, involving a knowledge of the physical properties of the materials used in constructing the compartment. Fortunately, the quality of the interior finish in today's cars tends to be good, so at low-to-medium sound levels, the panel vibration influences the sound less than in yesterday's cheaper models with tinny doors.

In this article, I would like to concentrate on a somewhat simplified approach where I assume that the vehicle's interior is a well-built, solid structure, with most panels exhibiting damping effect (soft but good-quality finish). I modeled this damping as a uniformly distributed square matrix, C[][] in my FEM computer-program analysis.

Furthermore, I used simple "brick" elements to approximate the complex geometry of the passenger space—the white, or non-shaded area in *Fig. 1*. With this in mind, I proceeded to estimate the modal influence of the compartment on the low end of the frequency response of the loudspeaker mounted in various places inside the cabin. *Figure 1* shows the chosen locations for the loudspeakers and microphone. I entered this model into the FEM computer program to obtain a 3D-view *(Fig. 2)*.

THE ANALYSIS

It is often beneficial first to determine the resonant frequencies of the passenger compartment. The actual modal frequencies and the corresponding distribution of the acoustic pressure are a great help in identifying the peaks of the frequency response of the space itself. The FEM analysis revealed 13 modal frequencies below 200Hz. As you might expect, the lowest mode (62Hz) follows the longest dimensions of the car, with peaks at the rear window and front pedals *(Fig. 3)*. Acoustic-pressure distribution for the third lowest mode is shown in *Fig. 4*.

The modal analysis also allows me to determine the areas to avoid as possible speaker locations. The speaker placed in the exact modal spot for a given frequency will produce little acoustic output at this frequency. It goes without saying that the choice of mounting locations for loudspeakers is quite limited, since the car was primarily designed as a means of transportation, not as a listening environment.

For the purpose of further analysis, I assume that my loudspeaker has a perfectly flat frequency response. Using such a source is quite legitimate and helpful in understanding the influences

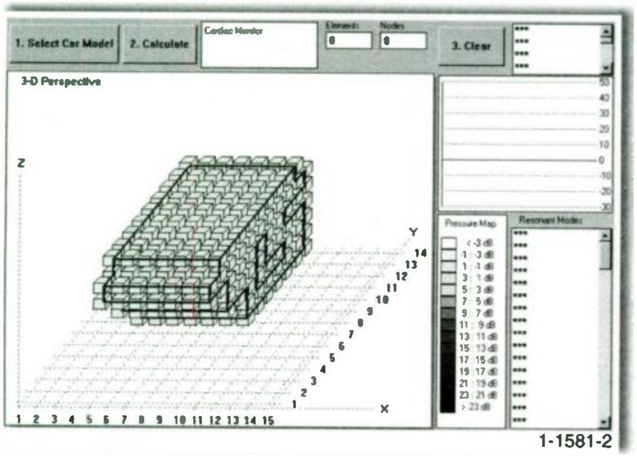


FIGURE 2: 3D passenger-compartment model.

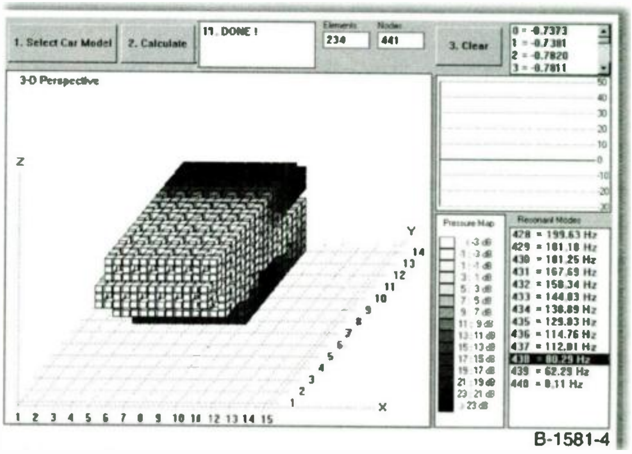


FIGURE 4: Acoustic-pressure distribution for the third-lowest mode.

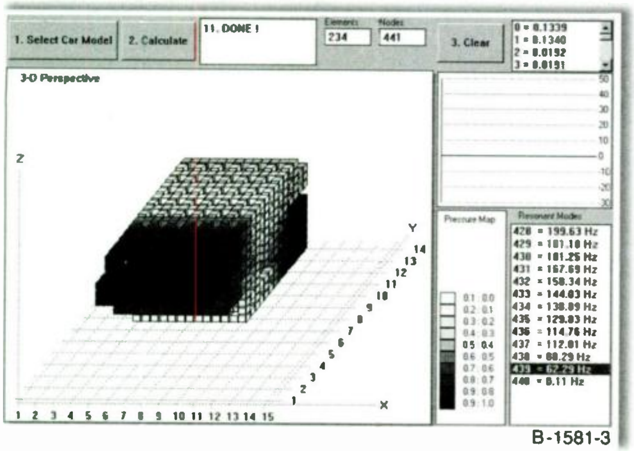


FIGURE 3: Acoustic-pressure distribution for second-lowest mode. Dark is high pressure and white shows modal line.

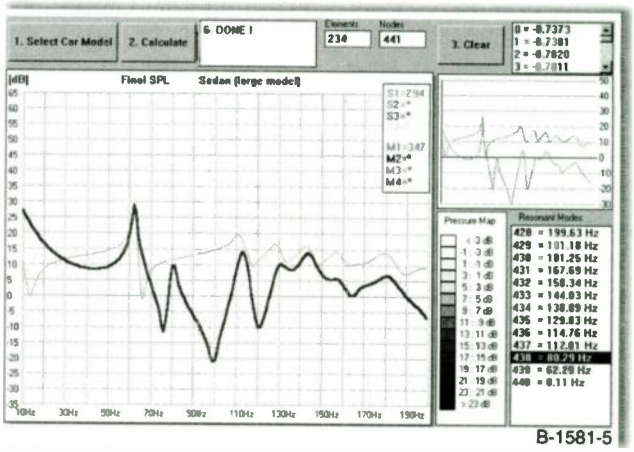


FIGURE 5: Final SPL; loudspeaker under rear window.

the compartment finish and geometry exert on the frequency response of a typical loudspeaker. When you use the "perfect loudspeaker," the only apparent amplitude irregularities are those introduced by the environment.

When a "perfect loudspeaker" is mounted under the rear window and the listening position is assumed to be the location of the driver's head, the modeled frequency response is that shown in *Fig. 5*.

Close inspection of the plot indicates (1) an overall gain of about 5-6dB averaged across a 10-200Hz frequency range; (2) a +12dB slope below 45Hz, due to the cavity effect; and (3) the frequency response is quite irregular from 60-130Hz, and then improves as modal density increases towards 200Hz. The 62Hz mode determined from my FEM analysis appears to be quite pronounced for the amount of damping assumed earlier.

Incidentally, a closed box with corner frequency at around 45Hz mounted in this car theoretically can produce flat acoustic frequency response to DC. The 12dB/octave slope of the closed box is ideally compensated by the 12dB/octave rise from the cavity effect.

DOOR-MOUNTED SPEAKER

With the loudspeaker mounted in the lower part of the front door, the modeled frequency response of my "perfect loudspeaker" is shown on *Fig. 6*. Again, inspection of the plot indicates (1) an overall gain of about 4-5dB averaged across a 10-200Hz frequency range; (2) a +12dB slope below 40Hz, due to the cavity effect; and (3) the frequency response is quite irregular from 100-190Hz, and then improves only slightly as modal density increases towards 200Hz. The 62Hz and 80Hz modes determined from my FEM analysis appear to be quite pronounced for the amount of damping assumed earlier. There is a significant energy concentration from 55-90Hz. Also, the sharp dip at 52Hz is likely to be audible.

Loudspeaker frequency response is strongly influenced by the windows' position. I have restricted my analysis to the windows-up position, which seals the vehicle interior and causes the space to exhibit resonances. Also, a vehicle under these conditions exhibits the cavity loading that introduces a 12dB per octave rise in the bass at the low end of the audio spectrum. You can estimate the corner frequency from the major dimensions of the passenger space. It varies from 45-90Hz, with the higher frequencies pertaining to smaller cars.

If it were possible to design vehicles with perfectly sealed passenger compartments, the loudspeaker cone moving forward would pressurize the space, and the pressure would be maintained as long as the cone stayed in the "forward" position. This is really equivalent to a DC (0Hz) acoustic response.

The plots shown in *Figs. 5* and *6* for two different loudspeaker locations captured both the cabin resonances and the +12dB/octave rise towards the low end

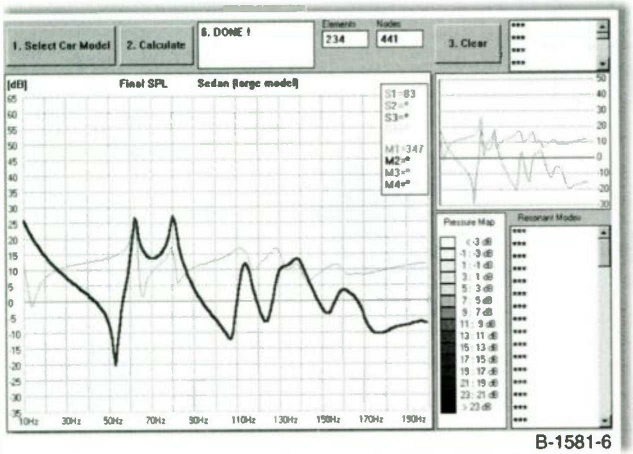


FIGURE 6: Frequency response; loudspeaker mounted in the front door.

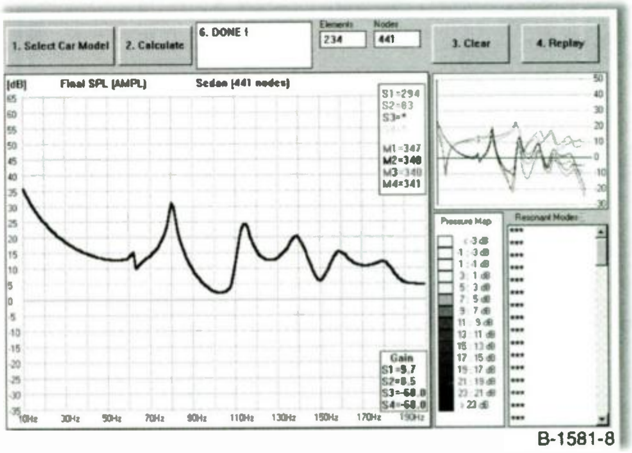


FIGURE 8: Frequency response due to two speakers with spatial averaging. Pressure amplitude squared at the four measurement nodes: 347, 348, 340, and 341.

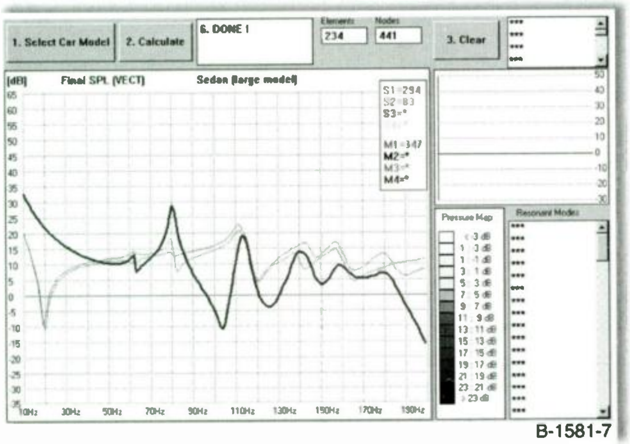


FIGURE 7: Frequency response due to two speakers.

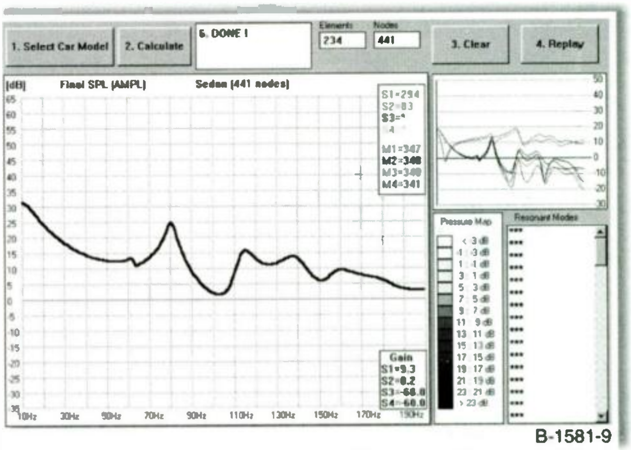


FIGURE 9: Nodes as in *Fig. 8*, but damping is increased.

of the audio spectrum. For the vehicle of the size chosen for my model, the corner frequency would be between 45 and 50Hz.

My initial assumption that the source of the sound is a point source implies that it radiates the sound uniformly in all directions. This assumption agrees well with restricting the analysis to about 200Hz, below which all sound sources appear to be omnidirectional.

With both speakers operating simultaneously, the combined frequency response would be similar to the one shown in *Fig. 7*. Despite its "bumpy" character, I would prefer this combined frequency response to either of the individual plots obtained for single-driver operation. The peaks and valleys cannot be avoided in the closed compartment, but you can significantly reduce their influence by making the interior "softer," i.e., more absorbent. You can further reduce the remaining irregularities by electronic equalization, thus making the total frequency response more acceptable.

CONCLUSION

In the preceding short discussion, I have presented one possible approach to modeling car acoustics. I based the discussion on the steady-state response, where the compartment modes carry the acoustic energy.[2] With the additional assumptions of decoupling the volume of compartment-air resonances from the car-body resonances, and interior panel damping represented by the uniformly distributed damping matrix C[][], I was able to obtain frequency-response plots for two loudspeaker/microphone locations (*Figs. 5* and *6*). The plots show clearly the modal (resonating) behavior of the passenger compartment, together with the pressurization at the lowest audio frequencies (sometimes called the cavity effect).

Another set of plots (*Figs. 8* and *9*) presents the more realistic situation of using space averaging over four microphone locations, placed in the horizontal plane of the driver's head. The accuracy of the analysis in the upper range of frequencies was limited by the size of the "brick" elements I have used. The dimensions were: Y = 27cm, X = 25cm, and Z = 20cm. Smaller elements would increase accuracy around 200Hz, but at the expense of significantly increased computational time. The final frequency response shown in *Fig. 9* seems quite acceptable compared to where I started (*Figs. 5* and *6*).

REFERENCES

1. I performed the preceding analysis using the SoundEasy V3.3 computer program.

2. Earl R. Geddes, "Small Room Acoustics in the Statistical Region," AES 15th International Conference, 1998.

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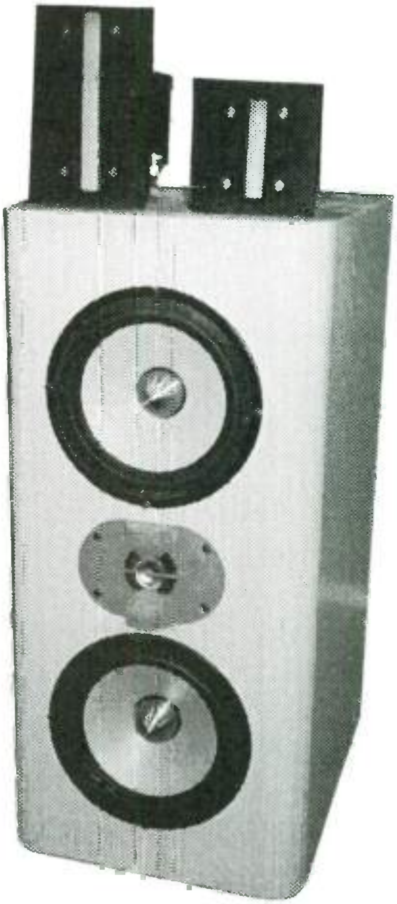

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With the conclusion of this three-part tour of transmission lines, you should now have enough information to appreciate what makes the TL special and to tackle building your own.

Part 3

Transmission Lines: The Real Story

By A. Monk

Part 3 deals with the heart of the transmission line, the characteristics of the fiber as it affects the optimization of the TL. This requires a bit of mathematics—the examination of Bradbury's equations. However, you can visualize the results in the graphs, and solving the equations is necessary only for a specific design problem.

In the examination of the TL response in standard acoustic texts, several questions arise relative to the modeling of the response of a piston in a long tube. I explore these questions in the section headed "TL Model Esoterica," which you can skip if you are not interested in the modeling question.

HELMHOLTZ RESONATOR

Before diving into the fiber mass, I will revisit a subject previously touched upon. Among TL practitioners, and even in the general DIY community, the question as to whether the TL is a Helmholtz resonator lacks a consensus. I hope to define the question more rigorously and see whether an answer is possible.

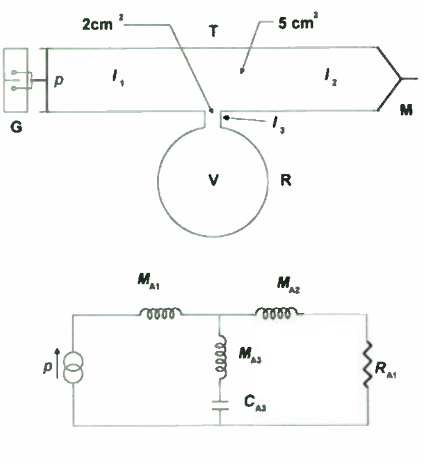

FIGURE 36: Representation of a Helmholtz cavity.

A model for the Helmholtz cavity (*Fig. 36*) is given in *Acoustics*, by Beranek (p. 69), along with the derivation of the response equation. The Helmholtz resonator is object R of volume V, with a neck length l_3 and a neck area S_R. The lower figure is the equivalent circuit model, where the M_{A3} and C_{A3} elements represent the Helmholtz cavity.

From this model you can derive the resonance frequency as a function of V, l_3, and S_R:

$$M_{A3} = \frac{\rho_a \times l_3}{S_R} \qquad [1]$$

$$C_{A3} = \frac{V}{\gamma P_o} \qquad [2]$$

$$\omega = (M_{A3} \times C_{A3})^{-0.5} \qquad [3]$$

Using these equations, you can simulate a typical Helmholtz-cavity response (*Fig. 37*). The physical cavity is a box of V = 4073.7cm^3, with panel thickness equivalent to neck length l_3 = 2cm, and neck area SR = 9cm^2.

With a frequency sweep of 20Hz–1kHz driving a speaker at the neck of the cavity and a microphone inserted through the side of the cavity, you obtain the following response: f_0 = 46.6Hz, BW_3 = 10Hz, and Q = 4.6. Magnitude and phase are plotted. Note that phase = 0^0 at f_0.

Now you can compare the response of a 0.914m TL. Two response comparisons are necessary: an active, normal TL response for an unstuffed line, and a passive response for the TL driven from the terminus end with an external source such as the Helmholtz resonator.

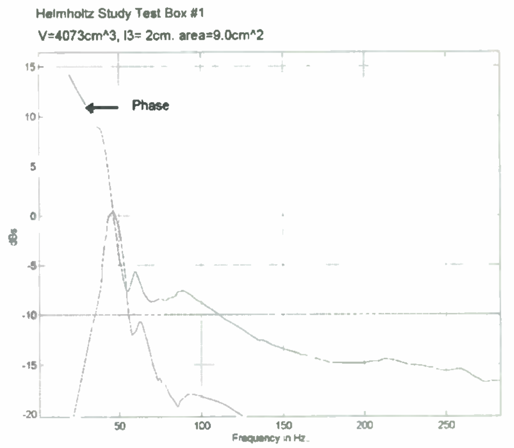

FIGURE 37: Measured response of a Helmholtz cavity.

Figure 38 gives the nominal magnitude and phase response for a line driven at the closed end. The unstuffed line response should be familiar. The harmonics are frequency shifted and attenuated as a function of line length.

The TL line has a distinct bandwidth (BW) response, with the low-end slope defined by −18dB/octave, and the high-end characterized by line length. Note that, unlike the Helmholtz response of *Fig. 37*, the phase transition is shifted lower from the f_0 peak.

Figure 38 is the line response at the terminus end; however, the Helmholtz is measured inside the chamber, so you need to see how the line appears at the top of the line, the closed end.

Figure 39 is the TL response at the top of the line, i.e., at the back of the woofer. Ignoring the nulls that are functions of the line harmonics, note the response around 100Hz. It is flat to about 20Hz, and when a fiber mass is introduced, the nulls are sharply

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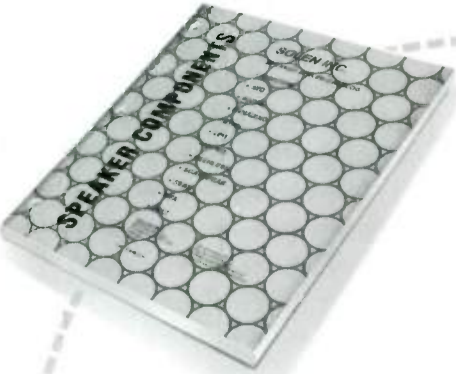

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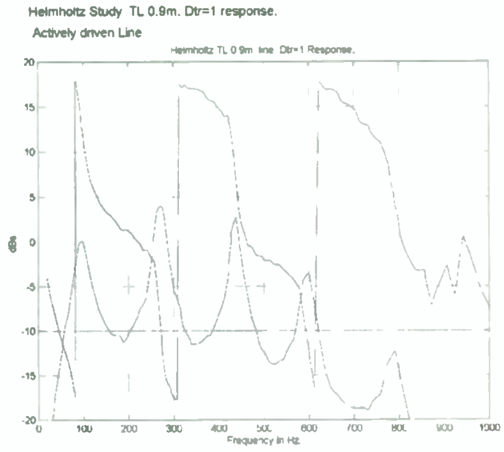


FIGURE 38: TL resonance response at the terminus end.

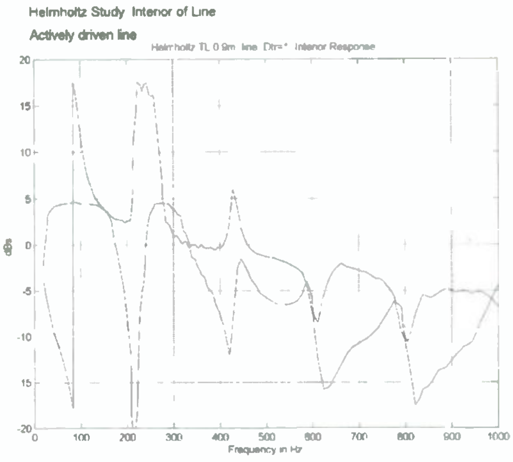


FIGURE 39: TL closed-end response at the top of the line.

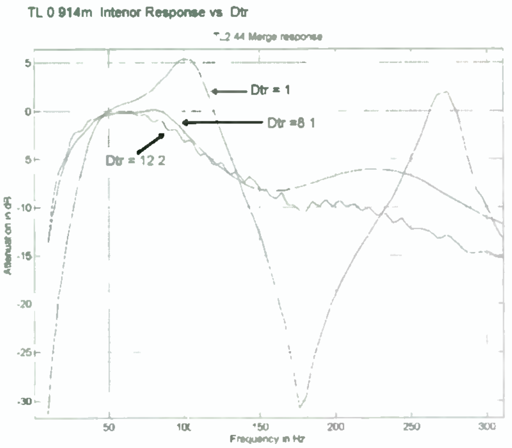


FIGURE 40: TL closed-end response.

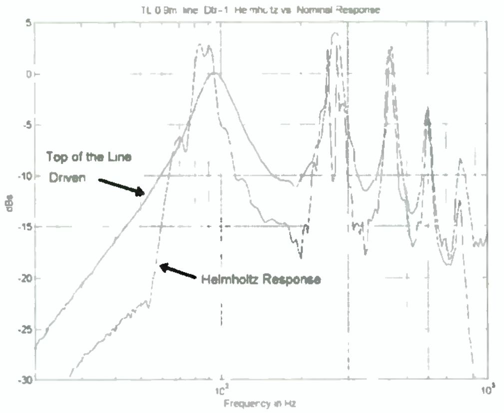


FIGURE 41: TL response comparison (active versus passive drive).

attenuated and the low-frequency knee tends toward the DC limit.

Knowing that the F_R is approximately 90Hz for a 1m line, you can compare it with the response BW around $F_R = f_0$ of *Fig. 37*, the Helmholtz cavity's BW. The two responses are significantly different.

TL MODEL ESOTERICA

In most acoustic reference books, the interior line response is modeled as the cone of the driver loaded by the air mass in the line,

$$M_A = \frac{\rho_0 l'}{\pi a^2} \qquad [4]$$

and the expected driver's response would be a high pass with the knee of the slope moving down in frequency. That is what you see in *Fig. 40* for the low-frequency slope. For the DTR = 1, the slope is approximately −18dB/octave at 50Hz, and as DTR increases, the low-frequency slope knee moves down to about 30Hz. As the DTR value increases further, you see a smaller but significant lowering of the slope point.

Thus you can surmise that the effective air-mass density increases as the fiber density rises, and that equation [4], which relates air mass as an inverse function of tube radius, is not adequate for a TL. The more significant point is that the interior response is defined by the line harmonics that are attenuated by the fiber mass.

A very interesting observation is that the F_R, defined as the peak of the response, moves higher in frequency from the calculated ¼λ value, and shifts lower in frequency as D_{TR} increases. I'll explore the significance of this later. For the present, the *Figs. 39–40* data shows that the response of the TL is more complex than the one-end-open piston-driven model of the acoustic texts, and that you must model it from the measured data.

The comparison should be done for a TL driven similarly as the Helmholtz. For this, you must remove the driver, seal up the mounting hole, and drive the line with an external source.

Figure 41 shows that the TL driven from the terminus, i.e., as a Helmholtz cavity would be driven, has a unique signature compared with that of the nominal TL $D_{TR} = 1$. The critical differences are the low-frequency slope, the shift in f_0, and the attenuation of the higher harmonics. The harmonic structure is similar, so the geometry of the line dominates.

To summarize the data:

- The unstuffed TL response is defined by a harmonic structure, a function of line length, and a complex BW whose lower slope has an 18dB/octave attenuation, while the upper slope is line-length dependent. The most prominent feature is the harmonic content.
- The signature of the TL line in its normal, active mode is different from that of the passive mode, i.e., when the line is driven like the Helmholtz.
- The Helmholtz mathematical model is inadequate to characterize the TL's response.

TABLE 7
REPRESENTATIVE FIBER PARAMETERS

	FIBERGLASS	LONG-HAIRED WOOL	MIRAFLEX (ESTIMATE)
Packing density P	21kg/m^3	35kg/m^3	42kg/m^3
Fiber diameter, d	0.005mm	0.028mm	0.032mm
Flow resistance, λ	12600 N × sec/m^4	5700 N × sec/m^4	970 N × sec/m^4

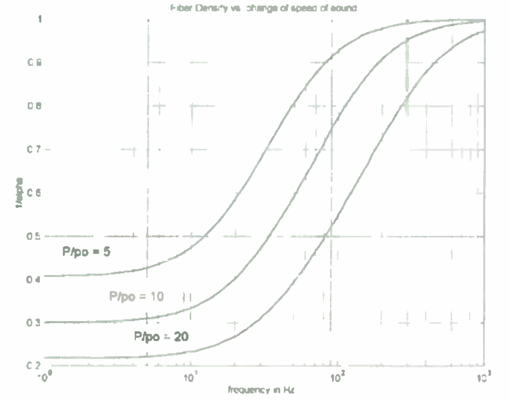


FIGURE 42: Change in speed of sound versus frequency for fiber density.

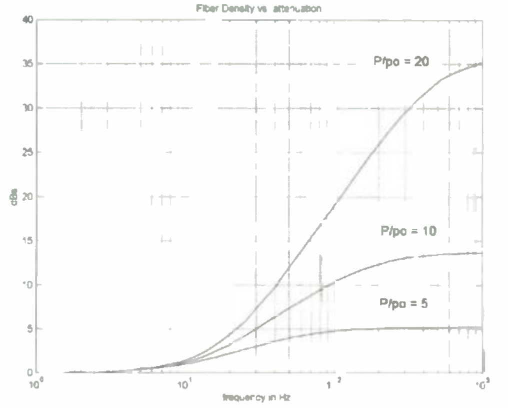


FIGURE 43: Attenuation versus frequency for fiber density.

The necessary conclusion is that the TL is a resonant line, but it is distinct from the Helmholtz cavity and must be studied using a distinct model. To forgo this distinction leads to verbal confusion and impedes the development of a mathematical model for the TL.

THE FIBER QUESTION

The fiber mass used in a TL occupies about 5% of the volume. The main effect of the fiber mass on the sound passing through it is aerodynamic drag, which is symbolized by λ, as used by Bradbury. Unfortunately, this is the same symbol as used for the wavelength when computing the line's resonant frequency. To change it would lead to confusion for those who will later refer to the Bradbury paper, so I'll leave it as is.

The fiber diameter is usually about 0.01mm, very much smaller than the wavelength of the sound passing through the stuffed line. In this model the aerodynamic drag is proportional to the velocity of the air flowing past the fibers. You can characterize this by Bradbury's equation:

$$p\frac{du_f}{dt} = \lambda\left(\mu_a - \mu_f\right) \quad [5]$$

where P is the fiber mass/unit volume, μ_a is the air velocity, μ_f is the fiber velocity, and λ is the fiber's drag coefficient.

This leads to the fiber equation, but before using that, it is necessary to compute λ. Unfortunately, the available data for defining λ is somewhat ambiguous as to the value of the exponent (1.4) and the constant a (27). The drag-parameter equation

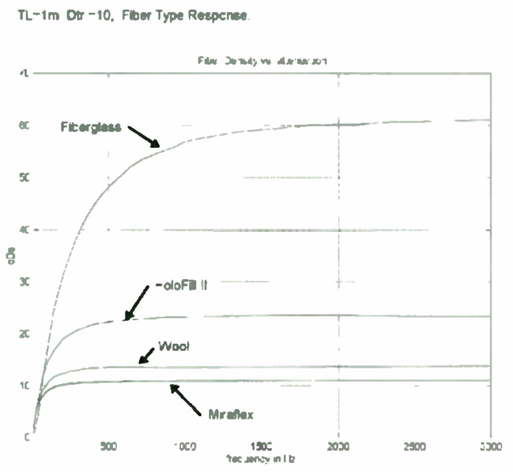


FIGURE 44: Fiber-type response comparison: 1/alpha response.

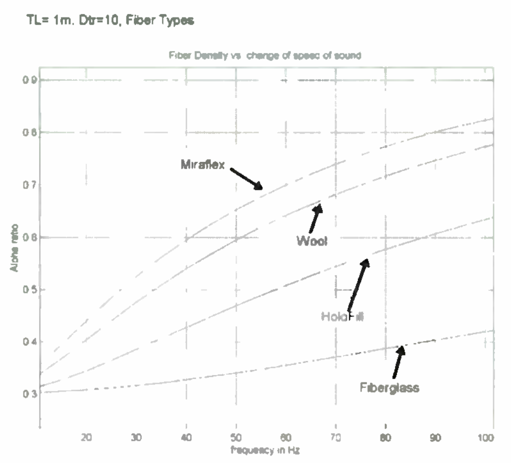


FIGURE 45: Low-frequency fiber characteristics.

$$\lambda = 27\frac{\mu}{d^2}\left(\frac{P}{\rho f}\right)^{1.4} \qquad [6]$$

(where μ = 1.18E–5 kg/(m/sec) at normal temperature) relates the fiber diameter, d, to the packing density P. Therefore you can regard this as the heart of the TL design, since it will define the optimum packing density for a specific line length. This is a very powerful result, since it will define a unique response curve for each fiber type. Thus, by knowing a single data point for a fiber type, you can identify and characterize the fiber's parameters (*Table 7*).

Using equation [5] and solving for a simple harmonic sound wave of angular frequency ω that propagates through a fibrous material, you arrive at the fiber equation:

$$\alpha + i\beta = \sqrt{\frac{(1 + P/\rho_a) - i\omega P/\lambda}{1 + i\omega P/\lambda}} \qquad [7]$$

where α is related to the change of speed of sound in the fiber mass; β is related to the attenuation in the fiber mass; ρ_a is equal to the density of air, 1.18kg/m^3; P is the fiber packing density; and λ is the fiber's flow resistance.

You can separate the real and imaginary parts of equation [7] and specify the attenuation and the change-in-velocity components of the wave in the fiber mass.

$$\alpha = \left[\frac{(1 + P/\rho_a)^2 + (\omega P/\lambda)^2}{1 + (\omega P/\lambda)^2}\right]^{0.25} \cos\theta \qquad [8]$$

$$\beta = \left[\frac{(1 + P/\rho_a)^2 + (\omega P/\lambda)^2}{1 + (\omega P/\lambda)^2}\right]^{0.25} \sin\theta \qquad [9]$$

$$\theta = ½\left[\tan^{-1}\frac{\omega P}{\lambda} - \tan^{-1}\frac{\omega P/\lambda}{1 + P/\rho_a}\right] \qquad [10]$$

Equations 8–10 can be solved numerically (*Figs. 43–46*).

Figure 42 shows the change in speed of sound in the fiber mass as a function of fiber density. The P/ρ_a is a density ratio, and I'll use the symbol D_{TR} to refer to it. The fiber type is wool, and I did the calculation for D_{TR} = 5, 10, and 20. To put these numbers into context, D_{TR} = 12 is the optimum value for a TL 0.914m long, since F_R is about 90Hz. The wool-type fiber would exhibit a 30% reduction in the speed of sound at F_R.

Notice that the curves flatten out around 10Hz, so you can assume that the fiber type will define a lower limit in effectiveness in modifying the speed of sound in the fiber mass. From empirical measurements for wool, this is about 50Hz. This data shows that your design should aim for the middle of the curve.

Figure 43 is the corresponding solution for β normalized to line length. Note that as D_{TR} increases, attenuation rises and it shifts in frequency. Thus for D_{TR} = 5, the effective range is 20–100Hz, while for D_{TR} = 20, the range is 20–500Hz. Since in TL design you wish to attenuate the line harmonics, you need to select a fiber that will give the maximum attenuation, but this is counterbalanced by the necessity for an effective 1/α ratio. Both these values change with line length. Now you should have a better understanding of the black art of the use of fiber in TL design.

EFFECTS OF FIBER TYPES

Next I'll examine the different response and flow-resistance values of various fiber types, and how these relate to line length.

Historically, fibers used to stuff TLs are wool and a Dacron type, HoloFill II, commonly referred to as pillow stuffing. Fiberglass has also been used, and two new types, Miraflex and Acousta-Stuf, have recently been advocated. Is there any basis for preference? Bradbury's equation [7] provides the means of classifying their characteristics; unfortunately, I do not have the fundamental parameters for the newer types.

Using these fiber parameters, you can compute some response curves for comparison. As an arbitrary reference, I'll use a 1m line and a D_{TR} of 10. *Figure 44* shows the response for the fiber fundamental variables of *Table 8* for an arbitrary TL of 1m and D_{TR} of 10.

Note that the knee region moves lower in frequency as the fiber flow resistance decreases. Equation [6] shows this is related to fiber diameter, which is a second-degree factor. Therefore you can say that fiber diameter dominates. Of interest here is the relative performance of the fibers at low frequencies, i.e., below 50Hz, where the TL construction is most difficult.

Figure 45 is a magnification of *Fig. 44* data for the low-frequency range. Note that below 50Hz, only wool and Miraflex has any slope and that fiberglass is essentially flat. This says you cannot expect any change in the speed of sound in the sub-100Hz region for fiberglass, or in the sub-50Hz range for HoloFill. Miraflex is slightly better than the old stand-by, wool. With this data, you can begin to gain a quantitative understanding of how fiber characteristics affect TL line-length tuning. Now take a look at the comparable data for fiber attenuation.

FIBER-TYPE ATTENUATION

Figure 46 shows the comparative attenuation for the fiber types of *Table 8*. The attenuation is greatest for fiberglass and least for Miraflex. The knee of the curves, as for the 1/α data (*Fig. 44*), moves lower in frequency with decreasing fiber flow

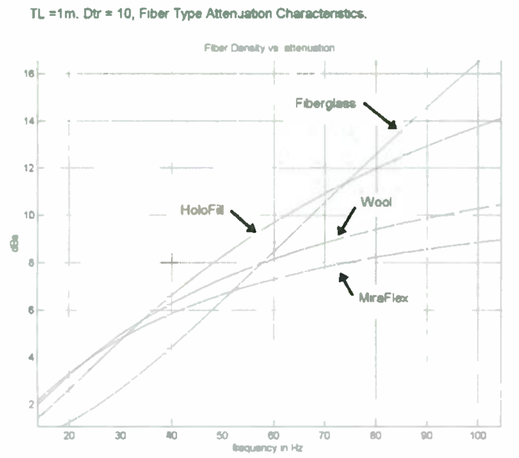


FIGURE 46: Fiber-type attenuation characteristics.

TABLE 8

FIBER TYPE FUNDAMENTAL CHARACTERISTICS

	PACKING DENSITY	DIAMETER	FLOW RESISTANCE	NOTES
Fiberglass	21.0 kg/m^3	5.0 E-6 m	4000 N × sec/m^4	Measured data
Holo Fill II	28.0 kg/m^3	2.0 E-5 m	1100 N × sec/m^4	Extrapolated data
Wool	35.0 kg/m^3	2.8 E-5 m	1000.9 N × sec/m^4	Measured data
Miraflex	42.0 kg/m^3	3.2 E-5 m	970 N × sec/m^4	Guess
Acousta-Stuf	45.0 kg/m^3	3.5 E-5 m	960 N × sec/m^4	Wild guess

Notes: The extrapolation for HoloFill is based on measured data versus wool, where the density for comparable response is approximately 30% that of wool in lines 0.914 to 1.5m. The Miraflex guess is based on simulation curves.

resistance. This result shows that the fiber with the smallest diameter is best for attenuating the higher harmonics; however, this is the opposite of the requirement for the change of speed of sound in the fiber mass for low-frequency design.

Here is the crux of the stuffing question: contrary requirements and the necessity to balance them for a specific line length. Now you can understand the fallacy of using a single stuffing density, usually 0.5 lbs/ft^3, for all line lengths.

Figure 46 is the magnification of the *Fig. 45* response for the low-frequency region. This data is a bit of a puzzle, since it shows that fiberglass has a lower attenuation below 50Hz than the other fibers. My expectation was that fiberglass would have exhibited a shelf-type response. It is impossible to say whether this is an accurate representation or an anomaly of the mathematical model, since I lack empirical data in this region to verify the computed model. The problem here is that the acoustics of the line-attenuation characteristics are larger than those of the fiber mass for the harmonics, and it is difficult to separate the two effects.

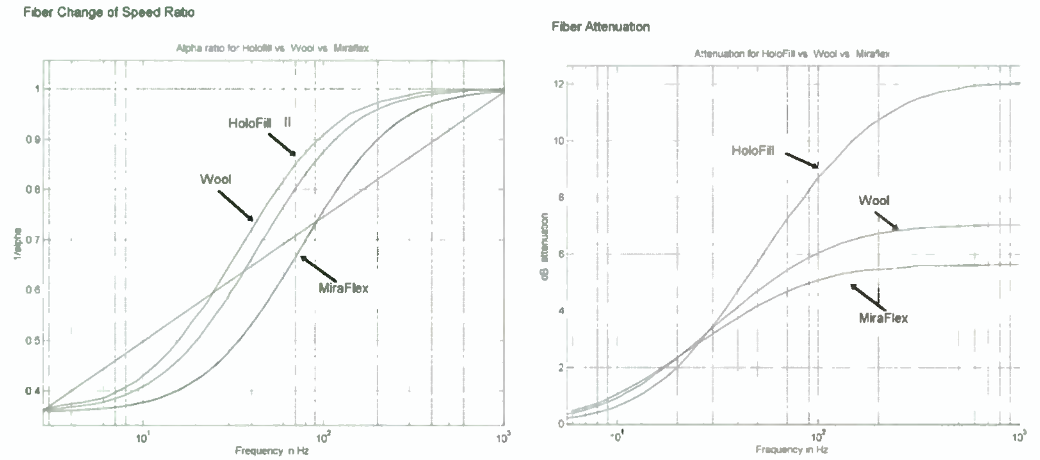
It is clear from the *Fig. 46* data that the harmonics of the longer lines will be minimally attenuated, so in order to remove the nulls in the TL's system response, you must look to other techniques than fiber density. The calculation was done for a D_{TR} of 10, while for a 2.5m line the optimum value would be about 4; therefore the expected attenuation for the first harmonics would be minimal.

FIBER-DENSITY PUZZLE

You might now have a good grasp of the fiber characteristics as related to the TL, yet remain puzzled as to how all of the foregoing applies to the optimum fiber density of a particular line design. In trying to answer this question, I'll examine two documented solutions. The first design is for a TL = 0.914m using Holofill, and the second is an application for a 2.25m line using wool fiber.

To predict stuffing density, all you can do is use reference-table data. It is not possible to form an equation that would be rigorous, since the variables versus line length are too complex. The prediction of the fiber effects on magnitude and phase of the transmission line's length remains in the realm of a mathematical TL model in which the response simulation is possible.

Such a hypothetical model would involve choosing a specific line length and examining the characteristics for the three most common fiber types. If you make the D_{TR} value a dynamic variable that you can change with a mouse drag, then the windows in *Fig. 47* become powerful visualization tools to understand the solutions of the Bradbury equations ([7], [8], and [9]).



Fiber 1/alpha, Window #1

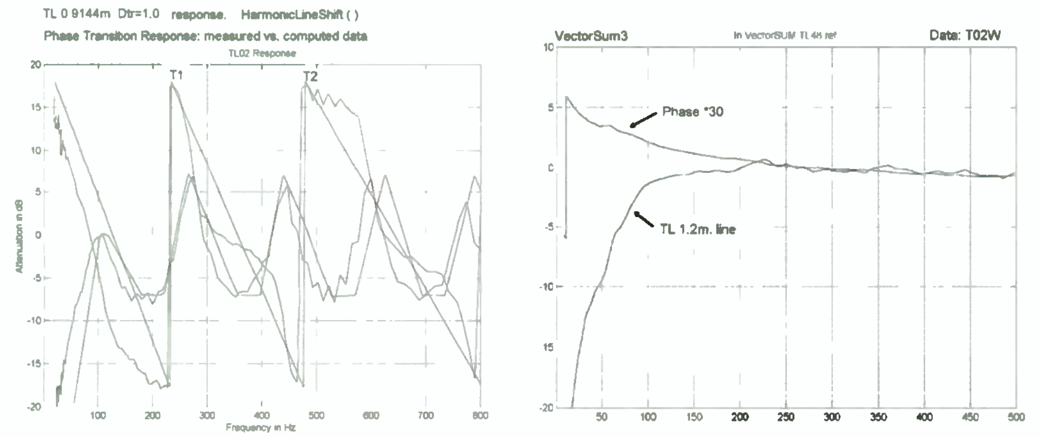
Fiber Attenuation, Window #2

FIGURE 47: Simulation data for D_{TR} = 8 and line length = 0.914m.

Such specific variable windows would be menu selected and could compare fibers or two types of woofer response in the TL line. The choice would depend on the design requirement. For instance, you could compare a saved design versus the on-screen design, or the response of parallel lines where one line's dimension is variable. The visualization of data opens new design options that were previously too difficult to consider.

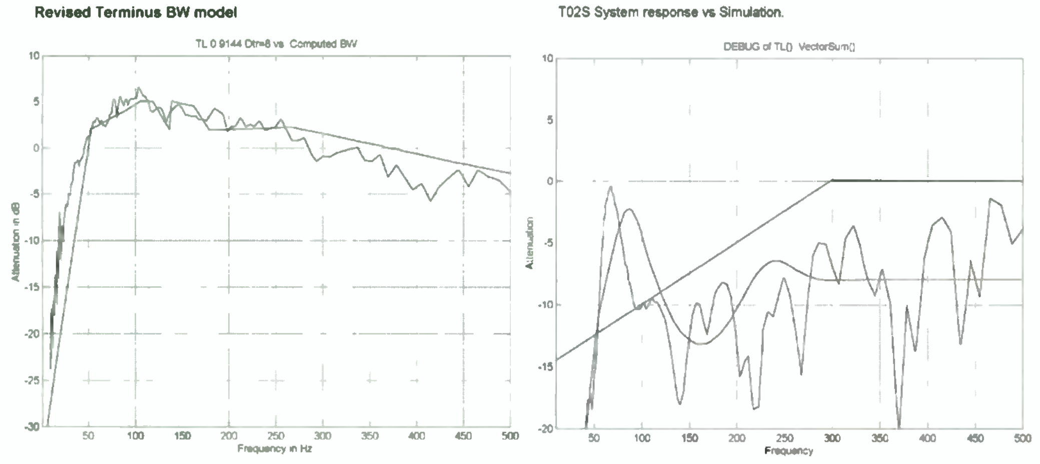
You could extend this concept to a hypothetical TL system-design window consisting of the following sub-windows (*Fig. 48*):

- the unstuffed line (D_{TR} = 1) response, indexed to line length. This would show the F_R slope and the resonant harmonic structure of the line;
- the woofer's Q_{TC} = 0.5 magnitude and phase response, as derived from T/S parameters. Correlated to the unstuffed line F_R frequency, this would show you the driver's applicability to the chosen line length. You could read the response data from a data file for a measured response, thus giving an indication of the large-signal response characteristics.
- the terminus response window, indexed to the line length, fiber type, and



Dtr = 1 Line Response Window #1

Woofer Qtc = 0.5 Response, Window #2



Terminus Response, Dtr variable, Window #3

TL System Vector Summation, Window #4

FIGURE 48: TL mathematical-model response simulation.

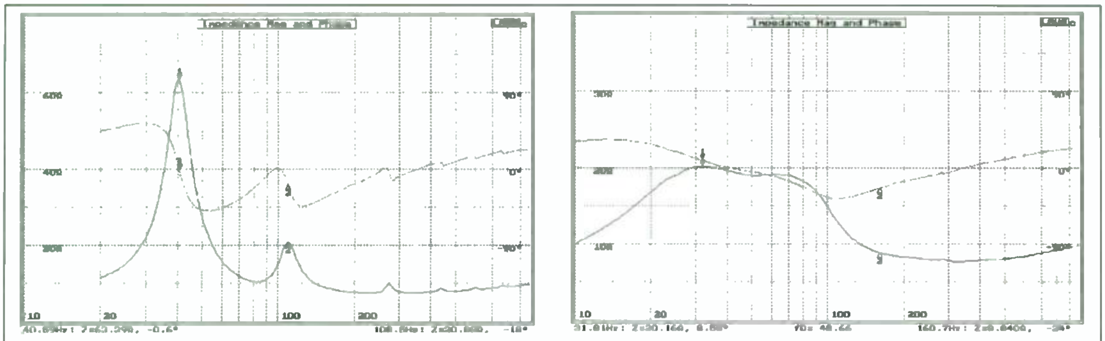


FIGURE 49A and 49B: Impedance shift: DTR = 1 to DTR = 12.

D_{TR} value. This would dynamically show the BW response and the attenuation of the line harmonics; and

- the TL system-response window, which would show the vector summation of the woofer's and terminus responses, and would indicate the effectiveness of the selected fiber type and the degree of optimum D_{TR} value achieved.

Since the display windows would be composed by the user, any overlay type of measured data from a reference file versus calculated response would be possible, and the calculated response would be dynamic, indexed to the chosen variable.

The visualization of the dynamic effects of the TL variables on the system response could be, as well as a design tool, a potent means of understanding the TL dynamics. The underlying mathematics would be hidden from the end user, and the TL's complexity reduced to an interactive graph.

TL 0.914-METER RESPONSE

With the accumulated knowledge of the first two parts of this article, you can examine the response of the line for an optimum fiber density. Due to the amount of necessary supporting data, the graphs I'll present will be small, useful only to jog the memory.

As you change the fiber density in the line, you see the change in response at several levels: the impedance, the terminus, and the system response. I will attempt to show how—according to fiber type—the change in the speed of sound ($1/\alpha$) is related to these system changes. Finally, I'll show how this leads to the vector summation of the near-field woofer and near-field terminus, resulting in system response.

The first system response affected by fiber density is the impedance data (*Figs. 49A* and *49B*). Note how the peaks of the impedance, the driver's f_S, and the line-resonance primary defined by F_R merge into the flat-topped response. The peak magnitude is diminished, the harmonics are attenuated, and the phase response is flattened.

The second system response is that

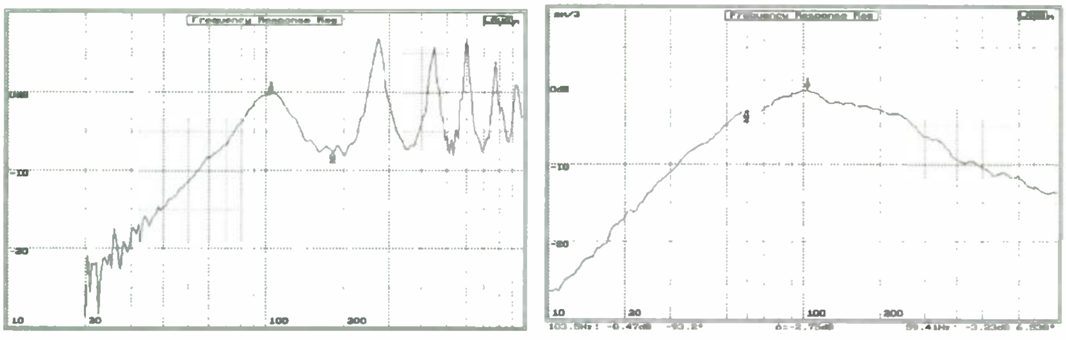


FIGURE 50A and 50B: Terminus response DTR = 1 to DTR = 12.

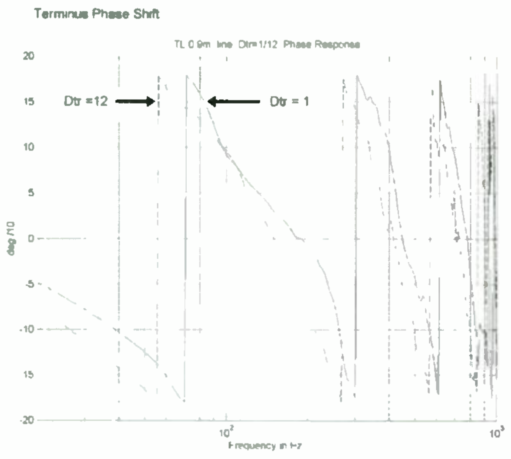


FIGURE 51: Terminus phase shift.

Cabasse 21NDC driver, Qtc=0.5 alignment
TL Cab response, note it is 100Hz band pass limited.

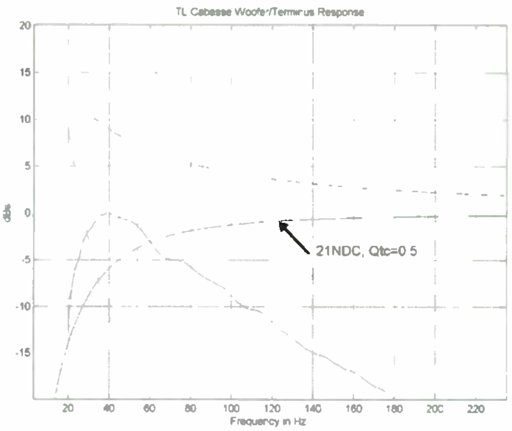


FIGURE 52: A TL sub implementation, system response.

Final Terminus Response (FinalVent.txt)
TLcab04T

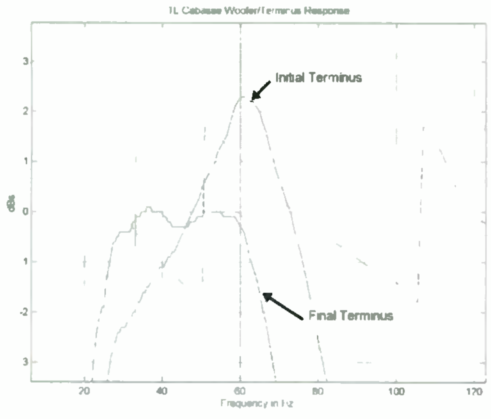


FIGURE 53: TL 2.3m; terminus versus D_{TR} value.

of the terminus (*Figs. 50A* and *50B*). Here you see that the harmonics of the empty line are attenuated and replaced with a BW shape response. The fiber density attenuates the harmonics, but how does it produce the TL system response characterized by the peaks and nulls? Simply adding the woofer BW and the terminus BW will not get you the 1m response. And what has the speed of sound to do with it? Phase! See how the phase changes as the fiber density increases.

Figure 51 shows the phase response of a TL of 0.914m for an empty-line (D_{TR} = 1), and at optimum density (D_{TR} = 12). Note that all the transition frequencies are shifted, but the biggest shift proportionally is around 50–70Hz, corresponding to the F_R of the TL.

TL 2.25-METER RESPONSE

The 2.25m TL is interesting from two points of view: it is a TL sub design, i.e., where the TL's response has been deliberately bandwidth-limited, and it extends and achieves an optimized response close to the limits of the wool fiber. As you examine the graphs, please keep in mind that the signal to the system has a −12dB/octave low pass at approximately 100Hz, producing a somewhat unusual slope response in the terminus.

The aim of the design was to achieve a 30Hz response in a small box, so it incorporated an unusual folding scheme. For the 2.25m line, the F_R = 38Hz that is fiber-shifted to about 35Hz resulted in an f_s of approximately 30Hz. The driver chosen was a Cabasse 21NDC, whose simulated Q_{TC} = 0.5 response is shown in *Fig. 52.* This choice necessitated a terminus gain of about 6–7dB, which is close to the maximum practical value and, when combined with the wool's fiber-response-curve limits, is what makes this particular design so interesting.

Figure 53 shows the fiber effect on the terminus response. The initial response was for an unknown density estimated as a D_{TR} of approximately 4 to 5, which was reduced until the final measured response of D_{TR} = 3.5 was accomplished. Notice that the peak gain is higher for the initial value, but at F_R = 35Hz the gain is 12dB lower. Thus the final value is the optimized value. Note also the phase shift as shown in the figure.

This is an excellent demonstration of the effect of phase on system response. If you understand the implications of this data on TL system response, you have understood the TL design process.

OPTIMUM D_{TR} VALUE

Several times I have used the term "optimum stuffing density" without giving a rigorous definition that could be used unambiguously in a design process. This was not due to oversight, but to the necessity of laying out the empirical data that would support such a definition.

It was necessary to provide a basis for understanding the magnitude and phase relationship in the vector summation of the two components making up the system's response, as well as the concept of fiber-flow resistance that defines the attenuation and the change of speed of sound in the fiber mass, and how this affects the phase of the terminus signal and the limits of a particular fiber type as related to these characteristics. This question of optimum fiber density has led to a great amount of

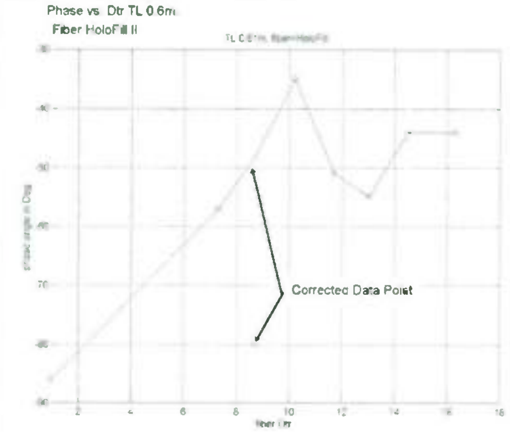


FIGURE 54: TL 0.6; D_{TR} versus phase angle.

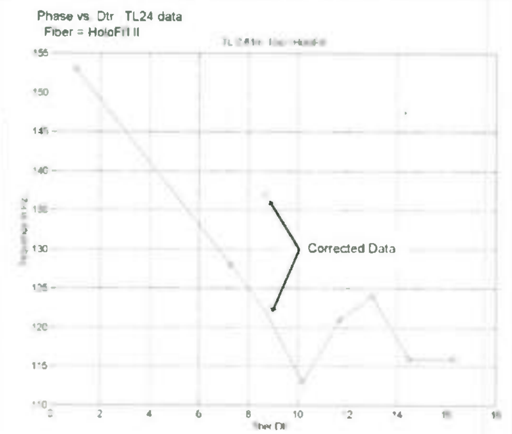


FIGURE 55: TL 0.6; D_{TR} versus F_R frequency.

confusion, sufficient proof of its complexity.

Figures 50A and *50B* showed how the terminus magnitude changed with the increase in fiber density, and *Fig. 51* showed the corresponding phase shift. Since the terminus response resembles a BW response and that of the woofer resembles a $Q_{TC} = 0.5$ response, and both are relatively smooth, continuous functions, magnitude addition does not account for the TL system's response of peaks and nulls around the F_R slope knee.

What changes is the phase angle, as shown in *Fig. 51*, and phase is directly related to the fiber's $1/\alpha$. This data gives an indication of the optimum density for a specific line length and fiber type, but it is soft data, and thus liable to misinterpretation. More desirable would be hard data, i.e., distinct characteristics of the optimum D_{TR} value.

TABLE 9
TL 0.62 METERS, FIBER HOLOFILL

	CALCULATED	$D_{TR} = 1$	ΔCALC.	$D_{TR} = 7.3$	$D_{TR} = 10.2$	
F_R	141Hz	153Hz	+12Hz, +8.5%	128Hz/–13Hz	114Hz/–27Hz	Opt=10.2
1st null	283	261	–22Hz, –7.8%	244Hz/–39Hz	238Hz/–45Hz	crossover
1st peak	424	387	–37Hz, –8.8%	353Hz/–71Hz	337Hz/–87Hz	
2nd null	565	523	–42Hz, –7.5%			
2nd peak	706	644	–62Hz, –8.8%			
3rd null	848	775	–73Hz, –8.4%			
3rd peak	989	870	–119Hz, –11.2%			

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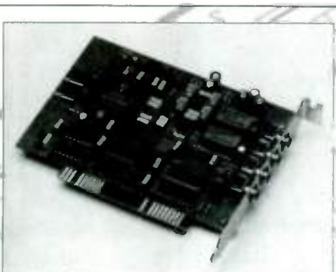
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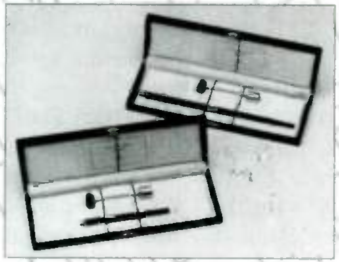
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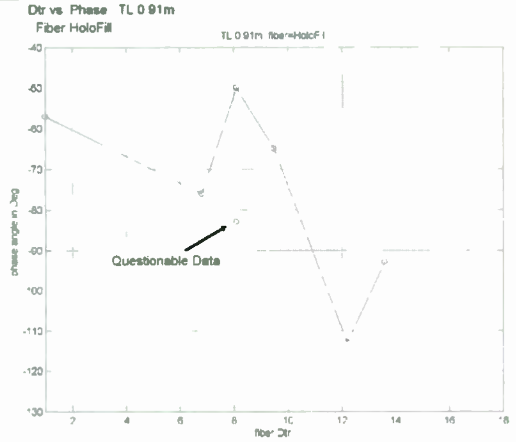

FIGURE 56: TL 0.914; D_{TR} versus phase angle.

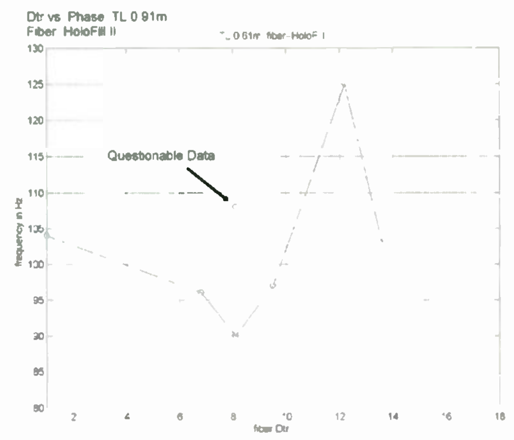

FIGURE 57: TL 0.914; D_{TR} versus F_R frequency.

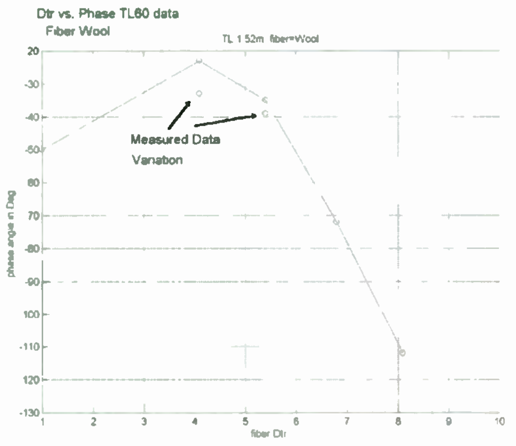

FIGURE 58: TL 1.52; D_{TR} versus phase angle.

Before tackling the definition, I'll look at it from a slightly different perspective: that of measured D_{TR} value versus phase angle around the optimum density point for several line lengths and fiber types.

The optimum fiber density for a TL of .61m is about 10.2 for the Dacron® fiber. The optimum value is indicated by the minimum phase angle and the maximum frequency shift relative to F_R at D_{TR} = 1. Therefore you can use either of these two criteria to define optimum fiber density for a specific line length. Please note that F_R is not a constant. While it is calculated from ¼λ for D_{TR} = 1, as fiber is introduced into the line, it will shift lower in frequency.

Figures 54–59 show data points that are questionable, and making such an interpretation requires both the recognition and repetition of the particular data point. This is but another example of the complexity of TL analysis. As the line becomes longer, the data around the optimum density point becomes more stable; however, the harmonic resonance peaks become more prominent, thus complicating the identification problem.

OPTIMUM STUFFING-DENSITY DEFINITION

The data in *Figs. 54–59* provides a basis for the following definition of optimum density: the optimum density is that which results in the minimum phase angle at F_R, and it is related to line length and fiber type. This definition requires that for accurate determination, you measure the phase angle as you change the fiber density.

The measured data has revealed a means to define the optimum fiber density. More desirable would be a model of how this comes about. *Figures 39* and *40* gave an indication of such a process. *Tables 9–11* are tabulations of three different line lengths for the shift of F_R for the empty and stuffed lines.

The tabulated data shows that for the empty line, the F_R will shift positive, and that the harmonics will generally shift negative. The difference from the calculated value seems to be almost constant regardless of line length, suggesting that it is related to a geometric value. Unfortunately, data for different cross sections of the line is not available to substantiate this.

END-CORRECTION DEFINITION

The standard model used in academic texts for calculating the acoustical mass of a long tube requires an "end correction" if the tube terminates in an infinite baffle. The assumption is that this would account for the frequency shift

TABLE 10
TL 0.914 METERS, FIBER HOLOFILL

	CALCULATED	D_{TR} = 1	ΔCALC.	D_{TR} = 8.1	D_{TR} = 9.6
F_R	94Hz	104Hz	+10Hz, +11%	90Hz/–4Hz	96Hz/+2Hz Opt=8.1
1st null	188	155	–33Hz, –7.8%	157Hz/–25Hz	157Hz/–25Hz crossover
1st peak	283	273	–10Hz, –5.6%	238Hz/–45Hz	238Hz/–45Hz
2nd null	377	353	–24Hz, –6.4%		
2nd peak	471	447	–24Hz, –6.1%		
3rd null	565	523	–42Hz, –7.4%		
3rd peak	659	600	–59Hz, –8.9%		

TL DESIGN SUMMARY

While a TL design cookbook is not possible (there are just too many variables interacting in very complex ways), I offer a design outline:

- A woofer's applicability for a particular TL line can be defined by simulating a Q_{TC} = 0.5 alignment from T/S parameters and using the f_{10} as an approximate F_R limit. The driver should be chosen for midbass qualities, since the low end is a line-geometry function.
- The line length is calculated from ¼λ, for a simple line.
- The fiber density is a function of line length and fiber type. Lacking a simulation model, the only option is a look-up graph with the following recommendations:
  a) for line lengths < 0.8m, fiber glass;
  b) for lengths between 1 and 1.3m, HoloFill II;
  c) for lengths between 1.2 and 2.2m, wool;
  d) for lengths > 1.8, Miraflex (however, hard data is lacking);
  e) line lengths > 3m should be designed as sub-BW types.
- To do an experimental design without instrumentation that can measure magnitude and phase is almost impossible. I recommend copying a reliable design. —A. Monk

from the calculated values in an empty line. In order to allow you to neglect viscous losses inside the tube, the radius of the tube must be greater than $0.05/f^{0.5}$, and to enable you to neglect transverse resonances, the radius must be less than 10/f. Thus for a 1m line, the radius (a) must be 0.5cm < a < 10cm, or, expressed as an area, $0.78\text{cm}^2 < S_R < 314\text{cm}^2$.

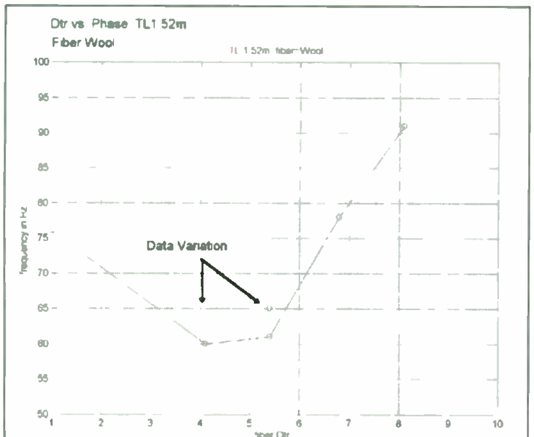

FIGURE 59: TL 1.52; D_{TR} versus F_R frequency.

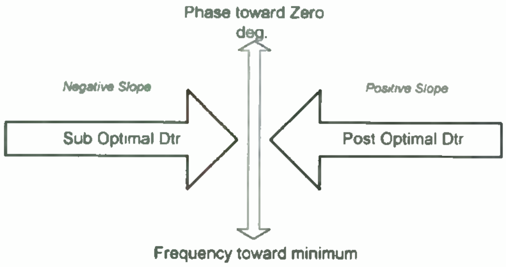

FIGURE 60: Optimum fiber-density block diagram.

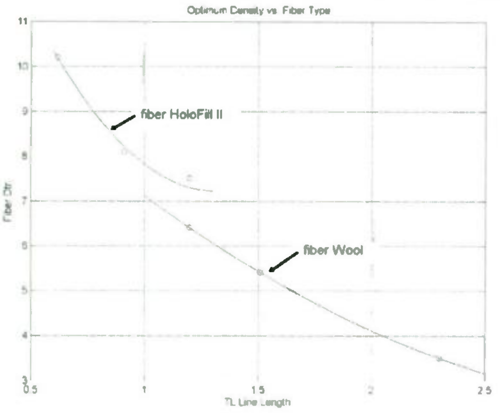

FIGURE 61: Optimum D_{TR} versus line length.

The end correction l″ is defined as:

$$l'' = \frac{M_{A1}\,\pi a^2}{\rho_0} \cong 0.85a \qquad [11]$$

Thus the calculated line length is equal to the sum of the actual length plus the end correction l″. This will move the F_R frequency lower, since the apparent line length is greater. So far so good; however, the *Fig. 40* data showed that for the empty line, the F_R initially shifts higher in frequency, and shifts lower only when fiber is introduced into the line.

Now, equation [11] is specifically for an empty line, and it is a function of radius (a), so the correction would be a constant regardless of line length, and would always shift the f_0 lower in frequency. However, the table data shows that f_0 is shifted higher in frequency, and is shifted lower only with the addition of fiber mass to the line. Examining the shift of the harmonics, it is evident that fiber-density shift is frequency dependent. This is defined by the fiber equations [5]–[7] and shown in *Figs. 42* and *43*.

The end-correction equation contradicts the TL measured data and the TL frequency shift; in my opinion, it must be modeled on the empirical data. Continuing with the data of *Tables 9–11*, the fiber effects can be summarized for the data of *Figs. 54–59* as *Fig. 60*.

Thus the optimum density is a very narrow line in the fiber-density range, and is defined by the minimum phase at F_R. To define the relative fiber density to optimum, it is necessary to determine the slope. Thus you need to take two data points as you change the fiber mass.

Based on this and similar data, you can compile a D_{TR}-versus-line-length plot that should provide some insight as to the fiber-type and line-length variables as you approach the fiber limits indicated by the Bradbury curves.

TABLE 11
TL 1.52 METERS, FIBER WOOL

	CALCULATED	$D_{TR}=1$	ΔCALC.	$D_{TR}=4.1$	$D_{TR}=5.4$
F_R	57Hz	76Hz	+19Hz, +33%	59Hz/+2Hz	58Hz/+1Hz Opt=5.4
1st null	113	120	+7, +6.2%	102Hz/–11Hz	102Hz/–11Hz
1st peak	170	174	+4Hz, +2.3%	155Hz/–15Hz	157Hz/–13Hz
2nd null	226	225	–1Hz, –0.05%	208Hz/–18Hz	204Hz/–22Hz crossover
2nd peak	283	279	–4Hz, –1.4%	258Hz/–25Hz	248Hz/–35Hz
3rd null	339	333	–6Hz, –1.8%		
3rd peak	396	389	–7Hz, –1.7%		

FIBER D_{TR} VERSUS TL LENGTH

Figure 61 shows the data for two fiber types for which I have empirical data that correlates with the fiber-equation data. For line lengths of over 2.2m, I recommend trying Miraflex, since the fiber analysis indicates it could extend the 1/α past the point where the wool curve flattens out. However, over 2.5m you are entering the TL bandpass response design, and the problems of folding a line and dealing with the harmonic nulls are not trivial. The reward is a TL that would complement the electrostatic loudspeaker (ESL). Good luck.

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Weems, David B., "Experiments with Tapered Pipes," *SB* 2/87.

Excellent article on TL/TQWP and taper, conclusions limited by data resolution.

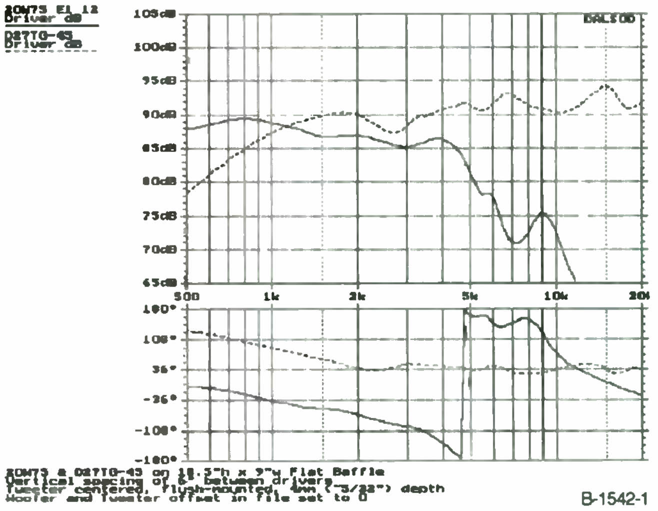
Using just the relative offsets and the right software, you can easily determine the acoustic centers of drivers to help with your system design.

Finding Relative Acoustic Offsets Empirically

By David L. Ralph

Designing a speaker system for the do-it-yourself crowd has a number of problems, one of which is how to determine the acoustic center of the drivers. Of greater importance is the relative difference between acoustic centers (called relative acoustic offset). Knowing the absolute acoustic center is useful if you intend to test a number of drivers without actually fabricating a baffle and mounting them. But if you know which drivers will be used and have access to a good measurement system and appropriate CAD software, it is possible to determine the relative acoustic offset without actually knowing the absolute acoustic centers.

FIGURE 1: Raw measurements after modeling in Calsod.



FRUSTRATION

My first experience with this was when I

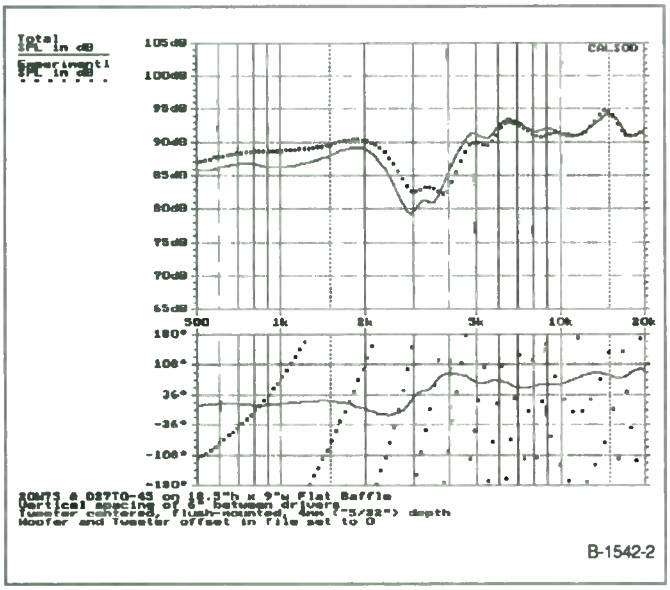


FIGURE 2: The initial Calsod summation curve.

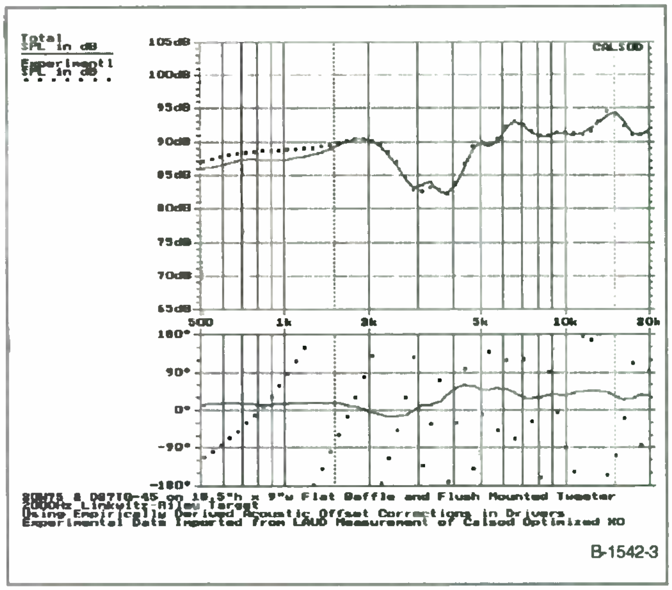


FIGURE 3: The summation with the best-guess iterated resultant offset.

had access to LMS and, later, MLSSA in 1996. I was learning how to use them and Calsod at the same time. I tried the typical physical-measurement techniques described in *Speaker Builder* and other books and magazines, but these never resulted in a good correlation between my optimized design and the subsequent measured combined responses. Also, I did not have good facilities for making and testing various baffles. I didn't even have a router for flush-mounting drivers.

I really did not need the absolute centers, but only the relative acoustic-center offset between them. How could I determine this? After much frustration, I came up with the idea (which I had never seen presented anywhere) of using relative offsets. I had a baffle with the drivers mounted, which would not change.

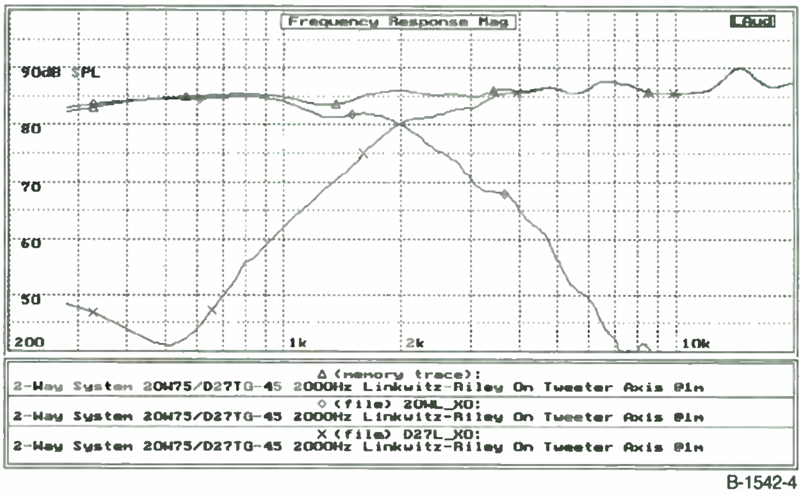


FIGURE 4: The measurement using optimized values for the final crossover.

EMPIRICAL BASIS

You determine the measurements for individual drivers, usually on each driver's axis, and import them into the CAD software. Then you add the relative offsets in the three axes, either by hand-measuring the cone depth, as some recommend, or by using the center of the voice coil. Why not, I thought, make a raw measurement of both drivers combined, from the same position? This would include the acoustic offset of both drivers. Now all I needed was a way to adjust one driver relative to the other for that specific microphone position.

Since I had the combined raw result, which intrinsically included the relative offset, all I needed were measurements of each driver taken individually, without moving the microphone. I could then import each measurement into Calsod and use its capability of combining driver responses to compare the result against the combined raw measurement.

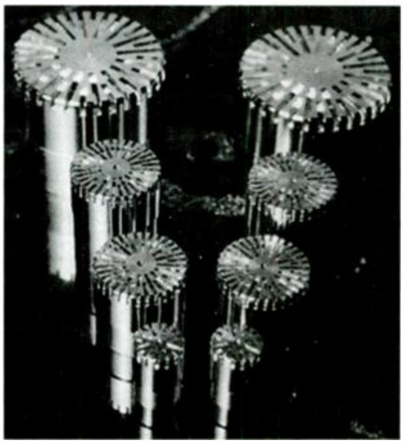
TECHNIQUE

The procedure is to import each driver's raw measurements into the CAD program, model them, and create a single file (in the case of Calsod) containing the two driver models. Then use the combined raw measurement as the reference against which the resultant CAD combined (system) result is compared. In Calsod, the file is imported as an experimental curve. It is important to point out here that no crossover components can exist in the model. All of this is done using only the raw models.

I always measure the combined result on the tweeter axis, since that is my typical listening position. I leave the tweeter offset at 0. I then modify the woofer offset repeatedly until the combined result from Calsod matches the measured result as closely as possible, with the emphasis on the area of the target crossover frequency. I do this because the acoustic centers of drivers vary with frequency.

I also use ⅙-octave smoothing in LAUD before I export the text file, thus getting rid of the minor fluctuations without changing the character of the curve significantly. This makes it simpler to model, doesn't impact the actual results, and makes for easier matching of the measured combined signal with the calculated combined curve.

I took the measurements with the woofer and tweeter connected in positive-phase polarity. It is possible to do it in any configuration, but you must be sure that the model in the CAD program



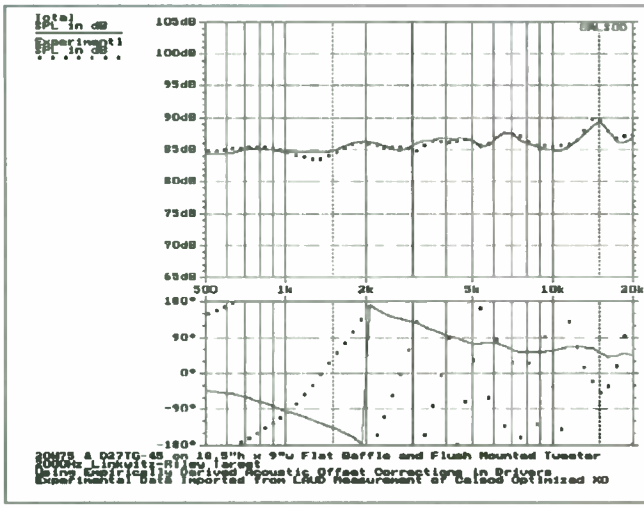


FIGURE 5: The optimized on-axis curve generated by Calsod.

properly reflects the connections to prevent it from being 180° out of phase, which may not be obvious, depending on the drivers' relative offset.

You can also determine the offset with measurement software alone, although I have never attempted to do so. I find that since I must model the drivers in Calsod no matter what else I might do, it makes more sense to use the program. It is also much easier, because the iterative process required is much simpler. You edit the offset value in the file, reload it, and display the two curves.

As an example, consider a two-way system comprising a Dynaudio 20W75 and a Vifa D27TG-45. The individual raw measurements are shown in *Fig. 1* after importation into and modelling in Calsod. Only the portion above 500Hz is shown, because I am interested only in the acoustic-center offset at the crossover point.

RESULTS

Figure 2 shows the initial Calsod summation curve, with both drivers' acoustic-center offset in the z-axis at 0. *Figure 3* shows the summation with the "best guess" iterated resultant offset for this driver/baffle combination when the target crossover point is 2kHz. Compare the two figures to see how small variations can have a significant impact, especially if you wish to design a minimum-phase system using first-order crossover slopes.

The difference in this example is actually very small. The acoustic-center offset added was only 0.006m (Calsod uses the metric system for distances), which is approximately 5⁄32″. This is initially a surprising result for an 8″ woofer, although the Dynaudio does have a rather shallow cone. The acoustic center of the Vifa at this low frequency may also be rather recessed. Since the typical acoustic-center curve tends towards additional recess as the frequency decreases, this should not be so surprising in the end.

Figure 4 shows the measurement using the optimized values for the final crossover. I wish to point out here that the crossover is actually one I derived from a 30° window of measurements. After determining the correct offset, I remeasure at −15°, 0°, and +15°, and average the result. Then I import this average for each driver and remodel it. I use this for the actual optimization for the final crossover, since this, to my ears, yields a more accurate-sounding system. The high-frequency upward tendency actually is seen only on-axis. The average is really closer to flat with this crossover.

Figure 5 shows the optimized on-axis curve generated by Calsod, with the imported on-axis measurement made using LAUD. You can easily see the close correlation, especially in the area of the crossover, 2kHz.

You can do this for any system, two-way or more. The procedure must be followed for each pair of drivers. For a three-way, it is probably necessary to make the measurements from the midrange or woofer position. You would then add the offset determined for the woofer to that of the midrange if the tweeter is left at 0. Then all three drivers will have the correct relative offsets.

One point to remember is that in the CAD program, you must enter the vertical offsets as well as any horizontal (lateral) offset. But this is academic, since these distances are usually known and are easily measured again in any case. Just be sure you enter them correctly into the CAD software before beginning the procedure I have described.

When done properly, measured results at the crossover point generally are within 0.5dB of the target curve. In three years of using this technique, I have never seen it fail to produce accurate, repeatable results.

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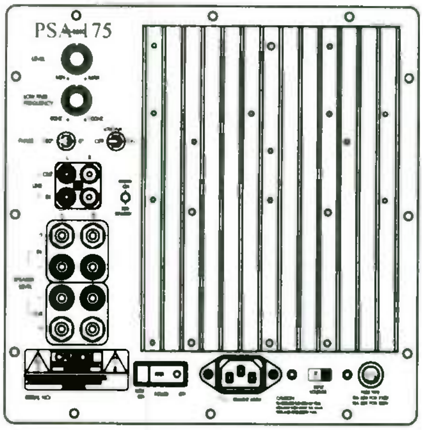

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Reader Service #12

World Radio History

Here's a timesaver that lets you quickly and easily test circuit configurations. The author details the construction and use of a breadboard for passive crossovers.

A Breadboard for Passive Crossovers

By Kim Girardin

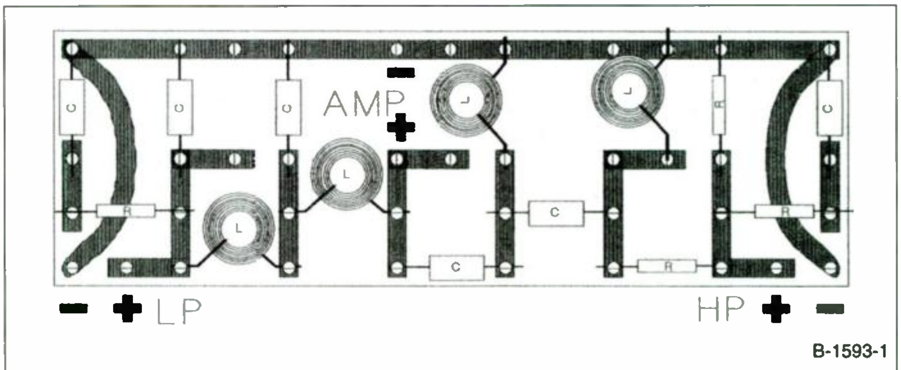


FIGURE 1: Fourth-order high and low pass.

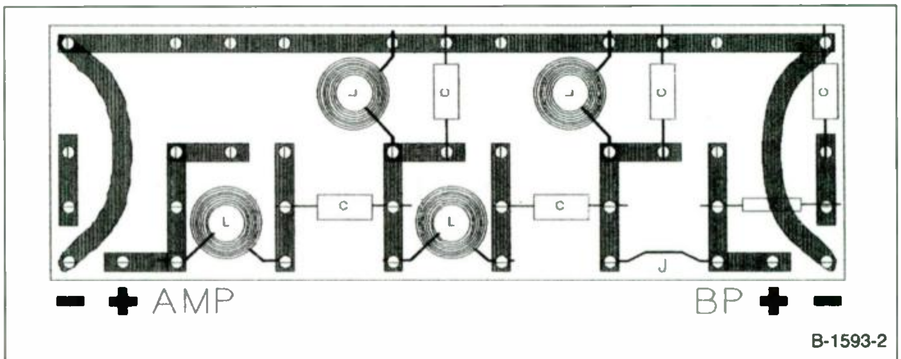


FIGURE 2: Fourth-order bandpass.

When it comes time to develop a crossover for your next loudspeaker project, you can eliminate the usual spaghetti of alligator-clip leads by making a breadboard, scaled to accommodate the capacitors, coils, and resistors of a passive crossover. You still use alligator clips, but instead of flexible wires, you solder the clips to brass screws connected to conducting paths laid out to permit most typical crossover configurations. I made a couple, liked them, made a couple for some friends, received positive and negative suggestions, made some changes, and ended up with the design I present here.

QUICK CONNECTIONS

The design lets you quickly and easily connect the components of a crossover and just as easily change them. Everything is mounted on a rigid board that you can pick up and move. Another feature is that the components are held in a configuration that closely resembles the way you would schematically draw the network.

This breadboard can hold the components to make a first-, second-, third-, or fourth-order high pass (HP) and low pass (LP), with Zobels on both bands and an attenuator on the high pass. Or it can be a third- or fourth-order bandpass (BP) with attenuator and Zobel. Or you can use it to make two second-order bandpasses with Zobels on both bands and an attenuator on one. With two breadboards you can make a stereo two-way, single three-way fourth-order, or a four-way second-order.

Figures 1, *2*, and *3* show some of the possible ways you can use the boards. The total cost should be around $10 to $15 for each board, plus shipping for anything you need to order by mail. The 2″ alligator clips, the equivalent of Mueller #60s, are available from Electronix Express and cost 10 cents each in quantities over 100. Brass screws are about $5 for a box of 100.

I buy 4′ lengths of 4-GA stranded uninsulated copper wire at 25 cents a foot. The 4-GA is made up of seven strands of 14-GA solid wire twisted together. Separate the strands, and you have more than enough wire to make two breadboards. Clean the wire with very fine sandpaper before you use it. Figure another $2 to $4 for the wood, solder, rubber feet, and varnish for each board. Each one will take about 1½ to 2 hours to assemble.

CONSTRUCTION

The board itself is made of ½″ plywood and measures 7″ by 22″. The distance between groups of clips needs to be 3″ to accommodate the components, and 1½″ between adjacent clips to accommodate your fingers. *Figure 4* shows the dimensions and layout of the board. Mark the locations of all the clips and the paths of the connecting wires (the shaded areas).

Using a 3/32″ bit, drill pilot holes for the screws. These should go all the way through the board, and must be smaller than the screw's diameter so the threads will bite into the wood. If you do not have access to a drill press, a hand drill should work, but make sure you drill straight. The clips will fit loosely enough around the screws to allow you to attach the clips reasonably straight before soldering. After drilling, put a coat of varnish on both sides of the board.

On the front side, use a felt-tip marker to draw the paths of the wires connecting the screws and clips. Drive the 40 1″ #6 brass screws into the back of the board, but do not tighten them all the way down. Leave enough of the shank of the screw exposed to wrap a turn of the wire around it.

On the back of the board, wrap the wire around the screws and then cut it to make the conducting paths (*Photo 1*). Then tighten down the screws, after which they should protrude about 3/8″ out of the front side. Double-check to make sure the paths of the wire on the back match those drawn on the front. Then solder the wires to the screws. I have found that a 100W to 150W soldering iron or gun is needed for this.

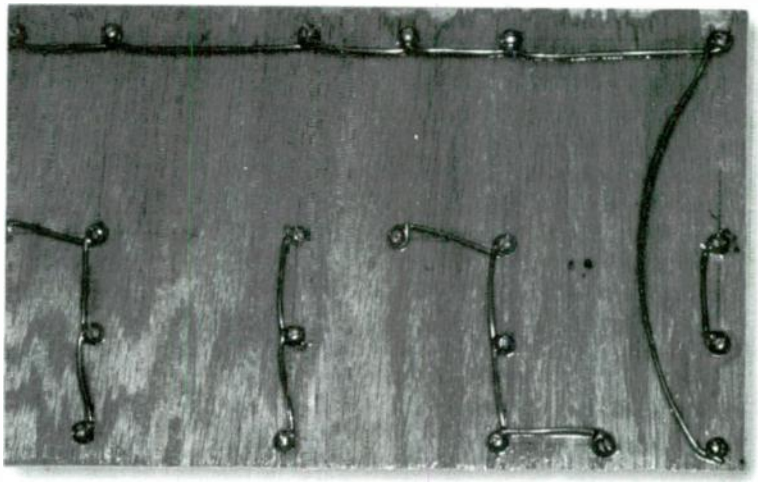
AFFIXING THE CLIPS

Align and solder the clips to the screws on the front side of the board, placing two clips at a time on the screws. In *Fig. 4*, the circles indicating the locations of the clips have lines showing the orientation of the clip jaws. Place a piece of ½″-wide thin metal stock in the jaws of the clips to keep them aligned with each other (*Photo 2*). A hobby store should have suitable strips of flat brass stock about .030″ thick.

The same wire you used for the conductors on the back side will work, but the brass strips are handier because you can pull them straight up and out of the jaws of the clips without needing to squeeze the clips to open the jaws. This speeds things up since you can remove the strips after the solder has set but while the clips are still too hot to touch. This piece of wire or flat metal should be 7″ long so that you can use the clips that have already been soldered in place to help align the next pair of clips.

To solder the clips to the screws, I recommend a butane mini-torch. Rosin-core

PHOTO 1: Board screws and wires.



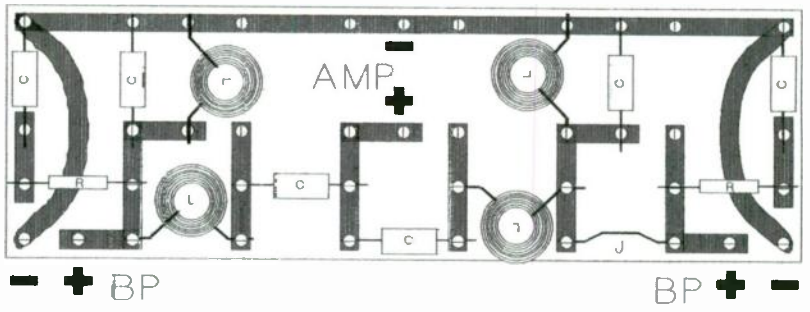


FIGURE 3: Second-order bandpass.

60-40 solder that is .062″ in diameter works best. I first solder the clips that hold components going to ground (*Photo 2*), which can only be done in pairs. Then I do those that will hold the components in the series branches.

Have about 6″ of solder sticking off the spool. Feed the end of it to the inside of the barrel of the alligator clip near the point of the screw. When applying the flame of the torch to the barrel of the clip, keep the flame aimed as low as possible without scorching the wood. If the flame is aimed too high up on the barrel of the clip or for too long, you risk overheating the spring and weakening the clip's clamping power. You wish the heated metal of the clip to melt the solder, so keep the direct flame off the solder.

When the solder begins to melt, feed about 1½″ of solder into the barrel. (If you try to use .031″-diameter solder, you will need to feed about 6″ into the barrel.) You will see the melted rosin pool near the top of the barrel. Then stop feeding the solder, but keep the flame on the barrel for about five sec-

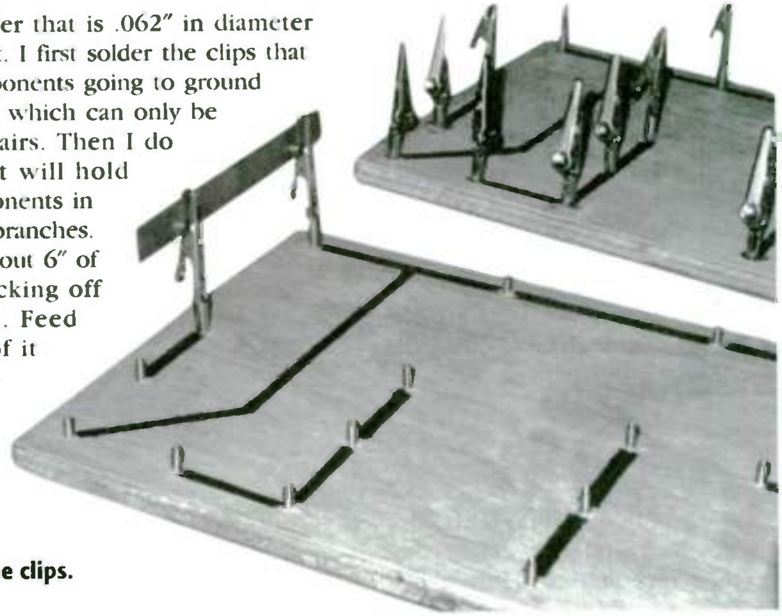


PHOTO 2: Aligning the clips.

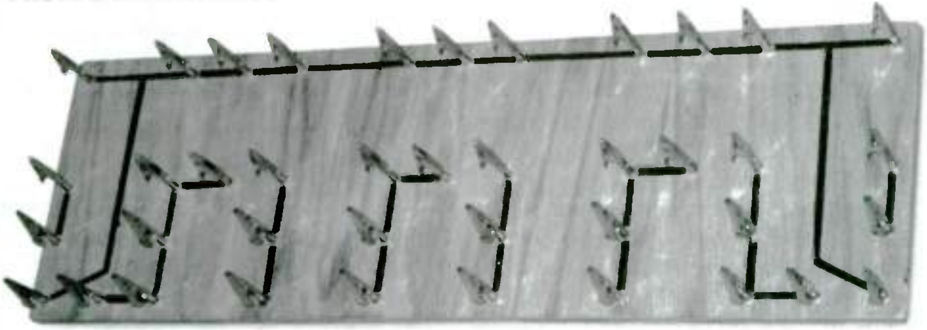
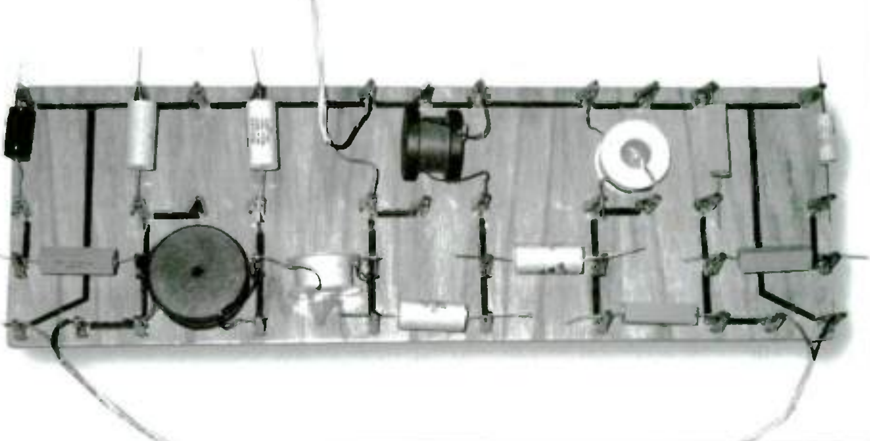
PHOTO 3: Finished board.


PHOTO 4: Loaded board.


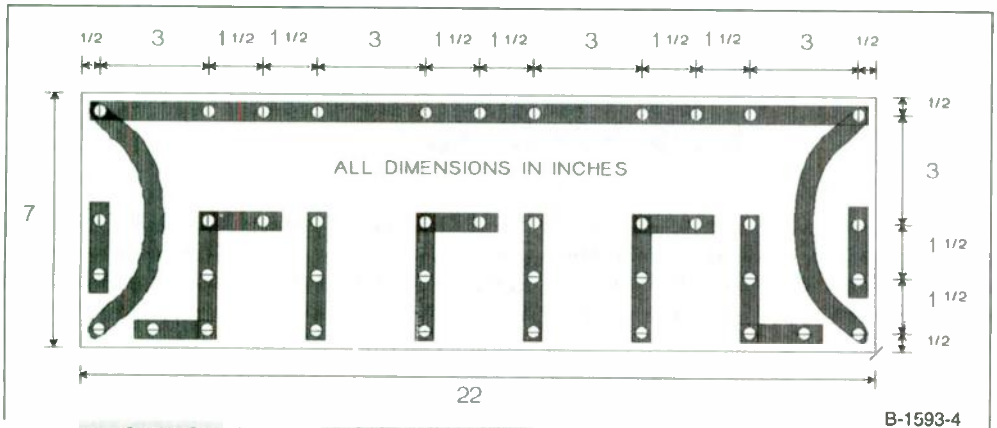


FIGURE 4: Dimension drawing and clip orientation.

onds to make sure the brass screw becomes hot enough to take the solder, while you make any necessary adjustments to ensure the clip is as nearly vertical as possible.

Remove the flame and let the joint cool for a few seconds. After the solder has set in the first clip, the alignment strip helps keep the next one aligned and vertical. Then solder the next clip. Move the alignment strip and install more clips, and so on until you have soldered all the clips to the screws. After everything is soldered in place, it would not hurt to measure the resistance between the clips to make sure you have made good solder joints.

FINISH WITH CARE

Some finishes will cause the copper to react. Consult the manufacturer to be sure. Minwax Polycrylic is good. Krylon makes a clear finish that is suitable, as well. I have been told the Krylon will melt back when heated (or maybe it was that solder will flow under it), so that if you ever must make repairs, you needn't strip or scrape it off to resolder. I have not tried this, so I can't say for sure.

You absolutely must not get the insulating varnish on the alligator clips. So be very careful if you varnish the top of the board after assembly. In fact, as I mentioned before, it would be better to varnish the top of the board before installing the screws. On the back side, brush on a couple of coats of varnish to protect and insulate the wire. Four to six adhesive-backed rubber feet will keep the board from sliding around. *Photo 3* shows a finished board, and *Photo 4* one that's loaded with the components for a fourth-order two-way.

TABLE 1
PARTS LIST

2″ alligator clip—Part No. 0700AC60
Electronix Express
365 Blair Rd., Avenel, NJ 07001
732-381-9020

60/40 solder, .062″ diameter
Digi-Key
701 Brooks Ave. South, Thief River Falls, MN 55987
800-344-4359

1″ #6 brass screws
14 gauge bare copper wire
100W soldering gun
butane mini-torch
Minwax Polycrylic

ACKNOWLEDGMENT
Many thanks to G.R. Koonce for his comments and suggestions about the early prototypes.

Share the Wealth

Speaker Builder offers readers the opportunity to share their knowledge and show off their handiwork through the Tools, Tips, & Techniques column. Send us your speaker-building tips or interesting circuit designs. If you have built an especially attractive or distinct piece of equipment, why not take some photos of it and write a description of your efforts? Send your submission to:

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Remember, it's your magazine, and your contribution can help make it even better. And, we're willing to pay you a modest stipend for your efforts. So, put a few bucks in your pocket, but, most of all, become an active part of the audiophile community.

SB Mailbox

SOUND ADVICE

Thank you for your letter in *SB* 6/99 ("Testing for What It's Worth," p. 60). It resonated.

I also prefer the Dynaudio D-21 to most 1″ (and 28mm) domes. Are you referring to the current D-21/2 with the flat front face or the original with the short horn? Sometimes I think that the Scan-Speak D2010 (19mm dome) sounds more musical; at other times it sounds more sibilant. Probably both are true.

I am now working on a system that uses a Dynaudio D-21/2 (19mm dome), a D52AF (50mm dome), and a Scan-Speak 7″ woofer (*Fig. 1*). My goal is to produce a more modern version of the AR-1, with its dome radiators and similar crossover frequencies. Notice that the crossover networks are electrically 6dB per octave (first-order). Do you prefer first-order crossovers or higher-order crossovers?

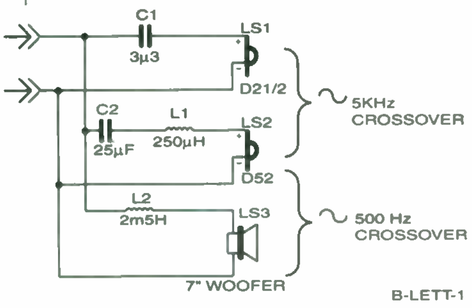


FIGURE 1: Reader Crawford's proposed setup.

Thank you for your recommendations on choral music for listening. My tired old ears sometimes have difficulty separating out all the relevant sounds, even with good loudspeakers. Can you recommend some recordings with single voices, such as Lena Horne and "The End of the Road?" Do you have any recommendations for orchestral music? How about guitar and piano?

I appreciate your time, and I apologize for having more questions than answers. I do make good loudspeakers, but I would like to make better ones.

Dick Crawford
Los Altos, CA

Jesse W. Knight responds:

Your first question is very easy. The tweeter I am referring to is the current Dynaudio D-21/2 with flat face plate. Your hearing can't be too bad or you would not hear the differences between tweeters, which are generally above 8kHz. Most audiologists only test to 8kHz, and if your hearing thresholds are normal below 8kHz, your hearing is "excellent."

Audio CD from Old Colony will allow you to test to 20kHz. Speech comprehension does not suffer until your high end drops to 5kHz. My father could not tell whether a tweeter was operating or not, as he probably heard nothing above 5kHz; however, he was very fussy about midrange and bass. This is because his brain was focused more on the lows to adapt to the loss of HF input from his ears. Our senses adapt to deprivation by becoming more acute to those remaining.

Now my bombshell: As we age (I am 52) our speakers should become bigger and our midranges must be of higher quality. In response, I have started a new system with two 10″ Madisound woofers (1052 DVC) per channel. If nothing else, this will reduce bass distortion by cutting cone excursion in half.

For midranges I will try a small Dynaudio woofer-mid such as 17W LQ. This will allow wide separation of crossover points, which I think is important for the older listener (150 and 3000Hz). With this wide separation of crossover points, I can try all crossover orders and polarities. This is a contentious area; I have never before worked with good enough mids to give a first-order network a fair shake. I will report what I find in detail.

Good solo voice recordings are very hard to find. Choirs sound good when recorded in a reverberant space with only two microphones at a large distance; hence, mike distortion is low due to low SPL at the mikes. There are no mix artifacts either. Solo voices require compromises that lead to inevitable control twiddling (tonemeistering) and mixing.

If you do not hear anything above 12kHz, make your own inexpensive recordings with Crown 6D pzm or Audio Technica AT 853 mikes. The major problems with these occur above 12kHz. You need an octave equalizer to correct their rising response curves.

I just set the EQ for a mirror image curve to the published curve; it works out to about 13kHz. Or you can open your wallet wide and buy a Brüel and Kjaer 4006 matched pair mike system with flat omni capsules and forget about distortion and response errors. To determine the curve for this mike, just draw a straight line with a ruler.

If you choose to use CD-R recorders, which don't have mike inputs, you will need to build a mike preamp (which is not hard; I have lots of ideas for everyone who wants them). At $400 these appear ideal in all other ways for making reference recordings, where mixing and editing will not be a concern. CD-R machines should be compatible with rewritable disks, which are expensive but reusable (check before buying). I think you will need only a couple of disks. I don't have CD-R yet, but a friend has reported that since he got one for his university music department, students demand CDs for their audition recordings.

Several years ago I worked for a studio that made only language tapes. The owner maintained that he could best test any audio gear with spoken-word recordings alone. This sounded to me like fantasy, but he proved me wrong. After years of speech recording, he had developed a killer ear. I can't tell you how to do this, only that it is possible provided you have a live reference.

Since I wrote this letter, two more CD recorders have entered the market. Recorders range in ease from setting the record level to automatic level adjustment, which is most undesirable. Check analog record features carefully before buying.

DESIGNING TLS

In part two of his very enlightening article on transmission lines ("Transmission Lines: The Real Story," *SB* 7/99, p. 18), Mr. Monk takes a pot shot at my Quick & Easy TL Design method by saying that the math equation for finding stuffing density in my book is pure numerology and that no proof is offered for its validity. Mr. Monk goes on to say that the results are logically incomparable, and I will not dispute that second statement. He is right... and this is why.

The equation, as shown in his article, is incorrect. This is how it appears on page 76 of *LDC-5*, which is also incorrect. The correct equation is shown here

$$D_S = \sqrt{\frac{A_{TL}}{S_D} \times Q_{TS}}$$

In his landmark TL article, "The UNLINE," *SB* 4/88, contributing editor John Cockroft stated that driver parameters of S_D and Q_{TS}, as well as the cross-sectional area of the line, all had an effect on stuffing density and line length. Mr. Cockroft said that as line area increased, so did stuffing density. And, as Q_{TS} increased, so did stuffing density.

This indicated to him that a line area larger than S_D would require a higher stuffing density, but that line length would be shorter. A higher Q driver would also need a higher stuffing density. Conversely, a low Q driver in a smaller line area would need a lower stuffing density, but a longer line length. To prove his point, he built the UNLINE, an 11″ long TL enclosure which he claimed sounded just as good as his larger TL projects.

The preceding equation simply ties all of these variables together to yield the best stuffing density for a selected woofer in a chosen line area. The other math equations in my empirical step-by-step TL design method use the calculated stuffing density to determine the actual line length, in inches, that equates to an acoustical quarter wavelength.

I make no claims that the Q&ETLD method is the only way to design a transmission-line speaker system. It is, however, a method that works quite well, as over 5,000 copies of the book have been sold, and the overwhelming majority of my customers are very satisfied with the TL speakers they designed and built using this book.

The transmission line has become legendary for its clean, natural-sounding bass and the clarity of its midrange. It has generated numerous articles, many construction projects, and countless questions. I look forward to reading the rest of Mr. Monk's series in *Speaker Builder*, and I hope that his work will add to the body of public technical knowledge that has been sadly lacking.

My thanks to Ed Dell and his staff for giving us this open forum for information exchange and discussion.

Larry Sharp
Mahogany Sound

A. Monk responds:

Thank you for the correction to the cited equation as well as for your opinion. Please understand that while my disagreement of the methodology in Q&E TL stands, I appreciate how difficult it is for an amateur to define and analyze the TL, and my criticism is not personal. However, once published, your work, as well as mine, is open to critical review and correction.

You cite that the equation in question is based on the published results of J. Cockroft. While I admire the contributions made by Mr. Cockroft, his design methodology, by his own words, is based solely on aural/subjective comparisons, as opposed to recent advances in instrumentation such as LMS analysis. It is my experience that without such tools the analysis of the TL is impossible.

The number of variables as well as the complexity of interactions mitigates against the possibility of using Mr. Cockroft's methodology. This does not imply that his results are invalid. Quite the contrary, I'm astonished by the achieved results, as in the Freeline TL. However, in my opinion, he is an artist whose methods cannot be readily taught or quantified into an equation as you have attempted to do.

In the equation

$$D_S = \sqrt{\frac{A_{TL}}{S_D} \times Q_{TS}}$$

you are expressing the proportionality of line stuffing density to the line area, driver cone area, and the T/S parameter Q_{TS}. First, for the equation to be meaningful, it must be consistent in the units of the variables. D_S is in lbs/ft^3, while on the right side of the equation A_{TL} is an area and so is S_D, thus canceling, while Q_{TS} is dimensionless. Thus the left side does not agree with the right side. You have committed a logical inconsistency.

Now to the derivation: "This indicated to him that a line area larger than S_D would require a higher stuffing density, but that line length would be shorter. A higher Q driver would also need a higher stuffing density." You offer no experimental data to buttress the conclusion. On the contrary, measured data shows that TL line length defines only the fundamental line resonance frequency and is not S_D or A_{TL} dependent.

TL stuffing density is a function of fiber type and packing density used. Q_{TS} is a T/S parameter relating whether a particular driver can be used for a given line length. However, this is a function of the terminus gain and not directly of Q_{TS}. Thus your variable usage in the equation is not syntactically consistent, not experimental-data-supportable, nor justified by measured data in the Q&E TL pamphlet.

Given the preceding analysis, in my opinion the characterization as numerology is not "a pot shot at my Quick & Easy TL Design method," but

inevitable. As a practical point, I have attempted to use your work as a starting point in my study of the TL, but Laud measurements have shown the results to be inconsistent and unable to define an optimized TL design.

The fundamental error is that Q&E TL does not show an understanding of fiber effects as to the change of speed of sound in the fiber mass and thus of phase. Since to measure phase you need instrumentation based on LMS, any formulation of the TL without this data must be incomplete.

TLS ARE TOPS

I thank A. Monk for contributing to the de-mystification of transmission-line construction ("Transmission Lines: The Real Story," *SB* 6/99, p. 20). I certainly look forward to part two.

Your explanations were clear and concise, but for one paragraph on p. 28: "Fig. 12 shows the data for dual woofer loading that results in a flat impedance curve and translates into an outstanding transient low-frequency response."

My question is, does "dual woofer" imply Isobaric or "dual woofer." If you are actually implying dual woofer, what would be the best way to mount the drivers at the start of the line (side by side, top and bottom, push-pull)? I would be most interested in your response.

By the way, I first fell in love with the sound of T-lines while listening to a friend's extremely well-executed speaker based on a relatively inexpensive Philips 12″ driver (paper cone, rubber surround, low Q and f_S, 1″ p-p excursion), which, unfortunately, is no longer available. I can honestly say that in all my years (quite a few) enjoying this hobby, I have heard most of what the high end has to offer in commercial products, yet I have never heard a loudspeaker reproduce the bottom octaves as realistically (yes, I do attend live concerts regularly) and with such timberal accuracy as did this T-line. It has left me quite dissatisfied with virtually any loudspeaker I have heard since.

Angelo Tullio
Adelaide, Australia

A. Monk responds:

Thank you for your kind letter concerning the TL article. I hope that you shall find the remaining parts as interesting and informative...perhaps sufficiently so as to build a TL and enjoy its unique characteristics. Your observation of the TL's transient response as compared to the sound of a live concert sound is very high praise indeed. As you mentioned, it can be achieved only by a very perceptive and dedicated designer, and my article is but a compilation of technical observations.

I included the impedance plot you mentioned to illustrate the relationship of a flattening of the phase curve that can be achieved with manipulation of the impedance as a function of the line-fiber affects. Since it is non-representative of a nominal TL design, I was hesitant to include it, so you have caught me out.

The dual-woofer design is a push/push topology that is unique to the pressurization of the TL's interior. In a non-TL configuration it would result in low-frequency phase cancellation, but in a TL it reinforces the terminus gain and is used in a small bipole design to achieve a 4π steradian response up to about 2kHz. Since this was not germane to the basic TL, I did not discuss it in the article; a full documentation would require a separate article, falling into the category of esoteric TL configurations.

Perhaps you would be interested in a similar usage described at http://139.142.118.15/sites/diy, an interesting TL construction site. Please understand that this site is run by a dedicated amateur and that it reflects the interest of the owner. You must exercise your own judgment.

HELP WANTED

I'm looking for a easy-to-build design for a bass unit to work with my LS3/5As. Lack of space prevents me from using a bass reflex, and I wondered if a column would be best. I can't see such a design in the list of back issues available.

I once ran across a design using a 10″(?) diameter concrete pipe. Was this ever successful, and do you have instructions? I would also need a crossover design.

Reg Kennedy
RegKennedy@kolumbus.fi

I am trying to locate replacement drivers for a Spica Angleus. I'd greatly appreciate any guidance you could provide.

Eric Vogel
evogel@flash.net

I am looking for a source of brown open-cell foam for use as speaker grilles. Any help for this would be greatly appreciated.

Don J. Cochran
907 Athan Ave.
Roseville, CA 95678-1405

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

Product Review

CD REPAIR KITS

Reviewed by Gary A. Galo

***SkipDoctor™ CD Scratch and Repair Device**. Digital Innovations, L.L.C., 906 University Place, Evanston, IL 60201, 1-888-SMART-58, E-mail sales@digitalinnovations.com, Website www.digitalinnovations.com. $34.99.*

***DiscRestore™**. DiscRestore, 1190 Spruance St., San Jose, CA 95128, (408) 298-9008, FAX (408) 298-0607. $14.95 (enough fluid for 50 uses), $19.95 (100 uses).*

When Sony and Philips introduced the Compact Disc, consumers were not just assured of "perfect sound forever," but we were also told that the new silver discs were indestructible. Finally, there was an audio storage medium requiring no care whatsoever. Scratches and fingerprints would have no effect whatever on the "perfect sound," since the miracle of digital error correction would replace any missing data caused by mishandling.

It wasn't long before music lovers realized that the hype had been grossly overstated (just like the perfect sound of the early discs and players). Error correction can certainly mask minor scuffs and scratches, but beyond a certain point, disc damage will cause discs to skip, distort, or simply not play at all.

SkipDoctor and DiscRestore are designed for repairing scratched CDs (*Photos 1* and *2*). DiscRestore comes with a bottle of repair fluid (light tan in color), a bottle of care fluid (clear), blue and white buffing cloths (called "Opticloths"), and two ultra-fine cushioned polishing sheets.

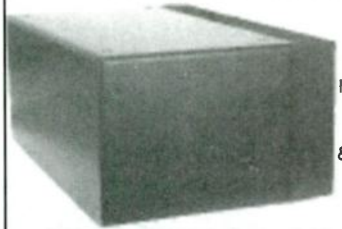
To repair a scratched disc, place the CD on a newspaper or paper towel, label side down. If the entire disc is scratched, the manufacturer suggests pouring about five drops of repair fluid around the disc. Otherwise, just place a drop or two on the scratched area. Then, firmly buff the entire surface of the disc with the blue Opticloth until the tan fluid disappears.

The manufacturer notes: "You have now created the miracle of DiscRestore." If this process is ineffective—which it may be on a severely damaged disc—use the ultrafine polishing sheets to buff the problem areas of the disc. You first use the coarser of the two sheets (#2), followed by the finer (#1). After successfully repairing the disc, use the clear care fluid, along with the white Opticloth, to buff a damage-resistant finish onto the disc.

SkipDoctor is an unusual repair system that involves a large plastic hand-cranked buffing tool, consisting of a rotating disc holder

PHOTO 2: SkipDoctor.

PHOTO 1: DiscRestore.



and a flexible plastic buffing wheel. The buffing wheel's mildly abrasive surface resembles the coarser of the two polishing sheets supplied with DiscRestore. To repair a scratched disc, open the lower jaw on SkipDoctor, insert the disc into the CD holder, and spray the disc surface with the supplied resurfacing fluid (which is simply filtered water).

Now, close the jaw and turn the hand crank until the CD has completed one counterclockwise revolution. Then, flip the reversibility switch and turn the crank until the disc has made a complete clockwise revolution. Open SkipDoctor's jaw, remove the disc, and dry it completely with the supplied aqua drying cloth. Finally, place the CD label side down on the folded drying cloth and buff the entire surface, radially, with the felt buffing square.

SkipDoctor supplied a CD and a piece of fine steel wool with my press kit and suggested scratching an area on the inside of the disc until the player would no longer index the CD. Scratches on the inside edge of the playing surface damage the lead-in portion of the disc, including the table of contents area. If the scratches are severe enough, the CD will be unreadable.

I was able to successfully restore the damaged disc to playing condition, with no skipping. The SkipDoctor process leaves radial marks on the CD, which the felt buffing square is supposed to remove nearly completely. Even with vigorous buffing, however, the radial marks are clearly visible. In order to render a useless disc playable once again, the surface of the disc will be made less shiny than it was when it was new. If only a portion of the disc is damaged, it isn't necessary to make a complete revolution with the SkipDoctor. By using the reversibility switch, you can go back and forth over only the damaged portion of the disc.

ULTIMATE TEST

I used the steel wool supplied with SkipDoctor to damage another CD, which I then tried to repair with DiscRestore. I found that DiscRestore was just as effective in repairing the damaged disc as SkipDoctor, and I liked the fact that DiscRestore didn't leave permanent radial markings on the CD. I then decided to give both repair systems the ultimate test.

Using a screwdriver blade, I put a wide, deep scratch on two different CDs, rendering both unplayable. I had to be very persistent, but both systems allowed me to at least restore the disc to the point where my CD player would index the disc and begin playback of Track 1. Both discs still exhibited some skipping, which I was unable to correct.

SkipDoctor is also marketed as GameDoctor, dvdDoctor, and DataDoctor. All four products are the same—simply targeted toward different markets. The manufacturer claims that the products are equally effective in treating CDs, PlayStation discs, other CD/DVD-based games, DVDs, CD-ROMs, recordable CD-Rs, and photo-CDs. DiscRestore makes similar claims for their product, noting that it is "100% effective" on all optical storage media, including CDs, CD-ROMs, Laserdiscs, and DVDs.

Both DiscRestore and SkipDoctor are quite effective in repairing discs with mild scratches and abrasions. While a severely damaged disc may be restored to a playable condition, it may still exhibit some skipping no matter how many times you repeat the process.

Given a choice between the two, I have a slight preference for the DiscRestore system, since it is easier to work on a specific area of a disc without leaving permanent marks elsewhere on the CD. DiscRestore will be the only choice for repairing 12″ video Laserdiscs, which are too large to fit SkipDoctor's mechanism. On the other hand, discs which are more or less evenly scratched around their entire surface will be easier to restore with SkipDoctor.

There is no substitute for proper care of CDs and other optical discs. If you take good care of your recordings, you won't need either of these products. But, when accidents do happen, you may find one of these products extremely useful.

Manufacturer's response:

SkipDoctor automatically provides fixed, even pressure across the entire surface of the disc, offering the greatest chance of repairing a damaged disc, without risk of further damage. With paste and sandpaper kits, the pressure is applied by hand, so manufacturers must decide to make the abrasive either fairly aggressive and risk burning the disc or so mild that it isn't very effective for the average user. As a result, the hand-applied kits can be somewhat effective for the skilled user (such as the reviewer), but are usually not very satisfying for the average consumer.

SkipDoctor works great for both the typical consumer who doesn't care to inspect the disc and make decisions about where and how hard to apply the repair, and for the more advanced user who prefers to make focused repairs on more severely damaged discs. This is why over a hundred thousand consumers (for home use) and a thousand game and video rental stores (for in-store repair of rental discs) purchased SkipDoctor in 1999, its first year on the market. The value of SkipDoctor was also recognized at the recent Consumer Electronics Show, where it was selected "Best of Show" in the highly competitive Audio Products division.

In addition to being harder to use than SkipDoctor, most paste-based kits are toxic. SkipDoctor uses only filtered water as a lubricant and is completely safe and environmentally friendly. It can be used by kids and will not stain your carpet or furniture.

As noted, SkipDoctor does leave behind a light radial pattern that is visible from an angle to the light. This pattern is invisible from straight on (which is how CD players read the discs) and has been shown by extensive scientific testing and, more importantly, the experience of our customers to have no effect on performance.

Despite the claims of some manufacturers of paste and sandpaper kits, no product is 100% effective in repairing damaged CDs. The good news is that most of them can be repaired–with the right product. We invite consumers wishing to know more about how CDs are made, how they work, and how to care for them to visit the "About CDs" section of our web site at www.digitalinnovations.com.

Collin D. Anderson
President
Digital Innovations

Manufacturer's response:

While Gary Galo did mention our Care solution "to buff a damage-resistant finish onto the disc," it would have been informative for your readers if he'd actually conducted another "damage test" after so treating a disc. We highly recommend use of this second stage of our kit to protect restored discs against further damage as well as treating new and undamaged discs. We've found that application of the Care solution very effectively prevents further damage (including intentional damage via application of a steel wool pad as Gary did in his tests) to restored discs as well as protecting new and undamaged discs from ever becoming unplayable in normal use.

Malfunctioning disc trays and changer mechanisms are the culprits we've most frequently encountered in addition, of course, to the usual "ohmigods" of dropping discs on the floor (where, in the time-honored manner of peanut butter and jelly sandwiches, they generally tend to land exactly the opposite of how we'd prefer). Everyone who uses digital discs (whether they be audio CDs, DVDs, CD-ROM discs, LaserDiscs, or game discs) will eventually encounter discs that have become damaged, and DiscRestore will simply and easily restore about 98% of them to full playability.

We've actually field-tested our kit with 10-year-old girls at an elementary school, and, with no instruction other than the printed one included with each kit, each of them was able to fully restore an unplayable disc in less than 10 minutes! And, because our patent-pending system uses no machines or solvents, it is completely safe for use by just about anyone old enough to read and follow the simple instructions.

Based on initial experiences with our new Rx4 formulas, we strongly believe that we have the world's best disc repair and preventative solution for the more sensitive data areas of DVD, CD-ROM, and game discs. During CES 2000 we were able to effectively restore damaged DVD demonstration discs for several other exhibitors, including one on which repair had already been attempted by a considerably more expensive "machine based" repair system. Should Gary have a bit of time to conduct some further tests, we believe he'd be amazed at how much more effective DiscRestore is at repairing these higher-density discs than any of our competitors.

While we're admittedly a bit prejudiced on the subject, it is our belief that DiscRestore is the simplest, safest, and easiest-to-use digital disc restoration and protection system available today, in addition to being the best value.

Rob Robinson
TRG Marketing (for DiscRestore)

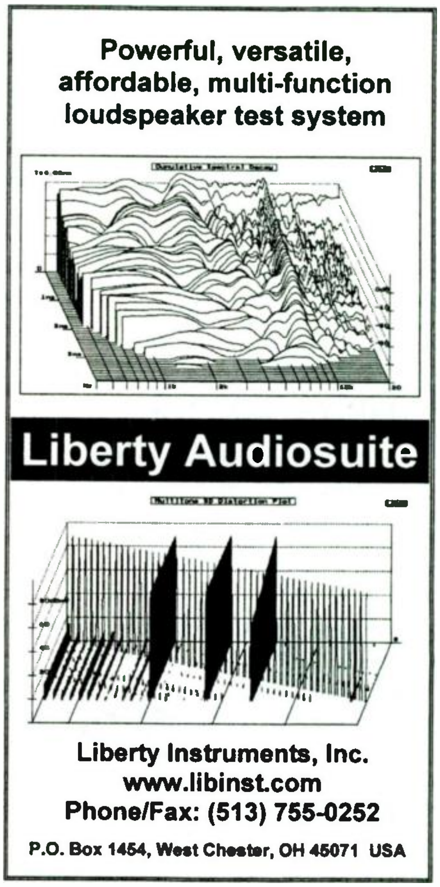
Editorial

from page 8

served greater differences between two pieces of cable. No one on the panel blinked, and no one in the large audience attacked Mr. Jung for expressing the view that cables sound different from one another.

In writing this editorial, I did not intend to provoke another heated, and irresolvable, debate on this issue. Indeed, these mainstream professional audio manufacturers may have already done so. Despite the concerted efforts of many of its members, the high-end may have found a permanent place in the Audio Engineering Society.

As audio manufacturers develop even more sophisticated digital hardware, I believe we shall see an even greater proliferation of high-end audio equipment at AES demonstrations, in order to hear these new products in their best light. I find this change most refreshing.



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ScanSpeak 18w8545 eight units, 18w8546 four units, $105 each; D2905/9300 six units, $50 each; Dynaudio T-330D Esotar pair, perfect, $350. All drivers new, tested for purity. Insured shipping included. Daryl, (530) 265-2575, E-mail datara@yahoo.com.

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Tools, Tips, & Techniques

PIPING COOL

By Scott Wolf

I recently decided to upgrade my speaker design from *SB* 3/91 ("Pipe and Ribbon Odyssey," p. 28). First, to clean up the look of my speakers, I used silicone rubber to attach birch plywood to the PVC to make suitable stands (***Photo 1***). I left the PVC unglued for ease of transport. The bass is very tight, and the enclosure is very nonresonant.

Second, I placed the crossover in a Sunnix enclosure (chassis) which sits beneath my Lang amp. I replaced the Solen air cores with CFAC inductors and then replaced the 100µF Solen caps with 3-3µF polystyrene, MIT caps (***Photo 2***) (3-20µF polypropylene film and 1-30µF/channel). These were on sale from Parts Connection ($415 both channels).

PHOTO 1: I siliconed the baltic birch to the PVC, which I left unglued. The PVC is very inert.

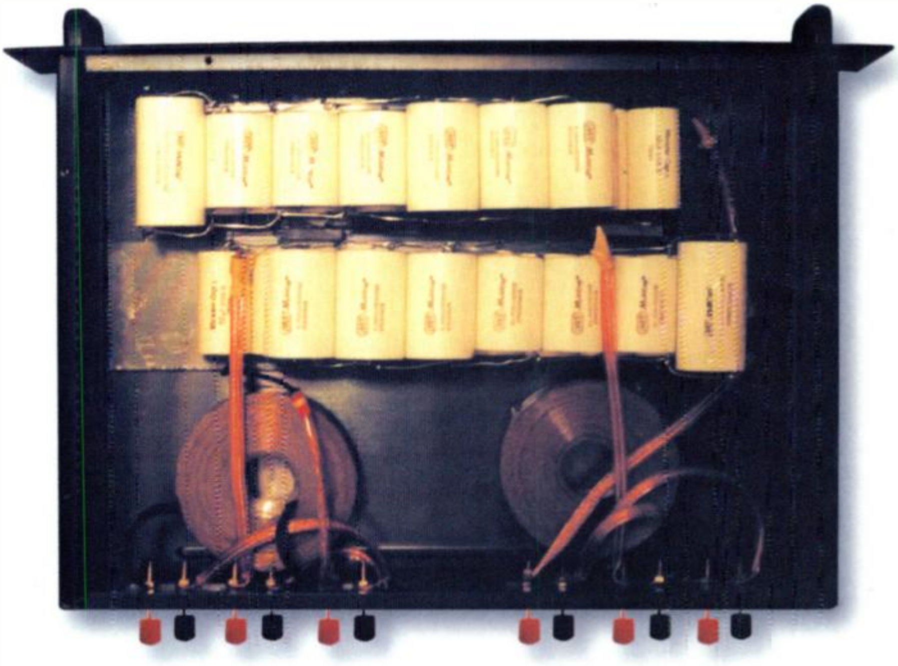

PHOTO 2: Crossover with upgraded MIT caps.

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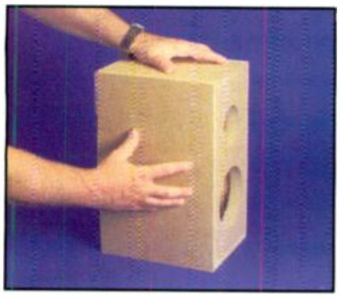
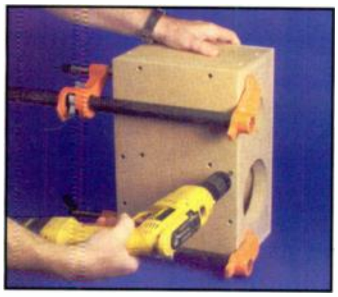
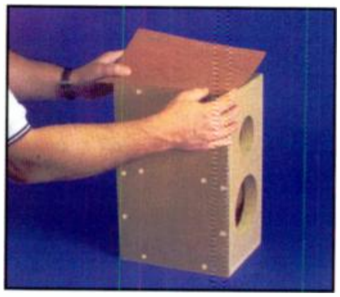
Blank Baffles: The cabinets come with pre-cut baffles for standard drivers. Blank baffles are available for you to rout yourself for flush mounting or custom drivers.



Step 1
Assemble cabinet on your workbench and pre-drill and countersink screw holes. Modifiy driver holes if necessary at this time.



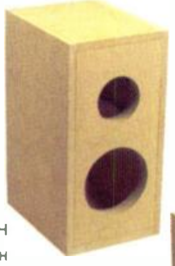
Step 2
Brush Polyurethane glue (available at most home centers) on both sides of all joints. Assemble cabinet (clamp if possible) and install screws.



Step 3
Fill screw holes with putty let dry and sand. Apply your veneer or laminate.

Step 4
Varnish or paint cabinet to your liking. Install crossover, rear terminals and drivers.

.25 Cu. Ft. Bookshelf Cabinet



Reminiscent of the classic British mini-monitor, this cabinet is well suited as a compact 2-way audiophile system or home theatre setup. .25 cu. ft. internal volume. Includes 1" Dado brace. 1" Front Baffle is pre- cut to accept most 5 - 6 in. mid/woofs and tweeters. 100% 1" MDF Construction. Internal dimensions: 5" W x 12-3/4" H x 7" D ◆External: 7" W x 13-3/4" H x 9" D ◆Woofer hole: 4-5/8" ◆Tweeter hole: 3" ◆Net weight: 12 lbs.

#300-704 .... **$34.50** EACH
#300-703 (Blank Baffle, 1" MDF) .... **$3.95** EACH

.55 Cu. Ft. Cabinet

This is the perfect cabinet for any single 6-1/2" woofer and 5-1/4" single or dual woofer arrangement. .55 cu. ft. internal volume including 1" MDF Dado brace. 1" front baffle pre-cut to accept 6-1/2" woofer and tweeter. Internal dimensions: 6-1/4" W x 15-1/2" H x 10" D ◆External dimensions: 8-1/4" W x 17-1/2" H x 12" D ◆Woofer hole: 5-5/8" ◆Tweeter hole: 3" ◆Net weight: 20 lbs.

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Note: All of our MDF cabinets are shipped "knocked down" ready to assemble. They include detailed assembly instructions and finishing recommendations.

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#300-714 .... **$59.80** EACH
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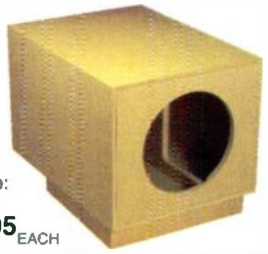
1 Cu. Ft. Esoteric Speaker Cabinet

When completed, this cabinet will rival audiophile systems costing thousands! Designed to accept dual 6-1/2" mid/woofs and a center tweeter in a D'Appolito configuration, or buy the optional blank front baffle to design your own system. Two internal braces to help eliminate unwanted cabinet resonance. Internal dimensions: 6-1/4" W x 21-3/4" H x 13-3/4" D ◆External dimensions: 8-1/4" W x 23-3/4" H x 15-3/4" D ◆Woofer holes: 5-5/8" ◆Tweeter holes: 3" ◆Net weight: 31 lbs.

#300-718 .... **$69.50** EACH
#300-713 (Blank Baffle, 1" MDF) .... **$7.95** EACH

3 Cu. Ft. Subwoofer Cabinet



Finally, a high quality, high performance MDF subwoofer cabinet at an affordable price. This cabinet utilizes 3/4" MDF (medium density fiberboard) not particle board. MDF has far superior sound deadening characteristics than particle board, plywood, or OSB. 3 cu. ft. cabinet is perfect for 10"-15" subwoofers. Internal Dado brace to reduce cabinet resonance. Inside dimensions: 16-1/2" W x 14-1/4" H x 22-1/2" D ◆Outside dimensions: 18" W x 15-3/4" H x 24" D ◆Woofer hole: 11-1/8" ◆Net weight: 43 lbs.

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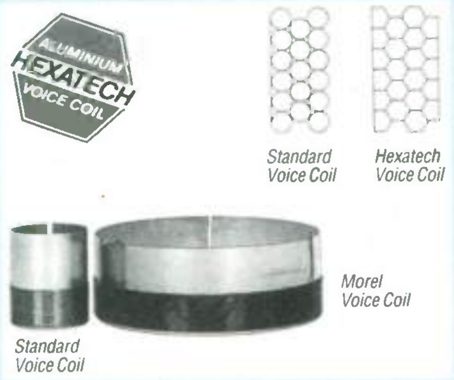

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