



TUBE CAD JOURNAL

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SRPP Decoded

This Issue

SRPP at last

Editor,

Congratulations for your web-journal. It is unique and a joy to "receive", every month (if the May issue is on time, we'll forgive the April joke). ...I have not read anything about SRPP and mu-follower (with the possible exceptions of hybrid versions) operations. Are you planning to write something about them? or is there some kind of aversion for these topologies, which would be a real contradiction with the extraordinary creativity and openness displayed throughout the Journal....

Olivier

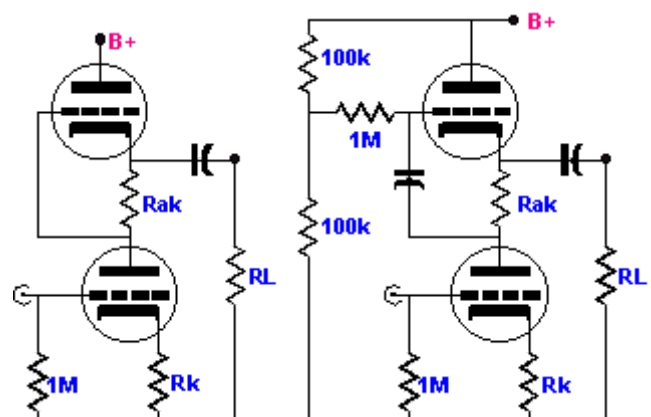
We have been meaning to expose the inner workings of the SRPP circuit for some time now, but we just have not got around to it. Why? Because this circuit topology is so popular, but so little understood, we knew that the SRPP would require a lengthy explanation, which damped our ardor somewhat. Second, we had hoped to get a copy of the 1943 patent for the article, but we never did. In spite of which, here is what will surely prove to be the first of many articles on the SRPP circuit.

Remember, if you have a request or suggestion of your own for either an article topic or circuit, please e-mail:

[Editor](#)

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Symmetrical SRPP and Fixed Bias SRPP

This circuit has many names: SRPP, SEPP, Totem Pole, Mu Follower, Mu amplifier, Cascoded Cathode Follower, and its original name, the Series-Balanced amplifier (Feb. 1943, US patent 2,310,342. Just what "SRPP" means is uncertain; maybe it stands for Series Regulated Push-Pull amplifier or Single-Ended Reflexive Push-Pull amplifier.

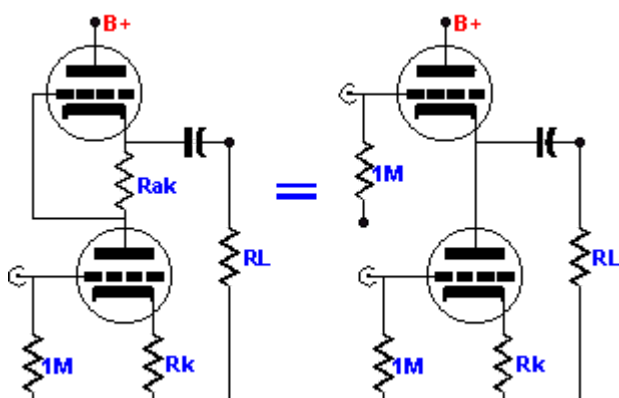
Wildly popular, this circuit was the defining vacuum tube circuit of the 90's. It appeared in high-end SE amplifiers, line stages, phono stages. Why all the fuss? This circuit promises the advantages of both the Grounded Cathode amplifier and the Cathode Follower: high gain and low output impedance.

Yet, in spite of its popularity, few realize that it is not a single-ended circuit. In fact, most tube fanciers are shocked when told that this circuit is fundamentally a push-pull amplifier and not that radically different than the output stage of the a push-pull power amplifier like the Dynaco ST-70. "It must be single-ended... look there's no output transformer!" (A quick re-read of the [June 1999](#) article on push-pull amplifiers is encouraged.)

How The SRPP Works

In a nutshell, one triode stands on top of another with a resistor spanning cathode and plate. First, the bottom tube receives the input signal; second, by reacting to that signal, it gives the top tube its drive signal. While this circuit has several topological variations, in all cases the output is taken at the top triode's cathode.

This circuit constitutes a push-pull output stage that happens to comprise its own phase splitter. Consequently, unlike most push-pull circuits, Class A operation is necessary to the SRPP's functioning. As the current flowing through the bottom tube varies, the resistor R_{ak} sees a varying voltage develop across its resistance in response. This variation in voltage is then given either through a capacitor or directly to the top triode's grid, which will conduct a varying amount of current as a result. Since the load resistance connects in between the top and bottom tubes and ground, it provides a path to absorb the change in current.



SRPP functions like a push-pull amplifier

Push-Pull One More Time

We have just described the push-pull nature of the circuit, but at the risk of boring some readers, let's cover this action one more time in greater detail, as a solid grasp of the push-pull functioning of the SRPP is needed to make sense of what will follow later.

Although at idle both triodes draw an equal current flow, in the presence of an input signal the triodes conduct in anti-phase. How is this possible with two tubes in series? Relative to the top tube's cathode, the signal developed across resistor R_{ak} is in anti-phase to the input signal given to the bottom tube's grid. For example, a positive pulse at the bottom tube's grid results in a negative pulse at the top tube's grid. Therefore, the top triode's change in current conduction will be in anti-phase to the bottom triode's change in current conduction; thus, the pulling and the pushing. As the bottom triode pulls the output voltage down, because it is experiencing a greater conduction, the top triode let's go, as it is conducting less. Conversely, as the top triode pulls the output voltage up by conducting more, the bottom triode let's go by conducting less. The load then sees the delta, the difference, in conduction between top and bottom tube.

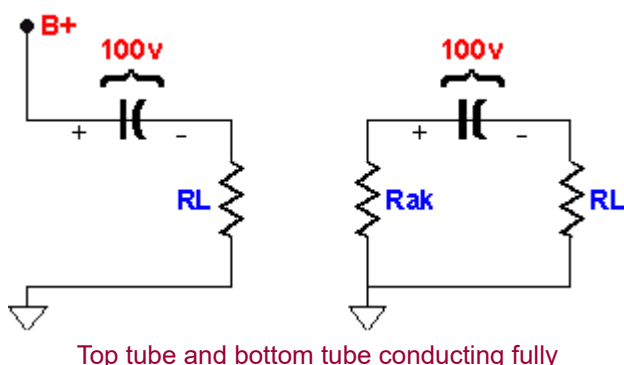
At idle we know there is zero difference between top and bottom tube current flow, thus no current is delivered into the load resistance. But if a positive pulse is applied to the bottom tube's grid, its current conduction might increase from 10 mA to 15 mA, while the top triode's current conduction decreases from 10 mA to 5 mA because of the bottom tube's greater conduction through resistor R_{ak} , which forces the top tube's grid negative. The difference between these two currents is 10 mA, which is delivered into the load resistance.

What if there is no load resistor? In this case, there will be voltage amplification at the output, but no current variation between tubes, for *there can be no difference in current draw between top and bottom tubes, as there is only one current path through both tubes*. The load resistance defines a second current path, which is available to both tubes.

When the top tube conducts more current than the bottom tube, the difference in current flows through the load resistance into the cathode of the top tube.

When the bottom tube conducts more current than the top tube, the difference in current flows through the bottom tube's plate into resistor R_{ak} and then into load resistance.

Wait a minute: doesn't current only flow from negative to positive? How can the current flow from a very positive cathode, 100 volts let's say, into load resistance at ground potential? The answer lies in the use of a coupling capacitor that connects cathode to the load. The capacitor (being very large in value) functions like a battery; in fact, it could be replaced by a high voltage battery. The capacitor maintains an almost fixed voltage across its leads, so when the bottom triode conducts more, it will pull the capacitor down negatively, making the connection with the load resistor become negative relative to ground, which in turn will allow current to flow up through the load resistor into ground. If you are still unclear how this could be, imagine that the bottom triode conducts so fiercely that it becomes effectively a dead short. Now, the voltage charge stored in the capacitor is still present and it will begin to discharge through the load resistance (and resistor R_{ak}) until it is completely discharged. Conversely, if the top triode conducts so fiercely that it becomes effectively a dead short, the capacitor will begin to charge up through the load resistance from ground until the charge across the capacitor equals the B^+ voltage.



If the load resistance is zero ohms, then the difference in current flows indirectly through the coupling capacitor into the ground.

Is Balance Possible?

Normally, the prime consideration in designing any push-pull amplifier is balance. Balanced drive voltages that yield balanced current swings make a clean push-pull amplifier. Matched tubes, equal cathode-to-plate voltages, equal idle currents--all are needed to ensure balance. But this circuit does not appear to be balanced in structure. Why is resistor R_{ak} value not strictly specified? Why does the bottom tube have to work into R_{ak} and the load, but the top tube directly works into the load? Should the bottom triode's cathode resistor be bypassed or not? Put more generally, can this amplifier be balanced at all?

**Unlike the White Cathode Follower,
the limitation to the SRPP is that it
can only be optimized for one
specific
load impedance.**

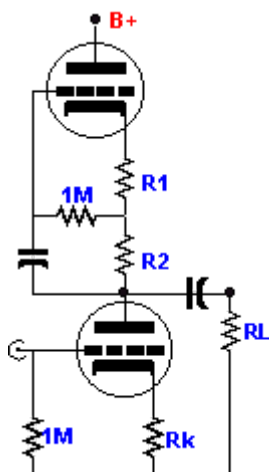
Yes, this circuit can be balanced by careful selection of part values and operating points *for a given load impedance*. Unlike the White Cathode Follower, the limitation to the SRPP is that it can only be optimized for one specific load impedance. Of course, if the circuit is optimized for a load of 10k, 15k will not totally ruin the amplifier's performance. But 600 ohms or 1M will prevent the optimal use of this circuit. Now this situation is not unusual, as most power amplifiers are designed with a fixed load impedance in mind in order to perform to their design standards. Still, this circuit is more sensitive to mismatching, as it does not benefit from the degenerative feedback and the loop feedback that keep the White Cathode Follower's output in line with its input signal. Furthermore, the SRPP uses the current delivered into the load impedance to define the drive voltage for the top tube; wrong load impedance equals wrong drive voltage and unbalanced operation.

Is This Trip Really Necessary?

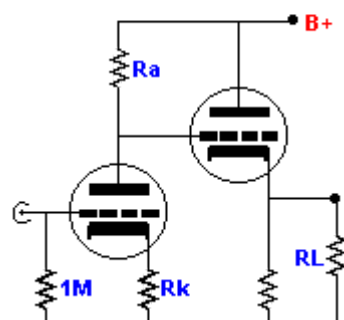
The first step prior to optimization is to ask ourselves if we really need a power amplifier. What are we trying to drive? If the load is a severe one, such as the Grado headphone's 32 ohms, then we certainly need a power amplifier. On the other hand, if the load is a 100k potentiometer, then we should not forgo the simplicity of a single-ended amplifying stage, such as the Grounded Cathode amplifier, a Cathode Follower, or a current source loaded Grounded Cathode amplifier. You see the whole point to a well designed push-pull, Class A amplifier is that it can deliver up to twice the idle current into the load, whereas the single ended amplifier can deliver only up to the idle current into the load. Do you need that much current?

How much current must be delivered into the load? If the amount is less than one fifth the normal idle current of the tube you prefer to use, then stick with single-ended circuits. If the amount is greater, then first consider using a beefier tube with more idle current. Do not fall into the trap of past practices: it used to be done this way; therefore, it must be done this way. Let the past inform, not restrict. (Aluminum foil meatloaf was a 30-year-old popular recipe that was going to be added to a cookbook of great American dishes. The recipe called for making a ball of aluminum foil and adding it to the meatloaf. The editor of the cookbook wished to discover the origin of the recipe and found the chef, who when questioned about her inspiration to include a ball of aluminum foil, replied that she had to jam the aluminum foil into a corner to keep her cracked pan from leaking. Or maybe you have heard of the Buddhist tradition of tying a cat to a tree during meditation. A great monk was often pestered during group meditation by a cat that lived at the monastery. So the rule was to leash the cat to a tree until the meditation was over. Even after the monk's death the cat was leashed to the tree and even after the cat's death, a new cat was found to be leashed to the tree. Many treatises were written about the meditative importance of a leashed cat.)

...if the peak current is equal to twice the idle current, consider using an SRPP stage instead.



Current source loaded
Grounded Cathode
amplifier



Constant Current Draw
Compound amplifier, where
the Cathode Follower's load
resistor = Ra

If you think vacuum tubes are expensive today, you should work out in absolute dollars the cost of tubes in the 1920s, 1930s, and 1940s. So too all the parts associated with tubes, the coupling capacitors, chokes, power transformers, and diodes were hugely expensive. Thus arose the need for economical design: fewer tubes and *less current*, as less current meant smaller, cheaper parts and power supplies.

Today, with the vacuum tube having made its home in the luxurious, cost-is-no-object world of high-end audio, the need to keep current consumption to a minimum does not apply. Yet for many tube gurus, the rule of thumb is 1 to 3 mA per small signal tube. While this amount of current draw is adequate for the 12AX7 and the 6SL7, it is not so not for most other tubes. A 6DJ8 sounds terrible at 1 to 3 mA, as does a 5687 or even a 6SN7. In general, an increase of current equals an increase in linearity. The bottom of the plate curves is not where the tube should be run. As a tube nears its current cutoff, its distortion increase greatly.

Remember, small signal amplification is not restricted to small tubes; a 300B could be, and maybe should be, used as a line amplifier tube.

If a 12AX7 based line stage amplifier cannot adequately drive a 20k input impedance solid-state amplifier, then replacing the 12AX7 with a 5687 and increasing the current flow through the line stage by tenfold is one possible answer; another is to use an SRPP circuit with a 12AX7, as the SRPP will deliver twice the current than the single-ended circuit would with the same idle current.

Once again, ask yourself this question: Is This Trip Really Necessary? If a severe amount of current is required or if the power supply cannot be any further burdened, then certainly the SRPP topology may prove handy. The quick test is to take the desired peak output voltage into the load and divide it by the load impedance to find the needed peak current into the load. Now if this value of peak current is less than one fifth the idle current of a single-ended circuit, such as the Cathode Follower or the Grounded Cathode amplifier, stick to these circuits. On the other hand, if the peak current is equal to twice the idle current, considered using an SRPP stage instead.

Over-Designing

In tube audio work, we must avoid the trap of over-designing; in other words, trying to get more out of a circuit than is possible. The gain of an SRPP circuit is given by:

$$G = \frac{-\mu(r_p + \mu R_{ak})}{2r_p + (\mu + 1)R_{ak} + (r_p + R_{ak})r_p/R_I}$$

and output impedance by:

$$Z_o = \frac{r_p(r_p + R_{ak})}{2r_p + (\mu + 1)R_{ak}}$$

Basically, the formulae for the SRPP tell us that the larger the value of resistor R_{ak} , the lower the output impedance and the higher the gain. A 12AX7 based SRPP circuit with a R_{ak} resistor of 100k has spectacular specifications on paper, but can output only a few mV into a Grado headphone. What went wrong?

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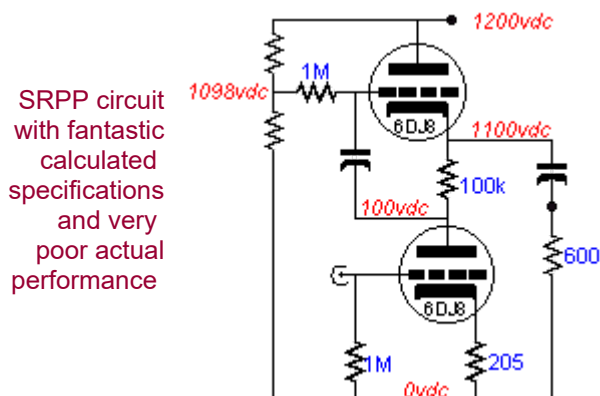


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Just as in the [October 1999](#) issue's analysis of the White Cathode Follower, we find that if we try to achieve a very high gain and a low output impedance, we end up limiting the amount of potential current swing the amplifier can swing into the load.

As an example, if we make R_{ak} equal to 100k and use a 6DJ8 with a 1200 volt power supply and an idle current of 10 mA and 600 ohm load, the static specifications are stellar: the gain is 27.8 and the Z_o is 79 ohms. But the maximum Class A negative output voltage swing is only 7 millivolts! Positively, the amplifier can swing 15 volts and still remain in Class A mode. Why the huge discrepancy?



Any variation in the current flowing through resistor R_{ak} will result in a signal voltage for the top triode. But the top triode can only see so much signal voltage before it either stops conducting or is overdriven.

The test of the degree of balanced operation we achieve is extent to which the peak negative output voltage swing equals the peak positive output voltage swing.

The idle current divided by the effective transconductance of the top triode gives us the maximum negative peak voltage the top tube can see before it cuts off. And this peak voltage divided by R_{ak} gives us the peak increase in current through R_{ak} needed to turnoff the top tube. This quantity of peak increased current through the load impedance defines the peak negative output voltage swing. Or expressed mathematically:

$$G_m' = \frac{\mu}{r_p + [(\mu + 1)R_{ak} + r_p][\frac{R_{ak} + r_p}{R_l}]}$$

$$V_{peak} = I_q / G_m' + I_q R_{ak}$$

$$I_{max} = V_{peak} / R_{ak}$$

$$V_{n\ max} = R_l \times I_{max}$$

(The formula for G_m' assumes that the cathode resistor is bypassed on the bottom tube.)



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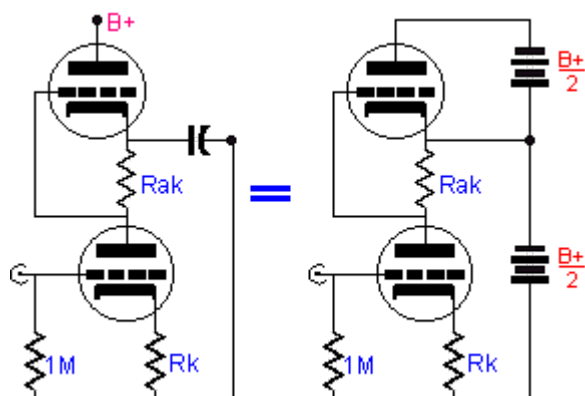
The maximum positive peak output signal voltage is roughly given by:

$$V_p \text{ max} = V(r_p + R_l),$$

where V equals the cathode-to-plate voltage of the top tube at idle. This formula assumes that the bottom tube has ceased to conduct so that its current draw is not subtracting from that of the top triode and that the top triode only sees only zero volts on its grid-to-cathode voltage. In the last example that would not be true, as the bottom triode requires a huge negative voltage pulse at its grid to be turned off and when its conduction decreases only slightly, a huge positive pulse results at the top triode's grid, forcing its grid positive relative to its cathode. Thus, we see that the selection of the value of R_k is critical to symmetrical peak voltage swings into the load impedance.

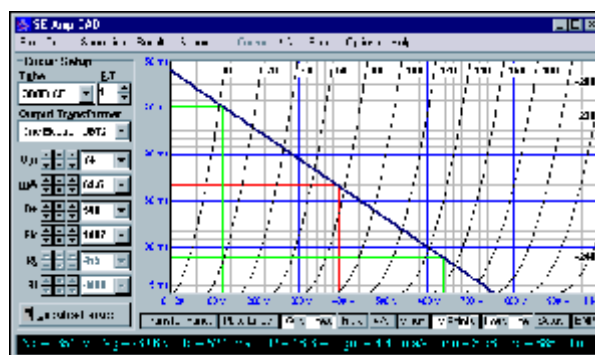
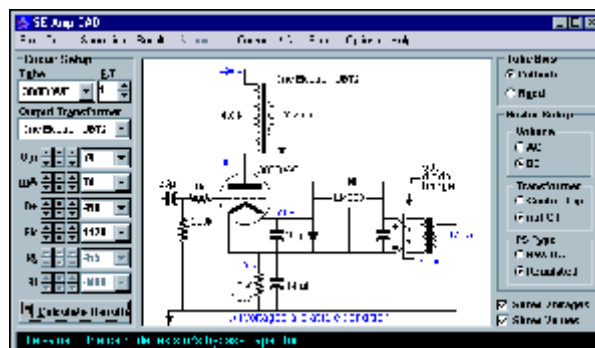
Where to Start?

Let us begin with the stipulation that we never want the grids of either the top triode or the bottom triode to be driven positive relative to the cathodes and that the circuit never leaves Class A operation and that R_k is bypassed. A further assumption is that the triodes used have a fairly high μ and that consequently the voltage drop across resistor R_k is not too great. If a low μ power tube such as the 6AS7 is used, then the effective B^+ voltage must be used in the formulae (in actual use, the best procedure would be to use fixed bias with a low μ triode).



SRPP working into a zero impedance load

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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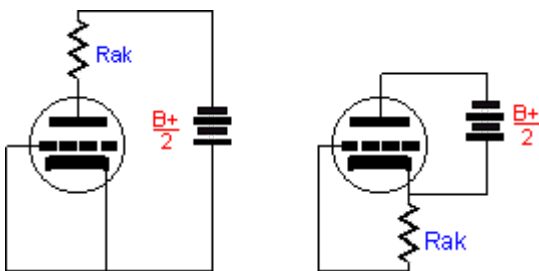
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Just as in the analysis of the White Cathode Follower, the first step to understanding a circuit is to redraw it so the output works into a short to ground, i.e. a load impedance of zero ohms. Ideally, the current should flow symmetrically in and out of the output into the ground. In other words, when the grid of the bottom tube is presented with a 1 volt pulse in grid-to-cathode voltage, the ensuing increase in conduction by the bottom tube should be met by the equal decrease conduction from the top tube. Now, a schematic for the bottom tube can be redrawn to show the equivalent circuit at zero grid voltage.



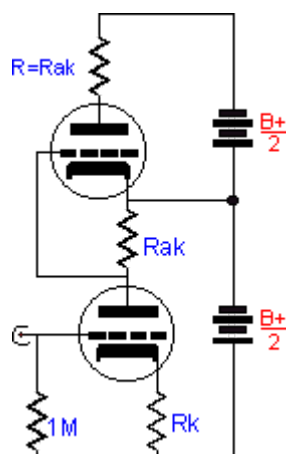
We see that the maximum potential current flow for the bottom triode equals the one half the B+ voltage divided by the sum of the r_p of the tube and the value of resistor Rak:

$$\mathbf{V1 \text{ Max. Current} = Vb / 2(Rak + r_p).}$$

The maximum current flow for the top triode under zero grid voltage is equal to the one half the B+ voltage divided by the r_p of the tube:

$$\mathbf{V2 \text{ Max. Current} = Vb / 2r_p.}$$

SRPP modified by the addition of a plate resistor to equalize the potential maximum current swings into the load impedance.



Immediately we see that the maximum currents do not equal. To restore balance, an additional resistor that equals Rak must be placed in series with the top triode's plate and the B+ power supply. Now the maximum current for the top tube equals that of the bottom tube. (This is not new, as the plate resistor was part of the 1943 circuit.)

The next step is to determine the optimal value for Rak for a given load impedance and idle current.

Optimal Rak Value

Too large a value for resistor Rak unbalances the push-pull aspect of the SRPP circuit, but too little a value not only reduces the circuit's gain and increases the output impedance, but also unbalances the amplifier. For example, if we reduce Rak to zero ohms, then the top tube effectively becomes a plate resistor equal to r_p in value and the circuit loses all its push-pull attributes. So the question is: What would be the optimal value this resistor for a specified load and a desired output voltage swing?

Once again, for any push-pull tube amplifier to perform well, there must be a symmetrical current delivery into the load impedance. Normally in a push-pull power amplifier, matched tubes and equal drive voltages are necessary. *Surprisingly, in the SRPP neither is necessary.* In this circuit, if the bottom triode sees a 1 volt increase in its grid-to-cathode voltage, then the top triode might see a 2 volt decrease in its grid-to-cathode voltage and still symmetrically deliver current into the load impedance.

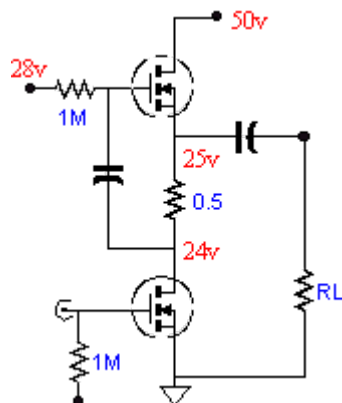
To see how this might be, imagine that we have replaced the triodes with devices that do not have a plate resistance, such as a pentode or a MOSFET. Now the math becomes trivial. The transconductance (G_m) of the top device is the only key variable to defining the value of Rak:

$$\mathbf{Rak = 1 / G_m.}$$

Now if a bottom MOSFET is used with a G_m of 1 amp per volt, it little matters if the top

MOSFET has a Gm of 2 A/V or 4 A/V, as using a Rak of 0.5 ohm and 0.25 ohm respectively would ensure symmetrical current swings into the load.

For example, given an idle current of 2 amps and a load impedance of 10 ohms, a positive 1 volt pulse delivered to the bottom MOSFET's gate will result in a 1 amp increase in current flow through both the bottom MOSFET and resistor Rak.



This increase in current flowing through Rak will result in a 0.5 volt increase in voltage across the resistor, which in turn will provoke a 1 amp decrease in current flow from the top MOSFET, as 0.5 times 2 equals 1. The difference between the 3 amp conduction of bottom MOSFET and the 1 amp conduction of the top MOSFET equals 2 amps of current into the load, which equals 20 volts of negative voltage swing.

Had we used a MOSFET with twice the Gm, then we would have had to use a Rak resistor with half the value so that the 1 amp increase in current would have yielded half the drive voltage for the top MOSFET, which would then also decrease its current draw by 1 amp.

How do we ensure equal current swings for top and bottom triodes? We could begin by finding the peak current flow, halving that value to specify the idle current, which then let's us determine the correct value for Rak. In other words, the idle current must be set to one half the value of the peak current draw when working into the specified load resistance with a known rp and a unknown Rak value:

$$I_q = V_b / 4(rp + R_{load} + R_{ak}).$$

It is a bit circular, is it not? We can ignore the value of Rak on the first try and then add to the second try, as the answer will be close, as long as the mu is high. Or for those who prefer graphically solving tube circuit operations, the load resistance is plotted at half the B+ voltage in same way it would be in the design of a Grounded Cathode amplifier and the intersection with the zero volts grid line marks the peak output current and half this value equals the idle current Iq.

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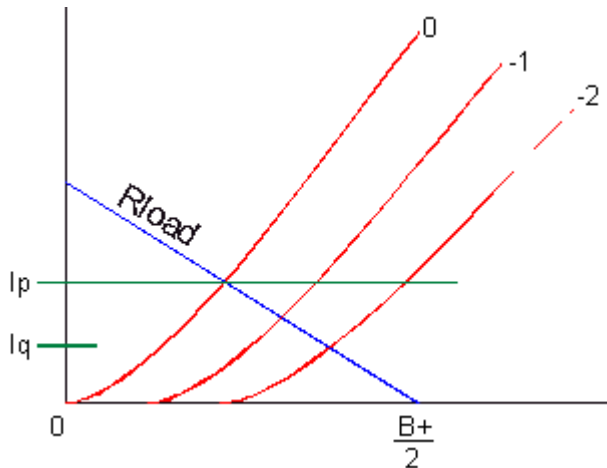
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Graphically solving the I_q and I_{peak} values

But how do we precisely determine the value of resistor R_{ak} ? Unfortunately, the simple rule that worked so well for MOSFETS, $R_{ak} = 1/G_m$, will not work for triodes, as triodes have r_p . Plate resistance is what separates triodes from FETs, MOSFETs, transistors, tetrodes, and pentodes. The r_p is the resistance that a triode offers a small change in plate voltage. However, unlike the example of the MOSFET based SRPP circuit, the r_p of top and bottom tubes greatly increase the complexity of the analysis of this circuit, as the circuit begins to resemble a knotty clump of rope: as we pull on one piece, some pieces bind together while others fall apart.

Still, do not think of r_p as a detriment, for without r_p this circuit does not work very well. It is the r_p of the triodes that gives the SRPP its low output impedance. The MOSFET-based SRPP circuit has wonderful current gain, but an unusable high output impedance; it is as if the pieces of rope were cut up into individual strands and left to float in a bowl, one piece can be moved without moving the others. Thus, finding the optimal value for R_{ak} will require taking in account all the variables and interactions of the SRPP circuit.

Here is the solution. Since we have split the $B+$ voltage equally between tubes and each tube sees an identical idle current, the value of R_{ak} must equal the value of the cathode bias

resistor, R_k :

$$R_{ak} = R_k = \frac{(V_b / 2I_q) - r_p}{\mu + 1}$$

The value of R_l seems to be missing from this equation, but it is implied in the calculation of the idle current I_q . But we could not find I_q until we found R_{ak} . Reducing both formulae to one formula gives us our answer:

$$R_{ak} = R_k = \frac{r_p + 2R_l}{\mu - 1}$$

While this formula gains much by virtue of its simplicity, it hides from the tube circuit designer some key information, such as the value of the idle current, and by extension, the tube dissipation and the peak current into the load impedance. Still, it is intriguing to see V_b and I_q both drop out of the mix, which shows just how decisive the triode's μ and r_p are in this circuit's functioning. This formula promises to give us the value of R_{ak} that yields the biggest, cleanest voltage swing into the load resistance. Let's give it a test.

If we set the load impedance to zero ohms, the formula reduces further to

$$R_{ak} = r_p / (\mu - 1),$$

which would yield 103 ohms as the correct value for a 6DJ8, as

$$103 = 3300 / (33 - 1).$$

To verify this result, let's plug this value into the following formula:

$$\text{Gain} = \mu R / (r_p + R),$$

Which is the formula for the gain of a Grounded Cathode amplifier,

$$\begin{aligned} \text{Gain} &= 33 \times 103 / (3300 + 103), \\ 0.9988 &= 3399 / 3403. \end{aligned}$$

The result easily rounds to 1, which means that a 1 volt pulse at the bottom tube's grid results in an increase in current draw sufficient to develop a -1 volt pulse at the top tube's grid.

Substituting 200 ohms for the value of R_{ak} shows an asymmetrical drive voltage:

$$\begin{aligned} \text{Gain} &= 33 \times 200 / (3300 + 200), \\ 1.88 &= 6600 / 3500, \end{aligned}$$

as does substituting 50 ohms for R_{ak} :

$$\text{Gain} = 33 \times 50 / (3300 + 50),$$

$$0.49 = 1650 / 3350$$

In all the previous examples the effective transconductance of each triode was the same, as the load impedance was set to zero:

$$Gm' = \mu / (Rak + rp).$$

But when the load impedance represents some positive value, then the top triode's effective Gm must differ from the bottom triode, as the load resistance unequally subtracts from the Gm of both tubes. So, given a greater than zero load impedance, will the calculated value of Rak be equal to the inverse of the top tube's Gm? As a design example let us take a 6DJ8 with a Vb of 200 volts and a load of 1550 ohms. The first step is to find Rak:

$$Rak = Rk = \frac{rp + 2Rl}{\mu - 1}.$$

Substituting variables,

$$Rak = Rk = \frac{3300 + 2 \times 1550}{33 - 1}$$

$$Rak = Rk = 200.$$

Now we find the effective Gm for the top tube, invert this value and compare to the value of Rak.

$$Gm' =$$

$$\frac{\mu}{Ra + rp + \frac{[(\mu + 1)Rak + rp][(Rak + rp)Rl]}{rp + Rak}}$$

$$Gm' = 0.005 = 5 \text{ mA/v},$$

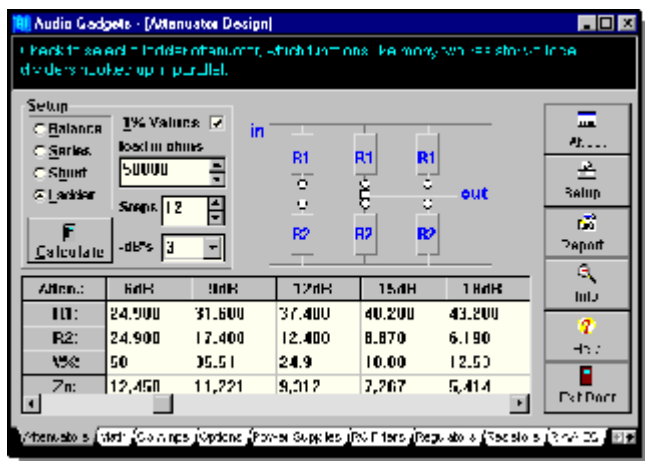
and

$$200 = 1 / 0.005.$$

And as Rak = 200, we know the formula worked in this case.

The test I like to use is to try the formula with a 6AS7, as its puny mu of 2 will quickly reveal a mathematical absurdity that a higher mu tube may hide. Let's even give this test some practical results: Sennheiser makes some wonderful dynamic headphones with an impedance of 300 ohm, the HD-580 and HD-600 for example. These headphones require a just few volts to sing. An OTL headphone amplifier that used a 6AS7 might be just what someone needs. So now that we have the load impedance and the tube, what we need is the power supply voltage. Let's keep the 200 volt power supply from the previous example as it is a sane power supply voltage for a headphone amplifier. Now let's find Rak's value.

Audio Gadgets



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$$R_{ak} = \frac{r_p + 2R_L}{\mu - 1}$$

substituting the variables,

$$R_{ak} = \frac{280 + 2 \times 300}{2 - 1}$$

$$R_{ak} = 880.$$

Here is an example of a cathode resistor so large in value that it must be eliminated from the circuit or its large voltage drop must be included in a revaluation of the circuit variables. Since this SRPP must have a driver stage to make up for the low gain afforded by the 6AS7, at least one coupling capacitor will be needed. Therefore, the better solution is to use a fixed bias on the SRPP stage, as it eliminates the need for a cathode resistor and its bypass capacitor.

The idle current can be found by using the following formula, now that we know the value of R_{ak} :

$$I_q = V_b / 4(r_p + R_{load} + R_{ak}),$$

substituting the variables,

$$I_q = 200 / 4(280 + 300 + 880),$$

$$I_q = 34 \text{ mA}.$$

The idle current times R_{ak} gives us the negative bias voltage needed:

$$V_{bias} = I_q R_{ak},$$

$$V_{bias} = 29.92 \text{ v}.$$

Now that we have taken care of the supporting details, let's see if our efforts were wasted. Once again we find the effective G_m of the top triode and take its inverse and then compare that value against R_{ak} to see how well the formula worked.

$$G_m' =$$

$$\frac{\mu}{R_a + r_p + \frac{[(\mu + 1)R_{ak} + r_p][(R_{ak} + r_p) \parallel R_L]}{r_p + R_{ak}}}$$

where $R_a = R_{ak}$, thus

$$G_m' = 0.001136 = 1.136 \text{ mA/v},$$

and

$$880 = 1 / 0.001136.$$

And as $R_{ak} = 880$, we know the formula also worked in this case.

Optimization and Gain

$$\text{gain} =$$

$$\frac{\mu R_L (r_p + \mu R_{ak} + R_a)}{(R_L - \mu R_{ak}) R_L - (R_L + R_{ak} + r_p)(R_L + R_a + r_p)}$$

New Variation

In the last design example, the I_q was 34 mA. This amount of current was dictated by the formula for an optimized SRPP. What if we wish to run the tube at a lower idle current, say 30 or 20 mA? Then we must either use a lower power supply voltage or a higher load impedance, as the formula comprises these two variables. But what if we wish to retain both variables while running less current? Then a different circuit topology is needed.

This variation takes the output at the midpoint of two resistors, R_1 and R_2 , that replace the single resistor R_{ak} . Since we have artificially decreased the idle current, we must artificially decrease the effective G_m of the top triode. Adding resistor R_1 has the effect of increasing r_p of the top triode to:

$$r_p' = r_p + (\mu + 1)R_1,$$

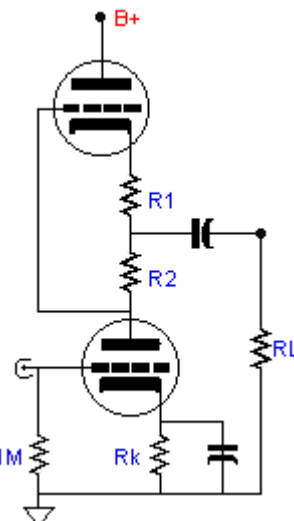
and since

$$G_m = \mu / r_p,$$

the effective G_m becomes

$$G_m' = \mu / [r_p + (\mu + 1)R_1].$$

Once again let's first set the load impedance to zero. Now the only load the bottom triode sees is resistor R_2 . Whatever signal voltage that develops across this resistor will be given to the top triode. The top triode must then match the bottom triode in increased and decreased current conduction to balance the push-pull operation. In other words, the inverse of the top triode's effective G_m must equal just the value of



resistor R2, rather than the sum of resistors R1 and R2. How do we find the values for resistors R1 and R2? The first step is to arbitrarily define the power supply voltage (Vb) and the idle current (Iq). The next step is to find the value of the cathode resistor (Rk), which will equal the sum of both resistors R1 and R2.

$$R_k = R_1 + R_2$$

Given RL, Vb and Iq,

$$R_k = \frac{V_b / 2I_q - r_p}{\mu + 1}$$

Next we must find the value of either R1 or R2 and by subtracting one of these resistor values from Rk find the value of the other resistor. And since R1 is added to limit the maximum positive current equal twice the idle current (2Iq) and to make the inverse of the top triode's effective Gm equal the value of R2, resistor R1 must be first determined:

$$R_1 = \frac{V_b / 2I_q - R_L - r_p}{\mu + 1}$$

thus,

$$R_2 = R_k - R_1$$

The peak current into the load can be no greater than twice the idle current and still remain in strict Class A operation. If the ratio between resistors R1 and R2 is set correctly, the maximum peak current the top triode will pull is equal to twice the idle current:

$$I_{pk} = V_b / 2(r_p + (\mu + 1)R_1 + R_L) = 2I_q$$

In case some readers imagine it would be cool to design a Class AB SRPP circuit, consider this :when the bottom tube completely stops conducting current, it can no longer control the current flowing through the load impedance. Here is an analogy that might make this point clear: an SRPP circuit is like a driver-training car with two steering wheels and two drivers. Each is able to steer the car simultaneously. The problem is one driver is blind, but as long as the sighted driver tells the blind driver when to turn left or right, all goes well. Obviously, if the sighted driver decides to let go of wheel and stop talking to the blind driver things do not go so well. To control, the bottom tube must conduct.

Now to give these formulae a test run, let's use a 6DJ8 with B+ of 200 volts and an idle current of 10 mA. Let's also continue to use a load impedance of zero ohms to simplify the math. First we find Rk:

$$R_k = \frac{V_b / 2I_q - r_p}{\mu + 1}$$

substituting variables

$$R_k = \frac{200 / (2 \times 0.01) - 3300}{33 + 1}$$

$$R_k = 197$$

Next we find R1,

$$R_1 = \frac{V_b / 2I_q - R_L - r_p}{\mu + 1}$$

$$R_1 = \frac{200 / (2 \times 0.01) - 0 - r_p}{33 + 1}$$

$$R_1 = 50$$

thus,

$$R_2 = R_k - R_1$$

$$R_2 = 197 - 50$$

$$R_2 = 147$$

Next we find the peak current Ipk,

$$I_{pk} = V_b / 2(r_p + (\mu + 1)R_1 + R_L)$$

$$I_{pk} = 200 / 2(3300 + (33 + 1)50 + 0)$$

$$I_{pk} = 0.02 \text{ A,}$$

and as

$$2I_q = 0.02 \text{ A}$$

our result is on the mark. In this example, as the load impedance was set to zero, the effective transconductance of the top triode is given by:

$$G_m' = \mu / [r_p + (\mu + 1)R_1]$$

substituting variables

$$G_m' = 33 / [3300 + (33 + 1)50]$$

$$G_m' = 6.6 \text{ mA/v.}$$

and

$$151.5 = 1 / 0.0066,$$

which is close to the 147 value of resistor R2. In other words, we have met both goals: a peak positive current swing of 2Iq (20 mA) and the top tube's effective Gm equal to the inverse of resistor R2. Consequently, this circuit will linearly work into a dead short, a severe test.

But will this new circuit variation work with an actual load impedance? Let's test it with a 300 ohm load and an idle current of 7 mA.

First we find R_k :

$$R_k = \frac{V_b / 2I_q - r_p}{\mu + 1},$$

substituting variables

$$R_k = \frac{200 / (2 \times 0.007) - 3300}{33 + 1}$$

$$R_k = 323.$$

Next we find R_2 ,

$$R_1 = \frac{V_b / 4I_q - R_L - r_p}{\mu + 1},$$

$$R_1 = \frac{200 / (4 \times 0.007) - 300 - 3300}{33 + 1}$$

$$R_1 = 104$$

thus,

$$R_2 = R_k - R_1$$

$$R_2 = 323 - 104$$

$$R_2 = 219$$

Next we find the peak current I_{pk} ,

$$I_{pk} = V_b / 2(r_p + (\mu + 1)R_1 + R_L)$$

$$I_{pk} = 200 / 2(3300 + (33 + 1)104 + 300)$$

$$I_{pk} = 0.014 \text{ A},$$

and as

$$2I_q = 0.014 \text{ A},$$

we are still on the mark.

The math gets quite thick here, so let's stop at an approximation; the effective G_m of the top triode is given *roughly* by:

$$G_m' \cong \frac{\mu}{(\mu + 1)R_1 + r_p + R_L}$$

$$G_m' \cong \frac{33}{(33 + 1)104 + 3300 + 300}$$

$$G_m' = 4.62 \text{ mA/v}$$

and

$$216 = 1/0.00462$$

which is fairly close to the 219 value of resistor R_2 . In the design example, we have come close to meeting both goals: a peak positive current swing of $2I_q$ (14 mA) and the top tube's effective G_m equal to the inverse of resistor R_2 . (Had we used a higher ohmage load, the R_k would not have as closely matched $1/G_m$.)

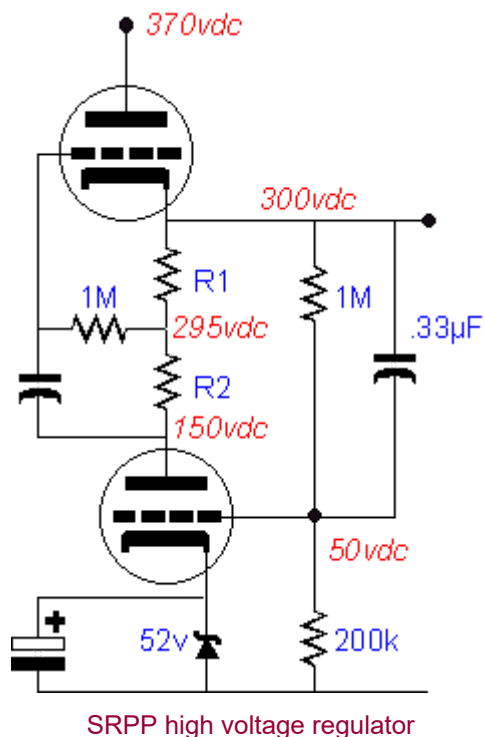
SRPP Series Voltage Regulator

An alternate use of the SRPP topology can retain many of the advantages of the "over-designed" version of the circuit. Remember, when we made the value of resistor R_k very large, we seemingly achieved high gain and low Z_o , but at closer examination, we saw that we had reduced the amount of symmetrical current swing into the load impedance. But what if we do not need symmetrical current to swing into the load?

The unspoken assumption was that music was the intended signal, which can be approximated by a sine wave. But what if the signal was not symmetrical? What if we only needed to amplify the top half of the sine wave? In this case the large voltage drop across R_k could be used to drive the top triode into greater conduction without risking turning off the top triode during negative current swings, as there would not be any.

A series voltage regulator is much like one half of a Class AB amplifier. In both circuits there is an asymmetry in current conduction: the devices are driven further in the on direction than the off direction. An output device in a Class AB amplifier sees a small idle current and an input signal that alternately drives the device into heavy conduction and into cutoff. The series regulator's pass device sees a correction signal that drives the device into heavy conduction and then back to idle level and occasionally into cutoff. And it is this asymmetry in current conduction that we can exploit with an over-designed SRPP, as usually a series voltage regulator is required to push the output voltage up more than it is required to pull it down. (If a reactive load presents a positive pulse to the output of the series regulator, it can only respond by ceasing conduction through its pass device. In this case, a shunt regulator is better suited because it is like a Class A SE amplifier: by running at a much higher idle current, it can push up its output voltage by conducting less and pull it down by conducting more.)

The SRPP circuit can effectively increase the transconductance of the top tube by using a large valued R_{ak} resistor. This increase in effective G_m lowers the output impedance of the regulator.

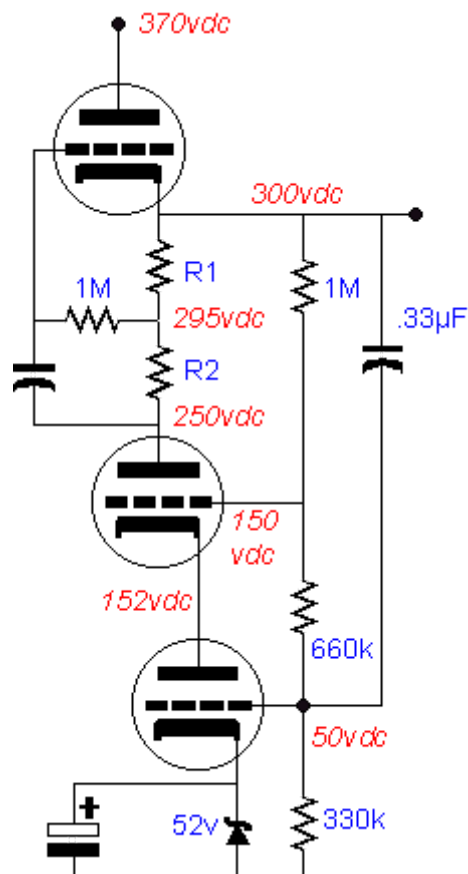


Any perturbations at the output of the regulator are relayed to the bottom tube's grid via the .33 μ F capacitor. The bottom tube then amplifies and inverts the relayed perturbation, which being fed to the top triode's grid, aggressively bucks the perturbation. And as we are no longer concerned with symmetrical current swings by top and bottom tubes, we can make resistor R_{ak} ($R1 + R2$) very large, which will increase the amplification of the correcting signal for the top triode. And by using dissimilar tubes, the output impedance of the regulator can be decreased even further. For example, a 2A3 or 6AS7 could be used as a top tube and a 6DJ8 or even a 12AX7 could be used as a bottom tube.

Still, we run into the usual limit to gain from a Grounded Cathode amplifier: the amplification factor sets the gain limit. No matter how large

we make resistor R_{ak} in value, it is still being shunted by the tube's own r_p , which (when multiplied by the tube's G_m) yields the gain.

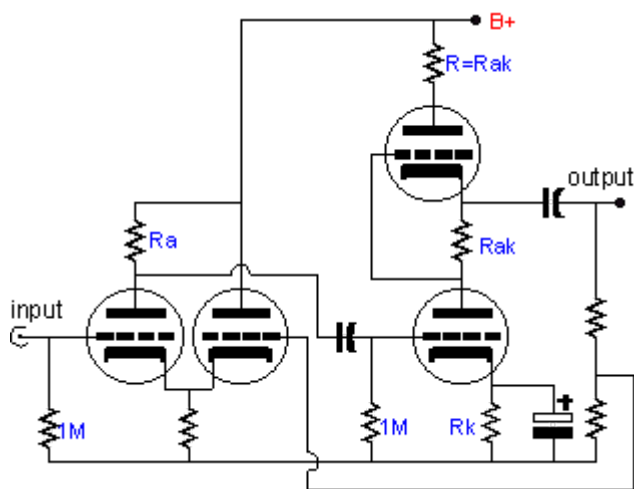
The Cascode circuit easily can yield a gain larger than the μ of the triode. The Cascode works to shield the bottom triode from the top tube's plate resistor, and thus it works to preserve its G_m . Below is a schematic of a cascoded SRPP voltage regulator.



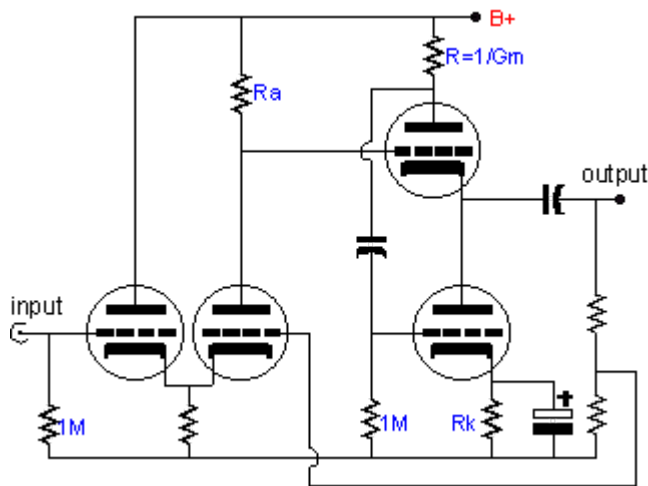
By cascoding, all of the bottom tube's transconductance can be brought to bare against resistor R_{ak} ($R1 + R2$), greatly increasing the gain over the straight SRPP circuit. Consequently, the output impedance of the regulator will be greatly reduced over straight version. The DC feedback is mitigated by the voltage divider formed by the 1M and 660k resistors. Still this could make an excellent series voltage regulator.

SRPP vs. White Cathode Follower

A test to determine which circuit is better suited to drive low impedance loads is presented here. The arbitrators are the oscilloscope, the distortion analyzer, and the ears. Two circuits need to be built: one using a Common Cathode amplifier driving an SRPP and another using a Common Cathode amplifier driving a White Cathode Follower. In both circuits, the output is not inverting and global feedback is used to set the gain to a fixed amount, say times ten (+20 dB). The load could any high quality headphones with a low impedance, say 32 to 600 ohms.



SRPP based headphone amplifier



White Cathode Follower based headphone amplifier

Conclusion

The SRPP circuit is a push-pull amplifier that uses the current flowing through the bottom triode to define an inverted signal to drive the top triode. It works best at one load impedance and can yield twice the idle current into that load impedance. It is often misused as a line stage amplifier (where the load impedance is not predefined) or as a driver stage (where the load impedance is far too high).

Preloading the output overcomes much of the mismatching problems. Preloading means adding a fixed resistor to the output a value slightly higher than optimal, so that when an external high impedance load is added, the combined paralleled impedance will prove optimal. Still the question remains: if the load to be driven is a high impedance one, why bother with a push-pull output stage? If high gain and a good PSRR figure are needed, use a current source loaded Grounded Cathode amplifier instead. If low output impedance is needed, use a White Cathode Follower, Plate Follower, Cathode Follower, or even a lower r_p triode instead. On the other hand, if only one tube envelope can be used per channel and the power supply cannot be greatly taxed and some gain is needed and a somewhat low output impedance is needed to drive a fairly low impedance load, then the SRPP is the best choice.

Are we done with the SRPP? Not likely. Expect to see a few e-mails and new articles on this circuit. And if anyone has access to the patent, please send it our way so that we can post it in this journal.

// JRB

Resources

MJ Stereo Technic, 1987/2, page 206

"Vacuum Tube Amplifiers," Valley & Wallman, pages 456-458, Dover 1965 (originally, McGraw-Hill 1948).