10 November 2004

Aikido Variations

Well, after that last sermon (yesterday's blog), I'm sure many will welcome more circuit analysis. After having learned of reader Paul's predicament with his Antique Sound Labs AQ-2004 line stage, I'm sure that a few readers have wondered how three 12AU7s could be used in the Aikido amplifier, as the circuit seems to require an even number of twin-triode envelopes. The answer lies in how the cathode follower output stage works: a conventional cathode follower is loaded by a quasi constant-current source that also works to buck the percentage of the power supply noise presented by the first stage. Now, if the input stage comprises two identical triodes that share identical cathode resistors, then the percentage of power supply noise will be 50%. This same 50% ratio, however, can be realized with one triode, if the cathode resistor's value is carefully chosen. All that is required is that the plate resistor's value be effectively equaled by the triode and its unbypassed cathode resistor.

The total effective impedance of the triode and cathode resistor is equal to

(mu + 1)Rk + rp

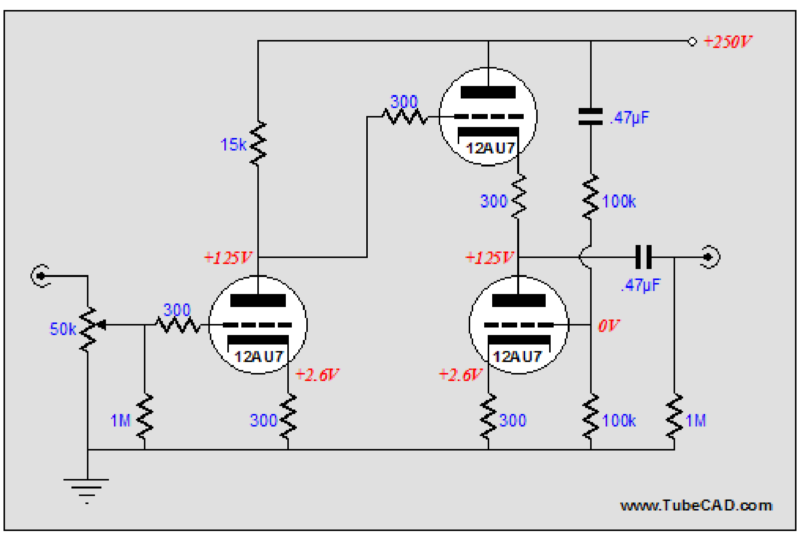
Thus, when

Ra = (mu + 1)Rk + rp

the voltage division will be 50%. Solving for Rk, we get:

Rk = (Ra - rp)/(mu + 1)

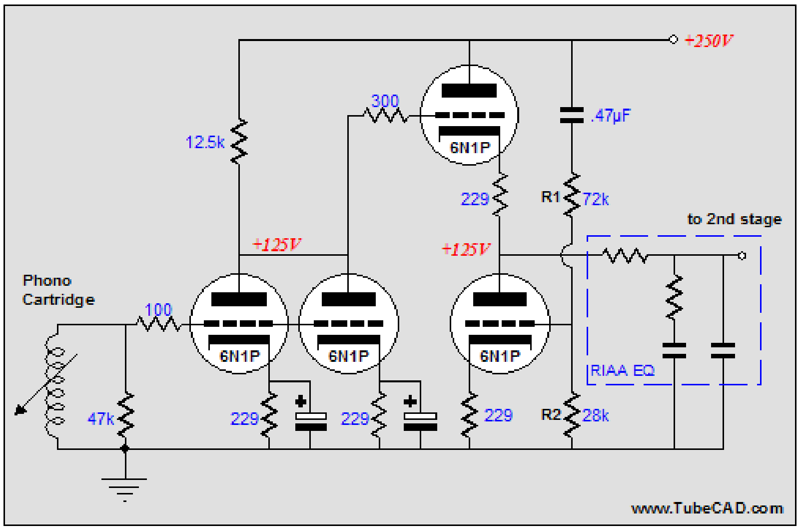
(Once again, it is important to remember that the cathode resistor must be unbypassed.)



In the schematic above, we see three triodes working in an Aikido amplifier. The input stage still halves the power supply noise at its output and the cathode follower stage still has half of the power supply noise injected to the bottom triode's grid. So, why bother with two triodes for the input stage? The advantage that two triodes hold is that we are not restricted to one triode type.

Usually each triode requires its own specific cathode resistor value to bias up to the desired idle current and to match a fixed plate resistor value, whereas in the balanced totem-pole configuration, we sidestep this need, as any fairly well matched set of triodes will always halve the power supply noise, with the idle current falling where it will and while still retaining the B+ voltage halving. In the test setup I had built for the Aikido amplifier, I was able to plug in 12AT7s, 12AU7, 12AV7s, 12AX7s, 12BH7s, and 5751s. In each case, the circuit worked beautifully, the gain being the only changing variable. Had a single triode been used in the input stage, then each different tube type would require a different cathode resistor value (in some cases, the plate resistor would have to be changed as well).

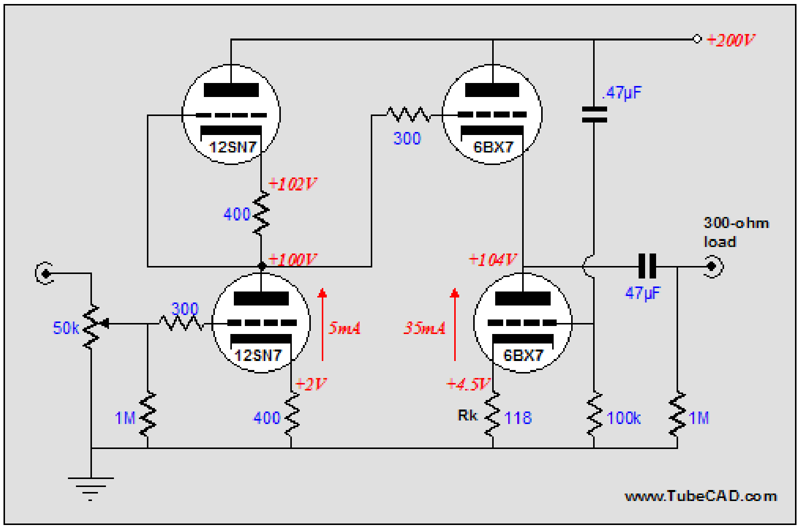
So, what we gain by using two triodes in the input stage is ease of use and universality. Laudable goals indeed, but there are times when another goal may trump (for example, more gain). In the balanced totem-pole configuration the gain is equal to the amplification factor (mu) divided by 2; whereas when the cathode resistor is bypassed, a grounded-cathode amplifier can deliver a gain much closer to the triode's mu. Bypassing the cathode resistor will alter the power supply noise division, so the percentage of power supply noise injected into the cathode follower's bottom triode will correspondingly be altered.



In the schematic above, we see basis of the first half of a tube phone preamplifier. The circuit begins with two 6N1Ps working in parallel into a common plate resistor. Each triode gets its own bypassed cathode resistor, which allows each triode to find its own quiescent idle current. Effectively, the two triodes act as one triode with the same mu and twice the transconductance (gm) and half the plate resistance (rp). At the specified plate voltage and idle current, these values become: mu = 36, gm = 7.5 mA/V, and rp = 4.8k. Thus, the 12.5k plate resistor is effectively in series with a 4.8k resistance, with a resulting voltage division of 28%. Therefore, the cathode follower's bottom triode's grid must be presented with 28% of the power supply noise, which 72k and 28k resistors yield easily enough.

The cathode follower half of the Aikido amplifier

Having looked into the first half of the Aikido amplifier, let's now move on to the second half: the cathode follower portion. What if attaining the lowest possible output impedance trumped universality? We can eliminate the top triode's cathode resistor, whose value was directly in series with the top triode's output impedance.



In the schematic above, we see a tube-based headphone amplifier. The intended load is 300-ohm headphones, such as those made by Sennheiser and others. The 6BX7 is a tough triode that can easily drive such a load. But how do we null out the power supply from the output? One way of looking at the output stage is to see the top triode as representing a plate resistor equal to rp/(mu +1), which in the case of the 6BX7 is about 118 ohms. Now, if we view the bottom triode as constituting a grounded-cathode amplifier with a plate resistor equal to 118 ohms, then we need to specify a cathode resistor whose value will result in a gain of 0.5, as its grid sees the full power supply noise. Thus, because grounded-cathode amplifiers invert the phase at their plate, we can null the noise at the output, thus: 0.5 – 0.5 = 0. Or another way of looking at this output stage is to see that if we halve the bottom triode's effective gm, the top triode's reaction to half of the power supply noise will be countered. The formula for effective gm (gm') is :

gm' = mu / [rp + (mu + 1)Rk]

Thus, half the gm results when rp = (mu + 1)Rk, or solving for Rk, when Rk = rp/(mu + 1). This works to null the power-supply noise at the output due to 50% of the this noise being presented to the top triode's grid from the preceding input stage, but it does not include the amount of noise current created by the top triode's rp. The math starts to get thicker here, alas. In the presence of power-supply noise, we must must establish an equilibrium between top and bottom current variations, which obtains when

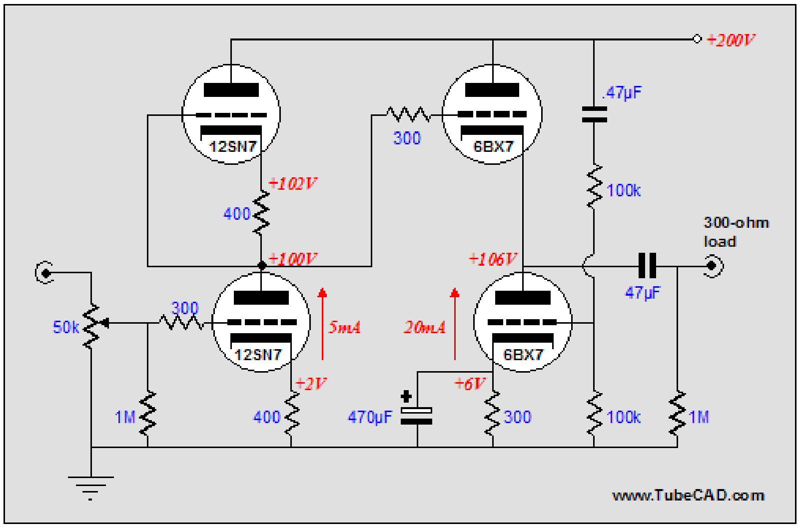
mu / 2rp + 1/rp = mu / [(mu + 1)Rk = rp]

After some long algebraic dancing with the formula, we arrive at

Rk = rp(mu -2) / (mu² + 3mu + 2)

With this cathode resistor value, the power-supply noise at the output is nulled. Notice that we must accept the whatever idle current that results from this cathode resistor value and roughly half of the B+ voltage for the bottom triode. What if this idle current is excessive? How do we lower the current while still nulling the power supply noise?

"math is for solid-state; poetry is for tube audio"

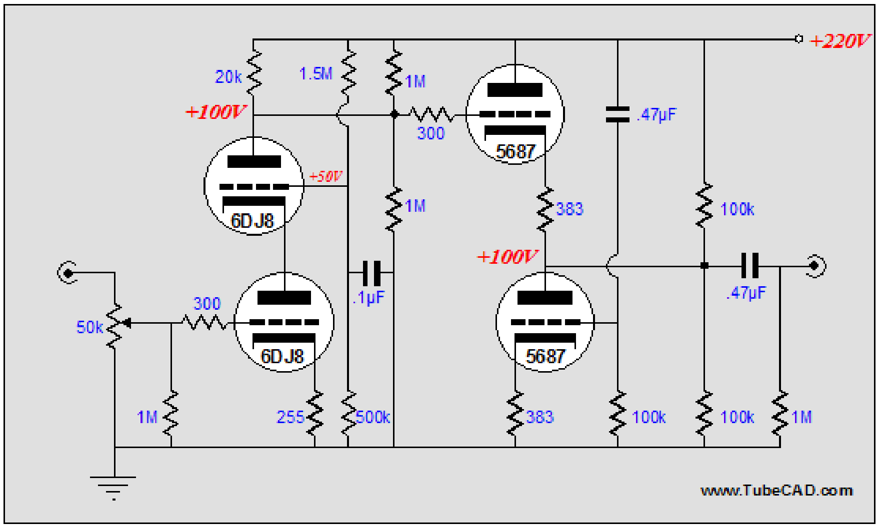


In the schematic above, we see almost the same headphone amplifier as before, save for the differently valued and bypassed cathode resistor and the addition of a second 100k resistor. Now the top and bottom triodes are balanced in transconductance, so the bottom triode needs to see half of the power supply noise at its grid. [The actual formula is a bit more complex, as the to resistor needs to be (mu - 2)/(mu + 2) times as big as the bottom resistor. The higher the mu, the less difference in resistance will result; with low-mu triode, such as the 6AS7, the difference is huge. In this example, with the 6BX7's mu equal to 10, the top resistor should be 68K, as (10 - 2)/(10 + 2) x 100k = 66.666k and 68k is the closest standard resistor value.]

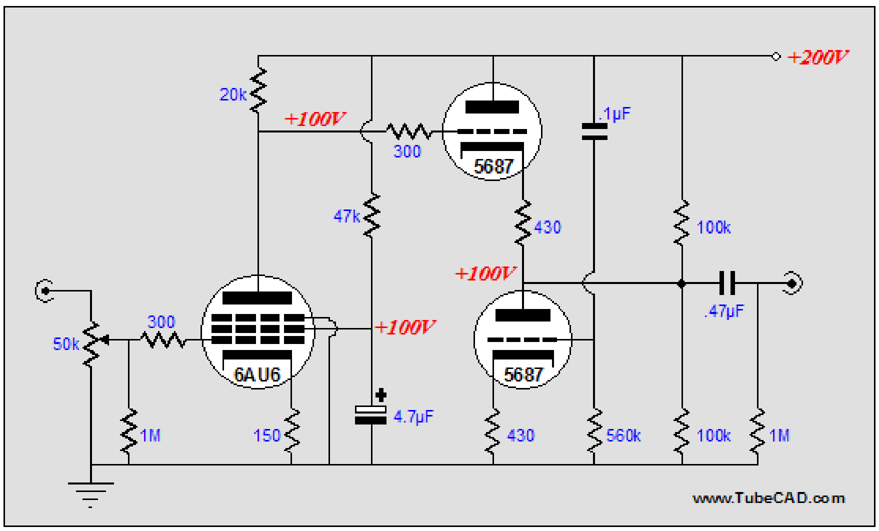
Cascodes, pentodes, and FETs

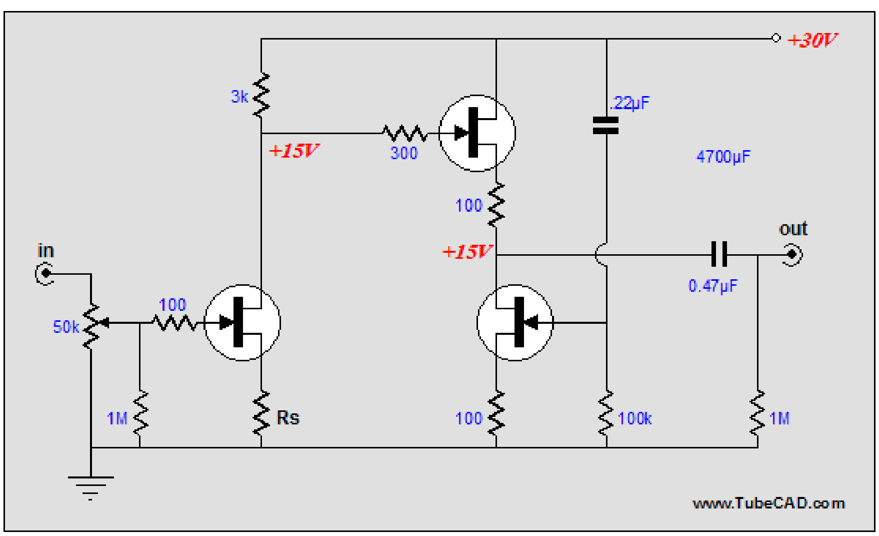
All of the Aikido amplifier circuit variations we have seen so far have relied on the triode's rp to define a leg in a two-resistance voltage divider. But what about Cascodes, pentodes, and FETs, which have near infinite output impedances? As I am sure you can guess, a little math will solve just about any problem. (Many readers hate it when I mention math (math is for solid-state; poetry is for tube audio). If you are one, just replace the word "math" with the phrase "rules governing interdependent relationships.")

The cascode amplifier exhibits an exceedingly poor PSRR, so much so that just about all of the power supply noise will make it to its output. The same holds true for the average pentode and FET circuit (pentodes and FETs also have a small triode region of operation at low voltages). In the schematic below, a cascode amplifier cascades into our special cathode follower. Since the cascode stage will pass all of the power supply noise, we must deliver all of the power supply noise to the cathode follower's bottom triode's grid.



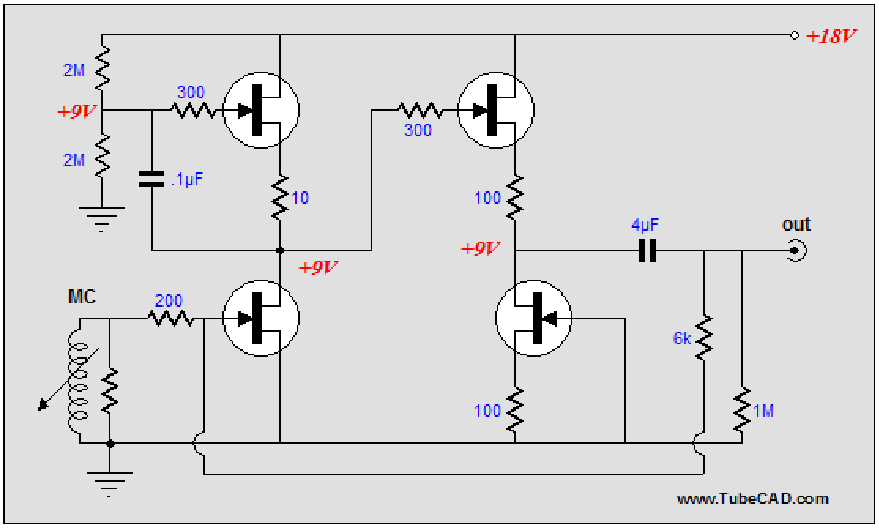
In the circuit below, a pentode has replaced the cascode. Once again, we inject all of the noise into the bottom triode's grid to counter the noise at its plate.





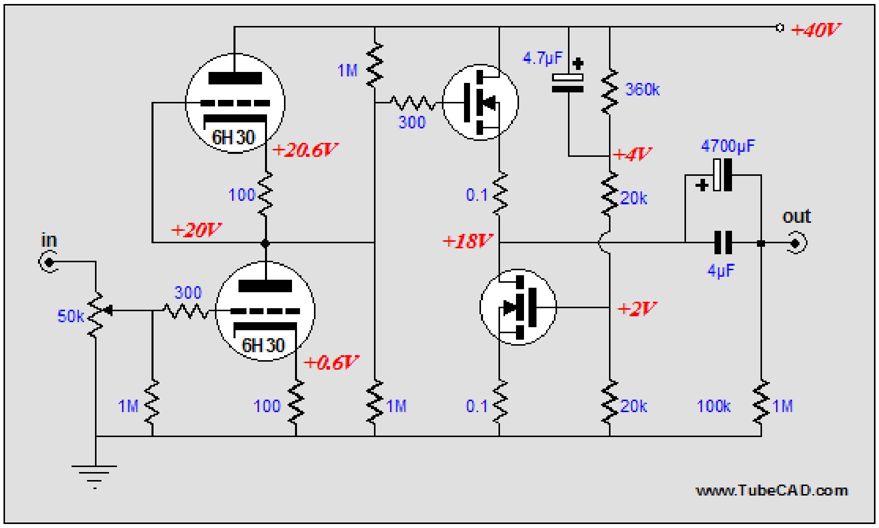
In the schematic above, we see an all-FET preamp. The gain will roughly equal the drain resistor divided by the source resistor, Rs. No matter what the final gain, however, all of the power supply noise will transfer to the top source-follower FET's gate, so we must offer the bottom FET the same amount of noise. This is easily done by attaching its bypass capacitor to the B+ rail. (This is exactly opposite of what 99% of electronic designers would do, as they always ground bypass capacitors, even when it results in worse performance, as consistency is a seemingly higher goal or maybe it has something to do with old dogs.)

Wait a minute. Couldn't we use two FETs, each with its own source resistor, just like the equivalent tube circuit? In theory, yes; in practice, no. The FETs would have to be perfectly matched, which they never are, which means that they would not define a 50% voltage divider for the B+ voltage. Still, we could force the voltage division by adding a few parts. In the schematic below, we see the bottom input FET being loaded by a FET-based constant-current source, whose DC point is set by the two-resistor voltage divider. In this circuit, none of the power supply noise should make it to the second stage, so we do not inject any noise into the bottom FET. Additionally, in this circuit, the input stage realizes a great deal more gain, so much that a feedback loop has been added. (This circuit would make a fine moving-coil phono cartridge pre-preamp.)

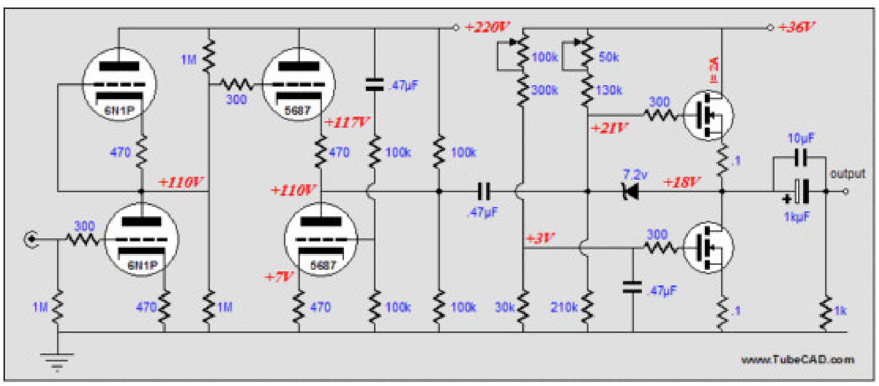


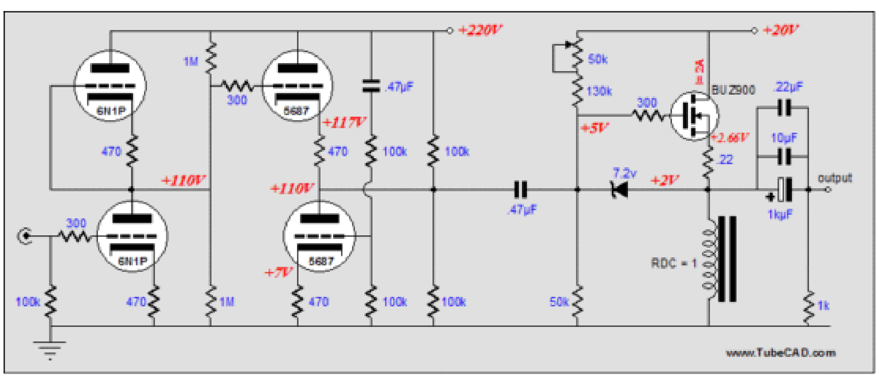
Variations

In the first blog on the Aikido amplifier, I mentioned seed ideas that gave rise to multiple circuit permutations...well, here are a few of them. In the circuit below, we see a hybrid amplifier. The output stage works in a strict, honest-to-God, no-marketing-hype, single-ended Class-A mode. Hallelujah. The tube provides all the voltage gain and the MOSFETs provide all the current gain into the load. The 50% of power supply noise that the top MOSFET sees is countered by the bottom MOSFET seeing the same 50% of power supply noise. Notice how the idle current can be changed without altering the power supply noise ratio into the bottom gate.



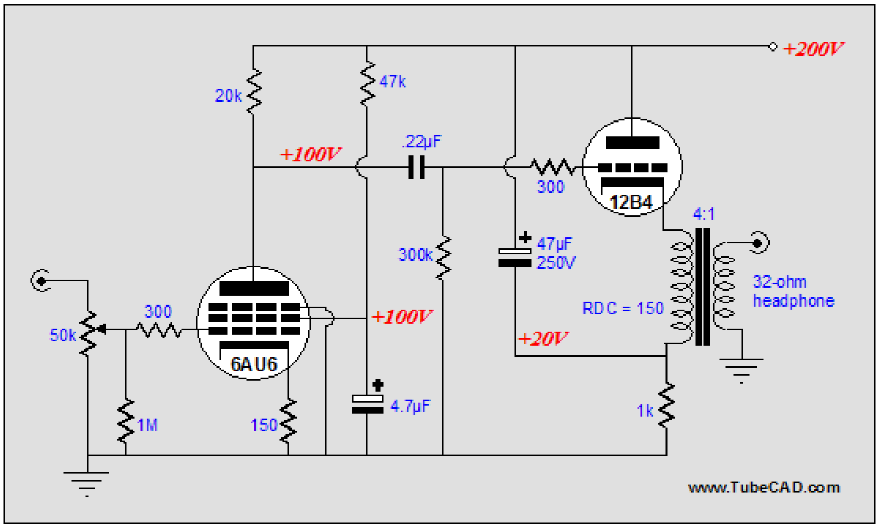
One problem with this hybrid is that we are asking a lot of the input stage, as it must deliver both high gain and a high current (for a tube) to drive the MOSFET's input capacitance. Splitting these tasks between two tube stages (i.e. the Aikido amplifier) would ease the design of a good hybrid amplifier. Additionally, we can use a much higher B+ voltage for the tube stages than any solid-state output stage could handle. Below are a few single-ended Class-A hybrid ideas. (The MOFET source-follower output stages already enjoy an exemplary PSRR, so if we feed the a clean signal, we will not have to work to lower its noise contribution.)

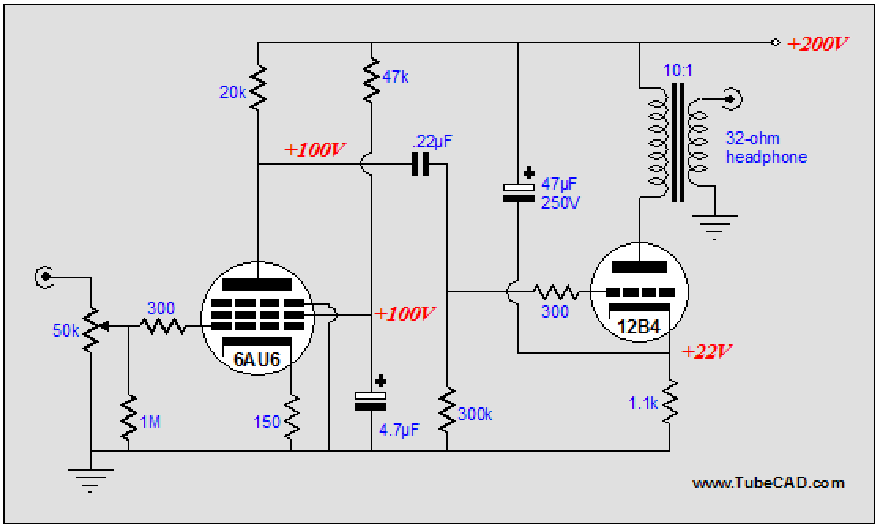




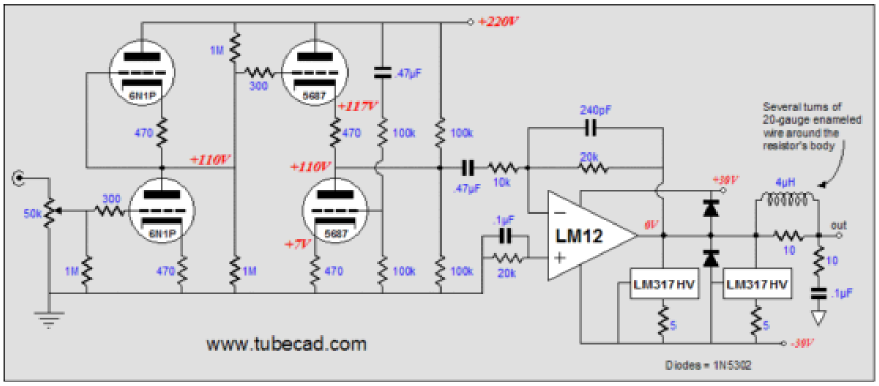
Click on images to see close up

Returning to pentodes, the schematic below displays a simple transformer-coupled, single-ended headphone amplifier. (It could readily be scaled up to a real power amplifier). The output stage is configured as a cathode follower working into a transformer primary, but with a difference. The 47µF capacitor couples the power supply noise to the other end of the primary, so the primary never sees a noise induced voltage differential. The primary also serves as a cathode resistor of sorts to self bias the output tube.





In this variation, we see the output stage configured as a grounded-cathode amplifier. This time the 47µF capacitor couples the power supply noise to the output tube's cathode. The result is that the output tube does not "see" the power supply noise about it, as it plate and grid also equally see the same noise.



Click on image to see closeup

Just in case my solid-state e-mail falls off, here is a simple hybrid that uses an LM12 power OpAmp, but with a few twists. Of course, the tube front end counts, but the two LM317s add a nice twist: they are configured as constant-current sources that force the LM12's output stage to work in single-ended Class-A mode for the first watt, with push-pull Class-AB thereafter.

//JRB

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