Odds & Evens Revisited

Including how to improve the performance of two-stage amps.

It has been a few years since I wrote "Odds and Evens" (*July 2001, p. 56*), but since then my work has continued to focus on the transfer curves of tubes and tube amplifiers.

By Graham Dicker

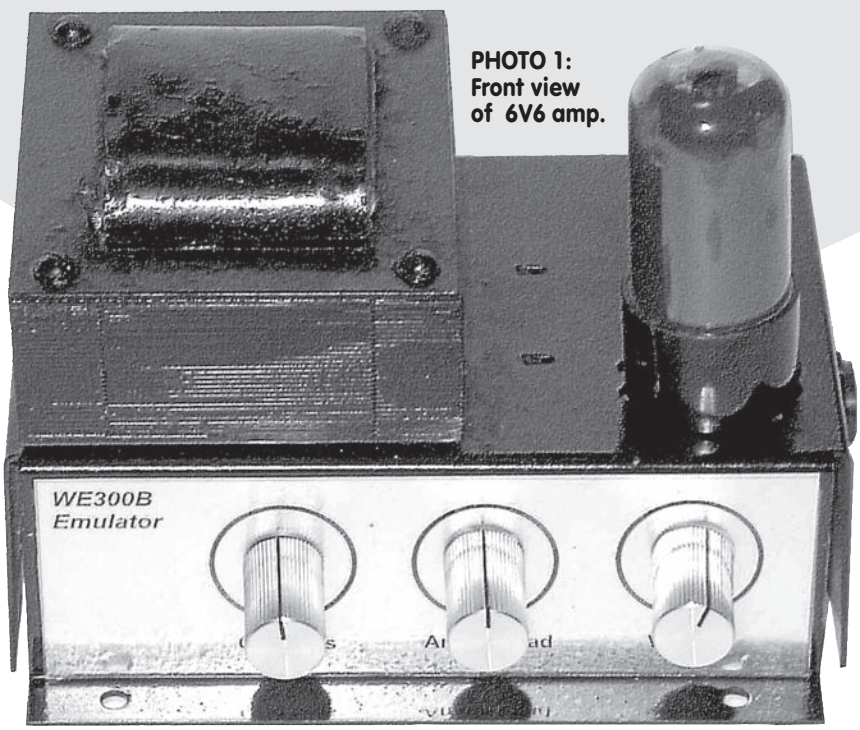


PHOTO 1: Front view of 6V6 amp.

THEORY ONE:

Two transfer curves equal and opposite in phase will cancel any distortion (from original article). One of my previous ideas is it is important to try to optimize each stage's performance as much as possible, using nonlinear devices—i.e., LEDs and diodes—in the local feedback path of each tube stage to make them as linear as possible.

My current thinking has changed somewhat. The basic idea of an even number of stages with the same transfer function to reduce distortion still holds, but I believe that trying to linearize each stage does not matter; you simply select stages which have similar transfer functions over the signal excursions actually used. This then broadens the scope to include dissimilar technologies, which are now co-compatible.

THEORY TWO :

The net algebraic sum of the two transfer functions over the used section of each curve should provide a linear end result. For example, a tube output stage could be complemented with a bipolar transistor and still achieve a linear result without feedback. Indeed, the end result need not be linear.

For example, should you choose to replicate the transfer function of a favorite tube (say a WE300b), you could now do so by using these two simple rules. Many amplifiers over time have accidentally ended up with a nice-sounding result, as trial and error experimenters and designers alike have found that certain tubes and operating parameters combine to produce the desired result. This article attempts to explain why.

LINEARITY NOT NECESSARILY A GOOD THING

Strange for me to say it, but as I listen to people telling me about amplifier sound (as I have done for the last 40 years or so), I have concluded that as an engineer I have always worked on the premise that an amplifier should do as its name implies (amplify a signal) and nothing else. This has always been the standard for 60 years or so. Today many of the top-sounding amplifiers certainly add coloration to the sound, but it is this character that is pleasing to the ear and sought after by many audiophiles and musicians.

This takes me back to the ol' black art days, when an amplifier may test terrible but sound great (and vice versa). Without doubt my conclusion (while still keeping an open mind and ear) is that the sound from a good amplifier using WE or other 300B or 2A3 tubes has more sonic merit than the sound produced from other tubes. I found, on initial investigation, a clean character was mainly due to the very linear nature of the tubes used and the previously stated rules.

In others the amplifier was not linear but had substantial second harmonic distortion. However, it was this sound that the owners liked. These amplifiers usually employed a less than linear triode or pentode which was triode-con-

nected as the voltage amplifier.

Tubes such as the 300b and 2A3s do offer better linearity than many others available, especially when you look at the plate transfer curves. This inherent linearity is what normally allows for low distortion without feedback in an amplifier. As I've already noted, you can employ other methods without feedback to achieve the same end result.

To many, the sound characteristic is worth the price paid. Being a little frugal myself, I thought it would be good to be able to achieve the sound qualities these "golden" tubes have to offer but without the cost. In my research I found that tubes such as the Eimac 300 TH and 100 TL—among other transmitting tubes—also offer great linearity for use in audio, so you should not discount them just because the anode lead comes out the wrong end of the tube.

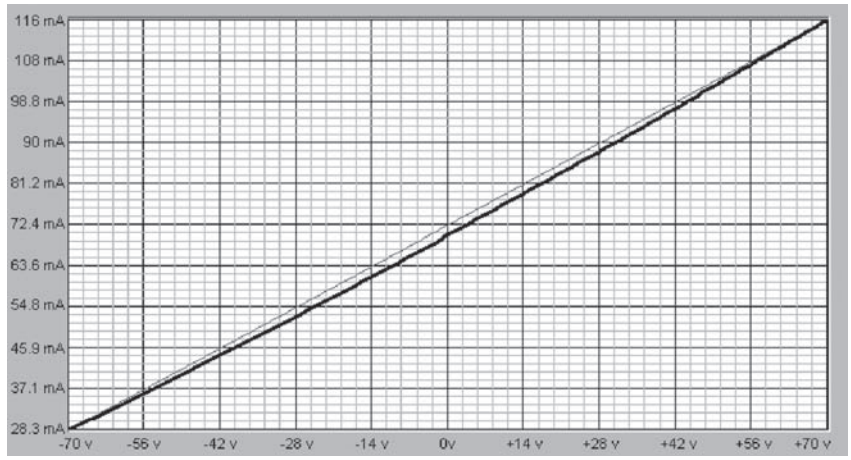
My current work has tried to emulate the transfer curves of classic tubes by using common off-the-shelf tubes. Because pentodes and tetrodes are readily available at low cost, these were the focus of my work (how to make a sow's ear sound like a silk purse or something like that).

EMULATING THE WE300B

Having recently purchased some NOS WE300Bs and some RCA 2A3s for customer projects and experimentation, I quickly managed to empty my bank account. These tubes, while nice triodes, will become harder to find over the next ten years or so. My advice is to buy now and put them away as an investment (you can add the Telefunken VF14 to this list as well). With this in mind, I spent some time trying out common tubes such as the 6V6, 6L6, 807, and EL34 in triode-connected mode, with generally disappointing results in comparison to the 300Bs and 2A3s. There must be a better way.

My experimentation in using composites in audio technology over the years has led me closer to a solution than I had imagined. My new theory, based on my odds and evens rethink, started me looking again at the transfer curves of the "golden" tubes with the thought of how to get a common tube to behave in the same manner, and emulate the transfer function. Initial experiments with the generic 6V6 were quite promising, but ended up with an extremely complex network of diodes, zeners, VDRs, and resistors to make the same shape transfer curve of a WE300B. The net result apart from circuit complexity was that the emulated device had less voltage gain than the 300B it was to replace.

FIGURE 1: Transfer function of the 300B exported from Glassware's SE AmpCAD.



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The next complication was to try to answer the question, Which part of the curve do you wish to emulate? A little explanation is due here. Obviously a 6V6 has less anode dissipation than a 300B so you could not use it as a one-for-one replacement. However, you could use other tubes such as a KT88 or 12E1 in a similar environment.

With this restriction, do you now look at how a 300B would perform in the standard 6V6 circuit? Or do you

look at the small part of the overall transfer function to emulate? Or do you look at the overall performance of a 300B run to its limits, and scale that performance down for a 6V6? I do not have the answers to these questions, but my experiments did lead me in the end to the latter solution as having the nicest sound qualities.

Where do you go when you have some serious number crunching? One of the main problems that I had in solving the 300B dilemma was trying to plot the difference between the transfer functions of many of the tubes available. Let me explain.

I needed a 300B transfer function and what I had was a 6V6. The difference between them is what I needed to apply to the 6V6 to get the result. Messing around with lots of graph paper in the early days solved the problem, but it also was time-consuming to plug in different tube curves.

The answer was to use a simple spreadsheet to just cut and paste different values to compare against and calculate the results. Better still, Excel allowed me to output to a graph so I could easily see what was going on. As a worked example, in **Fig.1** you can see the transfer function of a WE300b; **Fig.2** shows a 6V6; and when you crunch the numbers with Excel you get the result in **Fig.3**.

When I started to look at the transfer functions of the various tubes available, I found (when plotting the tube curves) that some tubes are more linear than others, with the pentodes and tetrodes shown triode-connected. In decreasing order of linearity, the results were tri-

FIGURE 2: Transfer functions of the 6V6 exported from Glassware's SE AmpCAD.

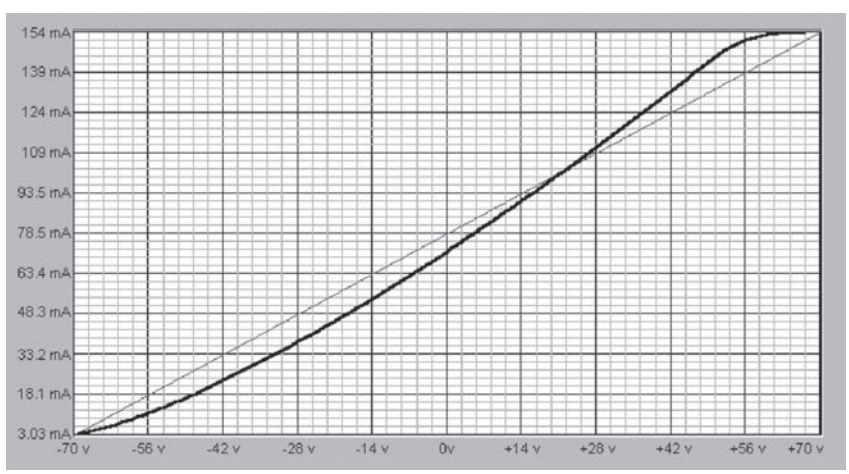

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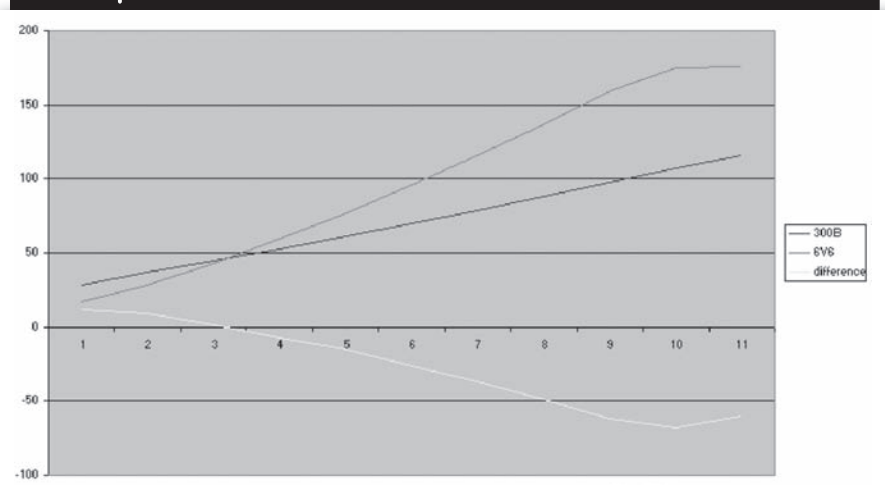
FIGURE 3: Difference between 300B and 6V6 transfer function from Excel spreadsheet.



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odes WE300B, CE300B, 2A3, and 811A, then the pentodes and tetrodes 6AQ5, 6V6, 12E1, 807, 6L6, KT66, KT88, EL34, and 6BQ5.

From the list, I found that of the pentodes and tetrodes available, both the 6AQ5 and the 6V6 were the best contenders in the linearity stakes to use for transfer function modification. The WE300B wins the linearity stakes in native mode with the 2A3 a very close second. Interestingly, the EL34 and 6BQ5 came in last.

MIXED MODE OF OPERATION

While operating in triode-connected mode did offer a substantial improvement in linearity over native pentode and tetrode mode, low efficiency was the drawback. The transfer function of a bipolar transistor is similar to a pentode tube, and as it transpires, by control of the voltage gain and the operating parameters, I was able to control the peak-to-peak grid voltage swing needed to drive the tube. Placing a resistor in series with the cathode bypass capacitor allowed the voltage gain to be varied by applying local negative feedback. By increasing the DC supply voltage and increasing the plate load, you change the transfer function and increase the grid drive requirements.

By adjusting the drive requirement, picking an appropriate DC supply voltage for a bipolar transistor, and setting the value of collector current (and hence stage voltage gain), I was able to adjust the overall linearity of a composite stage consisting of a bipolar transistor and a pentode or tetrode tube. This resulted in the pentode output stage operating at peak efficiency and still providing overall linear performance (by having an inverse nonlinear grid drive) with minimal feedback—all of this to emulate a triode valve. How close a match you produce will determine how close you get to the transfer function of a triode or to linear performance.

One of my experiments was to build a 2A3 amplifier using two 2A3s—one in the output stage, and one as the voltage amplifier—under the same operating conditions, and with an attenuator between the voltage amplifier plate, and the output stage grid, so that both tubes worked over the same operating range and conditions. The net result was exceptional but with even lower overall efficiency. The bigger problem was a lack of gain as these tubes have a relatively low mu.

To build a useful amplifier required four stages for the design. I ended up with two halves of a 12AU7 in front of the 2A3s as a gain stage. The overall performance was not as linear as using a single output stage and a matched characteristic voltage amplifier.

Tube Difference Spreadsheet.

	TUBE 1 300b	TUBE 2 6V6	
Grid V	Anode I	Anode I	Difference
-70	28.3	16.7	11.6
-56	37	27.9	9.1
-42	44.4	42.9	1.5
-28	52.3	59.4	-7.1
-14	61.7	77	-15.3
0	70.2	96.3	-26.1
14	79	116	-37
28	88.3	137	-48.7
42	97.4	159	-61.6
56	107	175	-68
70	116	176	-60

WE300B LOOK-ALIKE AMPLIFIER

An example of my WE300B amplifier is shown in **Fig. 4**. To make it a little more nonlinear to simulate a 2A3 circuit, I just added a 100R resistor and a 100mF capacitor in series across R1 (**Fig. 5**). A variation on the theme is shown in **Fig. 6** where, instead of using a separate negative supply voltage, I used a NPN transistor and a cathode regulated supply to achieve the same result. (**Figure 7** shows an all-tube WE300B circuit).

The difference in the grid and cathode voltages results in the appropriate bias voltage. The downside to this variation is that the cathode voltage is twice that needed for a conventional self-biased output stage. This results in more wasted DC power and an overall lower complete circuit efficiency. The approximate cathode voltage to use is the HT voltage divided by half the mu of the tube.

FIGURE 4: WE300B emulator schematic.

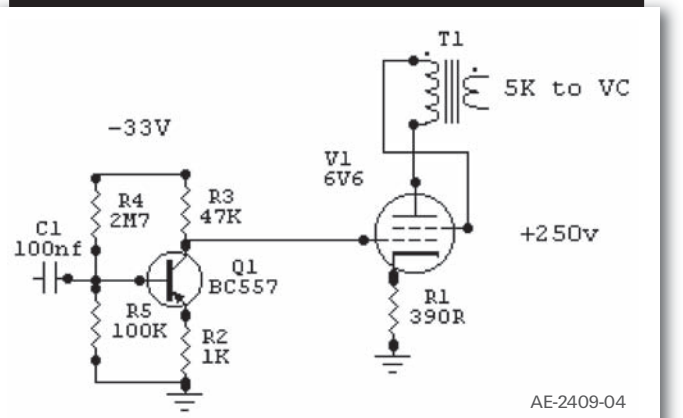


FIGURE 5: 2A3 emulator schematic.

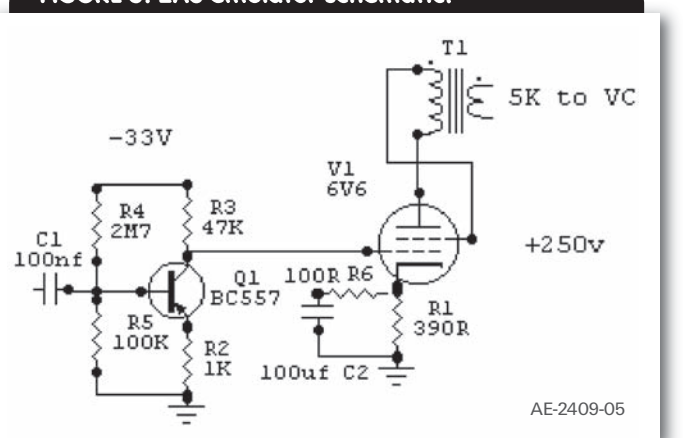
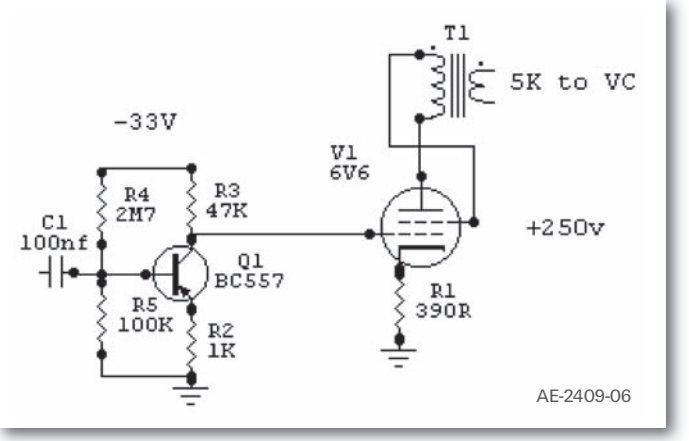


FIGURE 6: Variant of emulator schematic.



OPTIMIZING A TUBE DRIVER STAGE

Figure 8 shows the transfer curves of a 12AX7 tube. I noticed in practice that the theoretical curves apply quite well. Under low anode current conditions and high grid bias the tube transfer curve has quite a bend, whereas at higher anode currents and less grid bias the transfer curve is almost a straight line.

To optimize the voltage amplifier stage which drives the output tube, I needed to choose a part of the curve complementary to the curve of the output tube. You can work backward if you know the plate supply voltage, the load impedance, and quiescent current of the output tube. By looking at the tube characteristics and dividing the plate peak-to-peak voltage by the stage voltage gain, I ended up with the peak-to-peak grid driving voltage. With this symmetrically placed on the transfer

curve of the output tube and the correct grid bias offsets, I was able to draw the real transfer curve and transfer the information to my spreadsheet.

With a little juggling of the selected anode current and bias voltage on the grid of the 12AX7, I was able to override the peak-to-peak output voltage required by selecting a portion of the transfer curve similar in shape to that of the 6V6. In practice this reduced the THD of the amplifier, without feedback, from 11% to 4%—a large improvement. Not content with this, I eventually came up with a simple solution of having both a variable anode load and cathode bias resistor. These can simply be adjusted for the minimum distortion overall or to synthesize the sound of whatever tube combinations you wish.

With some juggling I was able to reduce the THD to a level of a little over 1% at full output and less than 1% at 1W. The downside to this method of operation is that you may run out of usable peak-to-peak output from the driver stage before you obtain the most linear overall results. The reason is that instead of optimizing the stage for maximum output, the Q point will now move away from the nominal half HT supply voltage on the anode, to a point somewhere above or below this figure to achieve the amount of nonlinearity required.

I have tried a few other audio tubes with great success, such as the 12AU7 and the 12AT7, which you may use for curve matching. For hard-to-match nonlinear tubes such as the EL34 and the 6BQ5, I have tried the 6ES8, which is pin-compatible with the 12Axx series tubes if they are wired for 6.3V filaments. The 6ES8 is an interesting tube to play with, because it is a semi-remote cutoff dual high mu triode normally used in TV tuners. The noise figures

FIGURE 7: All-tube emulator schematic.

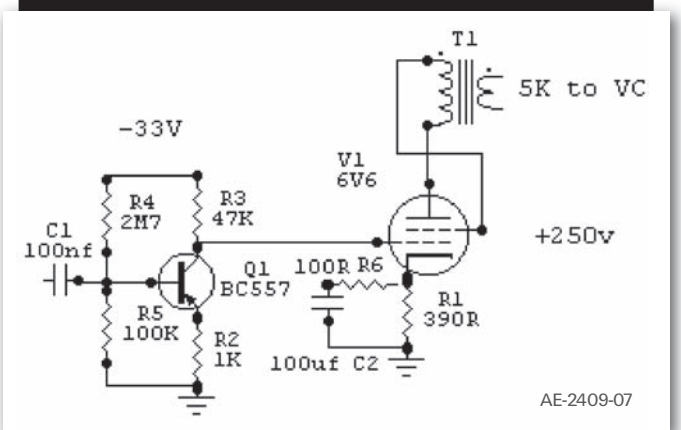
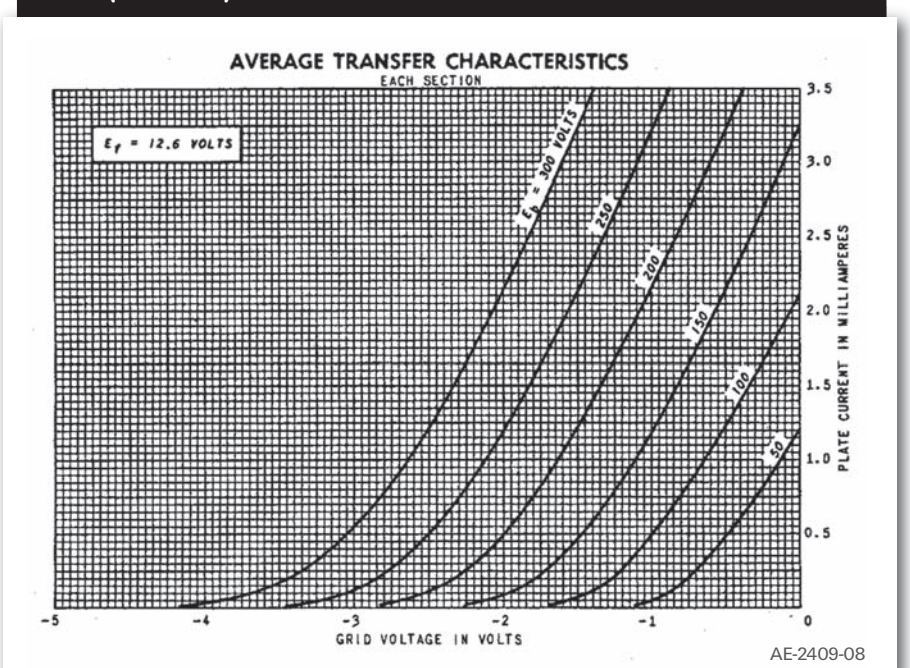


FIGURE 8: 12AX7 transfer function from the *STC Valve Data Handbook* (Volume 2).



and gain are quite high, but the tube has variable gain (slope) as well as a nonlinear (bendy) section of its transfer curve. This gives quite a bit of flexibility in this application.

As a side note, I have found that these tubes also make for an interesting-sounding overdriven cascade stage in a guitar amplifier. Amplifiers such as the Fender twin reverb produce a completely different character with the 6ES8 replacing the front end 12AX7. They sound particularly nice with a Stratocaster. I have also made the same transplant in a Marshall JCM800 with equal results.

LITTLE AMPLIFIER FROM DOWN UNDER

My all-tube prototype amplifier has now been passed around through the hands of many listeners here in my hometown of Adelaide, Australia, over the last two years. So far all comments have been complimentary, and several clones of this amplifier have been produced. Of the few people who have high-grade tube amplifiers to compare it with, only one has preferred the sound of his existing amplifier.

The 6V6 is a good low-cost tube. If you have a good junk box, you could build this amplifier in a day for little cost. Other tubes may also be used for higher output power. **Photos 1** and **2** show the prototype "little amplifier from down under."

Figure 9 shows the uncluttered front panel layout. One of my easy methods for making front panels is to simply use a laser printer to print onto a metalized art card and then laminate the panel. You can then cut it to size and spray the rear surface with craft adhesive. You can easily punch out holes for potentiometers and switches with a wad punch.

The result is a professional-looking front panel at nearly zero cost. The art card is available in a range of colors and finishes. My two favorites are aluminum and brass. The card does not cause any damage to the laser printer because the surface is non-conductive.

You can photocopy **Fig. 9** onto an art card instead of printing using a laser printer. Assembly is straightforward. There is nothing critical in the circuit, but be sure to heed the following comments about output transformers.

FIGURE 9: WE300B emulator front panel design.

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OUTPUT TRANSFORMERS

As in any high-quality amplifier the final results are only as good as the quality of components used, especially transformers. My current experiments allowed me to try normal series-connected SE output transformers and also shunt-fed circuits. I found the latter to be problematic in achieving good phase distortion and low leakage induc-

FIGURE 10: 6AQ5/6A3 adapter.

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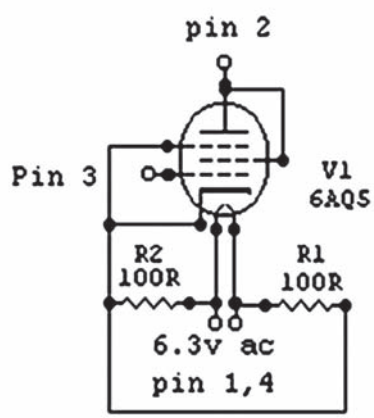

FIGURE 11: 6AQ5 pinouts.

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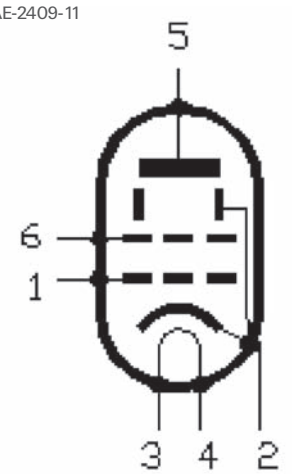

tance. The problem of using a series-fed SE output transformer is that the transformer will always be optimized at a single current by the choice of air gap at design and manufacture time.

During my experimentation I wound several output transformers—both E&I scrapless lamination types and also some "C" core designs. It was while experimenting with the latter that I replaced the usual soldered "C" core straps with some high-quality stainless-steel automotive radiator clamps, which allowed for easy tensioning of the cores and make for a variable gap output transformer. By tightening the bands you reduce the gap width, which decreases the standing current rating and also increases the primary inductance. Loosening it has the opposite effect. This allows for easy optimization with a change in operating conditions of the output stage.

MAKING A 6AQ5/6A3 ADAPTER

The 6A3 is a well-known 6.3V filament version of the classic 2A3 tube and a nice-sounding unit to use for developing and testing different circuits. When experimenting, it is always handy to have a good used set of tubes as testers until the circuit bugs are all worked out. It is better to destroy the tester rather than a brand new expensive NOS tube. 300b tubes and the 2A3/6A3 are in this category, but even testers can be expensive.

My simple solution to this problem was worked out about 40 years ago, but well-forgotten today. I often make small adapters to use available B9A and B7A base tubes, in place of less common 4-pin ones. This was often done in the '60s, making octal plugs to B9A bases for rectifiers. Making an adapter is a little more difficult for a directly heated cathode triode.

Figure 10 shows the schematic diagram of my 6A3 to 6AQ5 adapter. The 6AQ5 is wired triode-connected, which gives it approximately the same plate dissipation as a 6A3 (15W). The 6AQ5 has a plate dissipation of 12W and a screen dissipation of 2W, together 14W. The 6AQ5 pinouts are in **Fig. 11**.

To emulate a directly heated cathode is a little difficult. To solve this problem, wire two 100R ½W resistors from the 6AQ5 cathode to each of the filaments. The overall mu is a little higher than a 6A3, but the adapter is most workable, and the 6AQ5s are really easy to obtain at low cost. These are nice B7A base audio pentodes, electrically similar to a 6V6, very common, and available at a few dollars each. These are one of my useful sleeper tubes, such as the 6ES8, that everyone ignores and forgets about.

CONCLUSIONS

After much testing of classic and high-end tube amplifiers, I have come to the conclusion that those of two-stage design without any negative feedback tend to end up linear (to a degree) only by luck more so than by design. By applying the methods in this article, you may improve the performance of most two-stage amplifiers. By changing the operating conditions of the driver and/or the output stage, you can achieve better overall linearity. The simple modification to an existing amplifier is to replace the voltage amplifier fixed resistors with variable anode and cathode resistors. *aX*

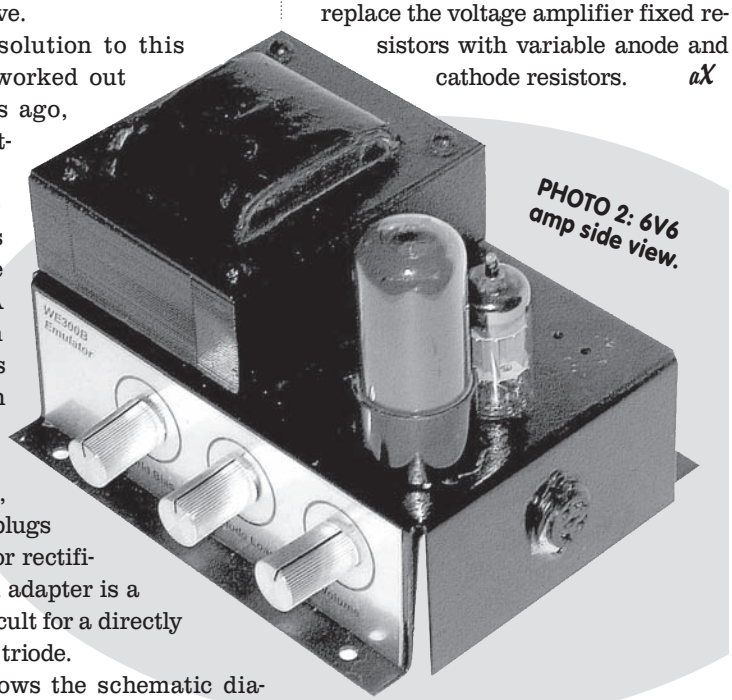

PHOTO 2: 6V6 amp side view.