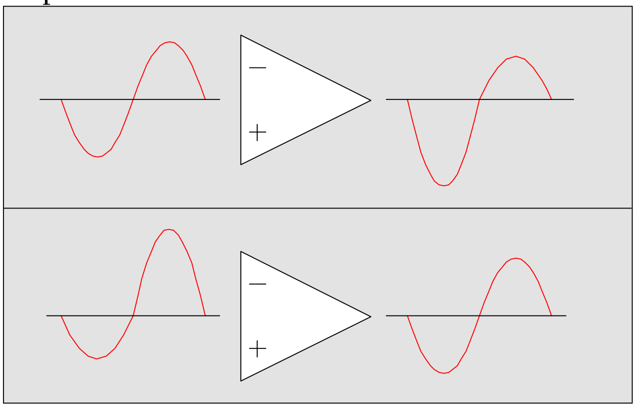
Inverse Complementary Distortion Cancellation

Adding distortion to eliminate distortion seems as contradictory as trying to prevent war by preparing for it. Yet in audio practice, seeming contradictions abound, feedback making an amplifier sound less clean, lower damping factors creating a better bass reproduction, for example. While these examples are controversial, adding negative distortion to distortion to yield no distortion should not be, yet this technique has few adherents. In fact, many do not know that this technique has been suggested. So it was after reading in *audioXpress's* July issue an article by Graham Dicker that asked why hasn't the lower distortion that occurs in amplifiers with an even-numbered stages and increase with odd-numbered stages not been noted before, I decided that the topic of distortion cancellation by complementary inverse pre-distortion is worth looking into again. (July--notice how long it takes me to get around to writing on a topic.)

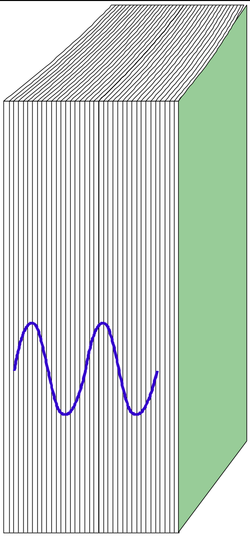
Half a century ago is the last time this topic was seriously covered; and the following two articles are well worth a trip to the library: "Non-Linearity Distortion," *Wireless Engineer*, January 1956, and "Nonlinear Distortion Reduction by Complementary Distortion," *IRE Transactions on Audio*, Sept-Oct 1959. It is fascinating to read the angry responses to the last article; but then anger often betrays a lack of understanding. (Paul Klipsh even got into the fray and on the wrong side if I remember correctly.) The argument against lowering distortion by pre-distorting went along the following lines: an amplifier that distorts will only end up distorting the pre-distorted signal, yielding no advantage, as the result will be a distorted pre-distortion; or that while it is possible to cancel 2nd harmonic distortion with this technique, it not possible to cancel the higher harmonics. Truly odd arguments; doesn't a distorted inverse distortion equal no distortion? And why only the 2nd harmonics?

If an amplifier's passing of a signal is labeled "function X," then feeding the amplifier inverse function X (1/X) will equal unity. For example, if an amplifier adds only gain and no distortion, then its function is "times 30," let's say. Thus if given an input signal that is divided by 30, the inverse of times 30 (1/30), its result is unity. The inverse RIAA equalization curve that a phono preamp implements is an example of an inverse function against the same function equaling a flat output response. Simple enough, so why the refusal to apply this principle to audio amplifiers?

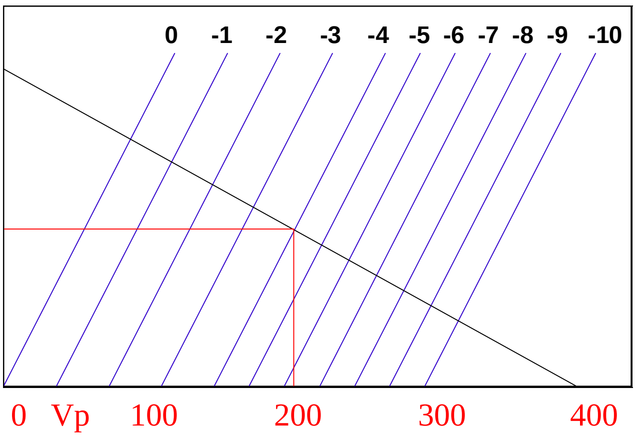


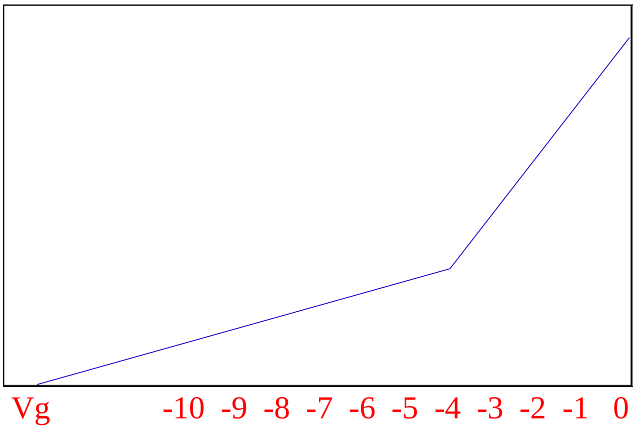
The answer lies not in the physics behind an amplifier operation, but rather a psychological obsession with frequency and sine waves. With the notable exception of the late Richard Heyser, few of us working with audio design are comfortable with anything other than sine waves. Maybe it is because instantaneous plate voltages do not seem as important as frequency response and harmonic distortion. Or maybe the oscilloscope's inability to display instantaneous voltages as well it can display sine waves makes us think exclusively in terms of frequency and sine waves. Yet at any given moment in time, a tube's plate voltage can be at only one voltage potential, just as a loudspeaker's cone can be at only one absolute fixed position or a resistor can experience a single absolute current flow at any given moment. It is only over time that these discrete plate voltages, cone positions, and resistor currents all add up to produce the fundamentals and overtones that we hear.

To get a feel for instantaneous voltages, take a thick telephone book and draw a sine wave on the open edge. Each page holds only one small dot of ink in much the same way that one slice of time hold only one plate voltage. (Digital recordings simply take the instantaneous voltage value for any given time-slice and convert it to binary code.



The next step to understanding how inverse distortion can lead to less distortion is to imagine a triode that displays an odd property: it has two sharply defined amplification factors. Form 0 to -4 grid volts, the mu is 40, but from -4 grid volts on, the mu is 20. And other than this break in a consistent mu, this triode is perfectly linear.



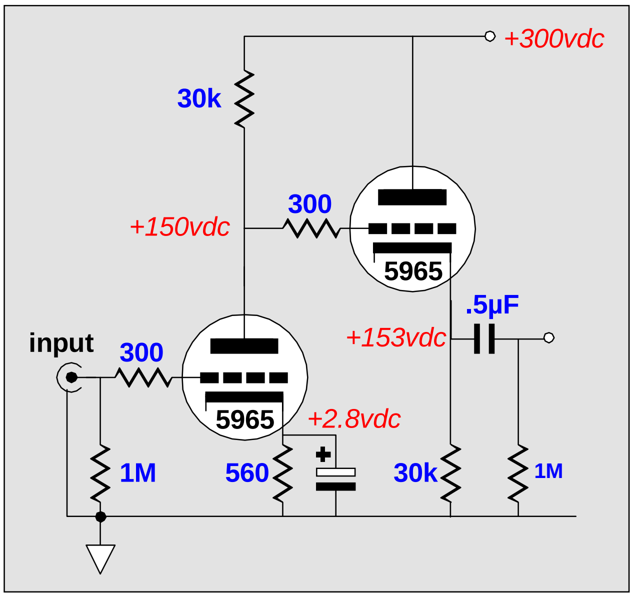


If the point of operation is set at -2 volts of grid bias or at -6 volts, we may never realize that the triode has a profound break in linearity. In other words, if we remain within a grid-voltage window of 0 to -4 volts, the tube's linearity is impeccable; the same holds true in the window of -4 to -8 grid volts. But at the -4 volts of grid bias point of operation, the tube's break in linearity is easily seen, as the triode offers a larger gain to positive going input signals than to negative going signals. In fact, the 2nd harmonic distortion is readily calculated to be 16.7% from the following formula:

$$\text{2nd Distortion} = \frac{0.5(V_{max} + V_{min}) - V_q}{V_{max} - V_{min}}$$

(To some extent, all triodes resemble this imaginary triode in that their amplification factors are not constant, decreasing with increased plate voltage and low plate current.)

Now let's imagine two of these imaginary, dual-mu triodes used in a line-stage amplifier. The first triode is used in a standard grounded-cathode configuration; the second, in a cathode follower configuration. Both triodes are biased at the -4 grid voltage point and both see the same cathode-top voltage and plate current. The first triode directly cascades into the second triode. How well will circuit made up of grossly non-linear triode work?

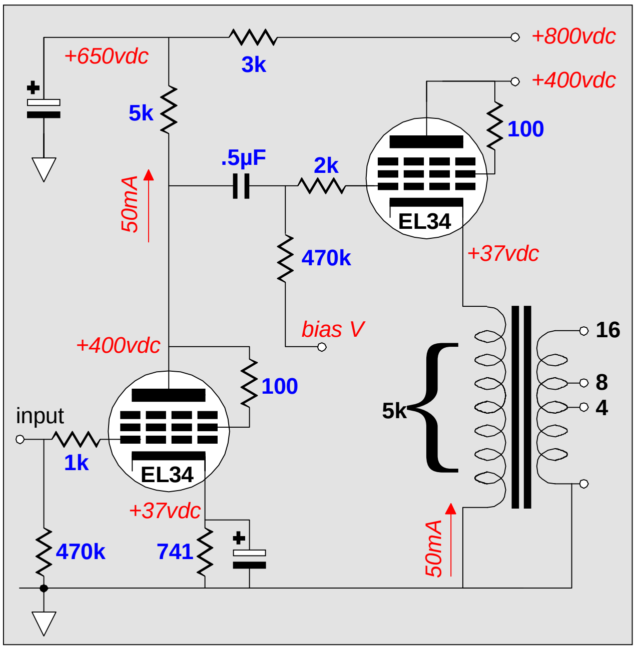


Constant-Current-Draw-Compound amplifier

When a cathode follower shares the same triode and load resistance and plate voltage and idle current as the grounded-cathode amplifier that precedes it, the cathode follower undoes much of the distortion of the first stage. This happens because the cathode follower is retracing the curves that the grounded-cathode amplifier traced. As the first stage's plate sluggishly swings positive, its cathode-to-plate voltage increases and its conduction decreases; as the cathode follower's cathode swings positive, its cathode-to-plate voltage aggressively decreases and its conduction increases. Inversely, when first stage's plate aggressively swings negative, the cathode follower's cathode-to-plate voltage sluggishly increases and its conduction decreases.

To the degree that a triode is consistently inconsistent, this circuit will make use of inverse pre-distortion to yield a lower distortion than either sub-circuit used independently. If this technique seems too optimistic, consider what goes on a multiple stage line amplifier with feedback; the penultimate gain stage delivers to the last stage an inverse pre-distorted signal that undoes the distortion that the last would impose in the absence of feedback. The feedback created this inverse pre-distorted signal precisely for the output device, as it is the output device that terminates the feedback loop. (It is interesting to compare a non-feedback amplifier to one with feedback. In the non-feedback amplifier, distortion grows larger at each proceeding stage from the input. In the feedback amplifier, distortion is largest at the input stage and grows cleaner with each proceeding stage to the output.) But feedback is not the only means to creating an inverse pre-distorting signal.

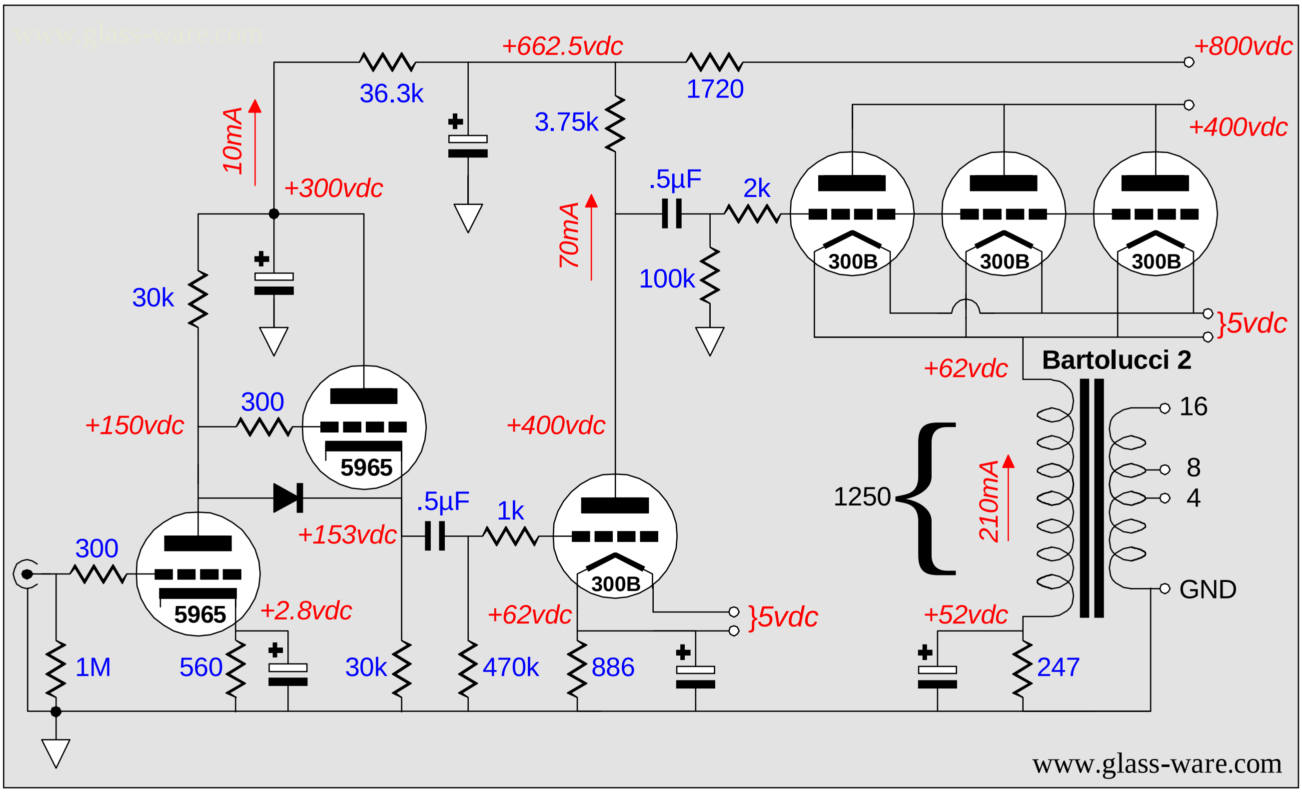
How do we use this trick to make a power amplifier? First of all, we must use the same triode type for both the driver tube and the output tube. Second, we must use same cathode-to-plate voltages, load impedances, and idle currents for both triodes. Third, we must cascade a grounded-cathode amplifier into a cathode follower output stage.



CCDC power amplifier

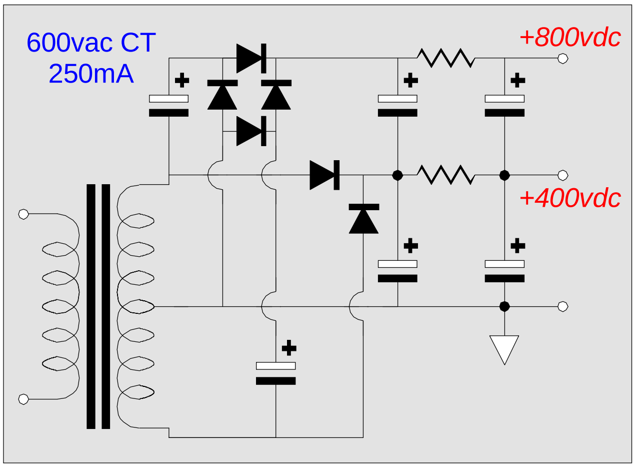
At first glance, it looks like we will have to lose half of the potential power output in order to reduce the distortion complementarily, as the first stage will have to work into the same load as will the output stage. For example, if the a single 2A3 output tube sees a load of 2500 ohms, then the 2A3 driver tube will also have to work into a 2500 ohm load; since both tubes undergo the same voltage and current swing, both tubes will deliver the same power into their loads. But as only one of these loads creates sound, half of the potential efficiency is lost. Considering that the average triode based SE amplifier is only about 20% efficient, we do not have much efficiency to throw away.

But if we increase the number of output devices used in parallel, we effectively increase the efficiency. For example, if we design a single-ended 300B power amplifier that uses three 300B output tubes in parallel, then only one 300B power tube is needed to provide the complementary inverse pre-distortion. So we end up throwing away only a quarter of our potential watts, rather than half. (Of course, the more output tubes in parallel, the better the efficiency.)



In the above schematic, you see an 300B based cathode follower output stage being driven by an 300B based grounded-cathode amplifier, whose plate resistor is three times greater (3750 ohms) than the reflected impedance on the output transformer's secondary (1250 ohms; the 247 ohm biasing resistor's value will have to be added to the primary impedance, if this resistor is not bypassed). The key feature is that the grounded-cathode amplifier stage's idle current and cathode-to-plate voltage matches that of each output tube.

The extra power supply voltage comes from a voltage doubler circuit, as shown below. Lest those who posses all-knowledge-of-all-that-is-worth-knowing-about-tube-electronics (a surprisingly small amount, it turns out, no more than can fill a few articles from the audiophile press and the odd rec.tube thread) lose their composure over the unseemly use of solid-state diodes, a tube rectifier can be easily used for the 400 vdc power supply voltage and, with some work, tube rectifiers could be used for the 800 volts power supply as well.



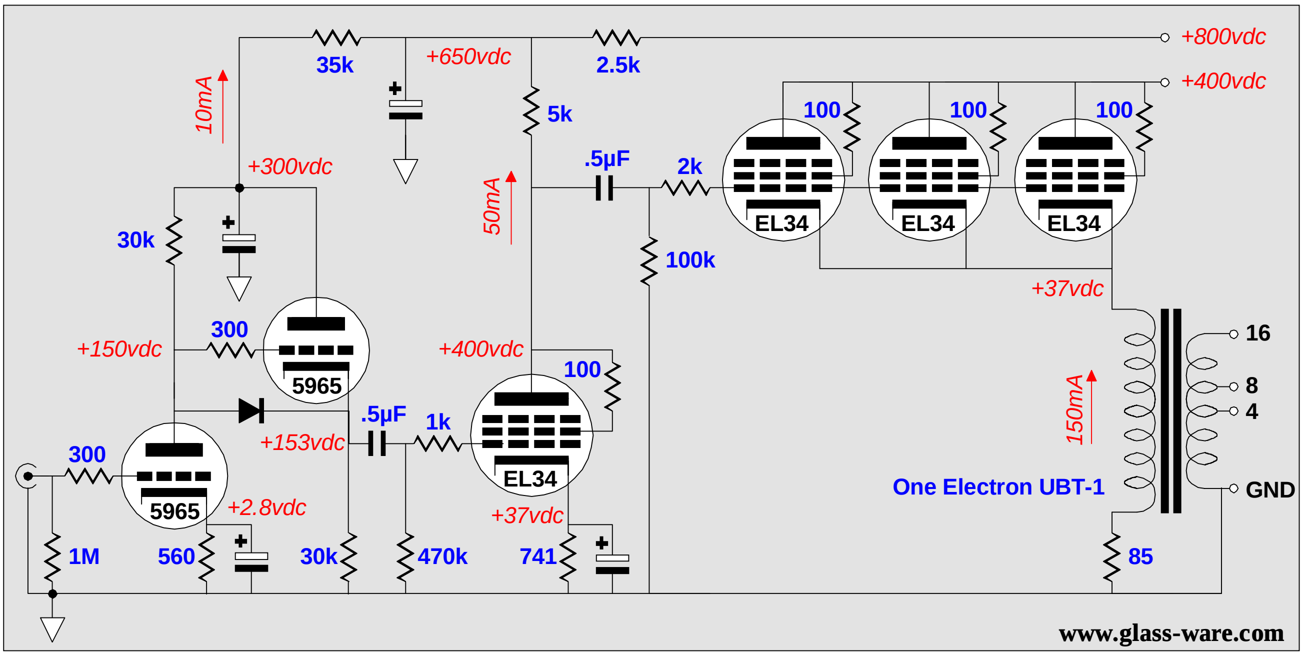
The 300B-based driver tube must realize a voltage swing large enough to drive the parallel cathode followers to full power output. Since the needed swing is not symmetrical, the potential swing need not be either. As configured, the driver stage can potentially swing down more voltage than up, which is what the output stage needs to see. This is the result of the triode requiring more voltage to turn it off than it requires to increase its conduction.

So when the driver tube sees an input swing of +62/-62 volts, its plate will swing -221/+195 volts, which in turn this imbalance will counter the imbalance that the output tubes will force onto the its output voltage swing, as it is the inverse of the output stage's imbalance.

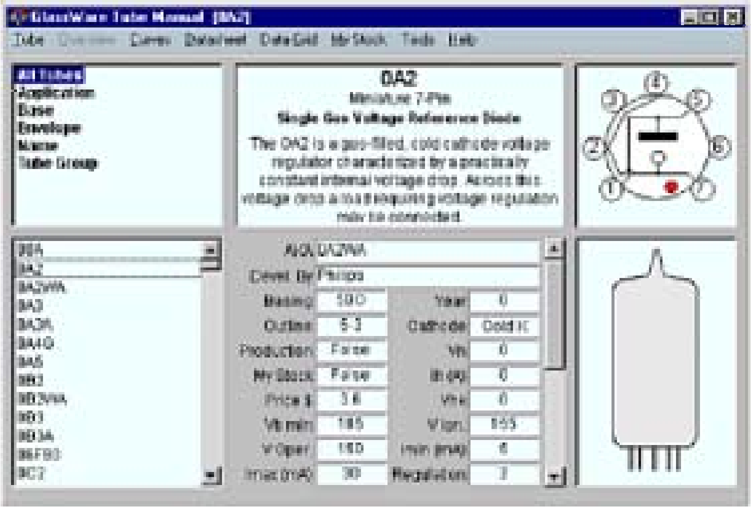
The unfortunate feature of this amplifier is that because the 300B mu is low, the output stage never realizes it full potential output, as the cathode follower output stage's low gain requires a much greater voltage swing at its grid to bring out the full output power that the 300B can give. Thus a better choice for an output tube might be triode connected 8417 or EL34. In the schematic below, we see an EL34-based output stage. This amplifier would provide about 15W of relatively inexpensive, clean, pure single-ended power.

The power amplifier's input stage also uses complementary inverse pre-distortion to lower this stage's contribution to the amplifier's final distortion figure by not adding excessive distortion to the mix. Thus the same principle of inverse-complementary-distortion cancellation that lowers the output stage's distortion is used to in the input stage. The same triode, the same cathode-to-plate voltage, the same load resistor value--all are used to inverse symmetrically cancel the distortion from the input stage.

The end result of all these techniques is an amplifier with a low output impedance and low distortion and wide bandwidth, an amplifier that does not use feedback (at least not a global feedback loop). The cathode follower output stage deserves some comments. This circuit employs 100% cathode degeneration of the output signal to keep the output in inline with its input. If the cathode fails to move as positive as the grid moves, then the grid effectively becomes more positive and the tube's conduction increases, which will force the cathode to a greater positive voltage. Conversely, if the cathode falls less negatively as the grid falls, then the grid effectively becomes more negative and the tube's conduction decreases, which results in the cathode's voltage to collapse. In other words, the cathode follower output stage uses all of the output tube's transconductance to force the output to follow the input signal. This short, quick feedback mechanism also brings the output impedance down and extends the bandwidth. It also serves to lower the transformer's distortion contribution, as output transformers distort least with low impedance input sources. This is an import advantage of this output stage, as the transformer is not enclosed in a distortion lowering feedback loop.



GLASSWARE TUBE MANUAL



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A true 32-bit Windows program, GlassWare Tube Manual is both user friendly and powerful. It's all here: plate curves, mu, rp, Gm, Vh, Ih, base and outline schematics, and essential characteristics for many of the tubes. Powerful search and filtering tools give control over this tube manual's large library of tubes (11,000). Look up your favorite tubes (6SN7, KT88, 2A3, and 6922) and discover other great tubes you didn't know existed. With the aid of easy-to-use editing tools, tubes can be added or subtracted to the database. Keep track of your own tube collection with your personal tube database. Like all GlassWare programs, GlassWare Tube Manual allows you to print the results. Hard copies of all the tubes in in this tube manual are a button click away. And tube substitutions are given for over 2000 tube types.

Windows 95 / 98 / Me / NT

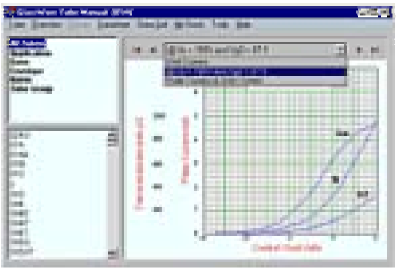
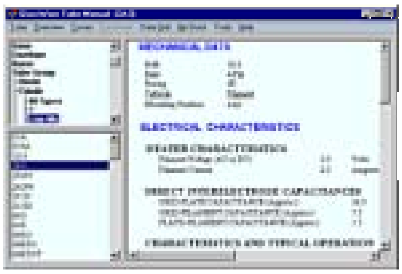
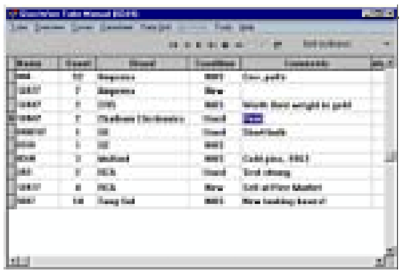


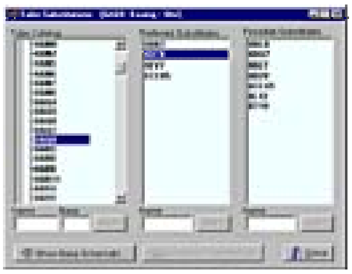
Plate Curves



Datasheets

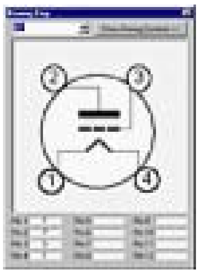


User's own stock DB

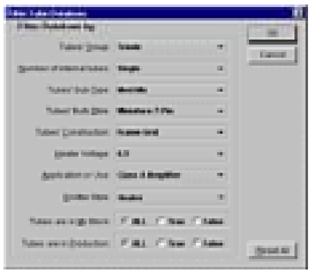


Tube Substitutions

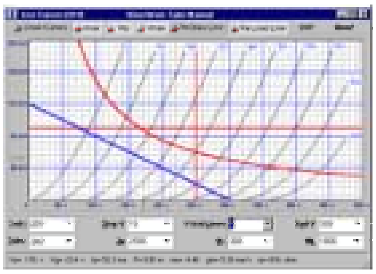
Tube Outlines



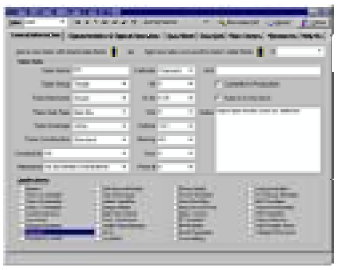
Tube Basing



Complex DB Filtering



Live Curves for over 40 tubes



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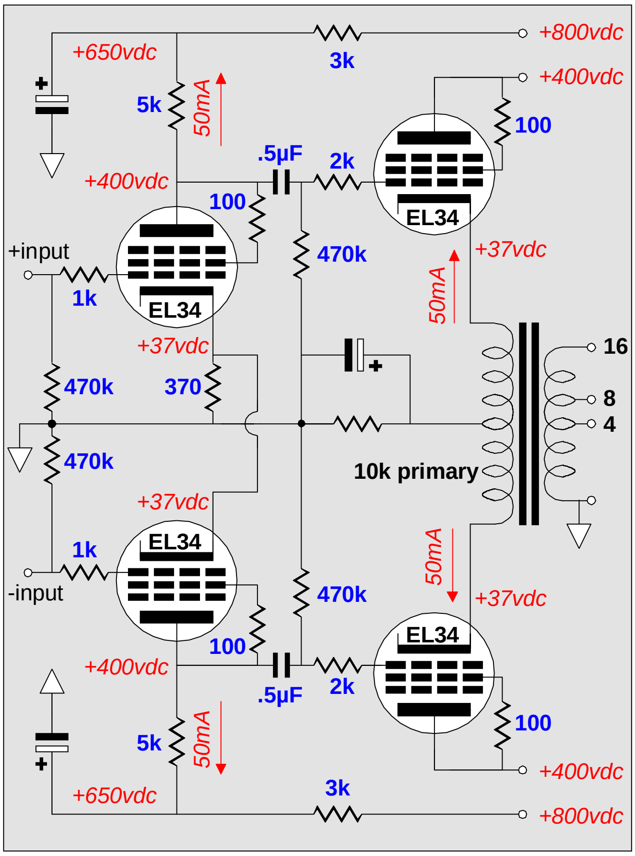
Push-Pull?

Doubling the SE circuit and adding a split-load phase splitter to the input of the amplifier, as the circuit below shows, could also easily make a push-pull version.



If a push-pull version were made, it would have be run in strict Class-A mode to ensure that the inverse distortion cancellation took hold. Note the common, un-bypassed cathode resistor that works to mimic the output tube cross-coupling in the output transformer. (Actually, this circuit would probably work best with an interstage coupling transformer.)

Realizing Full Output

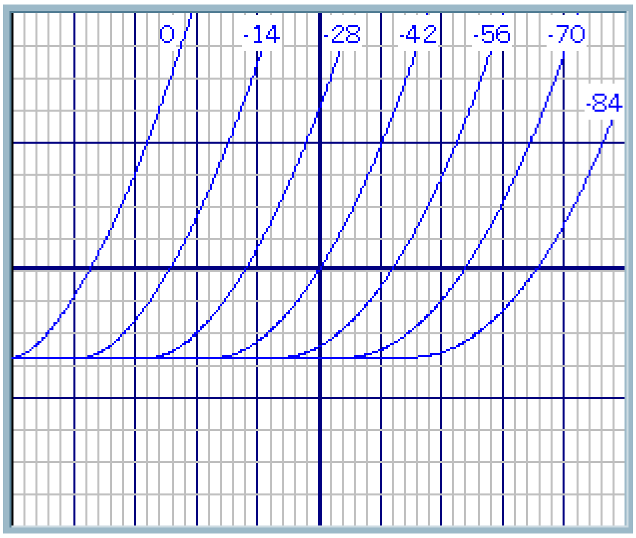
The problem we face is that in order to realize the full potential power output of either single-ended or the push-pull topology, the output stage requires a drive signal in excess of the drive signal available from the driver stage. One way out of this problem is to use a slightly higher value for the driver stage plate-load resistor, which would increase the potential power output at the expense of a slightly higher output distortion. How much larger should this resistor be? The math is simple enough:

$$Ra' = Ra + Rk$$

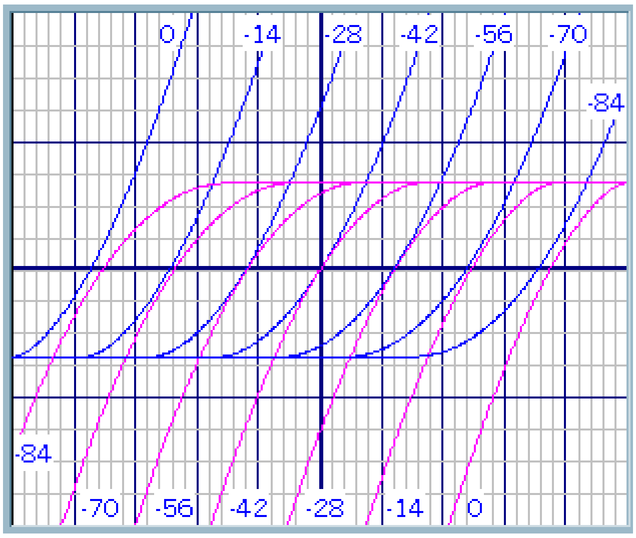
In the example just given, the plate resistor would be increased to 5741 ohms. What this value does is add the absolute value of the bias voltage to the peak output voltage swing of the driver stage, which compensates for the voltage gain lost by the output stage.

Pure Class-A
Push-Pull Distortion Cancellation

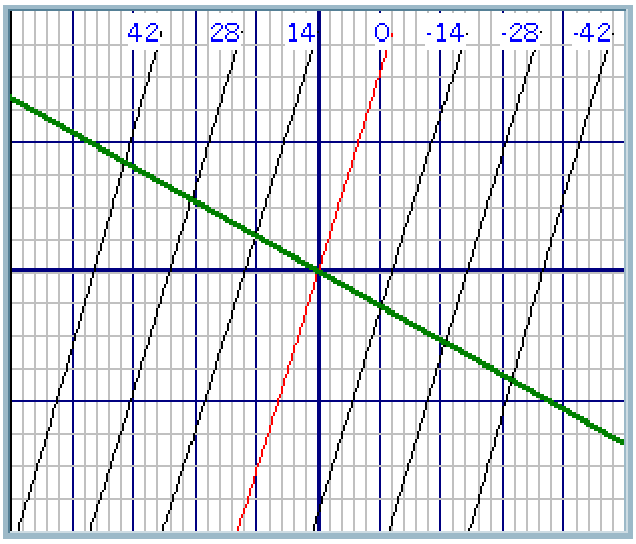
To those who queried the need for complementary inverse pre-distortion to lower the distortion of a push-pull output stage, you intuition is sound, as the inverse pre-distortion technique is definitely better suited to single-ended gain stages. The Class-A push-pull output stage already intrinsically cancels much of its output devices' non-linearity. The push-pull output stage (run under Class-A operation) effectively adds the two output devices' non-linear transfers into one flatter transfer function.



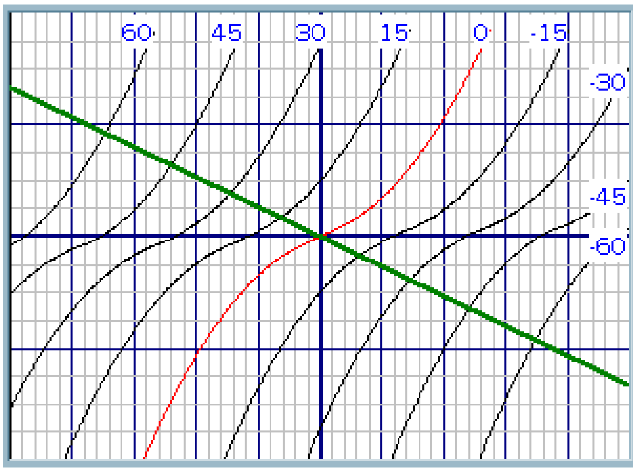
Single 2A3 with Vp of 250v and Iq of 51 mA



Two push-pull 2A3s with Vp of 250v and Iq of 51 mA



Composite curves of two 2A3 operating in Class-A with Vp of 250v and Iq of 51 mA



Composite curves of two 2A3 operating in Class-AB with Vp of 250v and Iq of 2 mA

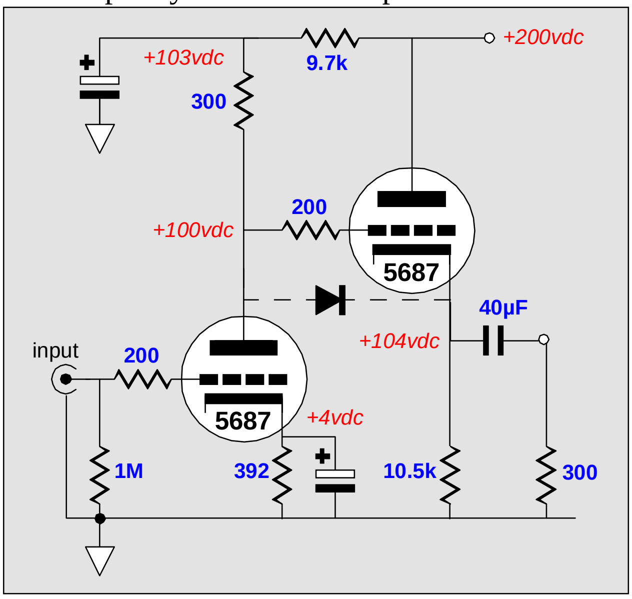
The composite curve are made by subtracting the second output tube's current conduction form the first. At idle, when bottom tubes conduct equally, the two currents equal and thus cancel, which places the center of the composite curves at zero grid volts and zero current into the load. As the output stage is driven by inverted drive signals, the non-linear transfer curves are averaged. So one tube's greater conduction is met with the other tube's lesser conduction, hence the straight lines formed in the composite plate curves drawn from two output tubes operating in pure Class-A and the wobbly curves formed by the same tubes in Class-AB.

Tube Headphone Amplifier

A smaller scale use of this distortion canceling technique might be a designing a headphone amplifier. The principle remains the same, but the output wattage is greatly reduced.

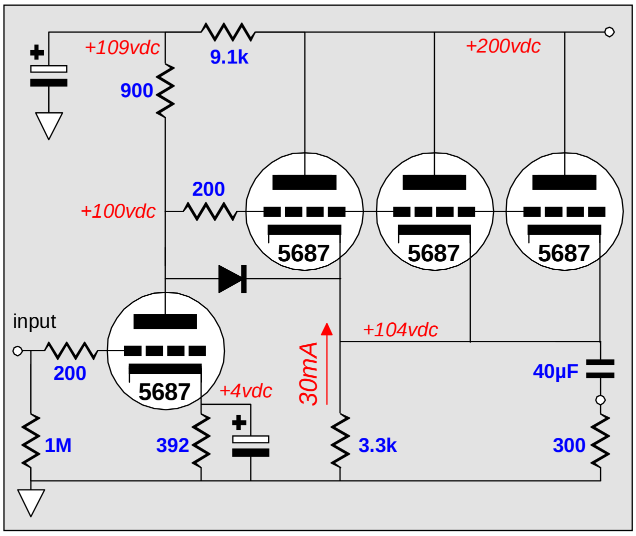
The two most popular high-end headphone brands are Sennheiser and Grado. Both of these companies make excellent headphones in the $100 to $600 range. I own a pair of Sennheiser HD-580 headphones and I can attest to their clean, smooth, tube-compatible sound. The HD-580 has been replaced by the HD-600, which sounds even better. Both Sennheiser headphones share a 300-ohm impedance. While this impedance is ten times greater than the Grado's, it is still quite a severe load for a vacuum tube. Used as a plate resistor value, 300 ohms would yield only a gain of 2.75 and a distorted output from a 6DJ8-based grounded-cathode amplifier. The same tube and load impedance in a cathode follower yields a gain of 0.73 and a still distorted output. How do we drive the 300-ohm load without using an output transformer?

The circuit below shows an complementary inverse pre-distortion cancellation headphone amplifier. As configured, this headphone amplifier will deliver slightly higher than unity gain and a fairly low output distortion. However, there is plenty of room for improvement.



Inv-distortion tube headphone amplifier

Increasing the number of output triode to three increases the gain and lowers the output impedance and distortion.

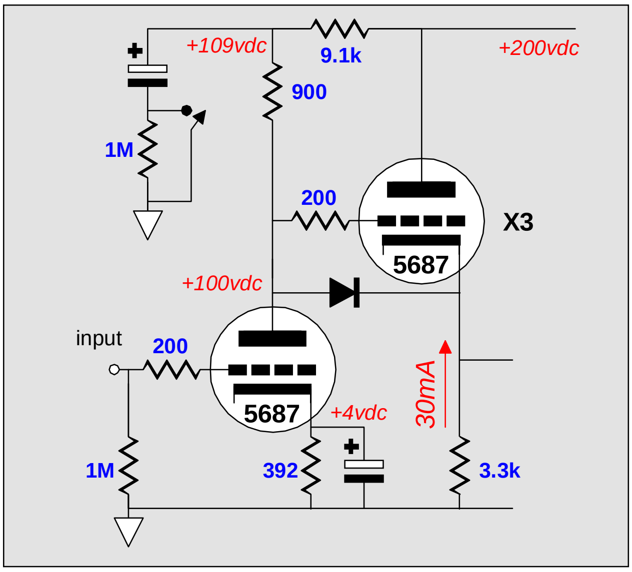


Inv-distortion tube headphone amplifier

The use of three output tubes effectively increases the 300 ohm load by threefold for each output tube, which in turn demands the use of a 900 ohm plate resistor for the input stage. The gain of this revised tube headphone amplifier is 3.6; the output impedance, 42 ohms; the maximum output voltage swing +/-8.5 volts. All in all, a very buffed headphone amplifier, but how good is it as a linestage amplifier?

The problem with the inverse pre-distortion technique is that the circuit is optimized for only one specific load impedance, thus limiting its universality. Unlike conventional line amplifiers, whose distortion decreases with unloading, somewhat paradoxically, the unloading of the circuit increases its distortion. One solution is to switch into place a 300-ohm load, when the headphones are removed. This would be easy to implement, as jacks with built in switches are readily available. The alternate approach is to switch out the shunting capacitor at the junction of the pr and the 9.1k voltage-dropping resistor. The 900 and 9.1k resistors combine to form a 10k resistor, which is three times the value of the cathode follower load resistor (3.3k). In other words, we now have a higher gain and lower distortion linestage.

Switching the shunting capacitor in and out of the circuit will cause loud popping noises, as this capacitor will have to be charged and uncharged. Placing a 1M resistor in series with the capacitor and ground keeps the capacitor constantly charged.



Headphone/linestage amplifier that switches plate resistors to adjust to the task.

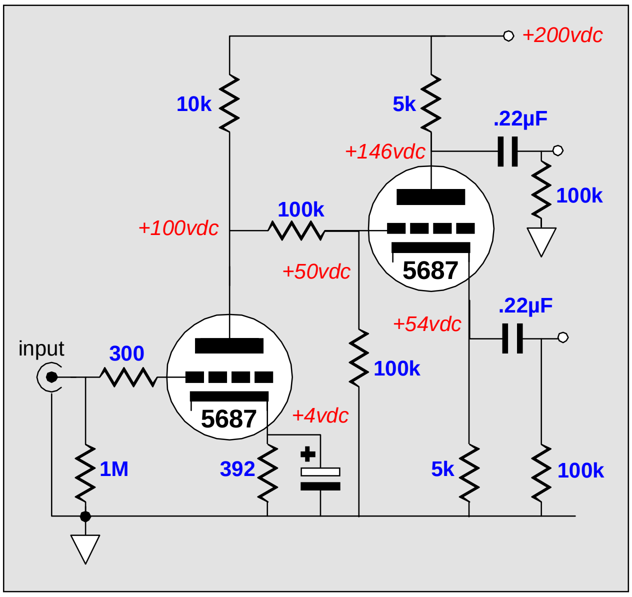
Driving Grado Headphones

The Grado headphone's brutally low impedance (about 30 ohms) can follow the same procedure as the Sennheiser headphones. Where the 300-ohm loads required a 900-ohm plate resistor values, the 30 ohms load requires a 90-ohm load. But with a 90-ohm plate resistor and a 5687 input tube, the final gain is only 0.2, hardily enough. Increasing the gain can be accomplished by adding an additional gain stage or more output tubes, but a better choice might be to use an output transformer with this circuit. Still, keeping the output stage transformerless is worth pursuing. Increasing the number of parallel output triodes to seven would demand a sevenfold increase of the plate resistor's nominal value of 30 ohms (210 ohms). This value of plate resistor yields a final gain of 0.7, which is much more usable. The added bonus is the corresponding decrease in output impedance down to 18 ohms. Finally, 5687s are so cheap and reliable that few would balk at the price of a re-tubing every 5 years.

But eight 5687s will require a truly robust power supply, as the heaters alone consume 45 watts of power and 20 watts of power will be needed to supply the rest of the circuit; truly extravagant. But maybe that is what is required to make the world's finest tube-based OTL single-ended headphone amplifier.

Push-Pull Headphone Amplifier With Inverse Pre-distortion Cancellation

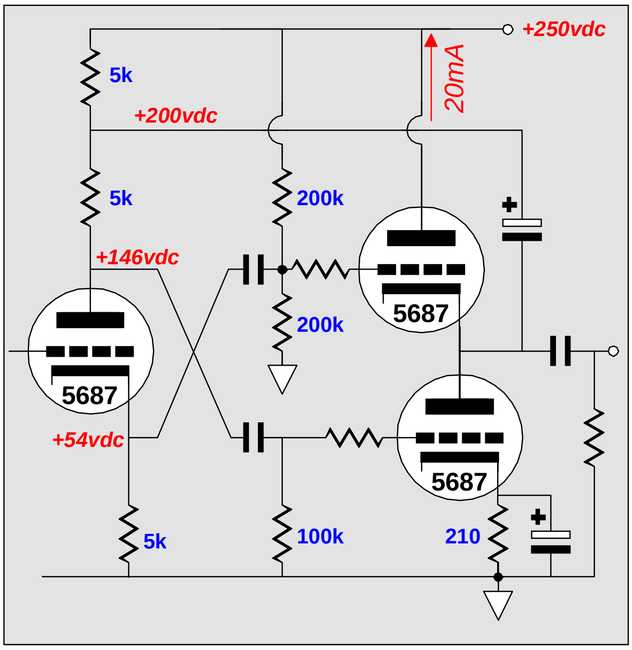
This circuit makes use of a specially designed split-load phase splitter that uses a variation on the inverse pre-distortion cancellation technique. In the circuit below, we find a grounded-cathode amplifier cascading into a 50% voltage divider. Yes, this means half of the first stage's gain is being thrown away, but it is purposely being thrown away. The voltage divider then cascades into a split-load phase splitter whose plate resistor and cathode resistor values combine to equal the grounded-cathode amplifier's plate resistor value.



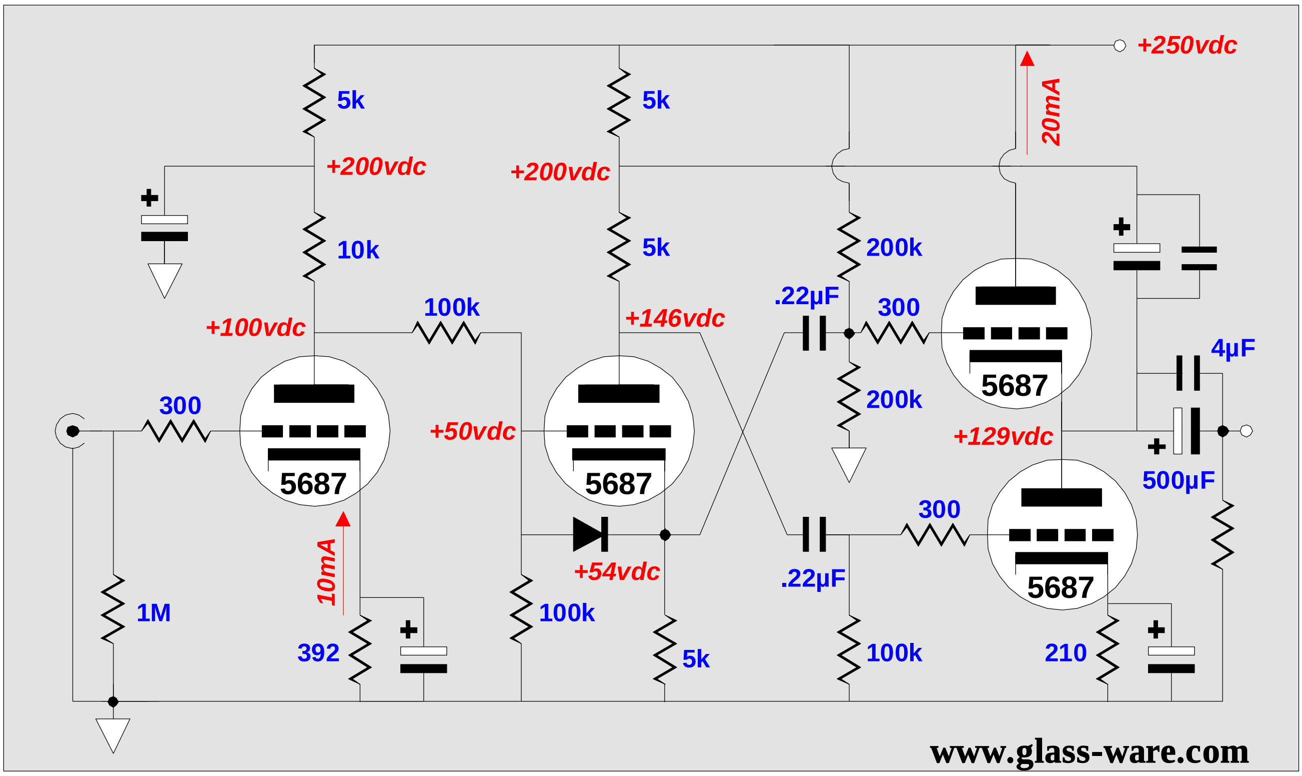
In other words, both the grounded-cathode amplifier and the split-load phase splitter undergo the same cathode-plate voltage swing and current swing, but in anti-phase. For example, if the first stage sees its plate voltage climb up by 50 volts, the phase splitter sees its cathode-to-plate fall by 50 volts.

In addition, when the first stage sees its plate current drop by 5 mA, the phase splitter sees its plate current increase by 5 mA; in contrast, when the first stage sees its plate current rise by 5 mA, the phase splitter sees its plate current fall by 5 mA. Without the 50% voltage divider bridging the first triode to the second, no juggling of plate and cathode resistor values would yield this perfectly anti-phase cathode-to-plate voltage and plate current operation. (If you conceder that the split-load phase splitter effectively has a gain of 2 and not unity because of the two outputs, then the voltage divider function is more obvious.)

The result is a phase splitter that with a final gain of 6 and very little distortion. Now all that is needed is a Class-A push-pull output stage that is strong enough to drive 30 ohm loads.



The circuit above includes the Class-A push-pull output stage. Both output tubes function as cathode followers, as the capacitor that bridges the phase splitter and output serves to return all of the bottom triode's gain back to its grid. The output stage has an idle current of 20 mA and thus can deliver twice that amount into a 300 or 20 ohm load impedance. (One point to remember is that a 30 ohm load requires a 265 µF output coupling capacitor.)



Shown above is the complete tube headphone amplifier. The amplifier provides a clean output signal and low output impedance without a global feedback loop. And yes, 6H30 triodes could be instead. And no, I will not provide the cathode resistor values for the 6H30 tube, as on the www.glass-ware.com site there is a link to a free download of the Live Curves program for this tube and determining the resistor values is an excellent homework assignment.

Conclusion

While we only scratched the surface, we had to start someplace. What was left out was circuits like phono preamps and electrostatic direct drive amplifiers. (We could try to create an inverse pre-distortion signal by loading the driver stage with an inductance in series with a plate resistor, as the output would be loaded by a capacitance in parallel with a plate resistor.)

As always, if you build any of these circuits, please give us some feedback on your results.

//JRB

