MU STAGE PHILOSOPHY

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"Mu-mode" gain stages are not new. What is relatively unique is the use of a pentode cathode follower (CF) or MOSFET source follower (SF) as the upper device of a series amplifier gain stage. The purpose in having a pentode CF up top rather than a triode CF is not to achieve better numbers (though a pentode CF or a MOSFET SF can achieve better numbers), but rather to achieve better sound by giving the bottom tube, a triode voltage amplifier, the highest possible load impedance as explained in the Mu Stage article. if the bottom tube is loaded by the highest impedance obtainable, the bottom tube will have maximum SONIC freedom to do whatever it wants, no however how subtle. Thus every nuance, every detail of the music is accurately reproduced.

When used as current amplifiers rather than as voltage amplifiers, that is, when used as CF's and SF's, pentodes and MOSFETs become very accurate. The transconductance (gm) of a pentode stage remains relatively constant despite changes in plate4o-athode voltage. This is highly desirable for a CF and contributes to the excellent sonic accuracy of the pentode CF. A power MOSFET maintains an even more constant gm which similarly benefits the MOSFET SF.

When the upper device is a MOSFET SF, additional important parameters are much improved, such as Z out and maximum voltage swing. plus of course the added advantage of no filament for the upper device.)

Another advantage is the Power Supply Rejection -SR), which is the ability of a circuit to be unaffected by power supply noise and variations. PSR is outstanding with a pentode CF and better yet with a MOSFET SF. This is helpful when the power supply is unregulated. The PSR of a MOSFET is so great that the only advantage in regulating its power supply would be to benefit other circuits being powered by the same supply.

In the highly regarded Valley and Wallman book VACUUM TUBE AMPLIFIERS it is stated that pentode CF's have good linearity. This is confirmed by measurements and listening tests. The MOSFET SF has likewise proven to be a very accurate follower. These are the reasons we use pentode CF's and MOSFET SF's in our Mu Stages.

Triodes make the most accurate voltage amplifiers, especially when loaded by the highest possible impedance. Pentodes and MOSFETs make the best current amplifiers Using each device to do what it does best results in superb sonic accuracy.

I have been interested in audio gain stages that have an active plate resistor ever since I first heard such a circuit. Right away, I knew they were some-thing special. Over the years I have sought to optimize this type of circuit, and this article outlines many of the things I learned.

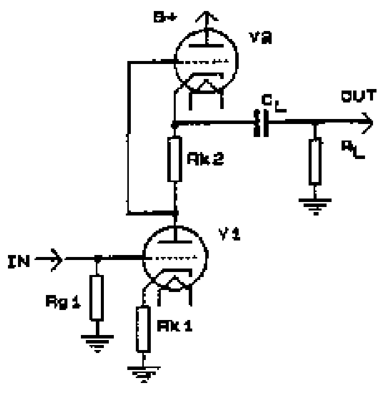


FIGURE 1: TTSA/SRPP.

The simplest example of a stage with an active plate resistor is the familiar circuit of Fig. I. This circuit is called by names such as TTSA (two-tube series amplifier), and SRPP (shunt-regulated push-pull). V1 and V2 are identical types, and Rk1 and Rk2 are the same value to keep the quiescent plate voltage of V1 at about half the B+ voltage. V1 is the voltage amplifier, and V2 functions as the active plate resistor for V1 by sensing the volt-age dropped across Rk2.

When the input signal to VI's grid goes positive, V1 conducts harder and the voltage drop across Rk2 is increased, which in turn causes V2 to conduct less. When the signal at V1's grid goes negative, V1 conducts less and the voltage drop across Rk2 is decreased, which causes V2 to conduct harder. Overall, this circuit attempts to maintain a net current change of zero, a state otherwise known as constant current.

Is It A C.C.S?

Why would we want constant current operation in the first place? Old electronics textbooks state that the higher the load impedance of a ton gain stage, the more linear the gain stage will be. Well then, the ideal load impedance for a triode would be infinitely high. An open circuit is infinitely high. But we can t use an open circuit for our triode's plate resistor because the triode couldn't work if it had no current at all.

We have a dilemma here. What we need is a plate resistor which can supply V1 with the current it needs to operate, and at the same time produce (ideally) the impedance of an open circuit. It just so happens that the ideal constant-current source has an infinite impedance.

Therefore, we want to supply our triode V1 with current that is as constant as possible. That way, VI gets the current to operate while at the same time it sees the highest possible load impedance. And if V1 sees the highest possible load impedance, it can operate in the most linear manner

In the past, at least one well known manufacturer has claimed that V2 (Fig I) is a constant-current source (C.C.S). But is it truly a C.C.S? An easy way to test a stage for constant-current operation is to temporarily place a small 100uF electrolytic capacitor across Kr1. If V2 is a true C.C.S, very little or no change in gain will occur. When this is done to Fig. 1, V2 fails the test. It doesn't even come close to being constant. At best, it might be "semi-constant."

Voltage Swings

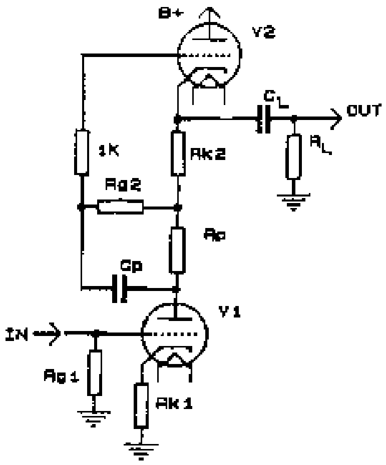


FIGURE 2: Mu follower.

The reason V2 cannot deliver constant current is because it hasn't enough gain to respond adequately to the small voltage changes which occur across Rk2. We have two options for solving this problem: (a) add a large resistor in series with Rk2 to provide V2 with more signal, or (b)) drastically increase the gain of V2.

The first solution is another circuit familiar to the readers of GA, the "MuFollower" (Fig 2). Again, V1 and V2 are identical and Rk1 and Rk2 are the same value, causing the same amount of volt-age to be dropped across both tubes. Resistor RP is much larger than Rk2 and is now in series with Rk2, thus V2 will see a larger signal than it could in the TTSA/SRPP stage. The Mu Follower is a real step forward. It approaches true constant-current operation and is a big improvement over Fig. 1

Figure 2, however, has some important limitations. Due to the relatively large DC voltage that is dropped across Rp, Fig. 2's maximum output voltage swing is limited. This may not be a problem in devices such as preamps, where the Signals are never very large, but if the application involves large voltage swings (such as occur in power amps), we could have trouble. About the only way to increase Fig. 2's output voltage swing is to use a higher B+.

The second solution above is easily accomplished by making V2 a pentode (Fig. 3). Now V2 has enough gain to adequately respond to the small signal which occurs across Rk2, and no large Rp resistor is dropping a lot of DC voltage. In this circuit, Rk1 and Rk2 will probably not be the same value. You can think of Fig. 3 as a modified TSA/SRPP, one which uses a pentode for the upper tube. Unlike the all-triode TTSA/SRPP of Fig. I, the circuit of Fig. 3 approaches true constant-current operation. If you are a triode enthusiast, please don't tune me out. In all of this article's circuits Vl. the voltage amplifier, is a triode.

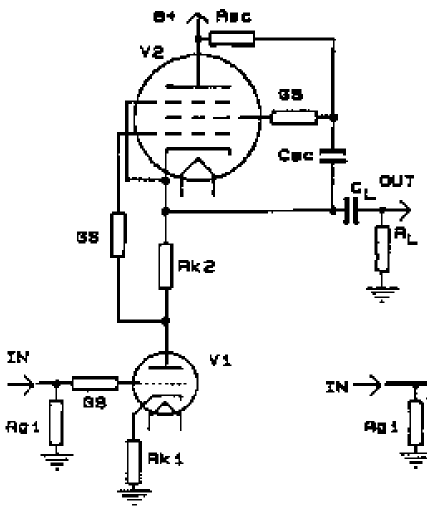


FIGURE 3: Modified TTSA/SRPP.

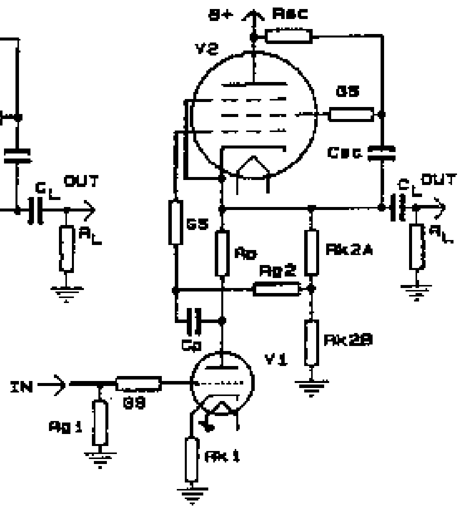


FIGURE 4: The Mu Stage.

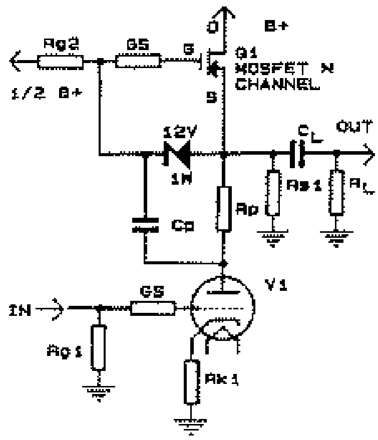


FIGURE 5: Hybrid Mu Stage.

Pentode Possibilities

All my designs/diagrams include grid stopper (GS) resistors in series with each grid, beginning with Fig. 3. It is good practice to use GS resistors in all audio circuits to suppress parasitics. A 150 value on line amp and driver tubes produces good results.

Although it's not a new idea, wing a pentode for the upper tube has been largely ignored. But I find that it produces excellent results. Properly utilized, pentodes are capable of extremely transparent sound reproduction. The Futterman amplifiers use nothing but pentodes.

The circuitry of V2 in Fig. 3 will look familiar to some readers. It has been used with power pentodes to make "single-ended push/pull" power output stages. To my knowledge, though, no one has actually implemented the same technique with preamp, line amp, or driver wbc circuits. To do so can yield excellent performance; indeed, I think you can get greater benefits by using this technique with preamp, line amp, and driver tube circuits than when you apply it to a power output stage.

Are CFSs Poor?

But we should not stop at Fig. 3. Still more improved performance is obtained from Fig. 4, which is the circuit this article is all about. It Is possible to make the gain of Fig. 4 closer to the mu of VI than it is in any of the previous circuits, which would indicate that VI is getting a more constant current.

Also, the circuit of Fig. 4 has a lower output impedance than any of the previous circuits, since V2 now has a separate cathode resistance (Rk2A + Rk2B, or simply Rk2) to ground. It is possible to add a grounded cathode resistor to V2 in Fig. 3, but Fig. 4 would still be better because Fig. 4 has resistor Rp. But now Rp can be a much smaller value than it is in Fig. 2. One reason for Rp in Fig. 4 is so V2 can receive a some-what larger signal than the V2 of Fig. 3. Besides helping to reduce the output impedance, this helps provide the most constant Current. However, we don't want Rp's value to be very large, since we don't want too much DC voltage dropped across Rp, which would limit the maximum output voltage swing. V2 is a cathode follower (CF). One of the latest fads is to criticize CFs, but some of the finest high-end audio equipment ever made use CFs. A well-designed CF is capable of superb performance. A cathode follower is not a voltage amplifier. Rather, it can be considered a current amplifier having a very high input impedance. By the term "current amplifier," I mean that the CF is capable of supplying a lot of current to the load.

The Tri-Pent Mu

While I'm talking about cathode followers, I believe pentode CFs deserve serious consideration. A pentode CF has several advantages over triode CFs, including lower input capacitance, larger voltage swing, lower output impedance. and lower attenuation. I think pentodes are better suited for CF service than for any other use.

Although pentodes make the best CFs, the bottom tube, V1, should be a triode because operating a triode at constant current allows it to reach maximum linearity. If you made V1 a pentode, you would have excessively high voltage gain. And while someone might think of exploiting that to build a phono preamp, keep in mind that a pentode pre amplifier could be less linear if operated at constant current. For best results, keep V1 a triode and V2 a pentode.

For lack of a better name, I call Fig. 4 a "Mu Stage" because its gain is very close to the mu of V1. A simple defmition of mu is the voltage gain a tube has when operated at constant current.

The Mu Stage uses bootstrapping to ahhieve constant current. Bootstrapping causes a particular resistor to attain an AC, or dynamic, resistance much larger than its ohmic resistance. This resistor lifts itself (in value), you might say, by its own bootstraps. Rp is the resistor being bootstrapped. This bootstrapping is accomplished by cathode follower V2.

Booting Data

Let's say a signal is being fed into the circult. The signal will appear at V1s plate (the lower end of Rp). That same signal is also coupled to our very faithful pentode CF. The CF's output, in turn, is coupled to the upper end of Rp. This causes the upper end of Rp to follow its lower end, and the voltage across Rp is hardly changing at all. Therefore, you have a constant voltage across a constant resistance. A constant voltage divided by a constant resistance equals a constant current. And although no one can make a perfect CC - that is, one that is 100% constant, we can come very close.

The amount of bootstrapping (and thus the dynamic value of Rp) is determined by the voltage gain of the CF as given by this formula:

$$\text{Dynamic value of Rp} = \frac{\text{Ohmic value of Rp}}{1 - Av(CF)}$$

Where

Rp =
the resistor being bootstrapped

Av(CF) =
the voltage gain of the cathode follower

If the cathode follower is a triode, a typical value for Av(CF) is 0.9. Let's say Rp is a 6.8- resistor. Plugging everything into the formula, we get 6.8k divided by 0.1 = 68k, a tenfold increase. Thus 68k is the dynamic value of Rp. Not very impressive, but the picture changes when we use a pentode cathode follower. For a pentode cathode follower, Av(CF) could be 0.995 (or even higher in some cases).

Plugging this into the bootstrap formula, we would get 6.8k divided by .005 = 1.36M, the new dynamic value of Rp. That's 200 times higher than 6.8k (20 times higher than the triode CF could raise Rp). The closer the CF gain is to unity, the more it can multiply the value of Rp. in fact, if the CF gain were exactly one, there would be virtually no limit on its ability to multiply the value of Rp. Thus, a pentode CF can provide a more constant current than a triode type.

Possible Pentodes

You might say, "Why not just give V1 a fixed plate resistor of 1.3M and omit V2?" Several penalties result from that approach. For example, VI would operate at a very low current, meaning that besides having a very high output impedance, it would have a rather limited bandwidth. Raising its current to a suitable value would require a very high B+. Since V1 will have a very high output impedance, you would have to couple it to a CF anyway, so why not use the method shown here? Besides, if in the above example the ohmic value of Rp was considerably more than 6.8k (say, 22k), we would have an equivalent resistance several times larger than 1.36M with the pentode CF.

To build a Mu Stage, first choose a triode for V1 that has a mu equal to the voltage gain you desire. I recommend the 12AX7, 6SL7, 6DJ8, or 6SN7. Next, choose a high transconductance pentode for V2 having current ratings greater than the triode's. Remember V2 will be operating at higher current than V1 due to V2's separate cathode resistor.) For pentode V2, I suggest the 6JC6. 6888, 12B-, or l2G-. You can use a triodepentode tube for both V1 and V2, but it maybe difficult to find one of these having a high transconductance pentode. The next step is to set up V2. To be of significant benefit, Rk2B should carry at least half of V2's current- Rk2B will have the largest power rating of all the resistors in the Mu Stage.

Speaking of power ratings, all resistors, in these or any other circuits, should he rated at least 4 times the power they will dissipate.

Screens, Plates & Ohms

The DC voltage across Rk2B will be about half the B +. We want to choose Rk2B's value so V2 is operated conservatively, keeping in mind that V2 handles not only the current through Rk2, but also V1's current.

Rk2A sets V2's bias. Rsc sets V2's screen grid (grid #2) voltage and current. The values of Rk2A, Rk2B, and Rsc are interdependent. if you lncrease or decrease any one of them, you must increase decrease the other two. in all these circuits we want the DC voltage across each tube to be approximately half the B + voltage. This will result if Rk2A and Rsc are adjusted properly.

Rsc's value must be small enough to adequately supply the pentode's screen grid, but not so small that It runs the screen too hot. if you know the screen voltage and current, you can compute the screen dissipation in watts (watts = volts x amperes). To measure screen voltage, connect a DVM from the cathode of V2 to the screen. The screen volt-age will be significandy less than the plate voltage. To measure the screen current, check the DC voltage across Rsc and use Ohm's Law to compute the current. (The screen current of most pentodes is supposed to be about 23% of the cathode current.)

Get Resistors Right

We must also compute V2's plate dissipation (wattage), which we can do if we know the plate voltage and current. V2's plate voltage is measured from the cathode of V2 to the plate. Pentode plate current is cathode current minus screen current. In the Mu Stage, V2's plate current is V1's current plus the current through Rk2 minus the screen current. I recommend that you stay within 25% of V2's maximum plate and screen dissipation ratings.

Csc should be chosen so its capacitive reactance Xc) at 10Hz is no more than one-tenth the value of Rsc. The voltage rating of Csc must be at least equal to the B + voltage due to the fact that if your B + comes up before the tubes warm up, Csc will see the full B + voltage. Rg2's value should be the maximum cathode-bias value specified by the tube manual for the pentode that you use for V2-typically, l-2M.

Rp's value is not critical; it can be from about 3k - up to several tens of kilohms. When V1 is a low current triode (12AX7, 65L7, and so on), use higher values for Rp. When VI is a higher-current triode such as the 12AX7, 6DJ8, 65- group, you can use low to high values for Rp. For example, if V1 is a 12AX7 or 65L7, Rp could be up to 33k). if V1 is a 12AU7, 6DJ8, or 65N", Rp could be as low as 3k or as high as 22k.

Ideally, the higher the value of Rp, the higher the B + should be. in any case, it is best to use the largest value that does not create any noticeable limit on the maximum output voltage swing. A useful rule of thumb would be to limit Rp's value so that no more than 10% of the total B+ voltage is dropped across Rp.

Correct Current

Rk1 sets V1's bias and thus determines the amount of current through VI, The DC voltage across Rk 1, which is V1's bias voltage, should be a little larger than the peak signal voltage that V1's input will see. However, it is unlikely this will ever be a problem. The Mu Stage handles large signals well.

We can compute V1's plate dissipation if we know V1's plate voltage and current. V1's plate voltage is, of course, the voltage from v1's cathode to the plate; it should be about half the B +. (When measuring v1's plate voltage, connect the DVM from ground to V1's plate, rather than from the cathode to the plate. This precaution will prevent any positive feedback from v1's plate to its cathode v1a the DVM leads.) To measure the current through v1, measure the DC voltage across RIc 1 and use Ohm's Law to compute the current. I recommend that you operate V1 within 25% of its maximum plate dissipation rating.

Impedance Input

I offer these general guidelines for achieving the lowest possible output impedance: The lower the plate resistance of v1, the lower the output impedance. The higher the transconductance (gm) of V2, the lower the output impedance.

Resistor Rp affects output impedance. Increasing Rp's value decreases the output impedance, and vice versa. Again, don't make this resistor's value so large that it begins to noticeably limit the maximum output voltage swing.

The greater the current through V2, the lower the output impedance. Reducing Rk2's value will increase V2's current. To reduce Rk2's value, reduce the values of Rk2A, Rk2B, and Rsc.

To reduce the output impedance further, youc an bypass Rk1 with a capacitor (Ck1). This will have minimal effect on the gain. Make Ck1 1kuf. A 16V voltage rating will usually be adequate. Use a high quality electrolytic capacitor (high frequency, low ESR, such as Pansonic's HF and HFS electrolytics available from DigiKey). Bypassing Rk1 may result in some slight sonic penalty.

An alternative to bypassing Rk 1 is to eliminate Rk1 by supplying fixed bias to v1's grid. To do so, connect v1's cathode straight to ground. insert a coupling capacitor in series with the input to v1, ahead of Rgi. Disconnect the grounded end of Rg 1 and connect it to a very stable negative voltage source of a few volts, more or less, depending on how much current you desire through v1. To measure the current through v1 without Rk 1, you must measure the DC voltage across Rp and use Ohm's Law to compute the current through Rp, which is the current flowing through v1.

Increasing the current through v1 by decreasing the value of Rk1 (and thus v1's bias voltage) will also reduce the output impedance.

Another way to reduce the output impedance is to parallel two identical triodes for v1. To parallel two triodes, connect plate to plate, grid to grid, and cathode to cathode; also, reduce Rk1's value to half the value for one triode.

Since V2 gets all of v1's current, any increased current through v1 will be passed on to V2. You may need to decrease the values of Rk2a and Rsc to move the voltage across V2 back to what it was - half the B +.

Any increased current through v1 will also increase the DC voltage drop across Rp. The drop will most likely not be enough to matter. In the unlikely event it does, reduce the value of Rp accordingly.

Ranking Rules

When you have finished your Mu Stage, check to see whether the voltage at V2's cathode is about half the B +. Also, see whether you have stayed within the recommended 25% of the maximum power ratings of the tubes.

All the above methods for reducing the output impedance will be necessary only if you wish very low output impedance. In most cases, it will not be necessary to implement all of them; try the easiest ones first.

Low output impedance is advantageous, but it isn't everything. There's no need to get the output impedance much lower than your application requires. As long as V2 is a high-transconductance pentode, the output impedance will be low enough for most needs. Regardless, you should stay well within the tubes' ratings.

The output impedance is more accurately measured than calculated, so use a DVM for voltage measurements and a sine wave of 1kHz. First, set the output voltage of the circuit to just under 2V with no load. (The DVM loading is negligible.) Note exactly the unloaded output voltage you have settled upon. For the highest accuracy, use the range that allows your DVM to show all of its dig-its. if your DVM ranges are 0.2V, 2V, 20V, 200V, and so on, use the 2V range; if they're 0.3V, 3V, 30V, 300V, and so on, use the 3V range.

Driving Intereleectrode Stuff

Next, connect a load resistor, say 15k, which causes a maximum of 10% reduction in the output voltage. Note exactly what that voltage reading is. The universal formula for measuring output impedance Is:

$$\left[\frac{\text{Load Resistance} \times \text{Unloaded Output Voltage}}{\text{Loaded Output Voltage}}\right] - \text{Load Resistance}$$

Any discussion of output impedance should include the special considerations regarding output capacitor CL. If a very low output impedance is required across the entire audio spectrum, capacitor CL becomes a problem (regardless of whether it is a Mu Stage or any other kind of stage). if a stage has an output impedance of a few hundred ohms or less, then CL must be prohibitively large (and electrolytic) to couple such a low output impedance down to 15 or 20Hz. Thus, the primary limitations on output impedance will be the size, cost, and quality of CL. Also, charging and discharging such a high-value capacitor through the typical grid resistor of the following rube takes a long time.

Unless you must use the stage to drive a very low impedance, the major advantage of a very low output impedance is its abIlIty to easily drive the interelectrode capacitances of the following tube or circuit at the highest frequencies; a large value CL is not required for that. CL should be chosen so its capacitive reactance, Xc, at 10Hz is no more than one-tenth the value of the load (RL). It should not be necessary to make CL larger than 3uF, and most readers won't need even that much.

Filtering & Hybrids

The B + supply to screen resistor Rsc should he well-filtered. One method which works well is to tap off of V2's plate supply with an additional stage of RC filtering for Rsc's B +. A suggested value for the RC filter resistor is about 5% of Rsc's value. A suggested value for the RC filter capacitor is about 25% that of V2's plate supply filter capacitor. Or you can simply connect Rsc and the plate of V2 to the same supply point as long as you have a well filtered power supply. Although It Is not necessary to use a regulated power supply with the Mu Stage, if you do, you can connect Rsc and the plate of V2 to the same supply point (or, you can regulate the B + to Rsc).

Do not forget that the voltage rating of Csc must be at least equal to the B + voltage.

Before leaving Fig 4, I'll just add that V2 can be a triode if you prefer, but doing so will impose Fig. 2's limitations, except that an all-triode version of Fig. 4 will have a lower output impedance than Fig. 2 due to the separate cathode resistance to ground.

If you are interested in hybrid designs, you can construct a good hybrid driver stage or line amp by replacing V2 of Fig 4 with an N-channel power MOSFET, as in Fig. 5. Besides the obvious advantages of no screen and no filament voltages, a MOSFET also offers a still lower out-put impedance.

MOS Matters

Since MOSFETs have even higher gain than pentodes, they can multiply resistor Rp's value incredibly high. Therefore, a smaller value of Rp can he used-typically, one-tenth of what Rp would he with a pentode. With a MOSFET sourcefollower (SF), I recornmend values for Rp of 680-7.5k), depending on the current ratings of triode V1. Again, the value of Rp is not critical. The rule of thumb is higher values of Rp for low-current triodes, and low to high values of Rp for high current triodes.

Because most MOSFETs are enhancement-mode types and cannot be self biased, we must supply fixed bias to it. This does not compromise the performance in any way. We want the MOSFET's source terminal lobe at about half the B +; therefore, our fxed bias must also be half the B+. We can derive this bias voltage by using a simple voltage divider of two equal-value (say, 220k)) resistors in series. Connect one end of the voltage divider to B + and the other end to ground with a l-5uF capacitor across the lower resistor.

The junction of the two resistors will be the fixed bias supply point to which gate resistor Rg2 will he connected. This simple aarangement has given excellent results. However, if you do not want a voltage divider, you can use a zener string for Qi's fixed bias voltage source. Operate zeners at about 20% of their maximum current rating and use a 1OuF capacitor to bypass the zener string. if you build a stereo pair or a push/pull pair of Mu Stages, the same voltage divider (or zener string) can serve both. No interaction will result.

MOSFETs are not sensitive to the value of their gate resistor. You can thus use a high value for Rg2, to minimize the load seen by V1. You will find that a value of up to 22M is okay. In such a case, reduce Cp's value to 0.02uF. Stay within 25% of Q1's maximum power rating.

How To Balance

Rs 1, the MOSFET's source-terminal resistor'(equivalent to Rk2 of Fig. 4), will have the largest power rating of all resistors in the hybrid Mu Stage. Use a power MOSFET of sullidendy high voltage and current rating and the lowest interelectrode capacitance. One possibllity is type IRF712. Due to the interelectrode capacitinces of power MOSFETs, it is best to USC 2 higher current dual-triode for VI, with both triodes paralleled. Be sure to use a heatsink on the MOSFET. Note that the 12V zener should he included to protect the MOSFET gate. With power MOSFETs, it is especially important to include the GS ("gate-stopper") resistor (15k - 33k is recommended) and to practice proper MOSFET handling.

It is possible to convert the Mu Stage's cathode (or source) follower into a White CF or White SF, but doing so requires much rearranging, as well as very carefull and precise adjustment of certain component values (not to mention an additional tube or MOSFET). Therefore, I do not recommend it. The output impedance of the Mu Stage is so low already that a White CF/SF will almost always he unnecessary.

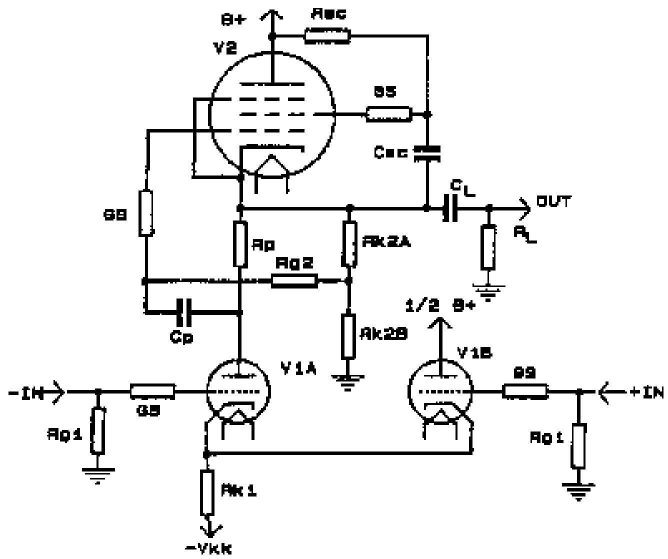


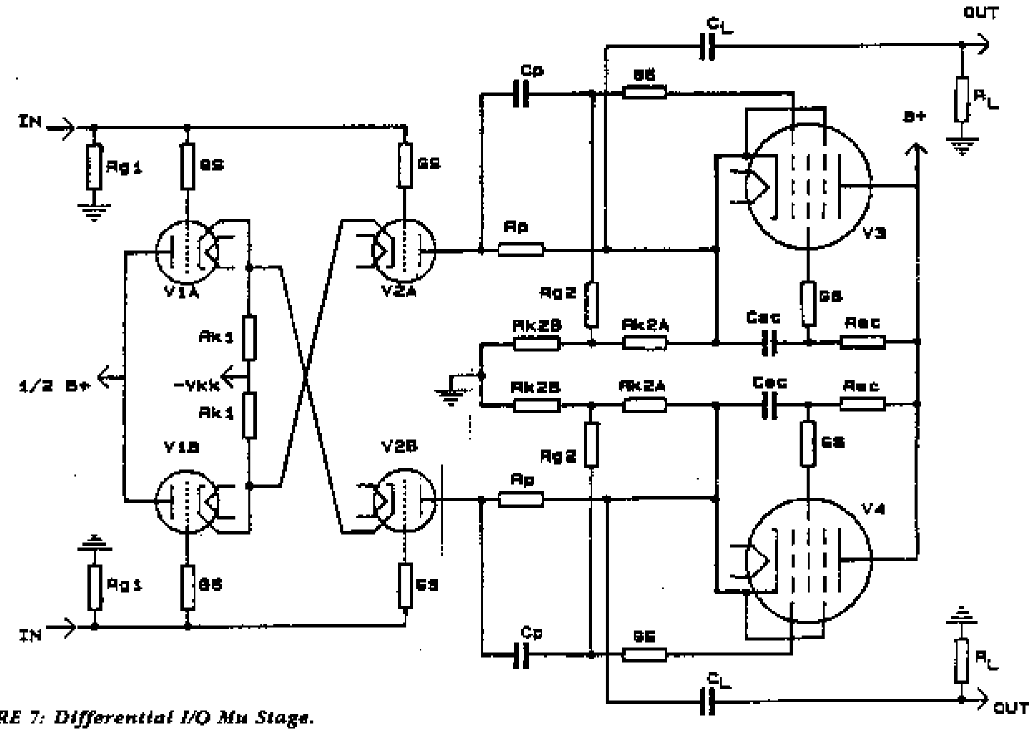
FIGURE 6: Differential input Mu Stage.

Th~ Mu Stage can he adapted to have differential balanced inputs (Fig. 6). The

- Vkk supply should he at least - IOOV DC and well filtered, or regulated; Ric 1 must be sized appropriately. The one-half B + voltage source must he able to supply the few milliamperes needed by V IB without sagging.

Curbing Clipping

To get a Mu Stage with push/pull outputs, most phase inverters can be converted to Mu Stage operation. One which cannot be converted is the standard two triode differential input/differential output (differential I/O) amplifier. The standard



'IGURE 7: Differential I/O Mu Stage.

differential I/Oamp works properly only if its two plate resistors are fixed if you need a differential I/O Mu Stage, use Fig. 7. Again, Vkk should heat least - lOOV DC, well filtered or regulated, and Rk1 must be size appropraately. The one-half B + voltage source, once again, must be able to provide the few milliamperes needed by V1A and V1B without sagging. Components shown with identical designations have the same value.

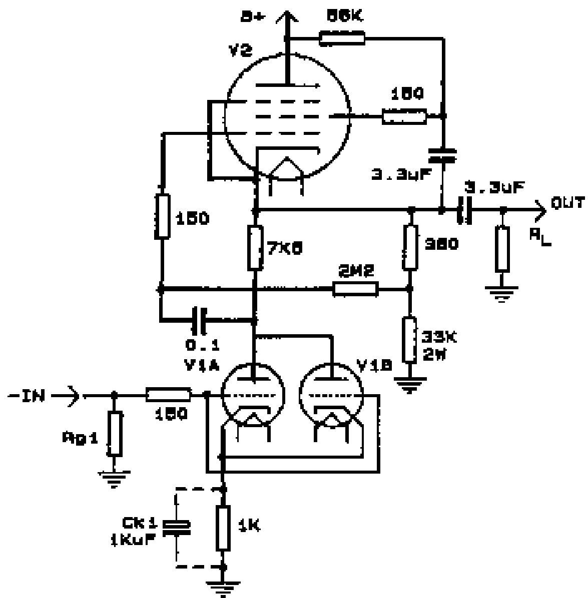


FIGURE 8: Mu Stage example, with V1 = 6DJ8.

Figure 8 is an example of a line amp or driver stage with component values. B + can he 300-360V. In this example, V2's current and power ratings are significandy higher than Vi's. Such a difference between the two tubes may not be necessary in your application, but it is feasible with the Mu Stage, allowing a lot of flexibility. I could just as well have used only one of VI's triodes, and at first I did. But realizing that the other triode was there doing nothing, I decided to use it. With a B + of 300V, the maximum unclipped output (no load) was 76V RMS (215V P-P).

Note the effect on output impedance simply by changing V2 to a higher trans-conductance tube. The effect of Ckl on output Impedance is also shown. Output impedances were measured with 19V no load and with a loading resistor of 10k. Incidentally, trying to measure the output impedance of low current stages under these same conditions can result in clipping when the load resistor is applied, even if the low current stage has an output impedance comparable to any shown in Fig. 8. It is easy to make a lowcurrent stage which has a low output impedance at low signal levels, but malntaining a true low output impedance at large signal levels requires a higher current stage, such as Fig. 8.

TABLE 1
TYPICAL Z_{OUT} AT 1kHz

V2	WITHOUT CK1	WITH CK1
12BY7	762Ω	227Ω
12GN7	346Ω	100Ω

How Sweet It Is

Capacitor Cp in Figs. 4-8 can be 0. 1uF. In Fig. 5, however, Cp should be 0.02uF if Rg2 is 22M. If you design a Mu Stage for phono preamps, be sure to use low noise tubes. These circuits, as do all "totem pole" types in which you have a substantial DC potential between the cathodes of VI and V2, call for certain filament-supply precautions. The ideal arrangement is to give V1 and V2 their own separate filament supplies. V1's should be grounded and V2's can float. But if you are limited to one common filament supply for both V1 and V2, you should use a voltage divider to "bias up" the filament supply to one-fourth the value of B +. This will be necessary if you use a triode-pentode tube. You can use a 360k upper resistor and a 120k lower one in the voltage divider, with a 1uF capacitor across the lower.

I have built and tested every circuit described in this article. Making the upper tube a pentode CF makes the best gain stage I've seen yet. With a pentode CF (or MOSFET SF) on top, the Mu Stage is capable of producing the most constant-current operation as well as very low output impedance. Although the Mu Stage can take many different forms, they basically all work the same way.

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