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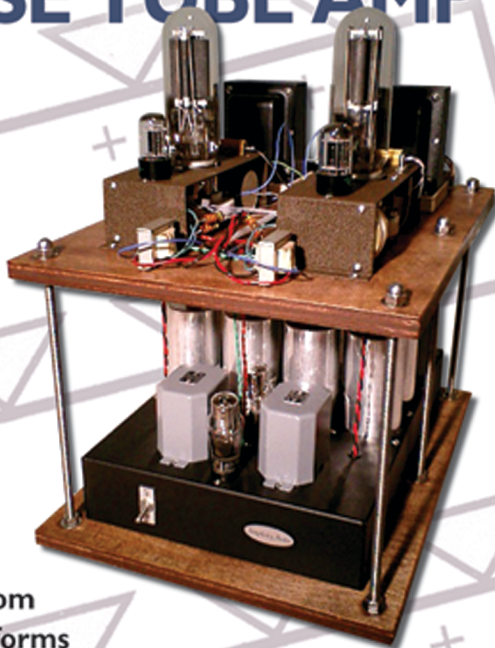


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A Phono PrePreamp for the (SA) CD Age, Part 1

By Norm Thagard

This three-part article takes a look back at a phono pre-preamp design featured in the premiere issue of *audioXpress*.

When re-published in *Electronics World* at the request of Ed Dell, my 2001 *audioXpress* phono pre-preamplifier design article¹ received a scathing condemnation by Douglas Self. The active-passive filtering was his principal stated objection. Brushing aside the example his review provided of the general decline in civility and addressing the objection itself, I decided to approach the design issue in the way that he apparently would. This approach is to generate the necessary poles and zero by active equalization in the feedback network around a gain block.

This article's title notwithstanding, the design described here should not be confused with a so-called "head amp." That term usually connotes a preamplifier with frequency-independent gain of ten or so that is designed to "bump up" the output of a low-output cartridge for

input into the MM phono input of a system preamplifier. Like my previously published "pre-preamp," this new offering provides RIAA compensation and, in this case, sufficient gain to drive a power amplifier directly, although most builders will probably opt to apply its output to one of the high-level (e.g., CD or tuner) inputs of a system preamplifier.

Although I made no specific attempt to optimize for input capacitance, another motivation for attempting a new design was knowledge gained from Raymond Futrell's useful article² indicating that cartridge interfacing might potentially be improved if input capacitance were reduced. My referenced design employed a complementary differential amplifier at the input, which is not optimal from the standpoint of capacitance. Therefore, I wanted to employ a single-ended topology in the first stage as a design exercise.

As is my usual practice, I shall attempt to explain the design process and principles thoroughly and provide derivation of those design equations that were not addressed in earlier articles. I attempt to limit equations to the algebraic variety unless there is absolutely no choice. I hope that this series of articles will have use as tutorials even if you do not construct the circuits described herein.

Increasingly, I am emboldened to attempt the derivations myself rather than by reference to a text or paper. Despite holding a terminal degree in medicine, I did, after all, begin life as an electrical engineer. But for the closure of the engineering science school at Florida State University in 1972 five quarters into my Ph.D. program, I would today be a Ph.D. electrical engineer rather than an M.D. Even so, with no one to proof these exercises, I expose myself to serious mistake.

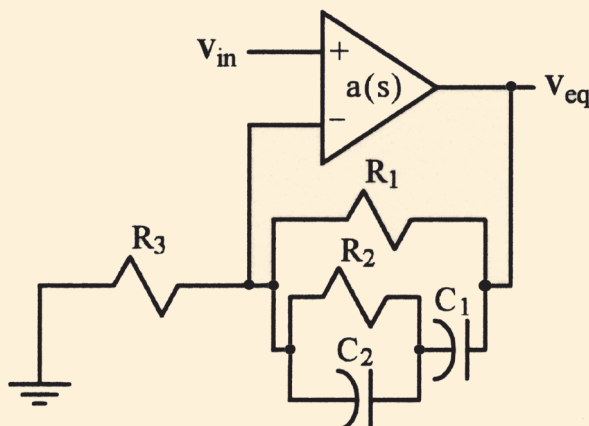
I welcome constructive criticism, and it is in all our interests to correct such mistakes quickly for the sake of the reader and experimenter. Whether my explanations of circuit operation are entirely correct, every design to date has been objectively tested on the bench and subjectively evaluated in a quite good stereo system for a reasonable period before publication.

THE TOPOLOGY, DERIVING THE EQUATIONS

In an article in *TAA*,³ Reg Williamson looked at methods of RIAA equalization through frequency-dependent feedback networks of gain blocks, including the noninverting configuration depicted in Fig. 1. He also provided the necessary formulae for calculating the component values.

I never believe I really understand something unless I can work through

FIGURE 1: RIAA compensation by the feedback network of a noninverting phono preamplifier.



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the derivations myself. For this reason and because I took a slightly different approach to component selection, I offer the following development of the design steps beginning with the impedance of the $R_1R_2C_1C_2$ network in **Equation 1**.

The feedback fraction—i.e., that portion of the output voltage applied to the inverting input—is shown in **Equation 2**.

Both numerator and denominator can be factored as $(s/s_1 + 1)(s/s_2 + 1)$. These factors, when equated to zero, yield zeros from the numerator and

poles from the denominator for the feedback fraction. From analysis of the closed-loop circuit, if open-loop gain $a(s) \gg 1$, then closed-loop gain $A(s) \equiv 1/\beta(s)$, and the zeros become poles and the poles become zeros in the closed-loop response.

The Laplace complex frequency value corresponding to DC is $s = 0$. Substituting this value in the impedance expression makes Z and the bracketed term in the feedback fraction equation identically one. Thus, DC gain is $A_0 \equiv A(0) \equiv 1/\beta(0) = (R_1 + R_2)/R_3 = 1 + R_1/R_3$. You

should recognize this as the gain of an ideal op amp in a noninverting configuration, and it is simply the inverse of the R_1, R_3 voltage divider ratio as expected from feedback theory. That this is true is obvious from the schematic because C_1 and C_2 are open-circuits at DC, thereby effectively removing themselves and R_2 from the circuit.

Making the substitution $j\omega$ for s in the numerator yields $(j\omega/\omega_1 + 1)(j\omega/\omega_3 + 1)$ or, alternatively, $(j\tau_1\omega + 1)(j\tau_3\omega + 1)$. In this case, the numerical values of these time constants are known because they are dictated by the RIAA equalization criteria. The numerator should yield the RIAA poles at 50.05Hz ($\tau_1 = 3,180\mu\text{s}$) and 2,122.06Hz ($\tau_3 = 75\mu\text{s}$). You can similarly write the denominator as $(j\omega/\omega_2 + 1)(j\omega/\omega_4 + 1)$ or $(j\tau_2\omega + 1)(j\tau_4\omega + 1)$. This must yield the RIAA zero at 500.5Hz ($\tau_2 = 318\mu\text{s}$).

The second zero, whose time constant is represented by τ_4 , is not part of the RIAA equalization but rather is the inevitable result of the impedance network shown. The only way to keep τ_4 from significantly affecting the in-band RIAA response curve is to make it as small as possible—i.e., to place $f_4 = \omega_4/(2\pi)$ as far above 20kHz as practicable.

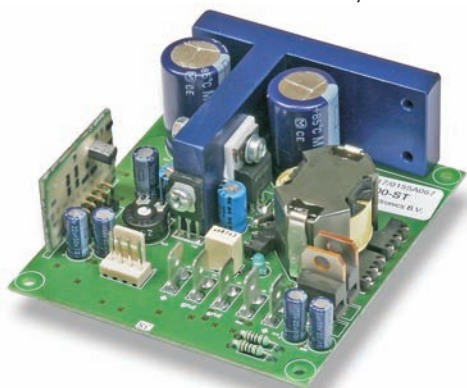
The task is to derive relationships for the determination of the five component values based on the three known time constants and the desired gain. Although it is the 1kHz gain that is usually specified, it is easier in this approach to specify the DC gain. There is no standard for absolute gain anyway, and the 1kHz gain should be 19.3dB less than the 20Hz gain, or about ten times less than A_0 .

Following gain specification, R_3 is often picked as a first component value selection on the basis of a compromise between a small value for minimum noise and a large value to preclude excessive loading of the amplifier's output by low feedback network impedance⁴. Ideally in a voltage amplifier, the feedback network would have infinite input impedance to preclude such loading effects and zero output impedance so that its (the feedback network) output is not loaded down by the impedance of the node to which feedback is applied. Once R_3 is select-

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ed, then $R_1 = (A_0 - 1)R_3$.

Note that the numerator is as shown in **Equation 3**. From this, it is apparent that:

$$(A) \tau_1 \tau_3 = R_1 R_2 R_3 C_1 C_2$$

$$\text{and (B) } \tau_1 + \tau_3 = R_1 C_1 + R_2 (C_1 + C_2)$$

Since τ_1 and τ_3 are the time constants of the RIAA response poles and R_1 would have been previously determined, there are three unknowns and only two equations. However, a similar operation on the denominator gives:

$$(C) \tau_2 \tau_4 = \frac{R_1 R_2 R_3 C_1 C_2}{R_1 + R_3}$$

and (D)

$$\tau_2 + \tau_4 = \frac{R_1 R_3 C_1}{R_1 + R_3} + R_2 (C_1 + C_2).$$

Time constant τ_2 corresponds to the RIAA response zero, so there are four independent equations in four unknowns. You can calculate the remaining undetermined component values and time constant τ_4 , albeit not without some algebraic manipulation of these equations. For example, you can rearrange equation (A) as $R_2 C_1 C_2 = \tau_1 \tau_3 / R_1$, with this substitution then made in equation (C) to yield **Equation 4**.

This is useful because it shows that

the second zero, which is not part of the RIAA equalization scheme, can only be pushed to a higher frequency by increasing A_0 . The values for R_2 , C_1 , and C_2 remain to be determined.

From equation (B), $R_2 (C_1 + C_2) = \tau_1 + \tau_3 - R_1 C_1$. You can substitute this result into equation (D) to eliminate unknowns R_2 and C_2 (**Equation 5**).

Again, from equation (B), $R_2 = (\tau_1 + \tau_3 - R_1 C_1) / (C_1 + C_2)$. Substituting this into equation (A) yields **Equation 6**.

Now that only R_2 remains to be determined, any of the four equations can be used. Equation (A) is the simplest:

$$R_2 = \frac{\tau_1 \tau_3}{R_1 C_1 C_2}.$$

It is an easy matter to march through the succession of equations just derived until all component values have been determined. The disadvantages of the equalization method used here are the interdependence of component values with gain and the production of a possibly unwanted zero at $f = 1/(2\pi\tau_4)$.

There is an argument that setting $\tau_4 = 3.18\mu\text{s}$ compensates nicely for the pole introduced by the cutting lathe. This would dictate the value of A_0 with the compensation network used here, but a modification to this network would allow independent setting of A_0 and τ_4 . I have not elected to do this, so the zero represented by τ_4 must be well above 20kHz in order to minimize its effect upon equalization in the audio band.

For the usual moving-magnet cartridge, $A_0 = 60\text{dB}$ seems to be a good choice. If it is less than this, then in my limited experience there is a significant disparity in volume control settings between phono and high-level sources. For my original phono preamp, I increased midband gain to 50dB to account for the use of first a Grado Sonata low-output moving-magnet cartridge and then an Audio-Technica OC9/MLII moving-coil cartridge. Even at this level, the volume disparity was significant because both cartridges output only 0.4mV at 5cm/s at 1kHz.

Ultimately, $|Z| \rightarrow 0$ and the feedback network will load the preamp's output with R_3 . This is readily seen by reference once again to the schematic, noting that C_1 and C_2 become short-circuits as $f \rightarrow \infty$, effectively producing a voltage follower whose output is shunted with R_3 . This is the effect that produces τ_4 .

One of the objections to this approach to equalization is exactly that the noninverting configuration becomes a voltage follower. RIAA equalization would allow gain to decrease indefinitely rather than have a minimum value of one. Maybe the various objections to this, that, or the other topology and/or equalization scheme are valid, maybe not.

For example, gain of the inverting configuration can continue to fall indefinitely with increasing frequency, a clear advantage over the noninverting configuration, at least in this regard. The inverting configuration can be realized by removing the ground at the left side of R_3 and applying the cartridge output there instead. The noninverting input is then grounded, producing a virtual ground at the inverting input due to feedback. R_3 now sets the input resistance of the phono preamplifier. For a moving-magnet design, cartridge interface requirements may dictate a value as high as $R_3 = 47\text{k}\Omega$, with the noise generated by this high resistance input directly to the preamp.

The input resistor in the noninverting configuration is shunted by the low or relatively low resistance of the cartridge and is therefore not usually a major contributor to noise. This is a clear disadvantage of the inverting relative to the noninverting configuration

Equation 1.

$$Z = R_1 \left\| \frac{1}{sC_1} + R_2 \left\| \frac{1}{sC_2} \right\| \right\| = R_1 \frac{R_2 (C_1 + C_2) s + 1}{R_1 R_2 C_1 C_2 s^2 + [R_1 C_1 + R_2 (C_1 + C_2)] s + 1}.$$

Equation 2.

$$\beta(s) = \frac{R_3}{R_3 + Z} = \frac{R_3}{R_1 + R_3} \left\{ \frac{R_1 R_2 C_1 C_2 s^2 + [R_1 C_1 + R_2 (C_1 + C_2)] s + 1}{\frac{R_1 R_2 R_3 C_1 C_2}{R_1 + R_3} s^2 + \left[\frac{R_1 R_3 C_1}{R_1 + R_3} + R_2 (C_1 + C_2) \right] s + 1} \right\}$$

Equation 3.

$$\frac{1}{\omega_1} \frac{1}{\omega_3} (j\omega)^2 + \left(\frac{1}{\omega_1} + \frac{1}{\omega_3} \right) (j\omega) + 1 = \tau_1 \tau_3 (j\omega)^2 + (\tau_1 + \tau_3) (j\omega) + 1.$$

Equation 4.

$$\tau_2 \tau_4 = \frac{R_1 R_3 (\tau_1 \tau_3 / R_1)}{R_1 + R_3} \Rightarrow \tau_4 = \frac{R_3}{R_1 + R_3} \frac{\tau_1 \tau_3}{\tau_2} = \frac{1}{A_0} \frac{\tau_1 \tau_3}{\tau_2}.$$

when used for moving-magnet cartridges. Even if R_3 is small—as it might be to interface with a moving-coil cartridge—there is the problem that R_3 is in series with the cartridge impedance Z_g , which perhaps could significantly affect gain and equalization.

Practically speaking, the approaches that have been used historically have all worked more or less satisfactorily, and the shortcomings of a given approach, if properly managed, tend to have little significance to the listener, at least on a verifiable basis. Therefore, no one should assume for him or herself the mantle of arbiter of phono preamp design.

HEADROOM

Another design factor is accommodation of the highest signal levels that will be encountered. Simply put, the phono preamplifier's output must have reasonably low distortion under any and all conditions of normal use.

Stylus velocities produce proportional voltages that are then amplified by the phono preamplifier. To determine

whether the preamplifier will potentially have a problem, you must consider the maximum velocities that can occur at all frequencies in the audio band. This requirement results from the RIAA response of the preamplifier.

To understand this better, consider that one author reported that in research in the Shure Labs, velocities of 50cm/s at high frequency were not rare and 25cm/s at 1kHz was frequently seen⁵. The modern Shure V15VxMR MM cartridge has 1kHz output of 3mV RMS at a stylus velocity of 5cm/s, so at 25cm/s it would produce 15mV RMS. The MM preamp variant presented in this article, with approximately 40dB gain at 1kHz, would produce about 1.5V RMS output from this input. The

author then states that headroom of 20dB is essential, meaning that the preamp should be capable of producing 15V RMS at 1kHz with reasonably low distortion.

Such a preamplifier must have power supply voltages in excess of $2 \times 15 \times \sqrt{2} = 42.5\text{V}$ or $\pm 21.25\text{V}$. It should be emphasized that this is the 1kHz headroom requirement. Potentially, it could be even higher at other frequencies because preamplifier gain rises below 1kHz while above this frequency velocities would tend to increase, all other things being equal. This can be thought of as a slew rate problem. A sine wave of frequency f would have maximum velocity of $2\pi A_{\max} f$, where $A_{\max}$ is the highest amplitude (displacement) pro-

Equation 5.

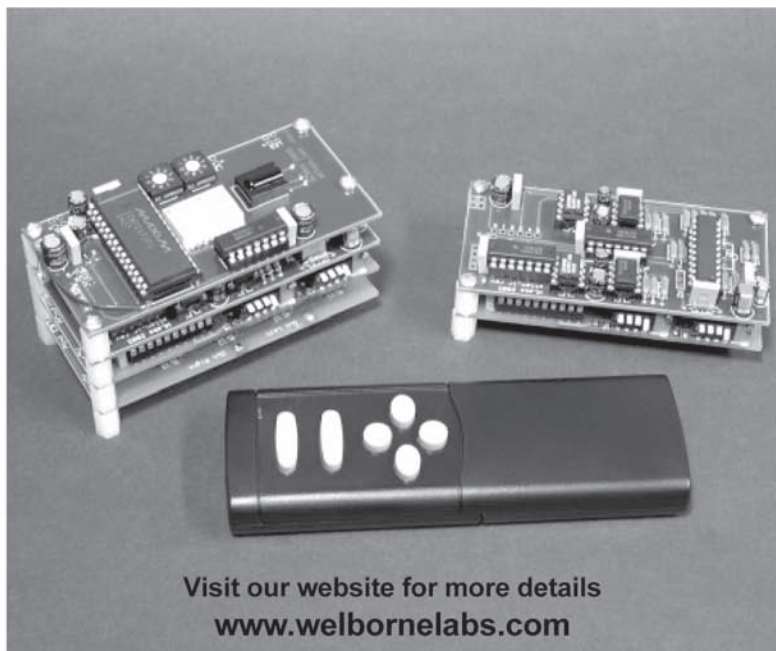
$$\tau_2 + \tau_4 = \frac{\kappa_I R_3 C_I + (R_I + R_3)(\tau_I + \tau_3 - R_I C_I)}{R_I + R_3} \Rightarrow C_I = \frac{(\tau_I + \tau_3 - \tau_2 - \tau_4)(R_I + R_3)}{R_I^2}$$

Equation 6.

$$\tau_I \tau_3 = R_I \left(\frac{\tau_I + \tau_3 - R_I C_I}{C_I + C_2} \right) C_I C_2 \Rightarrow C_2 = \frac{\tau_I \tau_3 C_I}{R_I C_I (\tau_I + \tau_3 - R_I C_I) - \tau_I \tau_3}$$

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duced at frequency f . Fortunately, it probably is reasonable to assume that satisfaction of the 1kHz criterion is sufficient due to lower recording levels at low frequency and lower preamp gain at high frequency⁶.

Given the unappealing power supply voltage requirement, I decided to take another look at the argument. On the Shure website, trackability for the V15V × MR in units of cm/s peak velocity was given as 30cm/s at 400Hz, 46cm/s at 1kHz, 80cm/s at 5kHz, and 60cm/s at 10kHz, all measured at 1 gram

tracking force. Shure rightly claims that their cartridge is among the best, if not *the* best, in terms of trackability. In my mind, if these results are accepted, it should be sufficient to base preamp headroom requirements upon them with perhaps some margin. It does not seem reasonable to levy a requirement upon the preamp that significantly exceeds the capability of the cartridge.

The preamp design offered here can produce low distortion outputs in excess of 12V RMS at all audio frequencies. Even assuming output limited

to 10V RMS, the MM-optimized variant would have headroom of 11.1dB at 400Hz. This is calculated as follows:

$\text{Gain}_{\text{dB}} \text{ at } 400\text{Hz} = \text{Gain}_{\text{dB}} \text{ at } 1\text{kHz} + 3.8\text{dB (RIAA-specified)} \approx 43.8\text{dB}$, which is 155 numerically.

$\text{Output voltage} = \text{numerical gain} \times \text{cartridge output} = 155 \times [(3\text{mV RMS}/5\text{cm/s}) \times 30\text{cm/s}] = 2.79\text{V RMS}$.

$\text{Headroom}_{\text{dB}} = (\text{maximum preamp output}/\text{actual output})_{\text{dB}} = 20\log(10\text{V RMS}/2.79\text{V RMS}) = 11.09\text{dB}$.

This result assumes that 400Hz cartridge output is the same as 1kHz output for the same velocity, a fair assumption if the cartridge is, indeed, a velocity-responding transducer. Similar calculations indicate that headroom is 11.2dB at 1kHz, and 14.6dB at 5kHz.

Assuming order-of-magnitude lower moving-coil cartridge voltages and order of magnitude greater MC preamplifier gain, headroom should be approximately the same in both cases. Due to loading of the output at high frequency by the feedback network, the initial moving-coil design could not slew fast enough at 10kHz to provide low distortion output above 8V RMS, and at 20kHz, the useful output was reduced to just 4.5V RMS. It is clear from this pattern that this should be no problem. In addition, studies have shown that there is little acoustic energy above 10kHz.

However, knowing that there would be criticism for this shortcoming, I increased second stage current levels enough to eliminate slew-rate limiting at audio frequencies. Fortunately, the resulting quiescent current levels were not so high as to require heatsinks for the transistors, although they do become quite warm. I chose to use small heatsinks anyway because I'm a conservative at heart. These heatsinks are grounded, thereby requiring insulation of the transistors from the metal sinks.

Obviously, this preamp does not meet the 20dB headroom requirement, but bear in mind that the calculated headroom is in excess of the *cartridge's* trackability limit. Well below the point where velocities are forcing this pre-

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amp into clipping, the stylus would have ceased to accurately track the groove and significant distortion would already be apparent. Perhaps tracking distortion is less objectionable than preamp distortion but I doubt it, especially given the “graceful” clipping that is seen on the oscilloscope.

As a matter of practicality, I ran the output of a Shure V15 Type V MR cartridge into the MC version of the preamp described in this article. Despite the very high gain and high cartridge output, on the oscilloscope I saw few peak voltages approach the clipping level (approximately 17V) and heard nothing abnormal in the sound while listening to several records with moderate to high recording levels. The preamp’s input resistance was set to 47kΩ per Shure’s recommendation prior to the test. This certainly seems to indicate that practical headroom of the MC version will be much more than sufficient in normal use with a low-output cartridge.

Admittedly, some magnetic cartridges have outputs in excess of 3mV at 5cm/s, but probably do not produce usable output significantly exceeding the levels just considered. In any event, it is possible to meet any requirement by either increasing power supply voltages or by reducing gain. The design for the former is more difficult than for the latter.

MOVING-MAGNET DESIGN

As an example, consider a design suitable for moving-magnet cartridges. $R_3 = 499\Omega$ is a reasonable value. It follows that for approximately 40dB gain at 1kHz, $R_1 = R_3(A_0 - 1) = 499\Omega(1000 - 1) \approx 499k\Omega$.

From the previously derived formulae, see **Equation 7**.

MOVING-COIL DESIGN

To accommodate moving-coil cartridges, consider a second design example. I’ve mentioned without elaboration that noise considerations lead you to make R_3 as small as possible. Noise abatement requires more attention not only due to higher gain, but also because cartridge resistance is generally lower. This latter fact means that resistances in the input stage must be kept correspondingly small, otherwise their noise will significantly lower signal-to-noise (SNR) ratio.

The spec sheets for the Audio-Technica OC-9/MLII and the Shelter 501 moving-coil cartridges that I own both indicate that 100Ω input resistance is optimal when used with a “head amp” or 20Ω when used with a step-up transformer. The resistance (d.c.r.) of the OC-9/MLII is about 10Ω. I chose $R_3 = 5\Omega$, knowing in advance that this would tax my design skills, but nonetheless I wanted to use a value no more than that of al-

most any cartridge. $A_0 = 80dB$ provides an order of magnitude greater gain than for the moving-magnet design.

The OC-9 and Shelter 501 have 1kHz outputs of 0.4mV at 5cm/sec, about 1/10 that of a Shure V15, so the extra gain should compensate nicely for the lower output. The choice of 5Ω for R_3 then dictates $R_1 = R_3(A_0 - 1) = 5\Omega(10,000 - 1) \approx 49.995k\Omega$. The closest 1%-tolerance value is 49.9kΩ.

At this point, I should mention that the amount of feedback is given by the difference between open- and closed-loop gain and is therefore not effective unless $|a(s)| \gg |A(s)|$. This requirement is the basis of a major problem with deriving all RIAA poles and zeros by feedback around a single gain block, especially for a moving-coil preamplifier. If $A_0 = 80dB$ (10,000), then satisfaction of the above inequality probably means that $|a(j\omega)|$ should be at least 100dB (100,000). Such gains are easily achieved with some op amps but can pose a problem for simple discrete designs.

Audiophiles usually prefer simple, yet high-performance designs. I accepted as a design challenge the task to realize a well-performing circuit in a two-stage gain block, although admittedly the two stages are both cascodes and therefore *compound* stages. A measure of open-loop gain adequacy at all audio frequencies is accuracy in tracking the RIAA curve.

The design tracks within 0.1dB in the 20Hz – 20kHz band, which is a good sign. However, feedback is squeezed at 20Hz, so it would not be unexpected that distortion might be proportionally higher at low frequency. The remaining component values are calculated as shown in **Equation 8**.

The *RC* time constants must remain the same, so if resistance values fall, capacitance values must rise by the same factor. Of particular interest is the very small value of τ_4 due to the very high gain. This time constant corresponds to a frequency of 2.12MHz. This is so far above the audio band that no significant effect on equalization should be manifest.

As always, there is no opportunity to use custom parts, so the values used in the prototype were $C_1 = 56nF$, $C_2 = 20nF$,

Equation 7.

$$\begin{aligned}\tau_4 &= \frac{R_3}{R_1 + R_3} \frac{\tau_1 \tau_3}{\tau_2} = \frac{499\Omega}{499k\Omega + 499\Omega} \frac{(3,180\mu s)(75\mu s)}{318\mu s} = 750ns, \\ C_1 &= \frac{(3,180\mu s + 75\mu s - 318\mu s - 0.74925\mu s)(499k\Omega + 499\Omega)}{(499k\Omega)^2} = 5.89nF, \\ C_2 &= \frac{(3,180\mu s)(75\mu s)(5.89nF)}{(499k\Omega)(5.89nF)[3,180\mu s + 75\mu s - (499k\Omega)(5.89nF)] - (3,180\mu s)(75\mu s)} = 2.04nF, \\ R_2 &= \frac{(3,180\mu s)(75\mu s)}{(499k\Omega)(5.89nF)(2.04nF)} = 39.8k\Omega.\end{aligned}$$

Equation 8.

$$\begin{aligned}\tau_4 &= \frac{5\Omega}{49.9k\Omega + 5\Omega} \frac{(3,180\mu s)(75\mu s)}{318\mu s} = 75ns, \\ C_1 &= \frac{(3,180\mu s + 75\mu s - 318\mu s - 74.925ns)(49.9k\Omega + 5\Omega)}{(49.9k\Omega)^2} = 58.9nF, \\ C_2 &= \frac{(3,180\mu s)(75\mu s)(58.9nF)}{(49.9k\Omega)(58.9nF)[3,180\mu s + 75\mu s - (49.9k\Omega)(58.9nF)] - (3,180\mu s)(75\mu s)} = 20.4nF, \\ R_2 &= \frac{(3,180\mu s)(75\mu s)}{(49.9k\Omega)(58.9nF)(20.4nF)} = 3.98k\Omega.\end{aligned}$$

and $R_2 = 4.02\text{k}\Omega$. There is a greater choice of resistor values than capacitor values, so if "tweaking" is required to achieve closer RIAA tracking, choose the capacitor values and then substitute different resistor values close to the calculated ones. It is always possible to "trim" values by series-parallel combinations of stock components to achieve any desired degree of accuracy.

NOISE CONSIDERATIONS

Open-circuit resistor "Johnson noise" is given by $V_{nR} = (4kTR)^{1/2} \text{ V/Hz}^{1/2}$. Since power is proportional to the square of voltage, the equation implies equal power per hertz of frequency. This component of resistor noise is said to be "white noise." The term "this component" was used intentionally, because while any resistance will have associated with it this noise term, resistors may have other noise components as well, producing "excess noise," i.e., noise above and beyond the resistance-dependent white noise just described. If low-noise were a design requirement⁷, you would probably choose wirewound

and metal film resistors, which exhibit less excess noise than carbon resistors.

While it seems intuitive that resistor noise would be proportional to resistance, at first glance it seems paradoxical that R_3 would be one of the bigger noise sources, especially given that it is small in comparison to its feedback network partners, R_1 and R_2 . However, R_3 noise voltage, given by $e_{n-R3} = (4kTR_3)^{1/2} = [4(1.38 \times 10^{-23} \text{ joules/}^\circ\text{K})(300.16^\circ\text{K})(5\Omega)]^{1/2} = 2.88 \times 10^{-10} \text{ V/Hz}^{1/2}$, is applied directly to the inverting input to be amplified by the closed-loop gain from that input. At 20Hz, the C_1 , C_2 , R_2 branch has little effect, gain is nearly 10,000, and RMS noise level slightly less than $2.88 \times 10^{-6} \text{ V/Hz}^{1/2}$ appears at the output due to R_3 .

This squares (no pun intended) reasonably well with the PSpice-predicted noise value of $7.909 \times 10^{-12} \text{ V}^2/\text{Hz}$. In fact, the PSpice-calculated gain at 20Hz is 9,769 due to the fact that open-loop gain is not infinite and some shunting due to the C_1 , C_2 , R_2 branch occurs. Using this gain value yields output noise of $(9,769 \times e_{n-R3})^2 = 7.906 \times 10^{-12}$

V^2/Hz , giving some comfort that the analysis so far is correct.

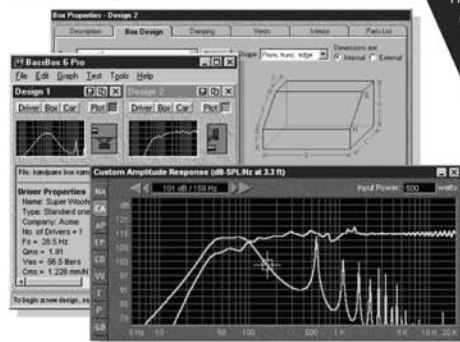
Anyhow, to continue, R_1 's noise influence is primarily due to noise current $i_{n-R1} = e_{n-R1}/R_1 = 2.88 \times 10^{-8} / 49,900 = 5.76 \times 10^{-13} \text{ A/Hz}^{1/2}$ flowing through R_3 , where it generates noise voltage, $(e_{n-R1}/R_1)R_3 = 2.88 \times 10^{-12} \text{ V/Hz}^{1/2}$. This noise voltage, too, is amplified 9,769 times to yield $[9,769 \times (2.88 \times 10^{-12} \text{ V/Hz}^{1/2})]^2 = 7.922 \times 10^{-16} \text{ V}^2/\text{Hz}$ at the output, which squares with the $7.953 \times 10^{-16} \text{ V}^2/\text{Hz}$ predicted by PSpice. PSpice models only Johnson noise for resistors, so on that basis it will tend to give lower noise projections than a real circuit can realize.

Amazingly enough, $R_3 \approx R_1/10,000$ produces about 10,000 times the noise at the output than that produced by R_1 . This ratio is true until shunting of R_1 noise current by the C_1 , C_2 , C_3 branch becomes significant at very high frequency. However, the absolute amount of output noise generation will fall with frequency due to falling gain dictated by the RIAA network.

Total output noise is the sum of all

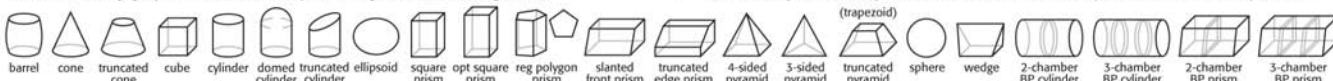
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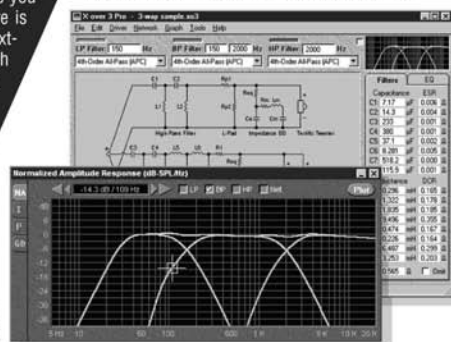
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contributions from each component multiplied by the appropriate transfer function (gain) from component to output. You must use the squared amplitudes when summing uncorrelated values. For this example, the values with units V^2/Hz could be summed, but not those with units $V/Hz^{1/2}$.

To determine the RMS output voltage, take the square root of the summed squared values of all the individual contributions. In practice, noise is treated as though the amplifier were noiseless with an exogenous noise source applied

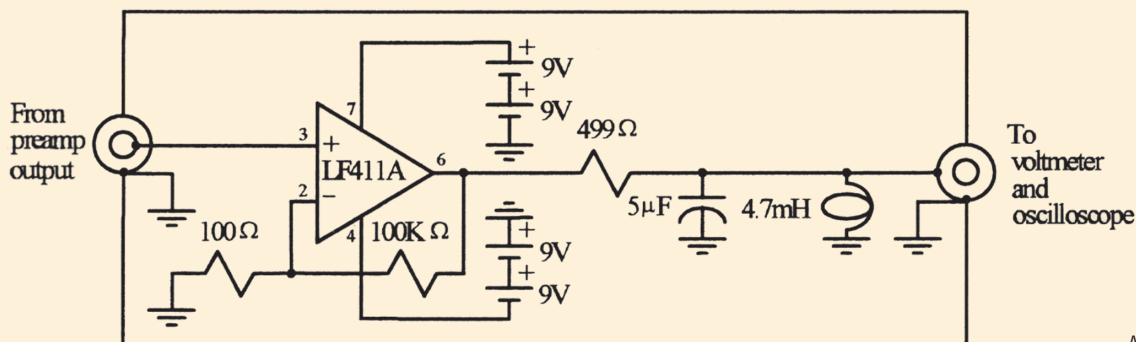
to its input. To find this noise source value, divide the total output noise by the closed-loop gain of the amplifier at the frequency of interest.

By the way, RMS noise voltage can be physically measured, but not, strictly speaking, on a $V/Hz^{1/2}$ basis. Rather, it can be measured with a bandwidth-restricted voltmeter as $V_{meter} = v_n B^{1/2}$, where B is the bandwidth. In the limit as $B \rightarrow 0$, the spot-frequency noise could in theory be found. Of course, the voltmeter ultimately responds to power and as $B \rightarrow 0$, the voltmeter reading be-

comes immeasurably small.

Due to the low levels of noise in high-fidelity audio equipment, amplification of the output of the component under test is typically required if measurements are to be made. In amplifying the noise to be measured, the addition of noise by this extra amplifier must be accounted for. Despite the apparent complexities, meaningful noise measurements can be performed⁸. While I knew this to be true because I devised a system and made a limited number of noise measurements for my master's

FIGURE 2: Spot noise measurement system.



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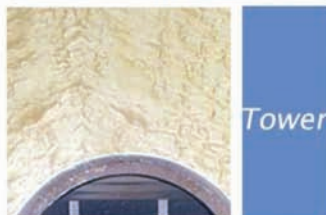
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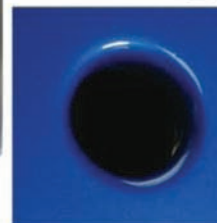
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thesis⁹, I nonetheless was reluctant to make noise measurements.

While I did not need to worry about it in my thesis measurements, electromagnetic interference (EMI) at 60Hz and 120Hz can be a major aggravation in audio system noise measurements. One laboratory in our engineering school had an EMI-proof room (Faraday cage) effected through complete shielding and elimination of AC power lines into the room. A room is not required but it may be necessary to place the component under test inside a metal box such as a large chassis. The box should preferably be steel or some ferromagnetic material because aluminum enclosures for electronic equipment, for example, while effective for electrostatic shielding, are less effective for shielding from magnetic fields¹⁰.

Some of my senior design students, as part of a noise measurement project on a tube-based microphone amplifier under my guidance, made a very nice steel enclosure with only one input and one output connector allowing access to the inside of the enclosure. After

their project was completed, I bought the enclosure from them. **Figure 2** shows the noise measurement system, consisting of a battery-powered op amp followed by a 1kHz center frequency, 100Hz (noise) bandwidth RLC band-pass filter placed inside the steel enclosure¹¹. Gain-Bandwidth Product of the LF411A is guaranteed to be at least 3MHz, so the measurement should be valid even in the gain-of-1000 configuration used.

With the 10mV scale selected, a HP 427A voltmeter read zero with the op amp input connector shorted. With a shorted RCA plug inserted into the phono preamplifier's input RCA jack and corresponding preamp output connected to the filter/amplifier, the voltmeter reading was about 5.5mV. An oscilloscope tracing on its 2mV scale was compatible with the meter reading.

The HP 427A is a wide-bandwidth meter but it is not a true RMS voltmeter, so I used a 1dB correction factor¹² to conclude that noise was 6.2mV RMS. Adding some feeling of validity to the measurements was the fact that both

preamp channels measured essentially the same while the phono preamp of my 2001 article measured significantly worse. Also, measured noise increased somewhat, after removing the short from the preamp input.

Due to component tolerances, filter mid-band frequency was just less than 1kHz. Preamplifier gain measured 1,006 at that frequency. Referred to the input of the phono preamplifier, this becomes $6.2\text{mV}/[(\text{op amp gain})(\text{preamp gain})] = 6.2\text{ nV}$ in a 100Hz bandwidth.

Spot noise is found by dividing the input noise by the square root of the bandwidth, which yields $620\text{ pV/Hz}^{1/2}$. This is not too much above the input noise predicted by PSpice at 1kHz. Assuming that this is white noise, which it almost certainly is, this corresponds to a resistor of the value shown in **Equation 9**.

This is not the best that can be done, but it is very respectable. By comparison, the LF411A op amp has input spot noise of about $25\text{ nV/Hz}^{1/2}$ at 1kHz.

With input shorted, unfiltered output noise measured about 2mV on the HP



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427A, whose bandwidth is advertised as 1MHz but which measured over 2MHz in testing on my bench. It hardly matters, though, because the preamp gain continues to fall at 20dB/decade from 100 at 20kHz until the zero corresponding to τ_4 is reached. Thus, output noise will be weighted toward lower frequencies due to the preamp's falling gain at higher frequencies, which is exactly the effect intended by RIAA equalization. Compared to a signal output of 12V RMS, signal-to-noise ratio is $20\log(12/0.002) = 76\text{dB}$.

In my view, noise is best evaluated subjectively. In this regard, the preamp is a superb performer. Nothing is audible with the ear placed immediately at the loudspeakers' high-frequency drivers as though the system were not powered. There is an impression with the ear placed immediately in front of the woofers of a low-frequency phenomenon similar to that heard when the ear is placed inside an open tube. This becomes inaudible if the ear is more than a few inches in front of the low-frequency drivers.

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Equation 9.

$$V_{\text{noise}}(\text{rms}) = \sqrt{4kTRB} \Rightarrow R = \left[\frac{V_{\text{spot noise}}(\text{rms})}{\sqrt{4kT}} \right]^2 = \left[\frac{6.2 \times 10^{-10}}{1.27 \times 10^{-10}} \right]^2 \approx 24\Omega.$$

This is very likely flicker noise and according to PSpice emulation, the biggest noise contribution at low frequencies is flicker noise from the input JFETs $J_{1A} - J_{1D}$. Total noise contribution decreases by roughly 40dB/decade, about ten times faster than the decrease in gain due to RIAA compensation. If you take the effect of falling gain into account, this certainly is the characteristic of "flicker noise," also for obvious reasons termed $1/f$ noise. This is interesting because some texts¹³ indicate this should be true while others¹⁴ indicate that Johnson noise should be the primary source of noise for an amplifier with JFET input stage whose driving source, in this instance a moving-coil cartridge, has low resistance.

In any event, paralleling JFETs can reduce noise with the penalties being added circuit complexity, the need to match devices, and increased input capacitance. This latter penalty, in general, can reduce bandwidth and interact with moving-magnet cartridge inductance to alter frequency response. As one text argues¹⁵, g_m/C_{rss} , where $g_m = 2(I_D I_{DSS})^{1/2}/V_P$ is the transconductance and C_{rss} is the common-source reverse transfer capacitance, might be considered a high-frequency figure of merit.

Because $C_{rss} = C_{gd}$ is the capacitance that will be multiplied by Miller effect, placing the JFET(s) in a cascode can help by reducing Miller effect. Since g_m at a given drain current value and C_{rss} are both intrinsic properties of a JFET, the device that maximizes g_m/C_{rss} should be chosen if high-frequency performance is to be optimal. Obviously, the application at hand is for audio frequencies, not *r.f.* Still, it is important not to allow Miller effect to adversely impact performance through interaction with the phono cartridge.

Noise reduction is the reason that I used four JFETs at the input in this design. One reason for choosing the 2SK170 was the manufacturer's spec sheet assertion that the device was intended for, among other things, use in moving coil "head amps." Capacitance is not as important a factor because the

low source resistance and inductance of moving-coil cartridges (you hope) makes them rather insensitive to capacitive loading. Even so, the topology is that of a BiFET cascode with Q_1 as the common-base portion.

Erno Borbely rightly argued that operating the JFETs at high drain currents can improve noise performance and also noted that overzealous application of this fact can actually increase noise¹⁶. The improvement is proportional to $(I_D)^{-1/4}$, which is not so dramatic to prompt the designer to increase drain current at the expense of degradation of other important properties¹⁷.

It should be admitted that BJTs are generally superior to JFETs in noise performance when driving resistance is small, as it certainly is with most moving-coil cartridges. JFETs, however, are

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generally easier to interface. This is because it is undesirable for bias currents to flow through the cartridge, and BJT bias conditions may require resistors that are large enough to produce significant noise in a circuit where overall impedance levels are too low to allow for effective bypass except with very large electrolytic capacitors. Even so, there are solutions that do allow BJT use while avoiding the above pitfalls¹⁸.

I, myself, designed a common-base input phono preamp with low-frequency noise performance significantly better than the JFET-input design offered here. If the actual circuit performs as well as its PSpice emulation suggests, then perhaps that design could be the subject of a subsequent article.

To quickly march through remaining noise issues, consider that only the input stage is important here. From a noise standpoint, the designer is free to do almost anything with the second stage, including use of MOSFETs if desired.

I chose the first stage BC549 and BC559 BJTs on the basis of noise properties, although there may be other devices

even better in this regard. The widely available 2N4401 and 2N4403 types could be directly substituted with only a slight increase in noise. However, the former transistors were readily and cheaply obtained from Mouser, so it is with no trepidation that they are specified.

Design specifics will be covered next month in **Part 2**. *aX*

Five-time astronaut Norman Thagard was the first American to enter space aboard a Russian rocket for a 90-day mission to the space station Mir. With a total of 140 days in space, he became the most experienced US astronaut ever. In addition to an MS degree in engineering science from Florida State University, he holds a doctorate in medicine from the University of Texas Southwestern Medical School. He is currently Professor and Associate Dean for College Relations at the FAMU-FSU College of Engineering. An avid audiophile, he designs and builds audio amplifiers as a hobby. On May 1, 2004, he was inducted into the Astronaut Hall of Fame, located at the Kennedy Space Center Visitors Center, Florida.

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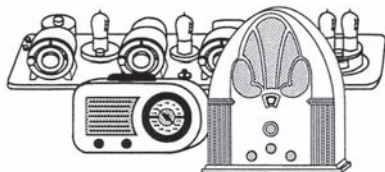
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A Unique Stereo Column System

The author describes an unusual system that will produce a new listening experience for stereo imaging and bass. No crossovers are used and electronic equalization corrects for response.

By Roger Russell

After years of struggling to match woofers, mids, tweeters, and those frustrating compromises called crossover networks, I decided to toss it all away and start from a new perspective. Here is a full-range, single-column system that contains 20 identical 4" drivers (**Photo 1**). There are no crossovers, woofers, mids, or tweeters. Although the system has a typical rolloff below 150Hz, I use electronic equalization to compensate for this lack of bass and extend the response to around 25Hz.

How can the little drivers handle any kind of power? Not only are they small, but the lows are being boosted as well. This seems very contradictory to good design and common sense. In fact, it seems totally unreasonable, but it works. . . and works unbelievably well!

Not only is the bass good, but my reaction when I heard it for the first time was the amazing coherence of the stereo images. When an entire orchestra is playing, the stereo image, depth, and spaciousness provided by this system are totally captivating and allow better appreciation of what the artist has produced. This unique listening experience is only possible because all frequencies are being radiated from the same vertical line.

The cabinet is the closed-back type you need to place close to a wall. It is 89" tall, 6½" wide, and 9¼" deep, and includes a 1½" thick base that is 14" wide and 12" deep. The total cost of the pair of speakers, including the cabinet materials, is about \$200.



PHOTO 1: The finished system in my living room.

TYPICAL MULTI-WAY SYSTEM DESIGN

Almost all recordings are made with small, single diaphragm microphones that handle the entire frequency range; but when it comes to speakers, drivers are almost always divided into at least one (or even more) woofer and tweeter. A woofer needs a large area in order to reproduce low frequencies effectively. A large woofer cone is normally used to accomplish this. However, a large woofer becomes directional at higher frequencies and has high moving mass that serves to attenuate the higher frequencies.

To overcome this, use a mid-range or tweeter of smaller size and much lower mass to maintain wide dispersion and extend the response. Use of a tweeter to complement a woofer requires a crossover network, either passive or

active. Achieving the optimum sound is often a challenge to select the best combination of crossover components that will make the system sound as good as possible. Systems can be made as a two-way, three-way, or more following this principle.

In the area of the crossover, both drivers radiate the same frequencies and may interfere with each other causing uneven response around the system. A different physical location for each driver adds to the problem. More important, and perhaps not so obvious, is that a driver used to cover one part of the frequency range does not have the same construction, tonal characteristics, or dispersion characteristics as a driver covering another part of the frequency range.

In the area of the crossover frequency, these differences between drivers

cause sudden discontinuities in the overall sound balance. It results in a loss of valuable stereo information. By using the same driver to cover the whole frequency range, you can avoid all of this and present a continuous coherent spectrum.

MULTIPLE DRIVERS AND POWER HANDLING

A popular misconception about small drivers is that they are not useful as woofers. However, you need to consider the cone area of all the drivers. The effective cone diameter for each 4" driver is 3 3/4", and the effective area is 8.3in². In comparison, the effective diameter for a 12" driver is 10 1/4", and the effective area is approximately 83in².

The area of 20 4" drivers adds up to 165in², or as much as two 12" drivers and more than a single 15" driver. That makes the equivalent of four 12" woofers for a pair of stereo speakers, and they can couple to the air very nicely. Very little excursion capability is needed when such a large area is available.

My solution to the power-handling problem is also provided by the 20 drivers. Each driver receives only 1/20 of the power. If each driver can handle a maximum of 15W, the entire column can handle 15 × 20, or 300W maximum. Twenty 3/4" voice coils can dissipate much more heat than two 2" voice coils. Distortion is low because the demand on each driver is small.

The systems are relatively efficient and can be played very loud. Typically, I drive the systems at about 2W, which fills my relatively small living room, which is 13' × 14' and has a sloped ceiling from 8' to 10'. I measured a sound level of about 85dB at 10'. You can obtain peak levels of up to 110dB if you drive them with over 100W (much too loud for me). The 25Hz heartbeats of Pink Floyd's *Dark Side of the Moon* are reproduced in stride, as well as the finale of Saint-Saens "Organ Symphony."

DIRECTIONALITY

The column is very directional vertically, but it extends essentially from floor to ceiling. So floor and ceiling re-

flections that would normally interfere with the direct radiation are effectively eliminated by the column. This also means that you are always directly in front of the coverage area. The sound will be the same whether you are standing, sitting, or at any other height.

This is a significant advantage over normal systems that not only radiate sound as much vertically as horizontally but also exhibit response changes with listening height. At the same time, the horizontal dispersion provided by the small drivers in the column ensures a wide radiation angle over most of the frequency range.

Theory predicts that response becomes directional when half wavelength of the frequency being radiated is equal to the effective cone diameter. The effective cone diameter for these 4" drivers is actually 3 3/4", which corresponds to about 8.3kHz. Equalization above 8.3kHz does not compensate for the directional characteristics of the drivers. You can improve this by toeing the columns in toward your listening position by about 15°.

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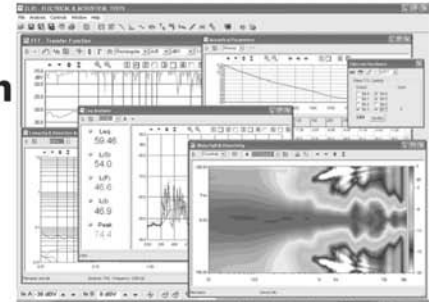


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OTHER ADVANTAGES

Another unique feature of a long column is the radiation characteristic. Normally, for a single speaker, the sound level decreases by 6dB for every doubling of distance from the speaker. In the long column, this figure is only 3dB, which means that as you get nearer to the system, it does not become as loud as an ordinary system. You can listen as close as 3' from the wall that the systems are against and still get excellent stereo sound including spaciousness. It means that you can also use these systems even in a fairly small room, where you can't avoid being close to them.

Elimination of unwanted floor and ceiling reflections, as well as less attenuation with distance, extends the useful listening area further into the room than conventional systems. This is sometimes referred to as the near field, where most of the sound comes directly from the speakers and not from room reflections. The sound coming mostly from reflections is referred to as the far field, and the sound will vary

depending on your room construction and furnishings.

This single-column system has a unique sonic advantage over other column systems because all frequencies are radiated from the same vertical line. It provides additional sonic clues contained in recordings that would otherwise be lost to the listener. Systems that have adjacent columns of drivers, each radiating the same or different frequency ranges, do not have the same distance to the listener, which can cause various degrees of image distortion.

Room resonances are greatly reduced. This may be because the lows are radiated all along the height of the column and the low frequencies are distributed over a wide location. This helps to reduce the amplitude of low-frequency room resonances. In comparison, subwoofers on the floor may excite only a few resonances and at greater amplitude.

You can easily incorporate the system into a wall for built-in home designs. The base, of course, would not

of the cabinet.

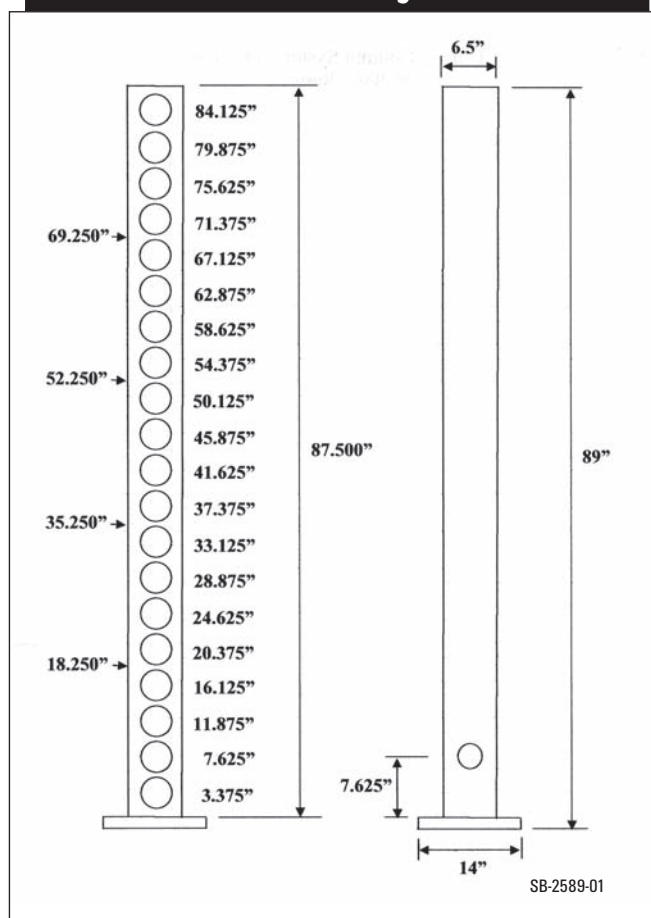
I had a second set of cabinets made by a friend who is also in the Central Florida Audio Society and has computer-controlled machinery, which can handle decimals, so I decided to show the centers for the driver holes and brace locations in decimal form. The location of the braces is indicated by the arrows on the left side of **Fig. 1**.

If this column is too tall for your home, simply construct a cabinet that is one or two drivers shorter. Substitute an 8Ω 15W resistor for each driver that you remove from the system. Removing one or two drivers will not make a big difference, but bear in mind that the fewer drivers you use, the lower the power handling and the less bass capability there will be. In any case, the column must run from floor to ceiling in your room to be effective. If your ceiling is higher than this column, you could use additional drivers, but these are not required, at least not for this design.

The cabinet is made of $\frac{3}{4}$ " kitchen counter underlayment and is reasonably inexpensive. This is a very dense and fine grain particleboard. **Photo 2** shows a partial cabinet assembly. Other woods will certainly work as well. All the pieces are glued and nailed together with finishing nails, which are countersunk.

I used four $\frac{1}{2}$ " thick internal braces with two $2\frac{1}{2}$ " circular holes shown in **Fig. 2**. You can use more braces if desired. This helps to break up internal

FIGURE 1: Column outline drawing.

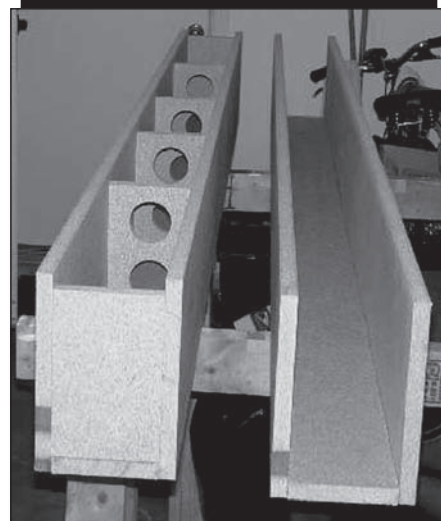


be needed and the width of the system would then be only 6 $\frac{1}{2}$ ".

THE CABINET

The dimensions shown in **Fig. 1** are for the size of the drivers I used. The center-to-center distance of $4\frac{1}{4}$ " is the driver height plus $\frac{1}{4}$ " for the space between the drivers. The distance from the bottom of the cabinet to the center of the bottom driver hole is $3\frac{3}{8}$ ". I have used the same distance from the top of the cabinet to the center of the top driver hole. I located a $2\frac{3}{4}$ " diameter terminal hole in the back directly behind the second driver, which is $7\frac{5}{8}$ " up from the bottom

PHOTO 2: Cabinet assembly.



resonances and strengthens the walls of the cabinet. They are located so they don't block the driver holes.

Because the front panel is so narrow and could be easily broken, I decided to cut all the driver holes after the cabinet was completely assembled. I located the centers of all the driver holes accurately and used a router with a pin attachment to make the circular cuts. The hole diameter for these particular drivers is $3\frac{1}{16}$ ". The left and right front edges of the cabinet are beveled at 45° , which might reduce edge diffraction effects and provide a more pleasing appearance.

The finished cabinets are shown in **Photo 3**. I used filler for all the rough surfaces, joints, and nail holes. After sanding, I primed the cabinet with an alcohol base primer to prevent raising the surface. Then, I used several coats of white latex, water-base paint with sanding in between coats. I decided on white because I think the cabinets look less imposing, being so tall.

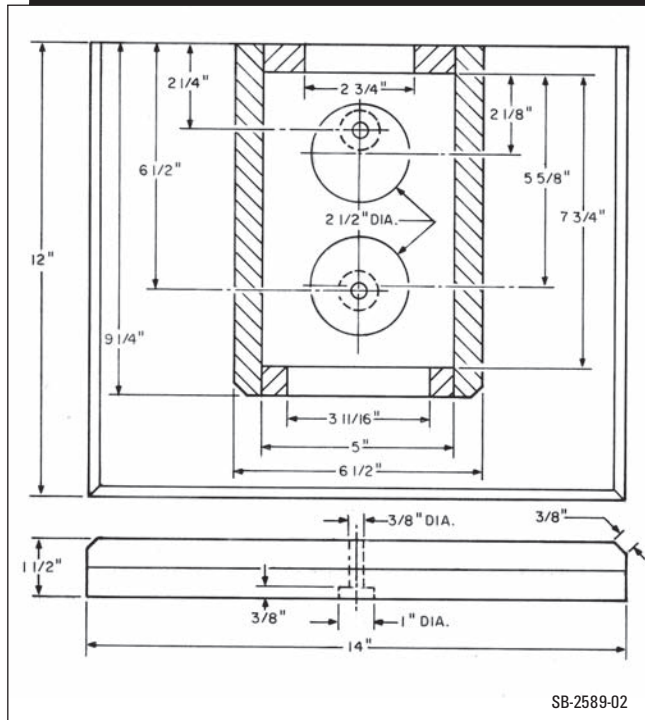
For the input terminal (**Photo 4**), I

used a 5-way binding post that accepts a dual banana plug. You may prefer other types of terminals. I made the terminal board out of a piece of $\frac{1}{4}$ " tempered Masonite and sprayed it black. Be sure you make the board no bigger than the diameter of the driver hole. Otherwise, you will not be able to fit the terminal board through the driver hole of the finished cabinet.

For my system, the board is $3\frac{5}{8}$ " square. Drill a hole in each corner for mounting inside the cabinet. I used foam tape to seal between the terminal board and the cabinet.

The construction of the stand is shown in **Fig. 2**. Two $\frac{3}{4}$ " thick pieces of

FIGURE 2: The stand and column construction.

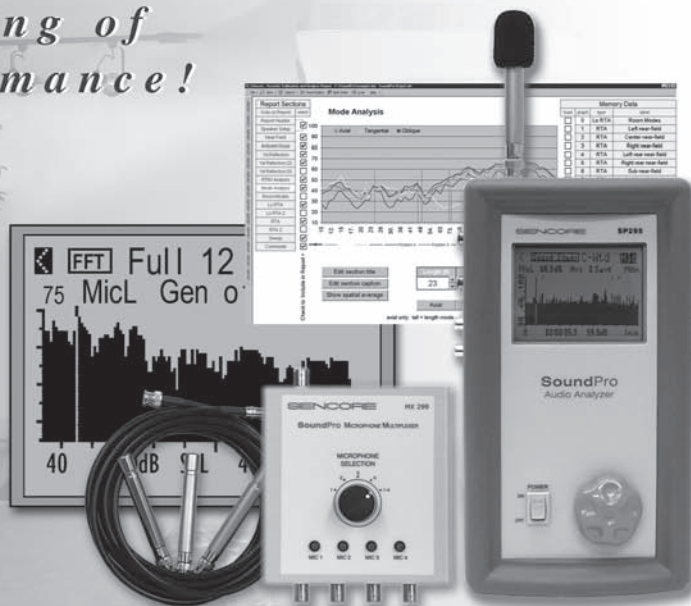


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FIGURE 3: Schematic.

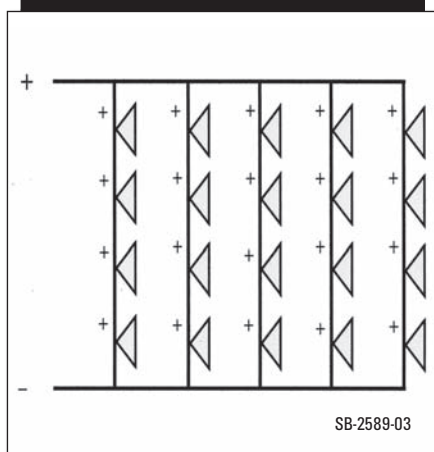
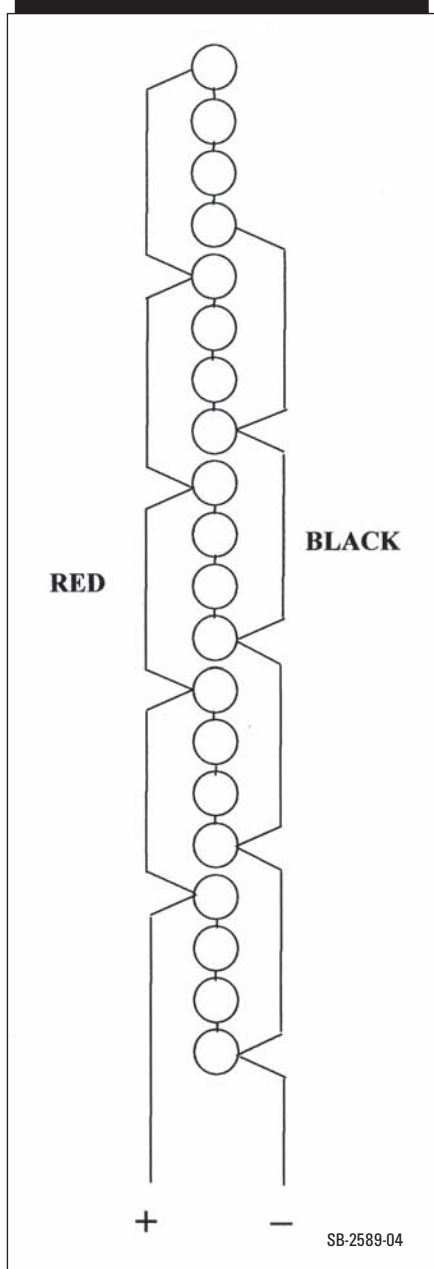


FIGURE 4: Wiring diagram.



particleboard are glued together. The bolt heads are countersunk in the bottom of the stand so they don't stick out below the bottom. The front and both sides are beveled at 45°. The position of the cabinet is shown where it is attached to the stand. The location of the holes for the bolts is shown for both stand and the bottom of the cabinet.

FINAL ASSEMBLY

I have wired the drivers in series-parallel as shown in **Fig. 3**. There are five groups with four in series in each group. All the drivers are in the same electrical phase. You could use other series-parallel arrangements, but I believe the net impedance of 6.4Ω is satisfactory for most amplifiers. It is pleasing for me to look at the entire circuitry for the system and experience the freedom from being bogged down with the choice of the best kind of crossover theory and crossover parts. In addition, there is no need for electronic crossovers or multiple amplifiers.

The wiring is shown in **Fig. 4**. I used #19 stranded hookup wires to connect all the drivers. You could use heavier wire, but the resistance of this wire is negligible compared to the speaker resistance. I used 20" red wires for the

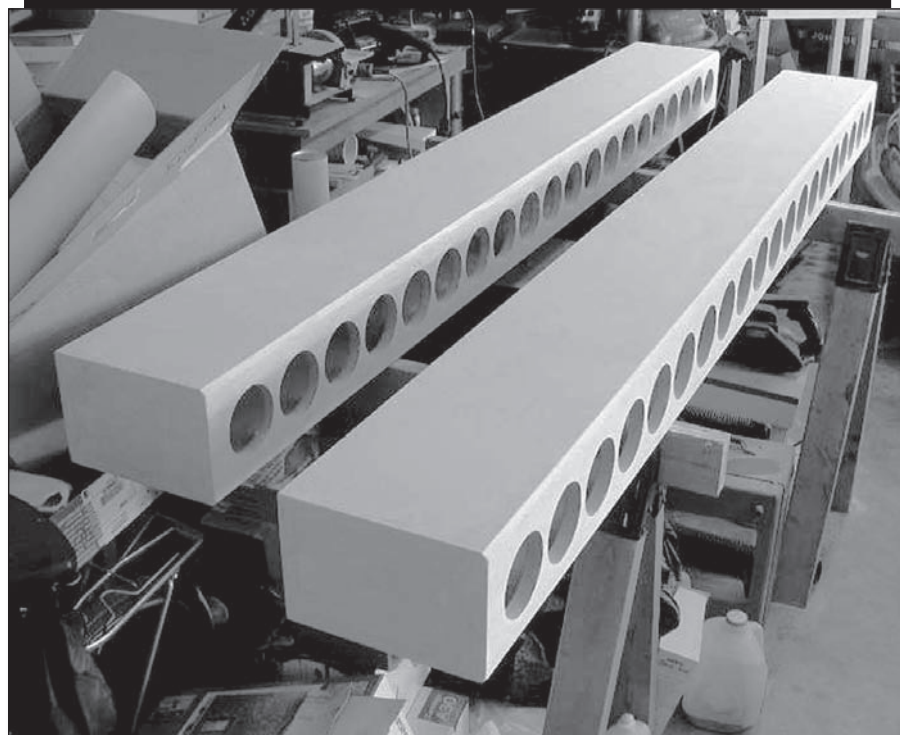
positive and 20" black wires for the negative. Use 12" long white wires for the connections between the drivers in series. I soldered all connections.

For a single wire to a driver, I twisted a $\frac{1}{2}$ " length of the strands together and tinned it with solder. Then I bent $\frac{1}{4}$ " of this 180° with thin nose pliers, fit the U-shape around the driver terminal, crimped it in place and soldered. When connecting two wires to the same terminal, you can twist the pair together, then tin, bend, crimp, and solder in the same way.

I used pink building fiberglass $3\frac{1}{2}$ " thick R-13 as acoustic material. I cut the fiberglass in pieces about 4" × 6" and distributed 30 of these pieces evenly throughout the enclosure. The 4" edge of the fiberglass should be toward the driver. The total weight of the fiberglass is 826 grams, or 1.82 lbs. I used gloves to install the fiberglass in the cabinet. I use two $\frac{3}{8}$ " × $3\frac{1}{2}$ " plated bolts (**Photo 5**) to attach the base to the cabinet, then a $\frac{3}{8}$ " lock washer and $\frac{7}{8}$ " washer under each bolt head and nut.

You can cut soft foam weather stripping to $\frac{1}{4}$ " width and attach it around the perimeter of the driver cutout. The foam compresses very easily and forms a good seal between the driver and the

PHOTO 3: The finished cabinets.



cabinet. It has adhesive on one side. The preferred screws are #6 x 3/4" deep thread, pan, black. The Parts Express number is 081-435.

After wiring the system, you can make a final polarity check by connecting a 6V battery to the input terminals. With the positive lead connected to the red terminal and touching the black to the negative, all of the cones should move outwards.

THE DRIVERS

I used 4" extended range drivers (**Photo 6**) that were originally intended for use in a TV set. I purchased them from Parts Express for 69 cents each. Part number is 269-469.

Although these particular drivers were in a closeout sale and are no longer available, you can substitute other drivers with similar parameters and smooth response. The square construction allows you to space them closely for best performance. The magnet structure includes an additional ceramic magnet attached to the back plate.

This is magnetized in the reverse direction to cancel out the stray magnetic field from the main magnet. It prevents rainbow patterns on a color TV picture tube that would otherwise be induced by the stray magnetic field when the speaker is placed near the set.

RESPONSE TAILORING

The advertised driver parameters are shown in **Table 1**. Free-air resonance for the drivers averages 118Hz, and the

TABLE 1: DRIVER PARAMETERS

Impedance: 8Ω
DC resistance: 7.52Ω
Frequency response: 118Hz-18kHz
Magnet weight: 3.3 oz
Fs: 118Hz
SPL: 90.5dB 1W/1m
VAS: 0.11ft³
Qms: 5.27
Qes: 0.71
Qts: 0.63
Net weight: 3/4 lb

PHOTO 4: The input terminal.



PHOTO 5: Lowest driver cutout showing bolts.



Silver & Oil



FP-106



Copper Foil



FI-25

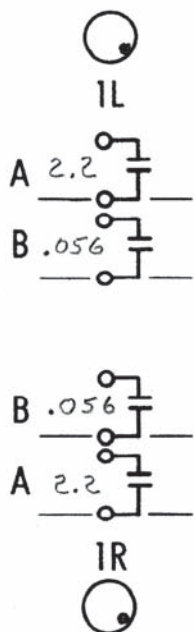
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FIGURE 5: MQ107 filter settings.



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sealed box is designed to go down to about 150Hz and then output decreases, reaching a slope of 12dB/octave. The bass equalization curve is the opposite of this rolloff. You can accomplish compensation of as much as 20dB or more. This is a lot of low-frequency power to boost, but remember that each speaker handles only $\frac{1}{20}$ of this power.

I have used a McIntosh MQ107 equalizer (**Photo 7**) for the necessary response adjustments. The equalizer was made from 1981 to 1993 and is often available through eBay or other places. The low-frequency and high-frequency compensation controls are used, plus seven adjustable filters are available to tune and further boost the low frequencies.

You can make the filters have a $\frac{1}{3}$ octave or 1 octave width. They can each boost or cut 12dB in the $\frac{1}{3}$ octave mode or 15dB in the octave mode.

Select the center frequency and filter width by plugging in two small capacitors for each filter. **Table 2** shows capacitor values for center frequencies and widths from 20Hz to 1kHz. All capacitor values are shown in microfarads.

You can insert capacitors in the corresponding A and B slots in the equalizer. Three holes are available for each capacitor. Only two holes are actually used, depending on the lead spacing of the capacitors. Each filter has a control with a center detent that can adjust the amplitude to boost or cut. The center position is electrically flat.

A compartment box with capacitors originally came with the equalizer,

but may not be included with the equalizer that you find. You can purchase capacitors from Mouser Electronics. Preferred capacitors are metallized polyester or equivalent for values up to 0.56 μ F. Non-polar electrolytic capacitors are used for higher values. Capacitors must have a voltage rating of 50V or higher.

You can use additional frequencies by calculating new capacitor values. The formula for these is indicated in **Table 3**. Please note that “stock” values are normally the only ones available. If, for example, you calculate a capacitor value of 0.095 μ F, the closest value available will be 0.1 μ F.

Figure 5 shows the capacitors and control settings that I have used. Only one of the seven filters is needed for each channel plus the low-frequency and high-frequency compensation controls that are set at maximum. I used the same settings in both channels. All capacitor values are in microfarads.

You can use other equalizers as long as the adjustments can complement the driver rolloff without exaggerating other areas where boosting is not wanted. The closer you match the initial equalization to the opposite of the woofer roll-off, the better the low frequencies will sound. However, further adjustments to compensate for room resonances could smooth response even further at your listening area.

The drivers are reasonably smooth through the mid-range but have a gradual rolloff above about 4kHz. This is not related to their directionality. A high-frequency boost is needed to maintain smooth and extended response. You can adjust high frequencies to suit your preference by using the high-frequency

TABLE 2: Capacitor Values.

Frequency	Narrow Filter		Wide Filter	
	Capacitor A	Capacitor B	Capacitor A	Capacitor B
20	1.0	.39	—	—
25	1.0	.27	4.7	.056
31.5	.82	.22	—	—
40	.56	.18	—	—
50	.56	.12	2.2	.022
63	.39	.12	—	—
80	.22	.12	—	—
100	.22	.082	1.0	.012
125	.18	.056	—	—
160	.12	.056	—	—
200	.12	.039	.56	.0082
250	.12	.022	—	—
315	.082	.022	—	—
400	.056	.018	—	—
500	.056	.012	—	—
630	.039	.012	—	—
800	.022	.012	—	—
1000	.022	.0082	—	—

PHOTO 6: The 4" driver used in this system.



SOURCES

Parts Express

725 Pleasant Valley Drive
Springboro, OH 45066-1158
1-800-338-0531
www.partsexpress.com

Mouser Electronics

1000 N. Main Street
Mansfield, TX 76063
1-800-346-6873
www.mouser.com

compensation controls at the right side in Fig. 1.

MEASUREMENTS

For the measurement shown in Fig. 6, both speakers were driven using random phase pink noise as a source. The Bruel & Kjaer 4133 microphone output is then fed to a $\frac{1}{3}$ octave filter and automatically swept from 25Hz to 25kHz. The microphone is located at the listening area about 9' from each speaker. The microphone height is 4'. Each major division

on the graph is 10dB. The first section at the left is 25-250Hz, the center section is 250-2500Hz, and the right section is 2500-25kHz.

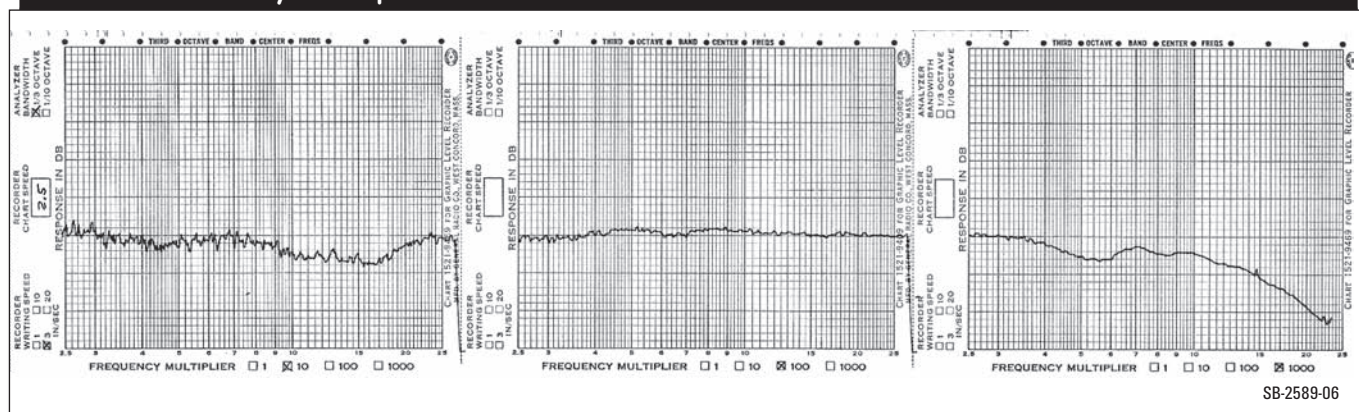
The response in my room is reasonably smooth from 25Hz to 15kHz. There is no question that room resonances have influenced the measurement at low frequencies at this distance. Although I had initially designed the equalization to follow only the opposite of the driver rolloff, I later decided to go a step further and make a

few minor adjustments for the room resonances. This was fairly easy to accomplish using an Audio Control real-time analyzer and adjusting the filters in the MQ107 equalizer. You can make further equalizer adjustments at low frequencies

TABLE 3: Capacitor Calculation.

Capacitor	Narrow Filter	Wide Filter
Capacitor A	23.5 divided by frequency in Hz	118 divided by frequency in Hz
Capacitor B	7.2 divided by frequency in Hz	1.44 divided by frequency in Hz

FIGURE 6: Combined system response.



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FIGURE 7: Equalizer response.

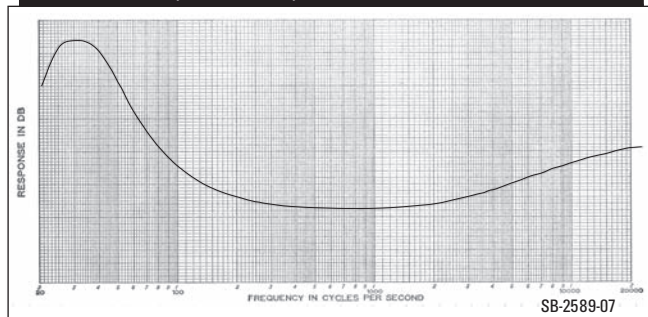
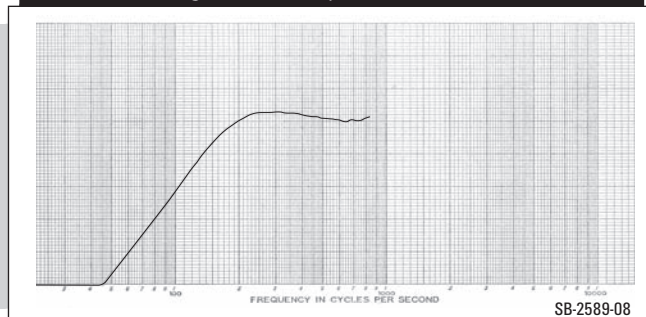


FIGURE 8: Single driver response.



for your room.

The final correction for the system is shown in **Fig. 7**. Each major division is 5dB. The measurement is from 20Hz to 20kHz. **Figure 8** shows the response of a single driver in a small test box. Each major division is 5dB.

The impedance curve for the entire system is shown in **Fig. 9**. The vertical scale is in ohms and is shown on a dB scale of 5dB per major division. The measurement is from 20Hz to 20kHz. System resonance is 158Hz.

SAFETY FIRST

Due to the possible tipsy nature of such a tall column, the base by itself may not make the system stable enough for your use. Each system weighs 81 lbs. You could increase the size of the base.

In addition, I recommend adding at least a set of floor spikes, particularly if you place the system on a soft carpet with thick padding underneath. You can find typical spikes (like those shown in **Photo 8**) at Parts Express. Drill holes in the bottom of the thick base near the corners for the spikes, which are thin and go through the carpet without damaging it. Even this may not be adequate if there are young children or large pets around.

You can further stabilize it by anchoring the top of the cabinet firmly to the wall. I found two different friction lid supports (**Photo 9**) at Home Depot that you

could use. The first is on the right in the photo, made by Ives-Schlage, H. B. Ives, New Haven, CT 06511 (www.schlagelock.com). Two screws anchor the support to the wall and two more screws anchor the support to the top of the cabinet. The support is adjustable for the angle and distance of the cabinet to the wall.

The second is a lid support made by The Stanley Works, New Britain, CT 06053 (www.stanleyworks.com). Two screws anchor the bracket to the wall and one screw anchors the bracket to the top of the cabinet. Again, the support is adjustable.

As with many other systems, I found that the best listening position is one that forms an equilateral triangle between the listener and each speaker and between each speaker. In my living room (**Photo 1**), the speakers are about 8' apart. My best listening spot is around 8 or 9' from each speaker. The systems are about 3" from the wall.

SUMMARY OF ADVANTAGES

1. High power handling through the whole frequency range
2. Single wide-range line source
3. More uniform sound level in a room
4. No floor or ceiling reflections
5. No right- and left-hand versions
6. Distributed low-frequency radiation
7. Less attenuation with distance
8. Wide dispersion

9. Uniform response at any listening height

10. Magnetic shielding
11. Small footprint
12. No woofers
13. No mid-ranges
14. No tweeters
15. No crossovers
16. No image distortion
17. No subwoofer needed
18. No bi-amping or tri-amping
19. No bi-wiring or tri-wiring

CONCLUSIONS

This single-column, full-range system provides a unique stereo listening experience. When you listen to some of the spacious new-age recordings, the sound field produced by the speakers seems to pull your full awareness right into the field. This is particularly true when listening in the dark where visual distractions are eliminated.

The coherence, depth, and spaciousness of the classical recordings are immediately apparent, and this is what first captures your attention. Imaging is extremely stable and permits you to easily hear how the recordings have been mixed. Smooth jazz and new-age music image exceptionally well.

You may spend weeks listening to your entire collection of recordings to hear stereo information that you have not heard before. That's what happened

FIGURE 9: Impedance curve.

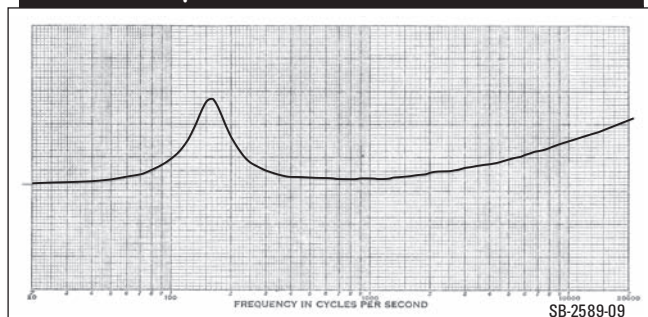


PHOTO 7: The McIntosh MQ107 equalizer, with cover removed.



to me, and I never seem to get used to the excellent bass from such small drivers. I was so encouraged by the sound of this system that I decided to build another pair using even smaller and much more expensive drivers that are of high-

er quality. Although the work is not completed, I expect excellent results. *aX*

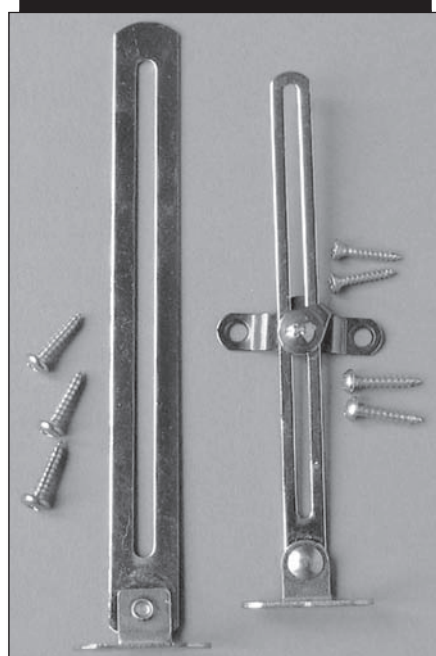
Roger Russell has a degree in electrical engineering from Rensselaer Polytechnic Institute. He has written several articles

about loudspeaker design, testing, and other audio devices. Several patents have been awarded for some of his designs. Although retired now, he was a member of the Audio Engineering Society and the International Society for General Semantics for many years. His interests range from stereo sound to photography, new-age music, mystery clocks, and science fiction. He has a web page at www.roger-russell.com.

PHOTO 8: Spikes.



PHOTO 9: Support brackets.



REFERENCES

Patent number 3,715,501 Loud-speaker System

Awarded to Roger Russell, February 6, 1973

This patent describes the use of equalization to compensate for the natural low-frequency rolloff of a loudspeaker system.

Patent number 4,267,405 Stereo Speaker System for Creating Stereo Images

Awarded to Roger Russell, May 12, 1981

This patent describes closely-spaced drivers arranged in a long column.

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Push-Pull for Single-Ended 211 Amp

This article describes the design and construction of a 25W single-ended 211 amplifier with a transformer-coupled push-pull driver stage.

By Lee Roitberg

Like a moth drawn to a flame, the light given off by a large transmitting triode is alluring. You cannot do anything but admire the glow produced by such a large tube. Then after countless minutes of amazement, the realization of the amp's physical size sets in.

Ever since I began building tube equipment many moons ago, I've had the idea of building a large transmitting triode amp. With no immediate need for such a large amplifier, I have been slowly collecting parts, planning on one day building a large transmitting triode amplifier. Well, the stars finally aligned, and I recently built the large amplifier I had dreamed about (Photo 1).

WHAT TO BUILD

I knew I wanted to build a large amp, but the question of what tube to use had always come up. The options were 211, 845, 813, GM70, or 833. All of the tubes are available as current production, and you can purchase some of them, such as the 211 and 845, for a very low price. My dilemma was simply answered when a friend, Darel Wieman, provided me with four GE VT-4 tubes.

With newly acquired tubes and a pile

DISCLAIMER

This circuit is intended for non-commercial use only. Lee Roitberg is not liable for any damage that may occur from the construction of this amplifier or any of the information provided within this article.

of power-supply parts in hand, I scoured the Internet and old magazines for schematics, ideas, and insight. During my quest, I ran across countless designs; some had tube rectifiers, some had solid-state rectifiers, and some even had a combination of both. I saw amplifiers with two, three, and four driver stages. There were capacitor-coupled, direct-coupled, and transformer-coupled drive stages. Of all the designs I had studied, one thing became evident—a 211 needed a low impedance driver stage in order to achieve full output power in class A2.

THE LIGHT GOES ON

Amorphous core, nickel core, cobalt core—these are the words that many an audio builder lust after. So, what stops most builders? Money!

During the search for nickel core transformers, I came across a little gem from Hammond, the 124B interstage transformer. It had a 49% nickel core, primary impedance rated at 10k, and secondary impedance rated at 90k center tapped. The most important part was that it was available for around

\$12.

So what do you do with a cheap step-up transformer that can't handle unbalanced DC? **You use it backwards as a push-pull plate transformer with a single-ended output.** Please reread the previous sentence, which contains an important concept.

I have been using the 124B configured backwards, on a few preamps, with incredibly good results. With a 3:1 step down, I figured it would be a natural to drive the honoree 211's grid.

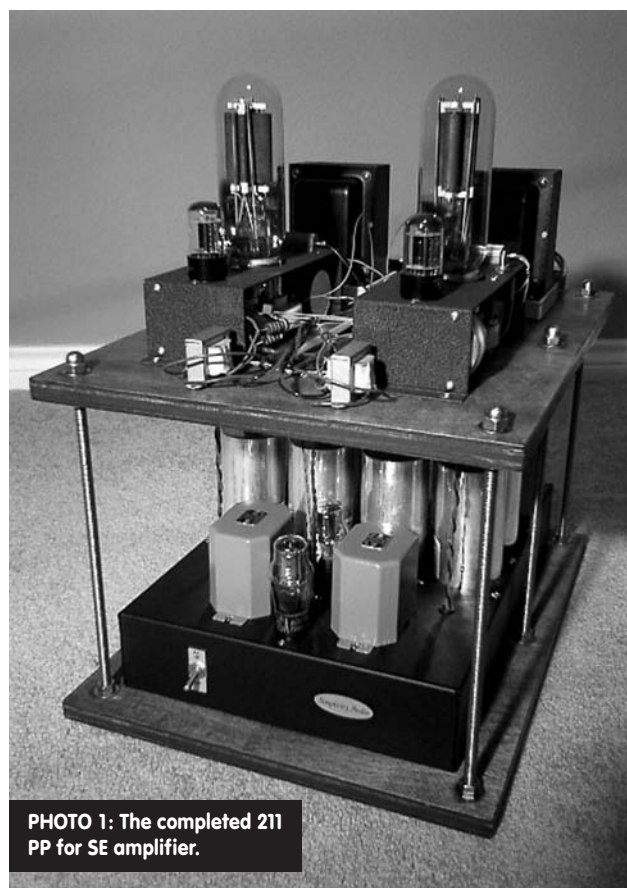


PHOTO 1: The completed 211 PP for SE amplifier.

CIRCUIT SYNERGY

In the world of audio, there are many claims when it comes to driver stage topologies. One myth is that two stages of amplification are better than three or four. Another myth is that a pentode drive tube driving a triode output tube is better than a triode drive tube driving a triode output tube.

So, what about a triode push-pull stage driving a triode output tube? Is this type of configuration sacrilege? I am proud to say that I am the owner of this odd combination and, most important, it sounds great.

DRIVER STAGE

The Hammond 124B transformer limits the driver tube selection to a tube with a plate resistance no greater than 12k Ω . This offers a large selection of tubes to experiment with. As for the balanced current limitations through the transformer, I have tried keeping them to less than 20mA. This number is just a guess, because there is no information from Hammond on this type of configuration and I have not taken the time to

measure the degenerative effects of DC through the transformer.

I believe transformer-coupled stages—as opposed to capacitor-coupled stages—allow the characteristics of the tube used to come through and not have those characteristics masked by the capacitor's own sonic flavor. Therefore, the tube selected will ultimately affect the sound characteristic of the amplifier. I experimented with three tubes—6J6, 5965, and 6SN7—that had similar characteristics. I know there are many other tubes you can use, and I recommend you give them a try. The differences are not subtle, and you may find a better-sounding combination for your stereo setup.

AND THE WINNER IS...

During my experimentation and listening evaluations, I found the 6SN7 to be my favorite-sounding tube. The flavor of the 6SN7 I chose is a topic for another discussion.

So, the 6SN7 has an ideal μ of 20 per side and the plate transformer steps down the output by 3. Unfortunately, this is not enough voltage gain to drive the

211 to full output. Plus, how do you drive the push-pull grids of the 6SN7? Simple, you use another 124B as a step-up/phase splitter input transformer.

The combination of the input transformer, the 6SN7, and the output transformer provide a total measured gain of 25. If you are using a passive volume control, the amplifier's gain will be too low and full output power will not be achieved with a CD player's direct output. You will definitely need a good pre-amp with gain. As a more expensive alternative, there are many other transformer manufacturers offering input transformers with a higher step-up ratio.

Look at the simplicity of the Fig. 1 schematic and the low parts count. There is no global feedback. Because of the push-pull driver stage, there is no need for a 6SN7 cathode bypass capacitor. Amplifier stability is very good to the point of not having to use any grid stop resistors.

WARNING

Building an amplifier with a B+ over 500V DC is extremely dangerous.



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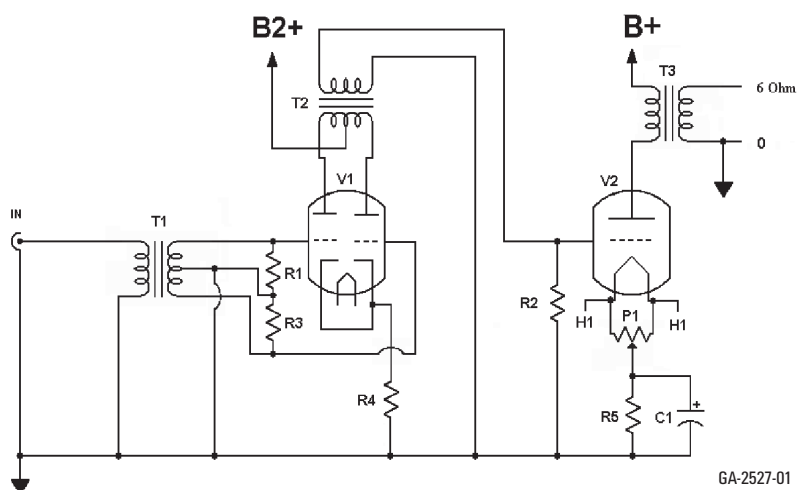
Z56548 Reproduction of the Z565 output transformer as used on the ST35 and SCA35 amplifiers, except that the output taps are **4 and 8 ohms**

A470S reproduction of the Dynaco A470 output transformer as used on the Dynaco (tm) ST70 and MkIV amplifiers

A431S a reproduction of the Dynaco A431 output transformer as used on the MkII and MkIII amplifiers and Sunn guitar/bass amplifiers.

Other stuff we're working on: A420 (6600 ohm 30W) and A442 (4300 ohm 60W with tertiary screen winding)..

FIGURE 1: Schematic of the transformer-coupled 211 amplifier. Only one channel is shown.



GA-2527-01

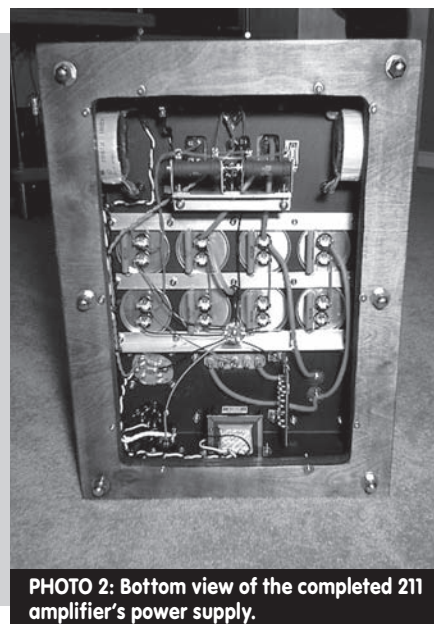


PHOTO 2: Bottom view of the completed 211 amplifier's power supply.

Parts selection is critical because resistors, capacitors, transformers, and wire are not normally rated to such high voltages. Most off-the-shelf components will fail with possible lethal consequences. Please, if you do not know what you are doing, do not attempt to build this amp. Do not risk your life or

the life of someone else.

CONSTRUCTION

As with any amplifier, there are trade-offs and compromises. My biggest constraint was that I needed to be able to lift the amp, by myself, onto my workbench. After debating about the amplifier's size and layout, I settled on a two-tiered amplifier with the power supply on the bottom and the audio section on the top.

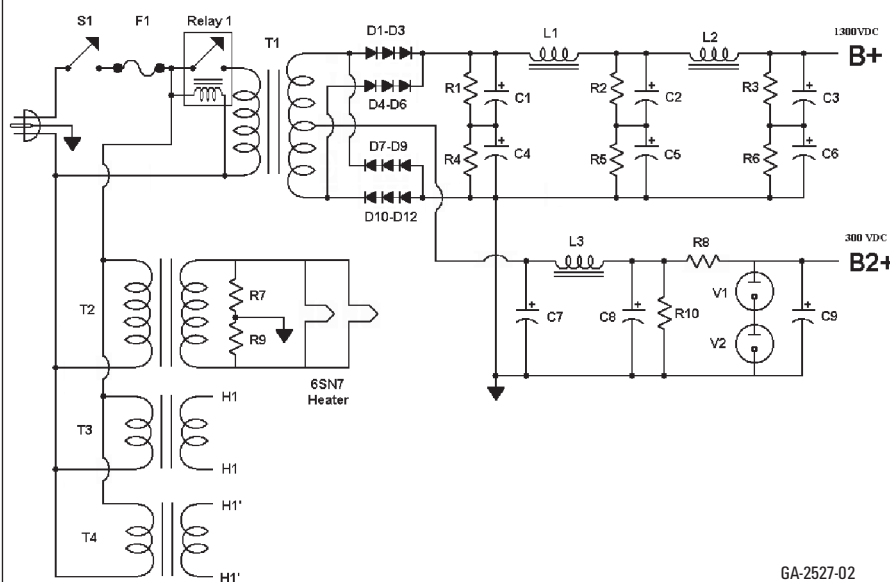
This amp was to be a cross between a breadboard amp and a finished product. I knew I could design and build the power supply so that it would not need

any modifications, but the audio section still posed many questions that needed to be answered.

THE POWER SUPPLY

I built the power supply (Fig. 2) on a very large Hammond steel chassis (Photo 2). It is 12" wide, 17" deep, and 3" tall. Weight and chassis limitations dictated I use a solid-state rectifier. Instead of choosing the standard 1N4007 diodes, I ended up using the NTE571 diode from Mouser Electronics, which is a 1000V PIV 1A diode that is listed as a fast switching/soft recovery diode. I placed three in se-

FIGURE 2: The power supply of the 211 amplifier.



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ries for each leg of the full-wave bridge rectifier.

The B+ voltage is generated by a dedicated plate transformer rated at 1200Vct at 400mA. This one transformer provides both the high voltage for the 211 plate and half of the B+ voltage to a shunt regulator for the driver stage. For delaying the B+ voltage, I chose a delay-on relay, available from Potter & Brumfield, connected to the primary winding of the plate transformer.

Filtering is provided by ASC oil caps and some vintage UTC chokes. Note that the capacitors are in series in order to meet the B+ voltage requirements. This configuration requires a balancing resistor across the capacitors. The resistors should be rated at 1000V DC or greater.

Wasting energy, as resistor heat, goes against my better judgment. I have never been fond of DC heaters or regulated heaters, mainly due to their inefficiency and the large amount of heat dissipated by their resistors. I find the only answer is to use AC heating for the filaments.

Please no comments on hum due to AC filament supplies. If you carefully select the filament components, hum will be very low. At present, my amplifier is running AC filaments on both the driver stage and output tubes. Measured hum, into an 8Ω load, is only 2.6mV for one channel and 4mV for the second.

THE AUDIO SECTION

Because the audio section is meant for experimentation and therefore will not be contained in a closed chassis, I took extra precautions in order to limit exposure to the B+ voltages. I rotated the 211 sockets 90° to each other so that the plate connections are towards the middle of the amplifier. Also, I rated all exposed B+ wire for 15,000V DC.

Along with price and quality, there were many considerations in choosing the output transformer. After narrowing my choices, I contacted Jack at Electra-Print. A short 30-minute phone conversation sealed the deal. The

TABLE 1.

Audio Section

T1, T1', T2, T2'	Hammond 124B nickel interstage transformer
T3, T3'	Electra-Print 10k to 6Ω 211 output transformer
R1, R1', R3, R3'	33kΩ 2W
R2, R2'	10kΩ 2W
R4, R4'	500Ω 2W
R5, R5'	1.3kΩ 25W
P1, P1'	100Ω 2W
C1, C1'	100μF 250V DC
V1, V1'	6SN7
V2, V2'	VT-4 or 211

' Denotes second channel

transformer had a 10kΩ primary impedance and a 6Ω secondary impedance. It was designed to handle the high B+ voltages along with the 100mA of current. After hearing the final amplifier, I was very happy with my decision to go with the Electra-Print transformer.

RING. RING. RING!

I finished building the amp and began testing it. The waveforms at both 100Hz and 1kHz were clean and linear all the way out to 25W. The bass output was around 1dB down at 20Hz. Everything was looking good until I decided to sweep the entire frequency range at a constant 8W output. I was expecting a ruler-flat frequency response, but what I got was slightly different. Everything looked good until 5kHz. The output began to climb until it peaked +4dB at 14.8kHz, then dropped like a rock.

You get what you pay for. Nothing in life is free. Every cliché I knew came to mind along with a plethora of four-letter words. I knew the \$12 nickel interstage transformer had been too good a deal. Experimentation led me to the conclusion that the ringing was being gener-

TABLE 2. POWER SUPPLY

T1	Plate transformer	1200VCT	400mA
T2	6SN7 filament transformer	6.3V AC	3A
T3, T4	211 filament transformer	10V AC	4A
S1	SPST switch		
F1	4A fuse		
D1-D12	solid-state rectifier	1A 1000V PIV	
R1-R6, R10	300kΩ 10W		
R7, R9	160Ω 3W		
R8	6kΩ 25W		
C1-C8	45μF 600V AC		
C9	0.01μF 1600V DC		
V1, V2	OD3		
L1	filter choke	6H 175mA	2500WV DC
L2, L3	filter choke	6H 175mA	1500WV DC
Relay 1	Delay-ON relay adjustable to 180sec		

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PHOTO 3: The 211 amplifier in front of the author's stereo setup.

ated by the input transformer.

The hook of a \$12 nickel transformer was too good a deal to abandon now. There had to be a solution to the ringing. I went back to the Internet for a little research and the hope that this issue had been tackled before. I stumbled across some information, on the Audio Asylum, regarding a similar interstage

transformer sold by Allied Electronics.

The solution discovered—on the Internet—was to use a small capacitor across the transformer from the primary winding to the secondary winding. I gave the proposed solution a try and sure enough the results were very promising on the bench. As I increased the transformer bypass capacitor from

MEASUREMENTS

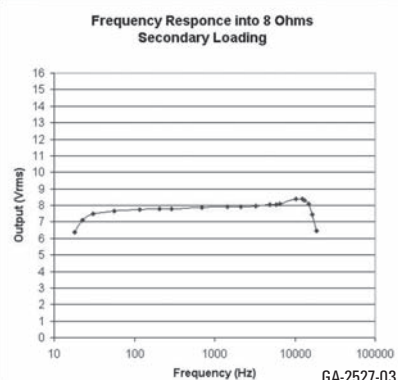
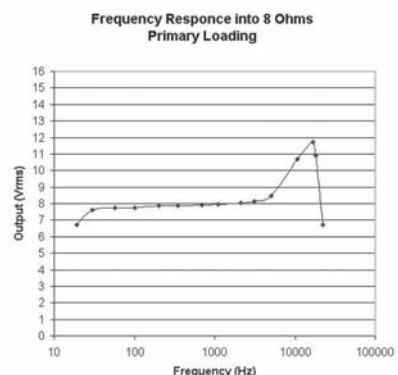
211 plate voltage = ... 1260V DC
 211 plate current = ... 58mA
 6SN7 plate voltage = ... 292V DC
 6SN7 plate current = ... 9.2mA p/s
 Maximum output power 8Ω
 load at 1kHz = ... 24.9W
 Input sensitivity = ... 4.2V RMS
 total weight = ... 86 lbs

10nF to 100nF, the high-frequency peak smoothed out. Unfortunately, listening to the amplifier with the input bypass capacitor made the amp sound lifeless and dull.

My friend, Dr. John Day, mentioned loading the secondary winding of the input transformer as opposed to the primary winding. I replaced the 10kΩ input resistor and transformer bypass capacitor with two 33kΩ resistors across the secondary winding. The high-frequency response peak smoothed out considerably, and the best part was that the sound was effortless and detailed.

Figure 3 shows the initial frequency re-

FIGURE 3: The frequency response of the 211 amplifier comparing different input transformer loading possibilities.



GA-2527-03

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ACKNOWLEDGEMENTS

Special thanks to Don Davis, Dr. John Day, and Darel Wieman.

sponse of the 211 amplifier with a 10k loading resistor across the primary winding and the final frequency response with the input transformer loaded across the secondary.

The idea of being able to tune the frequency response of the amplifier by selectively loading the input transformer was an interesting trick. If your speakers are lacking a little top end sparkle, place a 10k resistor across the primary winding of the input transformer and give it a listen. It may be the perfect little boost for Lowthers or single driver speaker owners.

SOUND

What can I say? I have a grin from ear to ear every time I hear or see the amplifier. The sound is exquisite and effortless (Photo 3). *ax*

Lee Roitberg received his BS in Electrical Engineering in 1997. Working in the high-tech industry since then, he has worked for Intel, Motorola, Dell, Foxconn, and most recently ModusLink. The last four years of his professional career have been in the area of root cause failure analysis. He recently joined ModusLink as a Senior Engineer managing Engineering Services.

In his spare time, he enjoys remodeling his 1959 house along with building audio equipment. Most recently, he completed a dedicated listening room in an effort to maintain marital bliss with his very understanding and patient wife.

SOURCES

Angela Instruments
10830 Guilford Rd. Ste 309
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Electra-Print Audio
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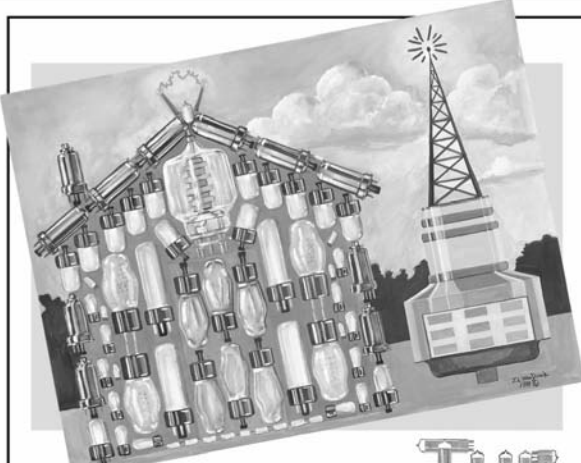
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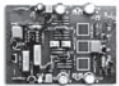
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A High-Quality Solid-State Headphone Amp

By Dennis Colin



PHOTO 1: Headphone amp.

This compact unit, powered by an external 24V DC “wall wart” or battery, provides very high sonic fidelity, no audible noise, and switchable loudness compensation.

The maximum output power of this phone amp is 137mW into 300Ω phones, and 218mW into 32Ω phones. With the (most excellent; see sidebar) Sennheiser HD 650 300Ω phones, maximum undistorted SPL is 119dB sine wave, corresponding to

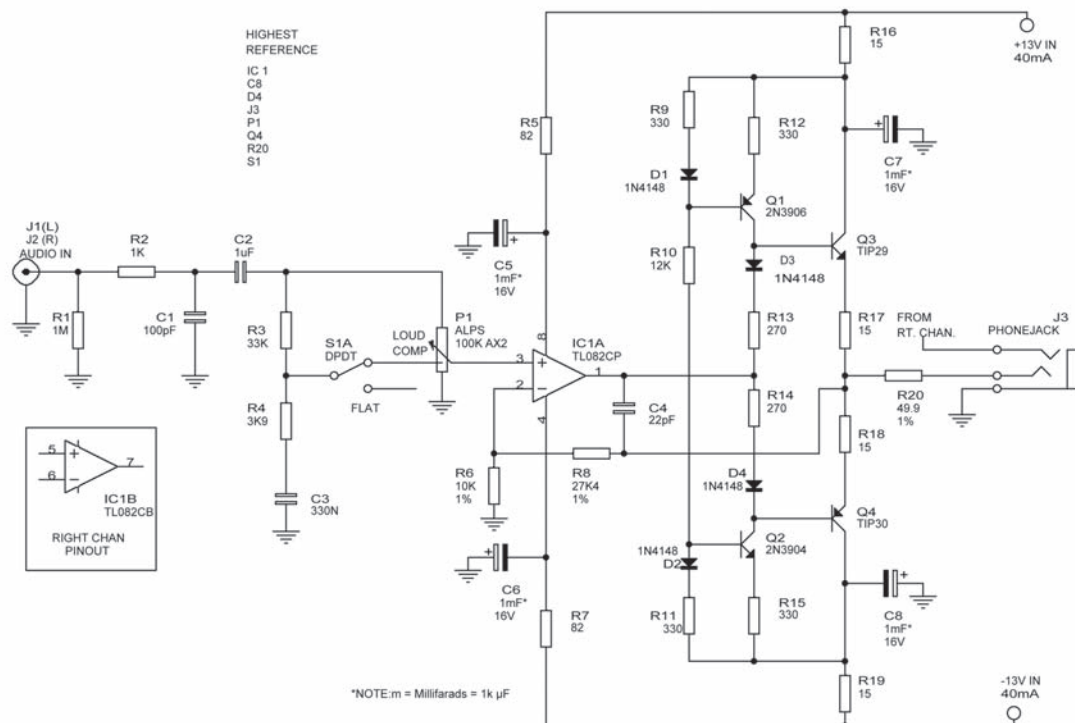
about 105–108dB music waveform average, which is about the SPL of a large orchestra playing full blast.

AMPLIFIER CIRCUIT

The output stage Q3-Q4, biased by constant-current sources Q1-Q2 (and asso-

ciated diodes and resistors), is a unity voltage gain power amplifier with a BW (bandwidth) of about 1.5MHz (Fig. 1). Q3-Q4 bias is about 30mA, enough to ensure Class A operation up to full power with 300Ω phones. With 32Ω phones, operation will be class AB at

FIGURE 1: Headphone amp (L channel shown).



A-2512-01

high power, but distortion will still likely be inaudible. But you can obtain full Class A with 32Ω phones by increasing Q3-Q4 bias to about 120mA, by changing R13, R14 to 1.2kΩ. This, though, increases the dissipation of Q3 and Q4 from 0.36W to 1.1W, so you should use small TO-220 heatsinks (or insulated chassis heatsinking).

The TL082 input stage has a Class AB output. However, measurements involving supply current monitoring established that the TL082 output bias is 0.62mA, and its operation is Class A up to a load current of about ±1.2mA peak. The application here draws only about ±0.5mA peak, so the TL082 is always in Class A. This, plus a 1.3MHz available BW (reduced to 230kHz by C4), ensures high-purity amplification by the TL082.

INPUT STAGE AND FEEDBACK

The (half per channel) TL082, operating in Class A as described, provides stable gain, low DC offset, and low noise (inaudible; about 4dB SPL with the most sensitive phones). Feedback resistors R6, R8 precisely set the gain. C4 applies negative feedback locally around the op amp, above about 230kHz (the -3dB roll-off frequency of the overall amplifier). This cap is not necessary for stability; without C4 the amp's -3dB bandwidth is 1.26MHz and stable, but this invites AM radio interference, and so on.

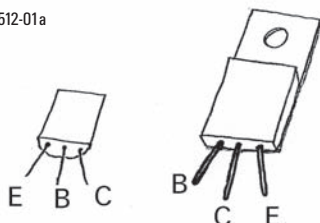
50Ω OUTPUT IMPEDANCE

The feedback is taken from emitter resistors R17, R18, giving this junction a very low output impedance (<1Ω). So why the series 50Ω R20? This, of course, sets the amp's output impedance at 50Ω. The reasons for this are:

1. Output is unconditionally stable—open, short, pure reactance.

FIGURE1a: Transistor Pinouts.

A-2512-01a



2N3904
2N3906

TIP 29
TIP 30

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Audio-Phyle Options

TABLE 1. Characteristics of Sennheiser Headphones.

Sennheiser HD 650 • Sound: Extremely Excellent • \$449
 $Z = 287\Omega + 1.227mH$ (both channels very well matched)
 Sens. = 103dB SPL at 1V RMS (manufacturer's data; confirmed by test) (3.3mW)

L-Chan		R-Chan.	
F	Z(Ω)	F	Z(Ω)
DC	287	DC	287
10Hz	296	10Hz	296
33.5	390	41.8	394
43.5	429	51.4	428
78Hz	481 LF Res.	100Hz	481 LF Res.
132	429	146	428
180	390	187	394
1kHz	307	1kHz	310
1.8kHz	304	1.8kHz	302
20kHz	356	20kHz	360

Comparing the HD650 with the Grado RS-2 (both about \$450), the Grado had some upper midrange roughness, while the Sennheiser sounded exceptionally smooth and tonally neutral.

2. Output is short-circuit proof.

3. Power delivered to 300 Ω and 32 Ω phones is approximately equal (about 3dB higher with 32 Ω phones, but they tend to be less efficient).

But what about "damping factor"? Unlike speakers, whose bass resonance might show a 10 $\times$ impedance rise,

phones have a nearly constant, nearly resistive impedance. The Sennheiser HD 650 (see **Table 1**) has a resonance Z of 481 Ω (re 300 Ω nominal). With a 50 Ω amplifier output Z, the signal increase to the phones at their LF resonance is only 0.5dB. If this concerns you, you can delete R20. But then a clipping signal level into 32 Ω phones could deliver about 2W, blowing the phones and perhaps your ears!

POWER SUPPLY

To eliminate concerns about AC line pollution, I decided on an external "wall wart" DC supply. The unit specified in **Fig. 2** works perfectly and causes no audible hum, or other noise (**Photo 4**). The circuit comprising Q1, 2 derives a stable voltage that's very close to the midpoint of the incoming single-ended DC supply voltage.

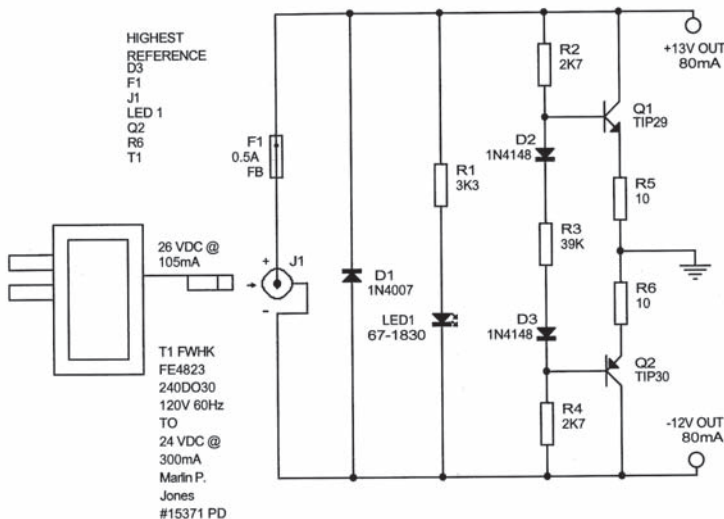
Basically a push-pull Class AB buffer amp, the output (R5-R6 junction) serves as the circuit ground, to which is then referenced the desired bipolar (about $\pm 13V$) supply. You could add voltage regulators, but they are not necessary because the amplifier has a very high power supply rejection ratio (PSRR). Including regulators would lower the supply voltage, and therefore the amplifier's maximum output power.

INPUT CIRCUIT

The ALPS 100KAX2 100k Ω stereo volume control pot (**Fig. 1**) is, as of this writing, available at Radio Shack for about \$3. This is a bargain—buy all you can. Quality appears to be excellent, and they have a 10% tap which I used for switchable (low) loudness compensation. Of seven units, I measured attenuation tracking (L/R), from 0 to -40dB, to be between about $\pm 0.2dB$ and $\pm 1dB$ (this does not depend on full-R matching, but rather on matching of the ratios of wiper-to-ground R to the full R). I suggest purchasing a number of units and selecting for best attenuation tracking.

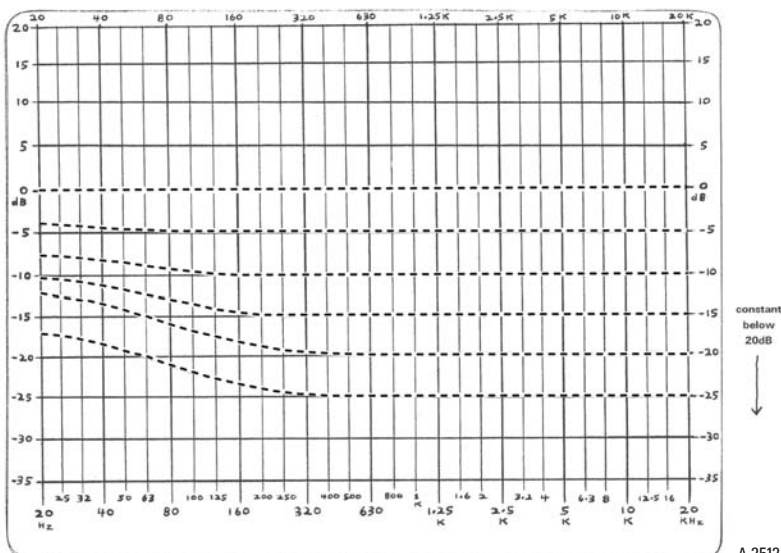
R2 and C1 filter HF interference, such as AM radio stations. C2, the only cap in the audio path, removes any source DC offset that would cause noisy attenuator operation. I used a 1.0 μF 100V metal poly cap from Digi-Key (EF1105), 10 for \$7.36. Or, you can spend whatever you like on the audiophile cap of your choice. R1 keeps C2 discharged with no

FIGURE 2: Power supply for HA-2 headphone amp.



A-2512-02

FIGURE 3: Loudness compensation responses—attenuator setting = 0 to -25dB in 5dB steps.



A-2512-03

input connected.

The gain (3.2W/300Ω phones) is such that at full volume (attenuation at 0dB), a 2.0V RMS input (Red Book CD 0dBFS = full scale) drives the amp to full power, producing 119dB SPL peaks, and about 107dB average music SPL—about that of a large orchestra playing full-blast—on the Sennheiser HD650 phones. But you can easily change the gain (with R6); the circuit maintains stability and adequate HF response over a gain range of at least 1 to 10.

LOUDNESS COMPENSATION

When S1 activates this, R3, R4, and C3 provide the LF boosts versus attenuation shown in **Fig. 3**. Maximum boost occurs at 20dB attenuation and then stays constant below that level. Down to about -30dB (re full volume), the boost nicely compensates the loss in LF hearing sensitivity (Fletcher-Munson contours) from ≥100dB SPL down to 70dB SPL, within about 2dB to 20Hz. The compensation is not adequate for much lower than 70dB SPL, but with good headphones why listen at lower volume?

Unlike many attempts at such compensation, that used here does not sound “boomy” or “muddy.” With a maximum boost of only 3dB at 100Hz, 7dB at 36Hz, and that only at and below -20dB volume, the compensation simply maintains natural bass fullness as the volume is decreased.

Note: If you use the ALPS 100k AX2 pot, you can use **Photo 2** as a calibrated dB template. These pots are very unit-to-unit consistent regarding attenuation versus rotation angle.

CONSTRUCTION

Don't do what I did—I (barely) stuffed everything into a 5 1/8" × 2 7/8" × 2 1/8" aluminum “Bud Box Clone” from Radio Shack (**Photo 5**). Fabricating a PC board, as opposed to the “rat's nest on balsa wood, lots of glue” construction I used, might save space, but I think the enclosure should be at least 6" × 3" × 3" in size*.

The DC supply input jack *must* be insulated from the metal enclosure. As **Photo 3** shows, I cut a 3/4" hole (with a Greenlee chassis punch—very precise and burr-free), then mounted over

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PHOTO 2: Attenuator dB scale.



PHOTO 3: Insulated 24V DC jack.

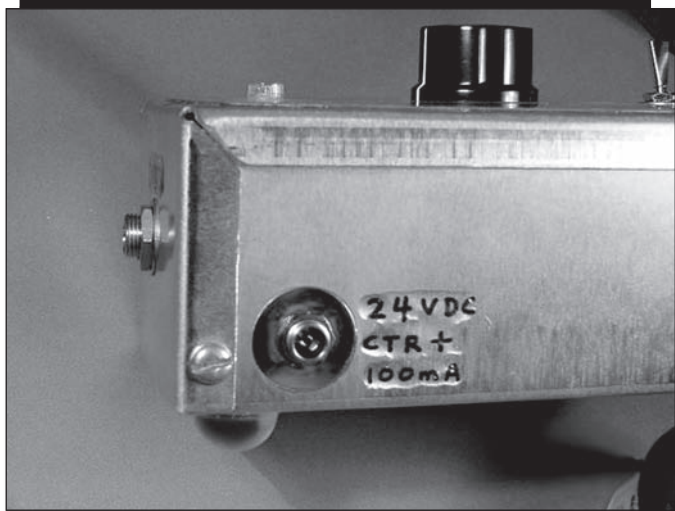


TABLE 2 HA-2 Headphone Amp Measurements.

Maximum Gain: 3.705 = 11.4dB, no load
3.176 = 10.0dB, 300Ω load
1.428 = 3.1dB, 32Ω load
At maximum gain, 0dBFS = 2.0V RMS (Red Book CD Full Scale Signal) drives amplifier to full output.
Maximum Output: 6.41V RMS = 137mW, 300Ω load
2.64V RMS = 218mW, 32Ω load
Maximum SPL with Sennheiser HD 650 phones = 119dB
Frequency Response: -3dB, 3.3Hz-230kHz
Half-Power Bandwidth: 360kHz, Slew Rate = 13.6V/μs (300Ω load)
Input Impedance: 27kΩ Output Impedance: 51Ω
Equivalent Input Noise: 31nV/√Hz density, flat spectrum (white)
(maximum with 4.38μV RMS unweighted, 20Hz-20kHz attenuator at -6dB;
3.42μV RMS "A" weighted, 20Hz-20kHz noise is 2.6dB lower with
attenuation at 0dB)
"A" weighted signal to noise ratio: 115dB re full output
Noise Level with Sennheiser HD650 phones: 4dB SPL (maximum with attenuation at
-6dB); 1dB SPL with attenuation at 0dB
Crosstalk: -66dB at 20kHz, -92dB at 1kHz (attenuation at 0dB, inputs term. in ≤1kΩ)
Output DC Offset: +2.1mV (left), +19.7mV (right), 300Ω load +0.9mV (left), +8.9mV
(right), 32Ω load
Loudness Compensation (switchable): Maximum at attenuator = -20dB; constant
below -20dB; +3dB at 100Hz, +7dB at 36Hz (close to equal-loudness contours for
80dB SPL re ≥100dB SPL)

the hole a piece of thick plastic, on which the DC jack was mounted.

I didn't use any shielded cables for the audio input paths, hence the 20kHz crosstalk of -66dB (not that anyone would notice it). But coax cable input connections would certainly improve 20kHz crosstalk, if only for the sake of impressive numbers.

Regarding **Photo 5**, I didn't use the transistor types specified in

the schematics; I used OHS (on-hand stock) types, similar enough to those specified. The circuit is very insensitive to transistor parameters (I've verified this by trying very different transistors; no noticeable degradation).

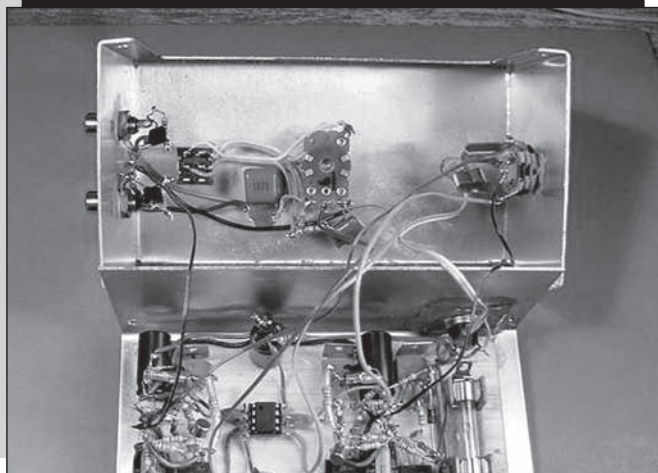
ADDING A SECOND PAIR OF OUTPUTS

You can connect a second 50Ω resistor to the R17/R18/R20 junction to drive a second output. If driving two pairs of 300Ω phones, the output stage Q3-Q4 will go into Class AB above about half the full voltage output. I've found that such Class AB loading appears clean (no visible crossover distortion nor obvious sonic anomalies). But you can achieve full Class A operation with two pairs of 300Ω phones by increasing the bias to 60mA (change R13, R14 to 560Ω). Small heatsinks on Q3, Q4 may or may not be needed; if Q3, Q4 are not too hot

PHOTO 4: 24V DC wall supply.



PHOTO 5: Balsa wood and glue construction.





SENNHEISER HD 650 PHONES

Is \$450 expensive for headphones? Well, to quote the Chuck Mangione song title, "Compared To What?" Most audiophiles wouldn't blink at spending \$450 for a good pair of speakers, especially if they were almost ruler flat from 20Hz to 20kHz, could produce 120dB SPL, and reproduced clean 16Hz at 100dB SPL. Not on this planet for \$450!

But these headphones do all of the above, plus they have razor-sharp, time-adjusted, pristine transient response (not to mention the obvious freedom from room acoustics). Tonal reproduction is effortlessly and extremely natural. "Coloration" doesn't appear to be in these phones' vocabulary.

As wonderful as this is, there's something beyond, difficult to describe, when these phones are driven by a highly transparent, sonically noiseless amplifier, fed directly from a player, particularly an SACD or DVD-A unit: You will be repeatedly startled into instinctively looking around as you hear quiet but clearly-revealed background noises, such as the conductor's footsteps, musicians' motions, distant glasses clinking, and everyone breathing. Every subtle sonic nuance produced by the instruments is revealed with crystal clarity. If an unexpected, well-recorded xylophone is played, for example, you'll swear the resonating metal is right in front of you—downright spooky. ■

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FIGURE 4: Square-wave responses; phones = Sennheiser HD650 (300 Ω); SPL = 109dB.

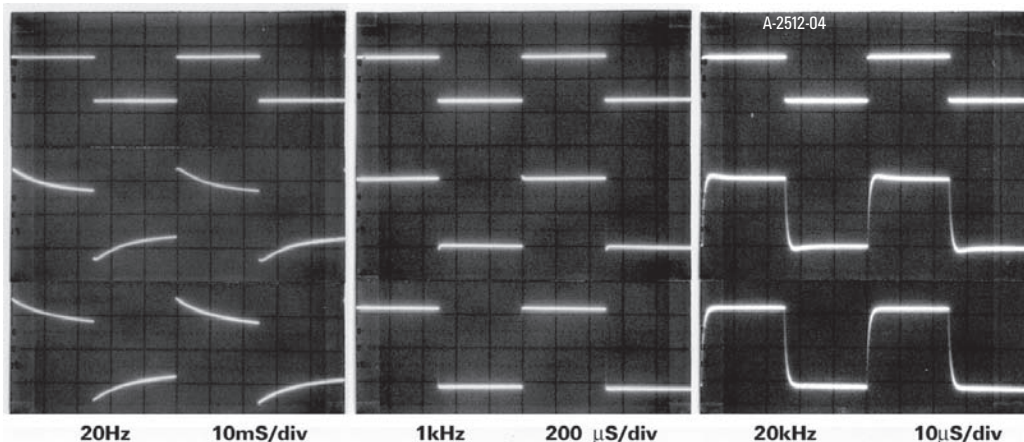


Figure 4 shows square-wave responses (20Hz, 1kHz, 20kHz) while driving the HD650 phones to 109dB SPL, and also with no load. The 20Hz exponential decay, and the 20kHz exponential rise time, reflect the -3dB bandwidth of 3.3Hz to 230kHz.

SONIC TRANSPARENCY

I compared various SACDs (1) with the HD650 phones direct-

to touch, they'll be fine.

The amp (with the pair of 50 Ω output resistors) can drive two pairs of 32 Ω phones, but since it's not recommended to increase Q3, Q4 bias above 120mA (the level for full Class A driving one pair of 32 Ω phones), operation about half the full voltage output will be Class AB. But the 120mA bias is more than enough to ensure the absence of crossover dis-

tortion; the sound will still be very clean.

ELECTRICAL PERFORMANCE

Table 2 summarizes the measurements. I don't have a distortion analyzer, but THD up to just below clipping is probably no more than the 0.004% typical of the TL082 (that figure is with its output stage Class AB loaded; here everything is Class A).

ly connected to the player output (the 300 Ω phone impedance and high sensitivity allow that) and (2) with the headphone amp inserted into the path (loudness compensation off, volume control set to match the direct connection). I heard no difference. Some might prefer a headphone amp that imparts a pleasing (euphonic) "sound"—warm, "romantic," and so on—but this unit

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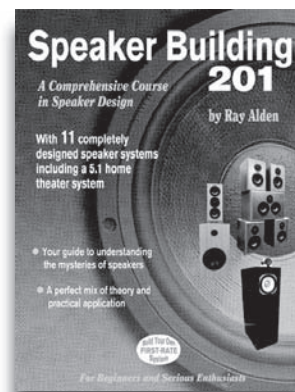
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Headphone Amp Parts List

Total Qty.	Schematic Ref Amp	Supply	Description	Source
1	A1		Dual opamp, TL082CP	
2	C4		Cap, 22pF	
2	C1		Cap, 100pF	
2	C3		Cap, 0.33μF 100V poly	Digi-Key EF1334
2	C2		Cap, 1.0μF 100V ply	Digi-Key EF1105
8	C5, 6, 7, 8		Cap, 1000μF 16V	
10	D1, 2, 3, 4	D2, 3	Diode, 1N4148	
1		D1	Diode, 1N4007	
1		F1	Fuse, 0.5A	
1			Fuse Holder	
2	J1, 2		Jack, RCA	Digi-Key SC1094
1	J3		Jack, 1/4" stereo	Digi-Key SC1048
1		J1	Jack for T1 (DC IN)	Digi-Key 67-1830
1		LED1	LED, Violet	ALPS 100K AX2
1	P1		POT, 100k stereo	Radio Shack 271-1732
2	Q1		PNP, 2N3906	Digi-Key 2N3906RLRAOSCT
2	Q2		NPN, 2N3904	Digi-Key 2N3904RLRAOSCT
3	Q3	Q1	NPN, TIP29	Digi-Key TIP29BOS
3	Q4	Q2	PNP, TIP30	Digi-Key TIP30COS
2	R20		RES, 1/4W, 1% 49.9Ω	
2	R6		RES, 1/4W, 1% 10.0k	
2	R8		RES, 1/4W, 1% 27.4k	
2		R5, 6	RES, 1/4W, 5% 10Ω	
8	R16, 17, 18, 19		RES, 1/4W, 5% 15Ω	
1		R3	RES, 1/4W, 5% 39Ω	
4	R5, 7		RES, 1/4W, 5% 82Ω	
4	R13, 14		RES, 1/4W, 5% 270Ω	
8	R9, 11, 12, 15		RES, 1/4W, 5% 330Ω	
2	R2		RES, 1/4W, 5% 1k	
2		R2, 4	RES, 1/4W, 5% 2.7k	
1		R1	RES, 1/4W, 5% 3.3k	
2	R4		RES, 1/4W, 5% 3.9k	
2	R10		RES, 1/4W, 5% 12k	
2	R3		RES, 1/4W, 5% 33k	
2	R1		RES, 1/4W, 5% 1M	
1	S1		Switch, DPDT	Digi-Key 360-1156
1		T1	"Wall Wart" 24V DC 300mA Alternate T1 →	Marlin P. Jones 15371PD
1			Suggested Enclosure Hammond 1590E (7.4" × 4.7" × 3.1")	Digi-Key T520-P6P Digi-Key HM155

isn't one of them. If the recording has *natural* warmth, you'll hear it clearly (with good headphones). *aX*

* The Hammond 1590 E aluminum enclosure, 7.4" × 4.7" × 3.1", Digi-Key HM155, is a good choice.

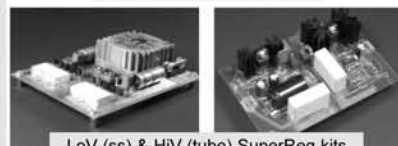
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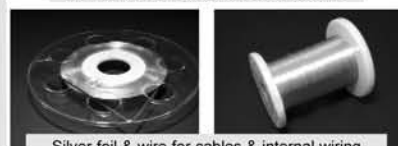
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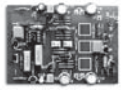
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House Music?

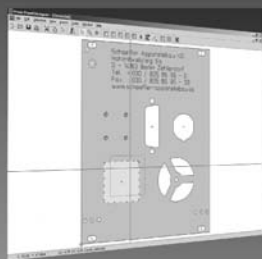
Music in every room? The author explores some easy options for DIY enthusiasts to wire their houses for sound.

By Simon Brown

Twenty years on, I only hope the neighbors of the house I lived in with a bunch of other engineering students liked Blue Öyster Cult as much as we did. They would have certainly heard enough of it played at startling levels of . . .

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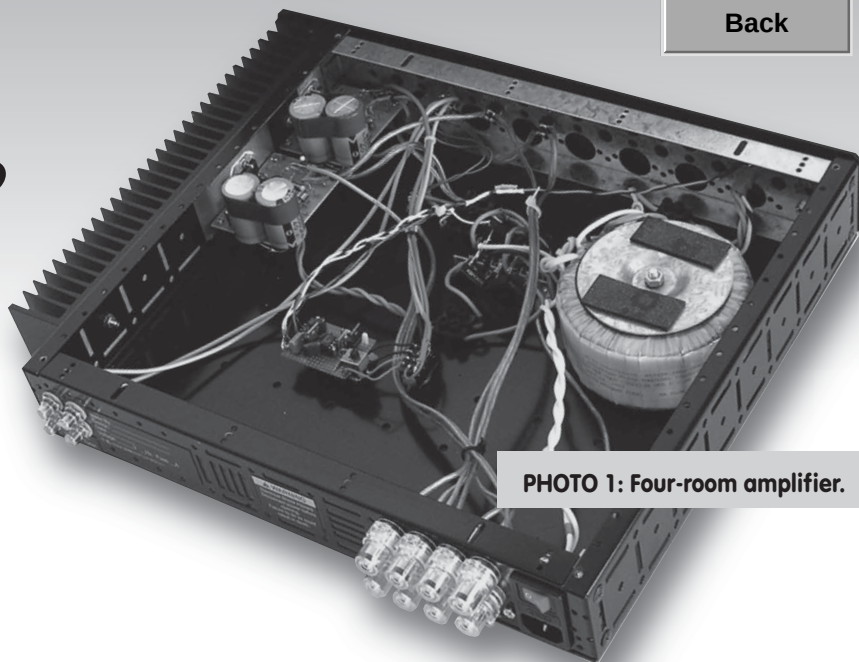


PHOTO 1: Four-room amplifier.

well, distortion.

In those Pre-Fi days, it wasn't that we were particularly inclined to audio animalism, rather we had combined all the best bits of gear we owned into one, nearly respectable system. To have music in our individual rooms, the upper reaches of volume knob were well explored.

I still enjoy having music throughout the house, but now the neighbors call less to "discuss" my music taste. This is because I now have music from my system wired into four other rooms beyond the main audio room. This was done simply, inexpensively, and provides good sound quality.

MAY THE SOURCE BE WITH YOU!

There are many complex "home automation" systems now available, but most could not be defined as "HiFi" and the ones that are, are notable for their cost. If you have invested time, energy, and money in good source components, you may be reluctant to either replicate them or rely on an indifferent source. In my mind, feeding sound from a good source to other rooms is the best way to achieve quality sound in other rooms. There are many ways to implement such a system, but my suggestion (at least to start) is to simply put speakers in the appropriate rooms and drive them from a "spare" integrated amp in the main audio room. This keeps wiring simple and means you maintain the ability to walk by using your legs occasionally.

MONOMANIA?

One concept that helps spread music round the house simply and inexpensively is a radical one—mono! Picture our kitchen/dining area for a moment: It's after work, my wife and I are making dinner, checking out some red wine as we go. Gradually we migrate to the table, eat dinner, then make coffee, talk, and read. All the time there is a nice wash of music present. But it's not "stereo"; if it was, we would almost never be in the right place to hear it "correctly."

For this context it's better to do mono and do it well. A friend has bought several mono Tivoli radios for different rooms rather than commit money to stereo. You can have more than one mono speaker for a more diffuse sound field. By going mono, you suddenly can cover twice as many rooms with your available amplification and you greatly simplify the wiring.

I use a two-channel amp, in which each output is switched between two rooms, giving me music in four rooms. This is built into an ezChassis cabinet, which has four sets of speaker terminal holes (Photo 1). It can be adapted for 0–6 sets.

Philosophically I would avoid switch contacts at the amplifier output, but the real world wins here. (Upset readers will be glad to know I'm intending another couple of directly connected channels when I start using this as a test bed for developing a LM3875 kit.)

Two cautionary comments: the first is that depending on what you are using as

your power amp, going mono might not be quite as simple as wiring L & R wires together. With power amps with no accessible "stages," you might need to add an op amp "adder" stage to avoid having mono throughout your system. The second caution is to think about the extra loading an extra amp places on the source components. This should not be a problem for most components, but some valve preamps may struggle.

AMPLE AMPS

Modifying an "old" integrated amp for this application is the easy option, but many audio builders may choose to build that little single-ended valve amp, which they know will never quite be up to driving the "main" speakers. There are also many other modest but good options to be drawn from *audioXpress* or cheaper kits such as the AKSA, Hypex, or Hagerman. My own "house" amp uses two LM3876 (50W) "amp on a chip" modules.

I discovered accidentally that these sound embarrassingly good despite having few pretensions. I have subsequently learned that there is a large distant corner of the Internet devoted to these "Gain-clone" amps. This has the usual mix of sensible and silly, but you could start with a cheap kit from an electronics supply house such as Jaycar and upgrade the component quality later (Jaycar Kit KC5150 costs approximately \$25 + power supply).

FRAMED?

Many houses in North America and Australasia are timber-framed, which can make the job of wiring audio surprisingly easy, especially for internal walls where there is less likelihood of encountering insulation. Because many walls have a horizontal joist or blocking (often about 3' up), running wiring up inside the wall cavity may not be possible unless you have access to a drill extender and a lot of patience or are re-facing a wall (Fig. 1). One way around this is to bring wiring up through built-in cupboards, allowing you to sit speakers on top of them, while wiring from below. Generally you will need to make the choice between going "under" or "over."

Canny audio enthusiasts trying to keep runs of expensive cable to a minimum may not infrequently be found crawling around the floor space under their houses. The



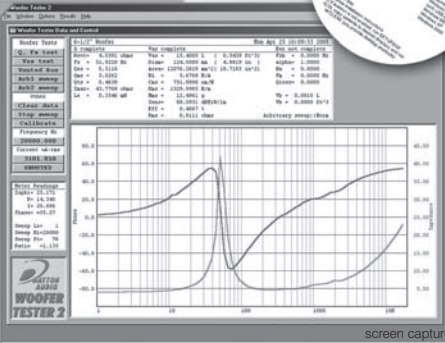
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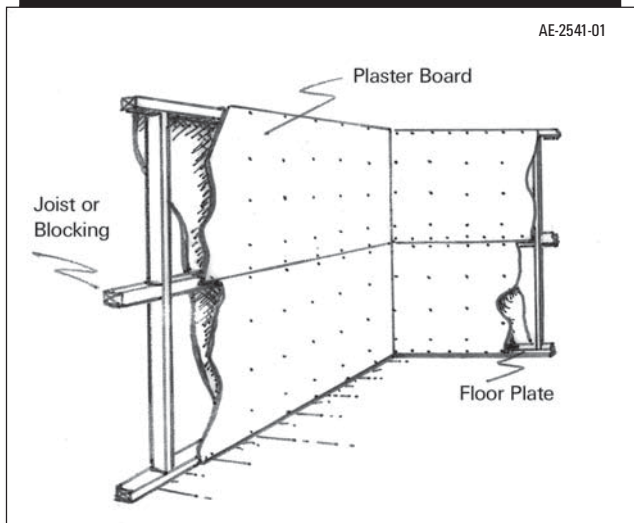
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FIGURE 1: Timber-framed wall construction.



same principles can be applied to running wiring between rooms. I've found drilling a cable hole between the carpet and the base molding (skirting board) is almost invisible. I suggest using a small drill bit, and crawling under the house to locate it first before using a "cable"-sized drill.

Standard warnings apply: Make sure there isn't household wiring in the area of

or ceiling is the most appropriate option. Our bathroom has a small plastic-coned driver installed in the wall cavity. OK, a 4" full-range speaker isn't going to have you punching the air while miming "Don't Fear the Reaper," but it's fine for Handel's Water Music while reclining in the bath. It's also resistant to steam and is discreetly covered with a white plastic grille. (I

the wall you are about to drill into and check that you are not going to infringe on any local wiring regulations.

WALLS OF SOUND

Many HiFi enthusiasts have "spare" loudspeakers around. If small, these units can sit on top of wardrobes or kitchen cupboards. Otherwise it can be a fun excuse to try out a mini audio project.

Sometimes building a speaker into the wall

used a Jaycar CW2104 driver, but this was a matter of convenience rather than the best available.)

A timber-framed house makes installation easy, but watch that the magnet to mounting face is less than wall cavity depth (usually 4"). Look for speakers with Qts ~ 0.7, as you are mounting them in a large but indeterminate cavity. I was fortunate that the bathroom had a tongue-and-groove timber lining, which was strong enough to mount a driver.

If the wall covering is only plaster board, you need to provide something more substantial. The simplest option is to bond 1/4" ply onto the board over an area somewhat greater than the driver, ideally to the nearest stud. Ceiling-mounted speakers have the advantage that you can install an already sealed box and screw it firmly to a joist above the ceiling panel, which may otherwise not be firm enough.

FINISHING DETAILS

If your chosen speaker cable looks capable of supplying a small city with electricity, you might not wish to bore such big holes

new!



By William
Fitzmaurice



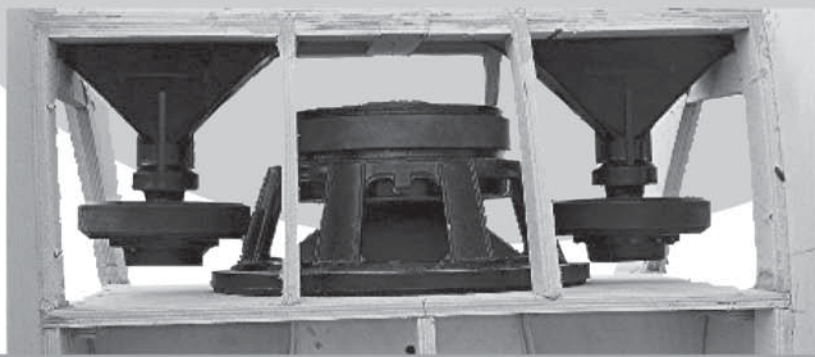
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in your floor. One tidy option is to use a wall plate with speaker terminals. These are available to visually match electricity outlets. Keep these low down on the wall to make it easy to "find" the wire you're poking up from below. Again you can use the "pilot drill from above" technique to show where you are under the floor.

I've described an uncomplicated system here. There are many other options possible, especially if you want to vary the volume while in the other room. "L-Pad" volume controls are a very simple option, but I can't confirm whether their

bad audio reputation is justified or not. Built-in power amps, and associated potentiometer, are a more complex option, but the availability of Class D amps (such as Hypex) may encourage this as they generate minimal heat.

Though I still occasionally play Blue Öyster Cult at high levels of distortion, it's more the result of a 20-year old LP that was once played with a "student stylus." Meanwhile, however, I am also now able to enjoy high-quality sound throughout the house, by extending my hi-fi system to other rooms via simple arrangements which neither compromise the sound of my main system nor the structure of my house! *ax*

Simon Brown is a professional engineer and has worked in Product Design in New Zealand and England. He has long been interested in DIY HiFi, having built speakers, amplifiers, and turntables over the years. This led him to set up Design Build Listen Ltd. to supply DIY HiFi components. Simon has had over a dozen articles published in HiFi magazines. Contact him via www.designbuildlisten.com.

SOURCES

Jaycar (Australasian component supplier) www.jaycar.com.au

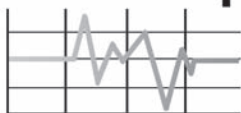
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29TAF/W

6 ohm

91.5dB

fs 950Hz

metal dome

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22TAF/G

6 ohm

92dB

fs 1100Hz

metal dome

\$26.60 each

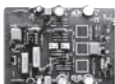


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Musical Waveform Peak and Average Power Frequency Distributions

Analyzing four music selections, this author relates them to amplifier peak power demand, maximum SPL, high-frequency distortion, and, in two cases, sound quality.

By Dennis Colin

SPL tends to be judged on the basis of average power, but it's the peaks that are amplifier limited. So the higher the peak-to-average power ratio, the lower will be the SPL capability without clipping. And while most music has a significant HF rolloff in average power, HF peaks can be quite strong. In one selection presented here, the peak power at 4kHz and 14kHz is 5dB higher than that at any lower frequency. And, of course, amplifiers usually have the highest distortion at high frequencies and with sharp transients.

I analyzed four musical selections during a sustained maximum-volume segment for peak and RMS voltages—both directly and within $\frac{1}{3}$ octave bands across the spectrum. I plotted the data in relative dB as peak and average power and tabulated it as a

percentage of total peak power present within octave bands; the latter allows estimation of an amplifier's clean HF power capacity requirement.

DEFINITIONS

1. Peak Power

Since amplifiers are rated in average sine-wave power (not instantaneous crest power, which is double), and because most of the highest peaks from acoustic instruments look nearly sinusoidal (**Photo 1A**), it's consistent and convenient to use the average power (or RMS voltage) in the highest transient half-cycles, averaged or RMS'd over their duration (**Fig. 1**). Then $V_{PRMS} \approx V_P/\sqrt{2}$. This voltage, when squared and divided by some load resistance, results in the average power of the transient.

V_{RMS} is the long-term RMS voltage (1.1s averaging time in my measure-

ments), which when similarly processed results in the long-term average power. Then $(V_{PRMS}/V_{RMS})^2$ is the ratio of the maximum sine-wave amplifier power needed to the average waveform power. Maximum sine-wave power (half the instantaneous power at the peaks) is used to be consistent with standard amplifier power rating practice.

In this article, the term "peak power" means "maximum sine power," not absolute peak power (twice as much). So defined, the peak/average power ratio in dB is $20\log(V_{PRMS}/V_{RMS})$. The crest factor (V_P/V_{RMS}) expressed in dB is $20\log(V_P/V_{RMS})$, 3dB higher than the as-defined peak/average ratio.

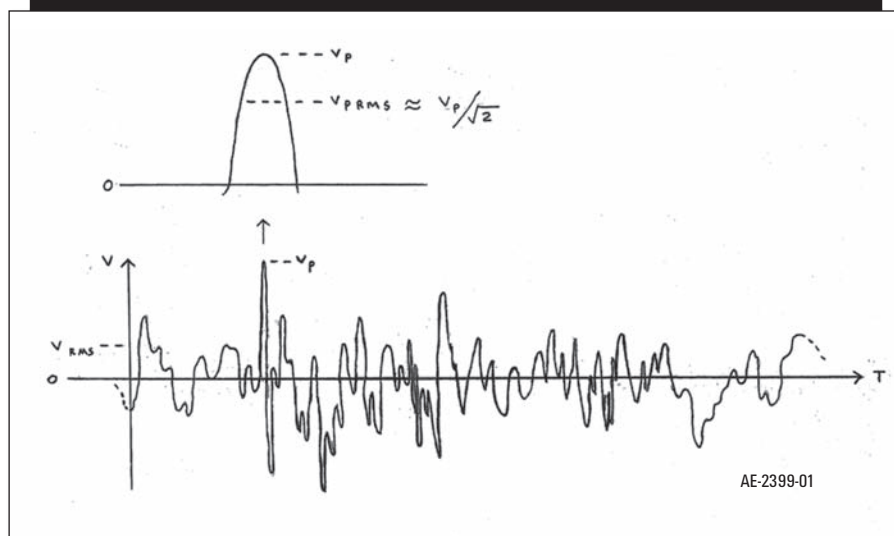
2. Average Power

Obviously with music this depends on the averaging time. The ear (also the eye) has an integration time of about $\frac{1}{20}$ second. Events repeating more slowly than about 20Hz are resolved as a time sequence, or rhythm. So a power averaging (or V^2 averaging for RMS voltage) time of $\frac{1}{20}s$ is a lower limit, and this duration also includes one cycle of the lowest audio frequency.

But in observing the output of an RMS to DC converter with variable averaging time constant, $\frac{1}{20}$ or even $\frac{1}{10}s$ allowed too much LF ripple or "flickering" on the output to obtain stable readings. Also, some peaks would undesirably increase the supposedly average result viewed on a meter.

With average times longer than about 0.5s, readings were stable and

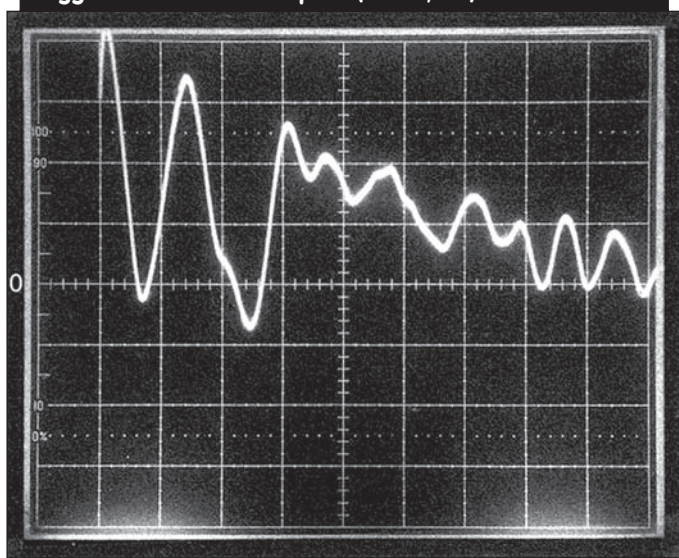
FIGURE 1: Definitions.



AE-2399-01

didn't change significantly with longer average times, if the perceived SPL was constant. I then wired the RMS detector for switchable 0.1 or 1.1s averaging times. No reason for the 1.1 figure (resistors and caps on hand, you know). For all but one measurement, I used the 1.1s averaging for RMS voltages.

PHOTO 1A: All My Exes Live in Texas scope 200mV/div, triggered on snare drum peak (0.2ms/div).



AND NOW, THE PERFORMERS

1. *Emmanuel Chabrier "España," Ansermet/L'Orchestre de la Suisse Romande, Decca 448 576-2*: A very lively piece, recorded in 1964 directly onto two-track tape. Probably not coincidentally, the audio waveforms have high peak/average ratios especially at high frequencies, and the sounds are very dynamic with natural "bite." Also, the stereo depth puts many modern recordings to shame. (Ask Ed Dell how he likes the Ansermet/Suisse Romande recordings!)

Also, the sounds are very dynamic with natural "bite." Also, the stereo depth puts many modern recordings to shame. (Ask Ed Dell how he likes the Ansermet/Suisse Romande recordings!)

2. *Handel "La Réjouissance," HiFi News HFN020*: A horn fanfare with (not too loud) fireworks. Even with the latter,

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strangely, the peaks and peak/average ratios were much lower than in *España*. And while the performance was dynamic, the sound seemed muted and the spectrum (even of peaks) was much more rolled off above 2kHz.

3. *John Pizzarelli: "If Dreams Come True,"* Telarc SACD-63546: Very well recorded popular song with George Schering on piano.
4. *George Strait "All My Ex's Live in Texas,"* MCA MCAD-5913. A great performance and clear recording, except for a highly (studio) boosted 3-18kHz content. Serving as an extreme example of HF peak power demand, the highest peaks (from a rhythmic snare drum beat) are at 4kHz and 14kHz, and at 5dB above the rest of the spectrum. At 14kHz the peak/average ratio is about 25dB, a 316:1 power ratio. About 33% of the peak amplifier power output will be in the 5kHz-20kHz band.

HIGHEST TRANSIENT WAVEFORMS

The high snare drum peaks in George Strait's recording allowed consistent scope triggering while also showing the complex waveform summation of the multiple instruments playing (**Fig. 2**); **Photos 1A-1C** present this on different time scales.

Photos 2A and **2B** show stereo X-Y crossplots (Lissajous figures). They aren't single sweeps as in **Photos 1A-C**, but $\frac{1}{8}$ s exposures where the dense average-signal central regions saturated the film, because high scope brightness was needed to capture (some of) the peak excursions.

Lissajous dis-

plays also reveal left-right correlation: mono produces a 45° straight line; a 90° shifted L-R sine wave makes a perfect circle, and natural-sounding stereo music generates a round, almost spherical-looking pattern as in **Photo 2B**, from *España*. This recording has excellent stereo depth and imaging.

LONG SWEEP STORAGE SCOPE WAVEFORMS

Photos 3-10 show a single sweep of 1s

TABLE 1: Audio Waveform Properties, 10S Interval of Loudest Playing.

	Chabrier	Handel	Pizzarelli	Strait
Peak Voltage	1500mV +2.7dBm	500mV -6.8dBm	850mV -2.2dBm	900mV -1.7dBm
RMS Voltage	275mV	98mV	155mV	98mV
1.1s TAVG	-9dBm	-18dBm	-14dBm	-18dBm
Crest Factor	5.45	5.10	5.48	9.18
$= V_p/V_{RMS}$				
Sine Weighted	14.8:1	13.2:1	15.1:1	42.7:1
Peak/Avg	11.7dB	11.2dB	11.8dB	16.3dB
Power Ratio				

PHOTO 1B: All My Exes Live in Texas scope 200mV/div, triggered on snare drum peak (1ms/div).

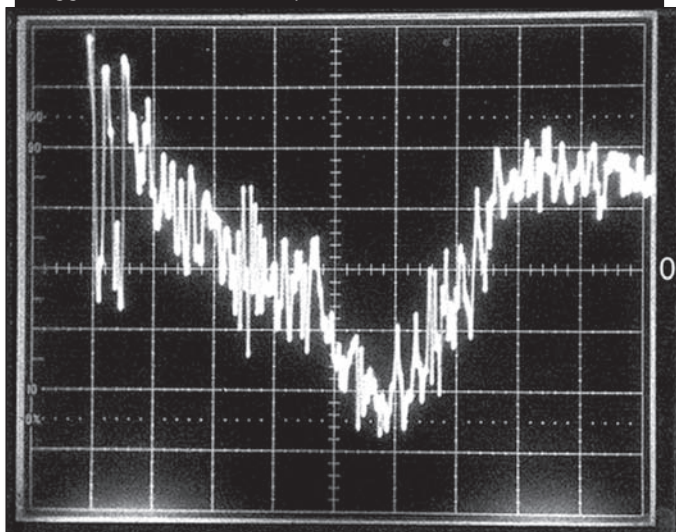


PHOTO 1C: All My Exes Live in Texas scope 200mV/div, triggered on snare drum peak (5ms/div).

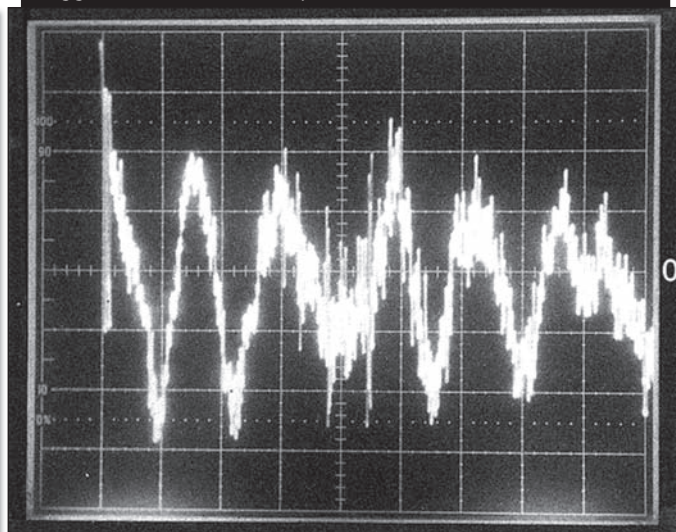


FIGURE 2: Test setup, unfiltered audio.

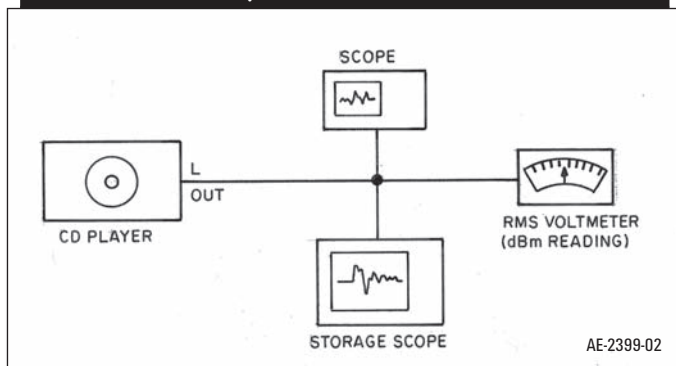
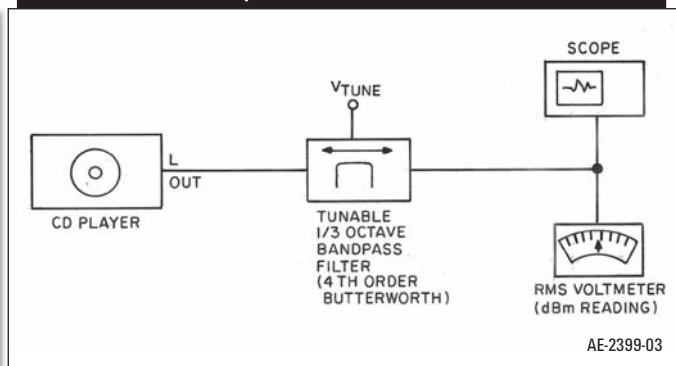


FIGURE 3: Test setup, 1/3 octave filtered audio..



(Photos 3-6) and 10s (Photos 7-10) for a steady high-volume segment of the selections. Of note in the George Strait country song in **Photo 10** are the repeti-

tive high peaks (containing very high relative power even at 18kHz); these are the snare drum accents.

TABLE 2: Chabrier "España"—Highest outputs through 1/3-octave BP filter during 10s interval of loudest playing.

Peak Frequency	mV	RMS dBm	dBm
20Hz			
25	3.5	-50	
31	7	-44	-53
40	17	-36	-44
50	42	-28	-32
63	77	-23	-30
80	210	-14	-22
100Hz	180	-16	-24
125	330	-10	-18
160	450	-8	-19
200	440	-8	-17
250	420	-8	-18
315	500	-7	-18
400	320	-11	-20
500	250	-13	-22
630	230	-14	-23
800	240	-13	-26
1kHz	260	-12	-24
1.25	280	-12	-24
1.6	230	-14	-26
2	210	-14	-25
2.5	240	-13	-26
3.1	210	-14	-27
4	170	-16	-28
5	140	-18	-30
6.3	160	-17	-30
8	180	-16	-30
10kHz	240	-13	-29
12.5	350	-10	-28
16	240	-13	-30
20kHz	130	-19	-38
	RSS Sum = 1413mV (+2.2dBm)		Power Sum = -8.6dBm
Unfiltered Audio:	1500mV (+2.7dBm) (peak)	-9dBm	(RMS)

$$\frac{\text{Sine weighted peak power}}{1.1\text{s average power}} = 4.8 = 11.7\text{dB}$$

crest factor = 5.45 = 14.7dB
(11.7dB more than a sine wave)

PEAKS AND AVERAGES OF AUDIO WAVEFORM

The highest peaks, RMS values, ratios thereof (crest factors), and peak/average power ratios are shown in **Table 1**. For the peaks, the dBm values (re 0dBm = 0.775V RMS, 1.095V peak sine) are calculated for a sine wave with the same peak voltage as the observed musical waveform peak. This is consistent with the stated definition of peak power as the average power within the highest peaks (which most often resemble sinusoidal half-cycles). This is also consistent with the average sine-wave power rating of amplifiers.

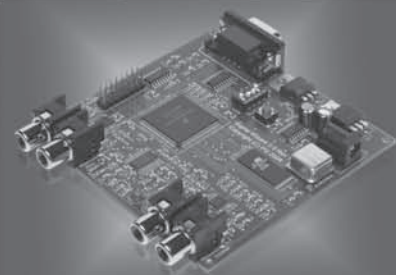
1/3 OCTAVE FREQUENCY SPECTRUM

The 1/3 octave filter (**Fig. 3**) was stepped through the audio spectrum, noting the highest peaks and RMS voltages at each filter frequency. Results are presented for *España* in **Table 2**.

Figures 4-7 show (top traces) the spectrum of

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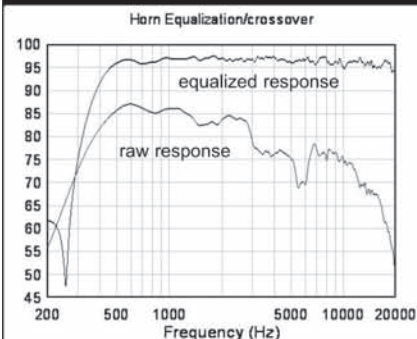
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PHOTO 2A: Stereo Lissajous pattern, scope 200mV/div, X=left, Y=right (All My Exes Live in Texas).

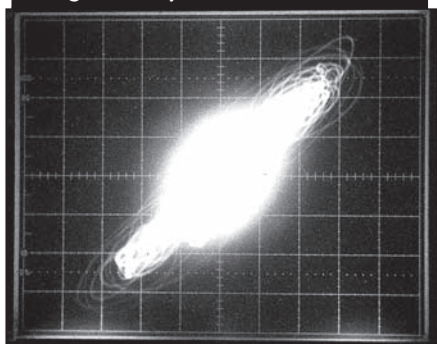
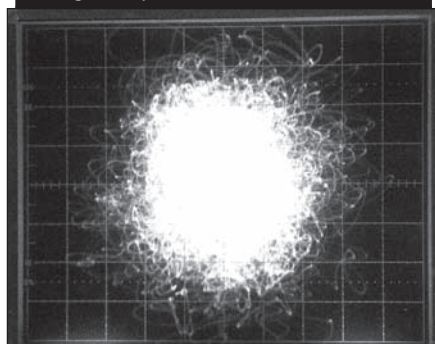


PHOTO 2B: Stereo Lissajous pattern, scope 200mV/div, X=left, Y=right (España).



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the highest peaks, manually plotted from this data; lower traces are the averaged values. Note that with peak

power as defined here, the “peak” and “average” traces would be the same for a sine-wave signal.

PHOTO 3: *España*, 1s sweep.

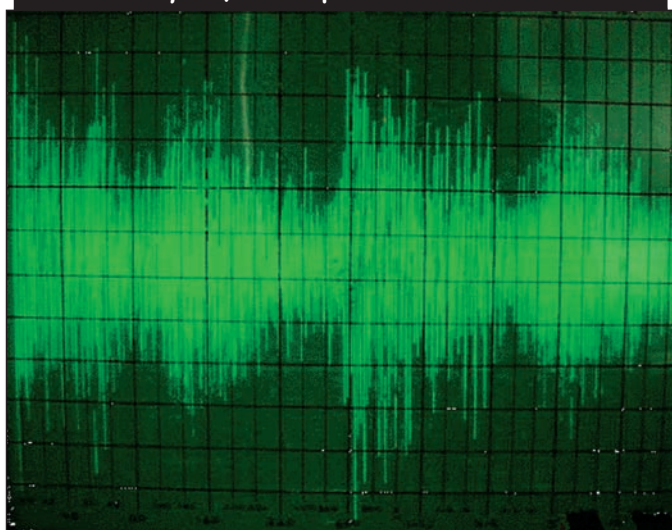


PHOTO 4: *La Réjouissance*, 1s sweep.

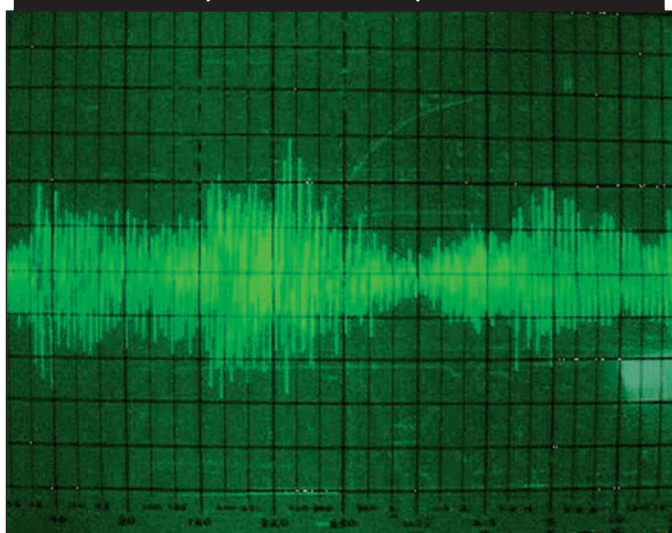
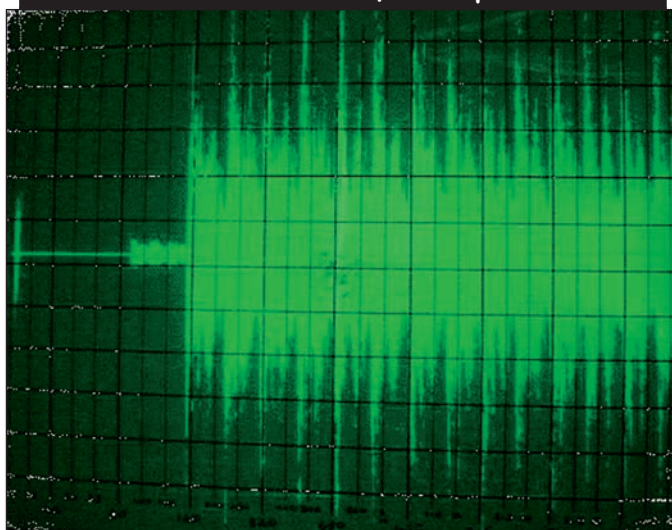


PHOTO 5: *If Dreams Come True*, 1s sweep.



NOTABLE FEATURES

1. The most surprising feature is the HF power in the peaks of George Strait's song (top trace, **Fig. 7**). I'd bet that someone in the studio cranked up two HF EQs to get peak power at about 4kHz and 14kHz, which is 5dB higher than at any lower frequency.

2. In **Fig. 7** only, I plotted the RMS level with 0.1s averaging time in addition to the 1.1s average RMS shown in all four selections. Note that around 200Hz, the shorter-time average nearly equals the peak. This implies a nearly sinusoidal waveform, of nearly constant amplitude within the 0.1s averaging time.

Such a signal can be produced by the upper notes of a bass (and standard) guitar: 200Hz is in the upper range of a bass guitar, where harmonics are most attenuated. Such notes can have nearly sinusoidal waveforms.

3. Note that only in the Handel piece (**Fig. 5**) does the spacing between

the peak and average traces stay nearly constant over the whole frequency range. With the other selections, although the

average traces roll off at high frequencies, the peak traces roll off much less or actually rise (Fig. 7), producing a greatly expanded spacing between peak and average at the highest frequencies. This is because most of the peak power in the high treble is from short-duration percussion accents (short relative to their repetition time); this low duty-cycle results in (for example, Fig. 7 at 12kHz) a 25dB peak/average ratio (about a 316:1 power ratio).

4. Below about 1.2kHz, the peak/average ratio in all selections is mostly within a 5-10dB range. Considering just for now the 3dB "crest factor" of a sine wave (twice the average power at the sine peaks), the crest factor of the signals below 1.2kHz is approximately 8-13dB, similar to that of Gaussian noise.

PERCENTAGES OF PEAK POWER IN OCTAVE BANDS

In Table 2, the filtered band peak output voltages were RSS (root-sum-square) totaled; this is valid for uncorrelated signals, such as different frequencies or noise sources. The result (1413mV) is

PHOTO 6: *All My Exes*, 1s sweep.

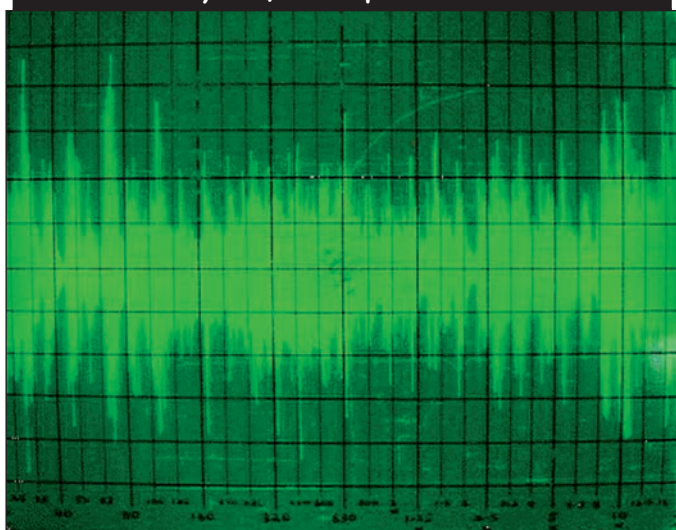


PHOTO 7: *España*, 10s sweep.

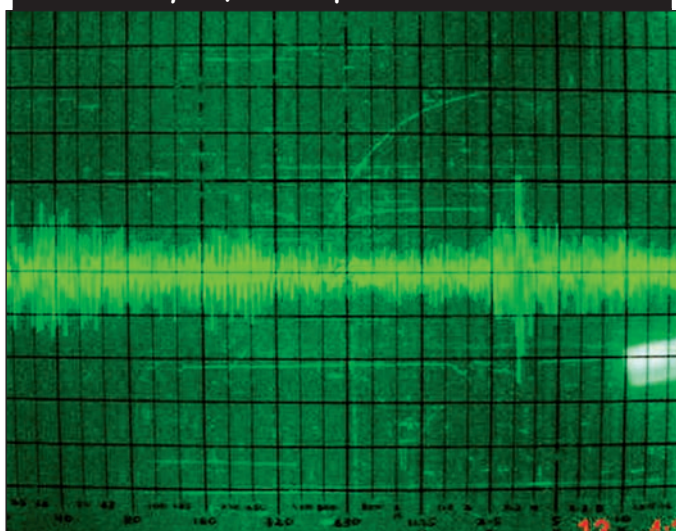
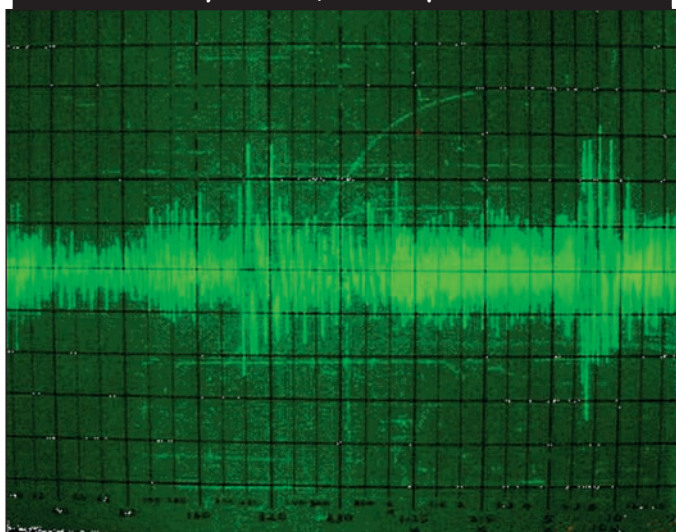


PHOTO 8: *La Réjouissance*, 10s sweep.



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within 0.5dB of the 1500mV input peak.

Next (not shown), I calculated RSS sums within octave bands and tabulated, in each band, squaring this octave-peak voltage and dividing by the 1500mV input peak squared. This result is a power ratio, the fraction of peak signal power present in a particular octave band.

Adding these octave percentages was within the same 0.5dB as with the **Table 2** results, of equaling 100% of the signal power; for convenience they were scaled to total 100% in **Table 3**.

Note that the validity of the calculations depends on different frequency peaks occurring reasonably simulta-

neously: consider, for example, an alternating duet between a bass guitar and a flute, of equal signal voltage for convenience. With this frequency separation, two separate sets of filtered bands will produce alternating, not simultaneous, outputs. So it would be wrong to sum them and expect this to equal the input signal; the bass range and the flute range powers would each be 100% of the input signal power, inappropriately "totaling" 200%. But with these four selections, the sums were within 0.5dB of the input power, so peaks across the spectrum must be occurring reasonably simultaneously.

This is not surprising, since in a musical climax or (especially) a strong rhythmic accent, all the instruments contributing would likely play loudly and in as close timing as possible.

Table 4 shows, for comparison, the octave band average power distribution for the *España* selection. Note that below about 600Hz the average power has a larger fraction than the peak power, but vice versa above 600Hz.

SONIC EFFECTS OF IM ON HIGH- FREQUENCY TRANSIENTS

With harmonic distortion, even-order is accepted as less objectionable than odd-order. Not so for high-frequency IM distortion. Consider a transient—say, mostly occupying an 8–12kHz, BW—of high peak power.

The maximum range of third-order IM products is 2(8kHz)–12kHz, and 2(12kHz)–8kHz, or 4–16kHz. So with enough IM the original transient-signal BW of 4kHz becomes tripled,

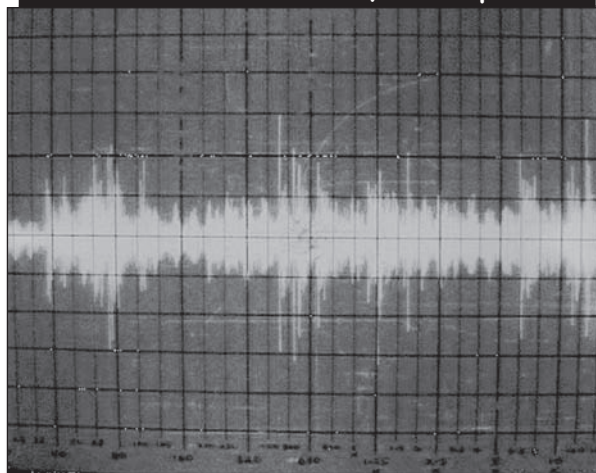
TABLE 3: Percentages of peak audio power present in each octave band.

Octave Band	Chabrier	Handel	Pizzarelli	Strait
20–40Hz				
40–80Hz	1.5	0.8	8.1	2.4
80–160Hz	13.3	6.9	21.7	6.7
160–315Hz	29.9	26.2	22.8	8.1
315–630Hz	15.8	24.0	22.1	8.3
630Hz–1.25kHz	9.6	17.8	12.3	8.3
1.25–2.5kHz	8.2	15.6	4.9	9.5
2.5–5kHz	5.6	6.8	3.2	23.4
5–10kHz	4.8	1.7	2.9	13.6
10–20kHz	11.3	0.2	2.0	19.7

TABLE 4: Percentages of audio power present in each octave band, Chabrier *España*.

Octave Band	Peak Power %	Average Power %
40–80Hz	1.5	3.4
80–160Hz	13.3	20.6
160–315Hz	29.9	35.1
315–630Hz	15.8	18.7
630Hz–1.25kHz	9.6	7.7
1.25–2.5kHz	8.2	6.2
2.5–5kHz	5.6	3.7
5–10kHz	4.8	2.2
10–20kHz	11.3	2.4

PHOTO 9: If Dreams Come True, 10s sweep.



spread out to a 12kHz BW. Still, within the HF range above 4kHz and of very short duration, a moderate amount of IM could be unnoticeable.

But second-order IM is very different. Here the products are simple frequency sums and differences, and the range of difference products from a continuous 8-12kHz signal band is zero (DC) to 4kHz. Enough second-order IM, or asymmetrical limiting, will produce an audible "spectral downwash," a crunchy sound extending into the lowest bass. This is why SET amps should not be overdriven.

AMP HIGH-FREQUENCY PEAK POWER

With an amp playing just below clipping, it's interesting to know how much of the amp's HF power capacity (often below normally stated midband power rating) is being used up; how much margin (if any) is there?

The extreme example with top octave studio boost needs the following fractions of peak power in the stated

bands: 5% (16-20kHz), 20% (10-20kHz), and 33% (5-20kHz). There could be recordings with even higher percentages, such as close-miked small bells or chimes, special effects, synthesizers, and so on. Also, SACDs (100kHz response) may contain significant ultrasonic content.

But it seems unlikely for audiophile-quality recordings to have more than one-third of the peak power above 5kHz; the *España* selection has about 16%, and it's a very (and naturally) brilliant sound.

Flash back to *Glass Audio* 5/2000, where the Antique Electronic Supply AE-25 "Super Amp" is reviewed. Rated at 15W/channel triode, Charles Hansen measured only 2.3W at 3% THD at 20kHz (p. 35). That's 15% of rated power. But even the George Strait recording needs only 5% in the narrower 1/3 octave 16-20kHz band.

Charles Hansen measured 19 +20kHz IM at 0.98% with 6V p-p, 8W, an instantaneous crest power of 1.125W, and average power of 0.281W (4:1 ratio, 2:1 voltage crest factor for an equal-amplitude two-tone signal). The $\pm 3V$ peaks would correspond to a 0.56W single sine wave (at 19 or 20kHz); 0.56W is 3.7% of rated power for 1% IM distortion at 19-20kHz.

Enough trying to mathematically predict the sound: Ken and Julie Ketler, whose many reviews testify to their sonic perceptiveness, gave the AE-25 a generally praise-filled review. One comment possibly relating to this article, comparing the AE-25 with a Valve Audio Lab VAA-100ES 30W p-p amp: "The snares on the bottom drumheads are much more clearly defined with the Super Amp. The difference is particularly noticeable during quiet sections." Regarding the latter sentence, I would guess

PHOTO 10: *All My Exes Live in Texas*, 10s sweep.

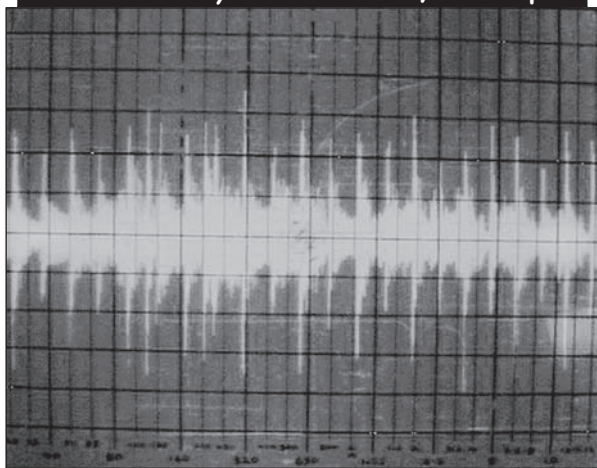
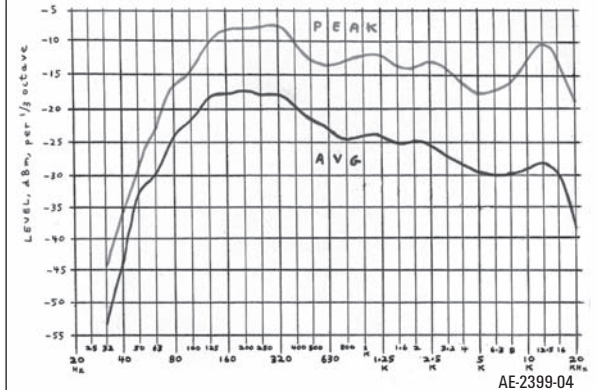


FIGURE 4: Spectrum *España*, 10s of highest SPL.



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Please help Katrina Victims

Poth Audio encourages Audio Xpress readers to contribute towards hurricane Katrina relief efforts. These efforts are not possible without your continual support. Poth Audio has donated a portion of its profits in addition to auctioning several products in order to help make a difference. Reputable charities include:

Red Cross: www.redcross.org
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that at louder levels the AE-25 runs out of HF power, degrading performance to that of the comparison amp (or the snare drum at louder levels overloaded the recording system or other component).

PEAK POWER VERSUS SPL

Suppose you desire a maximum SPL of 90dB—loud, but not that loud—and your speakers' sensitivity is 86dB, 1W, 1m. From ten feet away, this would be 76dB with 1W anechoically, but with

typical room reinforcement I measured a drop of only 3dB. So at the listening position, each speaker delivers 83dB SPL at 1W. With (generally non-phase correlated) stereo, each speaker needs to deliver 87dB SPL for the desired 90dB example. This requires 4dB

more than 1W, or 2.5W average power per channel.

With the George Strait recording, peak (sine-weighted) power is 42.7 times the average, so 107W per channel is needed for a 90dB average SPL without clipping. With the Handel recording, 33W per channel is needed.

Here's an extreme example: You heard an orchestra playing *España* with 105dB SPL climaxes (remember that perceived SPL relates to average power; the waveform peaks would be 11dB higher), and you wish to reproduce this level in your listening room with 86dB 1W/1m speakers. You would need about 1200W/channel, of which about 200W peaks will be in the 5-20kHz range.

And to hear from all your Ex's in Texas at 105dB, you'd need 3500W/channel! *aX*

FIGURE 5: Spectrum *La Réjouissance*, 10s of highest

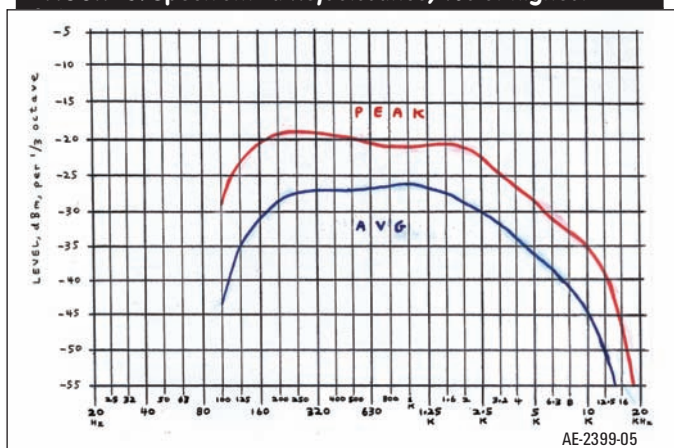


FIGURE 6: Spectrum *All My Exes Live in Texas*, 10s of highest SPL.

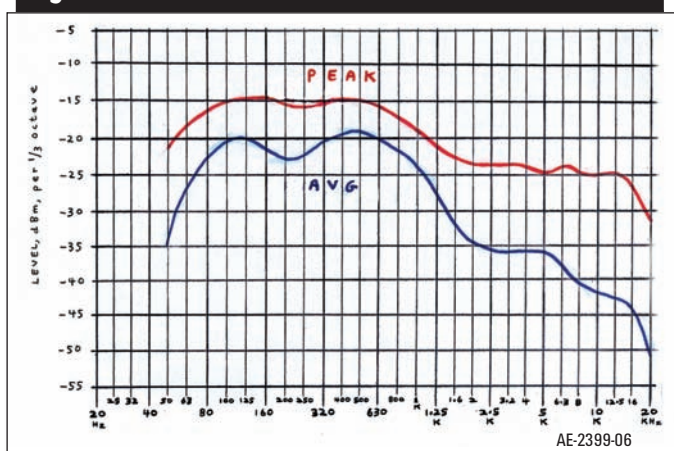
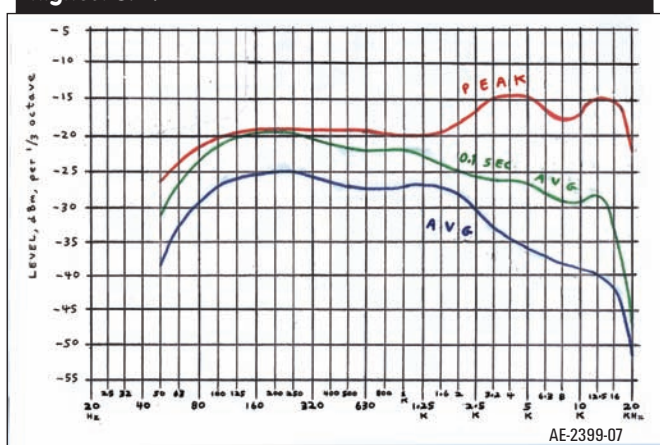


FIGURE 7: Spectrum *All My Exes Live in Texas*, 10s of highest SPL.



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THINAMP

The new **AXL ThinAmp** brings 15W of loud, clean tone from dual super-thin 5" **Alphatone** speakers, and now features customizable colors. It still includes RCA inputs/outputs, 18 digital effects, 3-band EQ, and more, as well as a metal grille and injection-molded exterior. Also available with a 3-hour rechargeable battery pack. For more information, visit axlmusic.com.



SPEAKER CABLES

Utilizing the latest production methods for coating processed copper, the **Atlas Hyper** speaker cable range gives full and natural, fatigue free sound. Available in 1.5, 2.0, 3.0mm², and a biwire, the cables provide improved resolution from OFC together with greater signal velocity and correspondingly lower loss from Teflon. To learn more, see the Atlas website at www.atlascables.com.

SRS DRIVERS IN NEW PC

New from **Toshiba**, the Qosmio G25-AV501 PC features the Toshiba Express Media Player, which supports WOWXT, TruBass, TruSurround XT, and SRS Digital Clarity. This model lets the user play DVDs or CDs and watch TV without booting up Windows for the PC. For more information, contact www.srslabs.com.

TUBE AMP

Containing four tubes and featuring a 10" Alphatone speaker with 25W RMS power, the **Johnson Loredo** Tube Amp can pump the preamp level up for real tube overdrive. The amp also features Accustronics reverb, an XLR line out, and is designed in a cabinet with a brown tolex cover and a vintage-style grille cloth. To learn more, visit johnsongtr.com.

LOUDSPEAKERS

Four new models have arrived in **Canton's** redesigned Karat M series loudspeaker lineup. The models, a three-way floorstanding speaker, two-way, and three-way compact speakers, and a 2-½ way center channel speaker, are all equally suited to use in high-end multichannel home theaters or two-channel audiophile music systems. The speakers employ a 6" aluminum cone driver with an unusual concave dustcap, and cabinets with narrow front panels for improved line-source imaging in the midrange and upper frequencies. For more information, go to www.cantonusa.com.

PORTABLE MIKE

SoundField has released a portable surround microphone, the ST350, which gets rid of the compromises associated with portable recording. Consisting of a lightweight multi-capsule microphone and fully featured compact mike pre/control unit, the package can be powered by either mains or battery. For more information, go to www.soundfield.com.

THE CITY OF NEW ORLEANS

New Orleans is the city that truly began America's contribution to the history of music worldwide. Without it, there'd be no popular music as we know it today.

When I wonder what they might need to get back on their feet, the stuff that gets

ruined under water, I think of all the sound boards, the cables, the lighting, the microphones, the instruments; I think of the stuff you need in the hundreds of little clubs and bars that bring the music to the street—the street that brings the people to the city. And I think of the many thousands of people who depend on those people for their livelihoods.

I am determined to help restore all of those little places and bring the music back as soon as possible. I am contacting Amtrak to help us take the train "The City of New Orleans" from Chicago all the way down to New Orleans. We'll take two weeks beginning in early December and stop along the way at depots or high schools or performance centers of all shapes and sizes. And we'll contact the manufacturers of the very stuff we're talking about and arrange to bring a Christmas present to all the small venues within the city—we'll purchase the gear as close to cost as we can, many will undoubtedly make substantial contributions.

Will you help me bring the music back? Working together with our friends in manufacturing, retail, transportation, the venues, the promoters, the press, the agents and managers and the artists—we can help deliver the stuff that helps make New Orleans sing its own uniquely American song.

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*Love as always,
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CORRECTION

Many readers have notified us of an error in the September issue. In Graham Dicker's article, "Odds & Evens Revisited," the schematic information in Figures 6 and 7 was incorrect. We regret the error. The corrected figures appear here, and are also posted in PDF format on our website, www.audioXpress.com. Simply click on "audioXpress," "articles and addenda," and then the "Odds & Evens Revisited" file.—Eds.

ics; e.g., video and audio. Thanks to these remarkable devices, you can achieve amazing performance with a handful of small chips instead of vast quantities of discrete components. Electronic signal-processing tasks are now performed in audio and video ICs that would take many cubic feet of space if done with discrete transistors, resistors, and so on, which would consume large amounts of power.

Any hobbyist can nurse stunning

mented and don't become a pathway for load-induced noise to propagate between the ICs. Many projects in *audioXpress* rely on the intervention of the hobbyist to add the quality components needed—but which are often ignored in production—to produce sparkling performance not normally experienced from consumer electronics.

Additionally, experiments with mechanical damping of integrated circuits have yielded agreeable improvements in performance. That introduces the specter of not-so-solid-state, which deserves an explanation, so I acquired and studied some background literature. Here are some useful findings.

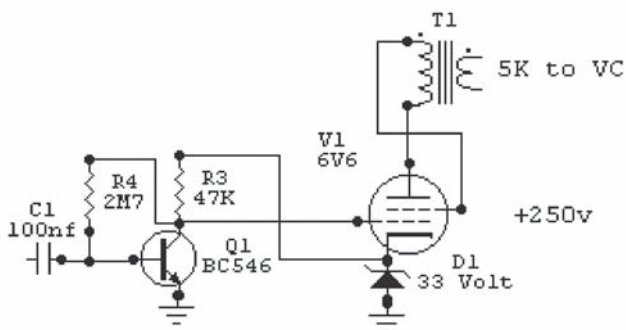
A Resource. The mechanical properties of ICs are well documented. The most informative book I bought to study the subject is *Microelectronic Materials* by C.R.M. Grovenor, a particularly detailed text in the Graduate Student Series in Materials Science and Engineering, Institute of Physics Publishing. Many other fine sources surely exist and will convey much the same information.

IC Architecture. There are some similarities between our familiar printed-circuit boards and the tiny architecture of ICs. Both rely on strips of conducting metal on an insulating substrate. The IC is also populated with many transistors, a smattering of resistors, and an infrequent capacitor.

All these features are laid down one after another in layers on a dielectric substrate, usually silicon or other oxide. The formation of conductors, transistor junctions, and so on, is done using masks to control where the features are placed as the various layers of exotic materials are built up. Sometimes the layers are modified by selective removal to arrive at the desired physical configurations.

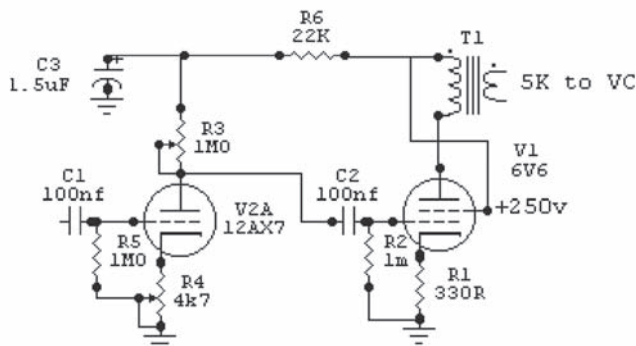
Corrected Figures

FIGURE 6: Variant of emulator schematic.



AE-2409-06

FIGURE 7: All-tube emulator schematic.



AE-2409-07

VIBRANT WORLD OF SOLID-STATE

By now it's clear that integrated circuits (ICs) are the dominant resources in the field of entertainment electron-

performance from both audio op amps and the much more complex video ICs simply by making sure that his/her power supplies are carefully imple-

Metallurgical Realities. A common way of applying the tiny quantities of conductor, semiconductor, and dielectric materials is by depositing vaporized alloys. These extremely hot deposits shrink when cooled by the layers below them, locking in stresses in the materials. Sometimes an interposing alloy is put down to help two layers bond to each other more securely.

The tiny dimensions of the conductors formed this way (one or a few microns wide, fractions of a micron thick) make them vulnerable to the electrical and mechanical effects of grain boundaries in the cooled metals. There arise other vulnerabilities, which you can find in the literature. The metallurgical problems overcome during IC manufacture are daunting, but many clever techniques are applied during production to result in high yields.

Thanks to the minute size of the conductors and their intimate contact with the layers below, it is quite easy to extract heat from them and remove it to the outside world. Knowing this, designers force conductors to sustain current densities vastly greater than our PC foil traces can withstand.

One of the resources used in modern IC design is the "silicon compiler," a software resource that lays out IC design features from libraries of pre-solved architecture. This can be risky business where audio and video quality is concerned, because most such compilers are used for computer-based applications in which digital data is much harder to corrupt, and significant jitter has no effect on results. For computers, feature size and low power consumption are prime objectives, neither of which are of much use to audio- and videophiles, who ultimately want to hear and see the data transformed into pristine analog sound or pictures.

Interruption: Strain Gauge Technology. The structural engineering profession has long been equipped with strain gauges. These small, thin resistive devices bond tightly to load-bearing structures, which deform when stressed. The calibrated strain

gauge resistance changes when deformed, easily measured with a Wheatstone bridge, and allows the analyst to compute the strain, and therefore the stress, in the instrumented structure. If memory serves, strain gauges were originated at the Baldwin Locomotive Works in the early 1900s.

The IC as Strain Gauge? When the conductors of an IC are forced to carry AC signals at high current density and are rapidly heated and cooled, they mechanically excite everything around them, because metals change dimensions when heated. The entire IC thus buzzes at signal frequencies, as then do nearby ICs. The resulting strain in neighboring conductors induces sympathetic resistance changes, so even more circuits are victimized by their unavoidable strain-gauge behavior. Every audio op amp I have experimented with has sounded better when equipped with a discrete output buffer, which means the op amps would then consume no more than their idle current.

The Package You See, Feel, and Hear. The packaging compound molded around the IC die—its lead frame (legs) and the wires connecting the two—is required to stiffen and damp the resulting monolithic package, as well as carry away heat and protect the IC within from the ravages of the atmosphere. We are offered plastic resins and ceramics as packaging materials. Stories abound about the sonic superiority of ceramic, but the people manufacturing our electronic instruments don't usually opt for ceramic due to the added cost.

Get the Lead Out. Having little or no choice in packaging material, the next best thing has been to bond a thin layer of lead foil to the top of the ICs to damp mechanical vibration. Still not solid, but better than before.

I tried one or two layers on each side of the op amps, but found that as long as the total amount of foil is the same, it doesn't matter whether it is on one or both sides. It matters how well it adheres to the IC, though.

Detecting the Improvements. Reactions to audio IC damping differ between listeners. It takes practice to learn what to listen for. Video, on the other hand, offers immediately recognizable changes when related ICs are damped. Edge sharpness, color purity, nuance, and small details are noticeable improvements any viewer can distinguish with ease. There is no "golden eyes" equivalent to the "golden ears" argument. Put another way, eyeglasses succeed vastly better than hearing aids.

Are We Alone? The question sometimes arises whether IC manufacturers ever receive feedback from users. Here is one instance: Over ten years ago I was at a holiday gathering in Arizona, and was introduced to a young engineer who was designing a new op amp for his employer. The fellow displayed infinite patience while he heard me rattle off a liturgy of op amp ills you just read about here. A surprise came a few months later when the mail contained specimens of the



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new op amp, which are still happily
at work in my preamp. This op amp is
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audioXpress contributor Michael
Danbury recently noted that many en-
during op-amp part numbers are being
redesigned so they can be packaged in
the ever-tinier surface-mount shapes,
and large performance improvements
are being implemented with little or
no fanfare. Mike discovered one such
instance of this in the Texas Instru-
ments versions of the NE 5532 and
5534, which sound remarkably better
than their originals. A pair of those
found a home in my CD player.

Conclusion. Historically, the uses of
earlier op amps and other IC designs
were so varied and unpredictable that
their manufacturers simply made them
as fast as they could. Now there are
more specific ICs aimed at target
applications. This usually brings with
it more competition, which is good
for the user if he is a careful shopper.
Good things are still yet to come in
the vibrant world of ICs.

*Darcy Staggs
Orange, Calif.*

CONTROL UNIT

In the April 2003 issue of *aX*, Joseph
Norwood Still has an article on a stereo
control based on the 12B4. I built this
unit and it is the best-sounding unit I've
ever heard! In your October 2004 issue
he appears again with another great
stereo control introducing his view on
a bass enhancement control circuit. My
question is: Can this bass control cir-
cuit be used in the 12B4-based control
unit or could the second control unit
be modified to use the 12B4 instead of
the 5687? The idea is to have the best of
both worlds in one or the other.

*Larry Epperson
Severna Park, Md.*

Joseph Norwood Still responds:

I'm gratified that you had such great suc-
cess with your control unit, and the out-
standing sound is attributable to the excel-
lent linearity and low mu of the 12B4s. I
assume your control unit includes a phono
amplifier. If it does, you can elect to install

the bass circuit in the last stage of the
phono amp, if you are only interested in
modifying the sound when playing records.
I found the bass adequate when in the FM
or CD mode. If you concur, then I recom-
mend the following: Connect a 10 μ F ca-
pacitor to plate and a 39k Ω resistor to the
grid of the last stage of the phono section
and insert a double pole switch between
the resistor and capacitor to engage or dis-
engage the circuit.

If you do not have a phono section or you
would like to add bass to the CD and FM
modes, then add the resistor, capacitor, and
double pole switch between the plate and
grid of the 12B4. To maintain the required
gain of the 12B4 when adding the bass cir-
cuit, bypass the 12B4 cathode resistor with
a 100 μ F electrolytic capacitor. This changes
the gain of the 12B4 from 2.5 to 5.0. I
noticed when doing distortion tests that no
difference in distortion is evident with the
cathode bypassed or unbypassed.

Of course, differences are evidenced
in the noise measurements. Using a mini-
switch instead of a variable pot is less cum-
bersome and aesthetically pleasing. Adding
to the value of the 39k Ω resistor decreases
the amount of bass enhancement. A 6dB
level is sufficient and recommended maxi-
mum for a truly hi-fi sound.

Again, I'm glad you like your control unit.
You obviously have a great deal of experi-
ence with electronic projects to obtain such
a successful outcome.

FREE CDS

I have restored two CDs (58 tracks) of
popular music I recorded on 1/4" reel-
to-reel tape in the 1950s. I'll send free
copies, including postage, to the first
100 requesters. You can download the
playlist (Adobe pdf file) from **www.
tdl-tech.com**. On the home page click
"What's New" and then go to the entry
for 2 August 2005.

*Ron Tipton
TDL Technology, Inc.
Las Cruces, N. Mex.*

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