An E-Mail

Subject: Why Just Tubes?

This is my third e-mail to the Tube CAD Journal and I thank you for your kind replies to the first two e-mails, which were quite lengthy and informative. However, those e-mails were never published in your journal. Was it that they were not deemed interesting enough to include or were they excluded because the circuits contained were pure solid-state? If the latter was the reason, then I must make a plea on behalf of the solid-state half of the world: your journal is one of the few places that audio electrical engineering is explained carefully and fully. Bless you and your writers. But limiting the journal to just tube audio is probably a big mistake. Here is why: my guess is that more than half of the journal's readers are from the solid-state camp anyway.

I know from my group of audiophile friends--mostly fellow college students--that none of the tube guys are technically inclined in the smallest degree. They love tube sound and spend huge sums of money on single tubes, but they cannot tell you what a cathode is. (This deep division reminds me of the one between Linux and Mac followers, with Windoze users in somewhere in the middle; never ask a Mac user which CPU their system uses, for example.) This is not, however, a plea that you publish only solid-state articles, but that you just include a few pure solid-state articles for the other half of your readers. (I would love to read your explanation of current-feedback amplifiers, for example.)

Now for the technical part of my letter, I like the warm and smooth sound from tube equipment, but I do not like the fat and shallow bass reproduction from tube gear. (Actually, I am sure the poor bass response comes from the coupling capacitors and output transformers and not from the tubes themselves.) Therefore, some sort of hybrid system would seem to be best: a tube preamp driving a solid-state amplifier for instances. This is what am currently using, with a tube line amplifier (your circuit) driving my 100 watt solid-state amplifier. This sounds better than either the pure tube or pure solid-state equivalent systems I have tried. But the sound seems to be too close to the pure solid-state side of the spectrum. Hell, maybe I am a closet tube fancier after all.

I have hooked up headphones to the line amplifier and the sound is just about perfect, so how do I preserve as much of that sound as I can? One idea I have is to build a solid-state amplifier that adds no gain or feedback, which means that the line amplifier will do all of the voltage amplifying and the power amplifier will do all of the current providing.

The attached schematic shows two circuits: the first is a pure solid-state unity-gain buffer and the second is a hybrid buffer. What do you think of them? Which would be the better path to follow? Thanks in advance for your kind reply and the possible publishing my letter ;)

Tony F.
United States

Tony, your first two emails were not published precisely because they were tube free, not because they failed to provoke interest.

The original intent of this journal was to mimic the *Math CAD Journal,* a magazine put out by the MathSoft people to asset users of their *Math CAD* program by providing math-related articles that illustrated how their software could be used. For example, users of *Math CAD* who explain how they found the program useful write many of the articles.

Well that was the intent, but the *Tube CAD Journal* went off in another direction altogether. Part of the reason was that many of the tube fanciers needed, as you pointed out, to be technically brought up to speed. Another part was my hope of expanding the tube-audio horizon, which I felt was collapsing into a few simple-minded topologies and practices.

In fact, you are not the first to recommend widening the journal's range of topics to include all audio related circuit devices and topologies. But I cannot see too great a need to cover pure solid-state topics when *Elektor*, *Electronics World*, *audioXpress,* and the solid-state manufacturers themselves (in their data books) do a good job on these topics. But then, maybe I am wrong on this. What do you, the readers, think? As for the circuits you submitted, you have an entire article as a reply...

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High-Power Buffers

Although buffers might be new to many audiophiles, they are a central part of the analog electrical engineering practice. In short, a high-power buffer is a special type of power amplifier: it relays its input voltage to its output un-amplified and it delivers the needed current increase into the load. In other words, like a conventional amplifier, the buffer can deliver power into a load, but the buffer does not add any voltage gain; instead, it only provides the required current gain. For example, a good tube-based line stage can usually put out at least 30 to 50 volts of peak output swing, which into an 8-ohm load would equal 50 to 150 watts of power, which if the line stage could deliver 4 to 6 amps of current, it would deliver that much power.

Buffers come in two basic styles: the global feedback buffer and the local feedback buffer.

Global Feedback Buffers

The global feedback version is simply a conventional power amplifier with all its gain being returned to its input stage. A typical power amplifier has a voltage divider in the form of a feedback loop, bridging its output to its input, which defines the gain of the final gain of the amplifier. The greater the voltage division, the greater the final gain.

What is happening here is that the feedback mechanism within the amplifier strives to keep the voltage divider's center voltage in line with the amplifier's input voltage. The greater the voltage division, the greater must be the output voltage to allow the same matching of amplifier's input and feedback voltages. If, on the other hand, we eliminate the voltage divider and return all of the output voltage to the negative input, the amplifier's feedback mechanism will force the output voltage to fall until it matches the input voltage. In other words, we have turned an amplifier into a buffer. (Not all power amplifiers, however, can be converted into buffers, as not all amplifiers are unity gain stable.)

Local Feedback Buffers

The local feedback buffer has no global feedback loop, relying instead on degenerative feedback at each active device's output to keep the output in line with input voltage. Yes, this is the same mechanism used in a cathode follower, which keeps both its output distortion low and its output impedance low. (Solid-state devices offer the added advantage of allowing a symmetrical topology not possible with tubes, as there is no P-channel version of a triode.)

Whereas the global feedback buffer is usually run in lean Class-AB mode, in order to reduce power consumption, the local feedback buffer is usually run in beefy Class-A mode, as the higher currents both enhance the linearity and extend the frequency bandwidth.

IC examples of both types are readily found in the National Semiconductors catalog. The LH4004, LH4006, LM102 and LM310 are of the global feedback type and the LH0002, LH0033, LH0066, and LH4001 are of the local feedback type. (Linear Technology also makes some excellent buffers.) Examining the schematics for these buffers is a good source for gaining insight into the designing of a buffer, as the schematics are often reduced to idealized versions that are much clearer than their actual implementation.

MJ Stereo Technic

The wonderful Japanese audio magazine, *MJ Stereo Technic* also known as *Audio Technology MJ*, has for the last two decades run articles that featured high-power buffer circuits. Usually, the circuits look like they are just the last half of a conventional amplifier, but a few have been more interesting. The aim of these buffers is to provide no gain, but sufficient current gain to drive loudspeakers.

Surely, the logic is compelling: tubes cleanly provide voltage gain, but are current limited; solid-state devices provide huge current gains, but are not as linear at voltage amplification. (A gross oversimplification, but essentially correct.) So why not use each only for its best use? In other words, why not have a hybrid system?

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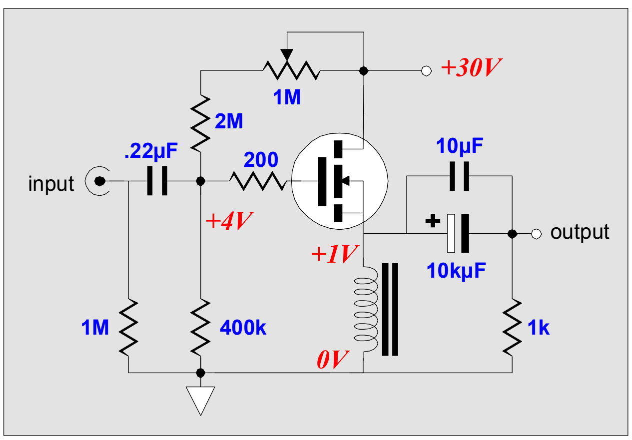
Yes, this is somewhat like breaking a hybrid amplifier into two components, line stage and buffer amplifier, which makes sense, as making a typical hybrid amplifier is effectively like placing two line stages in series with each other needlessly. On the other hand, if a passive volume control box is used in the line amplifier's stead, then the unity-gain buffer will not provide full output, only producing a few milliwatts of output power, as the line level voltage are seldom much over one volt.

Well, so much for the introduction to buffers, let us now look into actual topologies.

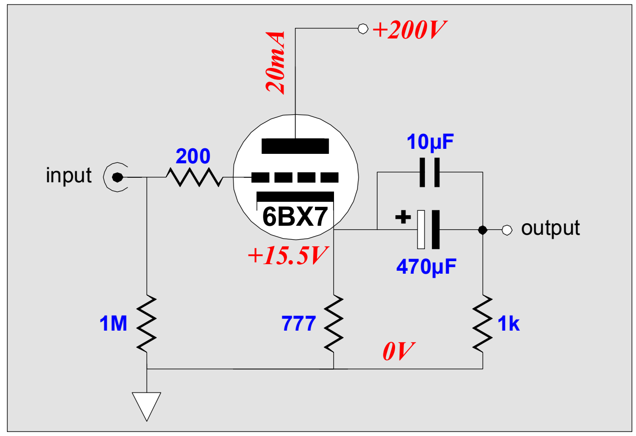
Local-Feedback Buffers

This type of buffers allows the greatest simplicity, as a local-feedback can be made from as little as one active device. The circuit below shows a single N-channel MOSFET loaded by an inductive load.



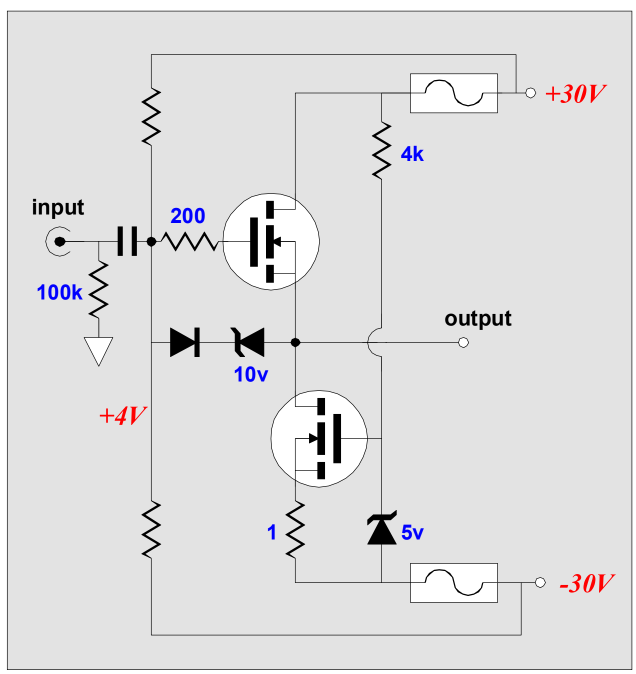
This buffer can *only* be biased in pure Class-A mode, as the inductor must be able to give up same amount of peak current into the load as the MOSFET pulls through the load during peaks. For example, if the idle current equals 2A, then the peak symmetrical output into a load impedance is 2A. Given an 8 ohm load, 2A equals 16 watts of RMS power. (The key word was "symmetrical," as the MOSFET could swing much more positive going current into the load, assuming that power supply can support the needed voltage swing.) Like all inductively loaded Class-A amplifiers, the maximum theoretical efficiency is 50%.

In actual practice, the actual efficiency will probably come in at 40-45% with solid-state devices and low DCR inductors.



No-gain triode-based headphone buffer

Using a resistive load would quarter the theoretical 50% efficiency figure (12.5%) and thus cannot be universally recommended. The exception might in the case of a pure tube low-power buffer for driving low-ohm headphones (8-32 ohms), as here we only need milliwatts of output. The circuit above shows a 6BX7 triode biased a single cathode resistor. The better approach for driving loudspeakers is to use an active constant current source, as the maximum theoretical efficiency falls to only 25%.



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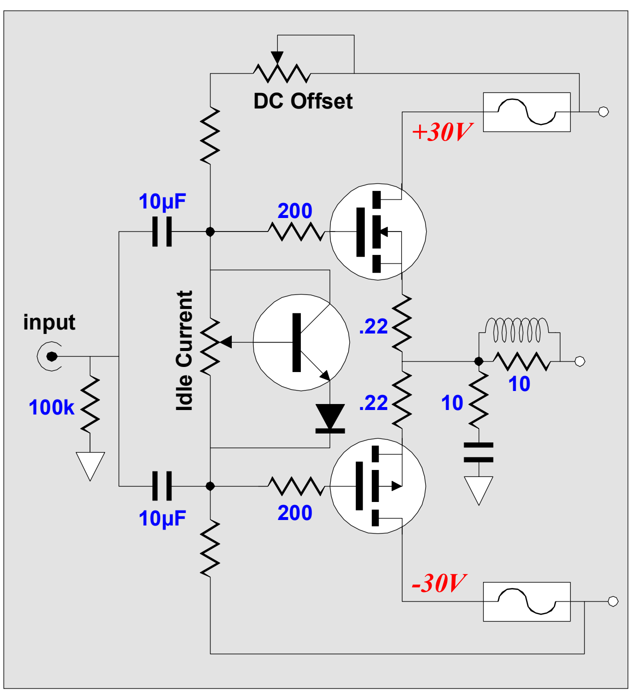
The constant current source also allows for DC coupling at the output (with a bipolar power supply). The simplest circuit topology would require only two MOSFETs. (Transistors would not work as well because of the transistor's low input impedance, which would drag down the line stage output stage.) Added features would include a DC servo loop.

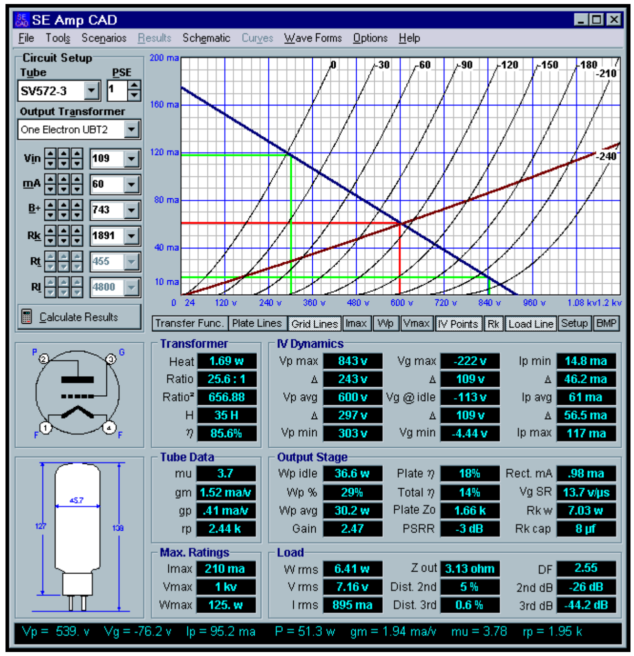
One feature, which is not optional, is a carefully designed fusing arrangement. The danger of placing the all of the biasing resistors on the amplifier side of the fuses lies with blowing a single power supply rail fuse, which would protect the output devices, but would not protect the loudspeakers, as a steady 2A current draw (from the top MOSFET or the constant current source) into loudspeaker would vaporize all but the most buffed voicecoils. Sown below is a push-pull power buffer with complimentary output MOSFETs. Should any power supply fuse, the output will remain close to ground and not slam to the opposing rail.

The downside to driving the output MOSFETs directly is the MOSFET's high input capacitance.



Push-pull buffer with an intelligent fusing topology

SE Amp CAD



Successful design and analysis of a single-ended amplifier output stage requires an accurate model of the tube's plate curves. SE Amp CAD is a tube audio design program that has a library of 30 tubes and over 100 output transformers and SE Amp CAD knows how these tubes really curve in a singled-ended amplifier.

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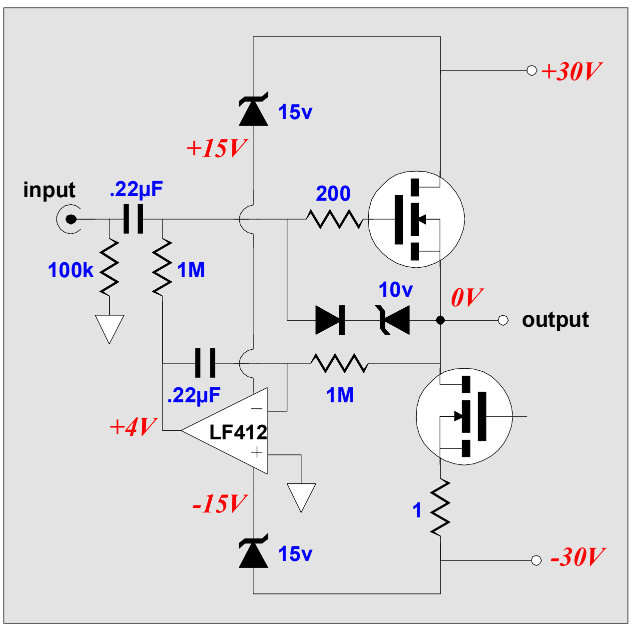
Added Complexity

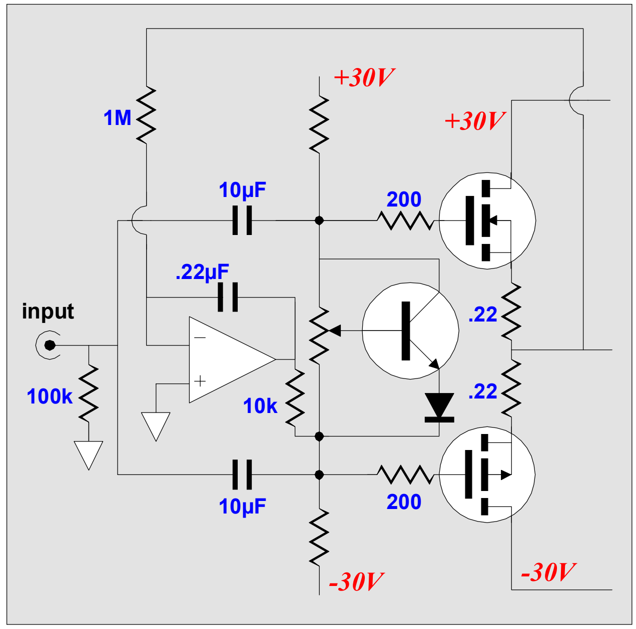
The Class-A mode of operation and the follower configuration both make the single-ended buffer amplifier a perfect candidate for adding a DC servo-loop. At all times, an IC strives to keep its positive and its negative inputs at the same voltage, which moves its output to swing positively or negatively in response.

Consequently, when the buffer's output drifts too positive the IC's negative input pin will see a greater positive voltage than the ground referenced positive input, which will provoke the IC's output to go negative until the its input once again match in DC voltage. DC is a key adjective here, as the .22µF capacitor effectively absorbs the AC part of the signal presented to the IC's negative input; if a scope's probe is attached to this juncture, all that will be seen are the frequencies below 1 Hz.



Single-ended buffer with a DC servo loop

The two 15 volt zeners are there to displace half of the 60 volts made available by the bipolar power supply, as the IC is voltage limited (a high-voltage IC would not require these zeners, but such ICs are expensive.) Basically, the Op-Amp does not need to see at its input the full output voltage swing of the buffer's output, only the few millivolts of DC offset at the output. Similarly, the Op-Amp does not need to swing anymore than a few volts positively at its output to keep the buffer's DC offset in line with ground. For example, a DC offset would likely never exceed 100 mV and the top MOSFET would at most only require 5 volts DC to set idle current to that of the bottom MOSFET.



Push-pull buffer with a DC servo loop

The next addition might be the creation of an active current source made up of the bottom MOSFET and an additional IC. In the circuit below, we see the current flowing through the 1-ohm resistor being monitored by the IC's negative input, which it will compare it to its positive input and thus work to keep the voltage across the resistor constant. A constant voltage means a constant current. The current is easily set by dividing the reference voltage by 1 ohm, thus in this example, the constant current source is set to 2.5A, which equals 25 RMS watts and 20 volts into an 8 ohm load, whereas increasing the current to 3A will increase the wattage to 36 watts and the peak output voltage to 24 volts.

This constant current source is a truly active one, with the IC *fully in the circuit*, as its feedback loop encompasses the bottom MOSFET.

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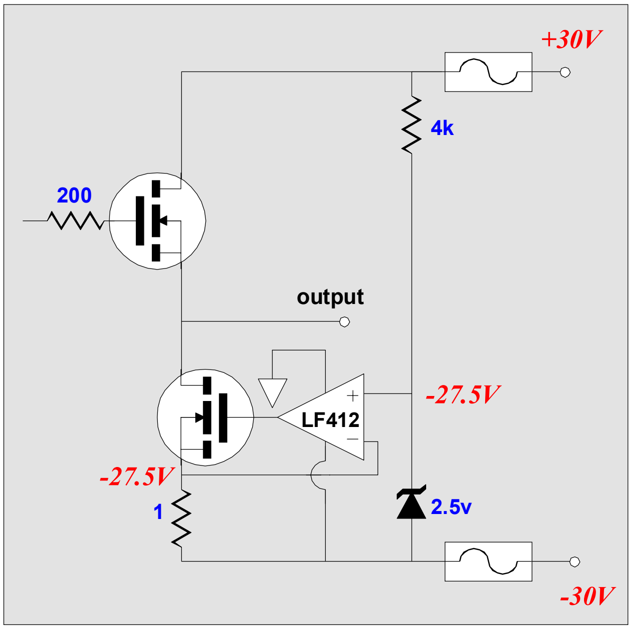
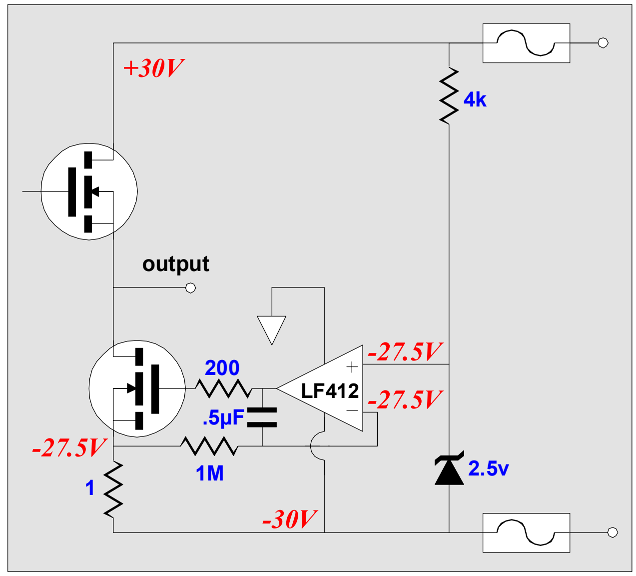


Buffer with an active constant current source

Here is a case where topological blindness can occur. If the input to the buffer had been an IC that fed and controlled the top MOSFET, many would complain that they did not want some cheap high feedback Op-Amp controlling the output. Yet if we move the same Op-Amp to the bottom of the circuit, there are no complaints. (A similar situation occurs when dealing with high-voltage regulation: few complain about an LM741 controlling a high-voltage transistor that is 100% in the signal path, although they would scream if the Op-Amp was moved to the middle or the bottom of the circuit. Very strange indeed.)

Overcoming the Op-Amp's sonic contribution is easy enough. Adding one resistor and one capacitor is all that is needed. In the following circuit, two feedback loops are made. The Op-Amp sees two feedback loops: one AC and one DC. The AC feedback loop extends from its negative input to its output. The DC feedback loop extends from its negative input to the top of the 1 ohm sensing resistor. Thus any AC signal coming from the voltage reference will be passed to the Op-Amp's output, but any AC signal from the sense resistor will be shunted away though the .5 µF capacitor, while any DC signal will be preserved.



Two Stage Buffers

The next step is to address the problem of the MOSFET's high input capacitance. High power MOSFETs carry the penalty of a large amount of capacitance from the gate to the drain, which requires a fairly heavy current to charge and discharge quickly enough to provide an adequate slew rate and a wide bandwidth. In fact, capacitance against slew rate equals current :

$$I = SR \times C.$$

The gate to source capacitance is not as much a liability, as the source will follow the gate closely, resulting in just a few volts of gate swing relative to the source. What is, in truth, an added hassle is the interconnect's capacitance, which can be substantial for long runs. So then, how do we drive all of this capacitance? Two possible solutions stand out: use a more robust line-stage amplifier; for example, one that used a 6BX7 or 2A3 as the output tube; or add a second stage to our high-power buffer.

The first approach is obvious enough, but the second approach entails a few subtleties. Adding a pre-buffer to our present circuit can take two forms, if were restrict ourselves to solid-state devices: adding a N or a P-device. (If we decide to use a vacuum tube our only choice is N-device, as that is the only flavor tubes come in.)

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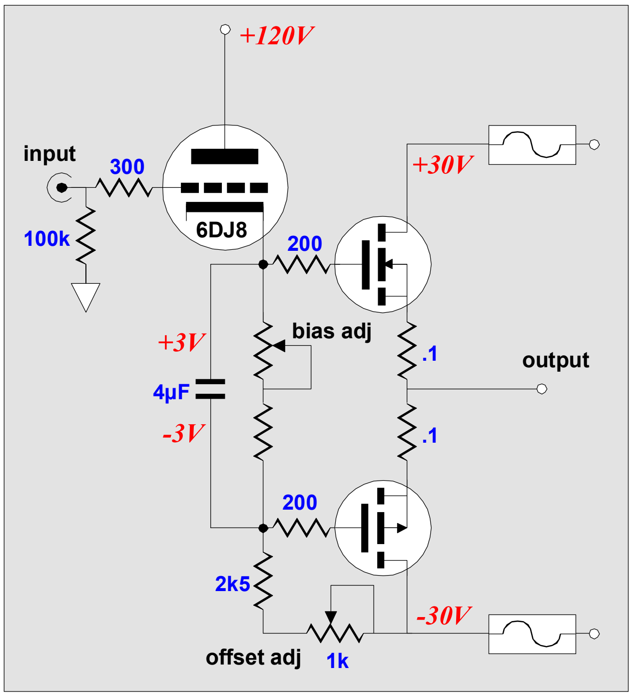
An NPN transistor or an enhancement P-channel MOSFET offer the advantage of shifting the input voltage more positive at the emitter or source, which works well with positive voltage requirements of the enhancement N-channel MOSFET used in the output stage, as its gate must be at some 1-4 volts positive voltage for its source to at 0 volts. The transistor offers a smaller, but predictable voltage shift, whereas the MOSFET offers a larger, but much less predictable voltage shift, as would a N-channel FET or, to a lesser degree, a vacuum tube.



Reader Tony's second buffer

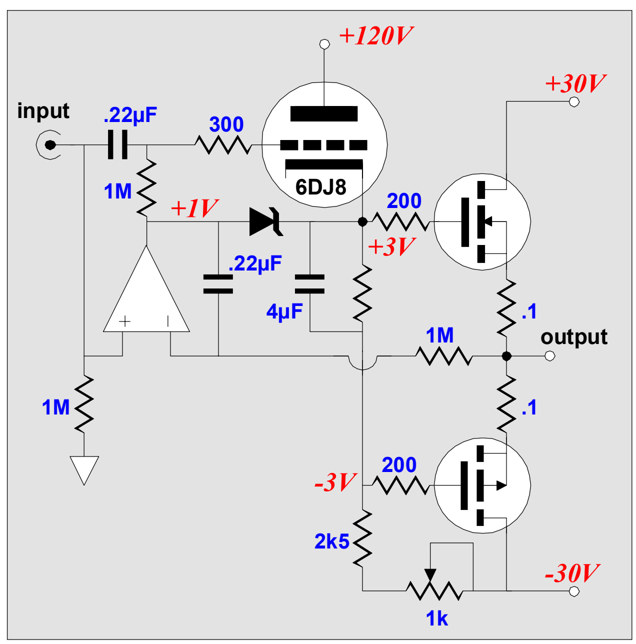
In the circuit above, reader Tony has designed a hybrid buffer that uses a triode to drive the output MOSFET's high input capacitance. The circuit differs from the last in that it need not be run in strict Class-A, as it can be run in Class-AB or even Class-B.

The fall from Class-A into Class-B will increase the output distortion, but greatly lessen the idle dissipation, allowing higher power supply voltages, with a consequent increase in output power. As an added feature, the input is DC coupled from into to output.

All in all, a very seductive circuit, except for a few major problems. The top potentiometer sets the output stage's idle current and the bottom potentiometer sets the DC offset. Unfortunately, these potentiometers do not work independently of each other, as a change in one setting will necessitate a change the other.

A more serious problem with the circuit is that it is not very safe. What happens when the tube fails or is pulled or jiggled? The answer is that the top MOSFET will be completely turned off and the bottom MOSFET will be completely turned on, which will slam the output to the bottom rail voltage and destroy the woofer's voice coil. A coupling capacitor and a DC servo-loop, when used in an alloyed solid-state buffer, eliminates the need to worry about the potential DC offsets at the output, but it only partially alleviates our worry when used with a hybrid buffer, for example when the tube is removed or jiggled while the buffer is in use. A DC servo can try to adjust all it wants, but if there is no grid for it to work into or if the heater opens, it cannot control the DC offset at the output.

One solution is to use coupling capacitors in between the tube and the MOSFETs. This modification allows the DC servo to directly control the output stage's DC offset, with or without the triode present in the circuit.



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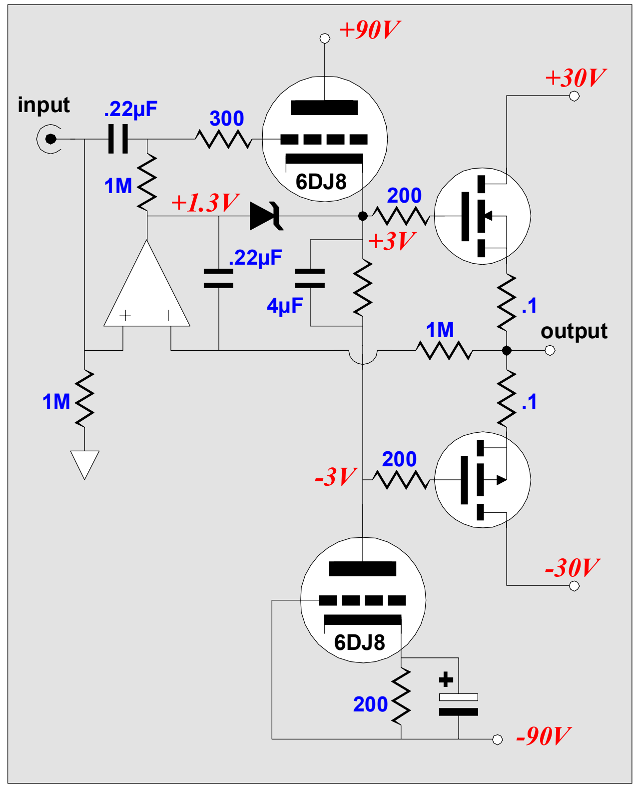
Another solution (shown right) is to modify the servo by adding a zener diode from its output to the tube's cathode and referencing the servo's input away from ground to the same input that the triode sees. So arranged, the servo offers greater protection, as even if the tube is pulled from its socket, the servo's output has a DC path to output MOSFETs' gates. This is a new servo design (as far as I know, this circuit is original and it could easily have been patented, instead it is another free idea to be used freely in an increasingly un-free intellectual and commercial environment). This circuit works on the assumption that the triode's grid never becomes more positive than the cathode under normal use. Consequently, the diode and the zener only conduct if something goes wrong. In other words, even if the triode is pulled from its socket, the servo will find a DC current path through the diodes to the output MOSFETs' gates or even if the tube becomes gassy and begins to conduct excessively, the Op-Amp can find a DC current path to the MOSFETs.

The remaining troubling issue is then the time constant set by the servo's capacitor and input resistor, which may be too slow to allow the servo to work at preventing damage to the loudspeaker. But just how often do tubes fail or pulled from their sockets or jiggled? Effectively, *something like this happens each time the buffer is turned on*, as the tube has a warm-up time before it can conduct, which will force the buffer's output negatively until the servo catches up. In other words, we should not set the transition frequency to anything below 1 Hz, as doing otherwise could damage the speakers.

A further potential problem is the added voltage swing requirement made on the Op-Amp. The Op-Amp's output must equal the buffer's input voltage swing. High-voltage Op-Amps are one possible solution. (Another solution might be to use a floating power supply for the Op-Amp. This floating power supply could then be referenced [that is its ground] to the buffer's output, which would carry the Op-Amp with the output swing.)



Additionally, replacing the tube's cathode resistor with a tube-based active resistor helps overcome the warm up problem. Given that both triodes come from the same single envelope, the odds are good that both triodes will heat up equally. Even the act of pulling the tube from its socket will be less likely to damage the loudspeaker, as the input to the output MOSFETs will float near ground potential until the servo regains control.

One interesting aside is that the bottom triode's cathode resistor should *not* be bypassed, as doing otherwise will allow power supply noise to make its way to the output. The idea here is that if the impedance that the top triode presents to the positive rail voltage equals that which the bottom triode presents to the negative rail noise, then the two will cancel out. Not bypassing the cathode resistor would greatly magnify the bottom triode's effective impedance, unbalancing the noise cancellation at the midpoint. The disadvantage to using the extra triode is the need for a high-voltage negative power supply rail and the possible exceeding of the tube's heater-to-cathode voltage ratings.

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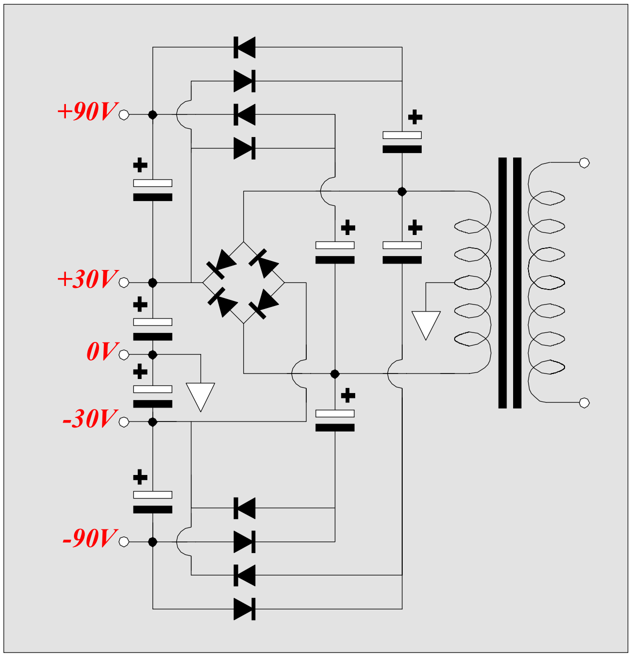

Still, this high power buffer deserves to be built and tested. Additionally, creating the high-voltage bipolar power supply is not that difficult as it can be derived from the existing low-voltage power supply. Adding four extra power supply capacitors and two more diode bridges allows the creation of new rail voltages equal to roughly three times that of the low-voltage rails. In this example, the +/-30 volts rails can also generate +/- 90-volt rails.

Solid-state Global Feedback Buffers

The MOSFET is certainly easier to drive than the transistor and potentially it offers more rugged service, with negative temperature idle current changes. Still, transistors have their advantages: they are generally much cheaper and they offer lower distortion and output impedances. If transistor are chosen, then a third stage will probably be necessary to meet the required current gain, as each transistor has a finite amount of current gain, referred to as its h_{FE} (beta). For example, if an output transistor has a h_{FE} of 100 and this device draws 3 amps of current, then its base will draw 30 mA of current. Then this 30 mA might be handled by a driver transistor also with a h_{FE} 100, which would need to draw .3 mA at its base. In turn, this .3 mA could be handled by an input transistor with the same h_{FE} of 100, which would reduce the needed input current to a mere .003 mA, a total DC current gain of 1,000,000.

(For those that use the tube exclusively, the wide tolerance variation revealed in solid-state spec sheets will prove disconcerting. I have received emails from worried readers who are tormented by a tube being 5% off the published curves. Transistors usually have +/- 300% range of actual h_{FE}.)

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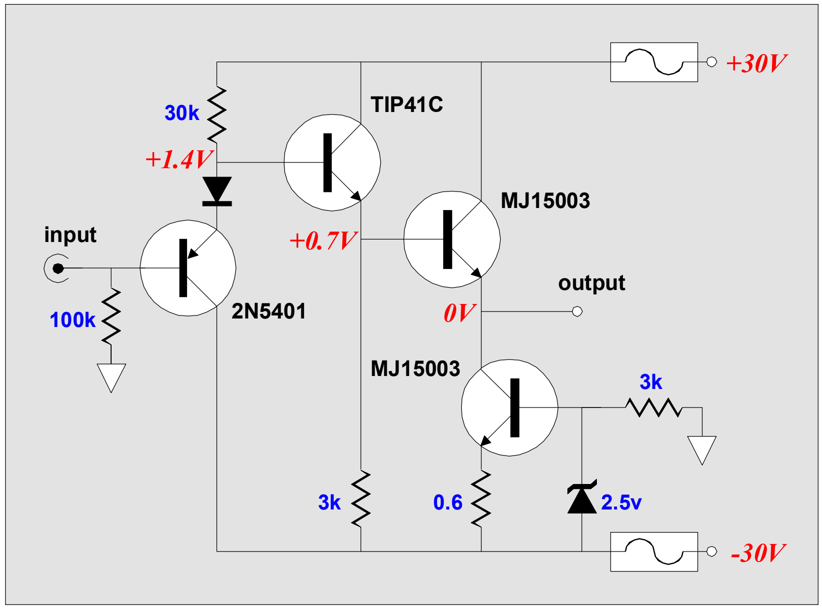
For example, the popular MJ15003 NPN power transistor lists a range of 25 to 150 for its h_{FE}. Thus, making a useable transistor-based buffer with just three transistors is difficult, given the actual potentially low h_{FE} of most transistors; with less than three transistors, it is near impossible.

All of which leads to reader Tony's first circuit: a global feedback free, completely single-ended, Class-A, three-stage buffer. This circuit's goal is to maintain DC coupling from input to output, without adding a DC offset. Will it work? Maybe.



Reader Tony's 3-stage, single-ended, Class-A buffer

Hand selecting high-h_{FE} transistors might give an adequate current gain, but a safer bet would be to add a fourth transistor. An added transistor would not only increase the final current gain, but would also eliminate the need for the first stage's diode. Each transistor has about a .7 volt drop from base to emitter. Thus, cascading PNP to NPN to PNP to NPN transistors should keep the output's DC offset inline with the input. Now, adding more stages to an amplifier is usually fraught with danger, as each stage introduces some phase lag, which in an amplifier that uses a global feedback loop potentially spells oscillation. In an amplifier that forgoes global feedback in favor of local feedback, the phase shift is of no real concern, but at the cost of dropping frequency response at the extreme high frequencies and higher output impedance.

So are we done with improving this amplifier? No, not at all. We have one large problem to face: the limited voltage swing due to the resistor loading of the three-emitter followers in series. These resistors limit the maximum voltage swing of following stage, as each proceeding stage requires an increasing input current, which must diminish with the collapsing voltage across the resistor.

One solution is to decrease the resistors' value, so as to allow for the increased current demand of the following stage. This would certainly help. However, it would also greatly increase the required current gain for the amplifier as whole and it would also greatly increase the dissipation of the transistors. Another solution would be to use a separate, higher voltage power supply for the input and driver stages. This would allow lower idle currents to be used and would increase the linearity of the emitter followers. However, it would also greatly increase the voltage breakdown requirements for the transistors.

The last solution is to actively load the emitter followers with constant current sources. This would allow a full voltage swing into the following transistor's base and it would also allow the retention of the simple bipolar power supply. (The full output swing of this Class-A amplifier is set by the output stage's idle current, as the constant current source can only deliver its set current into the loudspeaker, which in this example is 3 A, which in turn equal 24 volts and 36 RMS watts into 8 ohms. Thus the full +/- 30 volts of the power supply will not be fully utilized. Thus, the voltage lost across the constant current sources is not a concern.)

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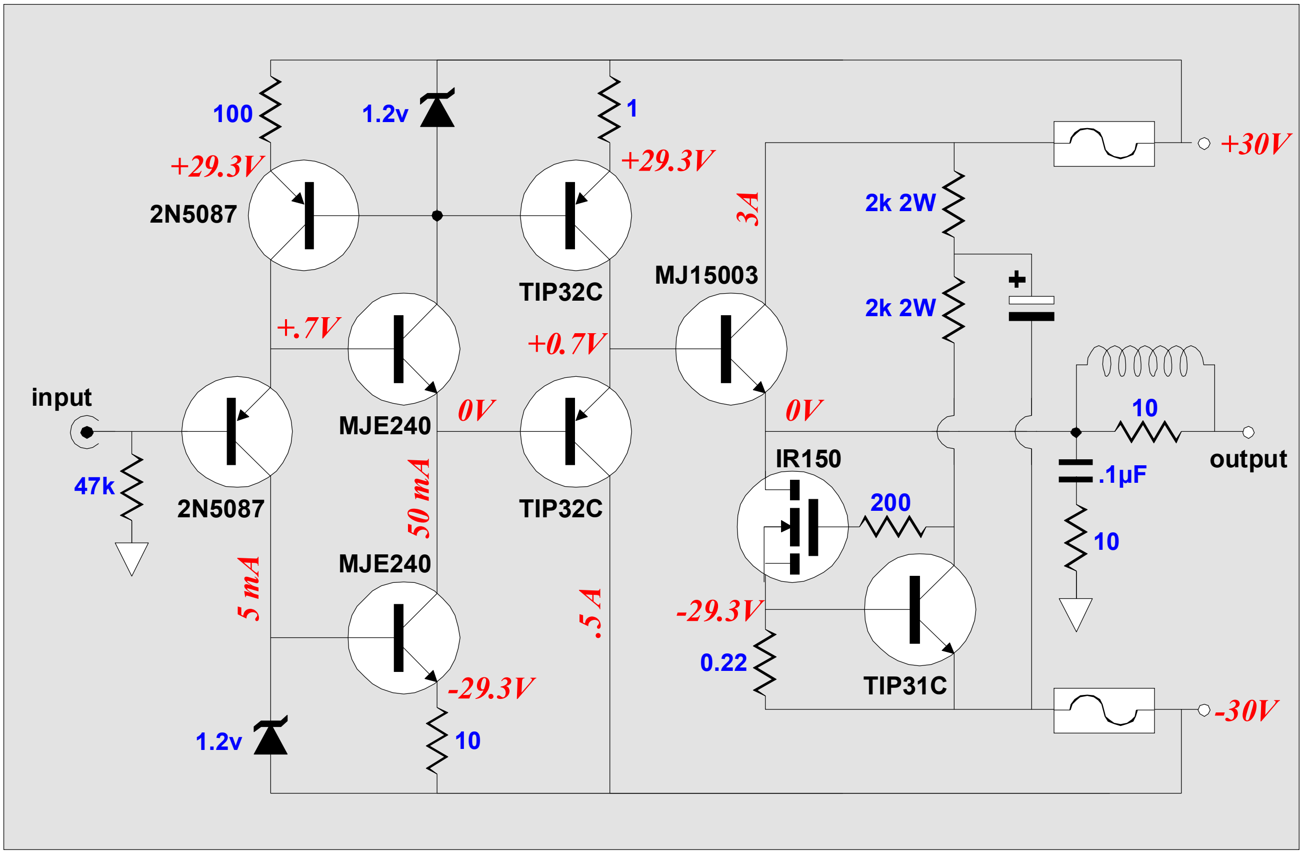

Shown above is the revised schematic. The amplifier now consists of four cascading emitter followers. Each is loaded by a constant current source and each operates in strict Class-A. The total dissipation at idle is about 214 watts (many square inches of heat sink are needed). Notice the half an ampere of idle current for the final driver stage, which equals 1 watt into an 8-ohm load. Also notice how the voltage references are placed in series with the transistor's collectors, which saves extra resistors and extra heat. Another feature worth looking into is the output stage's active constant current source. Notice how the NPN transistor has been replaced by a power MOSFET and how a transistor has replaced the voltage reference. The problem with the NPN transistor was that is required too much current into its base. The MOSFET, On the other hand, is voltage driven and easily controlled by the TIP31C. How was it possible to replace a 250-watt transistor with a 150-watt MOSFET? First of all, the current source, unlike the emitter follower, draws a constant current.

Additionally, MOSFETs do not suffer from the secondary breakdown problems that power transistors do and they are in general much more robust in actual use. For example, I would have little or no fear of running a 25 watt tube at 25 watts of continuous dissipation, nor would I have much fear of running a 150 watt MOSFET at 90 watts of continuous dissipation, but I am a quite a bit nervous about running a 250 watt transistor at 90 watts of continuous dissipation. Not all specs are equal.

So is this revised circuit perfect? No, of course not. One aspect that still troubles me is the output stage's emitter follower; I would prefer to use a MOSFET, but I realize this would ruin the low DC offset offered by the transistor. Of course, adding an input coupling capacitor and a DC servo loop would take care of any DC offsets, but for some, the DC from input to output aspect of this buffer is a key feature. (Here is one of those odd nonlinear behavior examples: I know many solid-state fans who would never dream of placing coupling

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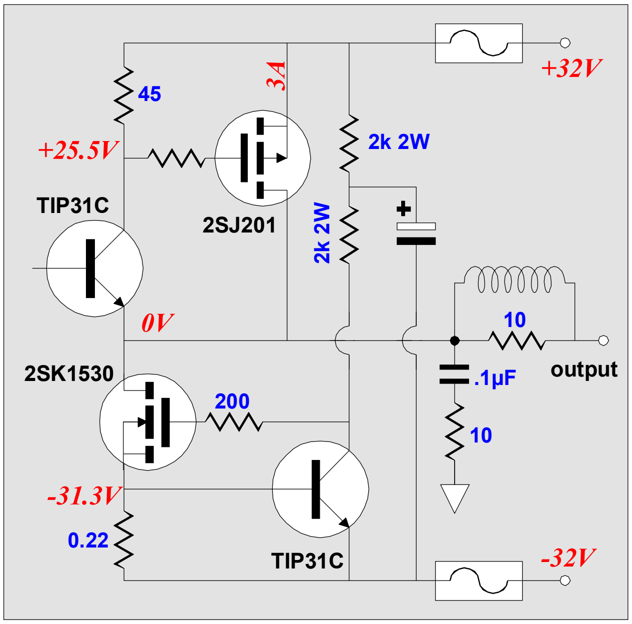
capacitor in front of their solid-state amplifiers, yet have no problem with the cheesy electrolytic capacitor that terminates the feedback loop of their amplifier. Somehow, this capacitor does not count; somehow, they imagine it is not in the signal path; it is.) The second possibility is to replace the output transistor with a transistor-MOSFET compound circuit. This would require adding a P-channel MOSFET and one resistor.



In the above circuit, a compound circuit is displayed. This topology is known for its linearity (it contains its own short feedback loop from the MOSFET's to the transistor's emitter) and some problematic switching distortion when used in a lean Class-AB or Class-B amplifier. But in this application, wherein the MOSFET is never completely turned off, this distortion does not occur. The P-channel MOSFET requires quite a bit of drive voltage, which explains the slightly increased rail voltage.

Class-AB Buffers

In spite of a few hundred pages of advertising copy, Class-A operation is brutal and not easily achieved and single-ended, constant current source loaded, Class-A operation is obscenely brutal. Thus the 99.99% prevalence of Class-AB and Class-B output stages. Yes neither class is as linear as Class-A, but given enough feedback, the amplifier will test well and sometimes even sound good. The big problem is the discontinuity at the crossover point between output devices. With transistors, increasing the idle current does not work well because of the gm doubling at the overlap of conduction.

The first
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TCJ Filter Designer lets you design a filter or crossover (passive, solid-state or tube) without having to check out thick textbooks from the library and without having to breakout the scientific calculator. This program's goal is to provide a quick and easy display not only of the frequency response, but also of the resistor and capacitor values for a passive and active filters and crossovers. Tube crossovers are a major part of this program; both buffered and unbuffered tube based filters along with mono-polar and bipolar power supply topologies are covered.

For more information, read the article "Tube-Based Crossovers" in the *Tube CAD Journal*.
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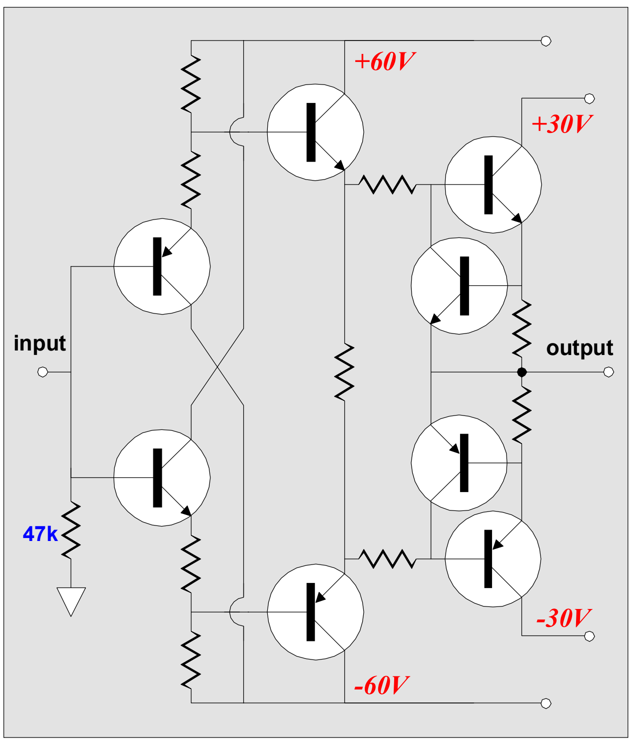
MOSFETs, on the other hand, have a much softer transition from off to on, which requires the heftier idle current of a rich Class-AB operation, say 200 mA versus the 50 mA of a transistor output stage. In other words, setting the bias to the lowest distortion point is going to be much more important in a Class-AB buffer than a Class-A buffer.

One possible buffer circuit is shown below. This buffer comprises only three current gain stages, so transistor selection is critical. Furthermore it requires two rail voltages, as the front-end circuit is not constant current source loaded. In addition, the buffer has a small insertion loss due to the voltage divider at each input transistor's emitter, which allows the output transistors to be properly biased.



This circuit includes a safety feature in the form of the two additional transistors attached to the output transistors. Should a output transistor draw too much current, its companion transistor will begin to conduct, pulling the output transistor's base back into a safe range. The value of the output transistor's emitter resistor sets the trip point, as once the voltage drop grows larger than .7 volts, the clamping starts.

Global Feedback Buffers

This type of buffer is actually just a conventional feedback amplifier with all of the gain being returned to the input stage. So can any power amplifier be turned into a global feedback buffer? No, as not all power amplifiers are unity gain stable for starters. Second, the average amplifier was designed under the assumption that the input voltage would not exceed a few volts and that, as a result, the input stage's voltage relationships would remain pretty much fixed. The current sources, the collector resistors, and the cascoding circuitry — all would see a fairly stable, fixed voltage. But when the input voltage must equal the output voltage, the whole of input stage must follow along the large voltage swings. (Here is where examining Op-Amp circuits is valuable, as Op-Amp must work in spite of huge input voltage swings. In sum, a power buffer needs to be designed from the ground up.)

Current Feedback

One circuit topology that causes much confusion is the current-feedback amplifier, marked by high speed and wide bandwidth; it achieves these results by breaking away from the normal Op-Amp ideal of ultra-high input impedance and zero input current at each of its inputs. In contrast, the current feedback amplifier has an ultra-low input impedance and zero input voltage (at least at its negative input). Returning the feedback to the input stage's emitter, rather than its base, realizes this goal and it ensures that the internal capacitances do not limit the Op-Amp's performance. The price paid for this benefit is the cost of having to drive the low impedance feedback pin. But in a power buffer application, this proves easy, as the output's output will easily drive input stage's emitters. So what is needed to make a current-feedback power buffer? First of all, we cannot use a conventional differential input stage, as its negative input is of the high impedance sort. Instead, we must try to drive emitters of the input stage as a negative feedback entry point.

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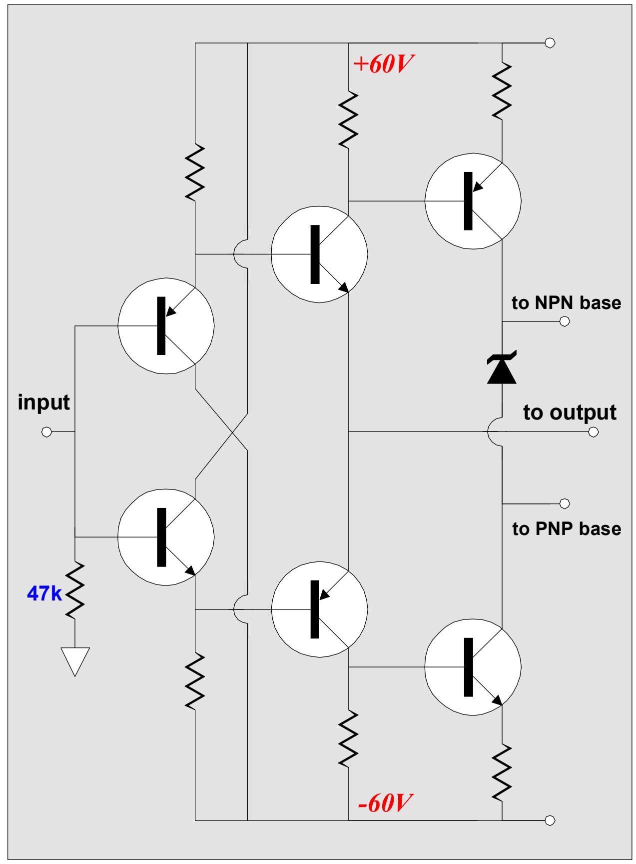
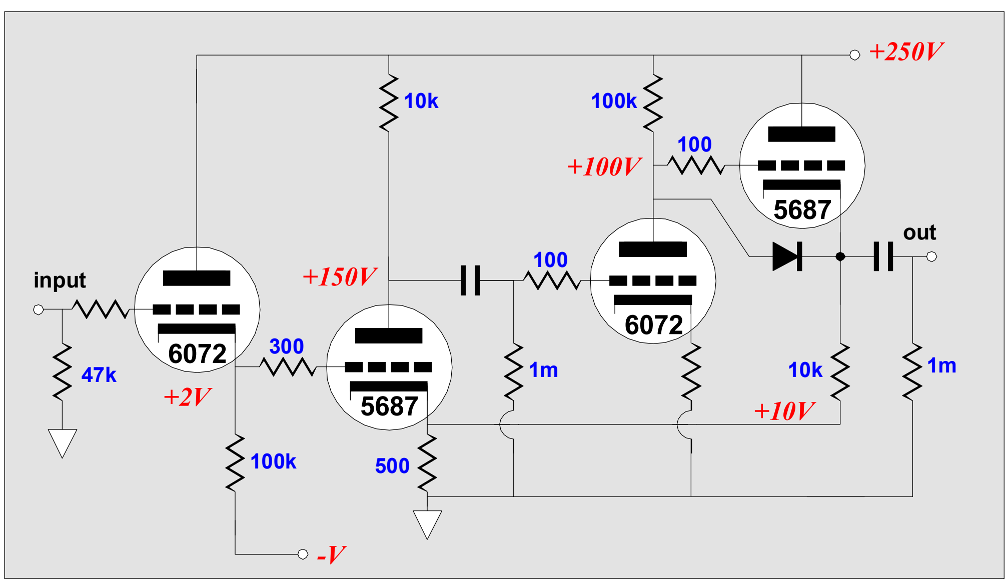


The circuit at the right shows a simple current-feedback power buffer. The input transistors provide some current gain and some voltage shifting for the following transistors, which can be regarded as making up the true input stage, as they are in charge of controlling the output. The emitters monitor the output and any deviation from the input will provoke a countervailing swing of the output stage's output. The following pair of transistors provide more voltage and current gain to drive the output transistors or MOSFETs. They also perform the needed phase inversion to bring the output in phase with the input.

Translating the current feedback topology into vacuum tubes is a topic I do not think you will see in rec.tubes (or anywhere else). In the circuit below, the aims of current feedback have been achieved. The distortion is low and the bandwidth wide. The input cathode follower presents little capacitance to bog down the attenuator's output impedance. The 5687 input triode's high idle current easily cuts through the 6072 grounded-cathode amplifier's Miller effect capacitance. Lastly, the 5687-based cathode follower yields a low output impedance capable of driving severe loads and the feedback loop.

Some are wondering why the tubes are in the wrong order. Why isn't the order: 6072, 6072, 5687, 5687? While such an order appeals to our sense of ever increasing strength, it does not provide as great a bandwidth, as the 6072's high output impedance and low idle current cannot drive a 5687-based grounded-cathode amplifier as far as the reverse order. (Some tube designers like to move from the smallest tube to the largest, with zero thought to the consequences.)

Current-feedback amplifier that uses tubes. Definitely not your fathers line stage.



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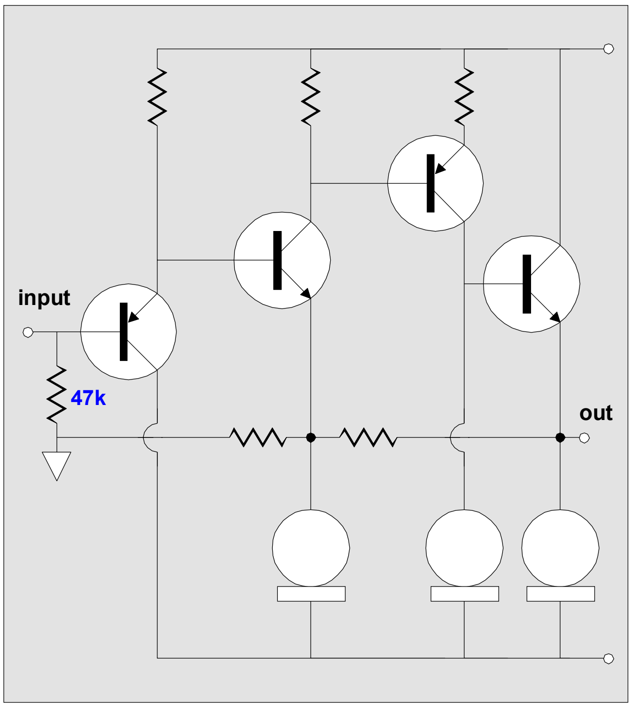
But doesn't this current feedback circuit look like some preexisting tube circuits? Indeed it does, as a single triode makes a very poor Op-Amp. The key difference is that this circuit was designed with current feedback operation in mind, which lent a focus and direction that is usually missing in tube designs.

The circuit below illustrates the transistor equivalent topology. It too is single-ended throughout. (The push-pull version was actually given in a previous schematic.)



Transistor-based current-feedback amplifier

Hybrid Power Buffer

For those few tube fans who haven't in disgust stop reading after the first mention of transistors, here is your reward: a tube front-end hybrid power buffer that can be run in Class-AB or Class-A. As shown at the right, the triode's own cathode bias voltage sets the bias for the top MOSFET. The potentiometer sets the DC offset. Only N-channel MOSFET are needed, which is a blessing in that are no *true* matched sets of P-channel and N-channel MOSFETs available, whereas matching two N-channel devices is easy. Ultimately, the DC coupling of the cathode to gate is probably not a good idea, as a coupling capacitor would provide a safer operation.

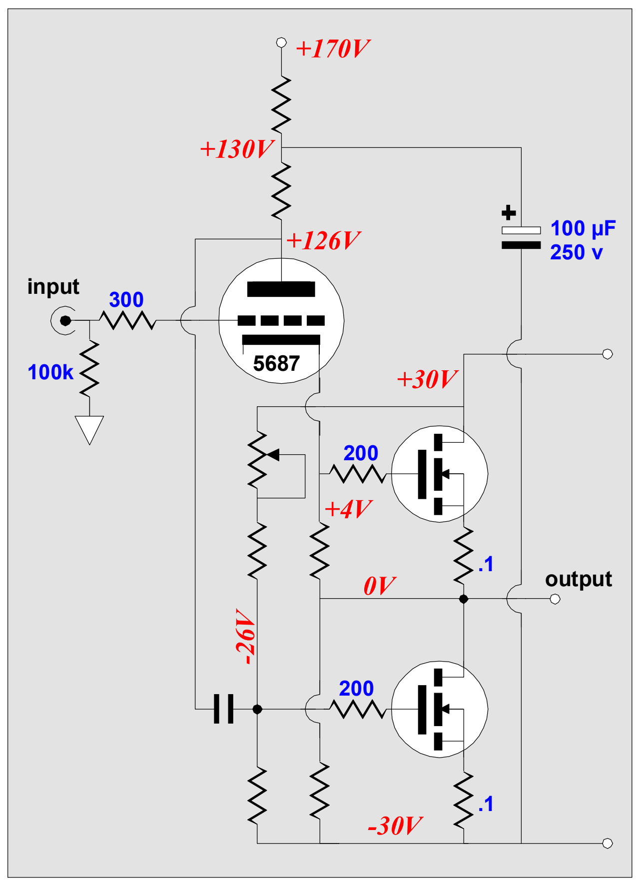
But adding both the capacitor and the necessary biasing resistors would tend obscure the operating principles in an already complicated circuit. (In fact, the MOSFETs could be replaced by many EL509s, if sufficient drive voltage is available and the input tube's cathode is raised by 50 volts.)

Tony, I hope this proves useful. For the rest of our readers, please send in your views on including pure solid-state circuitry.

//JRB

More Information

To learn more about current-feedback amplifiers, search out issues 30-3 and 30-4 of *Analog Dialogue*, wherein writer Erik Barnes does a beautiful job of explicating current feedback. (Tony, this means you.)



Hybrid buffer

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