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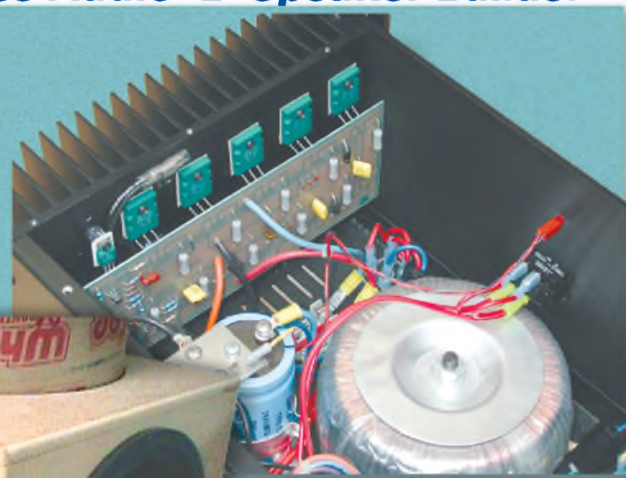

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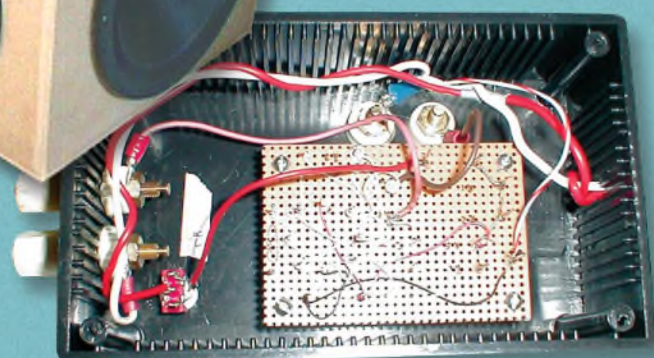

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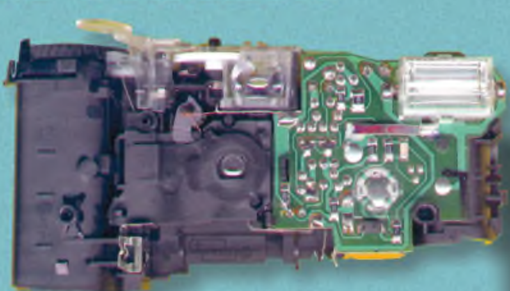

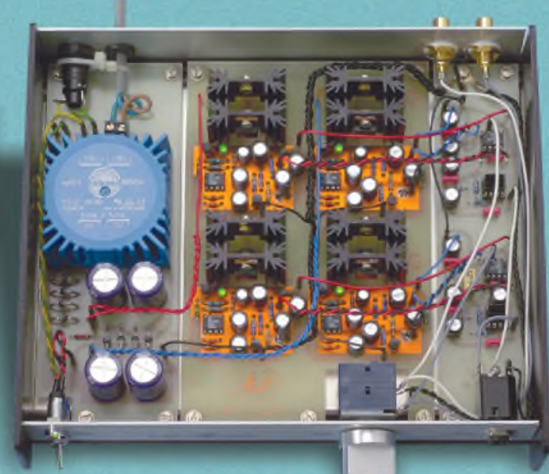

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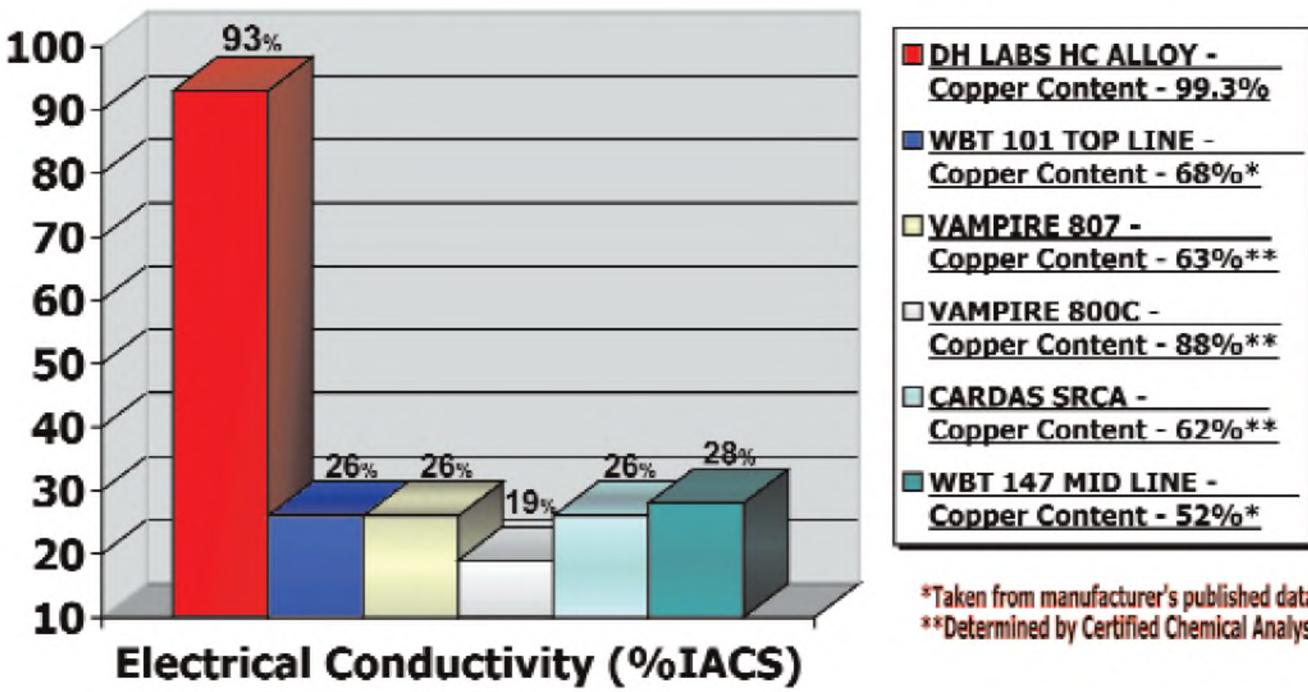

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The SPP Amplifier

Here's a long-forgotten, but still high-quality, power amp design that's easy to build, requiring no esoteric tubes or parts. **By Helmut Otte**

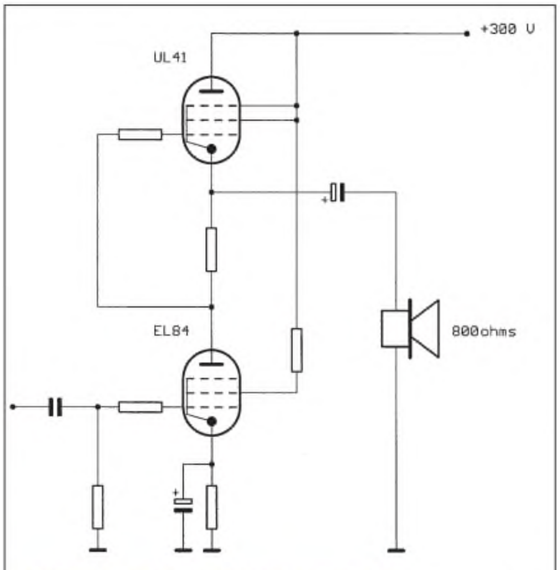

FIGURE 1: Philips' ironless power amp.

In the early '50s, Philips Europe began to equip some radios, TV sets, and hi-fi amplifiers with a so-called ironless power amplifier, a kind of SPP (series push-pull) with specially developed low-ohmic tubes and speakers of 200–800Ω, such as the famous 9710A and its derivatives. Depending on the kind of circuit used, the whole amplifier could become quite simple. Sophisticated design and the lack of an output transformer led to very good results—i.e., low distortion and wide bandwidth.

THE CIRCUITS

This kind of amplifier first appeared in a Philips high-end radio in 1955. This very asymmetrical circuit looks like the well-known SRPP with the upper pentode connected as a triode. The radio contained two of these amplifiers—one for the low frequencies and one for the high frequencies, feeding a total of four speakers (*Fig. 1*). It produced a fantastic sound.

About a year later, the low-ohmic EL86/6CW5 became available; it was better suited for the task, and the circuit changed to a more symmetrical one. The screen grids were supplied via resistors and coupled to their corresponding cathodes via capacitors. Output power was about 3–4W (*Fig. 2*).

The next step was to drive the grids of both tubes separately, increasing the output power and—with the help of a bootstrap—the symmetry, too. A phase splitter delivers the out-of-phase voltages. Because the upper pentode works as a voltage follower, it needs a high input voltage. A bootstrap configuration via CB feeds the grid with the correct voltage (*Fig. 3*).

ABOUT THE AUTHOR

Born in 1948, Helmut Otte learned about electronics while working for the Philips Service Hamburg from 1964–1968. Afterwards, he studied electrotechnics, obtained a "Diplom-Ingenieur," and since that time has worked at the University Of Applied Sciences Hamburg. His interests include listening to and making music (on bass guitar), as well as travelling and photography.

THE FINAL CIRCUIT

This section describes one of the SPP amplifiers I have built. I chose this circuit because no special parts are needed, and you can expect very good results. The circuit is simple and even a newcomer should be able to build it with success. The design is very flexible and suitable for all low-ohmic pentodes. There is no need for very high power-supply voltages (I dislike voltages of more than 350V).

To get as much power as possible the screen grids should be fed with voltages as high as the plate voltages from separate voltage sources, but this leads to a more complicated and expensive power supply. The tube manufacturer Valvo (a Philips division) developed a great idea to avoid this. In that circuit they replaced the screen grid resistors with chokes. The inductance of the chokes should be high—at least about 20H, the more the better. Normally these chokes will be mechanically large because there is a DC current—the screen grid current—flowing through them, and therefore they need a gap, enlarging the size to get a high inductance.

The published elegant solution is to use a double choke and connect the windings in reverse so the magnetic effect of the DC currents is cancelled out. Now no gap is necessary, the choke dimensions may be smaller, and you have only one part. I used a simple small toroidal mains transformer with two identical high-voltage windings (i.e., 115V/115V) for this task. The quality is sufficient.

As mentioned previously, the upper pentode V3 acts as a voltage follower with a little less than unity gain and therefore needs a very high control voltage at the grid. A normal-connected phase splitter cannot deliver such a high voltage, but with the help of positive feedback (bootstrap) from the screen grid, the problem is solved by carrying high DC voltage and the output signal to the plate resistor R8 of the phase splitter tube. Without negative feedback significant distortion occurs long before full output power is reached. A NFB path from the output to the cathode of the first triode system via resistor R15 keeps distortion low. The value of R15 influences input sensitivity.

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With a value of 47k the input voltage for full power output is 1.6V. A higher value increases the input sensitivity, but distortion will also increase. Symmetry is adjusted with potentiometer P1 until you have about half of the supply voltage at the cathode of V3. A better way to adjust symmetry is watching the output voltage at full power with an oscilloscope until the signal doesn't clip only at one side.

The recommended load for an amplifier with these tubes is 800Ω. Nowadays speakers with this impedance are scarce. But you can use normal speakers with impedances of 4–8Ω if you use an audio line matching transformer, which is available in very good qualities for only a fraction of the money you must spend for tube audio transformers. The low turn ratio and the low impedances yield a wide bandwidth and low losses. You can even build such a transformer yourself.

Output power of the amplifier with the values shown in *Fig. 4* is nearly 8W before clipping. Depending on the amount of NFB, the output impedance is about 100Ω, causing a good damping factor for the speaker. Distortion at 7.5W is below 0.5%. Bandwidth exceeds 100kHz.

The power supply is very simple. Because I used series-heated tubes, there is no need for an extra heater winding on the mains transformer. The transformer itself is a simple 1:1 transformer with sufficient power to feed the circuit and the heaters.

The diode D1 decouples the heater string from the filter capacitors C11 and C12, and the heaters are supplied with the unfiltered voltage from the bridge rectifier. This voltage is 230V instead of 320V at C12. With D1 the volt-

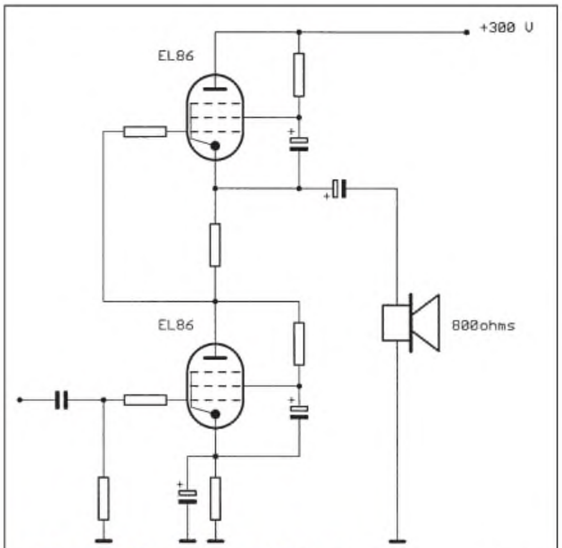

FIGURE 2: Circuit with EL86 tube. G-2140-2

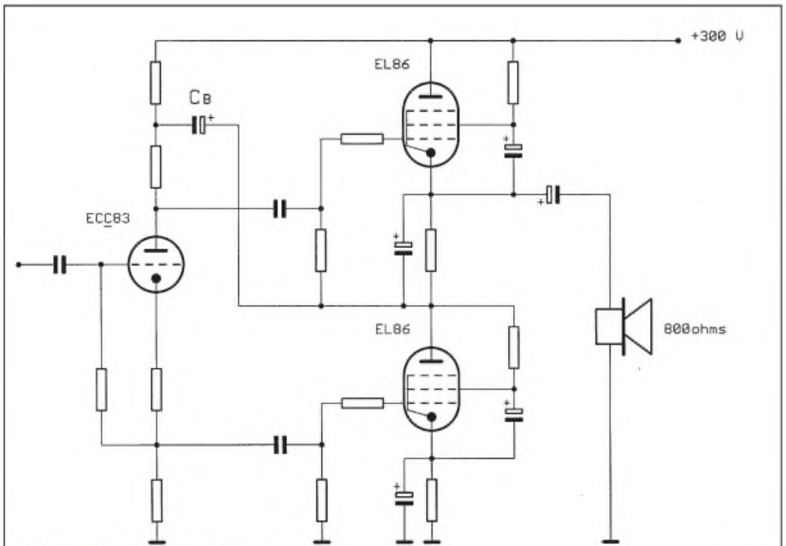

FIGURE 3: Circuit driving tubes separately. G-2140-3

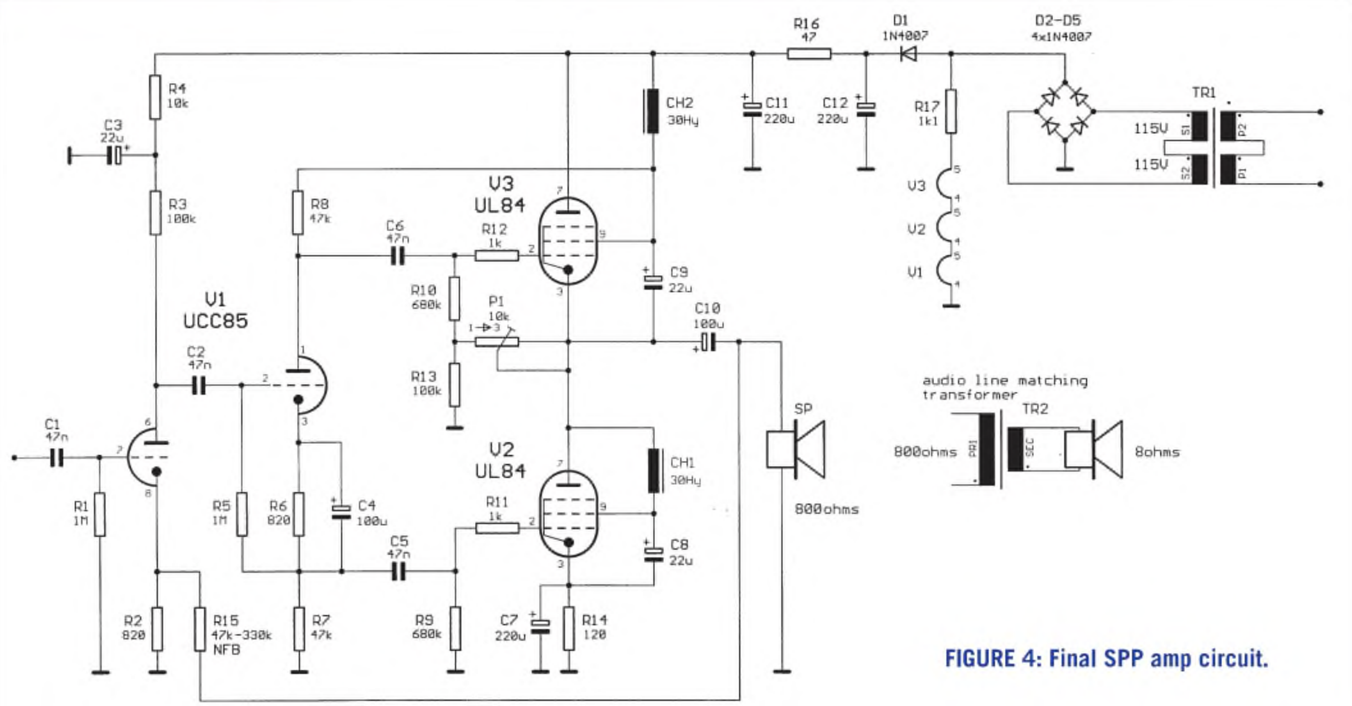

FIGURE 4: Final SPP amp circuit.

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age drop at R17 is much lower and therefore power losses are lower.

MODIFICATION

You can easily modify the circuit—i.e., use tubes with a 6.3V heater such as 6CW5 for the output and 12AX7 for the driver stage. Only a slight change in the values of the cathode resistors R2, R6, and R14 will be necessary, and you need an additional heater winding on the mains transformer. Be careful with the value of R14, and don't exceed the maximum plate power of V2 and V3!

You could make another modification in the driver stage by using a long-tailed phase splitter, which should work fine, too. You can increase output power using higher power tubes such as the 6KG6/EL509. Paralleling output tubes will also increase output power even further.

TUBES

For this amplifier concept I chose series-heated tubes for simplicity of the power supply. Most TV sweep pentodes are also a good choice, and there are many of them available for reasonable prices. One of the most powerful in current production by Svetlana, the EL509, will increase output power to about 30W with a load of 150–200Ω in this circuit. Another—perhaps the best but most expensive tube—is the E130L. And there are others. *Table 1* shows a list with some recommended tubes. ❖

TABLE 1
SOME SUITABLE TUBES

6.3V HEATER	SAME SYSTEM, DIFFERENT HEATER
EL81/6CJ6	PL81/21A6
EL86/6CW5	PL84/15CW5
	UL84/45B5
EL504	PL504/(28GB5)
EL508	PL508/17KW6
EL509/6KG6	PL509/40KG6
EL519	PL519
E130L	
E235L	

PARTS LIST

R1, R5	1M
R2, R6	820
R3, R13	100k
R4	10k
R7, R8	47k
R9, R10	680k
R11, R12	1k
R13	100k
R14	120
R15	47k–330k
R16	47 1W
R17	1k1 18W
P1	10k
C1, C2	47nF/400V
C5, C6	
C3, C8, C9	22µF/350V
C4	100µF/16V
C7	220µF/16V
C10	100µF/350V
C11, C12	220µF/350V
D1, D2, D3	1N4007
D4, D5	
V1	UCC85 Valvo, Telefunken, Siemens
V2, V3	UL84 Valvo, Telefunken, Siemens
CH1, CH2	Double-choke, see text
TR1	120VA, pri 2 × 115V, sec 2 × 115V
TR2	50VA, pri 800Ω, sec 4/8/16Ω
SP	Speaker 800Ω 9710A Philips or similar

REFERENCES
VALVO-Handbuch Rundfunk-und Fernsehröhren 1957
VALVO-Handbuch Spezialröhren 1961
VALVO-Brief 6, Dezember 1959
VALVO-Brief 4, August 1961
Philips Sevice Circuit, Saturn 653/4E/3D
Philips Sevice Circuit, AG 9017
Svetlana (www.svetlana.com)
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Behind the Scene

Dr. Joseph D'Appolito has been working as consultant for Usher Audio since early 2000. A world renown authority in audio and acoustics, Dr. D'Appolito holds BEE, SMEE, EE and Ph.D. degrees from RPI, MIT and the University of Massachusetts, and has published over 30 journal and conference papers. His most popular and influential brain child, however, has to be the MTM loudspeaker geometry, commonly known as the "D'Appolito Configuration," which is now used by dozens of manufacturers throughout Europe and North America.

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A MOSFET Update of the Forte 1a Amplifier, Part 1

A simplified version of the Pass/Thagard A75 serves as an update for the Forte 1a amplifier. **By Joe Berry**

Since it first appeared back in 1992,[1,2] the Pass/Thagard A75 amplifier has proven both a popular and a flexible project, with numerous and varied examples from around the world featured both here and on the Pass Labs website (www.passlabs.com). This article further demonstrates the versatility of the A75 by showing how you can adapt the design for use as an update to existing hardware. The hardware in this case is the Forte Model 1a, a 50W stereo Class A power amplifier whose original gain topology was also designed by Nelson Pass, but reflects an earlier design approach using a cascoded biFET voltage gain section feeding a Darlington BJT output stage.

This modification, which I've termed the Forte 1b, is guided by the requirement that it be fully reversible so that you can return the amplifier to stock condition if desired. In practice, this means that the basic update consists simply of replacing the Forte 1a's heatsink-mounted PC board assemblies (*Photo 1*). To meet this constraint, I modified the A75 circuit for complete compatibility with the Forte 1a's existing physical layout, power supply, fusing, and thermal protection schemes.

It follows that the resulting amplifier is less powerful than the A75 and does without one or two of its refinements. However, the Forte 1b does preserve the A75's basic all-MOSFET approach, and still offers you a choice between local and global negative feedback, and between two-stage versus partial folded-cascode operation of the front end. Perhaps most importantly, the Forte 1b offers a different subjective experience from the 1a, and one that listeners may prefer.

POWER-SUPPLY CHANGES

The original A75 circuit (*Fig. 1*) operates from two split DC power supplies—an unregulated ±40V for the output stage and a regulated ±50V for the "front end" or voltage gain section. Elevating the front end supply by 10V makes up for about 5V of output voltage swing lost through the HEXFET follower output stage, and another 5V lost through the cascoded second stage. This enables the A75 front end to swing the output to within a few volts of the unregulated supply rails, achieving a 75W output into 8Ω.

By contrast, the FET/bipolar circuit of the Forte 1a (*Fig. 2*) works from a simple unregulated ±36V DC power supply. The reduced voltage losses associated with the bipolar transistors in the Forte 1a allow the circuit to swing the output to within 4V or so of the supply rail without the need for a separate elevated front-end supply. Working from this power supply, the Forte 1a easily met its 50W (28.3V peak) 8Ω continuous power rating.

Simply operating the unmodified A75 from such a supply would result in a maximum continuous 8Ω output of some 35W, about 40% less than the Forte 1a's original power rating. This was a bit more loss than I could accept, so I removed the cascodes from the A75's second voltage-gain stage to reclaim about

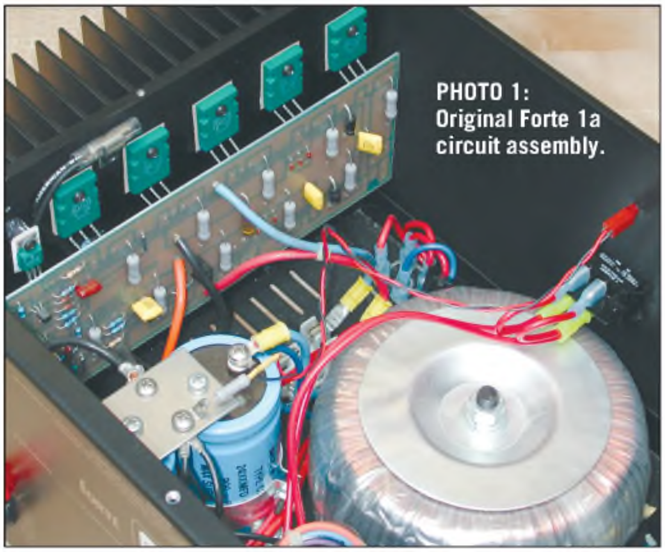

PHOTO 1: Original Forte 1a circuit assembly.

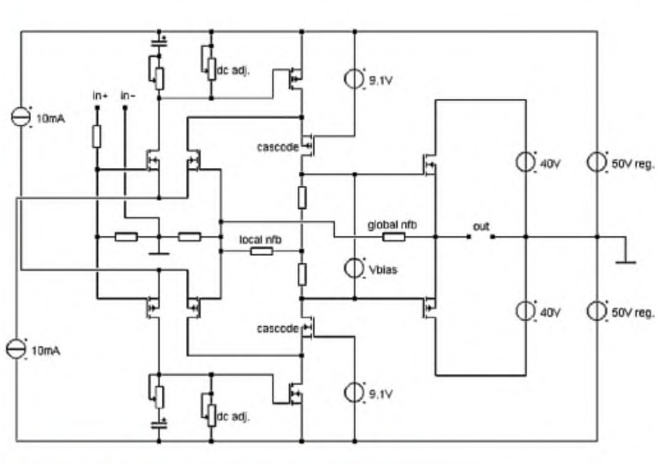

FIGURE 1: A75 conceptual schematic.

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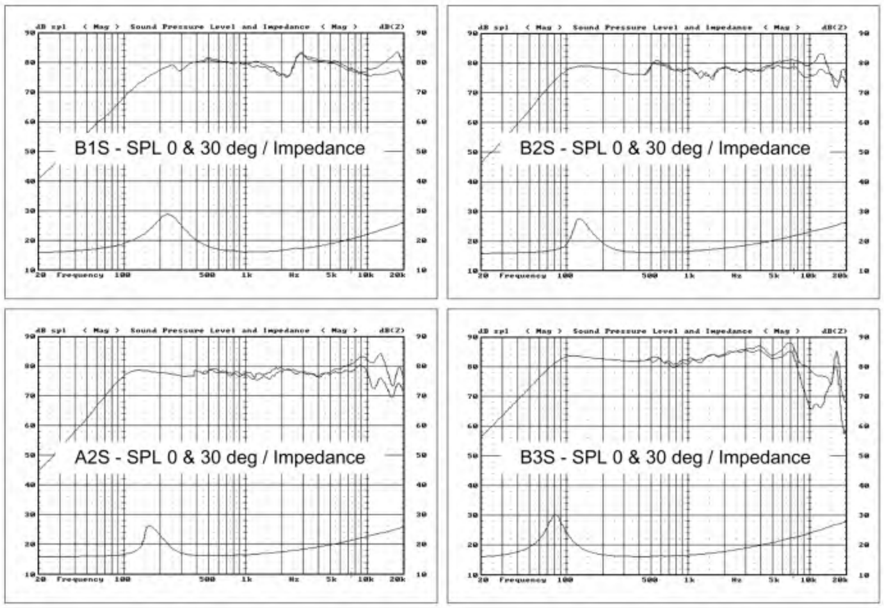

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5V of output swing. Thus modified, and working from the stock Forte 1a power supply, the new circuit just meets the Forte 1a's original 50W power rating.

CIRCUIT CHANGES

The conceptual schematic of *Fig. 3* provides an overview of the Forte 1b circuit topology. The prototype circuit was prone to high-frequency oscillation unless the second stage was operated in its optional partial folded-cascode mode.

To allow for stable operation without the folded cascode, I added source degeneration resistors to each of the four input stage MOSFETs. I treat these options (source resistors versus folded cascode) as mutually exclusive because the source resistors are needed only if you omit the partial folded-cascode option. Using both options together would reduce open-loop gain beyond the point needed for stability, and may audibly increase noise and distortion.

I also made a number of component-value changes to better match the circuit to the Forte 1a environment. For example, the heatsink was already drilled for ten plastic TO-3 power transistors, so I used physically similar TO-247 plastic HEXFETs in place of the metal TO-3 devices originally specified for the A75. Likewise, I removed the option of balanced input from the circuit because there is no balanced input jack on the Forte 1a rear panel.

In addition, I adjusted the values in the feedback network to give the Forte 1b the same closed-loop gain of 20 (26dB) as the Forte 1a. Finally, because the A75's unbalanced input impedance value of 75kΩ seemed higher than necessary, I reduced it to 23kΩ for reduced high-frequency distortion. This new value is still high enough to present no problems for most preamplifiers.

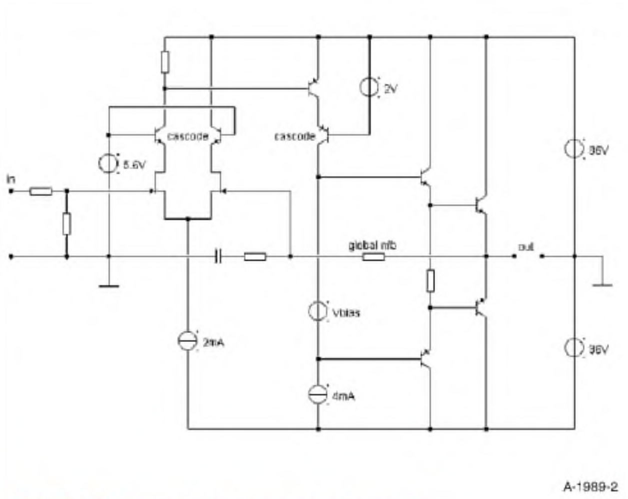

FIGURE 2: Forte 1a conceptual schematic.

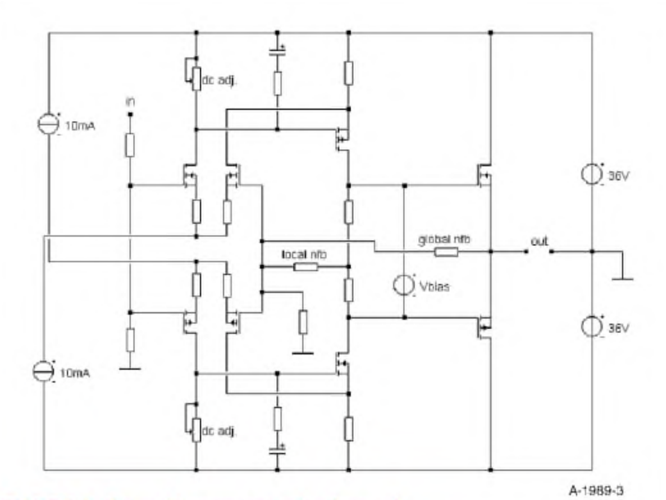

FIGURE 3: Forte 1b conceptual schematic.

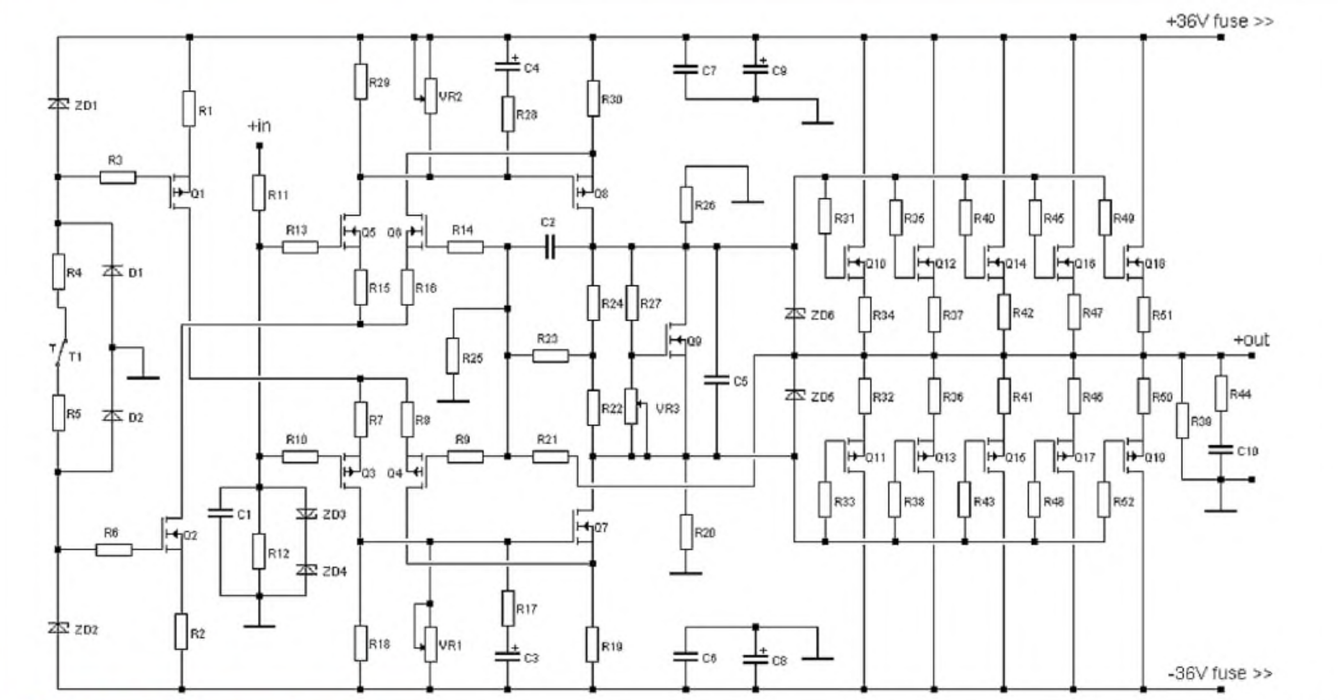

FIGURE 4: Forte 1b actual schematic.

THE CIRCUIT IN DETAIL

Figure 4 shows the actual schematic of the Forte 1b. Starting at the left, complementary MOSFETs Q1 and Q2 and associated components form the constant-current sources that bias the input stage. Current flowing through zener diode ZD1 sets up a constant 9.1V DC reference voltage at the gate of Q1, causing a constant current of about

$$(9.1 - 4)/R1 = 5.1/511 = 10mA$$

to flow in Q1. Likewise, Q2 and its associated components provide about 10mA of operating current for the N-channel half of the input stage. Gate resistors R3 and R6 suppress parasitic oscillations in these MOSFETs.

The series combination of ZD1, ZD2, R4, R5, and normally-closed thermal cutout T1 form a current path between the +36V and −36V rails. In normal operation, the current flowing through this path activates Q1 and Q2, and by extension, the circuit as a whole. If T1 or either of the two DC rail fuses (external to the circuit) opens, Q1 and Q2 both deactivate, shutting down the amplifier. In the event of a single DC rail fuse failure, clamping diodes D1 and D2 will ensure a hard shutdown of both Q1 and Q2 to prevent significant DC offset voltage from appearing at the amplifier output.

The complementary differential input stage consists of P-channel MOSFETs Q3 and Q4, N-channel MOSFETs Q5 and Q6, and associated components. Q3–Q4 and Q5–Q6 are matched pairs[3] for improved current sharing and DC offset stability. The input signal is conditioned by a network consisting of R11, R12, C1, ZD3, and ZD4. R11 and C1 form a 4MHz low-pass filter, shunting RFI to ground at the input.

The series combination of R11–R12 sets the input impedance of the amplifier at about 23kΩ, high enough to prevent problems with most preamplifiers, but low enough to avoid excessive HF distortion and instability. Series zeners ZD3–ZD4 clamp the input to protect the input MOSFETs from excessive gate voltage.

The conditioned input signal is presented to the gates of Q3–Q5, while negative feedback from either the second stage or the output stage (or both) is presented to the gates of Q4–Q6. (Note that Q3–Q6 are also equipped with gate resistors to suppress parasitic oscillations.) If you install R23, feedback comes from the second stage, whereas if you use R21, feedback comes from the output stage. With both R21 and R23 installed, feedback from the second stage and output stage are combined, and the amplifier's closed-loop gain will drop by 6dB unless you change R21 and R23 from 22.1kΩ to 43.2kΩ each. As in the original A75, you can also use different values for R21 and R23 to mix the feedback in different proportions, if desired.

Optional source degeneration resistors R7–R8 and R15–R16 are installed

ABOUT THE AUTHOR

Joe Berry is a long-time audio and radio enthusiast whose study of electronics began, as it did with many others, by reading the Alfred Morgan books in his grade-school library. Joe worked as an electronics service technician early in his career, but later moved into the field of technical education, where he has worked for 20 years, and in which he is now an independent design consultant. Joe holds a BA degree in Humanities from Emory University, where he also studied calculus, physics, and other subjects related to audio. E-mail: joeberry@mindspring.com.

to ensure stability in the absence of the partial folded-cascode option. These resistors add local negative feedback to each input MOSFET to reduce open-loop gain and increase input-stage bandwidth. Capacitor C2 forms a secondary feedback loop that enhances the stability of the closed-loop amplifier and defines the high-frequency rolloff of the amplifier (–3dB) at just over 200kHz. In this design, 22pF seemed to offer the best compromise between

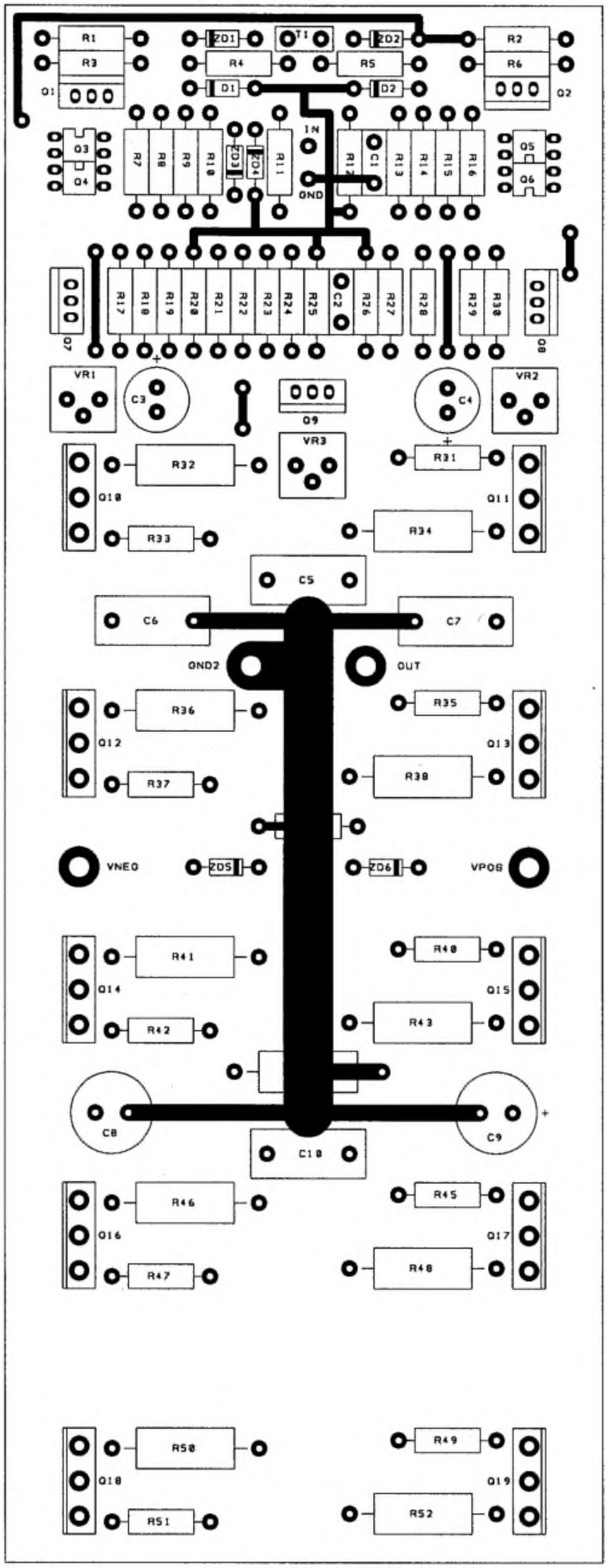

FIGURE 5A: Forte 1b PC board (top). Actual size is 3.65″h × 9.5″w.

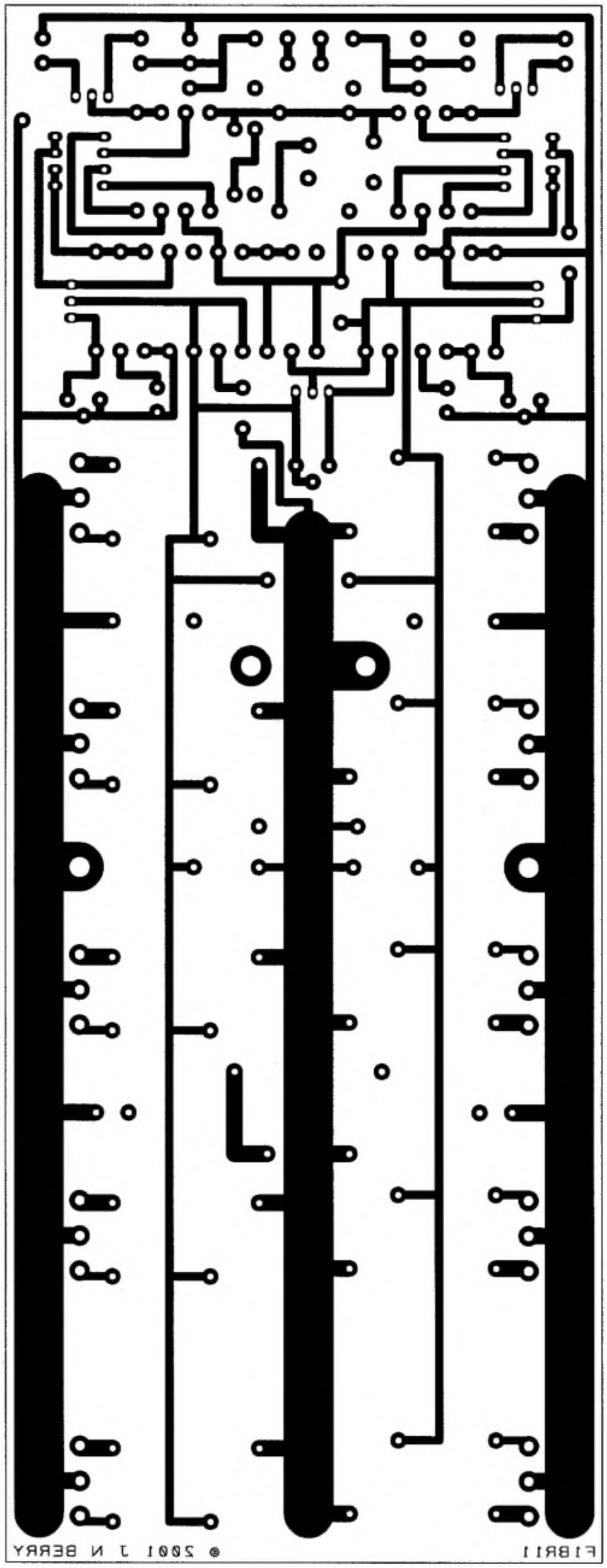

FIGURE 5B: Forte 1b PC board (bottom).

damping and stability while avoiding the need for additional lag compensation. (The original A75 PC board includes provisions for lag compensation, but source degeneration obviates the need for this option here.)

OUTPUT STAGE

The output of the first stage drives second-stage complementary MOSFETs Q7 and Q8 and their associated components. DC bias voltage for Q7 and Q8 develops across R18 and R29 as a result of the DC current flowing in Q3 and Q5. Variable resistors VR1 and VR2 trim the values of R18 and R29 to adjust the bias for Q7 and Q8 and null the DC offset at the amplifier output.

VR1 and VR2 are ultimately set to give 1V across R19 and R30, the source resistors for Q7 and Q8. This reflects about 30mA of idle current in Q7 and Q8, plus an additional 5mA drawn through R19 and R30 by Q4 and Q6. The drains of Q7 and Q8 are loaded by resistors R20 and R26 to limit the open-loop gain of this stage and flatten its open-loop frequency response. R22 and R24, also in the Q7-Q8 drain circuit, merely serve to produce a virtual ground takeoff point for the optional negative feedback connection via resistor R23.

At your discretion, you may set up the second stage to operate as a partial folded cascode by installing resistors R17 and R28 and capacitors C3 and C4. With these components removed, maximum signal voltage develops across R18 and R29, and Q7 and Q8 work mainly in common-source mode. With C3, R17, C4, and R28 installed, the signal voltage across R18 and R29 is attenuated, reducing the gain of the second stage by about 80%.

In this application, the nominal value of R17 and R28 is 221Ω, just high enough to enable a 2:1 output current swing from Q7 and Q8. Lower values enhance the effect of the folded-cascode, but may also degrade the amplifier's power bandwidth as well as cause excessive hum at the output. Values below 100Ω may cause self-oscillation in Q7 and Q8 and should be avoided. Also note that much higher values of R17 and R28 may produce feedback-loop instability unless you install R7–R8 and R15–R16.

The output from the second stage drives complementary-symmetry MOSFET source-follower output stage Q10–Q19 and associated components. These MOSFETs are in matched sets[4] with 221Ω gate resistors and .47Ω source resistors for improved AC and DC stability. ZD5 and ZD6 clamp the gate drive to the output stage to prevent damaging overvoltage that could occur if the amplifier output is shorted. These zeners also provide some protection against sustained overcurrent conditions, although in this application one or both of the channel's DC rail fuses will probably blow first.

The output stage is biased into Class A operation by adjustable voltage source Q9 and associated components. The bias voltage generated by Q9 has a mildly negative temperature coefficient that compensates for the tendency of the output stage bias to increase with temperature. VR3 provides the bias adjustment, and C5 bypasses Q9 at high frequencies.

A Zobel network consisting of C10 and R44 is included across the output

terminals to ensure that the amplifier sees a resistive load at frequencies well above the audio band. R39 is in parallel with this network to provide a leakage path for any standing charge that may remain on the power-supply capacitors after you turn off the unit.

A global negative feedback connection will do essentially the same thing, but if you elect not to use global feedback, R39 prevents mysterious DC offset voltages from appearing at the unloaded output terminals after shutdown. While harmless enough in itself, this voltage could give rise to erroneous fault symptoms during bench testing.

Finally, I added decoupling capacitors C6–C9 during prototyping to prevent amplifier self-oscillation and to enhance stability when driving capacitive loads. The larger capacitors alone appeared to take care of both problems, but I added the smaller film caps to comply with the general recommendations of IR, Hitachi, and others for MOSFET amplifier power-supply rail decoupling.

NEW PC BOARD

Figures 5a and *5b* are top and bottom views of the PC board developed for this project. The basic layout resembles that of the Forte 1a PC board, with the front-end components grouped together at one end and the output stage spread out over the remainder of the board. Ten TO-247 output MOSFETs mount directly to the heatsink in place of the Forte 1a's plastic TO-3 power transistors. Second-stage MOSFETs Q7 and Q8, which dissipate 1W each, mount to standoffs on the heatsink which formerly held the Forte 1a's TO-220 bipolar driver transistors.

The board layout shown here fits perfectly in the two Forte 1a samples I have modified. Still, key dimensions may have changed over the amplifier's three-year production run, so I suggest that you first copy the PCB layout to scale (actual size 3.65″ H × 9.5″ W) and use it as a template to check your amplifiers for compatibility.

Copper traces on the top of the board provide separate ground connections for the front end and output stage. This conforms with the Forte 1a's original grounding scheme, which keeps the input and output stage grounds separate until they meet at the metal plate tied across the grounded terminals of the main power-supply filter capacitors.

The holes for the output and power-supply leads on the new PC board are sized to accept the original #12 stranded leads from the Forte 1a. You can recycle the original PC board wiring or supply new leads at your discretion. You should pre-cut new leads to the appropriate lengths and fit them with ring and push-on spade terminals matching those of the original. The input lead holes are likewise sized to accept the original Forte input cable, but should also be compatible with most replacement cables.

I found it best to install as many components as possible on the new PC boards before taking the amplifier apart. This includes all passive devices as well as input-stage MOSFETs Q1–Q6 and the output-stage bias MOSFET, Q9. It does not include the input, power, and output wiring (unless new wiring is used); the thermal cutout (unless a new unit is used); or MOSFETs Q7, Q8, and Q10–Q19. It's best to add these components as part of the assembly process, which I will cover next month in Part 2. ❖

TABLE 1
PARTS LIST FOR ONE CHANNEL

R1, R2	511Ω, ¼W metal film resistor
R3, R6, R9, R10, R13, R14, R17, R28, R31, R33, R35, R38, R40, R43, R45, R48, R49, R52	221Ω, ¼W metal film resistor
R4, R5	6.2kΩ, ¼W metal film resistor
R7, R8, R15, R16	39.2Ω, ¼W metal film resistor
R18, R29	1.5kΩ, ¼W metal film resistor
R19, R30	27.4Ω, ¼W metal film resistor
R20, R26, R39	10kΩ, ¼W metal film resistor
R12, R21, R23	22.1kΩ, ¼W metal film resistor (43.2k if R21 and R23 are both installed; see text)
R11, R22, R24, R25	1kΩ, ¼W metal film resistor
R27	2.65kΩ, ¼W metal film resistor
R32, R34, R36, R37, R41, R42, R46, R47, R50, R51	0.47Ω, 3W metal oxide resistor
R44	10Ω, 3W metal oxide resistor
VR1–VR3	5kΩ, ½W cermet trimmer potentiometer
C1, C2	22pF, 500V silver mica capacitor
C3, C4	220µF, 25V electrolytic capacitor
C5–C7, C10	100nF. 50 or 100V plastic film capacitor
C8, C9	220µF, 50V electrolytic capacitor
D1, D2	1A, 100PIV diode (1N4002)
ZD1–ZD6	9.1V, 1W zener diode (1N4739)
Q1, Q8	IRF9510 P-channel MOSFET
Q2, Q7, Q9	IRF510 N-channel MOSFET
Q3, Q4	IRFD9110 P-channel MOSFET (matched pair)
Q5, Q6	IRFD110 N-channel MOSFET (matched pair)
Q10, Q12, Q14, Q16, Q18	IRFP240 N-channel MOSFET (matched set)
Q11, Q13, Q15, Q17, Q19	IRFP9240 P-channel MOSFET (matched set)
T1	Thermal cutout, normally closed, 85°C
Miscellaneous (per channel)	TO-220 thermally conductive insulating pads (2 qty) • TO-247 thermally conductive insulating pads (10 qty) • Conical/Belleville washers for #6 screws (e.g., McMaster-Carr Part # 90127A007) (10 qty) • Nylon shoulder washers for TO-220 (e.g., Digi-Key Part # 3049K-ND) (2 qty) • 3AG, 3A fast-blow fuses for testing (2 qty)
Optional (per amplifier; see text)	Keystone CL-60 inrush current suppressors (2 qty), three-lug terminal strip, ferrite clamps (2 qty), 14-gauge power cord (1 qty)

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1. Thagard. Norman, and Pass, Nelson, "Build the A75 Power Amplifier (Part 1)," *TAA* 4/92, p. 9.

2. Thagard, Norman, and Pass, Nelson, "Build the A75 Power Amplifier (Part 2)," *TAA* 1/93, p. 20.

3. *Ibid.* pp. 23–25.

4. Pass, Nelson, "Bride of Son of Zen: The Next Generation," *AE* 5/97, pp. 7–8.

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Budget Milliohmmeter Bridge

Build this device for those times when you need to measure voice-coil or other low resistance values. **By Charles Hansen**

When measuring the actual voice-coil resistance of a loudspeaker driver, most digital multimeters (DMM) do not have the accuracy or resolution for the job. Their test leads add a significant amount of series resistance that introduces additional error.

This project is designed to measure low values of resistance to 1% accuracy or better. I designed the original version of this bridge to measure generator and transformer winding resistances in situations or locations where it was impractical to use an AC line powered precision HP 4261A LCR meter. Parts cost is about $45.

HOW IT WORKS

The schematic diagram for the milliohmmeter bridge is shown in *Fig. 1*, and the parts list is in *Table 1*. The circuit is based on the familiar Wheatstone bridge. Power comes from a small 12V 1.3Ah sealed lead-acid battery that I bought surplus NOS (*Photo 1*). You could also use a *well-filtered* 12V DC supply.

R1 and R2 form two legs of the bridge. I chose their value to limit the test current to less than 60mA. The unknown resistance connects to binding posts J1 and J2. A known variable resistance then connects to J3 and J4. When the known resistance equals the unknown resistance, the bridge is nulled (balanced) and the voltage between J1 and J3 is zero.

The original Wheatstone bridges used a very sensitive center-zero analog meter movement called a galvanometer to indicate when the bridge was nulled. You could connect your DMM from J1 to J3 to indicate the null point, but you would run into the same accuracy and resolution problems that limit your ability to measure low resistance in the first place.

In order to obtain a very accurate null indication, I used an LT1017 dual precision comparator and two indicator LEDs. If the known resistance is too high, the output of U1a goes low, lighting the "HI" LED1. If the known resistance is too low, the output of U1b goes low, lighting the "LO" LED1. These LEDs tell you the direction you must change the adjustable known resistance in order to achieve null.

R3 and R4 introduce a small amount of hysteresis into each comparator circuit. At the exact null point, both LEDs are turned off. For an 8Ω unknown resistance, this null point is accurate to within 0.001Ω of the value of known resistance. Thus, the finer the adjustment of the known resistance, the finer the measurement tolerance of the unknown resistance. CR1 provides reverse polarity protection, while C1 and C2 filter any noise pickup from the comparator circuit.

DECADE BOX

My original application used a precision decade box accurate to 0.5% for the "known" resistor. Another alternative is

PHOTO 1: Top view of unit with battery.

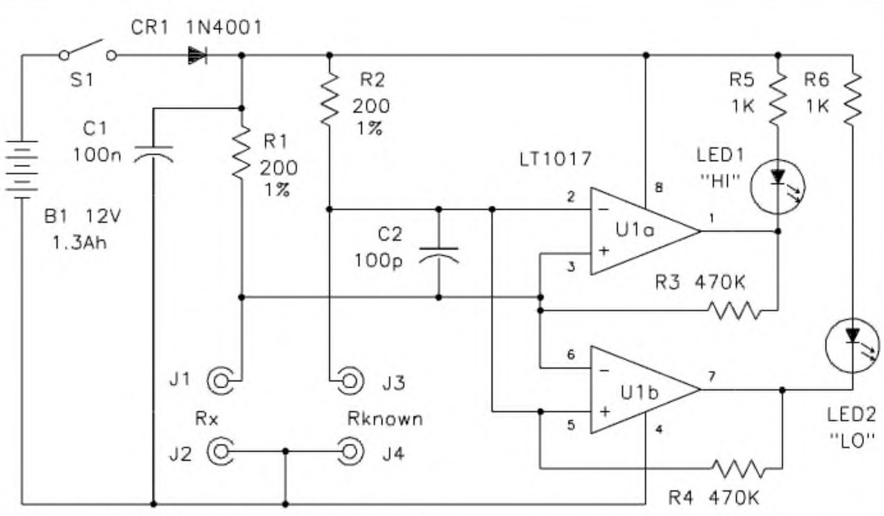

FIGURE 1: Milliohmmeter bridge schematic.

a precision multi-turn dial-counter potentiometer. Low resistance versions of these devices are hard to find and cost upwards of $100.

You can make your own 0.1Ω-step decade box with the precision 3W 1% resistors and switches listed in the parts list. The schematic is shown in *Fig. 2.* You can use the same ABS enclosure I used for the bridge circuitry.

The decade box uses inexpensive switches with nickel contacts. The total resistance of the internal connecting wire (22-gage), the switch contacts, and the binding posts add up to almost 0.1Ω. For this reason, the "0.1Ω" point

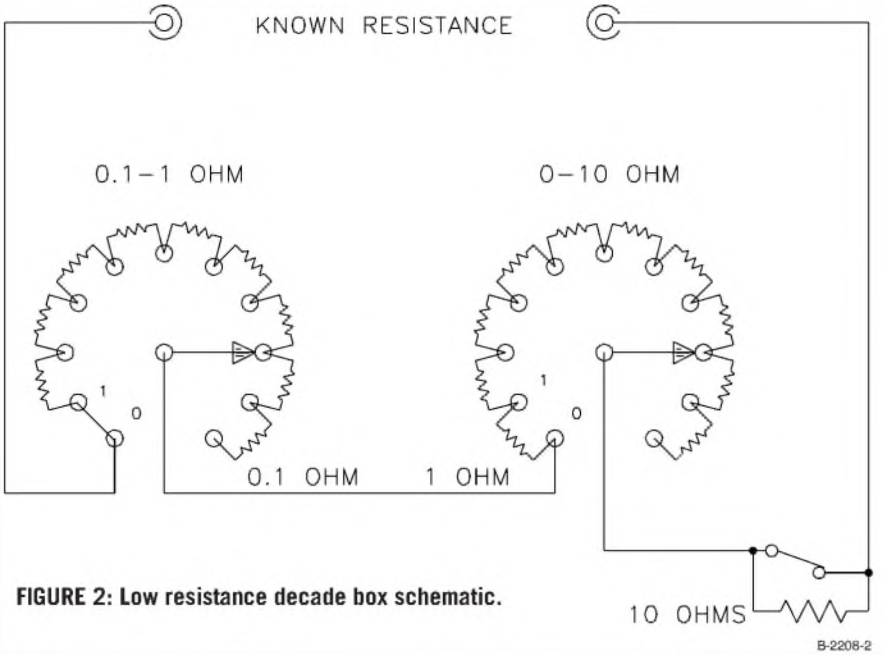

FIGURE 2: Low resistance decade box schematic.

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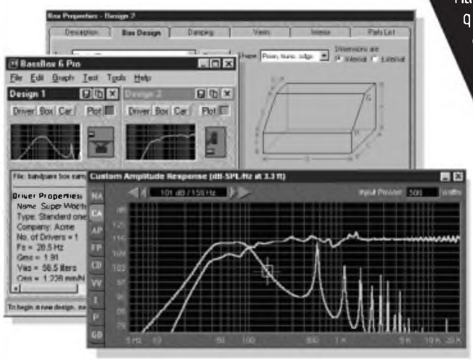

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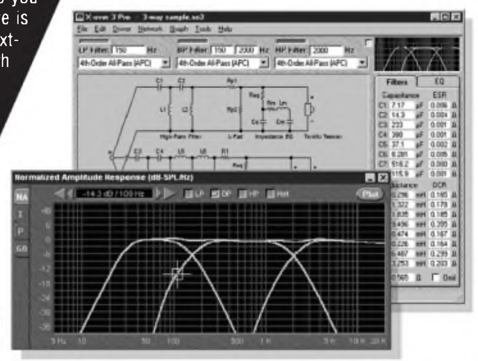

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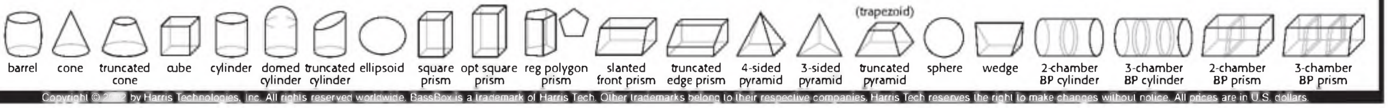

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on the first rotary switch uses a jumper rather than an actual 0.1Ω resistor. If you can borrow an accurate lab quality milliohmmeter, you can make a calibration label for your decade box and improve the accuracy of your measurements even further.

The design in *Fig. 2* is adjustable from 0.1Ω to 21Ω, which will cover all the voice coils you should encounter. The "12" position on the two rotary switches is not connected, allowing an open circuit position. If you like, you can add another resistor to the series string on each deck to extend the range by another 1.1Ω. You can also easily redesign the circuit to measure higher resistances by changing the values of R1 and R2, and the range of the decade box used to balance the bridge.

CIRCUIT BOARD LAYOUT AND CONSTRUCTION

I used a plastic enclosure for the bridge circuitry, with most of the parts on a small wire-wrapped perfboard connected with standard T49 wire-wrap pins and a wire-wrap DIP socket for U1 (*Photo 2*). Four 4-40 × ¾″ spacers support the PC board with the components facing the top of the enclosure. This allowed me to let the two lead-supported LEDs show through two $3/16''$ holes drilled in the top of the enclosure.

The unknown (Rx) resistor terminal posts J1 and J2 are just above the LEDs in *Photo 1*. J3 and J4 are on the right side of the enclosure. The power switch is on the lower right side of the top. The 12V battery is connected to the bridge enclosure with a two-pole flat trailer-towing connector that I purchased at Pep Boys.

There is nothing critical about the internal wiring, except the four inputs to U1 should have the shortest length possible, and C1 and C2 should be located as close to U1 as possible.

USING THE MILLIOHMMETER BRIDGE

One of the problems with accurate milliohm measurements is the length of the leads between the test meter and the unknown resistance. The HP 4261A uses 4-wire Kelvin leads to compensate for the drop in the leads carrying the test current to the unknown resistance.

You can provide another form of compensation by making two equal-length sets of test leads. One set connects from the Rx input jacks to the unknown resistance, the other from the known resistance jacks to the decade box. In this way the drop in each set of leads should be equal at null. Alternatively, you can measure the effect of the speaker cables you want to use by connecting them between the driver and the bridge unit, and using the shortest possible leads between the decade resistor and the bridge unit.

I was able to measure a precision 0.01% test resistor of exactly 6.98Ω to 6.978Ω using this simple test tool. You can obtain this extra decade of accuracy by shunting the low resistance decade box with a higher resistance and computing the parallel resistance of the two "known" resistors. ❖

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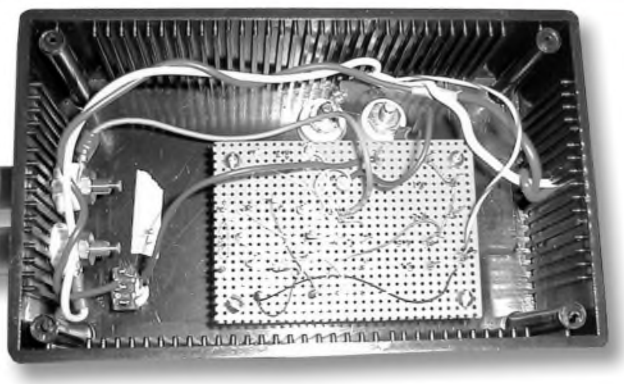

PHOTO 2: Interior view.

TABLE 1
PARTS LIST

SYMBOL	VALUE	DESCRIPTION	VENDOR/PART NO.
B1	12V 1.3Ah	Panasonic LC-R121R3PU	(surplus)
		(or Parts Express)	Parts Express 149-135
C1	100nF 100V	Ceramic Z5U	Mouser 140-100Q9-104Z
C2	100pF 50V	Ceramic NP0	Mouser 140-50S5-101J
CR1	1N4001	1A 50V	Mouser 583-1N4001
LED1, LED2	MV8013	Red T-1 3/4 LED	Mouser 512-MV8103
J1–J4		Binding post, white	Mouser 164-4206
P1		2-pole flat trailer connector	Pep Boys 47965
		0.250 × 0.032 female lug	Mouser 644-DNF18-250C
R1, R2	200Ω 3W 1%	Wire wound	Mouser 71-RS2B-200
R3, R4	470k 5% ¼W	Carbon film	Mouser 291-470K
R5, R6	1K 5% ¼W	Carbon film	Mouser 291-1K
S1, Sdb	SPST	Mini toggle	Mouser 108-MS550K
U1		LT1017 dual comparator	DK LT1017CN8-ND
		8-pin wire wrap DIP socket	Mouser 575-293308
		5.9 × 3.5 × 2.2 ABS enclosure	Mouser 400-1562
Rdb (9)	0.1Ω 3W 1%	Wire wound	Mouser 71-RS2B-0.1
Rdb (10)	1.0Ω 3W 1%	Wire wound	Mouser 71-RS2B-1.0
Rdb	10Ω 3W 1%	Wire wound	Mouser 71-RS2B-10
Jdb (4)		Binding post, white	Mouser 164-4206
Sdb (2)	1P 12 POS	Rotary sw	Mouser 10YX112

ADDITIONAL MATERIALS:
Perfboard, nylon spacers, hookup wire, solder, hardware, and so on.

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■Cartridge

Model	Price (US$)	Postage (Air Economy)
Denon DL-102 (MONO)	150	Area I $18: China, Korea, Hong Kong, Taiwan
Denon DL-103 (STEREO)	200	Area II $22: Singapore, Malaysia, Indonesia
Denon DL-103R (STEREO)	250	Area III $27: North America, Oceania, Europe
Denon DL-103 PRO (STEREO)	350	Area IV $34: Africa, South America
Shelter Model 501 II (CROWN JEWEL REFERENCE)	750	These Area I ~ IV are for all products except book.
Shelter Model 901 (CROWN JEWEL SE)	1,400	

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Postage $15

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Attractive Tube Amps Vol. 1&2	(Isamu Asano)	30 each
The Joy of Vintage Tube Amps 1&2	(Tadaatsu Atarashi)	30 each NEW
Direct & Indirect Tube Amps	(Kiyokazu Matsunami)	40 NEW
SE Amps by Transmitting Tubes	(Kouichi Shishido)	50
The Remembrance of Sound Post	(Susumu Sakuma)	30
Classic Valve	(Hisashi Ohtsuka)	40
MJ Selected 300B Amps	(MJ)	30
Top-Sounding Vintage Power Tubes	(Stereo Sound)	30
Output Trans of The World	(Stereo Sound)	30
20TH CENTURY OF AUDIO	(Stereo Sound)	30
Vintage Speaker Units	(Stereo Sound)	30 NEW
Tube Amp Craft Guide	(MJ)	30

■MC STEP UP TRANS

Model	Specifications			Price (US$)	Postage**
	Pri.Imp(Ω)	Sec.Imp(kΩ)	Response		
Shelter Model 411	3～15	47	20Hz～50kHz	980	Area I $25
Jensen JE-34K-DX	3	47	20Hz～20kHz	550	Area II $30
Peerless 4722	38	50	20Hz～20kHz	300	Area III $40
					Area IV $50

**Air Economy

■STAX

Model	Price(US $)
OMEGA II System(SR-007+SRM-007t)	Ask
SRS-5050 System W MK II	Ask
SRS-4040 Signature System II	Ask
SRS-3030 Classic System II	Ask
SRS-2020 Basic System II	Ask
SR-001 MK2(S-001 MK II +SRM-001)	Ask

■Speaker

Model	Specifications					Price* (US $)	Postage** (US $)			
	D (cm)	Ω	Response	db	w		I	II	III	IV
Fostex FE208 Σ	20	8	45Hz～20kHz	96.5	100	296	62	74	120	156
Fostex FE168 Σ	16	8	60Hz～20kHz	94	80	236	42	50	73	98

*Price is for a pair **Air Economy

■TANGO TRANS (ISO) 〔40models are available now〕

Model	Specifications				Price (US $)	Postage** (US $)				
	W	Pri.Imp(kΩ)	Freq Response	Application		I	II	III	IV	
XE-20S (SE OPT)	20	2.5 , 3.5 , 5	20Hz～90kHz	300B,50,2A3	396	47	56	84	113	Price is for a Pair
U-808 (SE OPT)	25	2 , 2.5 , 3.5, 5	20Hz～65kHz	6L6,50,2A3	242	42	50	73	98	
XE-60-5 (PP OPT)	60	5	4Hz～80kHz	300B,KT-88,EL34	620	62	74	115	156	
FX-40-5 (PP OPT)	40	5	4Hz～80kHz	2A3,EL34,6L6	320	47	56	84	113	
FC-30-3.5S (SE OPT) 〔XE-60-3.5S〕	30	3.5	20Hz～100kHz	300B,50,PX-25	620	62	74	115	156	
FC-30-10S (SE OPT) 〔XE-60-10SNF〕	30	10	30Hz～50kHz	211,845	620	62	74	115	156	
X-10SF 〔X-10S〕	40	10W/SG Tap	20Hz～55kHz	211,845	1160	90	110	180	251	
NC-14 (Interstage)	—	[1+1 : 1+1]5	25Hz～40kHz	[30mA] 6V6 (T)	264	30	40	50	70	
NC-16 (Interstage)	—	[1+1 : 2+2]7	25Hz～20kHz	[15mA] 6SN7	264	30	40	50	70	
NC-20F [NC-20] (Interstage)	—	[1 : 1]5	18Hz～80kHz	[30mA] 6V6 (T)	640	42	50	73	98	
NP-126 (Pre Out)	—	20,10	20Hz～30kHz	[10mA] 6SN7	264	30	40	50	70	

**Air Economy

■TAMURA TRANS (All models are available)

F-7002 (Permalloy)	10	3.5	15Hz～50kHz	300B,50	836	60	70	110	145	Price is for a Pair
F-7003 (Permalloy)	10	5	15Hz～50kHz	300B,50	836	60	70	110	145	
F-2013	40	10	20Hz～50kHz	211,242	786	70	84	133	181	
F-5002 (Amorphous)	8	3	10Hz～100kHz	300B,2A3	1276	65	80	120	160	

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The Legend of EL PIPE-O

This woofer transmission-line project takes achieving low frequencies to new heights. **By Kent English and Nelson Pass**

Most woofers just don't quite do the lowest octave. You read the specs that say "usable response: 20Hz–20kHz," and you know that the 20Hz part of it is wildly optimistic. Achieving very low frequencies at reasonable power levels is not an easy job; the acoustic impedance experienced by a speaker cone declines as the inverse of the square of the frequency. As a practical matter, woofers and their enclosures need to be very large to reproduce the lowest octave properly. Even when you compensate with frequency equalization and more amplifier power, the performance suffers as you reach the excursion and power-handling limitations of a small cone in a small box.

Let's face it. Size does matter.

This is the saga of El Pipe-O, an adventure in over-the-edge woofer construction. The name El Pipe-O came from its striking resemblance to a legendary smoking appliance belonging to one of Pass' roommates in college that was the object of worship by a small cult.

El Pipe-O consists of very large woofers mated to large cylindrical transmission lines. The goal is to get good powerful response down to 20Hz at levels where the room starts to rattle before the loudspeaker.

BASS REFLEX ENCLOSURES

Suspended by elastic material, woofer cones have a natural fundamental resonant frequency at which the motion increases dramatically, and below which the response drops off at a sharp rate. Many woofer enclosures attempt to set up some sort of counter-resonance that is used to damp out this uncontrolled motion and turn it into getting a little more bass out of the speaker. The two most popular approaches are the bass-reflex enclosure and the transmission line.

The bass-reflex enclosure has the woofer mounted in a box that has a specific internal volume and an opening to the outside. Any box with an opening has its own acoustic resonance, known as Helmholtz resonance, which you experience when you blow into the opening of a beer bottle. Varying the volume of the box or the size of the opening (called the port) adjusts the frequency of resonance, and you can tune it to the same frequency as the resonance of the woofer.

When the box's resonance is the same as the woofer's resonance, you get an interesting effect: The woofer experiences acoustic loading, which damps out its uncontrolled motion, and the port delivers extra acoustic output to the outside world. The performance

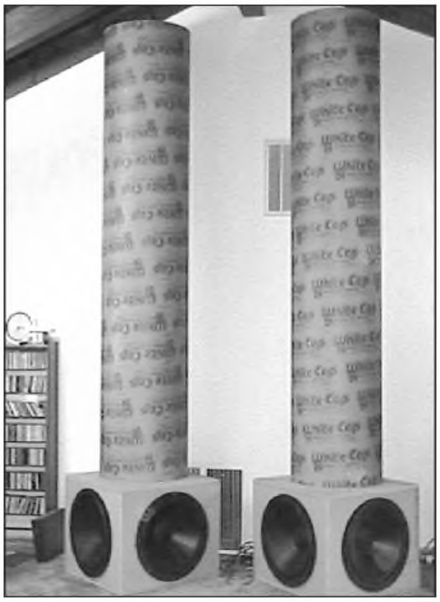

PHOTO 1: Sonotube speakers standing tall.

PHOTO 2: Closeup of speaker.

improves because the cone moves less and the output is boosted at the lowest frequencies. You can see this in the impedance curves of *Fig. 1*. The impedance of the woofer reflects the motion of the cone, and here you see a comparison between the woofer's impedance in free air versus its impedance in a tuned bass-reflex enclosure.

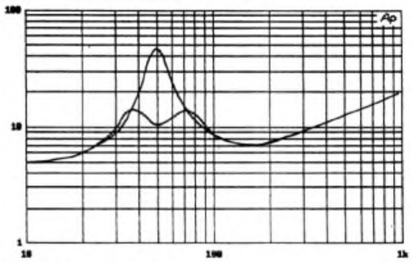

FIGURE 1: Woofer impedance in bass-reflex enclosure. B-311-1

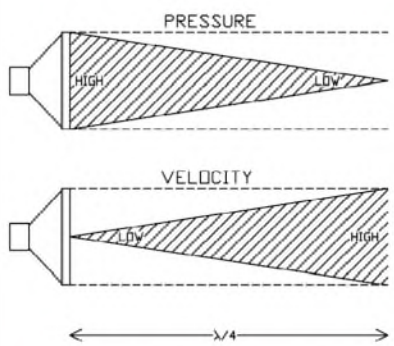

FIGURE 2: Air pressure and velocity relationship. B-311-2

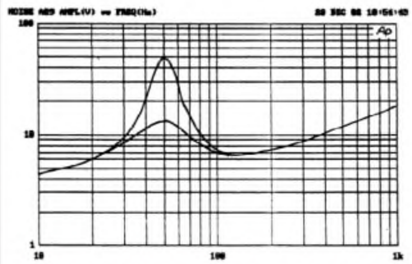

FIGURE 3: Woofer impedance in transmission-line enclosure. B-311-3

PIPE DREAMS

A transmission line offers a different approach to achieving a similar effect. In any tube-shaped object, closed at one end, a resonance develops at the frequency where the wavelength is four times the length of the tube. This effect is exploited in numerous musical instruments, particularly the pipe organ.

The wavelength of a frequency is the speed the wave travels divided by the frequency. For sound going through

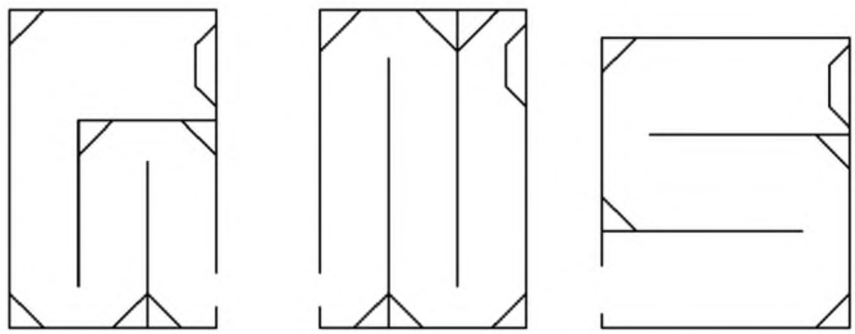

FIGURE 4: Sample transmission-line designs. B-311-4

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Specifications:

Fs	23.7 Hz
Nominal Impedance	4.0 Ω
Power	300 watts
Sensitivity	88.5 dB
Re	3.7 Ω
Vas	97.686 ltrs
Qms	9.627
Qes	0.517
Qts	0.491
Sd	0.0457 sqM
BL	12.075 TM
Cms	329.38 μM/N
Mms	136.92 gram
Le@1kHz	1.277 mH

Underhung voice coil geometry
Neodymium NRT magnet system
Polypropylene cone, inverted dust cap
X-max 15mm peak
Cast Frame with vented spider
Extra Long Stroke foam surround
Gold plated binding posts
Conex fiber spider
Large vented magnet system

Recommended Enclosures:

- 3 cubic feet vented, F3 25Hz (3" vent by 12" long)
- 2.7 cubic feet sealed, F3 35Hz

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air, that speed is approximately 1100′ per second. At 20Hz, the wavelength is about 55′, which is where a 14′ tube will resonate.

With a loudspeaker mounted at one end of the tube, essentially closing off that end, the mass and elasticity of the air in the tube will cause a favored frequency where the tube is one-quarter the wavelength. In *Fig. 2* you see that at this frequency the pressure and air motion are 90° out of phase with each other, so that high pressure develops at the closed end where motion is not favored, and high air motion occurs at the open end, where it can flow easily to the outside and no wall favors the buildup of air pressure.

This resonance is similar to that of the bass-reflex enclosure, and it has a similar effect. *Figure 3* shows the impedance of a woofer in free air and in a transmission line tube tuned to the resonant frequency. Like the bass-reflex, the transmission line damps out the

PHOTO 3: Reconfigured woofers.

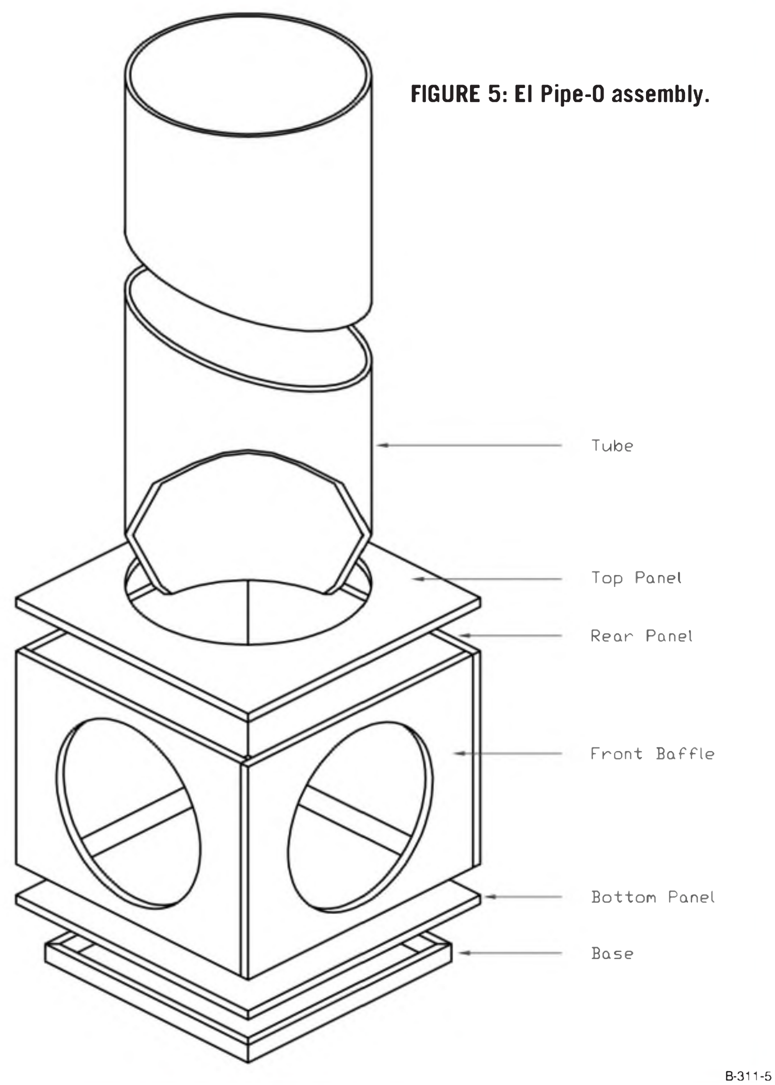

FIGURE 5: El Pipe-O assembly.

resonant motion of the cone, but with a lower "Q," or sharpness, so that you tend to get a single bump instead of the double bump of *Fig. 1*. Also like the bass-reflex, the output from the opening delivers more acoustic energy to the room, extending the response and power at the lowest frequencies.

We favor a well-done transmission line over a bass-reflex enclosure. The bass is tighter and less boomy. It also tends to extend deeper. Part of this effect comes from the actual lowering of the resonant frequency of the woofer due to the additional air mass it must push in the pipe.

You can adjust the "Q" or sharpness of both the bass-reflex and transmission line enclosures by stuffing them with wool, Dacron, or fiberglass. The more fibrous material you put in them, the more damped the effect. Resistive material of this sort also tends to increase the apparent volume of the enclosure for a bass-reflex and the length of the enclosure for a transmission line. Choice of the density of this material is often left to the discretion of the constructor, with the instructions, "Stuff to taste."

As with horns, the best transmission line is a straight one, with no bends. Bends compromise the effect, but often not so much that they still aren't useful. Quite a few transmission lines have been designed which have bends in them in order to fit them into a reasonable space. *Figure 4* shows a couple of examples. They work well, exhibiting only minor compromise.

Our favorite configuration is one in which the rear wave exits at the rear near the floor. In this case, the floor adds some acoustic loading for greater output, and the opening, pointed away from the listener, is at some distance from the front of the woofer. This approach minimizes interaction between the woofer's front and rear wave at higher frequencies and also effectively adds a little length to the line.

However, El Pipe-O is going to be a straight vertical tube, with the woofer(s) at the bottom and the open end of the pipe at the top. It is not going to fit in an 8′ high listening room.

ENTER THE SONOTUBE

Of course, we can build our transmission line any way we like out of wood, or those gigantic plastic storm drain type pipes, or even those monstrous concrete sewer pipes. Perhaps somewhere along the Alaskan pipeline is one happy audiophile, but we are going to do it the easy way—with Sonotubes.

Sonotubes are heavy-duty cardboard-type tubing used to cast concrete into pillars. They are available in a number of diameters and lengths, and are generally found in metropolitan areas. We usually buy them at White Cap stores, and we have played with 8″, 14″, and 24″ diameters. We get them in 12′ lengths, and the store will usually cut them to a desired length. If not, they are easy to cut with a saber saw. Oh yeah, and they are pretty cheap.

Because they are cylindrical, the tubes are very strong, like eggs, for pressure which is equal around the circumference of the tube, which is what they will experience in a transmission line. Also, the fiber material in the walls is dense and fairly dead acoustically, making them a good choice. For this project we bought a pair of 12′ long, 24″ diameter Sonotubes.

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THE WOOFERS

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Pass couldn't help himself and bought four of them. They sat around for a couple of years in boxes until we decided to make El Pipe-O. In fact, El Pipe-O was the excuse to use them up. They look to be copies of a large Focal woofer, but the manufacturing quality is not quite as high. If you buy these, we recommend that you test them right away for voice coil mis-alignment. You can do this by pumping a low-frequency signal into them while listening for scraping.

CONSTRUCTION

We decided to use two woofers per side to maximize the cone surface area and power handling of each speaker. We used MDF for the boxes so that the woofers were mounted on adjacent sides and the sonotubes were inserted from the top and supported on the floor of the box, with the sonotubes truncated at an angle that provided a good opening between the tube and the box.

Figures 5–10 provide details of the construction and dimensions of the boxes and cuts. The usual speaker construction techniques are appropriate, including the use of bracing and sealing materials.

Because of the size and weight of the speakers, final construction needs to be at the spot where they are to be used. We mounted the tubes and glued them in place at the box opening and on the box floor, and used silicone sealant around the juncture of box and tube. We also wired the woofers in parallel, to form 4Ω loads on each channel, and filled the box loosely with Dacron prior to mounting the woofers using lag bolts and string caulk.

Finally, we filled the tubes themselves with 20 lb of Dacron each. *Photos 1* and *2* show the finished speakers.

PERFORMANCE

Figure 11 shows the near-field response curve of the drivers without equalization or crossover filters, driven at 1W (2.83V). *Figure 12* shows the response curve of El Pipe-O at 1m away, where room effects can start to be observed. Both curves are calibrated so that zero equals a 100dB level.

Like many big woofers, the response curve extends out to higher frequencies irregularly and with questionable transient response. Also evident from the curves is the need for some equalization to make the woofer truly flat down to 20Hz. No problem . . . we will simply

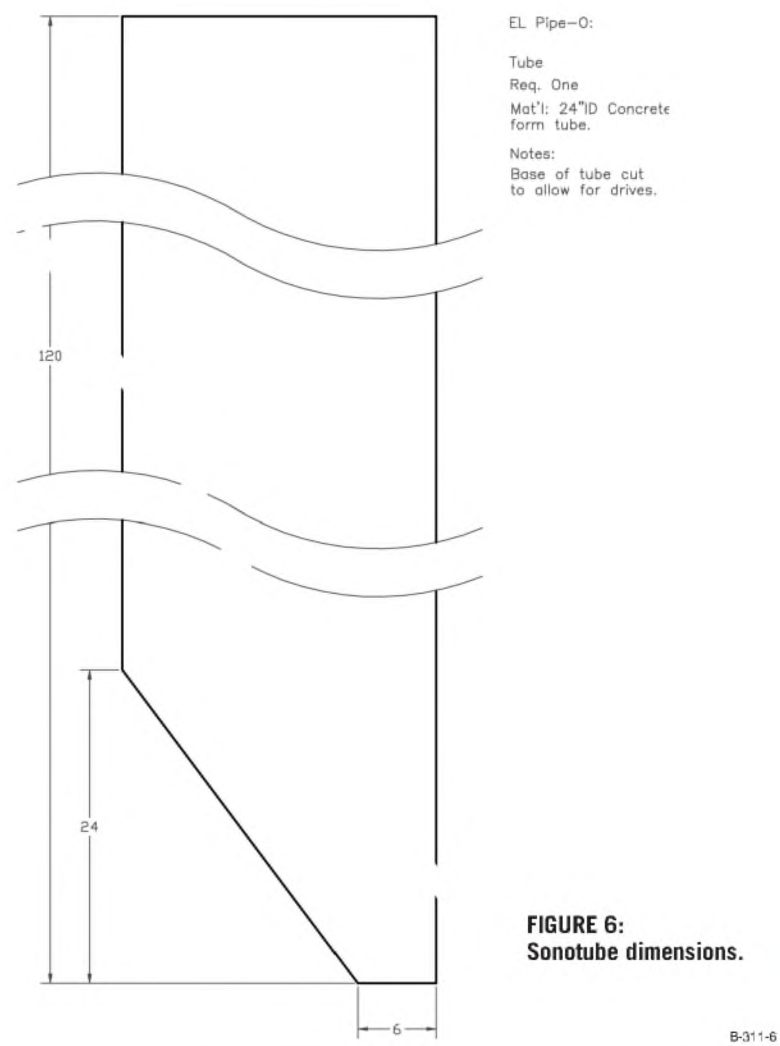

FIGURE 6: Sonotube dimensions.

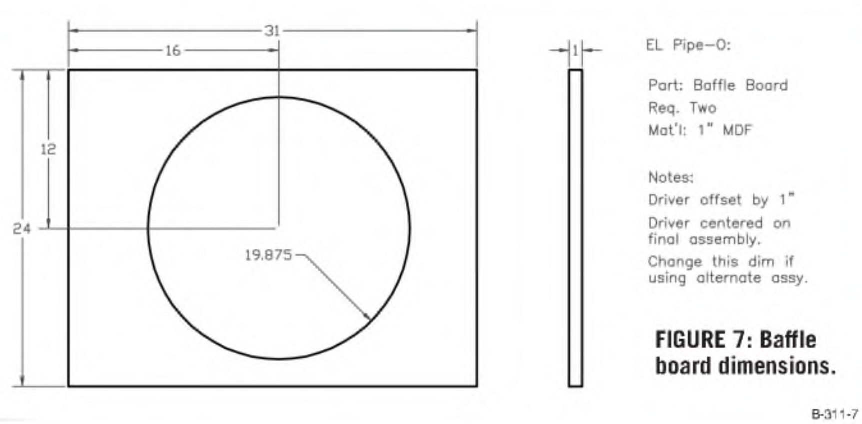

FIGURE 7: Baffle board dimensions.

make a crossover filter that accomplishes both requirements.

Using a Pass XVR1, we set up, measured, and listened to a wide variety of possible crossover filters—varying frequency, slope, and Q. Ultimately we settled on a two-pole, 22Hz low-pass filter as the best-sounding compromise. *Figure 13* shows the near-field response with no filter, one-pole low-pass (6dB/octave) at 22Hz, and the two-pole low-pass (12dB/octave) that we ended up using. *Figure 14* shows the response at 1m. Note that active filtering does not alter the sensitivity of the loudspeaker, which ranges from about 85 to 103dB/W.

Pass's listening room measures 30′ × 30′, with a 14′ ceiling at the center. The height of El Pipe-O at 12′ means that we were unable to play with corner placement, so we placed the speakers a few feet apart just behind where speakers would ordinarily be, allowing about 2′ space between the pipe openings and the ceiling.

The final result (bottom curve) measures about ±3dB in the room from about 13Hz to 75Hz, and it goes away rapidly enough at higher frequencies to avoid being obnoxious. We evaluated the performance in systems using the Fostex 204 "full range" speaker, the TAD1101 with a Raven R2 on the top, and (over time) a fairly wide sampling of conventional speakers, none of which had a particularly strong bottom end.

A very important consideration is the quality of transition from subwoofer to an ordinary woofer; the phase and amplitude of the mixed response must be smooth or it can sound pretty awful. If these aren't right, the bass can become very boomy from peaks or suffer frequency drop-outs that destroy the attack.

Fortunately, El Pipe-O "plays well with others," as long as there is not too much distance between the big woofers and the higher-frequency drivers. We found that placing the main speakers directly in front of the transmission lines worked best.

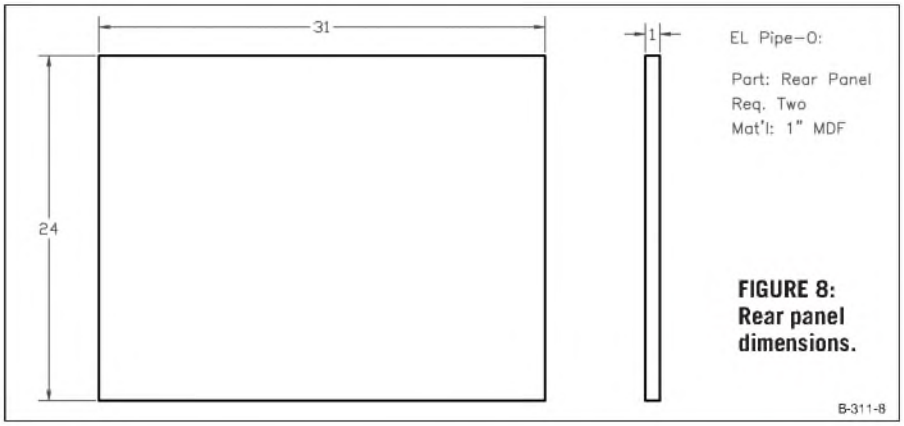

FIGURE 8: Rear panel dimensions.

ACTIVE CROSSOVER

Figure 15 shows an active op-amp-type circuit that delivers the crossover filter characteristic we used, which is a two-pole low-pass at 22Hz. The tolerances are not at all critical, and just about

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PHOTO 4: Closeup of single woofer on granite block.

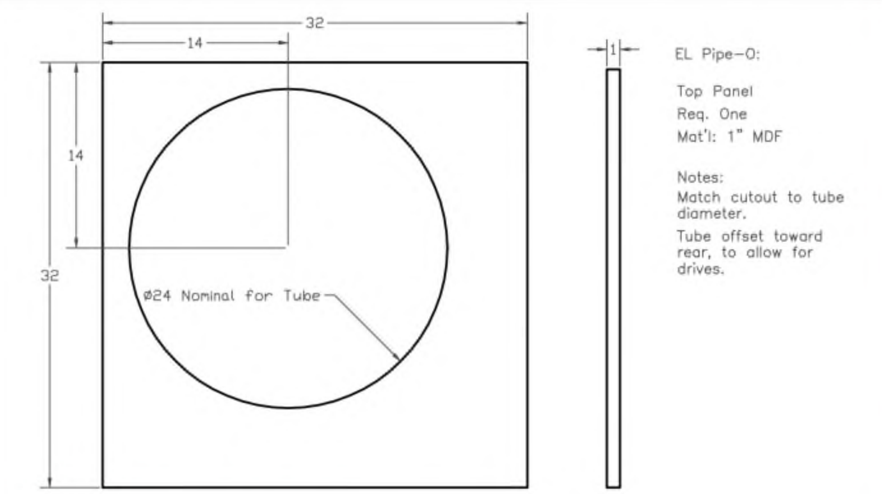

FIGURE 9: Top panel dimensions. B-311-9

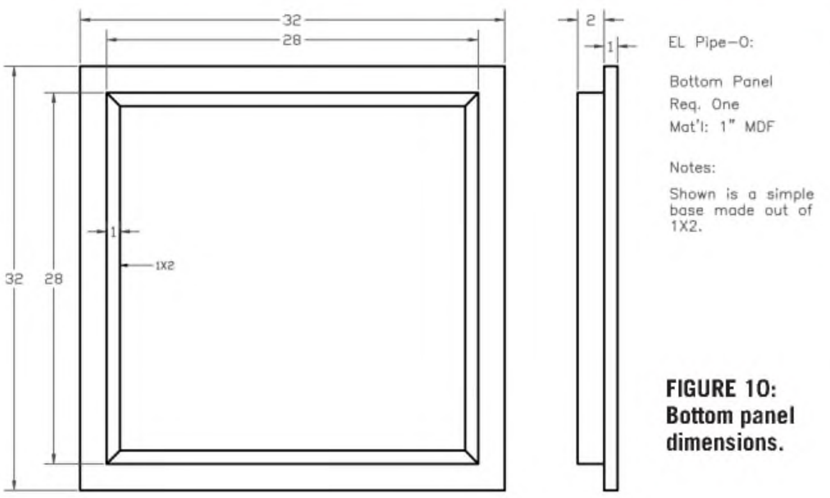

FIGURE 10: Bottom panel dimensions. B-311-10

any ordinary high-quality gain circuit will do.

PASSIVE ACTIVE CROSSOVER

Figure 16 shows a "passive" circuit designed to be placed at the output of the amplifier driving the main speakers which filters and attenuates that signal for feeding to the amplifier(s) driving El Pipe-O. As with the active filter, the tolerances and such are not particularly critical, but note that this circuit is not designed to be driven by an amplifier with balanced outputs, where both output connections are "live." It assumes the amplifier (–) connection is at ground, and also assumes that the

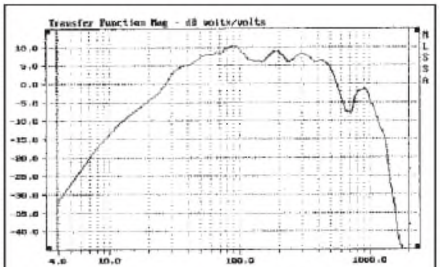

FIGURE 11: Response curve without equalization or crossover filters. B-311-11

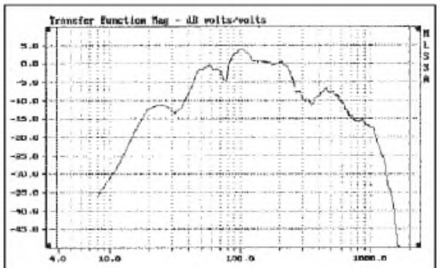

FIGURE 12: Response curve at 1m. B-311-12

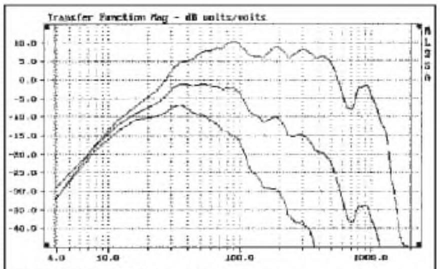

FIGURE 13: Near-field response. B-311-13

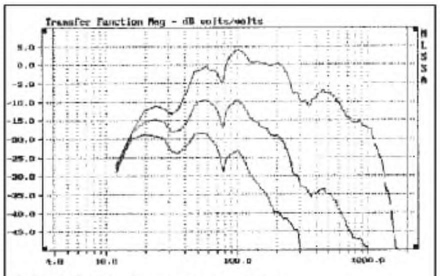

FIGURE 14: Response at 1m. B-311-14

ground of the driving amplifier and the ground of the bass amplifier are at similar potentials (which they usually are). If you wish to build just one El Pipe-O for both channels, you can give each of the two woofers its own crossover and amplifier, or you can mix inputs at the input of the crossover, giving each channel its own input resistor with twice the resistance value shown in *Fig. 16*.

THE SOUND

Well, of course this is the best part. First, you need to go through your record collection looking for material that goes down this low. A lot of nice-sounding music doesn't go below 40Hz or so, and if you listen to this material, you don't really get the impression that anything particularly special is happening.

This is good, because we didn't want the speaker to offer up a freak show of special effects where it's not wanted; we want neutral and seamless performance in the upper bass. No, we wanted the freak show to be down around 20Hz.

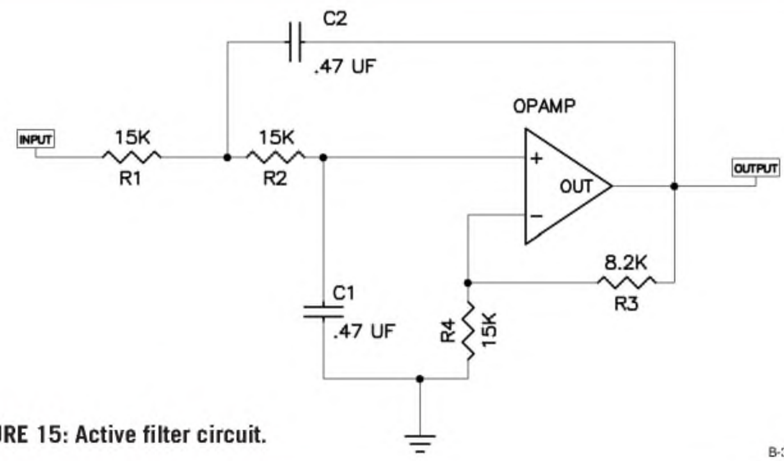

FIGURE 15: Active filter circuit.

Movie soundtracks are a good source of this sort of thing: *Jurassic Park* or *Dracula*. Pink Floyd's *Dark Side of the Moon*. You know what kind of records we're talking about.

Funny things happen when your speakers are flat to 13Hz. You need to be careful about your tonearm, your windows, your neighbors, and your bowels. After we got the system running, we spent a hour or so going around the room bolting down or otherwise re-arranging knick-knacks, shelving, furniture, and windows that began rattling. After that, we called up our friends and had a little party. And another.

THE PARTY INCIDENT

The first listening sessions were run with 100W amplifiers. Of course, the El Pipe-O calls for monster amplifiers, so we acquired Pass X1000s, which can do about 4,000W peak (per channel) into 4Ω. The occasion of firing these up called for another party, during which we drank a lot of Cabernet and then decided to test the power-handling claims of the woofer manufacturer.

These claims were fairly accurate at

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800W peak each, and at the end of this event we were down to two woofers.

RECONSTRUCTION

Rather than spend another $800 on woofers, we decided to try single woofers on each side, so we took apart the tubes and reconfigured them as 10′ tubes with a woofer at the bottom. We made a nice cylindrical coupler out of MDF to mate the woofer to the tube (*Fig. 17*) and set them on the woofer's magnet on blocks of granite (*Photos 3* and *4*). On top of the coupler, we placed some of the kind of plastic grid used in elevator lights to keep the Dacron from falling onto the woofer cones. The tubes were stuffed the same, and we used the same crossover filter.

Figure 18 shows the near-field output of the single woofer without the filters, which actually turned out a bit flatter than the twin driver models. The results of moving out into the room at 2m are shown in *Fig. 19*, and applying the filter in *Fig. 20*. Noting the differences between the twin- and single-woofer versions, you see that the single woofer gives flatter response at frequencies above 20Hz, but falls off more quickly below 20Hz. Nevertheless, it manages a respectable ±2dB from 20 to 80Hz.

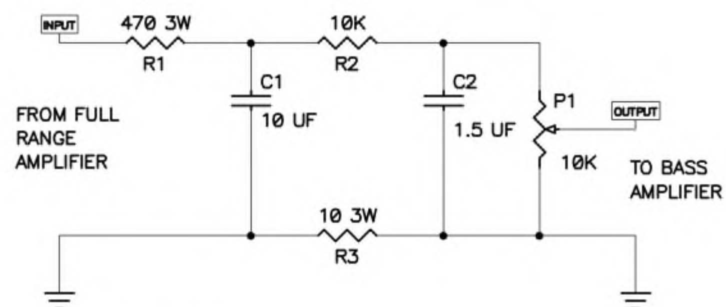

FIGURE 16: Passive filter circuit.

B-311-16

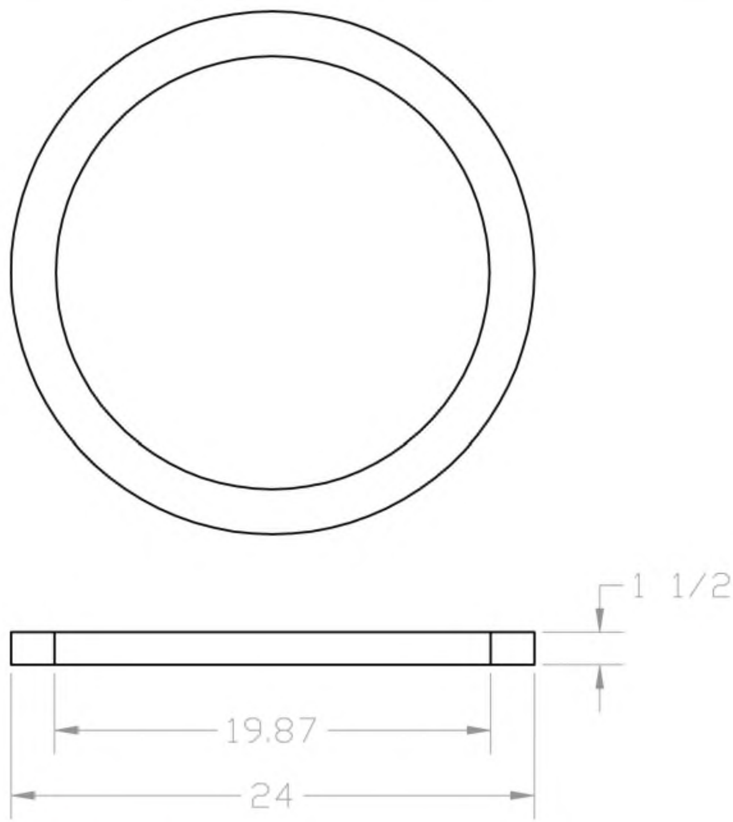

FIGURE 17: Cylindrical coupler.

B-311-17

The reconstructed version sounded about as good as the original, and probably gives a smoother transition to other speakers. It doesn't have quite the same power handling and doesn't go quite as low, but in our opinion, it ended up being a slightly more elegant result.

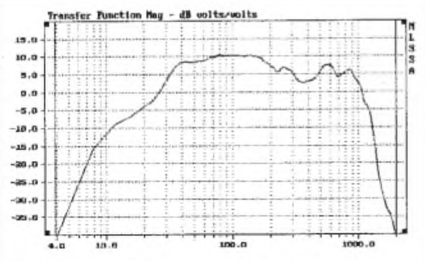

FIGURE 18: Single woofer near-field output. B-311-18

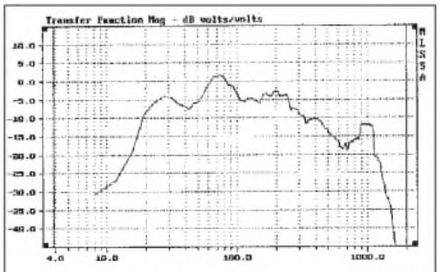

FIGURE 19: Response at 2m. B-311-19

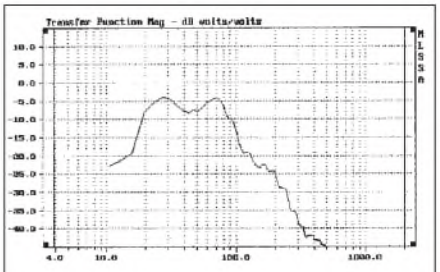

FIGURE 20: Response with filter. B-311-20

CONCLUSION

Except for the sheer scale of the endeavor, this was a remarkably easy proj-ect. Sonotubes make great transmission lines, and the vertical floor to ceiling approach is simple and effective. They might be tall, but the footprint is small, and maybe your spouse will let you keep them if you finish them properly. If you have an 8′ ceiling, you can make two out of a 12′ piece of 8″ diameter, and find yourself decent 8″ woofers resonant at about 40Hz. Then you can start having parties, too. ❖

Simple Satellites, Part 1

This pair of audio veterans presents their findings, as they set out to design a "simple" satellite system. **By G. R. Koonce and R. O. Wright, Jr.**

Since developing the infinite box (IB) subwoofer[1], we thought it useful to develop some simple companion satellites, requiring no crossover construction by the reader. Our goal was small satellites with a component cost limit of about $50 each; however, the costs of some selected drivers have since increased.

You could use two such satellites for a two-channel stereo system, or several for a 5.1-, 6.1-, or 7.1-channel multichannel system. The subwoofer covers the range 25 to over 100Hz. All we needed was a satellite that covered from about 100Hz to 20kHz!

Ideally, the satellites would be built with shielded drivers to allow use near a TV or monitor. Such a satellite might not fit the exact specifications for multichannel speakers, but could be used for that purpose. By the conclusion of this work, we had modified two of our satellite types so they were no longer simple or cheap, but their sonic performance warrants documenting the modifications. *Photo 1* shows the five small satellite types developed in this work.

BACKGROUND (BY R. O. WRIGHT, JR.)

The genesis of this article dates to the early 1980s, when I attended the Consumer Electronics Show in Chicago and saw a full-range speaker (approximately 100Hz to 20kHz is considered full-range by most commercial OEMs) manufactured by one of Japan's leading electrical firms for the car industry. It was an unusual flat planar design, and later I discovered that it never made it into final production.

With the turn of the century, I began another technical odyssey, which in its final form would bring me full circle and inspire us to document the Infinite Box (IB) design concept. Since the late 1970s, I had used Owens-Corning's 700 Series sound damping material in speaker enclosures, but I had never seen it in any merchandised speakers—only in the prosound speakers, and not much of it there. This led me to ship GRK a package of the sound damping material to experiment with. GRK found it to be a most interesting material, so much so, that we generated a research article on IB box design, which appeared in *audioXpress*[2].

When we analyzed the data for the IB box design, we found the box size was somewhat independent of the speaker parameters. This led to an article[1] on a simple, compact, and inexpensive subwoofer that would generate sound below 100Hz.

SATELLITE DRIVER(S)

To meet the criteria of a simple basic IB satellite design, we adopted a full-range speaker concept. This was the impetus for me to resume my search for a full-range driver. Those of you intrigued by the concept of a single full-range speaker and who have access to the Internet should try the "Single Speaker Website" (melhuish.org/audio/index.htm.). This is an extensive website dealing with full-range speakers.

The full-range speaker design configuration has many technical advantages:

- component simplicity
- no problems with a crossover design and the component assembly
- only one box design

These are only a few of the major physical and technical advantages this type of design offers. My original search for a full-range driver began in the middle to late 1980s and yielded only very expensive esoteric drivers

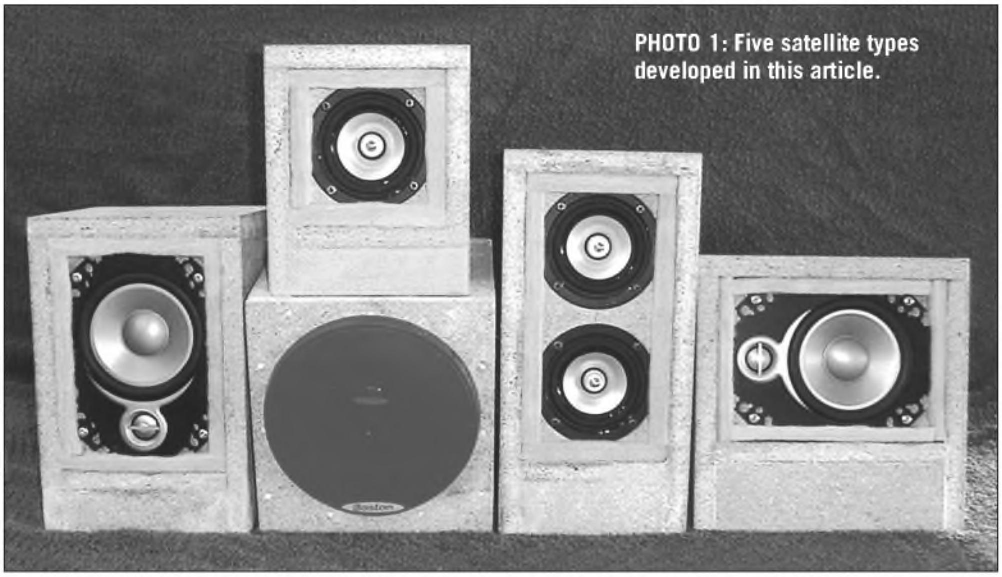

PHOTO 1: Five satellite types developed in this article.

that were not very practical for a normal design or pocketbook.

The modern-day search turned out to be an involved worldwide search spanning many months and did yield success. Over a period of months, GRK received a number of drivers to test to see whether they would meet our requirements (about 100Hz to 20kHz). In the end we chose only the best to turn into projects for this article.

DEFINITION OF SPEAKER

For the purposes of this article, we define a speaker as being composed of two components: the driver(s) and the enclosure/box, which is the mounting for the drivers. When combined, these two components form a complete speaker.

DRIVER CLASSIFICATION AND AUDIO CHARACTERISTICS

Basic moving-coil diaphragm drivers are designed in two general types. The first is a plain driver having a cone, or cone modified with a whizzer, a basket, and a motor mechanism. A whizzer is a small freestanding cone mounted to the existing voice-coil former and is used to extend the frequency range of the driver. Tweeters are a variation or special design of the basic driver. In a tweeter the diaphragm and the voice coil are made together. This produces a small, light assembly that can operate efficiently in the high-frequency range.

The second type is a compound driver, which consists of two or more plain drivers made as a single homogeneous unit with a built-in crossover. In smaller sizes, these drivers are mainly made for the automotive market and are classified as coaxial drivers or plate drivers, depending on their design. The drivers tested for this article were all two-way, and our discussion and definitions center only on these, although there are three-way and sometimes four-way compound drivers available.

The automotive coaxial drivers have the tweeter mounted in front of the low-frequency driver on the same axis. The plate drivers have a tweeter and the low-frequency driver mounted in a side-by-side configuration using one single mounting frame or plate.

In testing these, we noted some general patterns about their frequency response. Most truly full-range plain drivers had small cones, 3″ to 4″ or less. The frequency response of these ranged from excellent to only acceptable, depending on the design. The larger full-range drivers used whizzers to extend their frequency range. The ones we tested always had very rough high-frequency phase and magnitude responses.

The compound drivers tested generally gave a reasonably smooth bass response and sometimes a smooth midrange response. Many of the car coaxes had midrange anomalies due to a poor transition from woofer to tweeter using the very simple crossover. The high frequencies seemed to be a little exaggerated (often referred to as "hot" on the top end), which is to be expected in a car driver.

Cars have a great deal of sound damping material built into the passenger compartment, which absorbs the high frequencies. They are almost always listened to in an off-axis configuration, and making the high frequencies a little exaggerated will even-out the total listener response. Even in home applications it is not uncommon to listen to speakers in an off-axis mode.

Most of the coaxial drivers had rough high-frequency responses. The power cepstrum plots for the car coaxes also showed them full of echoes due to the tweeter structure mounted out in front of the woofer. Thus they might not sound as clean as other configurations. The only plate driver tested was the best of all the compound drivers. It gave a passable response in its original form.

MULTICHANNEL SYSTEMS

The two de facto standards in the multichannel systems are the present-day two-channel stereo, whose standards are well known, and the surround sound format by Dolby Laboratories, Inc. Dolby has three different standards in today's marketplace—5.1-, 6.1-, and 7.1-channel. We were able to obtain basic information on the three systems from the data on the 5.1-channel system[3], but the complete technical specifications were unavailable at the time of writing. All three are defined by using specification numbers as a key to the format.

In the 5.1-channel specification the

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MOUSER ELECTRONICS

"5" denotes five discrete independent channels: a front center, front left, front right, surround left, and surround right speakers. The surround channels drive the two side speakers. In addition, a low-frequency effects (LFE) channel denoted by the ".1" drives one or more subwoofers. The bass from the other channels, which may have bass-limited speakers, can normally be redirected to the LFE channel.

It is recommended that the center speaker be full-range while limiting the surround channels' bandwidth to 100Hz to 7kHz. Most applications won't permit a full-range center speaker, so bass management is provided, limiting the center channel to above 100Hz when needed.

Generally, commercial equipment limits the bandwidth fed to all channels. The LFE will get only low-frequency information (120Hz maximum) and the other channels only the higher frequencies. Lower-priced equipment may use a fixed frequency to separate the channels; however, much equipment offers a selectable frequency of 80, 100, or 120Hz. This information indicates that satellites that cover 100Hz up are applicable to a 5.1-channel system.

CROSSOVERS

Crossovers come in a vast variety of delineations and formats. Our market research showed that most available audio system crossovers (in contrast to mostly passive types built into speaker enclosures) are second- and third-order, with fourth-order being the top end of the range. The active crossovers were far more prevalent than the passive types in audio system designs. The automotive industry has pioneered the second-, third-, and fourth-order compact integrated low-frequency crossover amplifiers, which you could use for this application.

After considering our technical needs for finite control of volume to equalize the speaker SPLs and distinct separation of the bass from the treble so as not to over-drive the satellite speakers, we chose an AC powered active fourth-order (24dB per octave) crossover discussed later in this article.

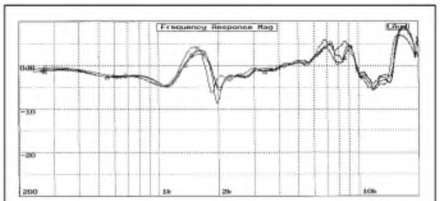
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FIGURE 1: Measured responses of four Infinity 462.5CFP compound drivers.

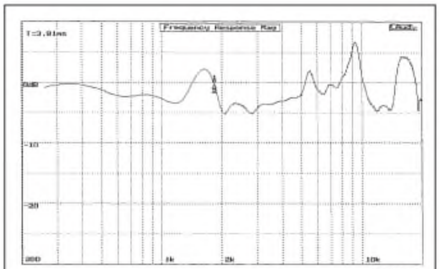
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FIGURE 2: Response of Infinity 462.5CFP at 20° off-axis toward woofer.

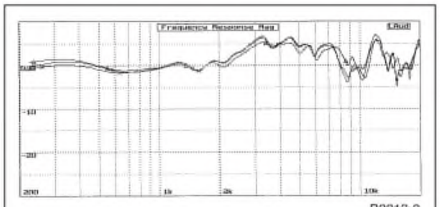
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FIGURE 3: Effects of grille structure on Boston Acoustics FX5 coax.

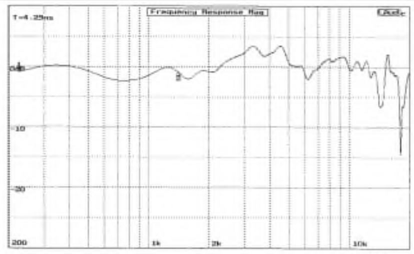
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FIGURE 4: Response of FX5 at 20° off-axis toward crossover capacitor.

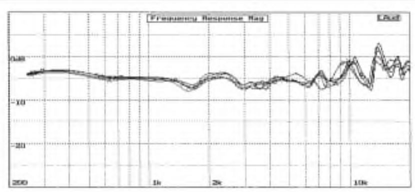
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FIGURE 5: Measured responses of five TBspeakers W3-871s drivers.

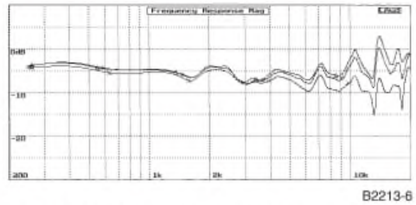
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FIGURE 6: Measured directivity of TBspeakers W3-871s drivers.

BOXES

We preferred to keep the satellites small while using the IB approach to continue learning about this technique. These boxes were not assured of performance down to 100Hz via the IB design rules[2]; that would have made the boxes too big. We simply built them at a minimum practical size, and we would take what frequency response they offered.

It is doubtful that the IB approach offers a big advantage for systems doing 100Hz up. Thus you might try the selected drivers in other box types. You could build closed boxes from the designs shown by omitting the damping layers and making the back solid. It would be good to retain the damping panel, which forms a perimeter stiffener for the box walls. You could partially fill the boxes with your favorite damping material. Unless you can definitely keep all low-frequency content out of the satellite, we do not recommend a vented box with these small drivers.

DIFFRACTION SPREADING LOSS

The concept of diffraction spreading loss (DSL) is covered in references 2, 4, and 5. It basically refers to the fact that a driver will produce a different on-axis response in a small freestanding box than it does mounted in a wall. This can result in subwoofer/satellite systems that sound weak just above the subwoofer's upper limit.

With very small satellites this "weakness" can extend up to almost 1kHz. The result is a system that has the bass and highs, but sounds "hollow" because the midrange is partially missing. Many subwoofer/satellite systems, unfortunately, produce such sound.

The cure for small enclosures is DSL compensation (discussed towards the end of the article). For enclosures out in the room on stands, compensation for the full theoretical 6dB DSL is recommended. Our experience with large floor-standing enclosures with low

TABLE 1
CATALOG INFORMATION ON INFINITY 462.5CFP DRIVER

Impedance: 4Ω
Power handling: 60W RMS, 180W peak
Frequency response: 75Hz–21kHz
Sensitivity: 90dB/2.83V/m (Equivalent to about 87dB/W/m)
Shielded: No

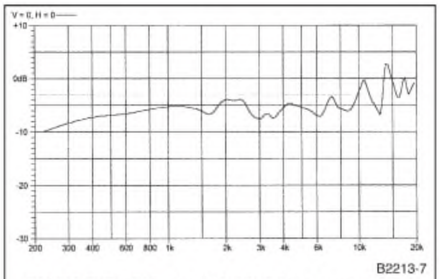

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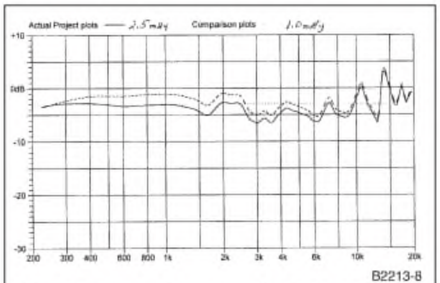
FIGURE 7: Effect of 6dB DSL on single W3-871s driver in 5⅝″ wide box.



B2213-8

FIGURE 8: Response of dual W3-871s drivers giving 6dB DSL compensation.

mounted woofers is that 3–4dB DSL compensation can provide a well-balanced sound. We hoped to learn the proper DSL compensation for small floor-standing satellites.

SELECTED DRIVERS

One driver of choice is the Infinity Kappa 462.5CFP 4 × 6″ plate compound driver (*Table 1*). *Figure 1* shows the measured responses for four of these units. The response is not too smooth or flat, but note the droop from about 200Hz to 1kHz. This would offer some DSL compensation for a small box. The best axis for listening with this unit is about 20° off the tweeter centerline toward the woofer (*Fig. 2*).

We developed two enclosures using this compound driver that attempt to place the listener on the desired axis. The first approach (boxes #1 and #2) has the woofer and tweeter mounted side-by-side. This configuration, as developed in reference 6, places the listener on the proper axis by using mirror-imaged pairs with the tweeter always outboard. With the boxes facing straight out, the normal configuration for stereo listening places the listener on the desired axis.

Getting the desired listening angle with the conventional tweeter-above-woofer layout would require an unrealistic tipping of the front panel. Thus we placed the woofer above the tweeter for

TABLE 2
CATALOG INFORMATION ON BOSTON ACOUSTICS FX5 DRIVER

Impedance: 4Ω
Power handling: recommended amplifier is 12 to 100W
Frequency response: 60Hz–20kHz
Sensitivity: 90dB/W/m
Shielded: No

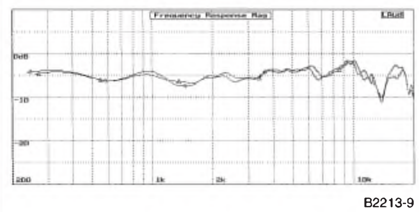


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FIGURE 9: On-axis responses for two W3-881s drivers.

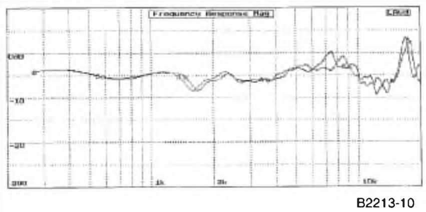

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FIGURE 10: On-axis responses for two W3-879s drivers.

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the other set of enclosures (boxes #3 and #4). This approach has worked well in the past.

A CAR COAX

The best car coax in our testing was the Boston Acoustics FX5 unit (*Table 2*). *Figure 3* shows the on-axis response for one FX5 unit with and without the grille structure supplied with the driver. Typical of the car coaxes, the tweeter level is too high relative to the woofer. Less typical is the fact that the grille and its mounting frame do not make a major response change.

The better-designed car coaxes had grille structures causing little adverse effect. On the FX5, the structure used to mount the tweeter gives a directivity that varies with which direction you move off-axis. The best angle for listening was about 20° off-axis toward the side where the tweeter's crossover capacitor is mounted (*Fig. 4*).

A reason for building with the FX5 unit was the simplicity of the enclosure. You just mount the FX5 on the front of a box and use the supplied grille and frame. The enclosure has a vertical front panel to get the desired listening axis, and the driver is mounted inverted with the crossover capacitor at the top (boxes #5 and #6). We wished to see whether such a simple satellite would be acceptable. Readers can try the same approach with other car coaxes they may have on hand.

A 3″ FULL-RANGE DRIVER

The final driver selected was the TBspeakers W3-871s shielded nominal 3″ driver available from NUERA Acoustic Technologies (*Table 3*). TBspeakers is the name used in North America for drivers made by Tang Band Speakers. Since completion of this work, we have identified Creative Sound Solutions and RAW Acoustics as alternate sources for this driver. This was the only single-cone, full-range driver that we originally located useful down to near 100Hz.

Good consistency is shown in the measured responses for five units (*Fig. 5*). This driver holds up well to 20° off-axis (*Fig. 6*). You need to listen to this driver nearly on-axis.

The small enclosures (boxes #7 and #8) developed for this driver indicated a potential DSL problem. The modeled on-axis response (*Fig. 7*) for this driver in a 5⅝″ wide box out in the room is suppressed all the way up to about 1kHz. Thus we developed a second enclosure (boxes #9 and #10) using two vertically aligned drivers per box. The top driver is used full-range, while the bottom driver is used only for DSL compensation. This

TABLE 3
CATALOG INFORMATION ON TBSPEAKERS W3-871S DRIVERS

Impedance: 8Ω
Power handling: 15W rated, 30W maximum
Frequency response: 110Hz–20kHz
Sensitivity: 87dB/W/m
Shielded: Yes

TABLE 4
BASIC DIMENSIONS OF ALL SATELLITES

BOXES	DRIVER(S)	FRONT HEIGHT	WIDTH	SIDE DEPTH	TIP ANGLE	APPROX. DEAD AIR VOLUME
#1&2	462.5CFP	8.4	8.3	6.0	19	66.7
#3&4	462.5CFP	9.55	6.3	6.0	10	66.7
#5&6	FX5 coax	7.35	7.0	7.3*	0	93.9
#7&8	W3-871s	7.0	5.63	6.4	10	43.2
#9&10	(2)W3-871s	11.4	5.63	6.4	12	82.4

Notes:
Linear dimensions in inches.
Front height is along front of box, not height when tipped.
Side depth is along side of box, not depth when tipped.
Tip angle is degrees front panel is tipped back.
Dead air volume is box volume between front panel and start of the damping layers in cubic inches.
*Depth for boxes #5 and #6 includes driver and grille sticking out in front of the box.

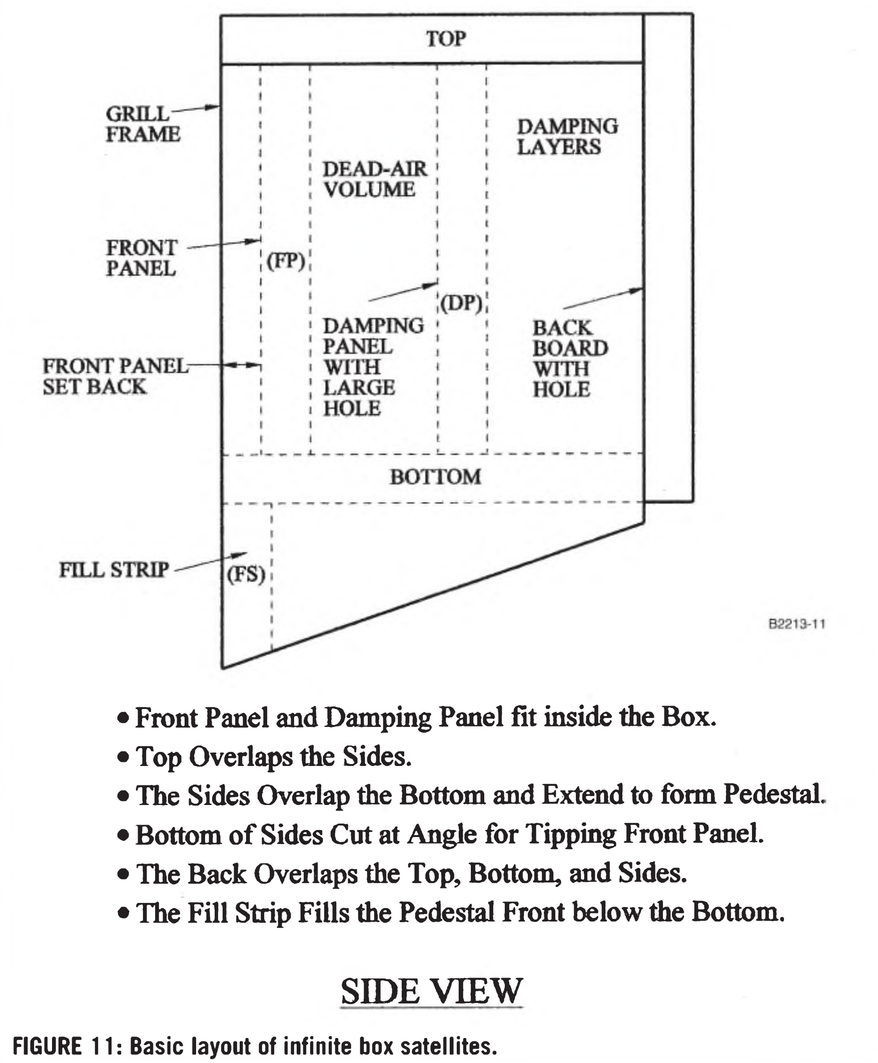

FIGURE 11: Basic layout of infinite box satellites.

violates our goal of no reader-built crossover, but it is simply a single coil.

The modeled on-axis response (*Fig. 8*) for the two-driver system with coils of 1.0 and 2.5mH shows the coil inductance is not critical. We thought the DSL compensation thus offered was worth the trouble of a second driver and single coil, because it stayed within our cost range.

A potential problem with these 3″ full-range drivers was their ability to play loudly enough. They are rated at 15W input with a power sensitivity of 87dB/W/m (*Table 3*). Its main advantage is being fully shielded.

With the single-driver satellite you have a system with no crossover above 100Hz. The dual-driver satellite has two of the same driver type producing the midrange slowly fading to a single driver for the high frequency portion. We designed both enclosure types using this driver to place the seated listener near on-axis with the driver producing the high frequencies.

ALTERNATE DRIVERS

Since completing the satellite construction, we discovered that Parts Express now offers some of the drivers sold by TBspeakers. They do not offer the W3-871s unit that we used, but do offer some other promising nominal 3″ units. We tested two of these types as possible alternatives. Factory response plots and other test results are available on the Parts Express website.

Figure 9 shows the measured response of two samples of the TBspeakers W3-881s shielded driver (Parts Express #264-812). This unit does not look as good to us as the W3-871s, but is surely a usable alternate. This driver will mount in the same hole as the W3-871s with a bit of filing and relocating the mounting screw holes. We performed no listening tests with this driver type.

Figure 10 shows the measured response of two samples of the TBspeakers W3-879s shielded driver (Parts Ex-

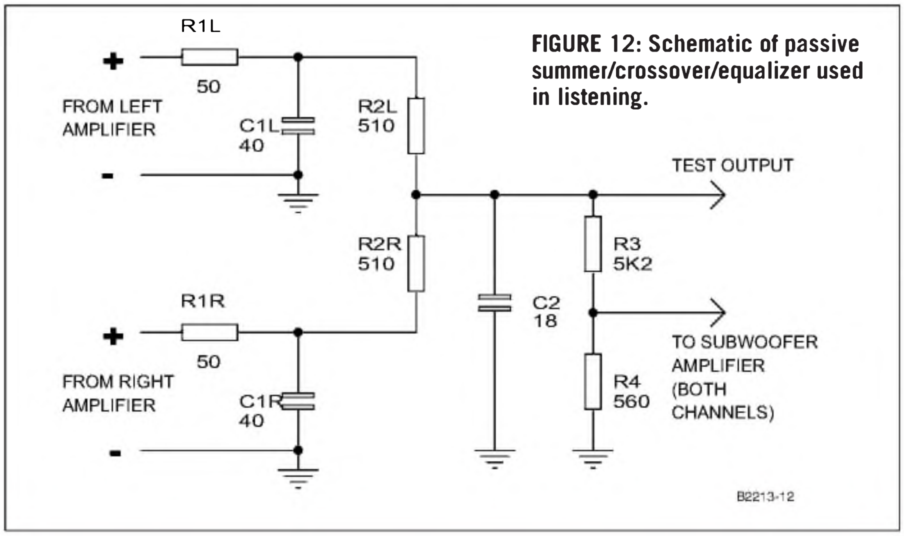

FIGURE 12: Schematic of passive summer/crossover/equalizer used in listening.

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press #264-810). These curves show a much larger dip in the 9 to 16kHz range than shown in the factory curve, and we doubt these units would sound as good as the W3-871s units. This driver mounts in the same hole as the W3-871s. Again, we did no listening tests with this driver type.

BASIC CONSTRUCTION

Table 4 shows basic dimensions of all the satellites as constructed from ⅝″ particleboard. For all boxes, except those for the car coax, the front panel is recessed to provide a frame for the grille cloth (*Fig. 11*). A vertical damping panel with its center cut out is mounted near mid-depth. This panel forms a perimeter stiffener on the box walls while retaining the forward side of the Owens-Corning #705 damping-material layers. The back board slightly compresses the damping layers and contains a hole about 120% of the driver cone area.

Owens-Corning offers a family of materials called the 700 Series Insulation. This series has rigid and semi-rigid fiberglass-based materials of a variety of densities, which are available in a variety of thicknesses and come unfaced or faced with various plastic materials. All these IBs use a nominal 2″ thickness of the #705 material, which we refer to as OC #705 damping material and has a density of about 5–6 lb per cubic foot. You could use one layer of nominal 2″ material, or two layers of nominal 1″ material as we did. If the material you have is "faced," peel it off.

At this time we do not know of a direct equivalent to the OC #705 damping material. For these satellites, operating from 100Hz up, you should feel free to experiment with other high-density fiberglass-based tangled-fibrous materials that you find available locally.

To minimize box size, we simply screwed the back on to the top, bottom, and sides of the box. Since particleboard has little holding power for screws driven into the edge, we glued ¼″ dowels into the box pieces to take the screws. Building a removable back that will cap the rear of the box and fit accurately is a problem. We cut the back about ⅛″ oversize in both dimensions so that after installation we could rout it to size with a flush-cutting bit. This makes extra work, but yields a small box that looks good.

Our plan for finishing the boxes was to apply stick-on vinyl, then staple on the front grille cloth, and finally put a thin frame around the grille edges. See details on finishing boxes using this construction in reference 7. You should feel free to use your favorite finishing method.

We built the boxes for the FX5 car coax drivers with the front panel capping the front of the box. This fit the same way as the back board: made oversize and then cut flush with a router. These boxes use the grilles and frames that come shipped with the drivers.

Most of the boxes required that the front panel be tipped at an angle. We accomplished this by extending the box sides past the bottom board and cutting them at the desired angle, thus tipping the entire box. All these boxes are rectangular internally.

For use on stands, you can cut this bottom "pedestal" such that the box stands vertical with perhaps another board added at the pedestal bottom. Note that even vertical-standing boxes need a short pedestal to accommodate the driver wire. With an IB you can't easily run the wire out the back of the box. The bottom pedestals of boxes #9 and #10, for the dual 3″ drivers, were extra high to mount the single crossover coil in this location.

Keep the following in mind when building small satellite boxes:

1) When you place a small driver in a front panel that is ⅝″ thick, you will "strangle" it by restricting the flow of air to the rear of the cone. The front panel must be relieved by router or by hand in the areas between the driver struts connecting the frame's front rim to the magnet structure. This is especially true of drivers intended for automotive application where they would normally mount in a thin metal panel.
2) You must accurately cut the various pieces to construct small boxes; you will not be able to hide 1⁄16″ errors. The designs shown minimize cutting error problems.
3) In some cases you must flush-mount the driver to assure the proper response.
4) Some front panel treatment is necessary to limit high-frequency edge diffraction problems at the grille frame.

LISTENING TESTS (BY G. R. KOONCE)

I performed all listening tests in my

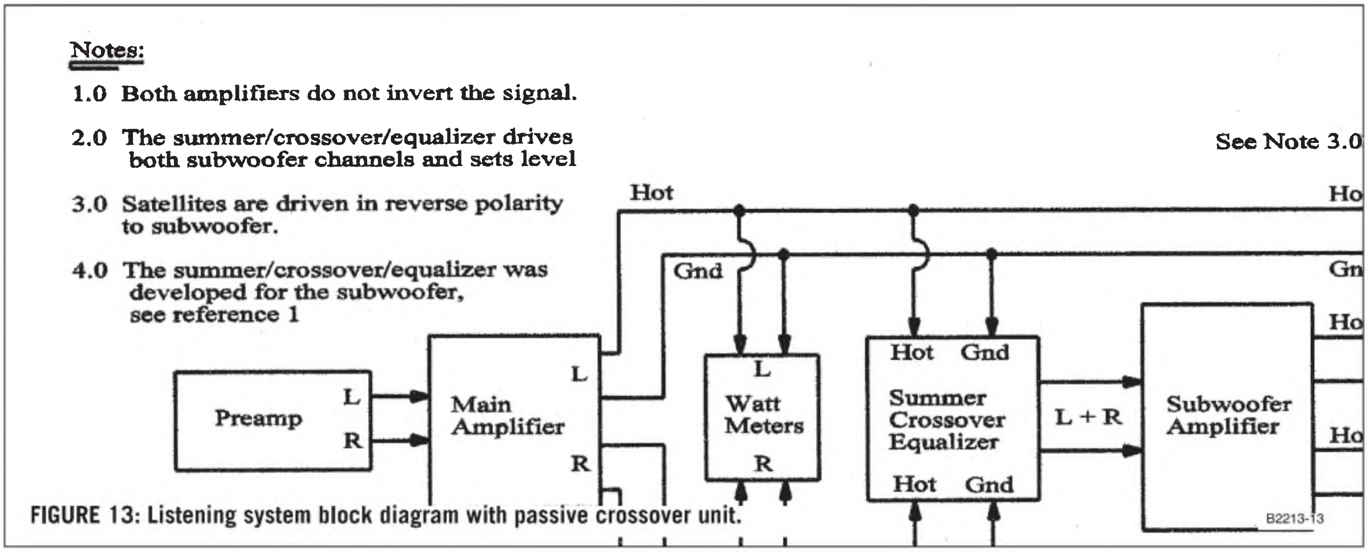


FIGURE 13: Listening system block diagram with passive crossover unit.

garage using the 12″ IB subwoofer developed in reference 1, for a two-channel stereo system with the subwoofer in the center and the satellites to each side. All speakers were on the floor and away from all walls. I used standard music CDs and SACDs, but no movie soundtracks or other special recordings.

PASSIVE SUBWOOFER CROSSOVER

The first listening tests included the passive summer/crossover/equalizer previously developed for the subwoofer (*Fig. 12*). This approach feeds the full bandwidth signals to the satellites (*Fig. 13*). These signals are then summed and filtered to provide a second-order low-pass and then fed to the subwoofer amplifier.

This approach requires that the main amplifier driving the satellites have both speaker returns tied to amplifier ground (see reference 1 for other requirements). The advantage of this approach is its simplicity. The disadvantage is that the satellites see the bass frequencies, which limits their ability to play loudly.

I tried all five-satellite pairs with this configuration. Warble tone sweeps verified that all satellites required connection with reverse polarity to integrate properly with the subwoofer. Both amplifiers I used in this testing do not invert the signal.

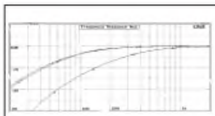
It was quickly evident that this approach severely limited the playing level, as the tiny cones in all the satellites were dancing around badly. The boxes with the Infinity plate drivers (#1–#4) could play at a reasonable level, as could the FX5 car coaxes (#5 and #6). The boxes using the 3″ full-range speakers (#7–#10) were limited pretty much to background playing levels via this approach.

The conclusions about each satellite type with this configuration are the same as for later testing using actual crossovers. The basic conclusion is that this simple approach is useful only for playing background level music with small satellite boxes.

SECOND-ORDER CROSSOVER PROBLEMS

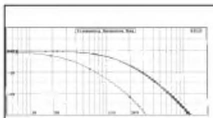
The plan next called for testing the satellites with second-order crossovers, first active and then passive units. All did not go well. Reconfigured with two active second-order monaural crossovers, the system was working as intended. Suddenly all sorts of bad sounds emerged from the speakers requiring immediate system shutdown. Fortunately, no speakers were harmed.

The basic system using only the main amplifier was determined to play



B2213-14

FIGURE 14: Response of FMOD high-pass crossovers.



B2213-15

FIGURE 15: Response of FMOD low-pass crossovers.

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just fine, and the subwoofer amplifier and electronic crossovers tested on the bench could not be made to act up. However, I was reluctant to try these crossovers again and decided to use the fourth-order crossover, which proved to be so "right" that I never returned to the second-order types.

Unfortunately, these active crossovers were needed to supply gain controls for listening with the passive second-order crossovers. I had purchased (from Parts Express) some of the small Harrison FMOD passive crossover units, which come as pairs for the left and right channels and plug into the amplifier input, and then the normal input wire plugs into them. They are available as second-order high-pass (HP) or low-pass (LP) units at a variety of frequencies. Because I was not going to be able to listen to these units, I decided to test them to see whether they did as claimed when "plugged into any amplifier."

I had purchased a pair of LP (Parts Express #266-254) and HP (Parts Express #266-274) units at 100Hz, so I could test the individual units as second-order crossovers or cascade the pair (plug one into the other) and test them as fourth-order crossovers. I had been told that these units could be "stacked" this way.

I tested the FMOD crossovers using Liberty Instrument's Audiosuite. Thus they were driven by a low impedance source and loaded by about 50kΩ, typical of the input impedance range for amplifiers. *Figure 14* shows performance of the HP units.

Individually, the units produce the anticipated response. The two units cascaded do not produce a fourth-order response and the level is about 13dB down at 100Hz. It is clear the HP units should not be used cascaded.

The LP units also show a reasonable response (*Fig. 15*) used alone into about 50kΩ. Note there is some low-frequency loss, slightly less than a dB. Again, cascading two of the units to attempt a fourth-order crossover does not work, as the response shows more low-frequency loss and is down about 13dB at 100Hz. Clearly, you should not directly cascade the FMOD units in an attempt to make a fourth-order crossover. Such cascading would be practical if you placed a buffer amplifier between the FMOD crossover units.

I then tested the individual crossover units with an additional 10kΩ load; the total load now being about 8.3kΩ. The HP test result (*Fig. 16*) shows the –3dB point has moved to about 162Hz and the response is down 5.7dB at 100Hz. The LP response (*Fig. 17*) shows a low-frequency loss of about 2.8dB and is only down by an additional 1.85dB at 100Hz. Clearly, you should use the FMOD units only when the input impedance of the amplifier they drive is about 50kΩ or above.

One problem with these passive crossovers is their expense. If you plan to try several frequencies, the cost could exceed that of buying a variable-frequency electronic crossover. However, they are handy for testing or where space is limited.

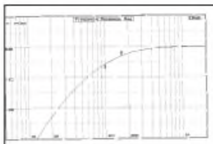

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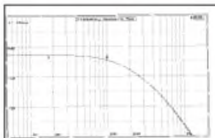
FIGURE 16: Effect of loading on FMOD high-pass crossover.



B2213-17

FIGURE 17: Effect of loading on FMOD low-pass crossover.

FOURTH-ORDER CROSSOVER

I next configured the system with an active fourth-order crossover (*Fig. 18*), an Applied Research and Technology Model #310 unit (available from Parts Express). This crossover can be used as either a single channel three-way or a stereo two-way crossover with adjustable crossover frequencies. It has gain controls for all outputs along with the ability to mute any individual output. This unit has balanced XLR jacks along with single-ended ¼″ mono phone jacks for all inputs and outputs.

I used the single-ended inputs/outputs with the Radio Shack phone plug to RCA phono jack adapters (#274-320 or #274-884). Be a bit careful with these adapters, because I found the shell contact for the ground was undersized, so I had to squeeze the phono plug shells with pliers to assure a solid ground connection.

This crossover worked well and con-

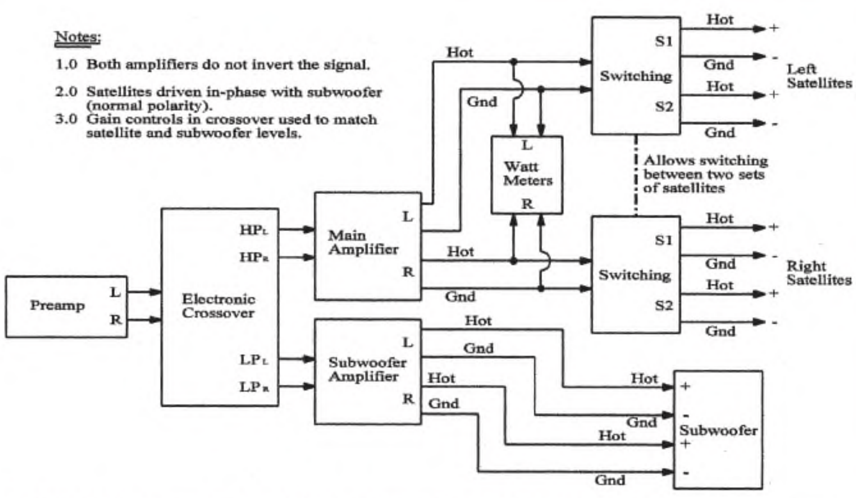
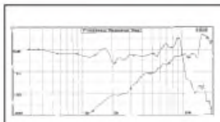


FIGURE 18: Listening system block diagram with active crossover. B2213-18



B2213-19

FIGURE 19: Individual driver with crossover responses for Infinity driver.

vinced me that a fourth-order crossover is the way to go when using small satellites in a two-channel system. A higher-order crossover would probably also be fine, but the fourth-order offers outputs that are in-phase at the crossover point. With a multichannel system, the receiver/amplifier should provide the needed crossover functions if you make sure to set it so all the satellites are fed a restricted frequency range. One of the labeled frequency points on the ART #310 crossover's scale was 110Hz, so we used it throughout the testing. In all cases using this crossover, the satellites were driven with the same polarity as the subwoofer.

Note in *Fig. 18* that the wattmeters monitor only the power to the satellites. Also, the system has switching between two pairs of satellites without changing the input to the subwoofer. This allowed direct comparison of two satellite pairs while playing music. With this crossover, the satellites could play at a much higher level, because they were not receiving low-frequency signals.

After many years of working with speakers, I was a bit shocked to hear drums pounding away while I lifted the satellite grille cloth to see the cones barely moving. Loud music was possible with less than 10W into the satellites.

INFINITY PLATE COMPOUND DRIVERS

By the conclusion of this work we had modified the Infinity compound drivers used in boxes #1–#4. The listening results in this section pertain to using the drivers as purchased; results with the optional modifications are covered later.

Boxes #1 and #2 use these compound drivers in a side-by-side configuration, while boxes #3 and #4 use them in a woofer-over-tweeter configuration. In comparisons, boxes #3 and #4 won on all points. The side-by-side configuration had shown a very wide sweet spot in past incarnations, but here seemed no better than boxes #3 and #4. From here on, discussion pertains only to boxes #3 and #4.

These boxes produce a very high presence sound, but are not "in-your-face," because the image is from the plane of the boxes rearward. They will play very loudly, and in general the sound is better than I had expected from looking at the driver test responses. The highs do not sound as clean as I would like, but are not "hard." I had hoped for better performance from these compound drivers.

This is an acceptable satellite, but should be used on the floor and not on stands. The tonal balance would probably improve with the boxes nearer the rear wall, but imaging might suffer.

The best listening was with the boxes facing straight out and not angled toward the listener. This is a good satellite choice if you play loud music. These drivers played at 20W average input and loved it. The drivers are not shielded, and the satellites are nominal 4Ω systems.

BOSTON ACOUSTICS FX5 CAR COAXES

Boxes #5 and #6 use these drivers. These satellites are clearly too "hot" in the high end and sounded a bit strident. The boxes sounded best angled outward slightly. By playing with this angle you can control the sound a major amount.

These satellites have very high presence with a bit of "in-your-face" sound. They are not good candidates for use on stands, but probably sound best near the floor/rear-wall interface.

These drivers have the highest sensitivity of all the ones we tested and will play loudly. On the floor, away from the rear wall, they do have that "hollow" sound due to DSL, and they do not

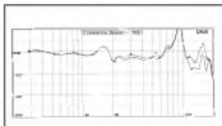


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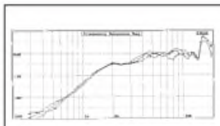
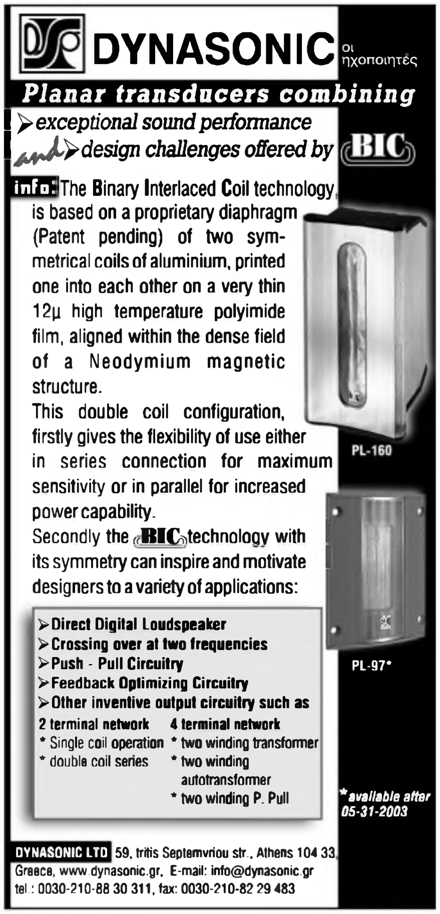
FIGURE 20: Response of bare woofer for Infinity driver.



B2213-21

FIGURE 21: Response of bare tweeter for Infinity driver.



sound as good as boxes #3 and #4. Their main merits are the very simple construction and low cost. These drivers are not shielded, and the satellites are nominal 4Ω systems.

TBSPEAKERS 3″ FULL-RANGE DRIVERS

We first tried the single-driver boxes #7 and #8. The satellites were toed in so that the drivers aimed directly at the listener. These boxes have a very pleasant musical sound, but something was missing. The highs were there, and it was clear you were not listening to a metal-dome tweeter, but to a mellow soft-dome tweeter.

I liked the basic sound, despite the "hollow" effects of small boxes due to DSL. If used on the floor against the back wall or in a bookcase, they might be fine. However, even on the floor out in the room they are not acceptable.

Playing level was not really a problem. Background listening was only a fraction of a watt into each satellite, and about 5W per satellite was reasonably loud. There should be no problem in this regard for a multichannel system. The imaging and clarity were good.

Switching to the dual-driver boxes #9 and #10—again aimed at the listener—was a shock. From systems that were weak in the 100Hz to, say, 500Hz range, you now had systems that were strong in that range. To my ears they were too strong when on the floor, sounding absolutely bass heavy. It made voices slightly husky. I needed to keep reminding myself that 3″ drivers were producing that sound.

As with the single-driver boxes, a few watts to each satellite was sufficient for listening. Switching between single- and dual-driver boxes on orchestral music was very interesting. The dual-driver boxes revealed all sorts of music that was being lost with the single-driver boxes. I thought the dual-driver boxes would sound better off the floor (more later).

I experimented with coils from 1.3 to 2.5mH and liked the design value of 2.5mH best. This is not a good satellite choice for boxes that will be on the floor and against the back wall, such as in a bookcase. It is an ideal choice for boxes on stands out in the room. Clarity and imaging were very good, but the strong output in the 100–500Hz range yields what I call "Cambridge" sound, and some may be bothered by a lack of high presence. On the floor, these satellites are just great for listening to classical music at background level.

I thought that perhaps the 6dB DSL compensation for boxes #9 and #10 was excessive. Reducing the DSL compensation to about 3dB could be accomplished by simply inserting a 3dB L-pad between the coil and the bottom driver. Theory says this is a bad idea. If you pad a driver, you raise its Q and destroy the electrical damping. Also, you now have the two tiny woofers sharing the same air volume while playing at different levels and having different Qs.

Would the use of an IB and the fact that the drivers were not used to handle the bass overcome these problems? It was simple enough to try, so I listened with such a pad included. Theory wins this one, as the sound was terrible. The DSL compensation was reduced, but the sound of musical transients was horrible and produced some very strange-sounding drums.

As an alternative, I raised boxes #9 and #10 up off the floor on 13″ tall open boxes of about the same footprint. This gave the best sound, even though this aimed the listening axis a bit too high. There is little doubt that these are the best satellites that we developed (with unmodified drivers), if you plan to put the speakers on stands out in the room.

Build boxes with vertical front panels and use stands that place the top driver at about ear level. With the boxes 13″ off the floor, the presence was better, yielding a better overall sound.

SUMMARY FOR 3″ FULL-RANGE DRIVER BOXES

Even when on the floor, the single-driver satellite boxes #7 and #8 suffer from a "hollow" sound due to DSL. They may be fine when near the back wall, as in a bookcase, but they would be terrible on stands out in a room. If you play your

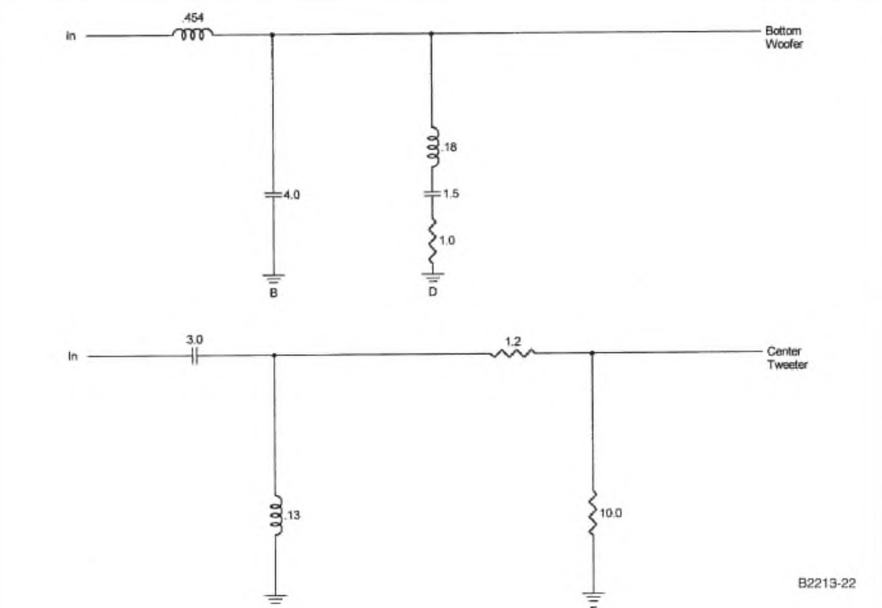


FIGURE 22: New crossover for Infinity driver developed via modeling.

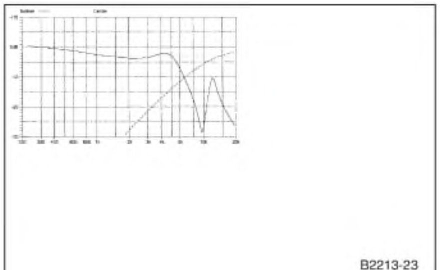


FIGURE 23: Electrical responses of new crossover networks.

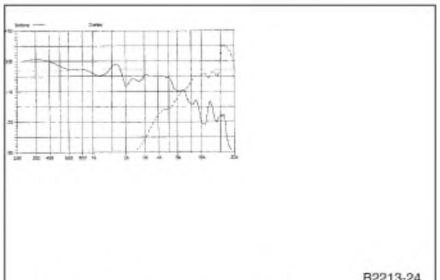


FIGURE 24: Responses of drivers with their new crossover network.

music extremely loudly, these are not acceptable candidates—they are shielded drivers, and the satellites are nominal 8Ω systems.

The dual-driver satellite boxes #9 and #10 are the best satellites we developed—before modifying the Infinity drivers. I thought that on the floor, they were a bit overcompensated for DSL. These small boxes would be ideal out in the room on stands. They can really play no louder than the single-driver boxes, even though they sound louder due to the filled-in 100–500Hz range. Thus they are not the best choice for playing loud music.

Used alone, without subwoofer, they would make good computer speakers because of the limited power requirement with the listener so close. Again, the drivers are shielded, but these satellites are nominal 4Ω systems.

INFINITY DRIVER MODIFICATIONS (BY G. R. KOONCE)

ROW and I both shun writing construction articles that require you to modify the driver. Here is a voluntary major modification that we developed after completing the basic satellite work. When done, your satellites will no longer be simple or cheap. They will, however, be good-sounding, small satellites that are worth the cost and effort.

I was not happy with the sound of the Infinity plate driver in either box type. I had expected more from this driver based on it being a real two-way compound driver and its reputation. These are high-technology drivers with the woofer and tweeter using a ceramic-coated aluminum cone and dome.

The test results had not been encouraging, leading you to expect a "bright" sound, probably by design because of the intended automotive application. I did expect clean highs with a ¾″ dome tweeter, but believed I did not get them. I thought that some simple modifications such as changing the crossover capacitors to film units and adding a little padding on the tweeter could improve the sound.

I started by examining the factory crossover (CO) network, composed of a second-order low-pass (LP) on the woofer and a first-order high-pass (HP) on the tweeter, both using non-polar electrolytic capacitors. Both drivers are nominal 4Ω with the tweeter driven with reverse polarity. The LP coil value was unmarked, but assuming a Butterworth LP for 4Ω, the 5.6μF capacitor would mean CO about 5kHz. The 3.3μF capacitor in the HP meant CO at about 12kHz. But the response (*Fig. 1*) sure did not show a gaping hole from 5 to 12kHz, so something was strange.

SOME STRANGE TEST RESULTS

I disconnected the tweeter from the woofer so I could drive them independently and tested one unit. The individual responses of the drivers with their CO (*Fig. 19*) tell the story. The woofer does not go away at 5kHz, but is the major contributor up to 10kHz. While not shown, the LP network interacts with the woofer impedance to produce additional electrical peaking. Those highs I did not enjoy were coming from the woofer and not the dome tweeter. The tweeter makes a low contribution

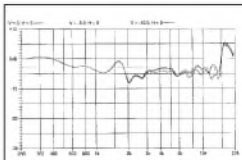


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FIGURE 25: Modeled system responses without DSL.

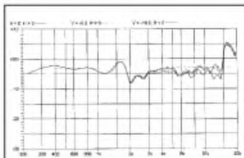

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FIGURE 26: Modeled system responses with 6dB DSL.

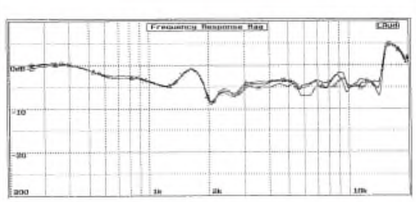

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FIGURE 27: Test system responses with new crossover.

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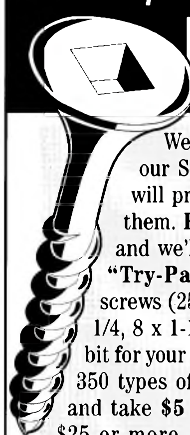

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from 10kHz to about 16kHz, then has a major peak to 20kHz.

Figure 20 shows the response of just the bare woofer on-axis and 10° off-axis. The woofer has a terrible peak in the 9kHz range that Infinity had included in the woofer passband. Such peaks are common with metal cone drivers and require some attention in the CO design.

Figure 21 shows the bare tweeter response from on-axis to off-axis 20°. Other than the nasty peak above, say, 16kHz, this is a nice-looking response for a ¾″ tweeter. Examination of the driver responses indicated that CO around 6kHz would be good with a second-order HP protecting the tweeter.

Based on the measured driver response and impedance curves, we developed a new CO using modeling techniques (*Fig. 22*). The woofer and tweeter are both driven with positive polarity. The LP consists of a second-order network optimized to increase the down slope from 200Hz to 1kHz for DSL compensation. The series R-L-C network shunted across the woofer terminals cures the peak around 9kHz. The tweeter HP is a second-order network followed by a 3dB pad.

Figure 23 shows the electrical responses of these networks loaded by their driver. The effect of the shunt network on curing the 9kHz peak is clearly evident. The acoustic response of each driver with its CO network (*Fig. 24*) shows the down slope for DSL compensation and CO at about 6.5kHz. We did not attempt to cure the woofer anomaly around 1.5kHz to 2kHz or the tweeter peak above 16kHz.

The modeled system response without DSL (*Fig. 25*) shows the droop from low frequency and then a basically flat response up to 16kHz. The response is stable from on-axis with the tweeter to 10° down from the tweeter axis toward the woofer. This is the response range used for listening with boxes #1–#4. *Figure 26* shows the same plots including 6dB of DSL, demonstrating that the system has a full 6dB DSL compensation.

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TESTING THE NEW CROSSOVER

We breadboarded the new CO and used it to test one Infinity driver. Note that the 0.180mH coil in the shunt network comes from the original factory CO. It has enough resistance so that you could omit the 1Ω resistor shown in the modeling schematic to save one more component. The test results (*Fig. 27*) for the same angles as were used in the modeling (*Fig. 25*) are in good agreement. Note that DSL does not appear in the type testing used here.

We modified the Infinity drivers for boxes #1 and #2 to remove the factory CO and brought out individual wires for the woofer and tweeter. After listening tests, we assembled the new COs under the box pedestal. We also tried the new CO in breadboard form and then installed it in boxes #3 and #4, which pose a problem, because the pedestal is very small.

Using small coils and putting the shunt network inside the box mounted on the driver allowed us to fit the CO under the pedestal. It is unlikely with the coils available today that you could fit the CO under the box unless you increased the pedestal height. *Table 5* lists the additional components needed to modify a pair of #1 and #2 or #3 and #4 boxes.

HOW DO THEY SOUND?

The original boxes sounded light just above the subwoofer range and had excessive highs that were not as clean as I had expected, but now I had very fine-sounding satellites. With this CO modification both box types are great satellites that can play loudly. You could use either type on stands built with a flat bottom rather than the tipped front panel. Adjust the stand height so a seated listener's ears are at tweeter height for boxes #1 and #2 and a bit above tweeter height for boxes #3 and #4. You could place boxes #3 and #4 on tall stands and build them upside down, i.e., invert the front panel to put the tweeter at the top.

At most times boxes #1 and #2 and boxes #3 and #4 sound very similar. Boxes #3 and #4 have very specific imaging—almost analytical. Boxes #1 and #2 now show the very wide sweet spot I had learned to expect with the side-by-side configuration. Their image is not quite as specific as boxes #3 and #4, but they offer a wider soundstage. On some music I preferred boxes #3 and #4, and on other music I preferred boxes #1 and #2, so I could never select a clear winner. Other listeners offered similar opinions.

Infinity has recently raised the price of the Kappa 462.5CFP plate drivers. This, plus the cost of parts for the new CO, make these rather expensive satellites. Also, you need to assemble a reasonably complex CO network.

TABLE 5
MATERIAL TO MODIFY A PAIR OF BOXES #1–#4

QTY.	COMPONENTS FOR NEW CROSSOVER
2	0.45mH coils for the woofer
2	4.0µF film capacitors for the woofer
2	0.18mH coils taken from original factory crossovers
2	1.5µF film capacitors for the shunt network
2	3.0µF film capacitors for the tweeter
2	0.13mH coils for the tweeter
Misc.	Extra wire to bring out tweeter directly

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3. "5.1-Channel Production Guidelines," Issue 1, S00/12957, Dolby Laboratories, Inc., www.dolby.com.

4. Gonzalez, Ralph, "Balancing Small Speakers," *SB* 3/87, p. 44.

5. D'Appolito, Joseph, *Testing Loudspeakers*, ISBN: 1-882580-17-6, 1998, p. 58. Old Colony Sound Lab, PO Box 87, Peterborough, NH 03458-0876, 603-924-9464, Fax 603-924-9467, custserv@audioXpress.com.

6. Koonce, G. R., "Side Saddle: A New Two-Way," *SB* 3/97, p. 10.

7. Koonce, G. R., "A Pair of Computer Speaker System Designs," March 2001 *aX*, p. 8, and April 2001, p. 30.

CREDITS

I would like to thank the many people and companies that supplied technical assistance in the performance of this work. Listing is alphabetical by company: Boston Acoustics; Eminence Speaker Corporation LLC, Tom James; Infinity Systems (Harman-Kardon), Andy Wehmeyer; Madisound, Bryan Kane; Near Audio (Bogen Communications, Inc.), Bill Kieltyka; NUERA Acoustic Technology (Tang Band Speakers, Taipei City ROC), Billy Lau; Parts Express, Karl Keyes and Darren Kzuma; RAW Acoustics, Al Wooley (formerly with NUERA Acoustic Technology). I would like to thank Mark Rumreich for his most valuable research work in finding active fourth-order automotive subwoofer amplifiers/crossovers for this article.

Modifying the Infinity drivers to remove the original CO parts and attach wires to the tweeter terminals exposes them to possible damage. Note that the woofer terminal closest to the wide input terminal is the plus woofer terminal. On the tweeter a red dot marks the plus terminal. While these are not simple satellites to build, they are good-sounding small boxes that show more of what I had expected from the Infinity Kappa drivers.

Part 2 of this article covers construction details for the five enclosure types, discusses diffraction spreading loss compensation, and summarizes the overall work. ❖

SOURCES

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AMPLIFIER SOURCES

Following is a list of some of the companies who can supply continuously variable frequency car amplifiers with 24dB per octave filter slope. These will all require a nominal 12V (13.8V actually) power supply at approximately a 20A rating for home use. You can purchase the power supplies from either Parts Express or MCM Electronics.

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800-421-2284
www.alpine1.com
Alpine MRP-M200, 150W × 1 into 4Ω, eq., subsonic filter, polarity switch.

USA Acoustics
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Alameda, CA 94501
510-864-7005
www.usacoustics.com
USACOUSTICS USX2050, 160W × 1 into 4Ω and USACOUSTICS USX2050, 280W × 1 into 4Ω.

JL Audio, Inc.
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Miramar, FL 33025
954-443-1100
www.jlaudio.com
JL AUDIO 250/1. 250W × 1 into 4Ω, eq., subsonic filter, class D.

For others who prefer to purchase a more conventional subwoofer amplifier with a built-in crossover, these crossovers are second- and third-order only, often referred to as "plate amplifiers." Here are several sources for these amplifiers:

Adire Audio
1111 Elliott Ave. West
Seattle, WA 98119
206-789-2919
www.adireaudio.com
Adire HS200, 200W into 8Ω, eq., subsonic filter, polarity sw., and Adire HS500, 490W into 8Ω, eq., subsonic filter, polarity switch.

Parts Express
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Disposable Camera = Tube Power

One man's junk is another man's treasure. Discover how you can recycle the cast-off camera into your next tube project. **By Graham Dicker**

TABLE 1
CAMERA INVERTER TEST RESULTS

LOAD (k)	VOLTAGE (V)	CURRENT (mA)	POWER (mW)
1000	300	0.30	90.00
330	255	0.77	197.05
220	253	1.15	290.95
100	235	2.35	552.25
47	203	4.32	876.79
22	165	7.50	1237.50

After building tube projects for many years, I find that one of the most annoying tasks is building the power supply for the project. The filament voltages never provide a problem, but the H.T. voltage supply always becomes a task. One of the easier methods I have used over the years is to use a reverse-connected power transformer and a rectifier to provide a few hundred volts H.T. An example of this method is shown in *Fig. 1*, which is the method I use in a future issue of *aX* in my sound card preamp power supply project.

Recently, however, I have discovered that disposable film cameras are being sold by the millions, with some being recycled and others ending up in the landfill. If you ask them nicely, most film processors will give the old shells away for free. Inside of these shells lies a nice DC to DC inverter ideal to use for small preamp or portable projects.

Photo 1 shows three of the most common cameras in the marketplace; most are made in Taiwan or China and marketed by a variety of companies. You can purchase them in quantities of ten for around $2.99 USD new with film, or $4 USD for single quantities. The ones you need for recycling are those with the built-in flash.

I pried apart with a screwdriver the two plastic clam shells, to reveal the inner workings of the camera (*Photo 2*). Inside were all the plastic mechanics, including the viewfinder and camera lenses, which you may choose to keep for optic projects. You can also see the printed circuit board with the DC to DC converter, which you can easily remove.

Photo 3 shows some examples. The different type numbers are shown in the same order as the original cameras

PHOTO 1: Some popular disposable cameras.

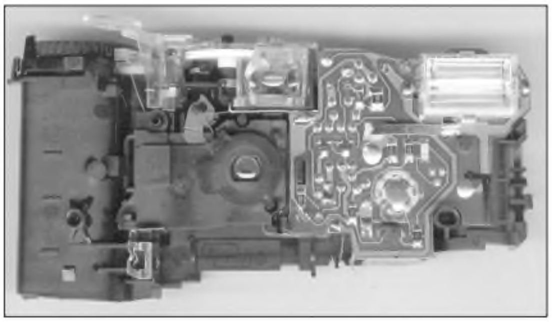

PHOTO 2: Inside the camera.

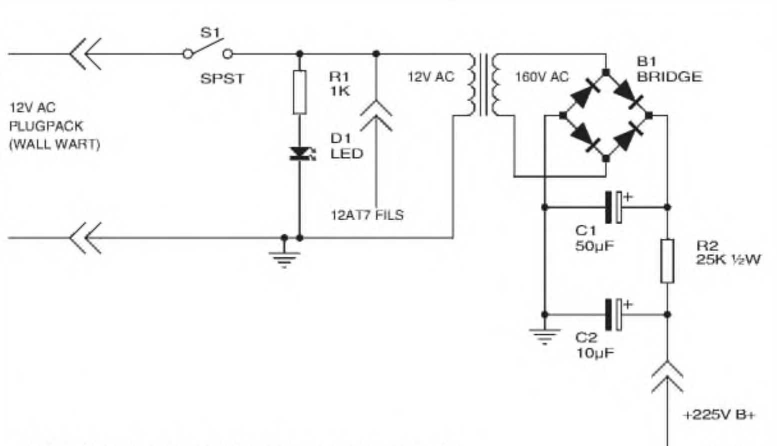

FIGURE 1: Sound card preamp power supply. G-2148-1

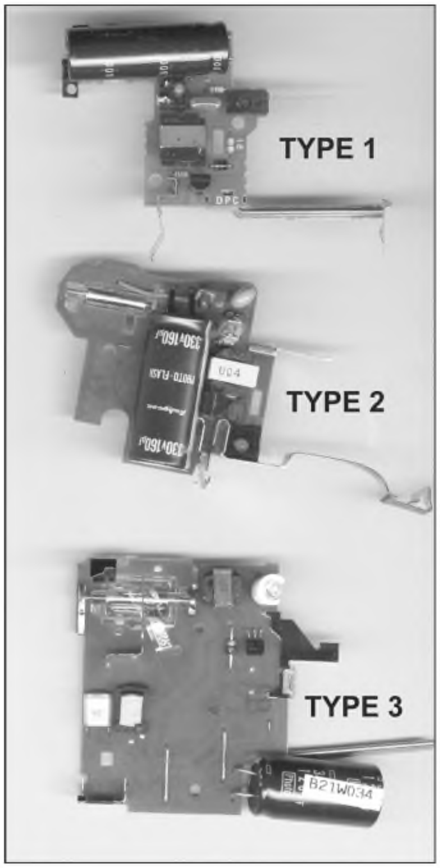

PHOTO 3: Converters from the cameras in *Photo 1*.

in *Photo 1*. The basic performance of each converter I tested was so similar that I tend to conclude that it doesn't matter which one you use.

The schematic diagram of one of the converters is shown in *Fig. 2*. A 1.5V single-cell battery is used to power the inverter. The inverter transformer consists of a small ferrite core with around seven turns bifilar wound for the primary and the feedback winding. The circuit is a self-sustaining feedback circuit that runs at approximately 6kHz. The secondary winding consists of around 175 turns providing about 220V AC, which is half-wave-rectified by a single 1N4004 diode. This is filtered by a 160µF 300VW electrolytic capacitor.

When the DC voltage approaches approximately 270V, the relaxation oscillator formed by the neon (and its stray capacitance) along with the 220k series resistor lets the neon flash to indicate charging of the filter capacitor. This voltage is applied across the flash tube, which is triggered by the secondary voltage of the trigger transformer. A large current pulse is provided by charging the .1µF capacitor through the

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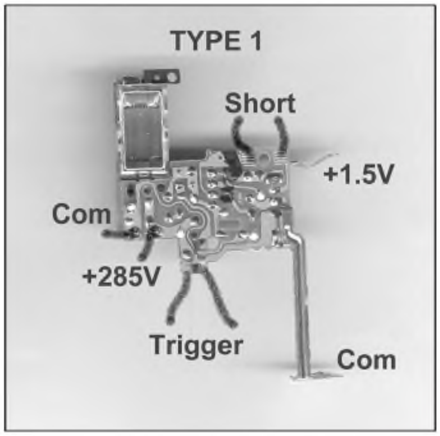

PHOTO 4: Modification to type 1 inverter.

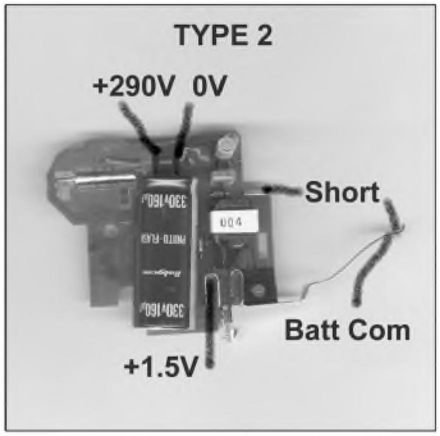

PHOTO 5: Type 2 inverter mod.

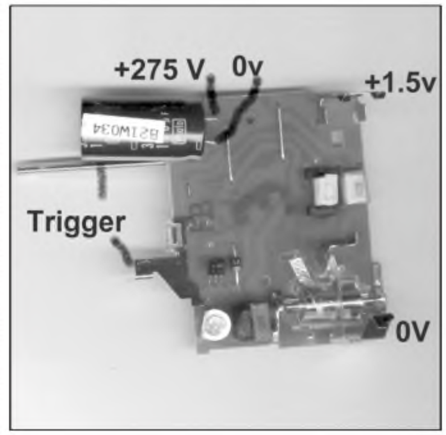

PHOTO 6: Type 3 inverter mod.

series 10k resistor, with the capacitor in series with the trigger transformer primary. When the trigger switch is closed, the capacitor discharges through the transformer primary, producing a high-voltage trigger pulse for the strobe tube.

Table 1 shows the test results of loading the output of the DC to DC converter with different resistors. You can obtain a range of load currents with useful output voltages and use these for tube amplifier projects. Loads above 7mA cause excessive heating of the ferrite core and/or the oscillator transistor.

The test figures also show a dramatic drop in output voltage above the 1W output level. Load currents from 1 to 4mA are, however, most useful to power up to four average triode sections with the usual 100k plate loads. The falloff in output voltage with load current is better shown in the graph of *Fig. 3*. The most useful output is in the 0–4mA and 200–300V region.

Photo 4 shows where I was able to tap off the DC voltage from a type 1 inverter, in this case around 285V. You can ignore the trigger contacts and

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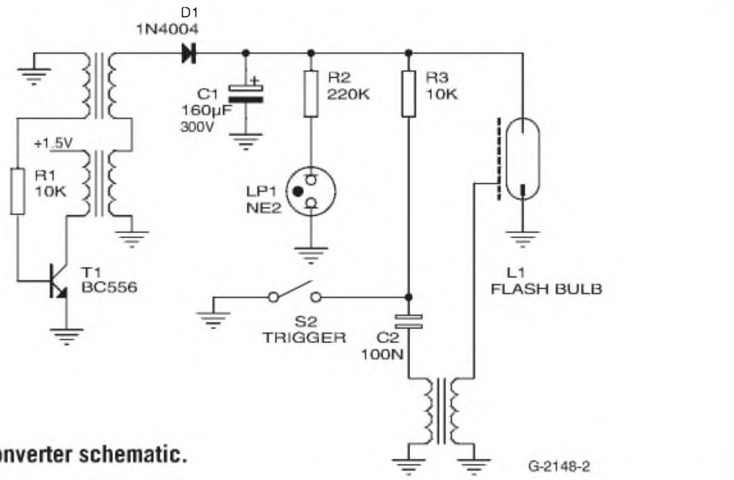

FIGURE 2: Converter schematic.

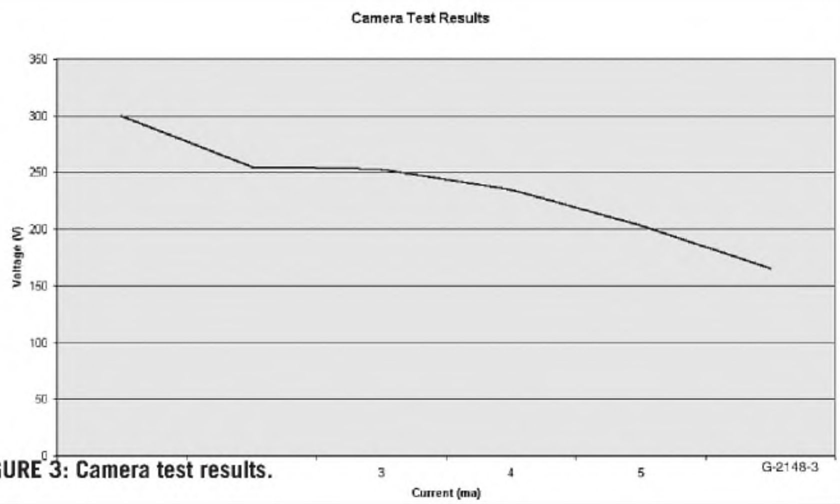

FIGURE 3: Camera test results.

apply a 1.5V DC supply to the contacts as shown. You also need to short out the two pads indicated to keep the oscillator working all of the time. *Photos 5* and *6* show where to hook up inverter types 2 and 3 in a similar manner.

All three inverters showed little ripple in the DC output and little radiated noise. If you wish, you can easily enclose the inverters in a metal tin for shielding. *Figure 4* shows a simple power-supply circuit to provide 1.5V for the inverter. I have one of these built into a jiffy box along with a 12V center-tapped transformer for filaments, which I use for prototyping valve circuits. ❖

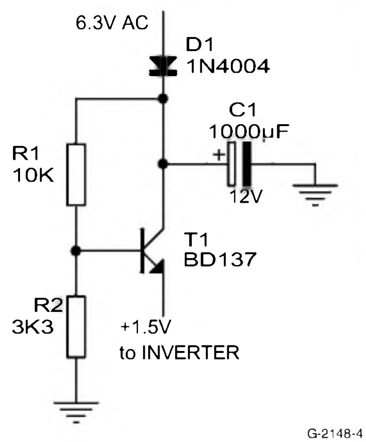

FIGURE 4: Power-supply circuit.

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Audio Uses of Transformers

The author calls on readers to contribute information and pool resources to retrieve wisdom otherwise partially lost. **By Peter Buddee**

As a long-time reader of Audio Amateur publications, I find it difficult to start writing without first answering the classic question: How did I become an audio addict in the first place?

In my case, it is very easy to pinpoint in time and space. As a teenager in the summer of '64, I accompanied my father to an industrial exhibition in a small Swedish town. In the exhibit booth of the most popular Swedish home electronics producer, I saw enthroned an open-reel tape recorder with its spools rotating at a higher speed than I had ever imagined possible, giving an almost hypnotic visual effect. At the side of the tape recorder there was a pair of headphones. So, what does a young teenager interested in music and electronics do in a situation like this? Right, he puts on the headphones!

Since this was my first exposure to true high-quality sound reproduction, I simply wasn't prepared for the result. Up until this moment, I had heard only medium-fi music reproduction, but now I was receiving the sound quality of an open-reel prerecorded tape at 7½ ips . . . plus the effect of stereo reproduction (also new to me), combined with the spooky "throwing you in the middle of the orchestra" effect given by the headphones.

There is only one expression able to register the impact this event had on me: "Wow!"

ACKNOWLEDGMENT
To Per Lundahl at Lundahl Transformers in Sweden, for his patience in answering all possible (and some quite impossible!) questions during this process. I think his major reaction now is surprise. With his company's background mainly in pro audio, he now seems to understand that the technology used in his products could prove eminently useful in audiophile applications.

Although I do not recollect the music I heard that day, the impact of the sound quality has set my priorities ever since. My favorite pastime became music listening—live or canned. But if reproduced, it needed to be of the "best possible" sound quality.

I began tinkering with replay equipment, trying to improve sound quality whenever possible. I became a classic *Audio Amateur* reader. Also, I joined a network of audiophiles that fed and sustained my interest. Some of the members of this group became designers and manufacturers of audio equipment, as well as recording engineers. Over the years, the number of active members would vary, but there was always a core group, keen on honoring continuity.

This group eventually accumulated quite some insight into audio-related matters. Also, it has access to a continuous timeline, stretching over decades, seeing the trends coming and going.

THE REAL ISSUE

There is one audio chain component that has remained—over the years—relatively unchanged in people's minds. If I said, "This component has always been seen as a necessary evil, to be used only when necessary," what would your first guess be? The right answer is (at least in this case!), "the audio transformer."

It has become clearer in recent years that the dominant perception of audio transformers does not contain the whole truth. As usual (!), the truth proves to be more complex than traditional understanding, giving good reasons to look a bit deeper into the matter.

Accepting (as always) the need to use a properly designed component in a properly designed circuit, this group has, over the last couple of years, compiled a list of possible uses for audio transformers. The more we thought about this issue, the more obvious it became to us that there seemed to be a lot of prejudice getting in the way of really good solutions. If you observe the recording industry, or the broadcast companies, you face a very different attitude towards transformers. The group found application after application coming to the surface, where a transformer potentially could provide a very satisfying solution.

Very early results of testing some new ideas (being primarily forgotten old ideas!) seemed to very much support our view. We also found that we had an interesting supplier of audio transformers, with strong goals, living in central Sweden close to the Baltic Sea. Oddly enough, it wasn't until rather late in the process we discovered each other, so that we could tap into the more detailed knowledge base available in this organization.

Overall, my wish is to challenge all readers, requesting input from each reader who has experience with any of the applications described here. I am quite convinced there is much more to tell than a single person could possibly manage to find by himself in a lifetime!

Enough background material for each application could result in one or more articles supporting the very best solutions for each application.

THE APPLICATIONS LIST

So, at last, here's our list. It tries to follow "the general direction" of the signal path, and so it would be correct to start with:

1. **The Moving-Coil Step-up Transformer**—a common place to observe a transformer. There could be many reasons why the transformer seems to be a common solution to bring the

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output of a moving-coil cartridge to the correct level for connecting to the 47kΩ phono input. To the best of my knowledge, I haven't seen any attempt in many years to analyze this solution compared to the "active MC input amplifier." Input, anyone?

2. **Line-Level Preamp Input Transformers**—rather unusual today, it does provide galvanic isolation between signal ground in the preamp and any device feeding it, at the same time providing an elegant way to go from balanced to single-end, or vice versa.
3. **Preamp Output Transformer**—galvanic isolation, impedance, and level matching are easily available for this configuration.
4. **Line-Level "Problem Solver" Transformer**—basically a "one-to-one" unit, you could insert between, say, a preamp and a power amp (in the cable) to ensure no DC interactions between the two. This application is a classic pro-audio solution to ground problems.
5. **Power Amp Input Transformer**—again, galvanic isolation, general matching and balanced to single end conversion are available here.
6. **Power Amp Interstage Transformer**—general matching, but also eliminating the coupling capacitor in the signal path before the output tube grids. Given a transformer with good enough symmetry, this would allow the transformer to be used as a phase splitter before push-pull output tubes.
7. **Power Amp Output Transformers**—the classic use for transformers in audiophile equipment. Most often used in tubed circuits, there are some exceptions in which solid-state solutions actually have output transformers. I would love to see what thinking is available today, for both of these applications!
8. **The Plate (Anode) Choke**—not being a true transformer, it has a lot in common with its brother. The most important feature here is the inductive load it presents the active device, giving the tube a more linear way of working. This is according to the textbooks, but what does experience say?

By the way, the fact that the (normal) transformer also provides this inductive load to the drive circuit is only rarely mentioned when discussing transformer applications. Is everybody aware of this fact?

Talking about chokes, there are several more applications including this device:

9. **The Grid Choke**
10. **Power Supply Filter Choke**

Having made this list to look more and more like a list of inductive components, there is one more item to go; at least it is a true transformer:

11. **Mains (Power) Transformer**—not actually in the signal path, it would still be able to contribute to the sound quality of the circuit it supplies. What do we know about the way the mains transformer influences sound reproduction?

Reading through this text, I would like to call it "NOS ideas"! Indeed, it all seems to be much about retrieving partially lost knowledge, and the phrase, "New Old Stock," could perhaps be viewed as appropriate.

Now, anybody who has anything to share with the rest of us, please do so! ❖

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Showcase

A Headphone Amp

By Klaus Noll

PHOTO 1: Headphone amp.

This project, a small headphone amplifier (*Photo 1*), was sparked by Gary Galo and his remark about the values of the Pooge 5 line amp stage (AD744/AD811) in conjunction with the Jung/Didden regulators (described in *TAA* 1–4/95 and reviewed in *AE* 4/00) in his kit review of PHONES-01 in *Audio Electronics* 2/00.

I had been toying with the idea of

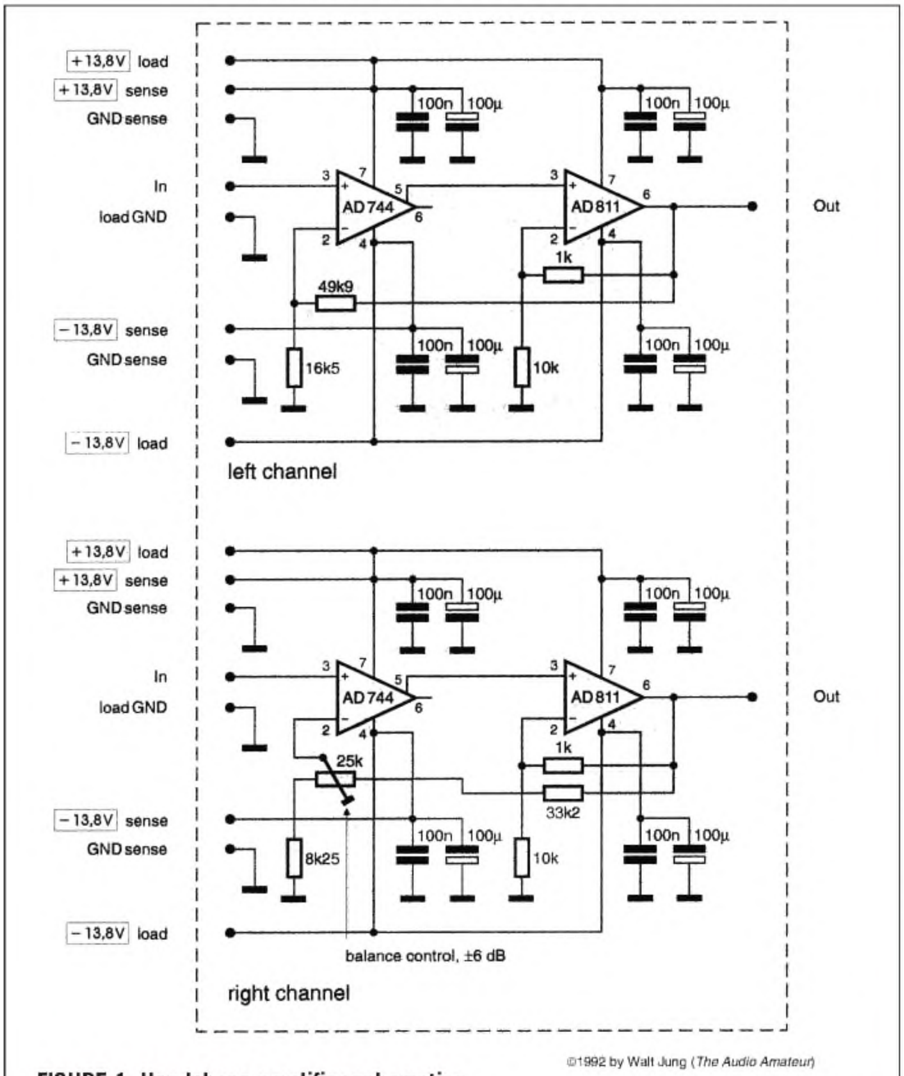


FIGURE 1: Headphone amplifier schematics.

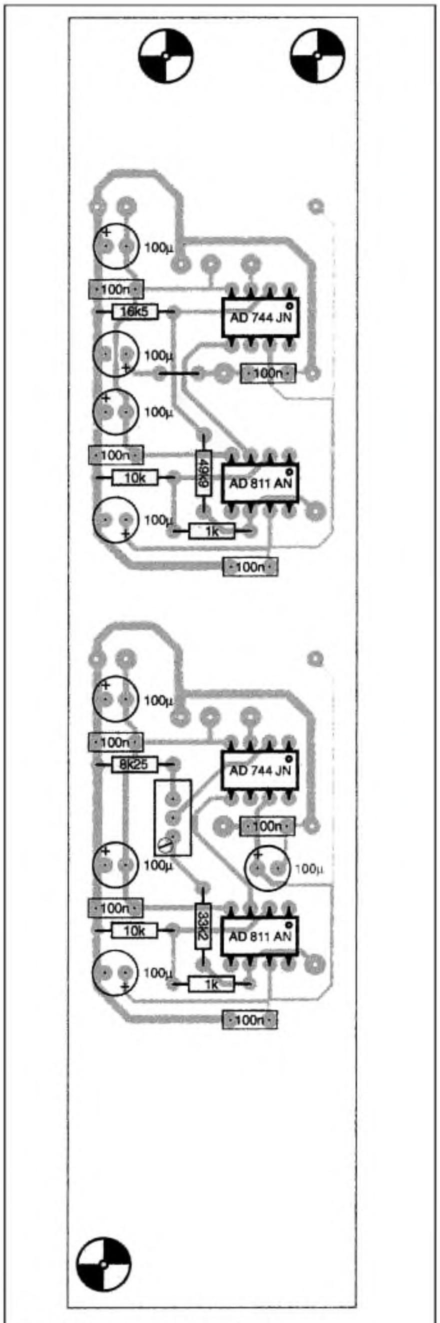


FIGURE 2: Amplifier circuit card stuffing guide.

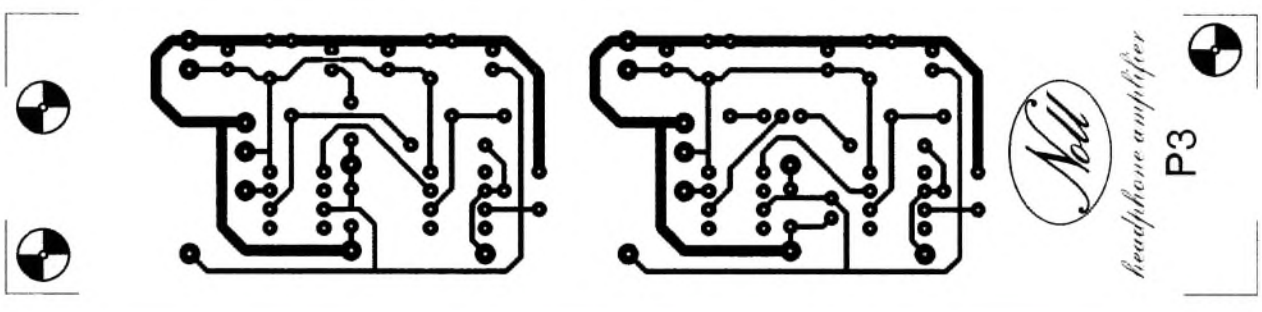
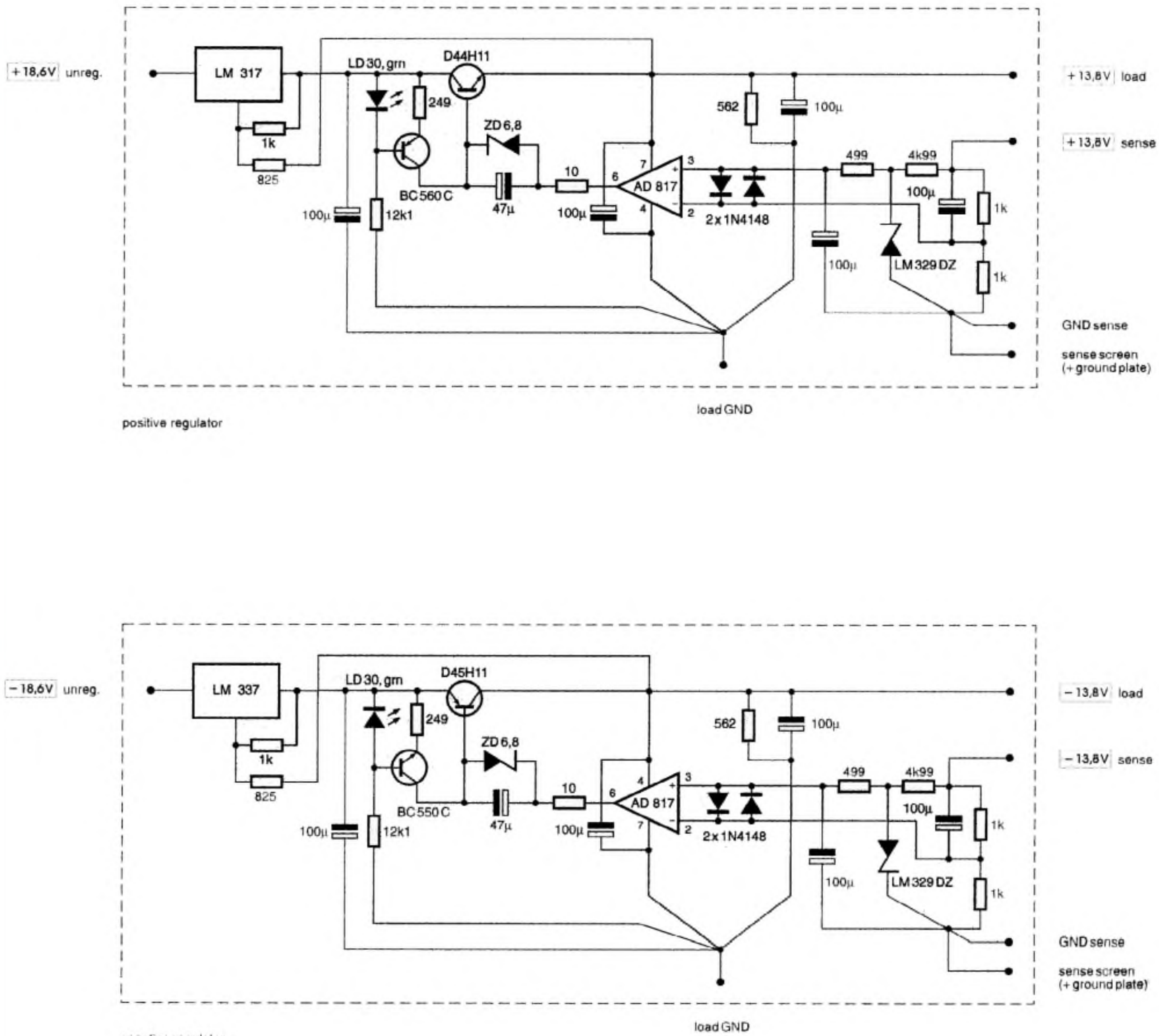


FIGURE 3: Amplifier circuit card.



left channel (right channel identical)

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FIGURE 4: Regulated DC supply schematics.

A-2134-4

working with the regulators for a while, but was deterred by the apparent complexity of the issue. The work-over in *AE* 4/00, I think, proves me right.

The purpose of the project was to design a piece of equipment which was first class in every respect. I incorporated all the suggestions Walt Jung had laid down in his review; i.e., special rectifier diodes (only type available: BYV 28–100), preregulators, and so on. I opted for the AD817, even at the risk of sacrificing a bit of performance, for two reasons: I found the header arrangement of the SMD AD825 too fiddly for my geriatric eyes, and, anyway, the AD825 wasn't available from any of the four retailers I contacted (Analog Devices ICs are very difficult for the amateur to acquire).

Figures 1–3 show the amp schematic

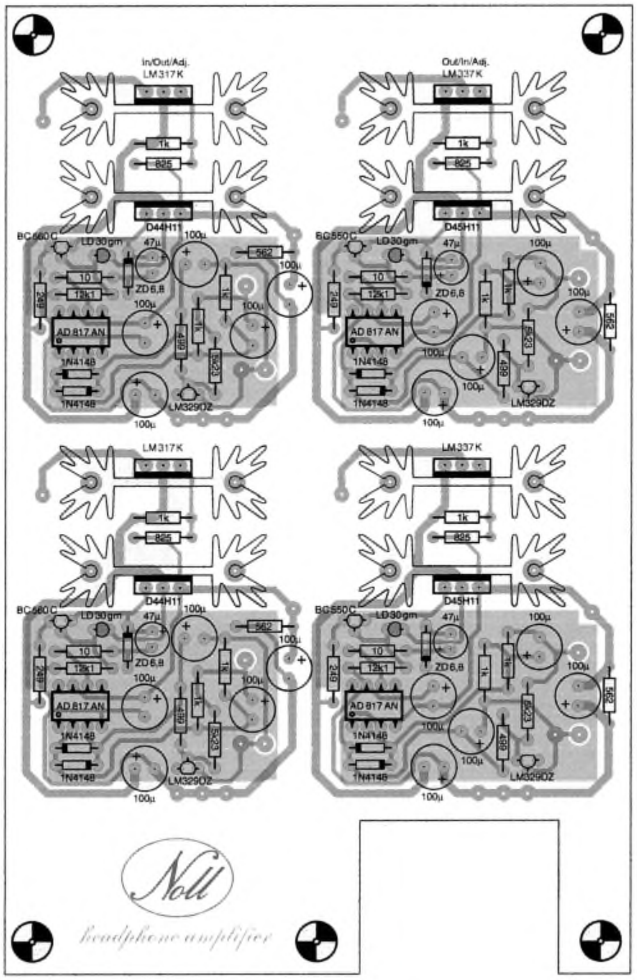

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FIGURE 5: Stuffing guide for amplifier circuit card. (75%)

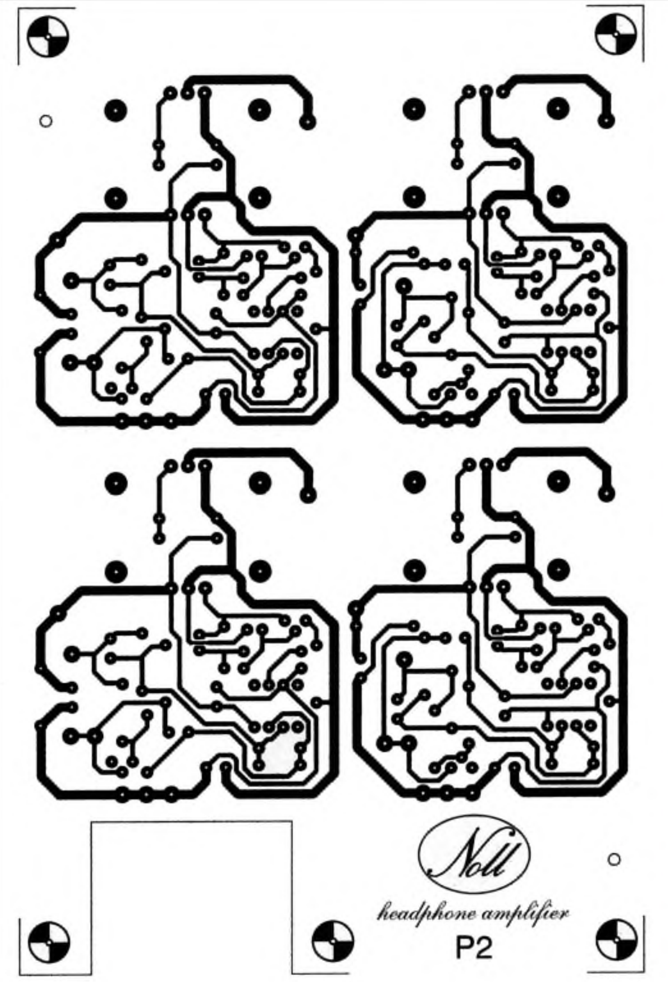

FIGURE 6A: Voltage regulator circuit card patterns, solder side, bottom. (75%)

A-2134-6A

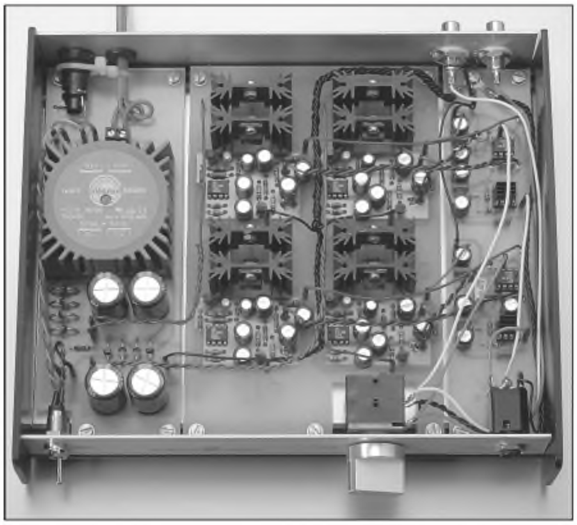

PHOTO 2: Inside the amp.

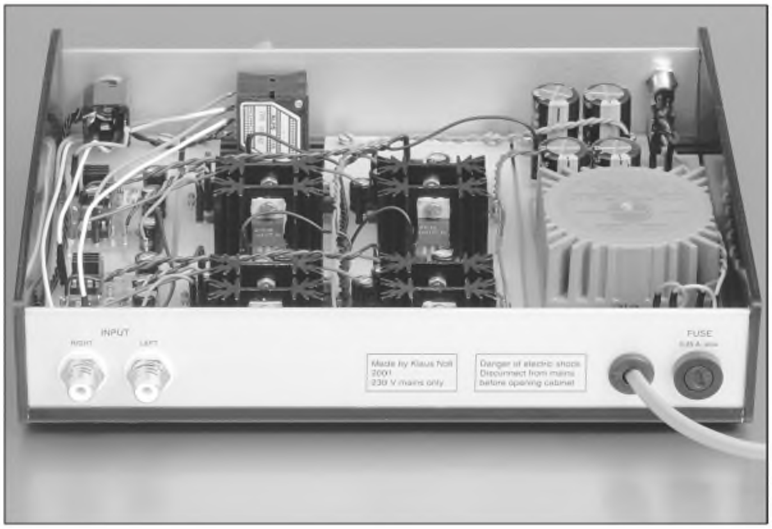

PHOTO 3: Rear view.

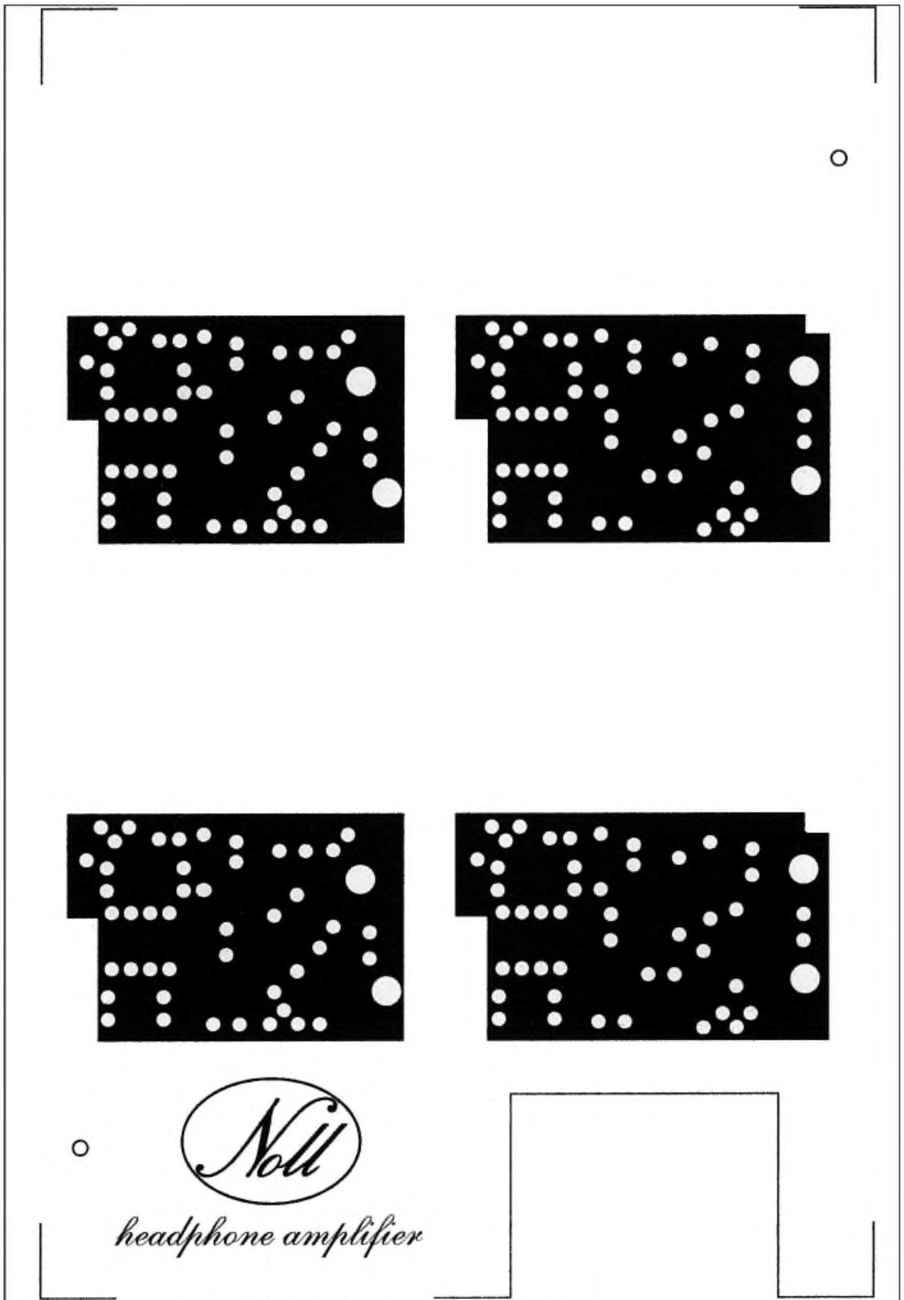

FIGURE 6B: Voltage regulator circuit card pattern top foil. A-2134-6B

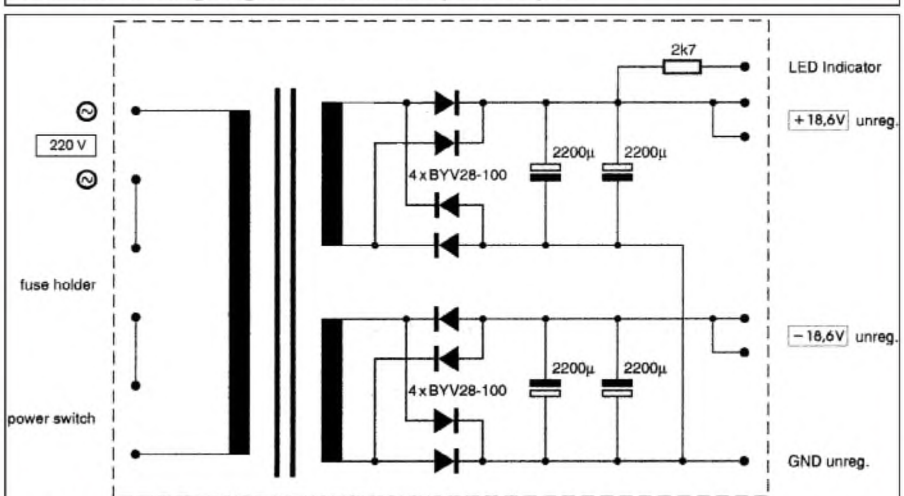

FIGURE 7: Raw DC supply. A-2134-7

and board layouts. The voltage regulator schematic and board layouts are in *Figs. 4–6*. And the DC supply information is shown in *Figs. 7–9*.

I designed a PCB for the regulator/prereg section, based on Jan Didden's original trace pattern, with space for two positive and two negative regulators/preregs, which provide ±14V for the two amplifiers. You can see this board (*Photo 2*) in the middle of the cabinet (which, by the way, is the MC-10 from Sescom, who were extremely helpful and friendly in getting the cases sent to Europe). All four regulators worked faultlessly right from the beginning. The eight heatsinks are probably hopelessly oversized, but I liked the looks of them (silly to put them in a closed cabinet). The AD811s carry little heatsinks, stuck on with heat-conductive sticky foil normally used for fixing heatsinks on CPUs.

The signal is fed straight to the volume pot from a separate line stage in my preamp, bypassing its volume control and then through the 744/811 amp to the phones jack (*Photo 3*). Amplification is four times and can be varied by ±6dB in the right channel to enable the adjustment of balance if necessary.

I use a Beyer Dynamics DT 880 pair of headphones (600Ω nominal impedance) which are rather ancient. (You may want to buy some modern phones.)

What about the sound? Gary Galo was right to maintain that this was probably the best headphone amp available. The sound is simply overwhelming and light-years away from what usually emanates from the outlets of commercial equipment, prestigious CD players, and tape machines. The amp, on the other hand, mercilessly reveals recording faults such as momentary clipping (even on noble records) or misbalancings in the soundstage.

Mr. Galo was a bit off the track as far as the costs of such an amp are concerned. I certainly didn't spend thousands of dollars on the project, but managed to complete it for under $300. ❖

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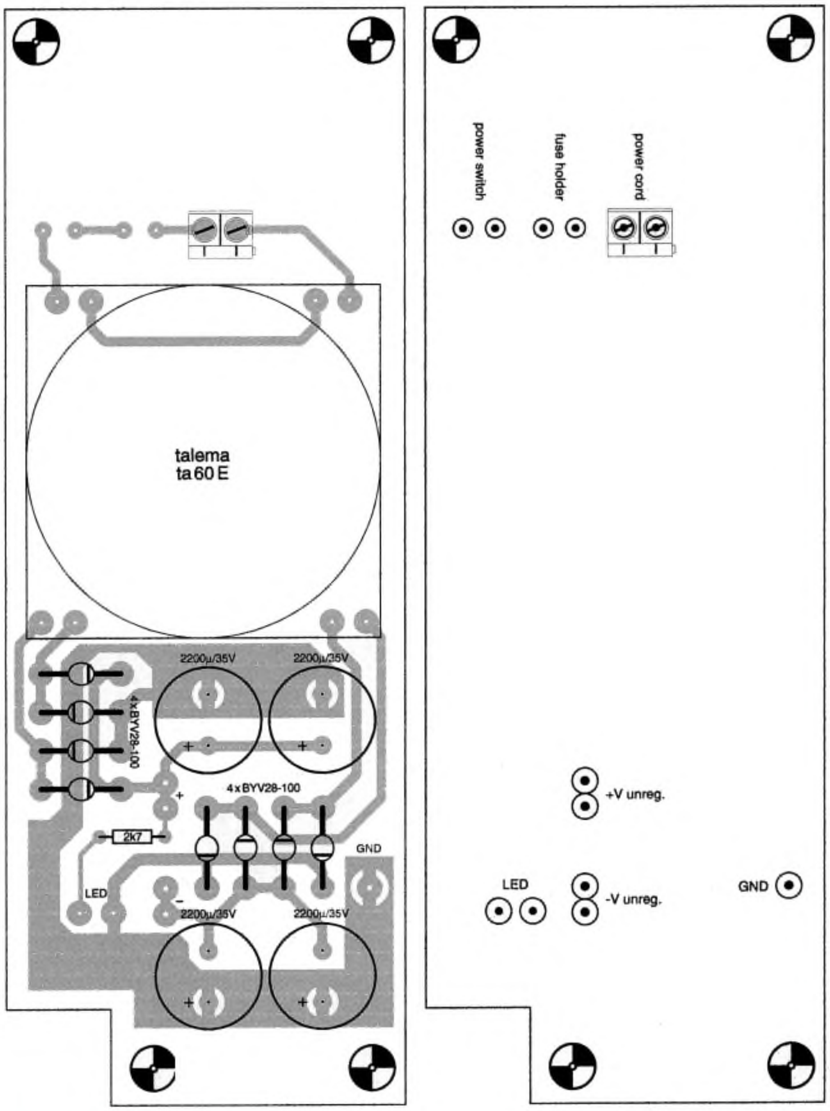

FIGURE 8: Circuit card stuffing guide for raw DC supply in *Fig. 7* components. (85%)

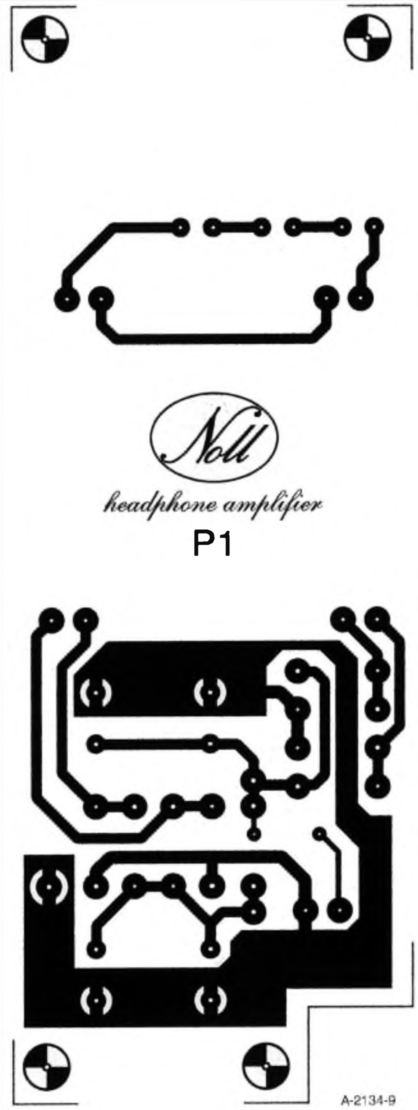

FIGURE 9: Raw DC supply circuit card foil pattern, solder side. (85%)

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POSSIBILITIES

"Damping Loudspeakers in Series" by Dick Pierce (*aX*, Nov. '02, p. 38) should convince anyone that series connection of (assumed identical) speakers has no effect on damping. But in the interest of encouraging people to look for the simplest solution to a problem, I'd like to point out the simplest analysis of series damping, namely, symmetry.

Consider two identical speakers (or any electrical impedances including reactance and/or nonlinearity) in series, with any voltage V_1 applied to the series pair. By simple symmetry, the voltage across each element must be $V_{1/2}$, for *all conditions*. Thus, with two identical speakers in series, each speaker always sees $V_{1/2}$. Therefore, if V_1 is constant, so is the voltage across each speaker, regardless of frequency or current drawn. *The speaker can't tell this symmetry-derived constancy from a voltage source $V_{1/2}$ driving it individually.* Thus all parameters, such as current vs. frequency, are the same (except for half the drive) as if the speaker were solely connected to a constant-voltage source. Hence, *damping also is unaffected.*

The argument that one speaker's resistance decreases the other's damping is flawed: if, say, a 4Ω speaker were connected in series with a 4Ω *resistor*, certainly the electrical damping would be halved (twice the Q_{ES}). But the second speaker is *not a resistor!* Rather, its voltage/current ratio and phase (impedance) varies with frequency (and anything else, such as nonlinearity of mechanics) in exactly the same way as the other speaker. *This preserves the symmetry, therefore the constancy of individual speaker voltages.*

As an aside, the electrical dual would be two identical speakers in parallel, driven from a constant-current source. The current would split equally.

But what about the real world of non-identical speakers (say in series)? No longer symmetrical, damping *will* be affected. For example, suppose (exaggerated for clarity) one speaker of a sealed-box pair has a resonant impedance peak at 40Hz, the other at 50Hz (acoustic interactions ignored). Then at 40Hz, the first speaker presents a higher impedance to the second than the latter's own. (Also, the impedance phases are different.) Vice versa at 50Hz. Thus, the voltage across each speaker will rise (> $V_{1/2}$) at its own resonance frequency; damping is decreased.

The same can happen if identical speakers in series are loaded differently acoustically, for example, if damping material is more densely packed around one speaker; or in a vented enclosure, if one speaker is significantly closer to the vent.

It is for such reasons that parallel speaker connection is preferable; only then is constant-voltage drive assured with dissimilar drivers, loading, and so on.

Electrical elements in series driven by a constant-voltage source (or the parallel/current source dual) are actually a form of feedback stabilizing, if you consider the time delay of reactances (even what we call "resistors" have parasitic L and C). Consider a 1Ω resistor with one end connected to a +2V source (with reference to some defined ground point). Initially, the resistor's other end is floating—zero current. Then, this end is connected to a second 1Ω resistor whose other end is grounded.

Now we have 2V across two series 1Ω resistors. The steady-state 1A of current doesn't flow instantly; parasitic L and C cause a build-up delay, possibly with damped oscillations (at RF frequencies, most likely). With identical resistor parasitics, each resistor would see an immediate and constant voltage of 1V across it (regardless of transient current oscillations) due to the symmetry.

But with dissimilar parasitics, of sufficient magnitude, the resistor midpoint voltage would oscillate about 1V until (theoretically never fully) decayed to zero. In the steady-state, the resistors' *resistance* values determine the final

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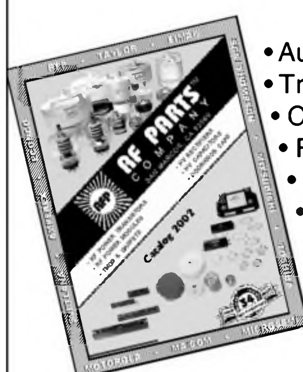
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voltage division. So considering the oscillations due to reactances, it is interaction between currents and voltages, damped by resistance, that stabilizes the final result. And any self-regulating interaction process is, analytically speaking, negative feedback. (So, fellow audiophiles, technically there's no such thing as a zero-feedback amplifier!)

A fellow engineer once witnessed positive feedback with resistors, producing sustained oscillation. Actually, this is unfair; the resistors were temperature-dependent; the circuit was an attempt to compensate some voltage-controlled RF device. One "resistor" had a strong positive temperature coefficient (TC); the other a strong negative one. The supplied voltage fed to these two in series was enough to significantly heat at least one element, thus changing its resistance. This changed the current, and therefore the heating of both itself and the other element.

The result was an oscillation of current and mid point voltage, frequency of about one cycle every 15 *minutes* (0.0011Hz), which lasted longer than the engineer's patience! The world's simplest ultra-low frequency oscillator—no transistors, no tubes! (You could call it a thermo-parametric oscillator.)

This example of unexpected feedback interaction with assumed-to-be-passive elements is not as remote from normal audio design as you may think—with high driving power, voice coils heat up and their resistance increases—oh, the possibilities!

Dennis Colin
Gilmanton, I.W., N.H.

Dick Pierce responds:

Oh, the possibilities indeed! The possibilities are endless.

Fortunately for us, the realities are far more limited.

First, a general comment on Mr. Colin's alternate explanation involving the notion of symmetry. It is certainly another valid approach to describing the situation, and is one that I am fully aware of and alluded to in the final section of my article in describing the inconsequence of identical non-resistive attenuators in series. The same holds for his comment about the electrical dual of a series connection driven by a voltage source versus parallel connection driven by a current source. My choice for the path taken was that it used the familiar Thiele-Small parameter set, the lingua franca of loudspeaker drivers.

However, the remainder of his comments take the discussion quite a ways away from reality in several aspects. Let's examine several of the flawed assumptions in his reply, because those assumptions are quite crucial to his premise.

Let's specifically examine one very important assumption, where he states "acoustic interactions are ignored." Unfortunately, the acoustic interactions cannot be ignored: at the frequencies we are talking about, these interactions not only cannot be ignored, they are important to the understanding of the situation.

Beyond that, Mr. Colin makes other assumptions that are physically difficult or impossible to realize. Take his example of two speakers in a sealed box having two different resonances. The resonant frequency arises from the interaction of the moving mass of the cone and the total compliance as seen by the cone: that includes the suspension compliance and the enclosure compliance. Moving mass is one of the easiest-to-control parameters in a loudspeaker: the variation in resonant frequency between otherwise identical drivers is due overwhelmingly to the variations in driver compliance.

Yet, Mr. Colin's example completely ignores the fact that in most cases today it is the enclosure compliance that is the controlling factor: thus, it is quite difficult to obtain the situation he describes, with two nearly identical masses seeing a common total system compliance. Expecting a sealed box with two drivers of the same model to have resonant frequency one-third octave apart is difficult to imagine, much less take as a serious challenge to the analysis presented. Indeed, I would say with all due respect, his example is highly unrealistic and at substantial variance with the actual behavior of multi-driver sealed box systems.

His example further purposely discards the mutual coupling between the drivers, which is significant at the resonant frequency of the system, unless Mr. Colin is suggesting placing these two drivers in a sufficiently large enclosure that the drivers are essentially uncoupled. That would suggest an enclosure size of a few yards for reasonable low-resonance woofers.

Other assumptions made by Mr. Colin bear some note. Take, for example, the notion that the difference in distance between the ports and the drivers, as a significant agent is, to be perfectly frank, far-fetched at best. At the frequency where the driver motional impedance is at its greatest, i.e., damping is significant, the wavelengths are substantially longer than the dimensions of the enclosure, the enclosure is working in pressure mode, and there, essentially, is no such distance issue.

Similarly, his comment about the difference that might arise because "damping material is more densely packed around one speaker" is highly unrealistic. First, as I am sure everyone is aware, the most significant mechanism for damping is the electrical loss in the speaker, followed by the mechanical losses, smaller by a factor of from 2 to 20. A very small part of the total dissipative mechanism that would have an effect on the driver are acoustic losses, suggesting that there would have to be a huge difference, more than would be realizable without someone being painfully aware of the difference when assembling the speaker, in the damping between the two speakers. Realize also the effects of such damping at the frequencies of interest: substantially less than at high frequencies. Lastly, who on earth would want to do such a thing purposely? Or what manufacturer would have such poor control over its assembly to allow such to happen?

Mr. Colin's comment that "electrical elements in series driven by a constant voltage source are actually a form of feedback stabilizing" is simply wrong. Feedback and feedback stabilization require effective power gain which is simply not relevant to the case at hand. The concept of "feedback" is one which is poorly understood in some corners of the hi-fi community, and is used as a bogeyman for explaining, inappropriately, all manner of problems, real and imagined. Indeed, you might even hazard to suggest that these wrong-headed notions of feedback are, in some respects, a cornerstone of high-end audio mythology.

His further comments on this topic once again ignore the reality that in the loudspeakers we use, the losses by far dominate and overwhelm the reactances, and the notion of coupled "active" oscillators, which his hypothesis implies, depends first upon the invalid assumptions of his feedback model and second on mechanical oscillators whose Q at resonance exceeds those of real drivers by orders of magnitude. In place of his RF parasitics, which can, in magnitude, exceed the bulk resistance of the resistors in his example, consider instead effective sizes of the reactive components represented by the mechanical *"parasitics" of real drivers and systems.*

Mr. Colin's hypothesis can be tested in practice: it leads to a set of behaviors that can be observed. In this sense, his hypothesis, no more or less than mine, is falsifiable: the proof is in the observational pudding. Probably the one example in my article that is the best candidate to support his hypothesis is the two separate speaker systems that are hooked in series: there is no common mutual capacitance and, if desired, the speaker can be separated by a distance to minimize the effects of mutual coupling. You do not, as a result, observe behavior other than what the model I presented predicts. This might suggest that some of the assumptions behind Mr. Colin's model need to be addressed. Occam, on the other hand, remains clean-shaven as always.

Yes, indeed, the possibilities. Physics has a way of winnowing the possibilities to manageable numbers, though.

OUTPUT BIASING

In response to a recent inquiry in this column regarding the use of individual versus common-cathode bias resistors in self-biased power amplifiers employing multiple output tubes, I would always use individual resistors and bypass capacitors on each tube. Use of a common-cathode resistor for two or, even worse, four tubes would aggravate mismatch between the tubes. With a common resistor, both or all four tubes are forced to operate at the same bias voltage, and if they are closely matched—meaning each tube draws the same cathode current at the same grid bias voltage—the total current would divide equally among them and everything would be fine.

However, if the tubes are not closely matched, one tube may draw considerably more current at the same bias voltage than the others, or conversely, need more bias voltage to reduce its current to that of the other tube(s). This tube would draw more than its share of current and force the voltage dropped across the resistor to be higher than normal. This, in turn, would bias the other tube(s) to a lower than normal current. Furthermore, since the value of the cathode resistor is one half (for two tubes) or one fourth (for four tubes) the resistance it would be for each tube individually, the tube drawing the high-

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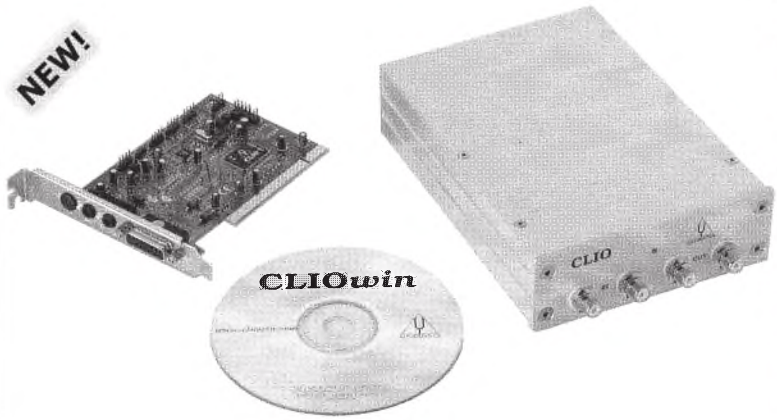

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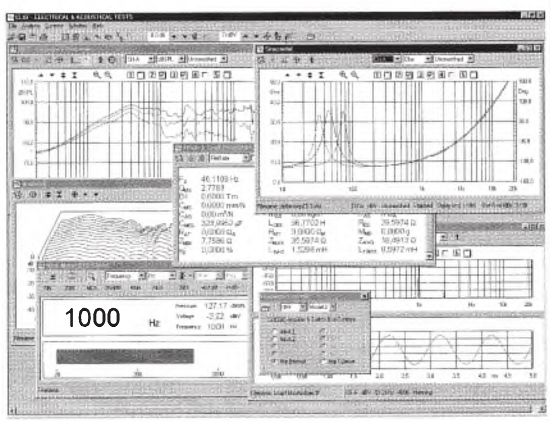

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er current would be less able to obtain the bias it needs.

As a result, in extreme cases, especially with four tubes on one resistor, the plate on the hog tube may glow red-hot, while the other(s) will be almost cut off. Providing a means to measure or compare the current drawn by each tube and adjust or balance these currents would be a solution to this problem, but it would be more complex than the individual resistors and bypass capacitors, and occasional measurement and readjustment would be needed.

With individual resistors, each tube could set its own bias independently and, to some extent, self-equalize. Imbalances can still occur, but not as much as with all tubes tied together, and you can easily detect these imbalances by measuring the cathode voltage on each tube. This also applies to push-pull drivers and other voltage amplifier stages, too.

The only time I use common-cathode resistors is in cathode-coupled long-tailed phase inverter and differential stages, where it is fundamental to the operation of the stage. Common-cathode resistors were generally used in the days when tubes were the cheapest (or only) way to amplify audio mainly for cost competitive reasons, but today, when tube amplifiers are a specialty, the added cost of a few extra resistors and capacitors is negligible.

Actually, fixed bias would be superior to self bias for power amplifiers, because the operating point will not shift with changes in signal level and tube current; more of the total B+ voltage would be available to the output tubes, resulting in more power with less distortion, and some electrolytic capacitors (the cathode bypass capacitors) would be eliminated from the signal path. However, the need to monitor the current and adjust the bias voltage of each tube is even more important for fixed bias than for self bias. For small (under 15 or so watts per channel) units intended for moderate volume levels in homes and other small spaces and where cost and minimal maintenance are important, individually self-biased output tubes would be a good choice.

Michael Kiley
Crestwood, Ill.

PAST AND PRESENT

While browsing through a copy of *audioXpress* several days ago, some thoughts crossed my mind. Current U.S. audiophile publications seem entirely devoted to reviewing equipment on the market and presenting little technical material beyond performance specifications plus reviewer comments. While *audioXpress* has some of this, it seems to me to be unique in having do-it -yourself construction and tutorial articles of interest to the serious hobbyist. There were past U.S. radio publications that devoted part of some issues to audio equipment construction, but to my knowledge they are no longer around. I believe the greatest contribution Audio Amateur Publications may have made—and is now making—is keeping interest in audio alive as a technical hobby.

My interest in audio goes back to my teen years, which began about 1940 when I built an amplifier using a pair of 45s in the output with parts mostly salvaged (scrounged) from old radios. My career as an engineer began in 1948 when I designed some components of a guided missile. Needless to say, design in the beginning involved vacuum tubes; later it involved solid state. Overall, I was at it for more than 40 years in one engineering capacity or another.

It is interesting to me to see renewed interest in vacuum tube amplifiers, and I believe that some opinions are not all on solid technical ground, but as hobbyists we are entitled to hear things that others may not, or may not exist at all. I am a little nostalgic, however. Tubes, unlike transistors, are forgiving even when operated so far above their ratings that the plates run a little red, but they usually survive.

I find it interesting that the audio hobby seems to have followed a path similar to that of ham radio. In the early days each was almost entirely a do-it-yourself hobby with high technical interest on the part of the builder. Kits appeared later, and became popular among those with little or no technical knowledge as well as those with experience; enjoyment probably came from having successfully built an operating system.

Currently audio equipment, like amateur radio equipment, is almost exclusively of commercial systems and components involving no more than interconnecting the parts. Interest seems not in the internal workings of the gear but enjoyment in listening (audio) or in communicating (ham radio). As hobbies, both have greatly changed from the early days.

I have subscribed to Audio Amateur publications since the 1970s and am privileged to have had articles published in them. I was an avid reader of *Audio Engineering* and at one time had issues going back to 1949. I don't have them anymore, but I now have each of the seven *Audio Anthologies*, obtained as they became available. The articles were by audio professionals and serious hobbyists, including C.G. McProud, the publisher.

When the publication name was later changed to *AUDIO*, it became somewhat less do-it-yourself and less technical, but I remember it having good equipment reviews and test reports and a quasi-technical article or two; I believe do-it-yourself was dropped later. I think *audioXpress* is much like *Audio Engineering*.

I am glad to see some of the great audio publications of the past such as Olson's *Acoustical Engineering* and Langford-Smith's *Radiotron Designers Handbook* and others being brought back by Audio Amateur Publications. Individuals interested in vacuum tube applications in audio would benefit from the latter.

The anthologies present a good panorama of audio as it developed over more than a decade. I obtained some of these publications, and others, about the time when they came out. I treasure my collection. I hope Audio Amateur Publications can get the rights to other great ones.

I think you and your staff are doing a fine job and wish you the best in the future.

J. Laurence Markwalter, Jr.
Port Charlotte, Fla.

THOR UPDATE

Since reading your article in the Sept. '02 issue ("Building the THORS," p. 14), I'm interested in how the THOR speakers sound now that they've settled in. The very favorable review by Dennis Colin (May '02) initially steered me towards this design (I've since noted there has been a mixed reaction from DIYers on the web). My problem is that I do not know of a finished pair here in Adelaide, South Australia, to audition. Your views would be immensely helpful.

Ross Yannis
Adelaide, South Australia

Edward T. Dell responds:

The THORs have improved, if anything, over the months since I completed building them. If the fact that this design was based on new, unprecedented transmission line research by G. L. Augspurger, the expert who evaluates speaker patents for both the Journal *of the Audio Engineering Society and for The Acoustical Society of America, and who for many years was production director for a very large speaker manufacturer, and that the design for THOR was done by one of the most well-known speaker designers on the planet, then I don't know what kind of pedigree you need to have confidence in a system. I do not, generally, put very much confidence in what I read on the web. At best it is a mixed bag ranging from genuine experts to totally uninformed folks who like to hear themselves talk.*

What I do put confidence in is the hour I spend each lunchtime since building the THORs, listening to CDs and for the last month to SACDs from a new Sony DVD player. This includes some 200 CDs so far. I have never heard this quality and resolution from any speaker system, either commercial or those I have built myself. The width of the frequency response—both at the top end and the bass—is without any competitors that I have listened to.

It is the most revealing speaker system I have ever heard. I am constantly surprised by what I hear. This is true for many CDs where the difference in recording methods is evident, sometimes painfully. I am beginning to note differences in microphone techniques. The regular CD issues from Nimbus, EMI, and Decca/London sound much better than many other brands. Only issues in the last year or two from DG sound worth listening to.

I very rarely use the cliche "awesome" about anything, and especially speakers. But the SACD reissue of Stravinsky's Rite of Spring *by Telarc rates that adjective, as does the Hohvaness "Mt. St. Helen's Symphony." The drums in both those recordings, as reproduced by the THORs and without a supplemental sub, are nearly overwhelming.*

I think highly enough of the THOR performance that I have plans in place to build another pair for an ambient system, powered by bi-amped Pass Zens.

Why not look for the Australian distributor for SEAS products and ask for any dealers who sell to DIY people who may have built the THORs. It is early days for this, since we published the original tests in May of 2002. However, I confidently predict that any DIY speaker enthusiast who carefully builds the THORS according to our published plans and uses decent power—even as low as 20W per channel—will be more than satisfied.

DIGITAL RIAA PLAYBACK

I wish to respond to a statement in Gary Galo's review (*audioXpress* Oct. '02) of the KAB preamp, which I quote from page 46:

"... Among the virtues of digital equalization is the lack of nasty phase shifts inherent in analog filters. In the case of playback curves, the lack of frequency-

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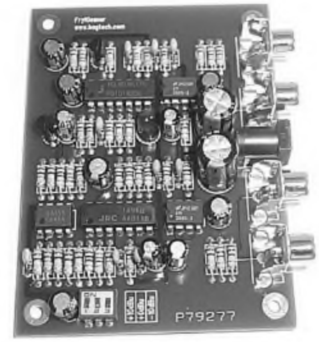

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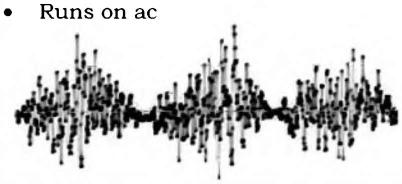

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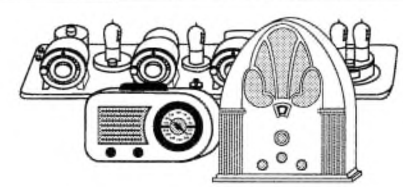

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dependent phase shifts presents a problem."

He goes on to say,

". . . It should certainly be possible to design digital filters to mimic both the phase and frequency characteristics of analog filters, but no one has done this commercially for playback equalization of disc records, as far as I know."

In my experience, the usual way of designing digital filters actually does mimic both the phase and amplitude characteristics of an analog filter as a function of frequency. So, it is quite easy to design a digital RIAA filter that does a highly precise job of compensating for this recording equalization on an LP.

The only issue is that the bass boost, combined with the treble rolloff, is likely to use up 40dB of the 90dB dynamic range available in 16-bit audio, leaving about 50dB with which to represent the signal after digital RIAA compensation. To work around this, it is preferable to convert the analog LP to digital form using a 24-bit digitizer, leaving about 60dB for representing the signal using commercial 24-bit sound cards.

The digital filter designer could probably adjust the digital equalizer's gain to preserve more than 50dB dynamic range with 16-bit recording, but you get the idea.

As for phase shift, I have designed a digital RIAA filter to be used on 44.1kHz audio samples in software, and I present graphs of only the error between the actual response and the ideal RIAA response.

Figure 1 shows the amplitude error, where the ideal response in dB was subtracted from the digital filter response in dB. The error is negligible up to a frequency of 10kHz, and by 20kHz the error is only +1dB. Since this is the range where most tweeters roll off, I don't consider this much of an error. The purist would sample at 96kHz, and the amplitude error up to 20kHz in this case would be effectively zero.

As for the phase error, this is shown in *Fig. 2*. There actually is a noticeable phase error because of the way digital filters behave as you approach the sampling frequency (even with pre-warping during the design). However, the curve of phase error is so close to a straight line that it looks like a pure delay, which is inaudible. The excess delay is about 15° at 20kHz, which I doubt is audible. Again, redesigning for 96kHz

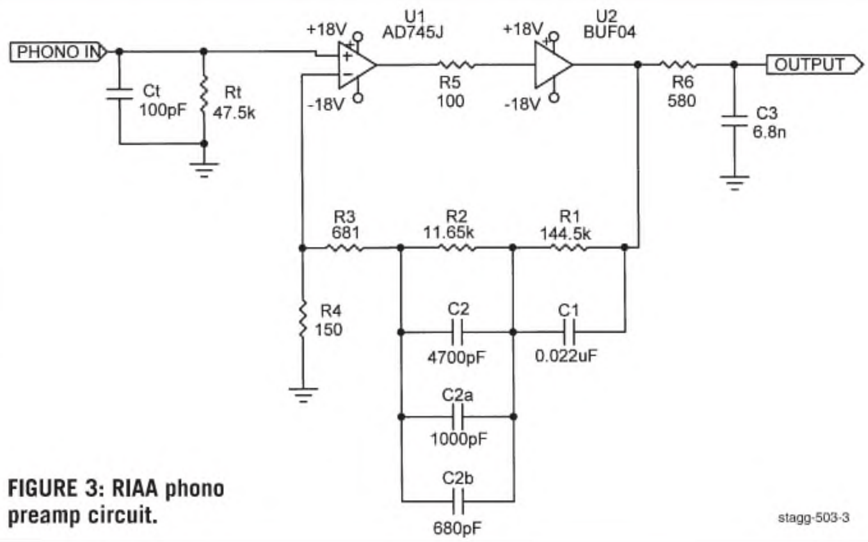

FIGURE 3: RIAA phono preamp circuit. stagg-503-3

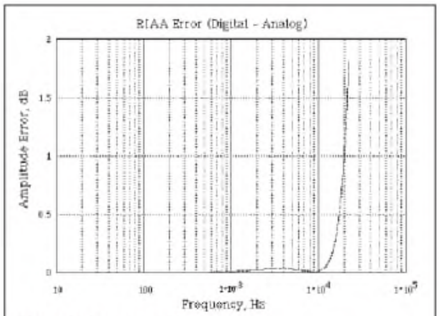

FIGURE 1: Amplitude error. stagg-503-1

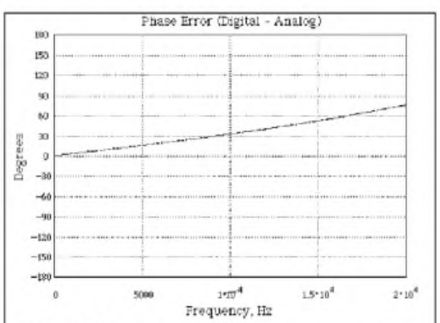

FIGURE 2: Phase error. stagg-503-2

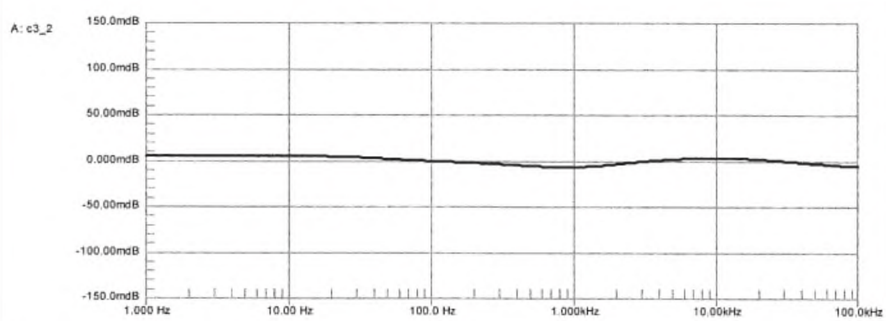

FIGURE 4: RIAA accuracy. galo-503-4

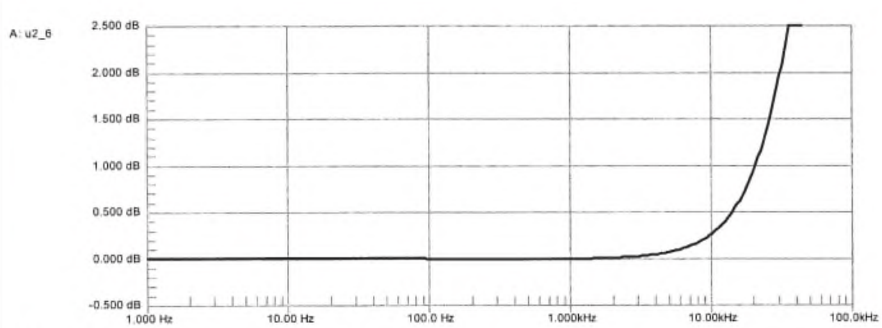

FIGURE 5: Response without equalization. galo-503-5

sampling will reduce even this error to effectively zero.

The only way to get non-analog phase response from a digital filter is to use non-analog design techniques. This is typically done in the antialias filters built into analog-to-digital converters in order to eliminate the large excess group delay inherent in steep filters, and similarly in the reconstruction filters in CD players.

It is even possible to use phase equalization techniques (without altering the amplitude response) on digitized LP tracks in order to improve the sound captured from some LPs, and I have done so. However, that is beyond the scope of this letter.

Victor Staggs
Torrance, Calif.

* Since I wrote this letter, a company has made a commercial software RIAA digital filter. The Griffin Technology Company, which makes monitor and sound adapters for the Macintosh computers, has released an RIAA equalizer digital filter to be used when importing LP recordings directly from a turntable, without any phono preamp. If you own their iMic sound input digitizer, the recording and equalization software is a free download at this date.

Gary Galo responds:

After receiving Victor Staggs' letter, I made inquiries to three of the leading manufacturers of digital editing equipment; namely, Sadie, Sonic Solutions, and Cedar. I asked them whether the algorithms for their digital equalization would mimic both the frequency and phase characteristics of analog filters. I also explained that I was specifically interested in phono equalization. I received no response from Cedar.

Ron Rigler of Sonic Solutions noted that they manufacture an equalization system specifically for RIAA de-emphasis. He further stated: "My understanding is that the filters are designed to mimic the phase response of an analog filter. You can use Desk Events or Complex Filtering in the background to produce any set of filters you desire."

Mike Porter of Sadie replied as follows: "The truthful answer is that we aren't 100% sure that the EQ does follow typical analog phasing characteristics. The EQ was designed several years ago before the "Linear Phase" phrase became a popular topic of discussion. We are fairly certain that "Linear Phase" was not designed in as a principal characteristic of our EQ. The gentleman who was the design engineer with Sadie at that time left the company a few years ago and we were not able to contact him."

So the answer to this question would seem to vary from one manufacturer to the next. I caution against using any digital equalization system for phono equalization without a guarantee from the manufacturer that their digital equalizers duplicate both the amplitude and phase characteristics of analog filters.

I agree with Dr. Staggs regarding the dynamic limitations of 16-bit digital audio. In professional workstations, and the best sound cards, 24-bit is now the norm, so this shouldn't be a concern.

However, I do not agree with Staggs on what constitutes sufficient accuracy in an RIAA equalizer. Long-time readers of these pages (I refer to the predecessor of aX, The Audio Amateur) *will recall the debates of the late 1970s and early 1980s regarding the audibility of differences between phono preamps. The view among some engineers was*

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that the only audible differences between phono preamps were those caused by errors in frequency response, phase, and absolute polarity. Those on the "golden-ear" side of the debate insisted that other, less easily quantifiable differences were also audible.

One thing that most audiophiles in both camps agreed on was the necessity of extremely accurate RIAA equalization, eliminating RIAA errors as a factor in LP reproduction. Errors of ±0.25dB are at the edge of acceptability, and for well over 20 years the better RIAA phono preamplifiers have generally offered accuracy to within ±0.1dB. Since Stanley Lipshitz published his paper "On RIAA Equalization" in the June 1979 issue of the Journal of the Audio Engineering *Society, the mathematics for designing extremely accurate RIAA networks has been readily available.*

As Lipshitz pointed out in his opening paragraph: "One fact, however, is indisputable, and that is that frequency response differences exceeding a few tenths of a decibel in magnitude between disk preamplifiers are audible. Such deviations tend to be broad band in extent, since they arise from gain and component errors within the RIAA deemphasis circuit." Lipshitz also points out that the additional high frequency time-constant, T6, inherent in feedback-based RIAA preamplifiers, can cause an audible rise in high-frequency response if not properly compensated.

I consider Dr. Staggs' RIAA accuracy to be unacceptable by either "scientific" or "golden-ear" standards. I doubt that very many audiophiles in either camp would consider the gradual rise in response in the top octave—a full 1dB at 20kHz—to be inaudible or otherwise of no consequence. In fact, it is an error very similar to what you can get if you ignore Lipshitz's T6 in a conventional analog RIAA de-emphasis circuit.

Figure 3 *is an RIAA phono preamplifier I designed a while back, using Analog Devices' AD745J op-amp as the gain block, buffered by their BUF04 closed-loop, current-feedback buffer. I designed the circuit for a 1kHz gain of 40dB. R3 satisfies the stability requirement of the AD745 (minimum voltage gain of 5), and I calculated the RIAA values using a spreadsheet I designed to do the Lipshitz math for all four RIAA topologies. The network R6/C3 compensates for T6. I have not dealt with the DC-offset issues here. Either a servo or an output coupling capacitor will be necessary. I have shown the parallel capacitor values necessary to make up C2, from available E12 values. R1 and R2 can easily be made from series or parallel combinations of E96 values.*

Figure 4 *shows a SPICE computer simulation of the RIAA accuracy, using a mathematically ideal RIAA emphasis model. As you can see, the circuit is capable of excellent RIAA accuracy, better than ±0.012dB.* Figure 5 *shows what happens to the RIAA accuracy when the R6/C3 network is eliminated. The RIAA response is up 1dB at 20kHz. If I were to publish such a circuit in these pages, I would probably be taken to task for a serious design oversight, and rightly so.*

I admit to being a purist, and agree with Staggs that a 96kHz sampling rate is probably a minimum requirement if RIAA EQ is to be done properly in the digital domain.

REVIEW AFTERWORD

I read and enjoyed your review of the K-12M stereo amplifier by S-5 Electronics. Your review was thorough and honest.

I was concerned about the part on the K-12M's muddy bass, which would probably be solved by an upgrade of the output transformers. Substituting those supplied with Hammond P-T1609s

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(10KCT: 4/8/16Ω) would clean up the bass.

It's also important to note that the 11MS8 is not a high-fidelity tube per se. It's a variation of 11BM8 (an 11-volt 6BM8). The 11MS8 and 11BM8/6BM8 were intended for single-end use in portable phonographs and tape recorders where chassis space is extremely limited. In this type of application, small speakers with limited frequency response were used anyway, so the 6/11BM8 filled the bill.

You had reported that the 11MS8 was made in Japan. Tubes produced in Japan have rated poorly in *VTV* (*Vacuum Tube Valley*) magazine's tube shootouts. It might help to replace those furnished with some purchased from Antique Electronic Supply—providing they're not just Japanese jobbers.

A similar kit, using 11BM8s, as opposed to 11MS8s, is available from AES for $140. While it costs $10 more, I would go with it. In addition to the earlier-mentioned opt upgrade, the 11BM8 is probably easier to obtain under additional brands names, making further experimenting possible.

Neal A. Haight
Castro Valley, Calif.

Duncan and Nancy MacArthur respond:

Thanks for your thoughtful comments on the S-5 amplifier.

We tend to agree with many of your ideas about parts with the caveat that sometimes parts choices are synergistic, and changing one may upset the balance of the whole. In the final analysis, it's the results that matter.

In particular, the transformer set would appear to be a weak point in this design. But good iron costs money, and each consumer will need to make decisions based on his or her own budget.

Our only experience with the AES kit is the description and small picture on their web page. It appears to be extremely similar to the S-5 and has the same designer. At any rate, the AES amplifier looks worth investigating if you're in the market for an amplifier in this price range.

We note that S-5 is now selling a case for the amplifier that appears to address many of our ergonomic concerns. As of now the existence of this case and the fact that we've heard it would tip the scales slightly towards the S-5 for us. (If you audition the AES, we'd be interested in hearing about your reaction.)

For more information, the websites are located at http://s5electronics.com/index.html and http://www.tubesandmore.com/.

SOFTWARE IDENTIFIED

Can you please tell me what software was used for circuit simulation in "A Passive, Low Level Crossover" (Nov. '02 *aX*, p. 16)? If it is not too much trouble, could you direct me to a vendor that sells this or a similar product to run these simulations.

David Miles
MilesAudio@aol.com

Cornelius Morton responds:

I used B² Spice by Beige Bag Software (www.beigebag.com, 734-332-0487, info@beigebag.com) for the simulation. Typing in "spice simulation" in the Google search window will bring up a ton of information and sites on SPICE simulators. A good start is the following link to a site listing numerous SPICE sources: http://www.et1.tu-harburg.de/private/kb/download.html.

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New Chips on the Block

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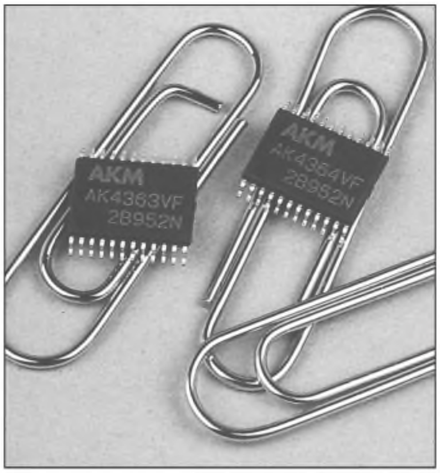
By Charles Hansen



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Book Review

Loudspeaker and Headphone Handbook

Reviewed by Richard Honeycutt

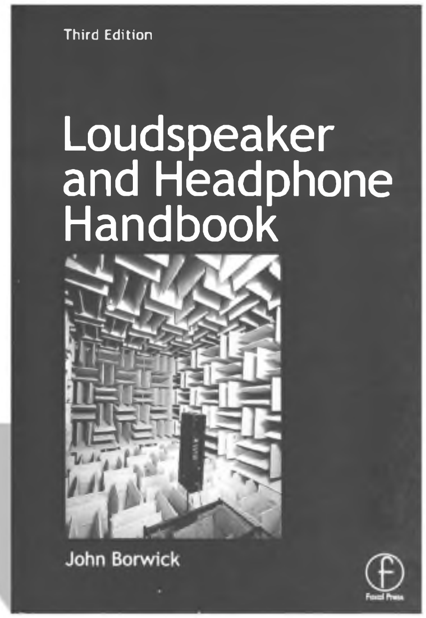
Loudspeaker and Headphone Handbook, *John Borwick, Ed., Focal Press, an Imprint of Butterworth-Heinemann, Linacre House, Jordan Hill, Oxford, OX2 8DP, UK; 225 Wildwood Ave., Woburn, MA 01801-2041, USA.* $120.

Perhaps the first in-depth book on loudspeakers was *Loudspeakers*, by N. W. McLachlan, published by Unwin Brothers in 1934. Since then, high-quality additions to the genre have been few and far between. Beranek's *Acoustics* and Olson's *Acoustical Engineering* each contained a treasure-trove of information, but neither was wholly dedicated to loudspeakers. Good books on headphones have been—to my knowledge—nonexistent, and even good papers on the subject in professional journals are not common.

First published in 1988, the *Loudspeaker and Headphone Handbook* jumps into the breach quite nicely. The current third edition contains the following chapters: Principles of Sound Radiation, Transducer Drive Mechanisms, Electrostatic Speakers, The Distributed Mode Loudspeaker (new to this edition), Multiple Driver Loudspeaker Systems, The Amplifier/Loudspeaker Interface, Loudspeaker Enclosures, The Room Environment: Basic Theory, The Room Environment: Problems and Solutions (these last two were a single chapter in the previous edition), Sound Reinforcement and Public Address, Loudspeakers for Studio Monitoring and Public Address, Loudspeaker Measurements, Subjective Evaluation, Headphones, International Standards, and Terminology. The third edition contains 718 pages, as compared to 592 for the second.

No single person could write equally well on all these subjects, so the *Handbook* is the product of specialists, each contributing one or more chapters. All are names well-known in the industry, including the late Peter J. Baxandall, Graham Bank, Mark Gander, Martin Colloms, Floyd Toole, and John Woodgate, to name a few.

This book covers principles, and it falls somewhere between being a design text and a general acoustics text. While it provides more depth and detail than the hobbyist books on the subject, it is certainly not a cookbook.



One example is the first chapter, which describes the principles of sound radiation, using an appropriate level of math (complex differential equations). The discussion is limited to mathematical models applicable to loudspeakers, and includes mention of the frequency range in which each model is useful. The chapter examines the effects of mutual coupling on frequency response and diaphragm loading, and discusses edge diffraction. It explains the function of a horn both as an impedance transformer and as a means of directional control, and discusses nonlinear propagation of sound in intense sound fields.

The chapter on transducer drive mechanisms begins with a short history of loudspeakers, then proceeds to discuss cone behavior, magnetism, several different magnetic field structures, interaction between the voice coil and the stationary magnetic field in a loudspeaker, the chassis, efficiency, power handling and dissipation, the dome driver, the horn driver, the ribbon speaker, modeling the motor, the compound loudspeaker, and motional feedback. As you can see, this chapter packs quite a bit of information into its 62 pages. So do the other chapters.

Another example is the chapter on headphones. On the one hand, it is only one chapter, but on the other, it is 108 pages long! Far from just cataloging the many ways that you can mount speakers in cans and strap them to your head, this chapter begins with a thorough discussion of the ways in which the acoustics of headphones differ from those of a loudspeaker—both from a design and a usage standpoint.

Next comes a section on modeling headphones, after which you are finally equipped to appreciate both the acoustical problems in headphone design and the ways in which the various realizations of headphones interact with the acoustic problems. This chapter presents sample low-frequency responses for closed circumaural, open foam circumaural, impermeable foam circumaural with fixed acoustical resistance, and integrated open headphones, then compares isodynamic and moving-coil transducers. It examines anomalies in response due to resonances involving the cushion/flesh resilience and the mass of the earcup, and studies in-ear phones.

This chapter provides a good bit of detail concerning the human hearing mechanism, especially in relation to the behavior of headphones. It discusses special-purpose phones, and, finally, describes headphone testing. From these two examples, you can see how much depth is provided in the *Handbook*.

Now, given the generous topical coverage, is there anything left out? Actually, not much. One important aspect of professional loudspeaker performance that tends to receive little coverage in the general press is directivity.

In the *Handbook*, while the information on directivity is spread among several chapters, it all sums to a pretty good outline of the subject. In particular, Peter Mapp's chapter on sound reinforcement and PA touches on most of the important considerations regarding directivity. You might hope for a complete chapter in a future edition devoted entirely to directivity, beginning with principles, and then moving to a discussion of cone drivers, horns, and various types of arrays. This sort of material is available, but has not been collected into a single reference.

The *Loudspeaker and Headphone Handbook* lends itself to numerous uses. The engineer who specializes in general electrical or mechanical engineering will find this book an excellent entré to speaker design.

To the practicing loudspeaker engineer, the book presents a helpful intro into the areas of speaker art and science with which (s)he may be unfamiliar. The engineer who designs electronic equipment that interfaces with loudspeakers, or the consultant whose work involves sound systems, can learn much that is important to their work. And the hobbyist (aren't most of us, really?) can develop a professional-like understanding. In addition, the generous end-of-chapter references lead you to information in further depth.

In short, this book should be in the library of every loudspeaker professional or enthusiast. ❖

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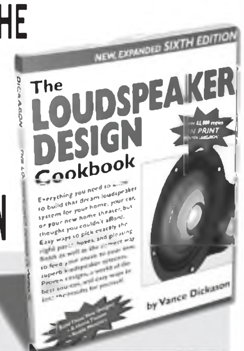

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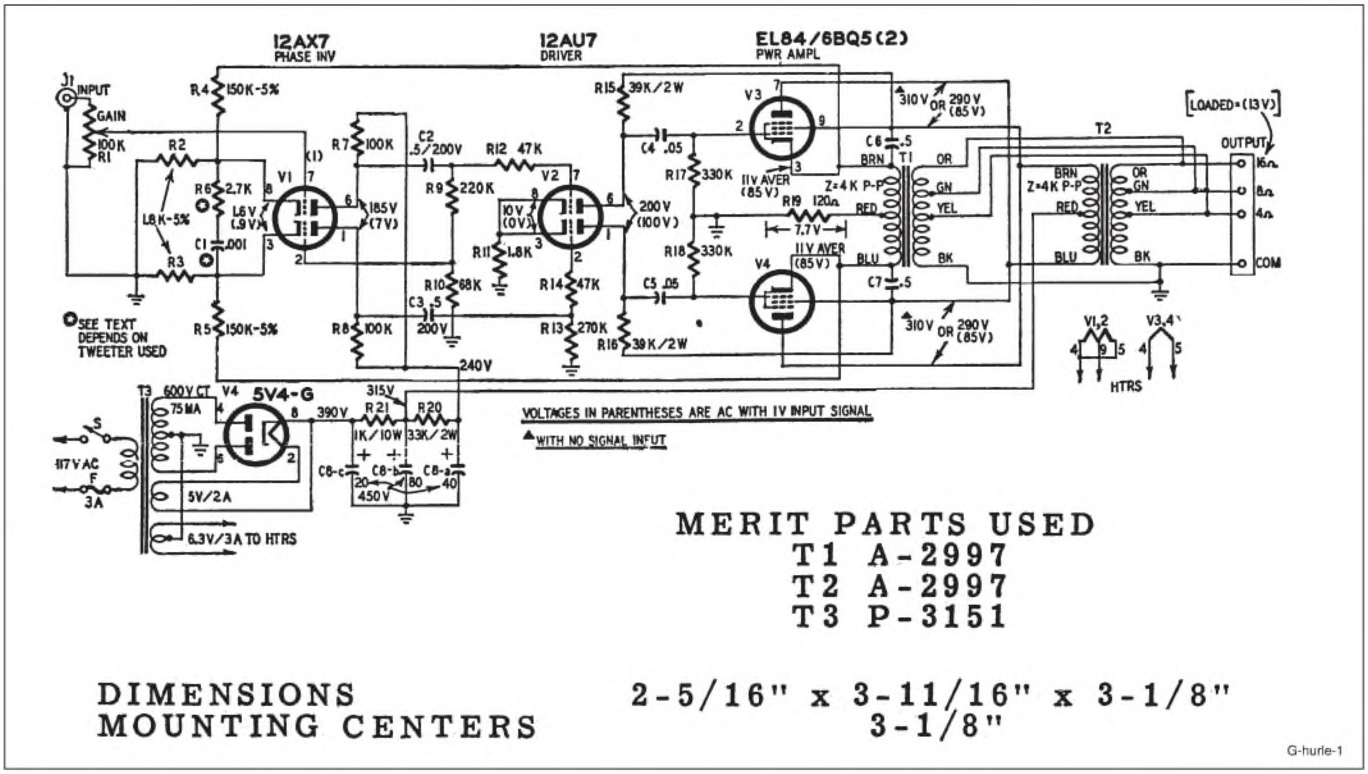

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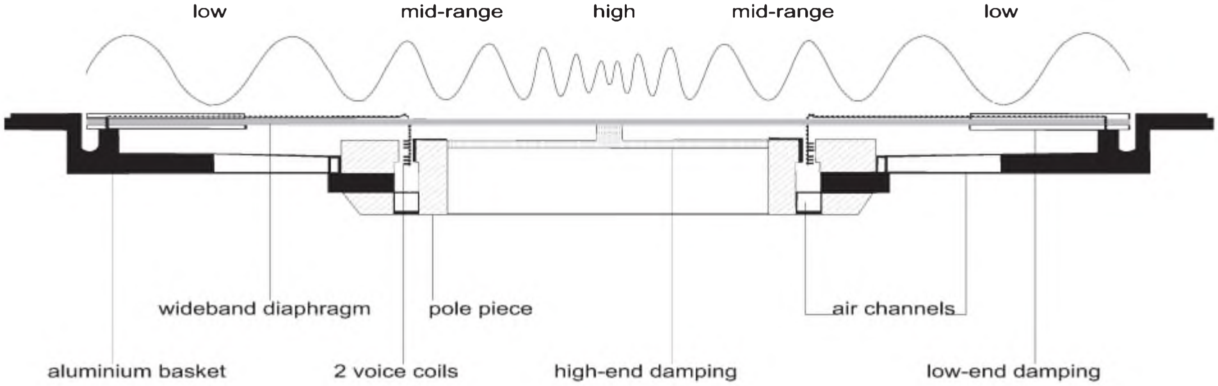

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