

The Mighty Midget

This tiny stereo amp puts out over 3W per channel using only two tubes.

By Pete Millett

Funny how some projects get started.

I was wandering around the little stalls that sell electronic parts under the train tracks in Akihabara. I often go to Japan on business, and usually find time to go to Akihabara to look around, see what's new, and pick up those few parts that are actually cheaper in Japan than in the US (such as Alps volume control pots).

In a stall that sells transformers (and nothing else), I spotted a cool-looking little transformer in an enclosed black metal case. About the size of a 20W filament transformer, it stood out from the dozens of other power transformers. I took a closer look, and it turned out to be a single-ended output transformer. The label said 8W, which seemed a little hard to believe for its size.

OK, sure, this was no Tango or Tamura piece of iron. But for only \$20? And it was just so...*cute*. So I picked up a pair, not expecting much.

When I returned home and took a closer look, the transformers really did look pretty nice. The primary and secondary were tapped so you could set it up for a number of impedances between 2.5k Ω and 7k Ω . A few casual measurements looked encouraging. So what to do?

Design an amplifier around them, of course.

MINIMUM TUBE COUNT AMPLIFIER

Because these output transformers were so small, I thought I would design a physically small amp to go along with them. I've also always been fascinated by the complex, multi-element tubes that were designed near the end of the

"vacuum age"; I figured I could probably come up with something using one of them.

My first thought was to use a triode/pentode tube, such as the ECL86/6GW8, that was designed for audio amp applications. The ECL86 is—more or less—a 12AX7 triode section together with a power pentode similar to the EL84. But a quick look on the web showed that they were too expensive, going for \$30 each!

The next candidate I considered was a dual dissimilar triode, such as the 6EM7. I've heard from many happy 6EM7 builders, who used the bigger 10W triode as a SE output stage and the smaller triode as a driver. This seemed promising, but when I put one on a breadboard, I wasn't very happy about the large amount of distortion and low output power that occurred.

OK, time to become more imaginative and dig around in my boxes of tubes. Whenever I feel "creative," I seem to gravitate toward oddball tubes, such as loctals and compactrons. Surely, there must be some multi-element compactron tubes that could work?

Between some archaeological explorations around my lab and some Internet searching, I came up with a list of compactron tubes that contain a power section plus a small-signal section. There

were dual triodes such as the 6EM7, and some triode/beam tube combos, both of which were designed for TV vertical deflection oscillator/amplifier use. There were also triode/high Gm pentode combos, used as a color blanker or AGC amp plus video output amp in color TVs. Then there were some tubes with a dual-control pentode for FM detector use along with a beam power tube for an audio output, again meant for TV use.

Looking over datasheets and checking prices (I imposed an upper limit of \$5 each—hey, I have two kids to send to college!) and availability online produced a short list: the 6T10, 6G11, 6AG9, 6AH9, 6AL11, and 6LR8. All had promise, and I think any of them could be made into a respectable audio amplifier.

To make a long story short, after doing some experiments I settled on the 6T10 tube for this amplifier design. The 6T10 has a beam-power section somewhat similar to a 6V6 (but with higher Gm) and a "dual-control" pentode in one 12-pin compactron envelope. It was designed for TV sound use, providing up to 4.2W out in SE pentode mode. It's affordable as well—I bought a handful from Antique Electronic Supply for \$1 each.

And in the right circuit, it makes a



PHOTO 1: The midget SE amp.

fine single-ended audio amplifier.

DUAL-CONTROL PENTODE?

So, what's a dual-control pentode, you ask?

Normal pentodes use the suppressor grid, or G3, to repel electrons that become dislodged from the plate back to the plate (secondary emission). To perform this function without getting in the way of the desired electron stream from cathode to plate, G3 is typically a widely-spaced wire grid that is held at ground (or cathode) potential.

A dual-control pentode is different in that G3 is designed to be used as a second control input, so that varying its voltage has an effect on plate current. To accomplish this, G3 in a dual-control pentode is wound more closely than in a normal pentode. Because of its increased density, it intercepts some of the electrons on their way to the plate. This causes it to draw current (sometimes even more than the plate), so it must have a more substantial structure that can dissipate some power.

Dual-control pentodes were intended mostly for detector and mixer applications, in which one RF signal is applied to G1 and a second to G3.

If you look at the plate curves for a dual-control pentode (the 6T10 curves are shown in **Fig. 1**), you'll see that the G1 curves look basically like a normal pentode, but are a bit rounded, somewhat nonlinear, and show a fairly low plate resistance (a bad thing for a pentode). If you look at the G3 curves, you see a strange characteristic somewhere between a pentode and a triode, which is not particularly linear. So, how do you make a decent audio amp out of *that*?

There are a couple of possibilities.

One is a triode connection; several choices will work and make a decent triode, including connecting G2, G3, and the plate together, or using G2 and G3 as the plate and not connecting the "real plate" at all. But I derived better results using the tube as a pentode, by biasing G3 a few volts positive, which has a dramatic shape on the G1 plate curves.

You can see this by looking at the plate curves. There is one curve on each of the graphs that corresponds to $G1 = G3 = 0V$; these curves are identical (note, though, that the vertical scale on the graphs are different). If you look at the G3 graph, notice how the *shape* of the curve changes as you move to $G3 = +3V$ —it becomes more horizontal with a squarer knee, which is what you want a pentode curve to look like to make a linear amplifier. Now imagine the entire family of curves in the G1 graph "squared up" like that. That's the resultant family of plate curves you wind up with by biasing G3 to a positive DC voltage.

PENTODES (AND BEAM TUBES) AS POWER AMPS

As most of you know, there are several ways to use a pentode or beam power tube as an audio amplifier output stage. You can operate it in pentode mode, where G2 is held at a constant voltage; in triode mode, with G2 tied to the plate to emulate a triode; or in ultralinear mode, with G2 fed a portion of the output signal to produce a characteristic somewhere between a triode and a pentode.

In triode mode, the circuit has a low enough plate resistance and low enough distortion that often no feedback is

needed to produce a good output stage. The downside is that the amount of power available in triode mode is substantially less than that in pentode mode—in other words, the plate efficiency is not very high. On the other hand, in pentode mode, more output power is available, but the output impedance is very high (and often distortion is as well), so some form of negative feedback is usually needed to produce acceptably low distortion and adequately high damping factor.

A common way to deal with the problems of pentode operation was to put a lot of "extra" gain into the amplifier, then feed a portion of the output (taken from the speaker terminals) back into the input stage.

This is referred to as "global" or "loop" feedback. I've never been a big fan of global feedback, especially where transformers are involved. Achieving good stability can be difficult, and it can produce higher-order distortion artifacts that sound unpleasant. And I'm just not ambitious enough to make it work well.

Another solution is to use local feedback. By "local," I mean feedback around only one amplifying stage—in this case, the output stage. There are several ways to implement local feedback in a pentode stage, because you have three grids and the cathode that you can play with:

- The ultralinear connection is a form of local feedback using G2, usually employing a tapped output transformer to give characteristics midway between a pentode and triode connection.
- Cathode feedback can be used by providing a winding on the transformer connected to the cathode. Even an un-bypassed cathode resistor is a form of cathode feedback.
- In some tubes, G3 can be used to control plate current (à la the dual control pentode), but it isn't very practical with most output tubes (especially beam tubes).
- Signal can be coupled from the plate to G1 ("plate-to-grid" feedback).

PLATE-TO-GRID FEEDBACK

There is an excellent article written by O. H. Schade of RCA in 1938 entitled "Beam Power Tubes" that discusses the application of beam-power tubes in

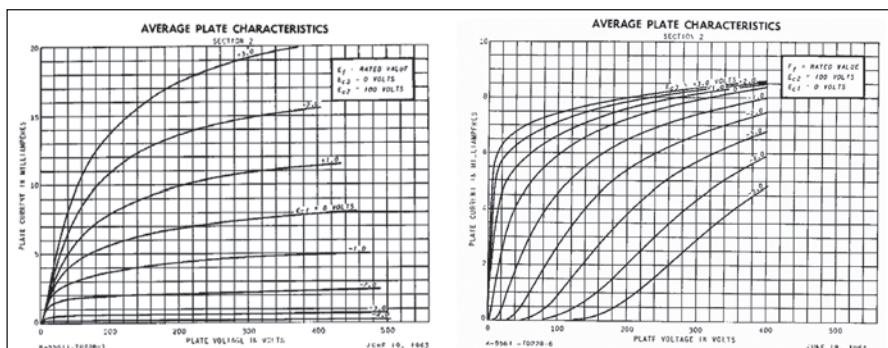


FIGURE 1: 6T10 dual-control pentode plate curves.

audio power amplifiers. (The article is available to download from my website www.pmllett.com). In this article, Mr. Schade discusses the application of local feedback in beam power tubes to produce essentially a “designer triode,” having the distortion and output impedance characteristics of a triode, but retaining the power output and plate efficiency of a pentode.

Following Schade’s instructions, I plotted plate curves for this “imaginary” triode for some of the tubes I was investigating. **Figure 2** shows these curves for the 6T10 beam power section.

These curves look like those of a pretty good output triode. Note that the curves can be used to show the R_p and μ of the resultant “triode,” but the tube is actually running in pentode mode; the grid voltage never really goes outside the range shown on the pentode curves.

I wound up with an operating point just slightly hotter than the one recommended on the 6T10 datasheet for pentode operation. I’m running a plate voltage of about 270V and a plate current of 35mA. This requires a cathode bias voltage of around 8V.

CIRCUIT DETAILS

The amplifier schematic (one channel only) is shown in **Fig. 3**. The driver stage bias is established by a string of LEDs and a zener diode. The cathode sits on one red LED connected to ground, providing about 1.8V of cathode bias. Two more LEDs bias G3 to about 3.6V above the cathode. A 100V 5W zener diode puts G2 at about 104V above the cathode, and a 30k 5W resistor provides current to this string from filtered B+. (I tried to bypass a cap on G2, but it

didn’t seem to provide any significant improvement, so I left it out in the interest of simplicity.)

The driver plate is connected to filtered B+ with a 64.9k Ω plate load resistor (R2), and also to a 357k Ω resistor that is connected to the output tube plate (R4). R4 provides the plate-to-grid feedback path. OK, technically, it is connected from the plate of the output tube to the plate of the driver tube; but from an AC perspective, the plate of the driver tube is the same as the grid of the output tube, because they are connected by a 0.22 μ F coupling capacitor. A 240k Ω resistor (R7) provides a DC return for the grid of the output tube.

Setting up this stage is a tricky task of getting the best values for the plate load resistor, feedback resistor, and the grid-to-ground resistor of the power tube. The DC operating point is affected by the plate load resistor as well as the feedback resistor, because it’s connected to the plate of the output tube, which is sitting just a tad under B+.

The amount of feedback is set by the voltage divider formed by the feedback resistor working backwards into the output impedance of the driver stage, and into the input resistor of the output stage (R7). The driver output impedance is formed by a parallel combination of R2, R4, and the R_p of the driver tube (which, being a pentode, is quite high). The gain of the driver stage alone is also affected by these same components, so you can see it’s not a simple process to figure out ideal values.

I used a combination of engineering, educated guesses, and trial and error to arrive at the values used in the schematic, making distortion and power

measurements along the way. I calculated the impedance of the driver plate circuit to be around 30-40k Ω , so the 357k Ω feedback resistor gives somewhere around 10% feedback, which was my target.

The output stage is straightforward, with a 200 Ω cathode bias resistor bypassed by a large capacitor. G2 is connected directly to B+ (through a grid stopper resistor). I experimented with different bias resistances, plate voltages, and load impedances, and settled on an operating point close to the datasheet spec. I found that a load impedance of 7k Ω provided a little nicer looking harmonic FFT than 5k Ω at only a small loss of power, so I used the 7k Ω : 8 Ω configuration of the baby output transformers.

THE POWER SUPPLY

Because I wanted this amp to be small and inexpensive, a big tube power supply with enormous chokes was out of the question. So I designed a small solid-state supply, using a Hammond 261G6 power transformer I happened to have on the shelf. Strictly for looks, I mounted the transformer inside of a box on top of the chassis.

Figure 4 shows the schematic of the power supply. Following the rectifier is an RC filter stage, then two LC stages. The RC stage (with a small capacitor) limits the peak currents in the rectifiers, which helps reduce noise. The separate LC filters, one for each channel, provide isolation at audio frequency between the two channels in addition to helping to achieve low supply ripple. Splitting the filter also allows the use of small chokes, because each channel draws only around

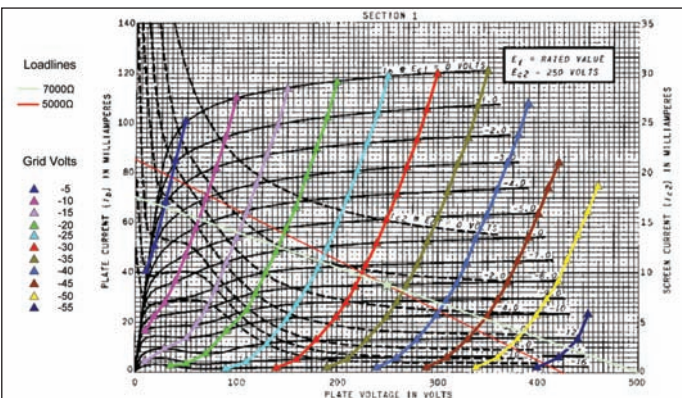


FIGURE 2: 6T10 beam power tube with feedback.

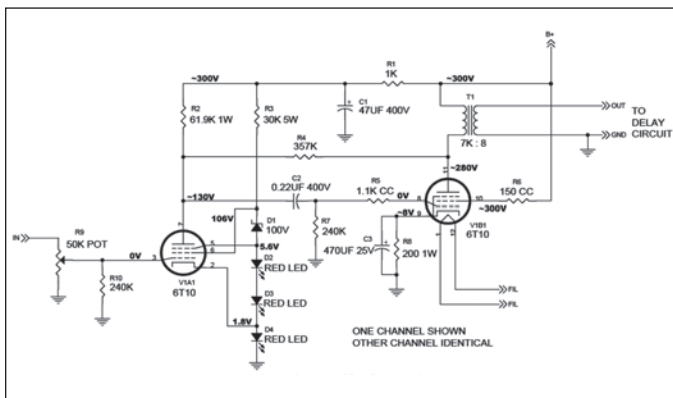


FIGURE 3: Amplifier schematic.

50mA. The chokes I used were surplus potted chokes (from the Danish telephone company!), but any small choke (I suggest the Triad C-3X, which is very inexpensive) will work fine.

Whenever you use solid-state rectifiers, especially inside a small enclosure, you must worry about reverse-recovery noise from the rectifiers getting into the signal path. The use of fast or ultra-fast recovery diodes is a must. I used 600V,

1A ultra-fast recovery MUR160s from On Semiconductor, and added small ceramic capacitors across the diodes.

AN AFTERTHOUGHT: THE MUTING CIRCUIT

After I built the amp and had it running, I discovered that when I turned it off, it made some really nasty noises. I'm not sure exactly why—maybe as the supply voltage dropped one stage

was operating in a negative-resistance part of its plate curve—but it emitted a loud squeal for a fraction of a second. It also made a little bit of a thump when power turned on. So I decided to build in a small power-on delay circuit that would keep the speakers disconnected for a while after power-on, and disconnect them immediately when the power switch was turned off.

The schematic of the circuit is shown in Fig. 5. It uses a power-on reset IC, the TL7700, from Texas Instruments, to drive a relay that disconnects the speaker outputs.

The 6.3V filament voltage is rectified and filtered to generate a DC voltage to run the circuit. The filter cap (C4) is not very big, because you want the DC voltage produced to drop very quickly on power-off, and you can tolerate lots of ripple. A dropping resistor (R11) in series reduces the DC voltage so the relay coil receives 5V when it's activated. Note that you may need to use a different value if you use a different relay than the one I used (an Omron G5V-2-H1-DC5).

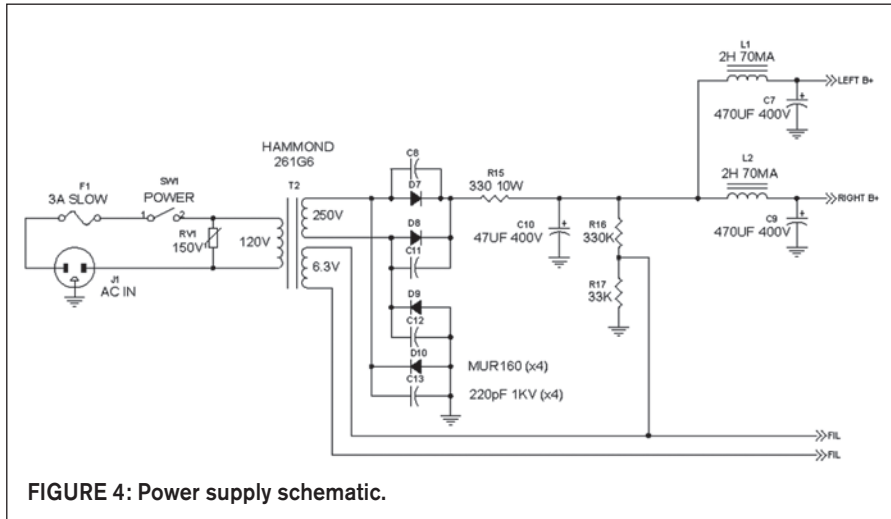


FIGURE 4: Power supply schematic.

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C6 sets the delay at power-on; with 100 μ F, the delay is about 20 seconds. R13 and R14 set the threshold voltage at which the circuit starts counting the delay, and the voltage where the relay will open when the power drops. This voltage is set to around 3.8V.

CONSTRUCTION

Wanting to keep the size to a minimum, I built the amp in a 6" $\times$ 10" $\times$ 2" aluminum chassis (Photos 1 and 2). This required a very tight layout. I used single-point terminals screwed to a blank piece of PCB material to hold most of the parts, as I've done in projects I've published in the past. (For details on this construction technique, refer to "A Low-Mu Triode Preamp," *audioXpress* 2/04.) The copper foil of the PCB is used as a ground plane.

I added some oiled bubinga wood to the sides to dress things up a bit, and

painted the chassis with aluminum-colored Hammerite™ spray paint.

Photo 3 shows the inside of the chassis. Because space is tight, I temporarily mounted the tube sockets to the PCB material, and wired most of the circuit outside the chassis on the bench. Then I mounted the assembly inside the chassis, using the four tube socket screws to hold the PCB assembly to the chassis. It was so crammed inside that I wound up needing to remove a coupling capacitor to fit the volume control pot in place.

The input wiring is routed along one edge of the chassis, and the AC mains wiring along the opposite edge. I used shielded wire to connect the input RCA jacks to the volume control, though I don't know that it was necessary.

Photo 4 shows a closer view of the terminal board before installation. The black-and-white twisted pairs you see are the input connections; the rest of the

wires are power supply connections.

I mounted the power supply components directly to the chassis, using single-point terminals and capacitor clamps for the big filter caps. If you can't find appropriate capacitor clamps, you can use a tie wrap that has a screw-mounting hole to hold the can caps to the underside of the chassis.

Photo 5 shows a closer view of the power supply section. The rectifier diodes are hiding under the ceramic caps.

Figure 6 shows the wiring layout. Note that some wiring is left off this drawing

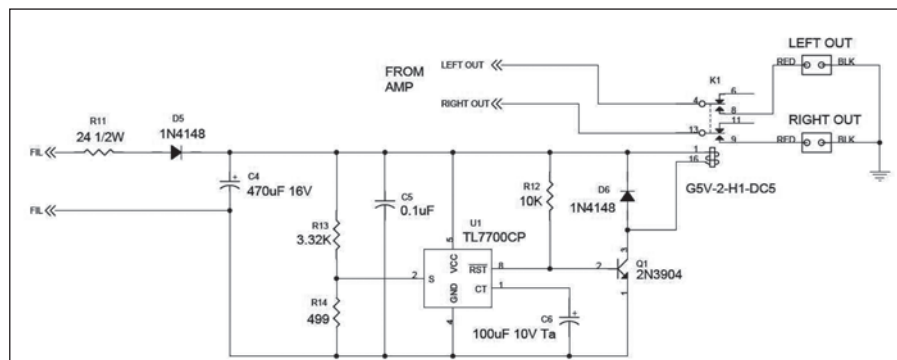


FIGURE 5: Delay circuit.

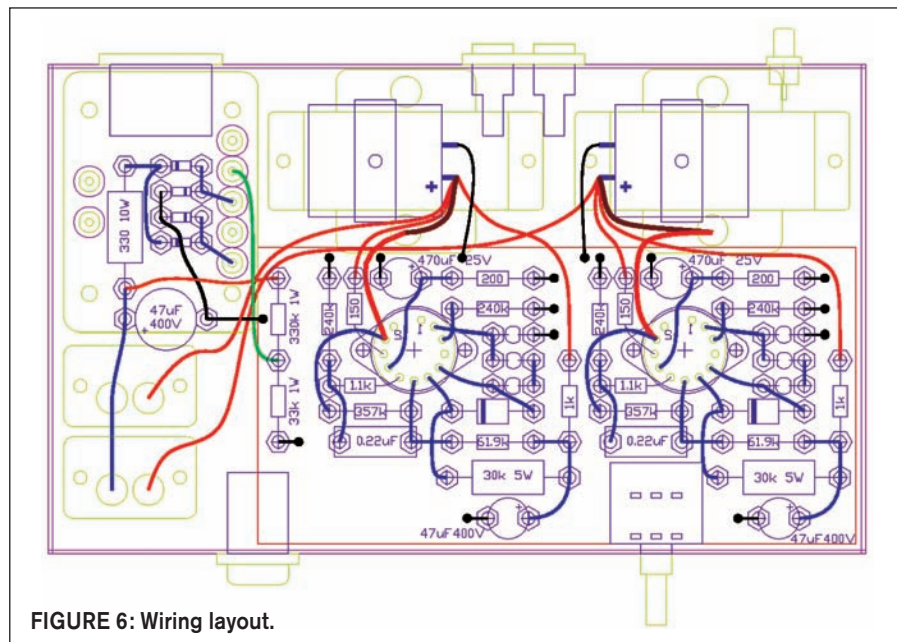


FIGURE 6: Wiring layout.



PHOTO 2: Back view.

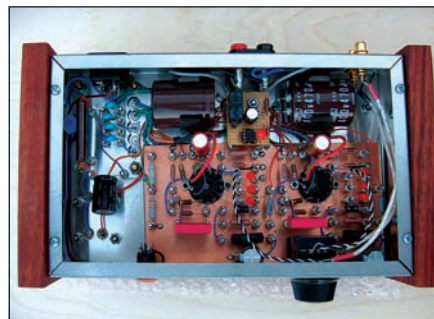


PHOTO 3: Inside the chassis.

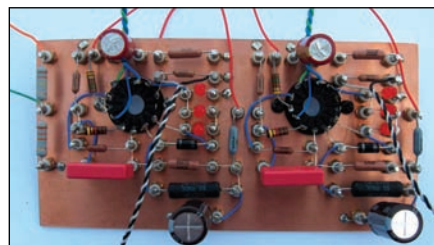


PHOTO 4: Closeup of the terminal board.

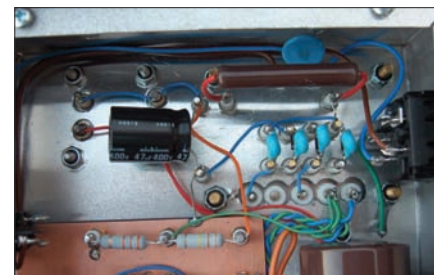


PHOTO 5: Power supply circuitry.

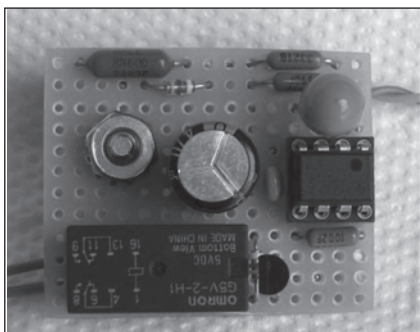
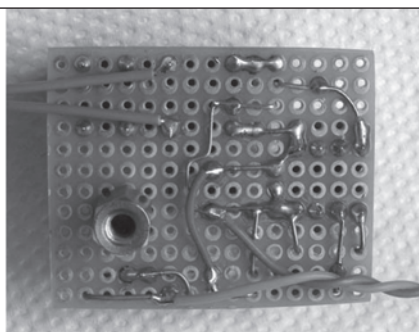


PHOTO 6: The delay circuit.



for readability; the filament, input, output, and AC wiring are not shown.

I assembled the delay circuit on a small piece of perfboard. Luckily (since it wasn't originally part of the design), I found a place to put it—I mounted it to a standoff that was attached by one of the output transformer mounting screws. You can see it in **Photo 3**, located near the output jacks; **Photo 6** shows a detailed view of the assembly. The orange and green wires connect to the 6.3V filament circuit; the gray wires connect to the output terminals. The OPT secondary wires are soldered to the relay next to the gray wires.

MEASUREMENTS

One of my goals in setting up the amplifier was to have a reasonable amount of distortion at 1W output, and, I hoped as much power as possible at the 5% distortion level. I also wanted to make sure that the harmonic content was dominated by the 2nd harmonic, at least at lower powers. **Figure 7**, an FFT of the output at 1W (into 8 Ω), shows the result.

You can see from the FFT that the highest harmonic is the 2nd, with the rest following at progressively lower levels. THD+N is about 0.7%. You can also see some “hum intermodulation” on the fundamental (1kHz) and even harmonics—these are the spurs that are ± 60 Hz relative to the signal. I don't know whether these are audible, as they are 80dB down. They appear to be induced from the AC heaters, since the B+ has very little ripple, and they also appeared when running from a DC bench supply.

The non-harmonic signals you see that are ~ 90 dB or more down (for example, at 4600Hz) are measurement artifacts generated by various pieces of

equipment on my bench.

I tried several different 6T10 tubes to make sure things weren't going to vary too much between tubes. I found that in this circuit there was a definite difference between GE 6T10s and Sylvania—the Sylvania had less THD, which dropped as the amp warmed up. The GEs had more second-order distortion, and their THD didn't change with time. Though I've only listened with the Sylvania so far, I'd guess the GEs would sound a little softer, and a bit “tubier.”

Maximum output power (at 5% THD) is about 3.5W into 8 Ω . Impressive for an output tube whose plate is dissipating around 10W! The distortion products increase smoothly as you raise the output power, with the 3rd harmonic exceeding the second at around 2.5Ws. The frequency response (**Fig. 8**) is good, showing 1.5dB down at about 18Hz and 20kHz.

Another important characteristic of an amp is the damping factor, or output impedance. I measured the output impedance of the amp to be 3.5 Ω . Not extremely low, to be sure, but not bad for a pentode amp that doesn't use global feedback.

LISTENING IMPRESSIONS

When I first set this amp up to listen, I connected it to a pair of full-range speakers in MLTQWP cabinets that use the Jordan JX92S driver. It sounded OK, but to be honest I wasn't impressed. The sound was OK, but dull and sort of lifeless. In retrospect, I shouldn't have been surprised—the Jordans really prefer to be driven with a low impedance, and really need more like 10W of power.

Next, I connected a pair of bass-re-

flex speakers that use Fostex FE164 drivers (you can see them in “An Affordable Full-Range Speaker,” *audioXpress*, 6/03). I already knew from earlier experiments that these speakers really sounded best when driven with a higher impedance, so I had high hopes that this amp would make them sing. I was not disappointed this time—starting from the first track I got that goofy smile I get when I know I put together something good.

The amp was quiet, with no trace of hum or buzz audible even with my ear next to the 92dB efficient speaker. There was some broadband white noise though, a bit of a hiss. I couldn't hear it at my normal listening position a couple of meters from the speakers.

The sound of this amp is not like any single-ended triode amp I've heard. It has a certain edginess, not the “liquid” sound everybody talks about triodes having. It sounds *live*. I suppose that this is partly because this amp does have a fair amount of odd harmonic distortion, compared to most SET

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amps. But I suspect there's more to it than that.

I never enjoyed listening to blues on the FE164 speakers, and I was fairly sure I couldn't reproduce listenable blues with 3W. But I was very surprised that this combination was fabulous with blues—there was bass coming out of the Fostexes that I'd never heard before, and it felt like I was getting a live audi-

ence with the King (B.B. King, that is) in my listening room.

With such good results from the FE164s, just for fun I thought I'd see what would happen with the amp connected to some *really* inexpensive speakers; bass reflex again, using Radio Shack's old 40-1197s (more or less a version of the Fostex FE103). They lacked low bass (what can you expect from a 3" paper driver in a tiny box?), but they really sounded nice—better

than they had with any other amp I'd tried with them. Vocals, in particular, were lovely.

As you've probably heard before, building a good-sounding audio system is all about synergy. The best amp with one set of speakers might not sound good with another. With this amp, it looks as though I hit upon a magic recipe to make inexpensive full-rangers sound good! *ax*

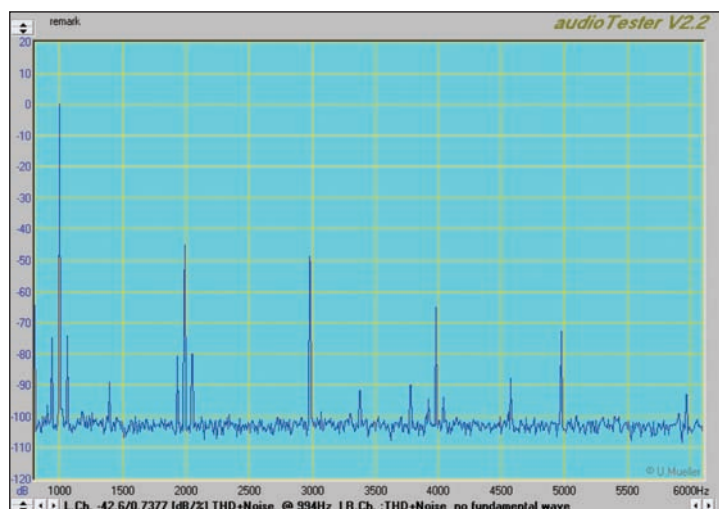


FIGURE 7: Output FFT.

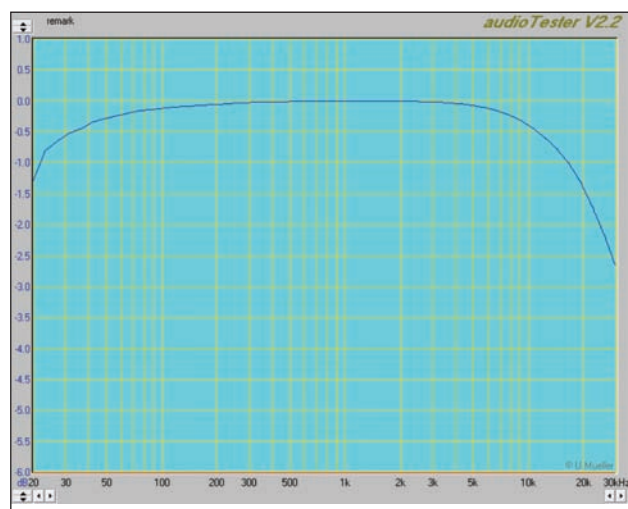


FIGURE 8: Frequency response.

SOME SUGGESTIONS FOR BUILDERS

This isn't too difficult a project to build, but I have a few suggestions that might save potential builders some pain and anguish.

Don't try to squeeze this amplifier into as small a chassis as I did, unless you have a fair amount of experience building point-to-point projects and a lot of patience. It really is difficult to work in tight quarters like this—I bear a scar from a very nasty soldering iron burn to prove it. I'd suggest at least an 8" × 12" × 2" chassis. Even in a larger chassis, you can still use the same terminal board design.

A larger chassis will also give you a little more flexibility with choosing transformers and chokes. Finding ones that match what I used could be a little difficult. I'm guessing most folks won't want to fly to Japan to pick up a couple of \$20 output transformers.

Luckily, there are domestic options. Both Hammond and Edcor Electronics have small single-ended output transformers that should work well in this amp. In particular, the Edcor XSE-10-8-8K is almost exactly the same size as the Japanese transformers I used, and is *very* reasonably priced. You want a transformer with between 5kΩ and 8kΩ primary impedance, good for at least 40mA of DC current and 5W of power.

The power transformer I used, the Hammond 261G6, seems to work fine, but I'm pushing its ratings a bit. It does run hot—so it may be better to use something a little bigger. You need around 220-250V AC, and 100mA DC (a rating of at least 180mA AC RMS would be good). Filaments are 6.3V at just under 2A.

An inexpensive option that should work well would be to use a 120V to 240V isolation transformer (one rated for 40-50W should do, such as the Triad N-68X), plus a 6.3V 2A filament transformer. Note that you can compensate (to some extent) for a different transformer voltage by changing the resistor in the filter (R15 in Fig. 4). You want to shoot for around 300V B+.

The TL7700 IC used in the delay circuit can be hard to find in a DIP package. I found some at Allied Electronics (www.alliedelec.com), which also stocks triad chokes and transformers. If you can't find a DIP IC, you can use an SOIC and mount it using an SOIC-to-DIP adapter board (available from the usual sources such as Digi-Key and Mouser).

You can download schematics and full-size mechanical drawings, including the layout of the terminal board, from my website www.pmillett.com. Happy building! ■