Thiele/Small explored • Transmission lines to match electrostatics

4/1980

SPEAKER BUILDER

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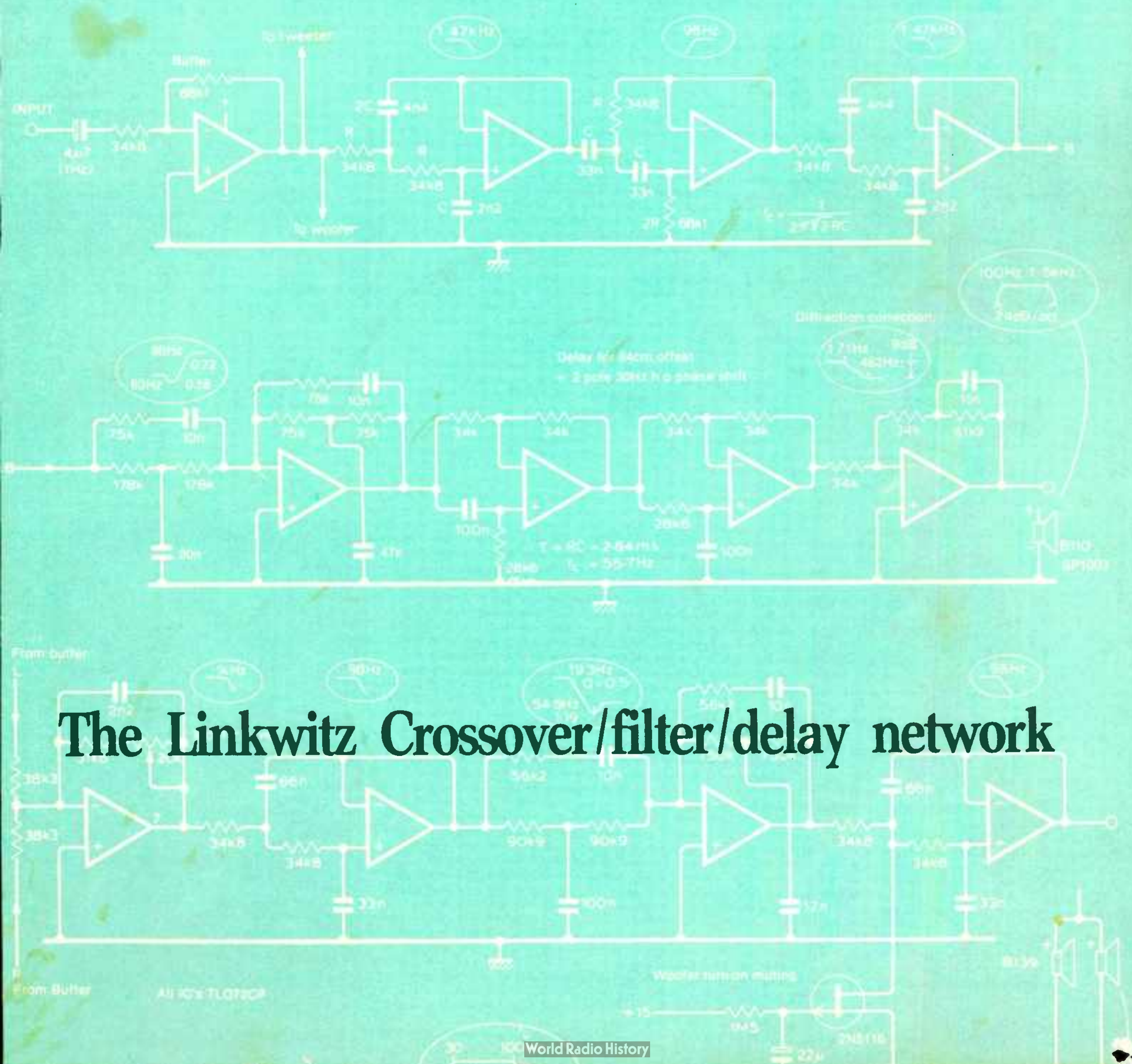


The Linkwitz Crossover/filter/delay network

Good News

A reader has sent along an ad from *db Magazine* carrying the news that the Bruel & Kjaer Pink Noise test recording with 1/3 octave bands, type QR-2011-1 is available for $38.00 each from **Bruel & Kjaer Instruments, Inc.,** 185 Forest St., Marlborough, MA 01752.

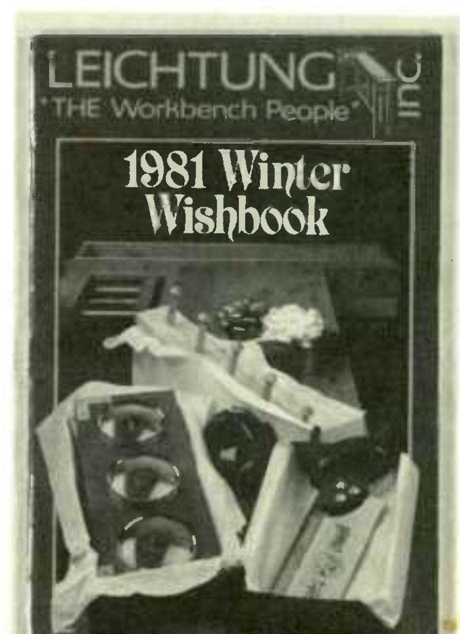
Readers who want to obtain copies of the Jordan Module manual mentioned in *SB* 2/80 may obtain them by sending two dollars to **Transcendental Audio,** 6795 Arbutus St., Arvada, CO 80004. For an additional dollar Transcendental will send along their complete catalog as well. The Jordan document is a very valuable tool for doing many things with speakers. A valuable reference for your speaker building bookshelf.

Orville Greene of **Eventide Clockworks, Inc.** informs us that their JJ193 digital delay mentioned in *SB* 3/80 is priced at $1195. and that their 254mS version, adjustable for 2mS increments sells for $895. Their address is 265 W. 54th St., New York, NY 10019. The same firm offers programs for three computers which provide 1/3 octave spectrum analysis. The programs are designed to run on Pet, Radio Shack TRS-80 and Apple machines and are priced at $545 to $595.

Several readers have written to express their enthusiasm for another supplier of woodworker's tools, veneers and almost anything the craftsman needs for finishing speaker cabinets. Justly famous, **Constantine's,** 2050 Eastchester Road, Bronx, NY 10461 has been in business since 1812. If you expect to do any serious work on beautifying the box, you'll need Constantine's catalog.

Audiophiles have inspired a host of small manufacturers who produce quite special products unavailable from the larger manufacturers. One of these, **DB Systems,** P.O. Box 347, Jaffrey, NH 03452, offers a fine preamp and power amp, but in the last couple of years has added an array of interesting accessories that any audiophile ought to know about. Their line includes such things as a resistive loading kit for use with moving coil cartridges, a capacitive loading kit for offsetting the effects of the tone arm lead capacitance among many others. Write for their complete list of those special, hard to find accessories that hardly anybody else offers.

Reader Robert Graf of Park Ridge, IL tells us that **Leichtung, Inc.,** 4944 Commerce Pkwy, Cleveland, OH 44128 has excellent supplies for woodworkers and a Japanese saw rasp he believes every woodcrafting person should own.



Horn fanciers who have longed for a Klipshorn but haven't a corner—or corners—to accommodate such formats will be glad to know about a "cornerless" version of the horn. **Soundbox** (Edneyville Acres, Rt. 1, Hendersonville, NC 28739) has a set of interesting plans for a bass horn which can be placed anywhere. It is 24x30x40 ⅝" and the horn exits on one long side of the unit. Soundbox will include a set of plans free to any reader who asks for them when ordering their catalog for $1. Soundbox offers a full line of supplies for speaker builders in all formats.

Small is beautiful seems to be a serious theme among speaker designers and manufacturers these days. **Visonik** (701 Heinz St., Berkeley, CA 94701) has a new one called the Mini-Euro 2 which is 9⅝x6¾x 5½" in a two-way acoustic suspension format. The 5" woofer is in a die cast frame and matched with a 1" soft dome tweeter crossing over at 2.3kHz. Cabinetry is finished in wood veneers. The new units can be used alone or with a common bass woofer system. Minimum power requirements: 15W. Price is under $140. each.

Dual Port loudspeakers (*SB* 3/80, p. 7) are now available in commercial form from a California manufacturer. **Modular Acoustics**, (C.C.L. Enterprises, 30682 San Antonio St., Hayward, CA 94544) manufacture a range of speakers in a number of formats: sub woofers, satellites, time aligned, tuned ports, and closed box among others. The good news is that this company will also supply component parts for the home constructor. Their dual port unit was reviewed in the July 1980 issue of *High Fidelity*. Their catalog is $2, and be sure to ask for their parts lists and prices.

Reliable test gear is something we all need for whatever work we do in speaker building or electronic construction. **Fordham Radio** (855 Conklin St., Farmingdale, NY 11735) issues a comprehensive catalog of all sorts of electronic test equipment at quite competitive prices. If you don't build your own you will certainly want to know about Fordham. Even if you do build your own, there are some pieces of gear that you may want to buy just for the super reliability and accuracy possible.

If you're having trouble finding that special grille foam you want to finish your speaker project **Custom Sound Corporation** has what you need. They supply custom designs in thicknesses from ½ to 1½" and in sizes up to 4x10 feet. They have an interesting flyer available on request to 8460 Marsh Road, Algonac, MI 48001. Their telephone is (313) 794-5400. Send a 15¢ stamp for the list and tell them *SB* sent you.

If you have trouble with gremlins in your system from either the power line or your FM antenna, **Electronic Specialists, Inc.** (171 S. Main St., Natick, MA 01760) probably has some sort of answer to the problem. They specialize in filters for power line and antenna lead-ins. Ask for their new catalog 801.

VOLUME 1, NUMBER 4 DECEMBER 1980

SPEAKER BUILDER
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Love and Marketing

KLH ONE OF THREE SPEAKER manufacturing concerns in which Henry Kloss was a major principal and resident genius, (the other two are Acoustic Research and Advent) is moving out of Westwood Massachusetts to the West coast where the parent company, Electro Audio Dynamics, manufactures its Infinity line of loudspeakers. EAD is the second new owner of KLH, Singer having bought it in 1967 and then sold it again. KLH has reportedly lost money for the last two years, and Advent, curiously enough, has been in the same plight.

AR, Advent, and KLH were all, at one time, Cambridge based firms. Now none of them is.

We have seen the decline, and in some cases, the demise of excellent audio firms which have become the property of conglomerates. We have no way of knowing the real reasons why. AR appears to be the exception to this trend with a lively sales record and a lot of excellent, basic research to back up a sales program.

I cannot refrain from observing that the role of individual imagination and genius is every bit as important to a company and its success, however, as the marketing and management skills which most business types seem to suppose are the *sine qua non* of success. I suspect that the special ingredient supposed by the presence of David Hafler at Dynaco, the insights of Edgar Villchur at AR, and the unique product concepts of Henry Kloss at Advent and KLH were vitally important to the health and progress of audio manufacturing enterprises.

Certainly marketing and money management have their place as all too many companies make abundantly clear—both in terms of sucesses and failures. But if marketing is no more than technique, then the consumer knows better than to fully trust such a company.

This magazine and its companion publication are firmly committed to the proposition that imaginative, loving regard for the end product must be the prime ingredient in any successful audio manufacturing enterprise. This attitude is more than a commitment to quality. It is the extra mile one travels in the direction of real understanding of the device and the way it solves the tradeoffs which Mother Nature always demands.

Martin Buber, a German philosopher and a devout Jew, put it well. Any human relationship to persons and things must be "I-Thou" rather than merely "I-It." By this he did not mean some kind of cutesy personification of things, but a deep respect for the uniqueness of persons and physical objects. Only a deep seated love for the nature and function of the product is motive enough to give a designer the comprehensive insight needed to make something that is really excellent.

For that reason we believe in the builder—*homo faber*—who is an amateur: who loves what he does. In my view the greatest of our designers are amateurs. The root of the word is the Latin *amo* for love. The buck is not the point. The love of excellent result—the neat, clever satisfying compromise which achieves something not possible before.

Better mousetraps don't come out of marketing departments. They come out of the heads of people who would rather know more about mice than anything else in the world.

Better audio gear will come out of the minds of amateurs, regardless of how many or few degrees they have earned or who they work for. And the better results and designs can come out of your workshops too. Discipline is most surely necessary. Hard work and long hours too. What we are talking about is not easy. But a genuine commitment to quality can make the work seem pleasure and the time all too short.

Over 360 loudspeaker companies dot the American landscape here at the threshold of the eighties. Apparently the definitive speaker has yet to appear—but the appetite for fully satisfying home reproduction is far from being satisfied.

As this issue goes to press we have passed the 5,000 mark in subscriptions to this fledgling publication. We think this augurs well for the spread of the reliable knowledge about speaker building but also opens a particularly exciting vista of information sharing and growth for us all. □

About this issue

Robert Bullock leads off this fourth and final issue of our first year with number one in a major series of articles which will fully explore the mysteries of the great speaker theorists Thiele and Small. These two began to write their landmark articles in the early sixties and published them in Austrailian journals. Not until the early seventies did these important insights begin to be noticed in the United States. Prof. Bullock's hobby is speaker construction, but he teaches mathematics at Miami University in Oxford, Ohio. **Siegfried Linkwitz** is back this time with the extensions and continuing exploration of his three-box system. In addition we offer a full circuit board and parts layout for the Linkwitz electronic crossover and delay which is the work of another Hewlett-Packard employee, **Robert Melanson.** Melanson, a *SB* reader and speaker enthusiast cooperated with author Linkwitz, although they had not met previously and work in plants 150 miles apart. Circuit boards will be available later this year through Old Colony Sound Labs. Those interested in the boards or a possible kit of parts should drop a postcard to Box 243, Peterborough, NH 03458.

Roger Sanders' final article in his series on electrostatics begins on page 26 with full details on how to build his transmission line bass system to provide his system's bottom two octaves.

Nick Palladino provides some handsome photos of his version of the popular Fried system which calls for pyramidal enclosures to house the mid and high frequency drivers with a large dual transmission line for th bass transducers. The rich patina of his rosewood veneer finishes made us wish we were able to use full color in this issue to show you how beautiful fine cabinetry can be.

Our Mail Box this time is full to overflowing and promises to remain that way. We appreciate every one of your letters although we are not able to acknowledge them. We will use as many as we have room for.

Our next issue will be in the mail at the end of February 1981. We have a rich trove of good things in store for the second year of *Speaker Builder's* publishing life. We will continue with the Bullock series, a fine article on how to get the last drop of performance out of your tweeter, a clever and innovative ribbon tweeter that you should be able to make for less than $10, a handy gadget for making driver measurements in the design process, a speaker test box for checking finished results *before* building the final box and many many more that you won't want to miss. □

Thiele, Small, and Vented Loudspeaker Design: Part I

by Robert M. Bullock III

The name Thiele and the term Thiele alignment are known by many with an interest in loudspeakers. What is a Thiele alignment? How is it obtained? How is it used?

To answer these questions, I shall describe the landmark work of A.N. Thiele and R.H. Small's subsequent refinements in the design of vented (bass reflex) loudspeakers. I have used their work in designing my own systems; it provides a method whereby the home builder can construct loudspeaker systems of truly impressive quality.

Before Thiele, vented loudspeaker design was simple but, more often than not produced poor quality sound. The earlier procedure did not allow for a vented system's critical dependence on certain amplifier and driver characteristics. Thiele and Small's procedures do allow for these characteristics and yield accurate and predictable results—in other words, they will produce good sound.

I shall describe the derivation of these procedures and their underlying assumptions. I shall also include the necessary data for designing your own system and provide some examples to illustrate the design procedures.

BACKGROUND

A loudspeaker system is a complicated combination of electrical, mechanical and acoustical components and this mixture of different components make analyzing its behavior quite difficult. However, years of research have led to a usable theory, that a loudspeaker system can be visualized as an electrical circuit for purposes of analysis— i.e., we can use an electrical circuit as a model of a loudspeaker system. Specifically, Novak[1] has shown that a high pass filter electrical circuit can be the model for a vented loudspeaker system.

A model's purpose is as follows. The system of interest (in this case a vented loudspeaker) is converted (in an abstract sense) into the model, a system chosen because its behavior can be analyzed by some known theory (circuit theory in our case). Having analyzed the model, we convert our conclusions back to conclusions about the system which interests us. This analysis method is much favored by scientists. Roughly, they discover new facts by interpreting old facts in a new setting.

The model of a vented loudspeaker system, the high pass filter, is a well understood electrical circuit. Any facet of its behavior can be determined by applying known theory to its schematic diagram. By using this model, Thiele and Small identified those elements of the loudspeaker system that significantly affected its behavior and quantified these elements and effects. They then based their design procedures on this information.

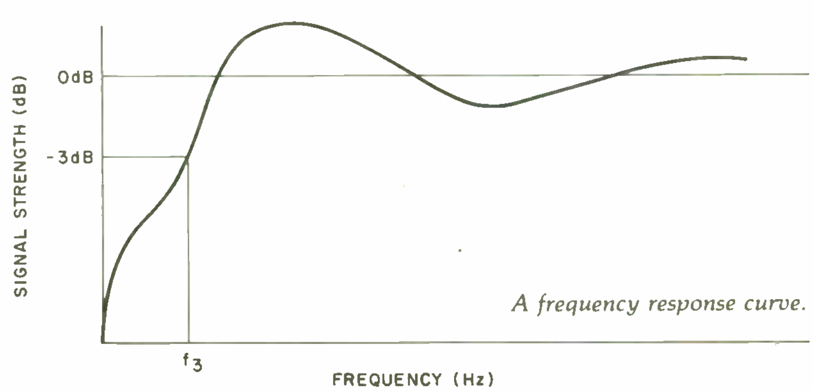
FREQUENCY RESPONSE

The most significant aspect of loudspeaker behavior for design purposes is frequency response. Think of a loudspeaker system and its model, the high pass filter, as devices which accept an input signal and operate on it to produce an output signal. Assume that neither device will alter the signal frequency; what we *can* alter is the relative signal strength. In other words, assuming that all input signals have the same strength, the device may produce an output that varies with frequency and this variation is the frequency response.

We can visualize this most simply in terms of a graph called a frequency response curve, signal frequency being plotted on the horizontal axis and relative signal strength on the vertical axis. Signal frequency is measured in Hertz (Hz) and relative signal strength in decibels (dB). *Figure 1* is a frequency response curve. Think of the 0 dB level on the vertical axis as a reference level, i.e., a positive decibel measure at a given frequency means the output strength at that frequency is greater than the reference, while a negative decibel measure means it is smaller.

Referring to *Fig. 1*, f_3 is called the cutoff frequency, frequencies above f_3 are said to be in the passband; those

FIG. I



A frequency response curve.

below, in the stopband. In practice, the stopband output is at such a low level it is insignificant, so, only frequencies above f_3 are "passed." We can think of *Fig. 1* as a typical response curve for either a loudspeaker system or its model, the high pass filter.

To decide whether a particular loudspeaker system will produce good sound, we must examine its frequency response curve. To find it use the high pass filter model and find its frequency response by studying its schematic diagram and applying electrical circuit theory. The resulting response will be that of the loudspeaker system.

The key to success in using a model is to establish a relationship between the parts of the model and the parts of the system in such a way that one can translate a requirement in the model into a requirement on the system being modelled. Thiele accomplished this by identifying various parameters of the loudspeaker system with parameters in the model, thus identifying the parts of the loudspeaker system which influence response.

Electrical engineers call the particular parameter relationships needed to obtain a given response in the model an alignment. Thiele adopted this term to describe the corresponding loudspeaker system parameter relationships; this is the origin of the term, "Thiele alignment."

POSSIBLE RESPONSE CURVES

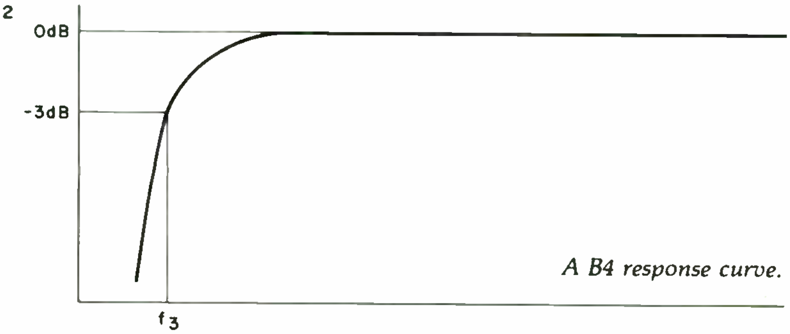
In order to know what kinds of response curves loudspeaker systems can have, let us consider some of the model's known response curves. High pass filters can exhibit a wide range of curves, so we need to make some assumptions as to what kinds of responses are desirable for loudspeaker systems.

We want the response curve to be as "flat" as possible in the passband. With this constraint, Thiele and Small identified three types of filter response curves. The first is that of a fourth order Butterworth filter, whose response curve is shown in *Fig. 2*. The filter's name is abbreviated to B4, and we shall use this designation for the response curve as well. A response curve generally takes the same name as the filter from which it derives.

Because drivers have different characteristics, we cannot always get a B4 response from a loudspeaker system. To cover a range of driver characteristics, Thiele and Small also used a quasi-third order Butterworth filter, QB3, and a Chebyshev filter, C4. *Figs. 3* and *4* show typical responses for filters of these two types. The main differences between a B4 and a QB3 are that a QB3 has more "droop" in the passband and its cut-off frequency is higher. C4 responses are distinguished

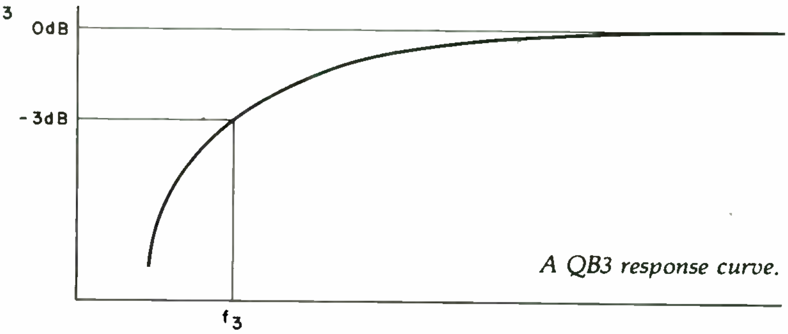
Continued on page 10

FIG. 2



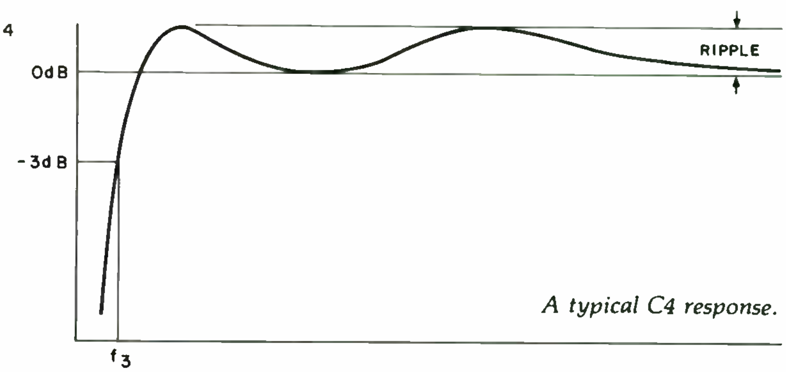
A B4 response curve.

FIG. 3



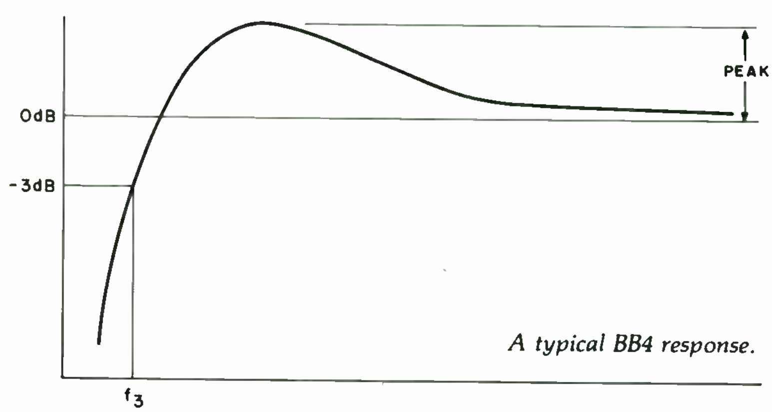
A QB3 response curve.

FIG. 4



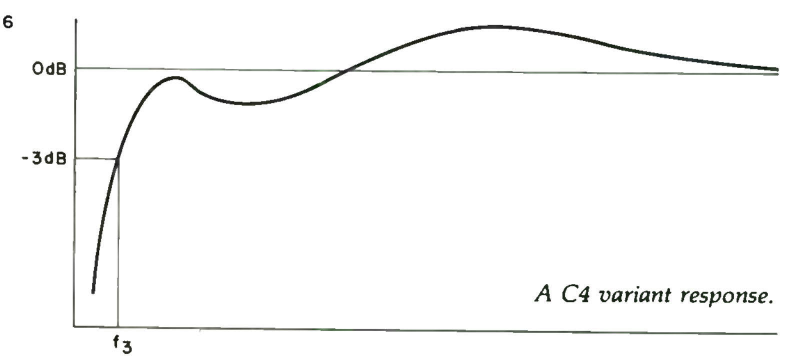
A typical C4 response.

FIG. 5



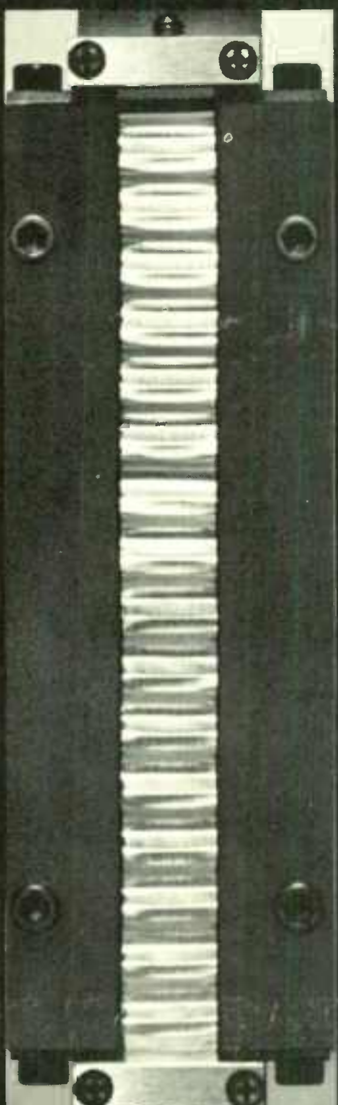
A typical BB4 response.

FIG. 6



A C4 variant response.

HF-1 Ribbon Loudspeaker



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THIELE, SMALL, and VENTED LOUDSPEAKER DESIGN

Continued from page 8

by a ripple in the passband and a smaller cut-off frequency than a B4. You need to know the size of this ripple before deciding whether this response curve would be desirable for a loudspeaker system.

Both Thiele and Small considered primarily these three responses as a basis for their alignments, but there are many other possibilities. Two are shown in *Figs. 5* and *6*. The *Fig. 5* curve is a fourth order boom box response, denoted BB4; alignments yielding this response appear in an article by Hoge[2]. In another article[3] Hoge gives alignments which are variations of Small's alignments; *Fig. 6* is a variant of a C4.

For improved transient response, Small recommends Bessel (Be4) and sub-Chebyshev (SC4), both of which resemble a QB3 (*Fig 3*) but have more droop in the passband. Thiele also considers what are called higher order responses. I have built a subwoofer system using a sixth order Butterworth response (B6) and the sound is outstanding. In this article, however, we will consider only the QB3-B4-C4 series of responses.

You may wonder about the use of the word "order" in the names of filters and responses. This term is used to classify high pass filters and the rate at which the response curves decrease at low frequencies. First order filters decrease at the rate of 6dB per octave, second order at 12dB per octave, etc.

Vented loudspeaker response curves correspond to fourth order filters and so their response curves decrease at the rate of 24dB per octave at low frequencies. Closed box loudspeaker systems are modelled by second order filters and so their responses fall off at 12dB per octave. This decrease in response at low frequencies just reflects the well-known fact that loudspeaker sytems do not provide significant output at very low frequencies. One of our design objectives is to obtain the lowest possible cut-off frequency consistent with a flat passband.

ALIGNMENT PARAMETERS

We need to know which parameters of the loudspeaker system determine its response curve. Thiele found the frequency response is completely determined by several amplifier, driver, enclosure, and vent parameters which reflect those parts of the loudspeaker system related to the model's electrical components.

Assume that the driver is a moving coil diaphragm type operating in its piston range. According to Thiele, this is from 0Hz to 5000/d Hz where d is the advertised diameter of the driver in inches. This means the driver will cover a frequency range from 0 to 5000/d Hz. Depending on its properties, it may be used at even higher frequencies and need not necessarily be used all the way down to 0Hz; for example, ElectroVoice sells a unit with a vented midrange driver. Nevertheless, vented designs are usually associated with the bass section of a multi-driver system.

Five parameters determine the driver's influence on response. First is the dc-resistance of the voice coil, R_E. Second is the resonant frequency of the driver, f_S. The next two are Q numbers and measure how effectively the driver's resistive parts damp it at its resonant frequency: the smaller the Q number, the more effective the damping. Q_{ES} is the Q due to electrical resistance; Q_{MS} is that due to mechanical resistance.

The final driver parameter gives the compliance, or springiness, of the diaphragm mounting, expressed in terms of a volume of air which would have the same compliance and denoted V_{AS}. R_E is given in ohms, f_S in Hertz, V_{AS} in cubic inches, centimeters, feet etc; the Q numbers are dimensionless. We arrive at these figures by measuring driver impedance. A driver's voice coil inductance can be sizeable, but we can ignore it since it usually has negligible effects in the driver's piston range.

The amplifier, crossover network, and connecting cable also contribute to driver damping. To take this into account, we must modify the driver's electrical Q. Suppose the crossover and connecting cables have a resistance of R_x ohms in series with the driver, and the damping effect of the amplifier is the same as a resistor of R_g ohms in series with the driver; then we change Q_{ES} to Q'_{ES} by the formula:

$$Q'_{ES} = [(R_E+R_x+R_g)/R_E]Q_{ES}. \quad (1)$$

One way to determine R_x is to hook

TABLE I
SMALL ALIGNMENTS FOR $Q_L = 5$

Q_{TS}	h	∝	f_3/f_S	Ripple (dB)
.2000	2.0014	7.5746	2.5914	
.2100	1.9080	6.7702	2.4566	
.2200	1.8232	6.0730	2.3332	
.2300	1.7459	5.4646	2.2198	
.2400	1.6751	4.9306	2.1151	
.2500	1.6101	4.4594	2.0180	
.2600	1.5502	4.0415	1.9276	
.2700	1.4948	3.6691	1.8430	
.2800	1.4434	3.3358	1.7637	
.2900	1.3957	3.0364	1,6889	
.3000	1.3512	2.7663	1.6183	
.3100	1.3097	2.5220	1.5514	
.3200	1.2708	2.3001	1.4877	
.3300	1.2344	2.0980	1.4269	
.3400	1.2003	1.9134	1.3687	
.3500	1.1681	1.7444	1.3139	
.3600	1.1378	1.5893	1.2592	
.3700	1.1093	1.4464	1.2074	
.3800	1.0823	1.3147	1.1576	
.3900	1.0568	1.1929	1.1095	
.4000	1.0326	1.0801	1.0632	
.4100	1.0095	.9757	1.0190	
.4200	.9877	.8785	.9767	-
.4300	.9652	.7920	.9377	-
.4400	.9425	.7154	.9016	-
.4500	.9200	.6480	.8684	-
.4600	.8979	.5888	.8379	-
.4700	.8766	.5370	.8100	-
.4800	.8560	.4915	.7844	-
.4900	.8364	.4516	.7609	-
.5000	.8178	.4166	.7395	-
.5100	.8002	.3857	.7198	.10
.5200	.7836	.3583	.7017	.11
.5300	.7680	.3340	.6852	.14
.5400	.7533	.3122	.6699	.17
.5500	.7394	.2927	.6558	.21
.5600	.7263	.2752	.6428	.24
.5700	.7140	.2592	.6307	.28
.5800	.7024	.2447	.6195	.32
.5900	.6915	.2314	.6091	.37
.6000	.6811	.2192	.5994	.41
.6100	.6713	.2080	.5903	.46
.6200	.6620	.1975	.5818	.5
.6300	.6531	.1878	.5738	.55
.6400	.6447	.1787	.5663	.60
.6500	.6367	.1701	.5592	.65

TABLE II
SMALL ALIGNMENTS for $Q_L = 7$

Q_{TS}	h	∝	f_3/f_S	Ripple (dB)
.2000	1.9393	7.7775	2.5289	
.2100	1.8494	6.9524	2.3968	
.2200	1.7678	6.2372	2.2759	
.2300	1.6935	5.6132	2.1647	
.2400	1.6254	5.0655	2.0620	
.2500	1.5629	4.5822	1.9667	
.2600	1.5054	4.1535	1.8778	
.2700	1.4522	3.7714	1.7946	
.2800	1.4029	3.4295	1.7165	
.2900	1.3571	3.1223	1.6429	
.3000	1.3145	2.8452	1.5732	
.3100	1.2748	2.5944	1.5070	
.3200	1.2376	2.3667	1.4439	
.3300	1.2028	2.1594	1.3836	
.3400	1.1702	1.9699	1.3258	
.3500	1.1395	1,7964	1.2702	
.3600	1.1106	1.6371	1.2167	
.3700	1.0834	1.4905	1.1651	
.3800	1.0578	1.3552	1.1153	
.3900	1.0335	1.2300	1.0674	
.4000	1.0103	1.1146	1.0215	
.4100	.9886	1.0070	.9777	-
.4200	.9662	.9113	.9373	-
.4300	.9436	.8266	.9001	-
.4400	.9212	.7521	.8660	-
.4500	.8992	.6868	.8348	-
.4600	.8780	.6297	.8064	-
.4700	.8578	.5798	.7804	-
.4800	.8385	.5361	.7567	-
.4900	.8203	.4978	.7351	.10
.5000	.8031	.4642	.7155	.10
.5100	.7870	.4345	.6975	.13
.5200	.7719	.4083	.6810	.16
.5300	.7578	.3849	.6659	.20
.5400	.7445	.3640	.6520	.24
.5500	.7321	.3453	.6393	.28
.5600	.7205	.3284	.6275	.32
.5700	.7096	.3131	.6166	.37
.5800	.6993	.2992	.6065	.42
.5900	.6896	.2865	.5971	.47
.6000	.6805	.2749	.5883	.52
.6100	.6719	.2641	.5802	.57
.6200	.6638	.2542	.5726	.63
.6300	.6561	.2449	.5654	.69
.6400	.6488	.2363	.5587	.74
.6500	.6418	.2283	.5524	.80

everything up as it would be in the finished system and measure the resistance between the amplifier connections. Subtract R_E from this and the result is R_x.

Small[5] describes the most accurate method for finding R_g; or, if we know the damping factor D of the amplifier, we can find R_g from the formula

$$R_g = R_n/(D-1) \qquad (2)$$

where R_n is the nominal impedance of the driver. Typical damping factors vary from 15 to 500; 25-30 seems to be fairly common. Thiele[4] says that if R_x+R_g is less than 5 percent of R_n, then we can use the unmodified value Q_{ES} if response variations of up to .4dB are tolerable.

The actual Q number used to specify an alignment is called the total Q, denoted Q_T or Q_{TS}, and is found from the formula

$$Q_{TS} = Q'_{ES}\,Q_{MS}/(Q'_{ES} + Q_{MS}), \qquad (3)$$

or

$$1/Q_{TS} = 1/Q'_{ES} + 1/Q_{MS}, \qquad (4)$$

which is sometimes more convenient.

The remaining influences on response are the volume V_B of the box on which the driver is mounted and the resonant frequency f_B of the box resulting from the presence of the vent.

ALIGNMENTS

Assuming we know the values for Q_{TS}, f_S, and V_{AS}, an alignment is a set of relationships which must be satisfied between Q_{TS}, f_S, V_{AS}, V_B, and f_B. The relations for given Q_{TS} are that the quantities f_B/f_S and V_{AS}/V_B must have specified values which we obtain from analyzing the model; Small denotes these two ratios by h and α (alpha) respectively. Thus, an alignment is equivalent to a list of the three numbers Q_{TS}, h, α: for example, a Thiele B4 alignment is $Q_{TS}=.383$, $h=1$, $\alpha=\sqrt{2}$. If you have a driver with $Q_{TS}=.383$, $f_S=$ 25Hz, and $V_{AS}=10000\text{in}^3$, then a B4 response will be obtained if $f_B=hf_S=1\times25=25$Hz and $V_B=V_{AS}/\alpha=10000/\sqrt{2}=7071\text{in}^3$. An alignment usually includes a value of f_3/f_S also so you can see what the cut-off frequency will be with the alignment; however, you do not need it to make your design.

An alignment uniquely determines a response curve for a particular driver and amplifier combination. Thiele and Small based their alignments on the QB3-B4-C4 series of responses so that only one possible alignment is obtained for each value of Q_{TS}. We will cover only these alignments.

Tables I, II, and *III* list Small alignments. To use a table, find the value of Q_{TS} in the first column and use the values of h, α, f_3/f_S found in that row. We can also find alignments by various formulas—for example, Saffran's formulas in *Speaker Builder,* Issue 1/80, p. 35 ("Mailbox" section). With these formulas, you can compute a Thiele alignment from a given value of $Q_T(=Q_{TS})$. Such formulas are handy but provide only approximate values, whereas accurately prepared tables will provide exact values.

THIELE ALIGNMENTS

Thiele[6] was the first to analyze the electrical circuit model in order to provide specific vented speaker system alignments. In this landmark paper he presented a large table of alignments, the first nine of which were in the QB3-B4-C4 series. These nine are just samples from a continuum of QB3-B4-C4 alignments that can be obtained by varying the value of Q_{TS} . If $Q_{TS}=.383$, the alignment is a B4; if $Q_{TS}<.383$, it is a QB3, and if $Q_{TS}>.383$, it is a C4.

There are usually practical bounds on the values of Q_{TS}. If $Q_{TS}<.2$, the cut-off frequency is usually undesirably high. At the other extreme, for large Q_{TS} the alignments are C4 and so the response has a ripple which increases in magnitude with Q_{TS}. By $Q_{TS}=.7$ this ripple exceeds 1.5dB and an audiophile would probably find it objectionable.

Exact alignment values are quite complicated to calculate and are best found using a computer. I will not provide Thiele alignments for reasons to be made clear below. If you would like to use them anyway, Saffran's formulas should be sufficient. Error can be as high as 5 percent. Be sure to correct his formula for h to $h=.38/Q_T$.

SMALL ALIGNMENTS

Small[8] observed that vented loudspeaker systems designed according to Thiele alignments did not always exhibit the frequency response predicted by the model. He determined that the box and vent were exerting a damping effect which altered the response curve. He referred to these damping effects as losses because they usually resulted in decreased output at certain frequencies, and accounted for them by "observing that these losses may be adequately approximated for design purposes by a single frequency invariant leakage loss."

In other words, he introduced another parameter which represented losses due to box and driver leaks, sound absorption in the box, and vent influences. This parameter is a Q number, Q_L; the larger this Q number, the less effect the box has on the response. In terms of Q_L we may regard Thiele alignments as Small alignments when $Q_L=\infty$; this, however, is an ideal value which cannot be realized in practice. For this reason I decided not to include a table of Thiele alignments. I have provided a sufficient number of Small alignments to cover most circumstances.

TABLE III
SMALL ALIGNMENTS for $Q_L=10$

Q_{TS}	h	α	f_3/f_S	Ripple (dB)
.2000	1.8960	7.9232	2.4845	
.2100	1.8085	7.0834	2.3543	
.2200	1.7292	6.3554	2.2351	
.2300	1.6569	5.7202	2.1255	
.2400	1.5908	5.1627	2.0241	
.2500	1.5301	4.6706	1.9299	
.2600	1.4742	4.2342	1.8421	
.2700	1.4225	3.8452	1.7599	
.2800	1.3747	3.4971	1.6826	
.2900	1.3303	3.1843	1.6097	
.3000	1.2890	2.9022	1.5406	
.3100	1.2505	2.6469	1.4748	
.3200	1.2146	2.4150	1.4121	
.3300	1.1809	2.2038	1.3521	
.3400	1.1493	2.0109	1.2945	
.3500	1.1197	1.8342	1.2390	
.3600	1.0918	1.6719	1.1855	
.3700	1.0656	1.5225	1.1339	
.3800	1.0409	1.3846	1.0841	
.3900	1.0175	1.2571	1.0363	
.4000	.9954	1.1390	.9907	-
.4100	.9732	1.0325	.9482	-
.4200	.9507	.9381	.9092	-
.4300	.9282	.8550	.8736	-
.4400	.9062	.7822	.8410	-
.4500	.8848	.7187	.8114	-
.4600	.8644	.6632	.7844	-
.4700	.8451	.6148	.7600	-
.4800	.8269	.5725	.7377	.10
.4900	.8097	.5355	.7175	.10
.5000	.7937	.5029	.6991	.13
.5100	.7787	.4742	.6823	.17
.5200	.7648	.4487	.6670	.20
.5300	.7517	.4261	.6529	.25
.5400	.7396	.4059	.6401	.29
.5500	.7282	.3877	.6282	.34
.5600	.7176	.3714	.6173	.39
.5700	.7077	.3565	.6072	.42
.5800	.6983	.3431	.5979	.50
.5900	.6896	.3308	.5892	.55
.6000	.6814	.3195	.5812	.61
.6100	.6736	.3092	.5737	.67
.6200	.6663	.2996	.5667	.73
.6300	.6594	.2907	.5601	.80
.6400	.6529	.2825	.5540	.86
.6500	.6467	.2748	.5482	.92

TABLE IV
ALIGNMENT FORMULAS

$Q_L = 5$
$h = .419/Q_{TS}^{.9721}$
$\alpha = .0743/Q_{TS}^{3.357}$
$f_3/f_S = .315/Q_{TS}^{1.323}$

$Q_L = 7$
$h = .420/Q_{TS}^{.953}$
$\alpha = .0569/Q_{TS}^{3.153}$
$f_3/f_S = .305/Q_{TS}^{1.330}$

$Q_L = 10$
$h = .421/Q_{TS}^{.933}$
$\alpha = .0689/Q_{TS}^{3.019}$
$f_3/f_S = .296/Q_{TS}^{1.335}$

The value of h is usually within 2%, the value of f_3/f_S within 6%, and the value of α between −17% and +25%.

The difficulty with the Q_L parameter is that we can find it only after constructing the system. This means for initial design purposes we must assume a Q_L value. According to Small, most systems have a Q_L of between 5 and 10, with a general tendency for it to fall with increasing box volume. Thus, the assumptions of $Q_L=10$ for small boxes, $Q_L=7$ for moderate boxes, and $Q_L=5$ for large boxes should be satisfactory.

For the most accurate design, after constructing a system using an assumed value for Q_L, we measure the actual value and modify the alignment on the basis of this value. Since I cannot discuss the measurement of box losses here, let us suppose the assumed values mentioned above result in an adequately accurate system. As an example of how box losses can affect performance, I designed a bookshelf system assuming $Q_L=10$. The completed system had a very weak bass response. Measuring Q_L, I found a value of 3. Investigation revealed air leaking through the driver's dust cap. I sealed the cap with glue, remeasured the driver parameters which were altered by the additional mass (the glue) and realigned assuming $Q_L=5$. Measurement confirmed $Q_L=4.5$ and final adjustments produced a system with a solid bass.

Table 1 contains Small alignments

Design Box

1. Driver: KEF B139. R_n(nominal impedance)$=8\Omega$, $R_E=6.9\Omega$, $f_S=24.2$Hz, $Q_{ES}=.34$, $Q_{MS}=6.86$, $V_{AS}=8500$ cubic inches. The driver diameter is taken as 10".
   Amplifier: Pass A40. D=500
   Connecting leads: $R_X=.06\Omega$ (no crossover, low loss cable)
   Design:

$$R_g=R_n/(D-1)=8/499=.016.$$

$$Q'_{ES}=(R_g+R_x+R_E)Q_{ES}/R_E=6.98\times.34/6.9=.344.$$

$$Q_{TS}=Q'_{ES}Q_{MS}/(Q'_{ES}+Q_{MS})=.327.$$

Using the $Q_L=7$ table and $Q_{TS}=.33$, $h=1.2028$, $\propto=2.1594$, $f_3/f_S=1.3836$.

Alignment values:

$$f_B=hf_S=1.2028\times24.2=29.1\text{Hz},$$

$$V_B=V_{AS}/\propto=8500/2.1594=3936 \text{ cu. in.},$$

$$f_3=(f_3/f_S)f_S=1.3836\times24.2=33.5 \text{ Hz}.$$

Vent design: Using a 1.5" radius tube and the tube length formula (5), the tube length must be 7.72".

The design volume of the box must be increased to account for the vent tube, driver, and any internal bracing. The length of tube inside the box will be about 7" if we use ¾" particle board. So the tube volume is $3.14\times(1.5)^2\times7=49.5$ cu. in. If the driver and bracing occupy 120 cu. in. (an estimate), the box must have an internal gross volume of 4106 cu. in. Some possible inside dimensions are 20H×16.5W×12.5D (=4125in³), 25H×14W×11.75D (=4113in³). This driver should be crossed over at or below 5000/10=500Hz.

2. Driver: same as Example 1.
   Amplifier: ST150. $R_g=.3\Omega$.
   Connecting leads and crossover: same as in Example 1.
   Design:

Using formula (1), $Q'_{ES}=.358$, and so $Q_{TS}=.34$.

Using the $Q_L=7$ table with $Q_{TS}=.34$ gives $f_B=28.3$Hz, $V_B=4315$in³, and $f_3=32.1$Hz.

For the vent, a 1½" radius will require a 7.36" length

Notice the increase in box size required when a lower damping factor amplifier is used. A crossover will add even more to the box size; on the other hand, the cut-off frequency is decreased. This looks like a good way to reduce the cut-off frequency, which can be reduced even more by adding a resistor in series with the driver. This will increase Q_{TS} and reduce f_3. In my opinion, added resistance tends to degrade other aspects of performance, so do not use it unless you must. Your own ears are the besst judge of the results, however. Added resistance can also be used to balance a stereo pair, as the next example shows.

3. Assume one channel is designed using the driver, amplifier, and connecting leads in Example 2, and a second channel is to be designed using a second KEF B139 with $R_E=7$, $f_S=21.8$, $Q_{ES}=.294$, $Q_{MS}=6.36$ and $V_{AS}=10200$in³. Without additional resistance the design values would be $f_B=30.6$Hz, $V_B=2975$in³, and $f_3=37.4$Hz. Thus, one box would be 4315−2975=1340in³ smaller than the other! Of course, you could build two larger boxes and block off part of one of them.

The alternative is to change Q_{TS} for the second driver by adding additional resistance. To figure how much, proceed as follows. The required value of $\propto$ to achieve the desired box volume is

$$\propto=V_{AS}/V_B=10200/4315=2.3638.$$

From the $Q_L=7$ table, a Q_{TS} of .32 will give $\propto=2.3667$ and so a 4310in³ box volume. The 5in³ difference should be negligible. So, we want $Q_{TS}=.32$ and we know $Q_{MS}=6.36$. Using formula (4),

$$1/Q_{TS}=1/Q'_{ES}+1/Q_{MS},$$

$$1/Q'_{ES}=1/Q_{TS}-1/Q_{MS}=2.9678,$$

and hence, $Q'_{ES}=.337$. By formula (1), we need a resistor R so that $.337=Q'_{ES}=(.3+.06+7+R)(.294)/7$

or

$$R+7.36=8.0227$$

and

$$R=.6627.$$

Thus, a resistor of 2/3 ohms in series with the driver will raise Q_{TS} to .32. This can be fabricated from three 1 ohm resistors in parallel. The new design values will be $f_B=27$Hz, $V_B=4310$om³ and $f_3=31.5$ Hz. Notice that the cut-off frequencies of the two boxes are now also closer.

4. Driver: Audax HD17B37. $R_n=8\Omega$, $R_E=6.5\Omega$, $f_s=36$ Hz, $Q_{ES}=.28$, $Q_{MS}=2$, $V_{AS}=1200$ in³. Driver diameter is 6½".
   Amplifier: ST150. $R_g=.3\Omega$
   Crossover and connecting leads: $R_X=.6\Omega$
   Design: The value of Q_{TS} can be computed to be .275, which we will round to .28. The box will be small, so using $Q_L=10$ we will obtain $f_B=49.5$ Hz, $V_B=343$in³ and $f_3=60.6$ Hz. If a 1" vent tube is used, it must be 16", clearly much too long for such a small box. Reducing the radius to ½" gives a length of 3.64". The radius of the latter tube is smaller than recommended, so there may be wind noise. Cross over at 770 Hz.

5. Driver: EMS 803, $R_n=8\Omega$, $R_E=5.5\Omega$, $f_S=39$ Hz. $Q_{ES}=.503$, $Q_{MS}=5.71$ and $V_{AS}=3320$in³. Driver diameter is 8".
   Amplifier: Radio Shack. Damping factor unknown.
   Crossover and connecting cables: $R_x=.7\Omega$ (measured).
   Design: The Radio Shack unit was inexpensive, so I will use a value of 20 for the damping factor. This may result in a slight response peak if the damping factor is actually higher, but I suspect it is not. This give $R_g=.42$, $Q'_{ES}=.606$ and $Q_{TS}=.547$. Using $Q_L=7$ and $Q_{TS}=.55$ gives $f_B=28.6$ Hz, $V_B=9615$in³ and $f_3=24.9$ Hz. This box is big enough that $Q_L=5$ should probably be used. This gives $f_B=28.8$ Hz, $V_B=11343$in³ and $f_3=25.6$ Hz. A 2" radius vent gives a tube length of 3.32". Cross over at 625 Hz.

The table indicates that the response will have .21 dB of ripple. If the amplifier actually has a high damping factor, there may be an additional variation of about .5 dB and this total possible variation of .71 dB may be objectionable. Notice how large the box must be considering the 8" driver diameter. Typical dimensions could be 36Hx21Wx15D.

for $Q_L = 5$, *Table II* for $Q_L = 7$, and *Table III* for $Q_L = 10$. These tables were generated on an HP3000 minicomputer and I have verified their accuracy. The entries are the exact theoretical values rounded to four decimal places and in my opinion provide the most reliable values for design. If your Q number is expressed to more than two decimal places, you can either round off or interpolate.

Formulas also exist for Small alignments; for example, Hoge[3] provides formulas for $Q_L = 7$. These formulas can be off by as much as 25 percent for some alignments. As an example of the consequences of this error, I have drawn the response for $Q_L = 7$, $Q_{TS} = .4$ (close to a B4), using the tables. *Fig. 7* shows this response, labelled T, with the response obtained from the formulas, labelled F, superimposed for comparison.

If you like to play with formulas, I have included some of my own construction for $Q_L = 5, 7, 10$ in *Table IV*. I make no claims about their accuracy except to say that they should be as accurate as those Hoge used. You can get an idea yourself by comparing formula values with the table values.

VENT DESIGN

Once you have chosen an alignment, you must design a vent. The type we will consider here consists of a circular tube mounted flush in the baffle board and extending into the interior of the box. We determine the proper length of the tube, denoted L, from the box volume, the box resonant frequency, and the radius r of the tubing to be used, by the formula

$$L = 1.463 \times 10^7 \times r^2)/(f_B^2 \times V_B) \times 1.463 \times r \qquad (5)$$

I cannot thoroughly discuss vent design here, but the following comments should help. The general consensus is that the vent radius should be at least one inch. I have used a three-eighths inch radius vent with barely acceptable results in a very small box. For a very large box, the radius should probably be two or three inches.

Take some care in selecting a vent radius, since the larger this radius, the longer the vent must be. Thus, you may wind up designing a 10″ vent to put in a box only seven inches deep! I have made my vents of plastic sewer pipe, which works quite well. Do not mount the vent extremely close to the driver as undesirable interactions may occur. The edges of the vent should be smoothly rounded.

ADDITIONAL INFORMATION

A few cautions about box construction. Do not design a cube or a box with a square base. Make sure all joints are air tight and that there is no leakage around the opening used to bring the amplifier leads to the inside of the cabinet. Make sure the driver is sealed into its opening so no air can leak out around the edge. Particle board is a good material for the box. Use plenty of screws and glue to insure that each panel is well clamped to the others. Battens along the seams are a good idea, as is bracing large panel expanses. Finally both Thiele and Small urge that you not stuff the interior of the box with sound absorbing material: a layer of sound insulation attached to all panels, except the baffle, is sufficient.

In order to use Small alignments you must start with a driver for which you know the parameters. Some manufacturers, such as Audax and EMS, make this information available. SRC, a company handling several brands of drivers, provide this information for some of their brands. Stamler's article[9] gives a table with values for f_S, Q_{TS}, V_{AS} for several drivers. Since Q_{ES} and Q_{MS} are not given, amplifier-crossover effects cannot be included in the design.

Continued on page 30

APPENDIX

Terms and Definitions

Mathematical symbols:

∞ A "number" larger than any other number.

< read as less than.

> read as greater than.

General terms:

Octave. A measure of distance from a fixed frequency to either twice or half the fixed frequency. An octave above 100Hz is 200Hz and an octave below is 50Hz.

Parameter. A parameter can be thought of as a variable number whose value can be fixed in a particular instance.

Physical terms:

Compliance. The ease with which the driver diaphragm is displaced. High compliance drivers are those for which a small force will cause a large diaphragm displacement. The support of the diaphragm can be viewed as a spring which tends to return the diaphragm to its rest position. A low compliance means this spring effect is strong.

Impedance. An alternating current analogue of direct current resistance.

Decibel. A unit used to measure the difference between two intensity levels, usually of acoustic or electrical power. In an electrical circuit a quantity of interest is the ratio of output power to input power at various frequencies, P_{out}/P_{in}. Thus, if the power out is three times the power in, $P_{out}/P_{in} = 3$. When measuring sound levels, all levels are compared to a reference level such as the threshold of hearing. If S_i is the sound power at the threshold of hearing and S_o is an arbitrary sound power, then S_o/S_i is a measure of sound level. These ratios can cover an extremely large range of values, say from 10^{-15} to 10^{15}. By considering $10\log(P_o/P_i)$ and $10\log(S_o/S_i)$ instead, the range will only run from −150 to +150. These numbers are of a more manageable size. The logarithm quantities are decibels. Using decibels also simplifies certain calculations by allowing addition to replace multiplication.

Piston range. The diaphragm of a moving coil driver exhibits two modes of vibration. In the first mode it vibrates rigidly back and forth, like a piston. In the second mode, different parts of the diaphragm may be displaced from the rest position by different distances at a given instant. This mode of vibration occurs at frequencies above the piston range.

One of a crossover's functions can be to limit a driver's operation to its piston range. In typical systems some drivers do operate outside their piston range and how good they sound is partially determined by how well controlled they are in this "breakup mode." Bextrene and polypropylene drivers have the reputation for exhibiting well controlled performance on some interval above the piston range.

Resonant frequency, damping. The phenomenon of resonance is the tendency of an object to vibrate at a certain frequency when a periodic force of the same frequency is applied. If two strings of a guitar are tuned in unison and one is plucked, the other will vibrate. The sound wave produced by the plucked string is the force acting on the unplucked string. A platoon of soldiers marching in step over a bridge can cause the bridge to vibrate. Here the applied force is the soldier's footsteps. A singer can break a glass by singing the right note with sufficient intensity; again, the sound wave is the force.

An object will usually tend to vibrate more at some frequencies than others. Such a frequency is called a resonant frequency. As the third example shows, a resonant frequency can be destructive. If the amplitude of the resonant vibration stays below a destructive level, it is because the object can dissipate the applied force to some extent. This dissipation is called damping. The Q numbers are used to quantify how much damping is present.

Transient response. Roughly, the ability of a loudspeaker to follow an input waveform, which is usually determined by applying an impulse input and observing the output. The loudspeaker's ability to follow the initial rise of the pulse is called attack ability, and is a function of the loudspeaker's high frequency properties. The continued vibration, after passing the impulse, is called ringing, as in a bell after it is struck—i.e., after an impulse is applied to it. A short ring time is desirable, and depends on the loudspeaker's low frequency properties. Thus transient response depends on both low and high frequency behavior.

A Three-Enclosure Loudspeaker System: Part 3

Changes and refinements to the system described in Parts I and II

by Siegfried Linkwitz

These notes are intended to encourage further development of loudspeakers, and bring increased enjoyment to those who want to undertake the task of building their own systems. The changes and refinements made to the original loudspeaker system, described in issues 2 and 3, are presented to show the completeness of the analytical design approach, and should not be taken as an indication that the previous system is obsolete. The audible effects of the changes are subtle and the added complexity of the circuits would be worthwhile only to someone trying to achieve greatest accuracy of reproduction. But the techniques described should be of general interest to any loudspeaker designer.

I believe the weakest link in recreating the illusion of a life source with loudspeakers lies at the microphone pick-up end of the signal chain. It seems likely that more than two loudspeakers are needed, but first a much better understanding for recording and reproducing the appropriate sound field has to be developed and demonstrated. Then it may be possible to transport oneself to Symphony Hall without moving out of the living room chair. Meanwhile the loudspeaker as the necessary electroacoustic transducer can approach a high state of development.

DRIVER/FILTER MATCH

Any moving coil driver has the general frequency response of *Fig. 22* (*Fig. 17*, ref. 6. Figure numbers prior to 22 refer to the author's previous articles, Issues 2 & 3, 1980) when driven from a constant voltage source. This is a second-order filter with an asymptotic slope of 12dB/octave below the resonant frequency f_o and flat sound pressure output above it. The height of the peak near f_o and Q_o are easily determined from an impedance measurement of the driver, *Fig. 18*. This general transfer function between terminal voltage and sound pressure output applies to woofers, mid-range units and tweeters as long as their cone dimensions are small acoustically, *Fig. 2*, and must be taken into account when designing a crossover network.

As an example, consider the high-pass section of a crossover to a 25mm dome tweeter which has a resonance of 800Hz with Q_o of 0.9, *Fig. 23(a)*. The desired acoustic output should follow the fourth-order high-pass characteristic of the 24dB/octave crossover with 1.5kHz as the −6dB crossover frequency (b). At first glance it seems sufficient to shape the driver terminal voltage to follow the 24dB/octave high-pass function of (b) because the filter has 22dB of attenuation at the driver resonance. Indeed, this was the procedure in the original crossover design for the T27 tweeter, *Fig. 10*. Such terminal voltage, however, causes a 36dB/octave roll-off in acoustic output from the driver for frequencies below resonance f_o.

To achieve the exact acoustic frequency response of (b) the terminal

Continued on page 16

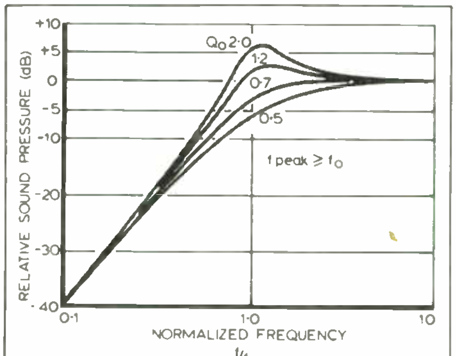


Fig. 22. Frequency response of a moving-coil driver with dimensions small compared to a wavelength, which must be taken into account when designing crossover networks.

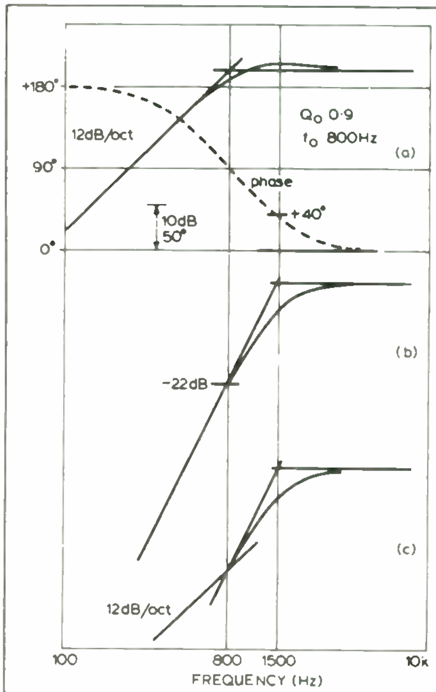
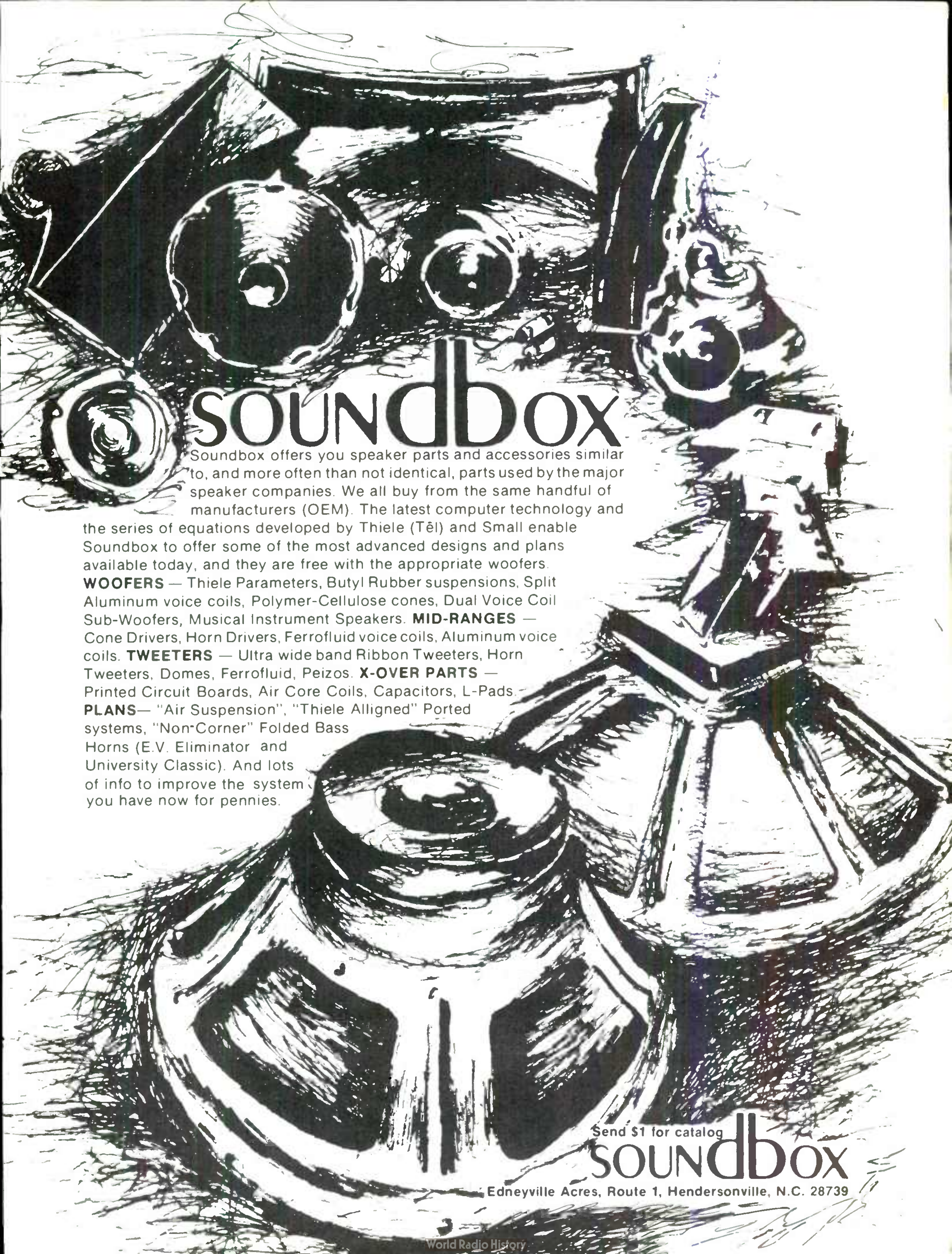


Fig. 23. To achieve an acoustic or overall high-pass filter response with 24dB/octave slope (b), requires the terminal voltage to follow a 12dB/octave slope below resonance to compensate for the effects of the driver, whose sound pressure and phase response are shown at (a).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A THREE-ENCLOSURE LOUDSPEAKER SYSTEM

continued from page 14

voltage must follow a 12dB/octave slope below the 800Hz driver resonance (c). This then compensates exactly for the phase shift and group delay which the driver would otherwise add to the acoustic high-pass function. The additional phase shift would cause a tilting of the radiation pattern as the sound pressures from the tweeter and mid-range unit would add to a maximum at a point off-axis.[10] The amount of the phase shift introduced by a second-order high-pass filter can be calculated for $Q_o \geq 0.5$ from

$$\phi = 180^0 - \arctan\left[2Q_0\frac{f}{f_0} + \sqrt{(2Q_0)^2-1}\right]\ldots$$

$$-\arctan\left[2Q_0\frac{f}{f_0} - \sqrt{(2Q_0)^2-1}\right]$$

For the above example, the driver contributes 40° of phase shift at 1.5kHz. Sound pressures from the mid-range unit and tweeter are therefore not in phase unless the measures described are taken.

DRIVER TERMINAL VOLTAGE

The acoustic high-pass function of the previous example requires an exactly-shaped terminal voltage to compensate for the driver's own frequency response. A fourth-order high-pass response is equivalent to the cascade of two second-order Butterworth sections.[10] The first step then is to equalize the driver output to follow a second-order Butterworth function by shaping the terminal voltage applied to it, *Fig. 24.* Design formulas were developed for a very useful network, *Fig. 25.* It is a modification of *Fig. 20* and will later be used also to extend the woofer response.

A note to those familiar with the description of transfer functions by poles and zeroes in the complex frequency plane: This network will generate a pair of complex zeroes (f_o, Q_o) which are positioned to cancel the complex poles of the driver (f_o, Q_o). In addition, a pair of complex poles (f_p, Q_p) is available which are placed at the crossover frequency in the case of the tweeter highpass or at the lower cut-off point of the woofer in the case of woofer equalization. The factor K in the design formulas is necessary for cancelling a pole-zero pair (f_{p1}, f_{z1}) which would otherwise be introduced by the network.

The second step in designing the acoustic high-pass filter is to follow this network with a standard second-order Butterworth section to achieve the overall drive voltage of *Fig. 23(c).* The complete circuit of *Fig. 26* is only slightly more elaborate than *Fig. 14* but it achieves the exact fourth-order acoustic output, *Fig. 23(b).*

Continued on page 18

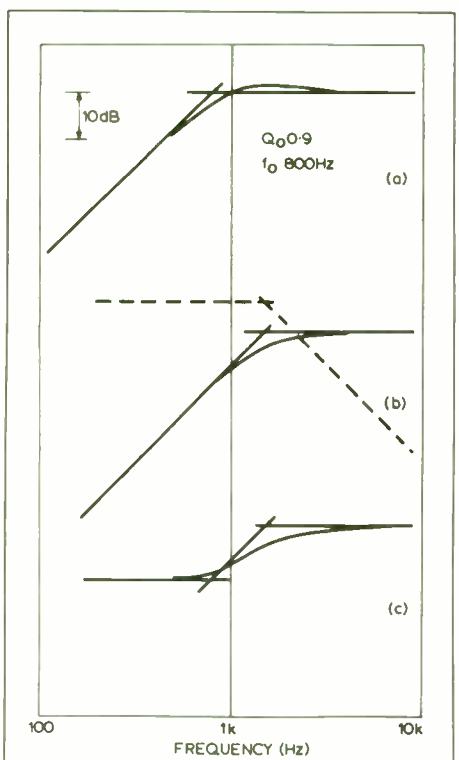


Fig. 24. Required drive voltage (c) has to be constant below the driver resonance frequency f_o to give the desired acoustic h. p. response (b) (cone excursion shown dashed), as a result of driver response (a).

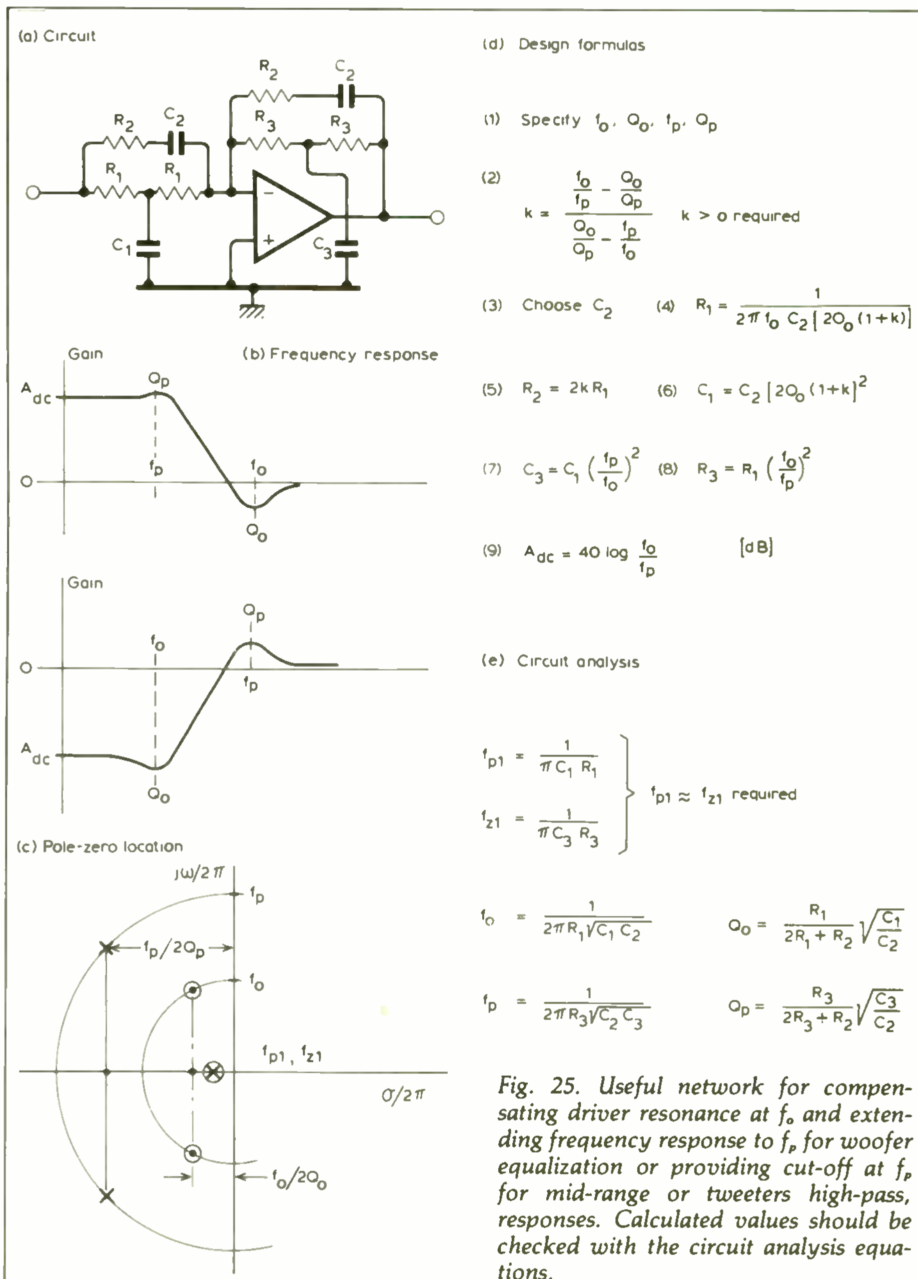
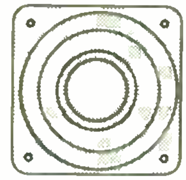
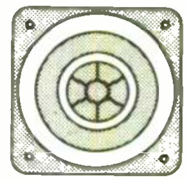


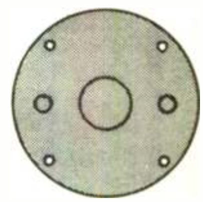
Fig. 25. Useful network for compensating driver resonance at f_o and extending frequency response to f_p for woofer equalization or providing cut-off at f_p for mid-range or tweeters high-pass, responses. Calculated values should be checked with the circuit analysis equations.

Philips Dome Tweeters give the best compromise between sensitivity, energy distribution, transient response, distortion characteristics and power handling.





When it comes to sound, advanced technology can put facts at your finger tips but, it's your senses that count.



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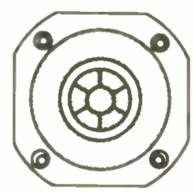

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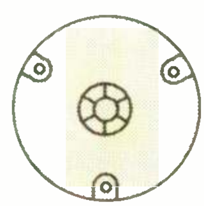

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A THREE-ENCLOSURE LOUDSPEAKER SYSTEM

continued from page 16

CROSSOVER FREQUENCIES AND DRIVERS

The technique described could be used to modify the original T27 high-pass filter (f_o 1.2kHz, Q_o 1.1). Instead, I used a Son-Audax HD12.9 D25 soft-dome tweeter with a 1.5kHz crossover frequency to the B110. I used HD12.9D25 with non-replaceable voice coil, is used instead of the HD12.9D25A because of flatter frequency response. It is available from Transcendental Audio, Arvada, Co. At 3kHz, the previous crossover point, the B110 cone diameter is about one wavelength so that a certain amount of directionality can be expected, *Fig. 1*. Further, the mid-range and tweeter units are separated by one wavelength at 3kHz so that the combined radiation pattern begins to narrow in the crossover frequency range *Fig. 3(b)*. The lower crossover reduces the acoustical dimensions by a factor of two so that a wider and more uniform dispersion is obtained over all frequencies in both the vertical and horizontal planes of radiation, *Fig. 2*. The loudspeaker then approaches more closely the acoustical point source.

While the mid-range unit has to cover one octave less in frequency, the tweeter must now have four times the excursion capability to maintain the same acoustic output. The Son-Audax unit works well in this application and there is no sacrifice in overall smoothness of response compared to the T27. The new unit does not slope down towards the high end. For most commercial recordings a slight droop of about 3dB between 2k and 15kHz seems subjectively preferable and such response can be easily adjusted with properly designed treble controls.

The crossover point between woofer and mid-range units has been raised from 70 to 100Hz, thus reducing the maximum cone excursion for the B110 by a factor of two for constant sound output. Experience has shown that only the mid-range power amplifier is occasionally driven into clipping. If carefully fused, a 100W amplifier might be considered for driving each B110. The three-way system is very forgiving to clipping of the mid-range amplifier. It is not audible on short transients because the woofer and tweeter channels still reproduce their undistorted portion of the total signal. The reduced frequency coverage of the B110 at both low and high frequencies improves the amplifier power distribution between the drivers.

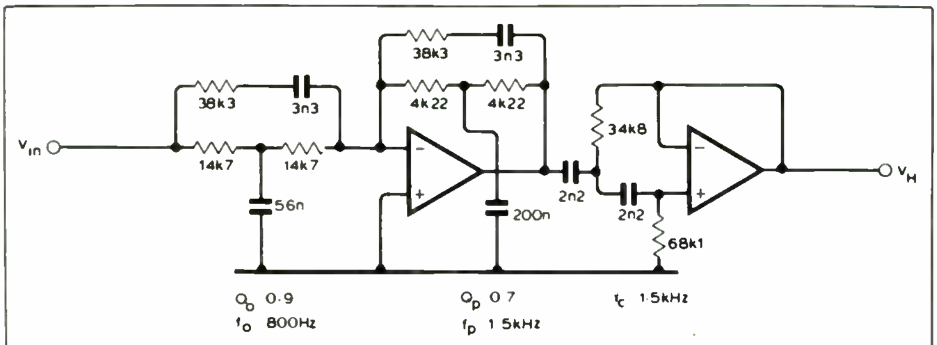

Fig. 26. Network for a 1.5kHz 24dB/octave acoustic highpass filter for a Son-Audax HD12.9D25 dome tweeter. The first op-amp stage compensates exactly for the driver resonance at 800Hz and gives a 12dB/octave 1.5kHz acoustic high-pass response. The second op-amp stage is a conventional Butterworth section. Design formulas for this network are from Fig. 25 and Fig. 14.

The crossover frequency between woofer and mid-range units was not raised further because the center woofer is positioned 0.84m behind the mid-range unit and the phase shift

$$\Phi = 360° \frac{d}{\lambda}$$

due to this path length would become excessive. Further, the stereo effect might suffer from the blending of left and right-channel information for too high a crossover frequency.

In the future it could become necessary to have truly full range, separate speakers for reproducing an appropriately recorded sound field. Previously the mid-range resonance at 70Hz was used as one section of the 24dB/octave acoustic high-pass function. The second section was provided by an active network. Now, both sections are implemented electronically using the circuit of *Fig. 25* to compensate for the B110's resonance in its enclosure, with f_o and Q_o determined from *Fig. 18* (f_o 73Hz, Q_o 0.6). The complete network has therefore a configuration similar to that of the tweeter, *Fig. 26*.

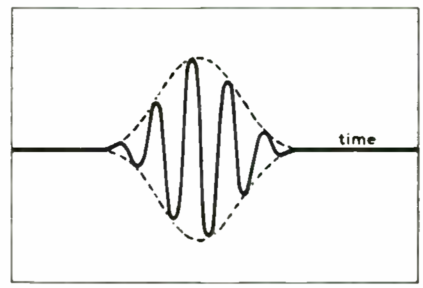

Fig. 27. Shaped toneburst used to evaluate the audibility of phase distortion.

WOOFER EQUALIZATION

The center channel woofer covers a relatively narrow frequency range. Of particular interest is the lower cut-off point and cut-off rate. There is some indication that the low-end phase behavior of a system can have audible effects. A 5Hz square wave for example, which sounds like a sequence of clicks, will change its tonal character when transmitted through an all-pass network.[10] From network theory we know that any high-pass filter with a slope of more than 6dB/octave will

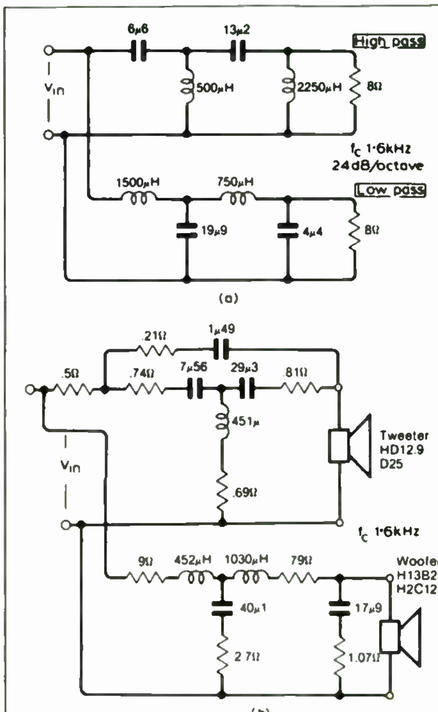

Fig. 28. Passive network for 24dB/octave acoustic slopes and 1.6kHz crossover frequency. If constant terminal impedance is assumed for the drivers then the network and its element values can be determined analytically[20] (a). Computer optimized network for actual drivers shown at (b).

produce some amount of ringing to a step input.[17] It is impractical to roll off the woofer at a 6dB/octave rate because it would mean that its cone excursion has to continue to increase at 6dB/octave even below the 3dB corner. The only practical way is to use a 12dB/octave rate. If the Q of this high-pass network is kept low at 0.5 then a minimum of overshoot is combined with a minimum of cone excursion.

The original network *Fig. 13* is a good approximation. The revised crossover uses the circuit of *Fig. 25* with f_p 19.3Hz and Q_p 0.5 which gives a 30Hz, 3dB corner frequency.

The high-pass nature of the woofer channel introduces phase shift at the 100Hz crossover to the mid-range unit according to the previous formula for Q_o 0.5:

$$\Phi = 180^\circ - 2\arctan \frac{f}{f_p} = 22^\circ$$

This amount of the phase shift by itself is insignificant, but combined with the phase shift due to the woofer location of 0.84m behind the mid-range it becomes necessary to add delay to the mid-range channel. It is implemented with the network of *Fig. 16* which has a phase shift of:

$$\Phi = -2\arctan(2\pi fRC)$$

Both the absolute value of the phase shift and the slope of the phase curve, or the group delay, can be made to coincide between woofer and mid-range channel. The specific network component values R and C depend upon the set-up of the loudspeaker system and no compensation is needed when mid-range and woofer radiate from the same plane. The two phase correcting stages have negligible effect at the 1.5kHz crossover.

AUDIBILITY OF CROSSOVER NETWORKS

Lowering of the tweeter crossover to 1.5kHz raised some concern over the audibility and phase distortion. The combined mid-range and tweeter sound pressure has an all-pass characteristic. Sound pressures from the two drivers are in phase at all frequencies relative to each other but the overall sound pressure has a frequency-dependent phase shift relative to the electrical signal at the input to the crossover network. The group delay is not constant with frequency.[10] Figure 11.

A new form of test signal was used which consists of a five-cycle tone

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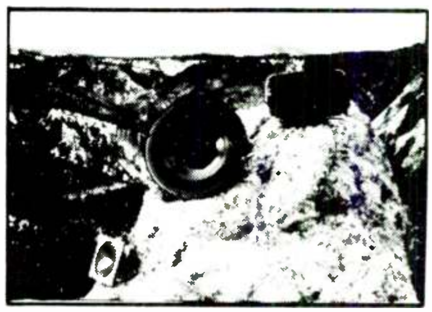

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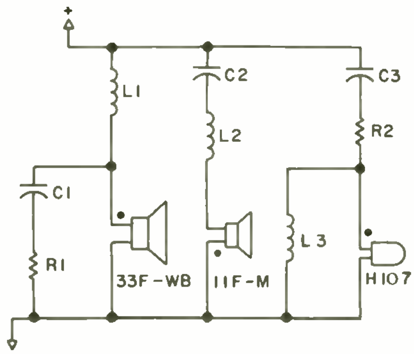
Issue #3 of *Speaker Builder,* in its comprehensive review of our largest kit, #603, pointed out that we do not include in the kit detailed specifications on the drivers and crossover. Engineering data sheets are available for the designer, of course, and here we have condensed those for the popular 603 system. Reprints of the review are available on request. Do it and say it: "See Us".

H-107

TECHNICAL DATA:	6Ω
Recommended enclosure volumes:	—
Closed box	—
Bass reflex	—
Recommended frequency range	3000-25000 Hz
Lower limiting frequency (DIN 45500)	—
Upper limiting frequency (DIN 45500)	25000 Hz
Free air resonance	1000 Hz
Operating power (DIN 45500)	3,2W
Characteristic sensitivity	91 dB
Nominal power (DIN 45573)	50W[1]
Music power (DIN 45500)	—
Flux density	1,80 T
Force factor (B1 product)	3,5Wb/m
Voice coil diameter	26 mm
Voice coil height	1,5 mm
Air gap height	2,0 mm
Voice coil resistance	4,8Ω
Effective diaphragm area	7 cm²
Moving mass	0,3 g
Air load mass in baffle	—
Mechanical suspension resistance	—
Weight	0,58 kg

1) Crossover frequency 4000 hz, 12dB/oct.

603 KIT SYSTEM



603 Crossover: 600 & 3000 Hz

R_1	3.9 ohm, 5 watt
R_2	2.2 ohm, 5 watt
C_1	48μF, 50 volts
C_2	24μF, 50 volts
C_3	5μF, 50 volts
L_1	4.7mH, 0.8 ohms
L_2	0.47mH, 0.8 ohms
L_3	0.48mH, 5.1 ohms

11F-M

TECHNICAL DATA:	4Ω	8Ω
Recommended enclosure volumes:		
Closed box	1,5-3 litres	
Bass reflex	—	
Recommended frequency range	400-5000 Hz	
Lower limiting frequency (DIN 45500)	—	
Upper limiting frequency (DIN 45500)	—	
Free air resonance	150 Hz	
Operating power (DIN 45500)	5,0W	
Characteristic sensitivity	89 dB	
Nominal power (DIN 45573)	100W[1]	
Music power (DIN 4500)	—	
Flux density	1,10 T	
Force factor (B1 product)	4,2Wb/m	4,7Wb/m
Voice coil diameter	26 mm	
Voice coil height	5,8 mm	
Air gap height	4 mm	
Voice coil resistance	3,1Ω	6,5Ω
Effective diaphragm area	55 cm²	
Moving mass	4,0 g	
Air load mass in baffle	0,5 g	
Mechanical suspension resistance	—	
Weight	0,53 kg	

1) Crossover frequency 800 Hz, 6dB/ckt.

SEAS

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Tucson, AZ 85711

PERFORMANCE IN CLOSED BOX

box volume (litres)	resonance frequency (f_O (Hz)	Q-value at f_O 4Ω	Q-value at f_O 8Ω	lower limiting frequency (Hz)[1]
50	65	—	0,75	40
70	60	—	0,65	38
100	50	—	0,55	35

1) DIN 45500
²₃ of cabinet filled with mineral wool

PERFORMANCE IN BASS REFLEX BOX

box volume (litres)	port area/ length (cm²/cm)	Helmholz resonance (Hz)	lower limiting frequency (Hz)[1]	natural frequencies of transfer function
70	40/20	25	33	14 Hz, Q = 0,9 60 Hz, Q = 0,75
100	40/20	22	30	13 Hz, Q = 1,0 50 Hz, Q = 0,6

1) DIN 45500
Cabinet walls internally lined with 5 cm mineral wool

THIELE/SMALL PARAMETERS:
Q_{MS}: 3.3 Q_{ES}: 0.41 Q_{TS}: 0.36 V_{AS}(m^3): 0.23

33F-WB

TECHNICAL DATA:	8Ω
Recommended enclosure volumes:	
Closed box	50-100 litres
Bass reflex	70-100 litres
Recommended frequency range	30-1000 Hz
Lower limiting frequency (DIN 45500)	see tables
Upper limiting frequency (DIN 45500)	—
Free air resonance	30 Hz
Operating power (DIN 45500)	1,6W
Characteristic sensitivity	94 dB
Nominal power (DIN 45573)	80W
Music power (DIN 45500)	200W
Flux density	1,20 T
Force factor (B1 product)	12Wb/m
Voice coil diameter	39 mm
Voice coil height	24 mm
Air gap height	10 mm
Voice coil resistance	6,0Ω
Effective diaphragm area	550 cm²
Moving mass	45 g
Air load mass in baffle	7 g
Mechanical suspension resistance	3,0Ns/m
Weight	5.65 kg

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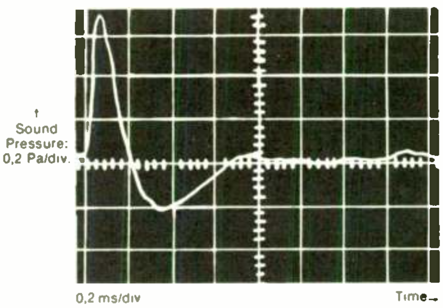
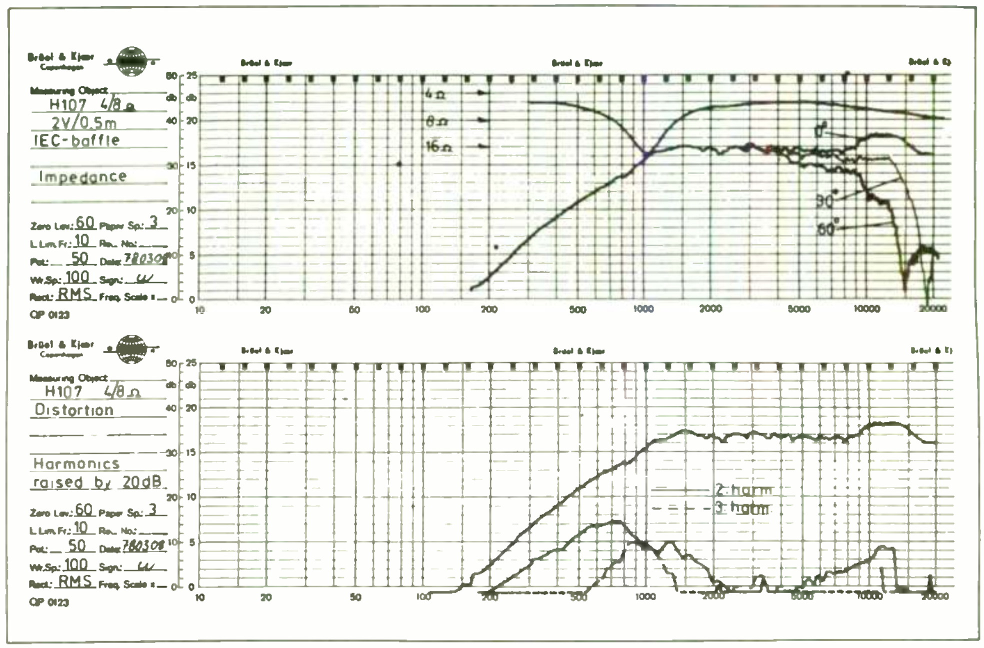
A high efficiency 1″ dome tweeter with exceptionally smooth high frequency response. The optimally shaped vacuum formed high loss plastic diaphragm does not require coating, and thus no protective grid is needed.

TRANSIENT RESPONSE *measured in IEC baffle; measuring distance 1 meter.*





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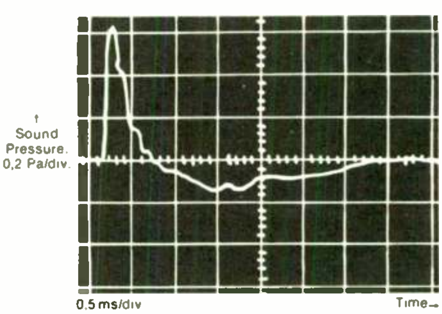
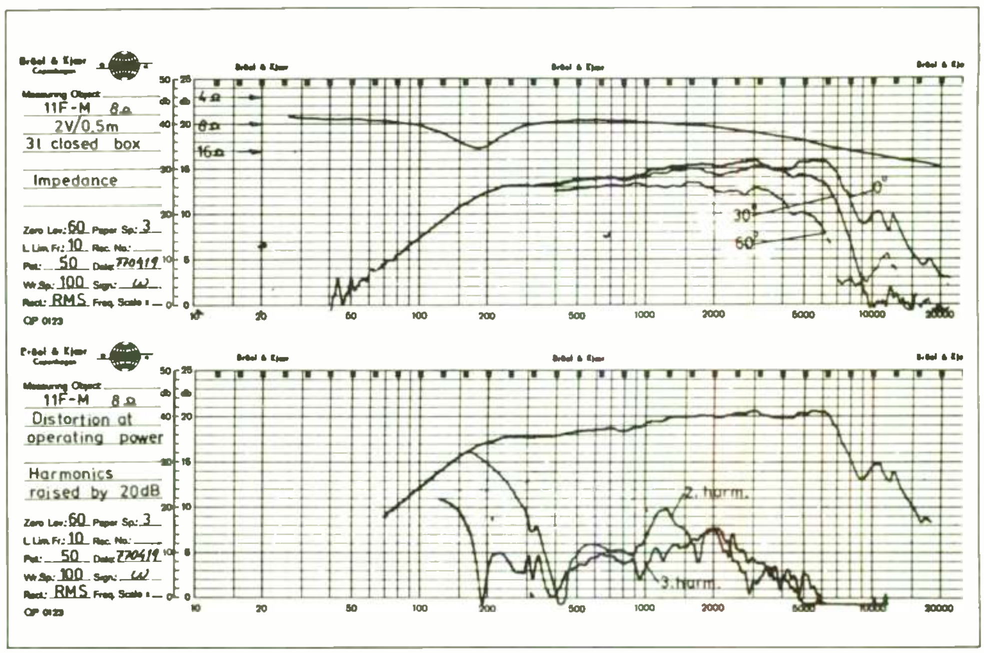
A high power 4½″ midrange with a paper cone and foam surround. Engineering a proper impedance match between cone and surround, plus coating the cone with damping material, drastically reduces cone resonances.

TRANSIENT RESPONSE *measured in 3 litre closed box, measuring distance 1 meter.*

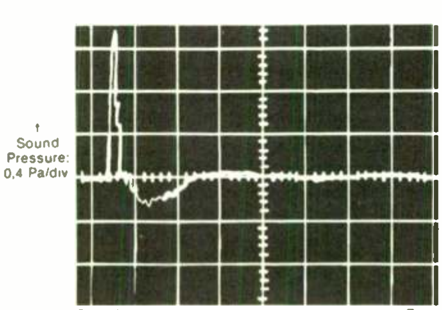


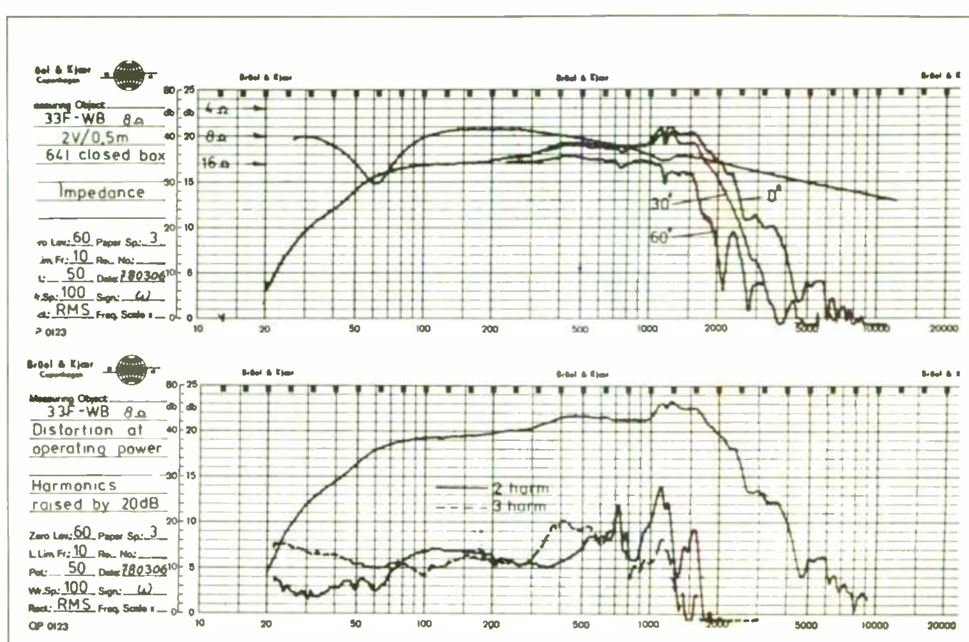


(SEAS) 33F-WB

A very high efficiency 13″ woofer with foam surround delivers improved large-signal transient response optimized by the slightly progressive suspension, and extremely low bass distortion through an unconventional magnetic design.

TRANSIENT RESPONSE *measured in 64 litre closed box, measuring distance 1 meter.*





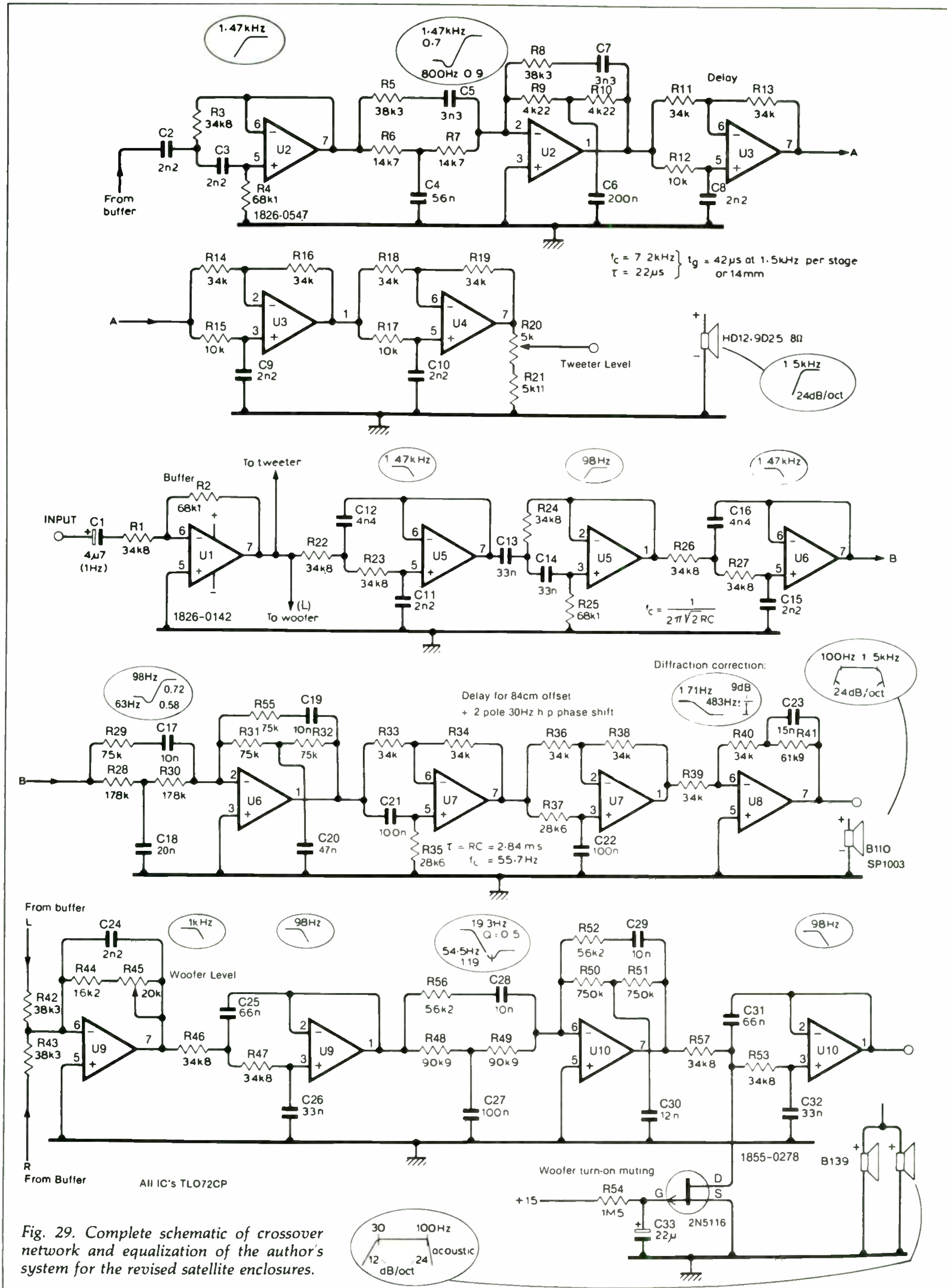


Fig. 29. Complete schematic of crossover network and equalization of the author's system for the revised satellite enclosures.

THREE-ENCLOSURE LOUDSPEAKER DESIGN

Continued from page 19

burst of variable frequency. The tone burst is not turned on and off in the usual abrupt fashion but instead it builds up and decays gradually, *Fig. 27*. The envelope of the burst follows a raised cosine function.[18] This signal is ideally suited to measure the psychoacoustically important blend of frequency and time response of loudspeakers. The spectral content of the shaped tone burst is concentrated in a narrow frequency range. The ear appears to be very sensitive to phase distortion of this signal, while a square wave or rectangular envelope burst are almost useless at higher frequencies for such tests.

A system with 24dB/octave crossover filters has the phase shift of a second-order all-pass network with complex poles and zeroes of Q = 0.7. No audible change could be noticed on insertion of this network into the test signal path. The Q had to be increased to 2.4 before any effect was noticed with the test signal at 1.5kHz. Observation with an oscilloscope indicated ringing of the trailing edge of the shaped burst which became increasingly more audible as Q was raised above 2.4. It can be concluded safely from these tests and others with program material that the phase distortion of a 24dB/octave crossover is insignificant.

Often, claims are made for the superiority of low-order crossover networks with 6dB/octave slopes. It should be obvious from *Fig. 24* that a 6dB/octave acoustic response cannot be realized with a passive network because the driver itself introduces a 12dB/octave slope and the aforementioned associated phase shift. Merely applying a terminal voltage which changes with 6dB/octave would guarantee an 18dB/octave slope below the driver resonance and 6dB above it, but with excessive phase shift which defeats the whole phase argument for this type of network.

Even a 12dB/octave acoustic high-pass filter would be extremely difficult to achieve passively as can be seen from the required terminal voltage of *Fig. 24(c)*.

The lowest-order acoustic high-pass filter which can be realized with a passive network has 18dB/octave slope, sometimes called an acoustic Butterworth.[19] This filter still suffers from the phase quadrature between low and high-frequency driver outputs and the resulting frequency-dependent irregularity in the radiation pattern.[10] Surprisingly then, the 24dB/octave crossover is the lowest-order function for which the all-important radiation pattern has a stable axis. So-called "linear phase" loudspeakers are based on wishful thinking and not on physical realties.

PASSIVE CROSSOVERS

Not everyone is at home with the electronics and the rather elaborate op-amp circuits for this loudspeaker system. A passive crossover seems attractive as it would consist only of inductors, capacitors and resistors in a relatively simple interconnection. Unfortunately it is considerably more difficult for the home constructor to arrive at the correct element values for a passive network than to design active networks with their great flexibility to change transfer functions and gain.[19]

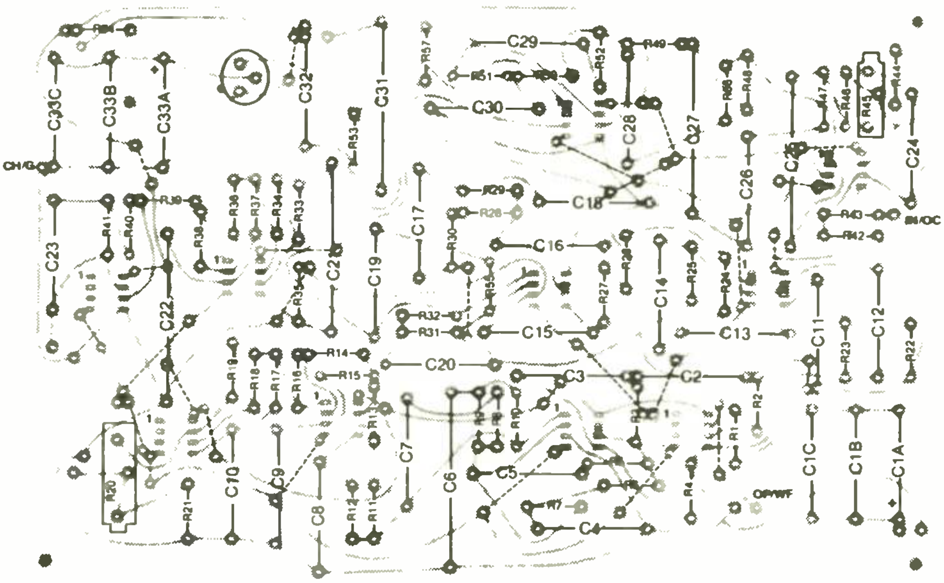
To design a passive network for a 24dB/octave acoustic crossover requires a computer optimization routine unless one is satisfied with the trial and error procedure on which most loudspeaker design has been based un-

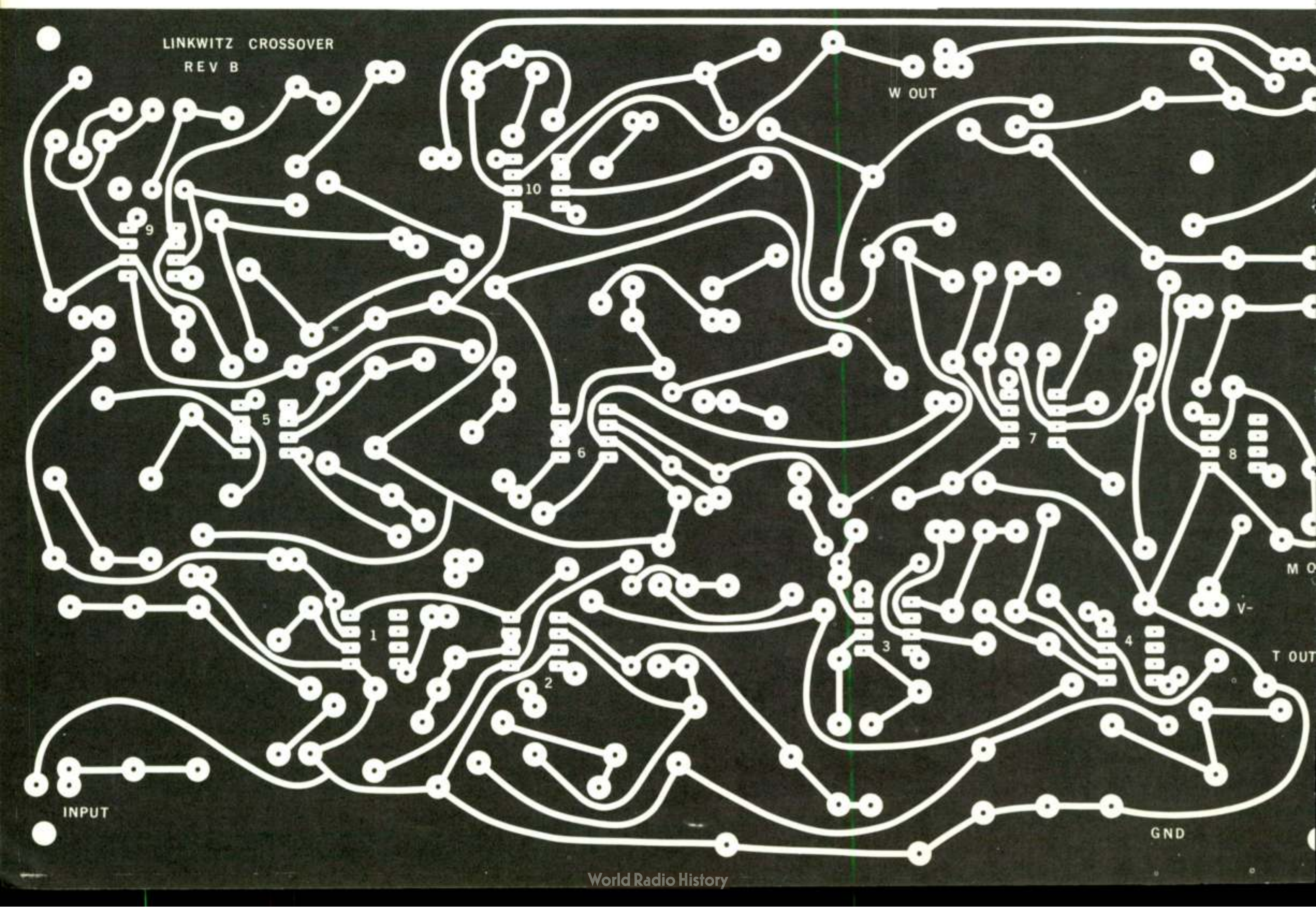
See overleaf; text continued on page 30

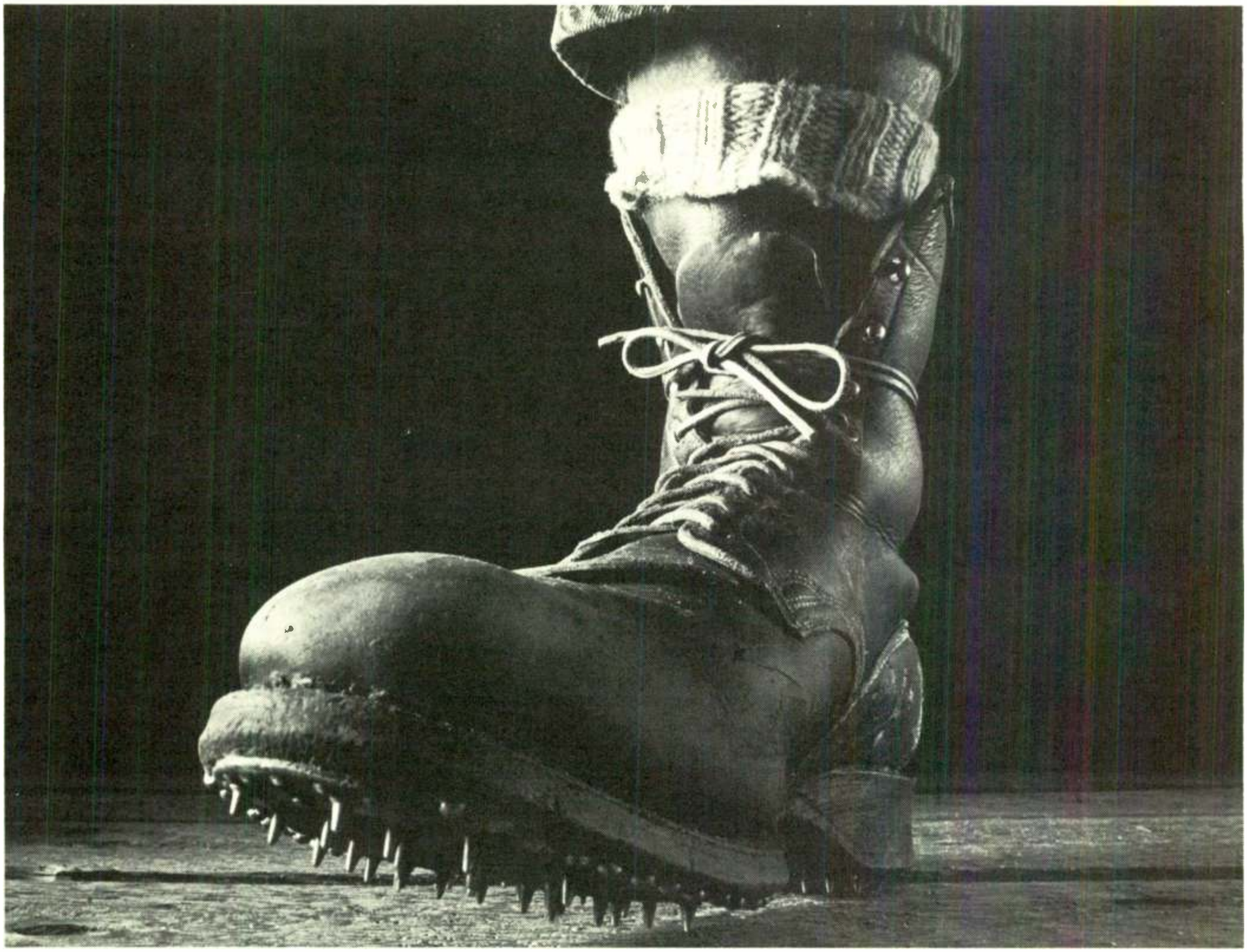
LINKWITZ CROSSOVER—PARTS LIST

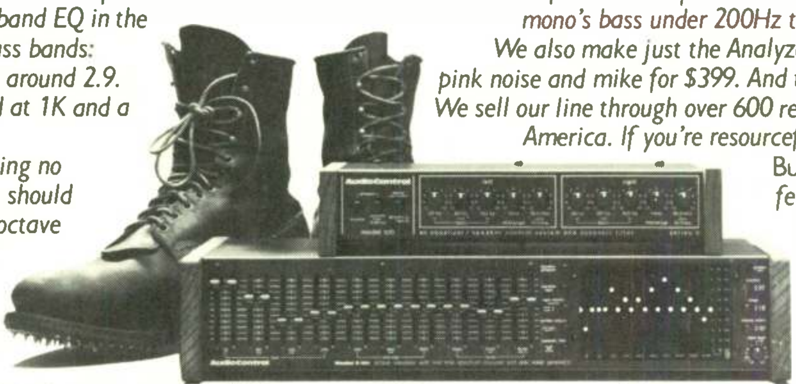
	Qty	Value
C_{1}	1	4.7μF
$C_{2,3,8,9,10,11,15,24}$	8	2200pF
C_{4}	1	5600pF
$C_{5,7}$	2	3300pF
C_{6}	1	.2μF
$C_{12,16,20}$	3	4700pF
$C_{17,19,28,29}$	4	.01μF
C_{18}	1	.02μF
$C_{21,22,27}$	3	.1μF
C_{23}	1	.015μF
$C_{25,31}$	2	.068μF
$C_{13,14,26,32}$	4	.033μF
C_{30}	1	.012μF
C_{33}	1	22μF
$R_{1,3,22,23,24,26,27,46,47,53,57}$	11	34.8k
$R_{2,4,25}$	3	68.1k
$R_{5,8,42,43}$	4	38.3k
$R_{6,7}$	2	14.7k
$R_{9,10}$	2	4.22k
$R_{11,13,14,16,18,19,33,34,36,38,39,40}$	12	34k
$R_{12,15,17}$	3	10k
R_{20}	1	5k POT
R_{21}	1	5.11k
$R_{28,30}$	2	178k
$R_{29,31,32,55}$	4	75k
$R_{35,37}$	2	28.6k
R_{41}	1	61.9k
R_{44}	1	31.6k
R_{45}	1	20k POT
$R_{48,49}$	2	90.9k
$R_{52,56}$	2	56.2k
$R_{50,51}$	2	750k
R_{54}	1	1.5M
U_{1-10}	10	TL072CP
Q_{1}	1	2N5116

Parts listed above are for one channel. The builder need not double the components for the woofer if only one woofer is to be used. The circuit layout was designed to accept polypropylene, polystyrene, parylene and polycarbonate capacitors in both filter and bypass applications for sonic improvement. If you wish to bypass electrolytics, choose values that are 2% of the preceding value, i.e. 4.7μF = .094μF (.1μF); 1880μF (1800pF). All resistors are ¼W, 1% metal film. For the ±15V power supply the Sulzer design (TAA, 2/80) is suitable.









An Electrostatic Speaker System: Part III

by Roger R. Sanders

The woofer system is an important factor in the overall performance of the speaker system. Of the total sound energy radiated by the complete speaker system, probably 80% to 90% of the sound is radiated by the woofer. The ESL appears to make all the sound when you have a woofer system that is doing its job properly. In all the commercial ESL hybrid systems I have heard, woofer system problems usually destroy the system's coherence. The usual complaint is that two different types of drivers are obviously at work. The sound is not homogeneous.

In comparison to such a system, a full range ESL sounds considerably more coherent and detailed, even given its limitations. However, if you construct a transmission line speaker system to use with the ESL's the sound will be superior to a full range ESL. Electronic crossovers are a large factor in this superiority so do not attempt to operate the system without them or by using a single amplifier and a passive, high level crossover. A biamped system is absolutely necessary.

You may expect the following improvements with a T.L./ E.S.L. system: 1. greatly improved SPL's, 2. deep bass which is not available from the ESL's, 3. improved detail in the bass and midrange when compared to the full range ESL's, 4. the system will seem at ease.

T.L. construction is more complex than that of your average box. A number of designs for T.L.'s are available and I refer you to J. Theodore Jastak's articles on design and construction, particularly his first in *TAA* 1/73.

The transmission line's basic concept is to direct all the energy from the rear of the driver into a tube. The length of the tube essentially determines the low frequency cutoff of the speaker; the longer the tube, the deeper the response. Typically, 6' to 8' tubes are used, although this varies to some extent with the size of the woofer. I use a 10' tube in my design which is for 10" woofers. Some of the shorter lines can decouple from the woofer at lower frequencies so that the woofer flapping and fluttering becomes a problem. This does not occur in my design because of the 10' line. In fact, woofer excursions even at very high SPL's are amazingly small.

MULTI-RESONANT

A typical box enclosure has many resonant frequencies which markedly affect the sound. T.L.'s are generally free of resonances for two reasons: 1. The tube is tapered, which results in an infinite number of tiny resonances rather than a few large ones. 2. It is completely filled with damping material. Most T.L. designs do not use completely tapered tubes because of difficulties in construction, but have a number of steps in them to approximate a taper. My design tapers steadily along its entire length.

The tube terminates at a port. Most of the energy has been absorbed by the time the sound waves reach it. However, very low frequencies will escape the line there. I believe these frequencies have been slowed enough by the damping material to shift their phase by about 180 degrees by the time they escape the port. Therefore they come out in-phase with the woofer's front radiation and support the deep bass. However, I have no data to confirm this.

The general theory says the cross-sectional area of the line should be somewhat larger than the driven area of the woofer at the beginning and then taper to approximately the same size as the woofer area at the port. Several English engineers believe the line may be the same size as the woofer initially and taper to about 70% of woofer size at the port.

I chose to use larger areas and my enclosures are rather large. The drawings (*Figs. 17 and 18*) are for enclosures 3" narrower than mine. They will work adequately since they are still larger in cross-sectional area than the woofers and the cabinets will be more attractive.

DESIGNS & MATERIALS

Ted Jastak demonstrates several types of construction techniques which should work well if you feel that my design is too difficult to build. I have not tried them, however. My design is a composite of ideas gleaned from Jastak,[1] I.M. Fried, Reg Williamson, and Bert Webb[2]. the basic design is the classical Bailey line[3] with modifications.

I used ¾" high density particle board in construction. Although there is no such thing as too much mass in a speaker enclosure, the ¾" sides of mine do not flutter at high SPL's, and the sound is clean and free of resonances when measured with a spectrum analyzer. If you want to use 1" particle board, or cast the enclosure in concrete, do so.

I did not insert the parts in grooves because I am not much of a wood worker. I just cut the parts accurately on a table saw and used wood screws about every eight inches along with plenty of "Tightbond" glue. A certain sequence should be followed during assembly. Take one side and attach the front, back, top, and bottom. Then add the internal partitions. These form a folded tube since a tube 10 feet long behind each woofer would be rather awkward. I wait to cut the port and woofer cutout until I have this basic box constructed because it is then a rather simple task using a sabre saw.

Run the speaker wires and jacks inside the box. Once you put the last side on the box, you will not be able to do this. Staple or otherwise firmly attach the loose end of the wire near the woofer cut-out so that is will not fall back when you turn the speaker upright.

Next lay a straight edge across the internal partitions, making marks on the edges of the box to show the locations of these partitions. When you put the last side in place, you will know where to drill the screw holes.

STUFFING GUIDE

You now must completely stuff the box with damping material. There is little question that natural long fibre wool is best for this. However, it is expensive and you must moth proof it. Other materials, such as polyester fluff, fibreglass, and open cell foam can be used, although they don't damp quite as well.

If you use wool, you will need to support it with nylon mesh or a dowel every eight inches so it will not gradually compress. Sprinkle it with moth crystals before putting the side on, and use a fine grille cloth over the port.

Determining the correct amount of damping material to use is at best a guess. Even if you know how much to use, determining the density in the enclosure would be impractical. Jastak suggests using about ½ pound of wool for every cubic foot of space. The material should be set up in a constant impedance mode, meaning that it should be packed tighter behind the woofer than at the port. I ended up putting in the wool very lightly at the port and pushing it gently to compress it a bit as I went up the line.

In my opinion it is better to overstuff rather than understuff. You need not stuff the area immediately behind the woofer at this point; you can do that after the box is completed and you are about to mount the woofer.

When you have completed the stuffing, attach the last side and finish the enclosures as you choose. I puttied the screw heads

Continued on page 28

Old Colony KITS

POLICY: OLD COLONY SOUND LAB is a service agency for readers of *The Audio Amateur* and *Speaker Builder* magazines. It attempts to provide circuit boards and the basic, or hard to find, parts for construction projects which have appeared in the magazine. **Old Colony assumes that the constructor will use the** *Audio Amateur* **or** *Speaker Builder* **magazine article as the guide for building his unit.** Kits, with noted exceptions, are not priced to include article reprints or construction instructions. Old Colony kits, with stated exceptions, do not provide metal work, cabinets, line cords and the like. We suggest that before purchase amateurs secure and evaluate the articles, which give details on each unit. Kits vary widely in complexity and required construction skills. A very few can be assembled by the beginner. If you are just starting in audio, get some experience building Heath or Dyna kits before tackling an Old Colony kit, or locate an experienced friend to help in case of difficulties.

CROSSOVERS

ELECTRONIC

For both electronic crossovers: crossover points and R_1, R_2, C_1, C_2 MUST be taken from Fig. 3, p. 11, Issue 2, 1972, TAA. No other values can be supplied.

KC-4A: ELECTRONIC CROSSOVER, KIT A. [2:72] Electronically divide the signal before the amplifier. Requires one amp for bass; a second for treble (or one stereo amp per channel). Lowers distortion and dramatically increases power capability. Single channel, *two-way*. Values of R_1, R_2, C_1, C_2 must be specified with order. All parts and C-4 circuit board. Includes new LF351 ICs. Each **$8.00**

KC-4B: ELECTRONIC CROSSOVER, KIT B. [2:72] Single channel, three-way. Values of R_1, R_2, C_1, C_2, must be specified with order. All parts and C-4 circuit board. Includes new LF351 ICs. Each **$11.00**

KK-6L: WALDRON TUBE CROSSOVER: Low pass. Single channel, 18dB/octave, Butterworth, [3:79] includes Bourns 3-gang plastic pot, level control, Mullard tubes, board, and three frequency range determining capacitors. *Specify ONE frequency range per kit please.* (Hz.): 19-210; 43-465; 88-960; 190-2100; 430-4650; 880-9600; 1900-21,000. Single channel. Each **$43.00**

KK-6-H: WALDRON TUBE CROSSOVER: High pass. Single channel, 18dB/octave, Butterworth, [3:79] includes Bourns 3-gang plastic pot, level control, Mullard tubes and 3 frequency determining capacitors. Please specify **one** of the frequencies above. No other can be supplied. Each **$45.00**

KK-6-S Switch Option. 6-pole, 5-pos. rotary switch, shorting, for up to five frequency choices per single channel. Each **$8.00**
When ordered with two kits above, Each **$7.00**

KK-7: WALDRON TUBE CROSSOVER POWER SUPPLY. [3:79] All parts, including board, transformer, fuse, semiconductors, line cord, capacitors. Will power four tube x-over boards (8 tubes), one stereo bi-amped circuit. Each **$88.00**

PASSIVE

KF-7: CROSSOVER FOR WEBB TLS. [1:75] Passive four-way crossover, in pairs, assembled. Components are included for both STC and Celestion tweeters. Made by Falcon of England. Pair **$76.00**

FILTERS & Speaker Saver

KF-6: 30Hz RUMBLE FILTER. [4:75] Rolls off system response at 18dB/octave below 30Hz to eliminate rumble and garbage on discs below 30Hz. Cuts speaker distortion and wasted amplifier power. Two channel universal filter card supplied with WJ-3 (F-6) circuit board and all basic parts, 1% metal film resistors and 5% MKM capacitors for operation as an 18dB/octave 30Hz rumble filter. 30Hz, 0dB gain only. Kit may be adapted as two- or three-way single channel crossover with added capacitors and resistors. Each **$19.75**

KH-2A: SPEAKER SAVER. [3:77] Protects speakers from destructive transient signals by quick shutdown of amplifier output. This basic two-channel kit includes board and all board-mounted components for control circuitry and power supply. It features turn-on and off protection and fast opto-coupler circuitry that prevents transients from damaging your system. 4PDT relay and socket included. Each **$35.00**

KH-2B: OUTPUT FAULT OPTION. If the amplifier goes into self-destruct mode, this added feature cuts off drive to output devices quickly. Additional board mounted components for speaker protection in case of amplifier failure. Each **$6.75**

KH-2C: COMPLETE SPEAKER SAVER WITH OUTPUT FAULT OPTION. Each **$40.00**

KK-8: COMPEX C. Signal compression ina repeatable format for tape recording or signal transmission. Two channel board with all parts to compress signal, including 1% polycarbonate capacitors and large tantalums. [3:79] Each **$45.00**

KK-9: COMPEX E. Signal expansion in tape replay mode or after transmission via limited phone lines. Two channel expansion board with all parts including precision Rs & Cs, [3:79] Each **$35.00**

SYSTEM ACCESSORIES

KH-8: MORREY SUPER BUFFER. [4:77] All parts & board for two channel output buffer to isolate tape outputs in your preamp from distortion originating in a turned-off tape recorder. Many uses for this versatile matchmaker. Each **$14.00**

KF-1: BILATERAL CLIPPING INDICATOR. [3:75] Single channel, all parts and board for any power amp up to 250W per channel. (Does not work well with Leach Amp). Powered by amp's single or dual polarity power supply. Each **$5.50**
Two kits, as above **$8.25**

KK-14A: MacARTHUR LED POWER METER. [4:79] Two channel, two sided board and all parts except switches, knobs, and Mtg. clips for LEDs. LEDs *are* included. No chassis or panel. Each **$110.00**

KK-14B: MacARTHUR LED POWER METER. [4:79] As above but complete with all parts except chassis or panel. Each **$137.50**

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

BENCH AIDS & Test Equipment

KH-7: GLOECKLER PRECISION 101dB ATTENUATOR. [4:77] As basic to measuring as a good meter, and more accurate than most. All parts except chassis and input/output jacks to build author's prototype including all switches and loads. Resistors are MF 1% and 2% types. Each **$50.00**

KB-8: INVERSE RIAA KIT. Six precision components to shape your audio signal generator's output to the response curve of a recorded disc. Checks phono preamp inputs. Each **$5.75**

KL-3C: INVERSE RIAA NETWORK. [1:80] Revised, precise, deluxe network. Two channels, 1% polystyrene capacitors and metal film resistors, gold jacks, cast aluminum box, solder lugs and alternate 600 ohm or 900 ohm r_2'/C_2' components. Each **$35.00**

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

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

E-2: JUNG REGULATED POWER SUPPLY. ±15V @ 1.5A. [4/74] Lab quality device but excellent for powering system components. Includes board, all board mounted parts plus two LM395K regulators. Transformer and filter caps not included. Each **$35.00**

KF-4: MORREY'S MOD KIT FOR HEATH IG-18 (IG 5818) SINE-SQUARE AUDIO GENERATOR. [4:75] Includes two boards and all added parts needed to modify the Heath unit to distortion levels of parts per million range. Replacement sine-wave attenuator resistors not included. Each **$35.00**

KG-2: WHITE NOISE/PINK FILTER [3:76] All parts, circuit board, IC sockets, 1% resistors, ±5% capacitors. No batteries, power supply or filter switch. Each **$22.00**

KJ-7: VTVM BATTERY REPLACEMENT KIT. [4:78] All parts to replace your VTVM's battery with a regulated supply. Each **$7.50**

KJ-6: CAPACITOR CHECKER. [4:78] All parts to build an accurate meter for measuring capacitance, leakage, and insulation. Check phono & speaker lead capacitance effects. Includes all parts with 4½" D'Arsonval meter. Each **$68.00**

KK-3: THE WARBLER OSCILLATOR. [1:79] For checking room response and speaker performance without anechoic chamber. All parts and board. Each **$56.00**

KL-6 MASTEL TIMERLESS TONE BURST GENERATOR. [2:80] Highly valuable and useful device for testing speakers and room response. All parts with circuit board. No power supply. Each **$19.00**

ORDERING INFORMATION

Prices, except as noted, are prepaid in the USA and insured. We prefer to ship via UPS, which requires a street address. If you cannot receive UPS delivery, please include an extra $2 for insured service via Parcel Post. We cannot accept responsibility for safety or delivery of uninsured Parcel Post shipments. PLEASE ADD $1 service charge for all orders under $10.

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SPEAKER SYSTEM PART III

Continued from page 26

(they were counter sunk during construction), sanded the edges and joints, and painted them with flat black latex paint. You may want to put a veneer on them or wrap them with some kind of cloth. If you use the cloth, it will probably be necessary to paint them black first so that the wood and silver screw heads do not show through. For cosmetic reasons I also added a 2" rim of wood on the bottom of my boxes recessed about 1" from the edges, to form a base.

HOOKUP & BALANCE

Now hook up the woofers and the ESL's and phase them. Place them in the position where you plan to listen and spend some time listening carefully. Reverse the leads and listen again with the idea of getting the best, most satisfying sound. One phase should sound fuller than the other; this is the in-phase condition.

Finally, adjust the woofer level to match the ESL level. You will undoubtedly find that your woofers will play louder than your ESL's so you must reduce the drive to the woofer amps to match the ESL's. Presumably you have level controls on your amplifier. If not you will have to mount attenuators in your crossover output on the low pass section. See *Fig. 19* for general attenuator design.

CRITICALLY IMPORTANT ADJUSTMENT

Virtually all constructors make a critical mistake in setting up their system: they adjust the woofer so that it is too loud! This is because most of us are used to hearing the sound of conventional woofer systems that are usually designed with a pronounced peak in the area somewhere between 60Hz and 120Hz. Most manufacturers have found that linear speakers do not fare well in the typical dealer's showroom in the conventional "A-B" listening test. To sell, a speaker must sound "bassy," even if it sounds unnatural. If you doubt this, notice that your dealer probably normally runs his showroom equipment with the bass jacked up and/or the "loudness" switch "on!"

You may be used to hearing this midbass peak and you will miss it immediately in T.L.'s. Notice that speakers with this midbass peak do not sound as if they have deep bass because the bass is attenuated compared to the peak. The T.L.'s will have a lot

FIG. 17

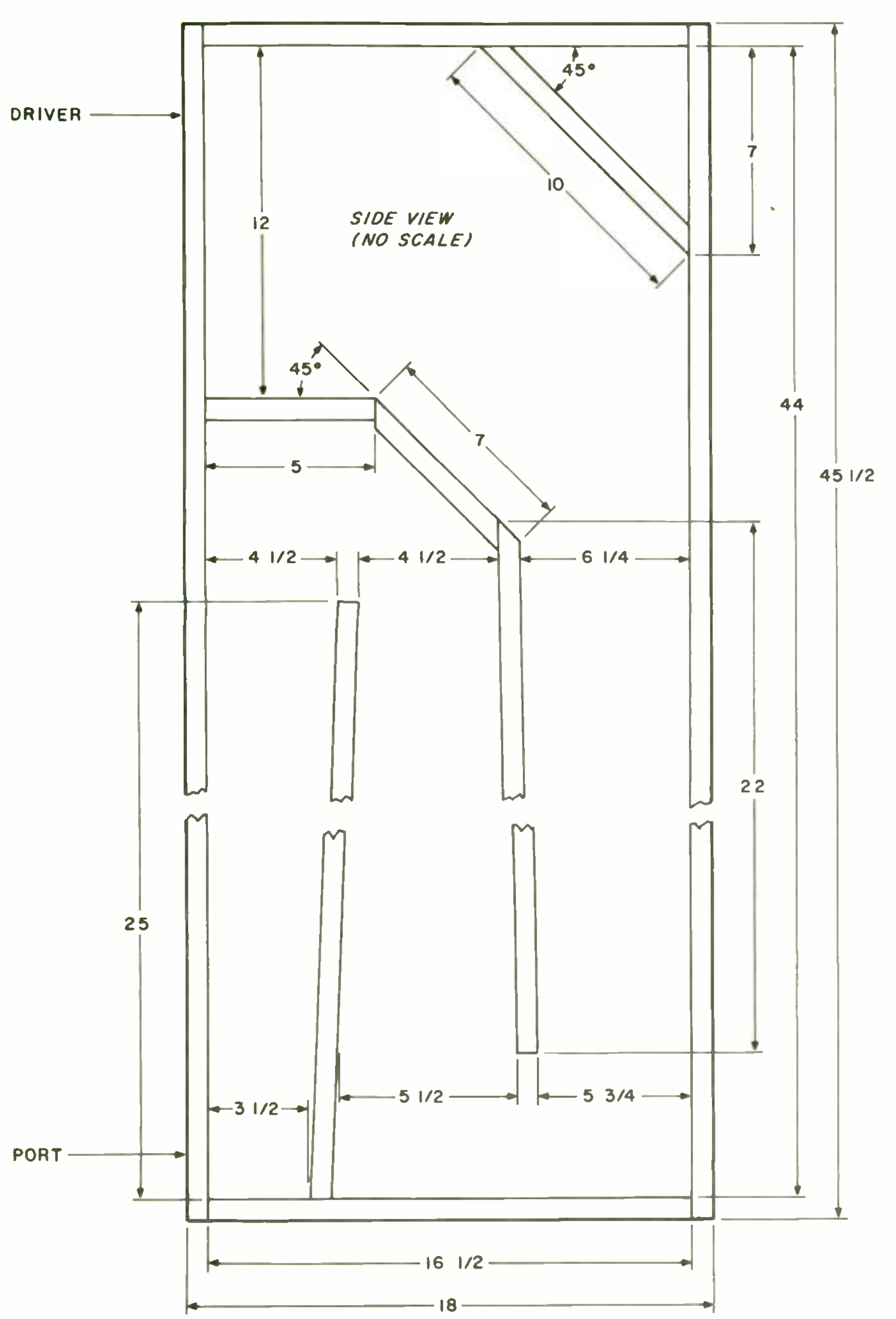
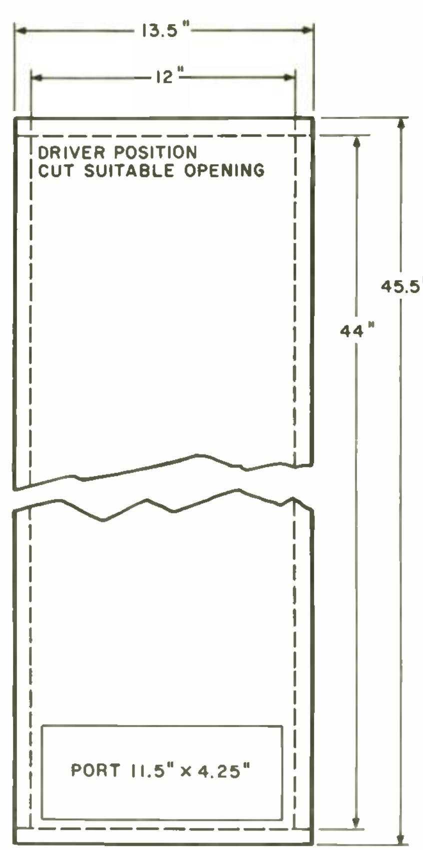
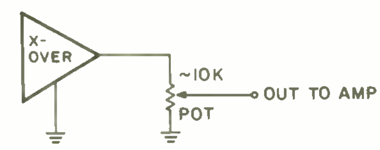


FIG. 18



Note: Entire enclosure stuffed with wool or dacron fluff. Pack loosely at port, moderately tight behind driver. Design suitable for 10" drivers, KEF B139 recommended, all wood ¾" particle board (hi density) or ply.

FIG. 19



Attenuator

of deep bass because it will not be masked by a midbass peak. Your tendency will be to turn up the level of the T.L.'s until you are satisfied that there enough bass is present. This will probably be too much woofer level. The deep bass will be exaggerated with rumble and other garbage, and more importantly, the midrange will sound muddy.

I thought I would be able to tell when the adjustment was correct, but I couldn't seem to get the midrange straightened out. I was cursing the woofers until I used a spectrum analyzer. It was then clear where the problem was. I turned the woofers down and as usual, the sound wasn't bassy enough. But after a few hours of listening, particularly to master tapes, it was obvious that this was the correct level. We get used to errors in the sound and then we can't recognize the problem.

Since few of you will have a spectrum analyzer, the rule of thumb is to listen to the midrange. If it is not absolutely clean, your woofer level is too high. Another good technique is to turn down the woofers to where you are sure they are too low. Listen to that level for several hours and then turn them up a little at a time, and listen again for a full, but clean midrange.

THE SOUND

It is difficult to describe the system's sound because nothing about it is impressive . The problems that plague other speakers, such as poor resolving power, poor imaging, boxiness, poor frequency response, edginess, distortion, etc., are absent in this system. Nor does it have the typical "electrostatic sound," caused by the rising high end and falling midrange, which makes most ESL's sound bright and thin. Yet the legendary electrostatic detail is there.

The speaker has extended highs with good detail. It does not sound edgy and does not exaggerate hiss and noise. I attribute this to lack of tweeter resonances. Hiss seems to be suppressed, yet the highs are obviously present and the system never sounds dull.

Another unique feature is that the speaker system is easy to listen to at low levels. It has been my experience that conventional dynamic speakers must be driven at loud levels in order to "bloom" and sound reasonably good. With this system, you will no longer keep turning up the level to hear the sound well. You will be listening at lower levels and enjoying it more.

The image the speaker produces is unique and must be experienced. It is three dimensional and stable. For the first time you will clearly hear the hall sound and ambience as it was recorded (although this is totally dependent on the source material). The directional design virtually eliminates room acoustics at all but the bass frequencies.

The speaker sounds as natural with hard rock as it does with classical chamber music. Many of the better dynamic speakers make good source material sound well, but make marginal material sound

Continued on page 30

THREE-ENCLOSURE LOUDSPEAKER DESIGN

Continued from page 24

til today. If a driver could be represented by a resistor then exact network values are easily calculated,[20] *Fig. 28(a)*. Real drivers have complex terminal impedances, *Fig. 18*. This not only affects the component values of the theoretical network but also the topology as can be seen by comparing the two networks of *Fig. 28*. Here a prototype design is shown for a 1.6kHz crossover between the Son-Audax tweeter and a 110mm woofer/mid-range similar to the B110 in the plywood enclosure of *Fig. 4*. Even the computer-optimized network of *Fig. 28(b)* has the desired acoustic amplitude and phase characteristic only for about one octave either side of the crossover frequency. Additional electrical equalization is required to correct for the diffraction effects below 1kHz and to extend the low frequency response to 50Hz.

The active network in contrast to a passive one can be exact because the voltage source at the driver terminals is able to impose any desired acoustic frequency response on the driver, without interaction between the source's frequency response and the driver impedance. □

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19. KEFTOPICS, International Edition, Vol. 1, No. 2A, 1976, and Vol. 3, No. 1 1978, KEF Electronics Ltd., Tovil, Maidstone ME156QP, Kent.

20. Linkwitz, S. H., Passive crossover networks for non-coincident drivers. *JAES*. Vol. 26, March 1978, p. 149.

THIELE, SMALL, and VENTED LOUDSPEAKER DESIGN

Continued from page 13

Parameters obtained in this way are subject to typical production spreads of up to 20 percent. You will obtain the most accurate design by measuring the parameters of the actual driver you will use. A good, but brief description of how to find these parameters can be found in the catalog offered by EMS, Inc., who provide good reasonably priced drivers and crossovers. If you cannot do the measurement yourself, a competent audio repairman should be able to do it for you.

The foregoing design procedures take into account the actual amplifier-speaker cable to be used. Except for some integrated systems, commercial manufacturers obviously cannot do this. They probably design assuming the speaker cable resistance and R_g are both zero. If you wish to simplify the procedure you can do this too. However, response variations can easily reach several decibels, depending on the amplifier and speaker cables. Even ignoring these effects, modify Q in the presence of a crossover. Failure to do this will cause even more variation, so you might just as well include all effects. In this aspect of design, you could achieve better sound than the manufacturer.

I would also like to emphasize that these procedures apply *only* to a driver in its piston range. In other words, it is implicit in the procedure that the driver be crossed over within its piston range. If it must operate above this range, as is commonly the case in two-way systems, then the voice coil inductance and the altered mode of diaphragm vibration for example, may have a significant influence on response and you must take them into account.

In order to hone your design skills, given in the Design Box are a number of examples. The first one is in detail; the others contain only the results so you can do the calculations. The drivers in the examples are actual units I have used, and I measured the parameters. My bass amplifier is the ST 150 for which I measured R_g. The Pass A40 was built by a friend and is an impressive sounding amplifier with a most awesome damping factor of 500. Using it you could surely ignore R_g.

Thiele-Small alignments provide an accurate, predictable design method for the home builder, with a potential for sound superior to any commercial system using raw materials of equal quality. I encourage you to build a vented system using these procedures and prove it to yourself. □

REFERENCES

1. J.F. Novak, "Performance of Enclosures for Low-Resonance High-Compliance Loudspeakers", *IRE Trans. Audio*, Vol. AU-7, 1959, pp. 5-13.

2. W.J.J. Hoge, "A New Set of Vented Loudspeaker Alignments", *JAES*, Vol. 25, 1977, pp. 391-393.

3. W.J.J. Hoge, "Confessions of a Loudspeaker Engineer,", *Audio*, August 1978, pp. 47-55.

4. A.N. Thiele, "Loudspeakers, Enclosures and Equalizers,", *Proceedings of the IREE*, November 1973, pp. 425-447.

5. R.H. Small, "Direct Radiator Loudspeaker Analysis", *JAES*, Vol. 20, 1972, pp. 383-395 .

6. A. N. Thiele, "Loudspeakers in Vented Boxes" *JAES*, Vol. 19, 1971, pp. 382-391, 471-483.

7. R.Saffran, letter in "Mailbox", *Speaker Builder*, Issue #1, 1980, pp. 35-36.

8. R.H. Small, "Vented-Box Loudspeaker Systems, Parts I-IV", *JAES*, Vol. 21, 1973, pp. 363-372, 438-444, 549-554, 635-639.

9. P.J. Stamler, "How to improve that small, cheap, speaker", *Speaker Builder*, Issue #1, 1980, pp. 18-27.

AN ELECTROSTATIC SPEAKER SYSTEM PART III

Continued from page 29

awful. This design corresponds well with everything. It is able to extract as much detail as is available from the source material without exaggerating any of the distortions or edginess present in so much of our corrupted source material.

SUMMING UP

I hope this series of articles has been useful to the home constructor. I am confident that those who build the system will be awed by their accomplishment, particularly when they hear the results. I wish to again thank David P. Hermeyer for his invaluable assistance several years ago, when the idea of my ESL was still a dream. Many of the techniques described here were developed by him and he generously allowed me to publish them. Thanks also to Bob Unterbrink for all his work and experimentation on practical methods of building the curved ESL's.

As always, I stand behind my work and remain willing to answer questions and assist readers who may be having problems. I would appreciate a S.A.S.E. if you write, particularly from foreign correspondents. I can also be reached evenings at 209-358-1427 California time. □

SOURCES

The Audio Amateur, P.O. Box 576, Peterborough, NH 03458. ESL and electronic articles.

DeCoursey Engineering Laboratory, 11828 Jefferson Blvd., Culver City, CA 90230. Precision 18dB/octave electronic crossovers.

Old Colony Sound Laboratory, P.O. Box 243, Peterborough, NH 03458. Electronic kits nd parts, Williamson amplifiers 12dB/octave crossovers.

B&F Enterprises, 119 Foster St., Peabody, MA 01960. Surplus electronics & power supplies, catalog available.

Roger R. Sanders, 1578 Austin Street, Atwater, CA 95301. ESL matching transformers ($35 each, $40 foreigners) Polyester film 36" width, (25¢ running foot).

PARTS LIST

- 8 Perforated metal 24" x 36", 20 to 36 mil thick
- 40 Insulators (1/16" acrylic sheet or 80 mil polycarbonate sheet) 0.5" x 22.5"
- 16 Insulators 1.5" x 22.5"
- 16 Insulators 1.5" x 37.5"
- 1 Polyester film 1/4 mil clear, minimum 20 feet, 40 recommended, 36" wide
- 1 Tube of fine powdered graphite
- 1 Epoxy adhesive, 32 oz.
- 12 4-40 x 3/4" brass, round head nuts and bolts for electrical connections.
- 1 Steel bar stock 12 feet long, 1' x 0.25"
- 4 Bolts, steel 6-32, 2 inches long
- 1 Roll "Scotch" double sided tape
- 1 Roll masking tape, 1/2" wide
- 1 Roll plain cellophane tape
- 4 Aluminum foil 1" x 0.5"
- 1 Plate glass, 1/4" thick, 38 x 26
- 1 Package rayon or cotton balls
- 2 10" dynamic drivers (see text)
- 2 Sheets 4' x 8' x 3/4" particle board
- 1 Woofer damping material, approximately eight pounds long fibre wool or synthetic material (see text).
- 200 Long wood screws
- 1 Pint "Tightbond" glue

Misc: Electronics as required for ESL drive. Frames as desired for ESL cells. Hook up wire, suggest high voltage test prod wire for ESL's. Finish trim and grille cloth as desired.

Craftsman's Corner

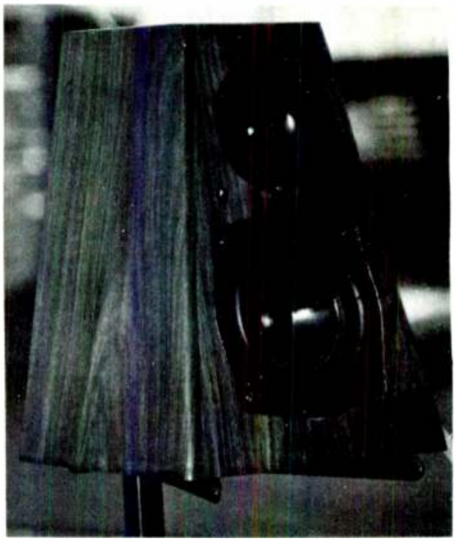

Photo C. Closeup of the small enclosures showing the careful veneering and without the foam grilles Palladino fashioned for his units.

CRAFTING A KIT

I HAVE JUST FINISHED reading the first issue of *SB*. I must agree there is a definite need for a magazine devoted to the amateur speaker builder, it has been a long wait.

I am a woodworker by trade with almost seven years in the business and can remember being bit by the bug to build my own speakers about a year ago.

I am in the opposite position from Mr. Stamler who did the article in *SB*'s first issue "How to Improve That Small, Cheap Speaker." Where he could not do the woodwork, I cannot do the math. As hard as I tried to figure it out, I had no luck.

Could *SB* do an article or two or three on popular drivers, give their specifications and work through the complete problem giving not only the symbols but an explanation for people like me who need to know what we are doing? (There are lots of us.)

The Stamler article was a great idea but when it came to the math I was left in the dark. In the equation:

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

I know f_3 = low frequency cutoff, f_s = driver free air res., V_{AS} = compliance equivalent to vol. of driver, V_B = cabinet internal volume, but now what?

Not being able to cross the bridge I had to go the next best, buying a kit. Checking out most of the kits available, I settled for the Fried "C" monitor satellite and "T" transmission line subwoofer. (see photos) I must say it was a very enlightening experience to say the least.

The Fried C's are made from (fine chip) particle board sides and back 1" and the rest ¾", 48 lb./ft.³ All edges are joined by finger joints and white glue for the strongest possible enclosure. The interior is sealed with silicone for air tightness and uses Fried's edge-on foam filters.

CONSTRUCTION TIPS

I would not recommend these speaker enclosures to anyone who hasn't some woodworking skills and experience as well as access to a table saw. The pyramid shape requires compound angle cuts which are best made with a jig to produce the eight mating mitered sides. I used finger joints but these are not necessary. I think it advisable to build each cabinet completely and cut the holes for the speakers and the vent after it is complete. After the sides are assembled, measure and cut to fit the top and bottom pieces.

Since the drivers are flush, front mounted they must be routed to achieve this. The 6.5" midrange and the 10" woofers are an odd shape which requires a lot of skill to cut the odd routed pattern. Practice on scrap until you are proficient enough to cut them successfully.

Mount the crossovers and foam damping through the speaker holes. I replaced the 20 gauge wire which came on the crossovers with much heavier stranded types. Before mounting the drivers make sure the foam is not blocking the pressure relief hole.

The exterior is hand veneered in Brazilian Rosewood. Matched butted sheets are finished with Danish oil and about 20 coats of wax. Front corners have ⅜" radii for better dispersion. The crossover has the latest mods with 4-way binding posts. The grilles are of my own design as Fried has none yet. I cut them with an electric knife, which works beautifully. They are open cell foam cut for the drivers and pressure release hole. The stands are Levitation to which I added a set of casters. I made the plastic covers to keep the dust out as the Fried tweeters have a "sticky" dome that attracts dust.

The kit instructions specify ¾" particle board but I believe you will have less spurious resonances with 1" stock if you can find it in your area. If you must use ¾", line the walls with felt or undercoating for damping. I found it necessary to place open cell foam at the termination of the transmission line because I was getting excessive amounts of bass in my small listening room (17.6x10.5x8.5').

I made the baffles removable by mounting them on 1" cleats with tee nuts and screws. I had the glazier cut a piece of ⅜" thick plate glass and bevel the edges to add a special touch. Knowing it would be heavy I built a base platform from 2x3's & ¾" plywood and covered it with black formica to match the grilles.

Heavy duty casters are a must.

And the best part is, they sound as good as they look.

My system consists of a Dynaco 416 with two C-100's on the bottom and Tom Holman's Apt 1 on the top end connected by monster cable. I use a modified Dahlquist LP-1 as well. Control is from a Yamaha C2A with input from a B&O 4004, Nakamichi 582, and a Yamaha T-2 tuner linked by Audio Technica and Cotter cables.

Following suggestions by Linkwitz in *SB*

Continued on page 32

Photo A. Palladino's complete Fried system.

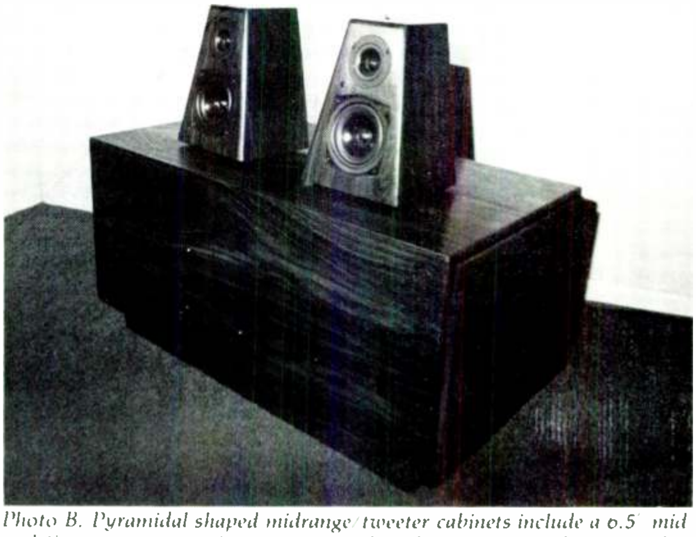

Photo B. Pyramidal shaped midrange/tweeter cabinets include a 6.5" mid and 3" tweeter unit with crossover inside. Edges are rounded for least diffraction. The small enclosures are normally mounted as in Photo A.

SB Mailbox

MR. BULLOCK REPLIES TO KNITTEL AND REES

After reading Small's discussions of reference efficiency η_o, I agree with Professors Knittel and Rees (*SB* 3/80) that η_o is dependent on "driver parameters alone and...independent of enclosure volume or type." The confusion is caused by regarding $k\nu$ as a constant in their formula (2). However, mathematically from Small's derivation, it is not a constant. The only possible constant in the formula is the reference efficiency itself. Small did not derive the formula to calculate system efficiencies. He used it to describe trade offs which could be made among efficiency, cut off frequency, and enclosure volume if one were free to choose a driver with the necessary characteristics.

The above comments do not mean that the enclosure has no effect on efficiency. For example, the driver parameters themselves are not constants but depend on driver mounting conditions. Thus, to determine system efficiency, the driver parameters should be determined under the mounting conditions which exist in the system. In some systems I have constructed there is enough variation in the parameters from their free air values to change the efficiency by 10%. Another way the enclosure can affect efficiency is described by Small (1) as follows: "If deliberate mass loading of the driver is employed in the system, e.g., placing a restricted aperture in front of the driver, the system reference efficiency will be less than the basic efficiency of the driver."

It is clear that my suggestion to Mr. Stamler to raise the cutoff frequency will not result in a more efficient system. It is true that my suggestion will result in a flatter system response. Whether this is desirable is a matter of taste, but it should be considered.

Another benefit of my suggestion is that the realigned system will have less distortion at the same output or be capable of higher output with the same distortion level. The realigned system won't have to reproduce frequencies as low as the original, and so cone excursion requirements will be less. For example, raising the cutoff from 27Hz to 31Hz will permit either an output increase of about 2.5dB with the same distortion or the same output with cone excursions of about 75% of those required in the original system. In the latter case, the distortion levels will be lower because of the reduced excursion requirements. Again, whether these reasons merit a change is somewhat a matter of taste. But, when using a small woofer as Mr. Stamler did, I would make the change because of the possible reduction of distortion.

Robert M. Bullock
Oxford, Ohio 45056

REFERENCES

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BUILDERS AHOY

While we have many fine manuscripts in hand for future publication in these pages—we need your contributions too. How about those offerings for our *Craftsman's Corner, Tools, Tips & Techniques*? We also need accounts of your construction adventures with specific projects. Why not plan to take pictures (black and white preferred) and make notes when you're building that next project—or kit. Write it up just as you would a letter to a friend. Send it along to us and we'll give it every consideration. We pay for articles, so you might have a nest egg for that next project you want to try, as well. We have a nice sheet of suggestions for authors which you may have just by asking for it. □

CRAFTMAN'S CORNER

Continued from page 31

2/80 I removed the drivers from my system and mounted them with rubber grommets on each hole. The change made everything cleaner and at a cost of 80¢ was well worth the effort.

Nick Palladino
Brooklyn, NY 11223

MR. STAMLER REPLIES TO KNITTEL AND REES

Messrs. Knittel and Rees set my mind straight on a point which had been confusing me for awhile. I had overlooked the crucial equations in Thiele and Small's papers. Their exposition is lucid, complete, experimentally verified, and correct.

To summarize: For a given driver, the efficiency is more or less fixed, although it *can* be lowered by a lousy cabinet design. In a vented box, the tradeoff is between cabinet size and f_3, with f_3 varying inversely with the square root of cabinet size. In a closed box, the tradeoff is between cabinet size and system damping, with a larger box yielding a more heavily damped system, and hence better impulse response. The lowest value of f_3 will be found when the system is designed for a maximally flat (Butterworth) characteristic, where Q_{TC} = .707. Keeping the same driver and closing the vent in a vented box so that it becomes a closed box with the same internal volume, the effect will be to raise f_3 and to change the impulse characteristics, usually toward a more highly-damped response. The efficiency, however, will remain the same.

I am preparing a new version of my table of speaker characteristics, with corrected efficiency figures and data for some new drivers. My tests on KEF B110's, incidentally, seem to show that KEF's figures as given in the table are more accurate than the ones I used for my original calculations, but that there are quite considerable unit-to-unit variations. I am presently completing a modified vented-box system designed around the KEF data.

Spectrum Loudspeakers, 2136 Perth St., Toledo, Ohio 43607 is selling felt donuts for alleviating diffraction on 1" dome tweeters such as the T27. While I haven't tried them yet, they should work as well as the cotton donuts and look a lot better.

Also, Transcendental Audio, 6796 Arbutus St., Arvada, CO 80004 is offering a collection of bextrene drivers from Polydax and (hurrah) a goodly shelf stock of polypropylene capacitors in respectable sizes. Their catalog is *very* informative and only $1.00. Their service is prompt. Replacing non-polarized electrolytics with film capacitors in the DN-13 dividing network made a very considerable difference in quality.

SANDERS QUERIED

In regard to the article about electrostatic loudspeakers by Roger Sanders, I was absolutely amazed that someone who claims to have hands-on experience and knowledge of electrostatic speakers appears to know so little.

As I was reading the article, I found at least 15 statements which were either not true or could be very misleading. Since a detailed reply to each would require too much editorial space, I have picked some of the more important ones and would like to comment on the following:

1. Electrostatic speakers do not use any power.
2. Graph vs. wavelength
3. Wavelength of a 20kHz frequency
4. Speaker draws no current
5. Add some series resistance to make the amplifier stable
6. It is not possible to achieve bass in a reasonable sized ESL without an enclosure
7. Electronic crossovers are a must. They are superior to high level crossovers.
8. Difficult to get proper response from a passive equalizer.

The above statements can be grouped into three categories. The first three statements deal with the principles of acoustics, the next two are concerned with electronics, and the last three are the author's opinion.

In the first group, statement one says that an electrostatic speaker uses no power. However, unless Mr. Sanders has discovered the perpetual motion machine this cannot be true. To be specific, the author states in his article that he likes to listen to his speakers at a sound pressure level of 103dB at a distance of four meters. If we take the simplistic view that the required sound pressure level is solely due to the source (and not from reflections) we can then calculate an equivalent power level. The following equation defines the power level in dB related to a given sound pressure level.

$$PWL = SPL + 20\log(r) + 10.5$$

Where PWL = Acoustic power level in dB
SPL = Acoustic sound pressure in dB
r = the measuring distance

From the figures given in the article we find that:

$$PWL = 103 + 20\log(13.2) + 10.5$$
$$= 135.9 \text{ or approximately } 136\text{dB}$$

By itself this figure doesn't mean much, but let us convert this to acoustic watts.

$$W = \log^{-1}\left(\frac{PWL}{10}\right)W_{ref.}$$

Where W = Acoustic power in watts
$W_{ref.}$ = Acoustic reference power (10^{-13} watts)

From the above, the acoustic power output of Mr. Sanders speakers is:

$$W = \log^{-1}\left(\frac{136}{10}\right)10^{-13}$$

= 3.98 acoustic watts.

This power (approximately 4 watts) is the amount of power required at the source to produce a SPL of 103dB at a distance of four meters. Since there are no frequency terms in the equation, this power is independent of frequency.

While this doesn't tell us whether the speaker uses any power, and the author did not state the efficiency of his speakers, let us be generous and use a figure of 25%. (Note: most conventional speakers are in the range of 1 to 10%). With this figure, the input power to the speaker is:

$$P_{in} = \frac{P_{out}}{\text{eff.}} = \frac{4}{.25} = 16 \text{ watts}$$

In our extremely conservative case, we see that the speaker does require some power, and this should be expected as it is difficult if not impossible to achieve 100% efficiency which Mr. Sanders claims for the speakers.

The last two acoustic items deal with the author's graph vs. wavelength and the wavelength of a 20kHz frequency. First of all, the graph is misleading. The curve shown implies that wavelength and frequency are a non linear function. The problem here is the choice of scales used in the graph. Instead of using linear-log scales, the author should have used log-log scales. The graph would then be linear. Readers are referred to the *Audio Encyclopedia* (by H. Tremaine) p. 16 for the correct form.

As for the wavelength of a 20kHz frequency, the velocity for sound in air, under normal conditions, is taken as 1129 ft/sec. If we multiply this by 12, we obtain the velocity in inches/sec. The wavelength is then determined by:

$$\lambda = \frac{c}{f}$$

Where λ = the wavelength in inches
c = the velocity of sound in air
f = the frequency in Hz.

For a 20kHz frequency:

$$\lambda = \frac{13543}{20000} = .677 \text{ inches}$$

This says that the wavelength of a 20kHz signal is almost 2.5 times greater than what the author claims. Those readers who wish to verify the above equations are referred to such texts as *The Handbook of Noise Measurement* by General Radio, and *Acoustic Noise Measurement* by Bruel and Kjaer as well as the one previously mentioned.

In group two, which deals with electronics, we have statements that "the speaker draws no current," and "...add some series resistance to make the amplifier stable." Of these two statements, the most serious is the first. In an electrostatic speaker, beside the current needed to achieve the acoustic output power, there is also a large wattless current required to charge and discharge the speaker capacitance.

To give you an idea of the type of currents we are talking about, suppose we determine the values at 1kHz and at 20kHz. At 1kHz, the reactance of the author's 2400 picofarad speaker capacitance is 66250 ohms. The secondary winding resistance of his 44:1 stepup transformer is about 500 ohms so that the total impedance in the circuit is 66251 ohms. The resulting current flow, if we assume a peak voltage of 2000 volts (which equals the polarizing voltage) is 30mA. Calculation of the phase angle shows that the current is leading the voltage by about 89 degrees so that the power required in the electrical circuit is very small. From this we might conclude (as the author seems to have done) that an ESL requires no current or power.

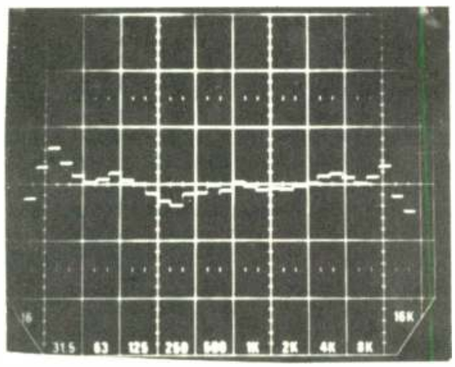
However, let us see what happens at 20kHz. At this frequency the capacitor's reactance is 3313 ohms and the total impedance is 3351 ohms. With a peak voltage of 2000 volts, the current is now .88 amps and the phase angle is 81.4 degrees. This still doesn't appear to be too bad, but remember this is on the secondary side of a stepup transformer. The current in the primary winding is equal to the secondary current multiplied by the turns of ratio or about 39 amps. Just as the current has increased, so has the power. At this frequency the power required = 131 watts. This power is in addition to the power previously calculated. These values of current and power are a long way from the values originally stated, and is the reason that ESL's need high powered amplifiers.

Mr. Sanders also states that when you connect your amplifier to the speaker, it may oscillate, and the way to correct this is to connect a resistor of one to ten ohms in series with the transformer's primary winding. If you do this, it may make the amplifier stable but it may also have some other undesirable effects. For instance if the 2400 picofarads of speaker capacity is referred to the primary winding it now becomes 4.6 microfarads. If a 10 ohms resistor is connected in series with such a capacitor it will form a low pass filter so that the output will be 3dB down at 3.4kHz.

If you follow this approach, the maximum resistance you should use is about two ohms. This will place the 3dB point at 17kHz. If this doesn't solve your problem, get a different amplifier or forget about driving the author's speakers.

Mailbox

This brings us to the last part, and concerns some of Mr. Sanders' opinions about electrostatic speakers and crossover networks. To show that his conclusions can be misleading, I am enclosing a photo of a 2' by 2' ESL radiating 90dB of pink noise at 3 feet. From the photo it can be seen that diaphragm resonance is at 30Hz. This speaker which has been in development for more than 10 years is monolithic in design and requires no enclosure, no electronic crossovers and all equalization is done with high level passive equalizers; which also solves the dispersion problems. It is also interesting to note, that when the same test was done at 4 meters there was very little difference in the result.



Frequency response of a 2' by 2' ESL radiating 90dB SPL at 3 feet. Microphone on axis with speaker centerline. Vert. 10dB/cm. Horizontal is ⅓ octave. (Note dip in the response curve at 2500Hz is a room refections.)

In closing, I only hope that in future articles Mr. Sanders will stick to details about constructing his ESL and leave the technical details to those who understand or are trying to determine the how and why of these speakers. It might also be advisable for Mr. Sanders to keep his opinions about the techno-freaks to himself. If it weren't for such men as Kyle, Walker, Janszen and Hunt to name a few, the author would not be able to build an electrostatic speaker.

Ronald H. Wagner
Fremont, CA 94538

MR. SANDERS REPLIES:

Mr. Wagner is obviously a competent electrical engineer and his comments regarding acoustics and the electrical requirements of ESL's are accurate. However, I am puzzled about the tone of hostility in his letter. He is attempting to discredit the author by attacking omitted details and opinions as though he were criticizing a technical journal article. He overlooks the substance of the article. In my numerous articles, I have not attempted to be extremely technical. I am writing for the reasonably intelligent audiophile who wishes to build something, and needs a basic understanding of the factors involved and clear instructions written in English, not math. I omit a great deal of technical information and virtually all the math with the exception of the information that is necessary. There simply is not enough space in a magazine to present all the information available to support all the opinions and general statements that must be made.

Let me use an example. Mr. Wagner is upset that I stated that ESL's do not require amplifier power. He uses the example of driving an ESL at 2kV at 20kHz and then calculates that it will take over 100 watts to drive it. To begin with, I hope that nobody is listening to 20kHz at that level. Music does not require such performance. In the energy spectrum of real music, the majority of energy is below 1kHz. The remainder rolls off rapidly above there, and even source material that actually had musical information at 20kHz would be at an extremely low level relative to the rest of the spectrum. My system (ESL's, woofers, both channels driven) will reproduce music at your listening location at concert hall level (103dB, measured in a concert hall, row A, full orchestra, maximum loudness). But let's see what is going on with the ESL amplifier at this level. The woofers are generating the majority of the energy. There is little information at the high frequencies that would require current from the ESL amp. The most taxing area for the ESL amp is in the midrange, where little current, but large voltages, are required. I have measured the power supply current requirements in amps when they were played at levels where they were distorting. Oscilloscope tracings revealed that all the distortion was due to voltage clipping. There was never any current clipping.

A Williamson 20-20 used about 120mA from the power supply when voltage clipping at a system level of 96dB, and 80mA of the 120 was the ever present bias current. These studies made it clear to me that I could design a direct coupled amp that delivered 2200 volts to the speakers, but only 28mA was necessary for complete freedom from current clipping Matching transformers rated at 15 watts are adequate for 200 watt amplifiers, and also it works better to connect a tube amplifier to the transformers for a deliberate impedance mismatch. It is no problem to sacrifice current capability when striving for voltage. Conventional amplifiers should run fairly cold even when driving the speakers to amplifier clipping levels. The transformers should never show any temperature rise at all. The speakers do not require power. They require voltage. I suspect that Mr. Wagner would feel better if I said that the speaker require *essentially* no power. ESL's require some power, but this is not a problem, and for the purposes of a "how to" article, we need not concern ourselves with it.

Mr. Wagner deals with the wavelength of sound, even to the point of criticizing the type of graph scales used. It is true that a 20kHz wavelength is not ¼ inch long, but about ½ inch long. It is not difficult to make an occassional detailed error after long days at the typewriter. The point is that the wavelength is much shorter than the 2 foot minimum dimension of the speaker, and therefore, the speaker will be directional. It doesn't matter if it is ¼ inch, or 4 inches, it is going to be directional. Perhaps Mr. Wagner noted that the graph is quite correct. His objection to my choice of scales for the graph is nonsense. The graph gives a quick reference to the wavelength of sound so that the reader can see that a large dipole is needed for freedom from low frequency phase cancellation problems. What difference does it make that the line is curved or straight?

It is not possible to get bass from a reasonably sized ESL without an enclosure if you want high SPL's and linear frequency response. I detailed the problems, compromises, and options to the readers. There is only one ESL I have heard that would produce high level bass SPL's, and that was the Dayton-Wright. However, I do not call it reasonably sized, and it will not perform well above 6kHz. A one foot square ESL that will produce 100dB in the range below 50Hz and that can be driven by conventional amplifiers and reproduce the rest of the audio spectrum, would make an enormous amount of money. I will be pleased to retract my statement if and when such a speaker is demonstrated to me. Until then, I am giving readers accurate information.

Electronic crossovers are a must. I have never heard any speaker system with passive, high level crossovers that could not be improved with electronic crossovers, regardless of what theory might say. But more importantly, a home constructor must be able to construct whatever type of crossover system is used. It must also be reasonably priced. Electronic crossovers are cheap, and so are amps. Passive high level crossovers are very difficult to design because the ESL load is so far from resistive. And there is the problem of getting parts for passive high level crossovers. When was the last time you tried to buy magnet wire in Idaho, Canada, or Switzerland? Where would you get inductor cores? How about large, non-polarized capacitors? If you could get them, how much would you pay? What about the fellow who only wants one cell rather than two, or the reader who wants a large array? Electronic crossovers not only work better, they are the only practical way to do a "how to" article, particularly when a large percentage of readers do not live in the United States.

It is difficult to get proper response from a passive equalizer, but it is not impossible. Feedback from readers revealed that impedance matching can be a problem for many home constructors. Most of these readers do not have access to the instrumentation required to "tweak" their systems. The reader must rely on the author's schematic and build it to the letter for proper performance. Variables beyond the author's control can cause big problems. To solve this problem, I went to active equalization. Furthermore, regardless of what the techno-freaks may say, you cannot detect any difference between passive and active equalization in this application.

Techno-freaks are their own worst enemies when it comes to achieving good sound. I have not met Mr. Kyle, Walker, Janszen, and Hunt. I would like to do so. I seriously doubt that they would be classified as techno-freaks as they had some understanding of the problems, rather than being led to advertising hype, and they must have had open minds in order to reach out and break new ground.

My article is a tool that a home constructor can use to build a speaker system that will surpass the performance of the finest commercial systems, and hundreds of home constructors have already verified this. My information is as complete and accurate as necessary to achieve this goal.

Mr. Wagner's comments are more appropriate for an engineering colleague writing a technical article than for an author doing a "how to" article for the audiophile public. If Mr. Wagner has extensive background, engineering skill, and long experience with ESL's, he should share some of his discoveries. An article describing a simple to build, inexpensive, small durable speaker that has adjustable dispersion, can reproduce the entire audio bandwidth without need of crossovers, has low distortion, is easy to drive, and can reproduce music at levels in excess of 100dB would be very well received. Of course, the article would have to have years of technical research, experiments, and data greatly simplified and presented in summary form. And then there is this little problem that engineers have about writing their manuscripts with their calculators rather than with a typewriter...hummmm?

CONSTRUCTOR FEEDBACK

In reference to Mr. Marsh's Double Chamber Enclosure (*SB 3/80*), I built a couple of them following the original article in about 1972 and they worked exactly as described. The bass was very low in distortion. The drivers I used at that time were two 6.5 inch Philips woofers with 1 lb. magnets. I no longer have the number of the Philips driver but I believe it is still available today. If not something similar should be fairly easy to obtain.

I congratulate Mr. Sanders on a fine series of articles. I built electrostatics per his earlier articles in *TAA*. They sounded absolutely fantastic. I would caution readers with less than perfect ability to follow instructions to the letter that you should think twice about tackling the job. I listened to my electrostatics for approximately 14 months with at least 7 or 8 failures of one kind or another. I finally gave up because I couldn't take the silence while I repaired them. I believe a completely reliable set of electrostatics can be built at home following the articles, but it ain't easy.

RION DUDLEY
Seattle, WA 98119

LA SCALA SEARCH

DOES ANYONE KNOW where I might obtain a set of plans for the Klipsch La Scala speaker? I would like to try this as my next speaker project, and perhaps one of *SB's* readers might be able to help me out.

GLENN J. BEHRLE
P.O. Box 5147
Woodmont Station
Milford, CT 06460

MODS WANTED

HAVING RECEIVED MY first two issues of *SB* I especially enjoyed the article by Paul Stamler. Unfortunately, most of the construction pieces I've seen seem to address themselves to the scratch building of esoteric and expensive or relatively cheap speakers. I would like to see more modification articles on the more popular "bookshelf" speakers. Some are: the Dynaco A-25, EPI-100, Advents, and old AR's. These could range from simple crossover component updating to complete speaker replacement with, perhaps, the new bextrene drivers.

Most of these speakers were excellent in at least one area but had shortcomings elsewhere. For instance, I found the AR-5's mid to highs very good while the bass was somewhat heavy and ill defined, whereas the large Advent's bass was smooth and tight with a slightly rough midrange and treble. In cases like these perhaps the offending drivers could be replaced with newer units and appropriate complementary crossovers. I have never attempted speaker construction myself, so I can only speculate on the effects of such modifications as larger gauge internal wiring, mylar crossover caps, long hair wool, and speaker phase alignment might have on the performance of the old classics.

If these mods were designed for specific brands and boxes with the appropriate circuit and driver recommendations, the average music lover who is handy with screwdriver and soldering iron, but not necessarily a MIT graduate would have a good chance of upgrading his old classics.

I recently replaced the woofer in a used popular bookshelf speaker. I ordered a driver and a crossover capacitor. I received the entire masonite mounting board with wiring and speaker lead push-in clips. I was quite unimpressed with the 18 to 20 gauge wiring, absence of a balancing pot, and the fact that the capacitor was epoxy mounted at one end and merely soldered to the speaker lead at the other.

R. W. CLIFFORD
Lancaster, CA 93534

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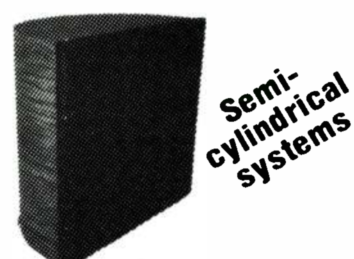

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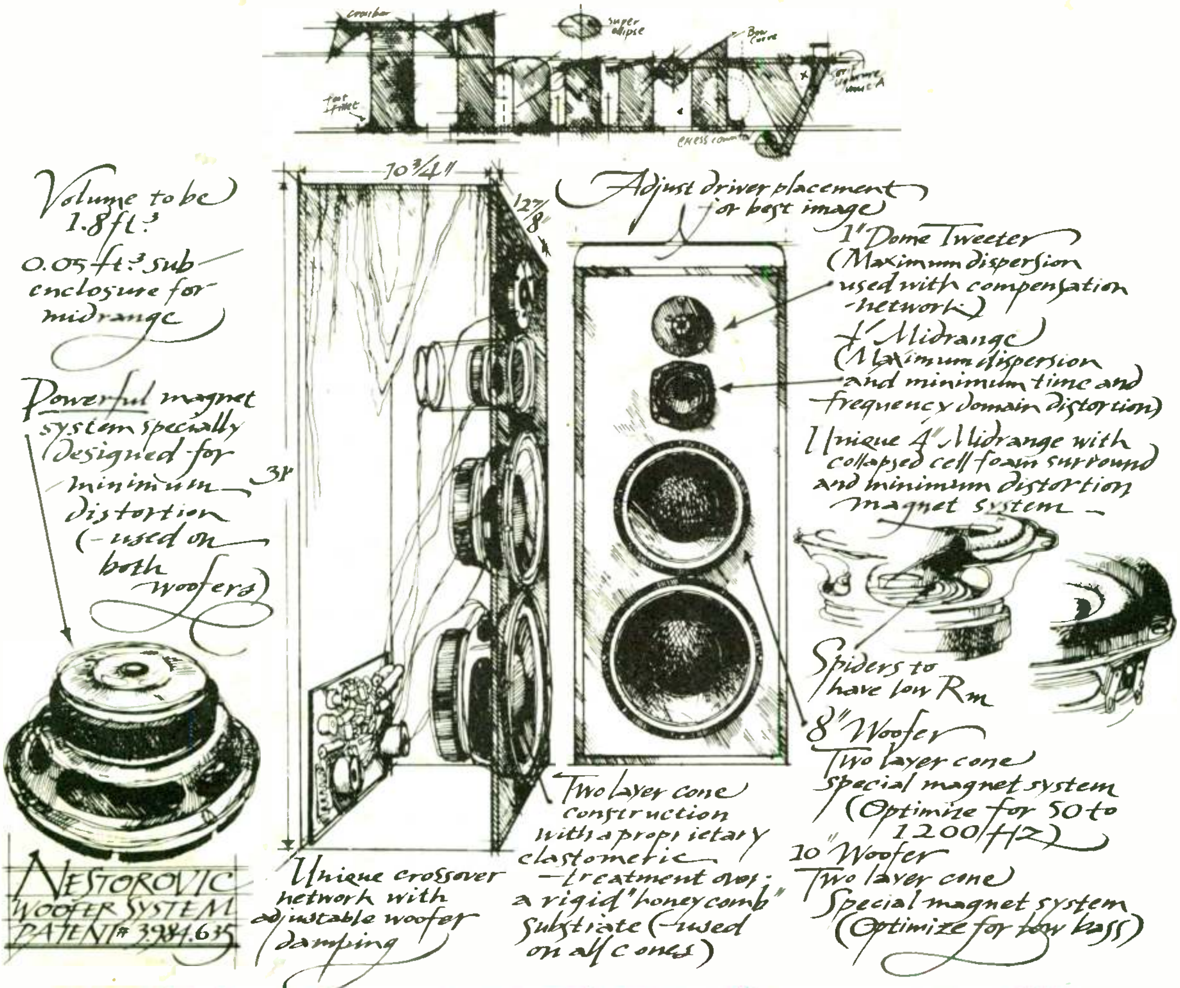

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