Notes on Shared Cathode Resistors in Cathode-Biased Push-Pull Class AB Output Stages

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Introduction

This article discusses some advantages and disadvantages of shared, or individual, cathode resistors in cathode-biased push-pull output stages. The effects of bypass capacitors are also considered.

Ideal Pentode Characteristics

As the simplest possible model, consider an ideal (fictitious) pentode with the characteristics illustrated in figure 2.

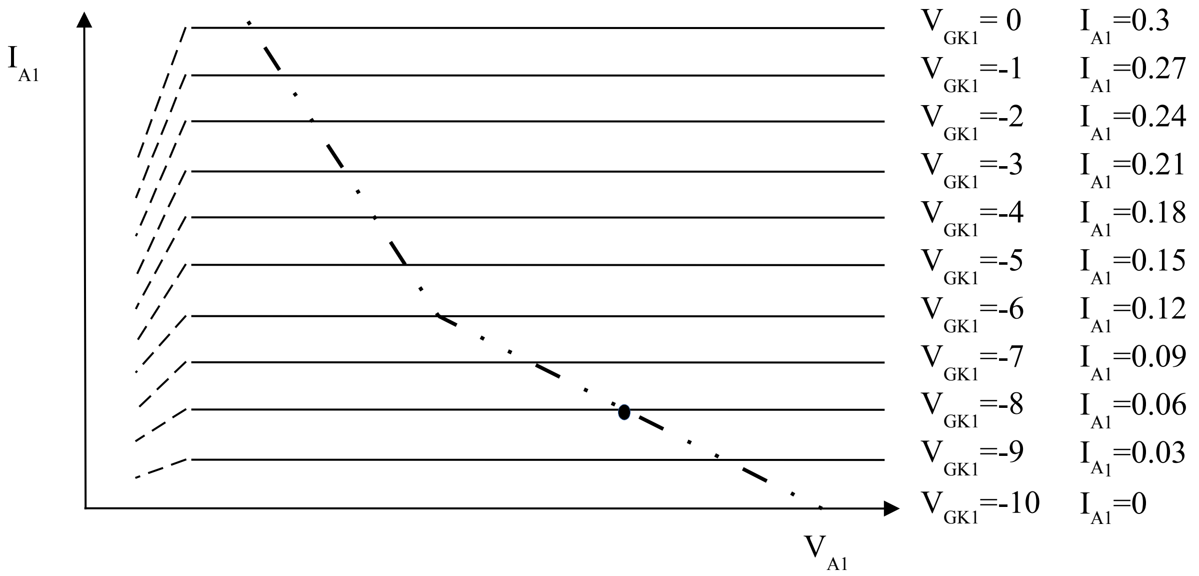

Figure 1: Ideal Pentode Characteristics (with Class AB Load Line)

The ideal pentode acts as a perfect current source, with the value of the anode current (I_{A1}) set by the control grid voltage (V_{GK1}). Assume that operation is always 'above the knee' so that the dashed curves in figure 1 (at low anode voltages) do not come into play. We will also assume that the screen grid current is a fixed proportion of the anode current (e.g. 15%).

This ideal pentode is perfectly linear, cutting off at V_{GK1} = -10 volts with I_{A1} = 0.0 amps, through to I_{A1} = 0.3 amps for V_{GK1} = 0 volts. Assume two ideal pentodes are arranged in push-pull and biased to give quiescent currents $I_{A1} = I_{A2} = 0.06$ amps. The control grid voltages are relative to the cathode, so the bias voltage between control grid and cathode is -8 volts. This choice of quiescent point (shown as a black dot in the figure) will allow the push-pull stage to operate in class AB; one valve will cut off when the other valve reaches an anode current of 0.12 amps. The load line is shown by the dot-dash line in figure 1.

We can now consider the relationship between the control-grid voltage (V_{G1}) and the total current which will be transformed to the loudspeaker (I_L), for various types of cathode bias.

Case1: Shared Cathode Resistor with Bypass Capacitor

At the quiescent point the combined cathode current (I_K) for both valves is 0.06 x 1.15 x 2 = 0.138 amps. (The factor 1.15 allows for the screen current.) To obtain our stated bias voltage (-8 volts) we need a shared cathode resistor (R_K) of 8 / 0.138 = 57.97 ohms. If we assume that the bypass capacitor is large enough to hold the cathode voltage constant, we can calculate the following table:

I_{A1} (amps)	I_{A2} (amps)	I_K (amps)	I_L (amps)	V_K (volts)	V_{G1} (volts)
0.30	0.0	0.345	0.30	8.0	8.0
0.27	0.0	0.3105	0.27	8.0	7.0
0.24	0.0	0.276	0.24	8.0	6.0
0.21	0.0	0.2415	0.21	8.0	5.0
0.18	0.0	0.207	0.18	8.0	4.0
0.15	0.0	0.1725	0.15	8.0	3.0
0.12	**0.0**	**0.138**	**0.12**	**8.0**	**2.0**
0.09	**0.03**	**0.138**	**0.06**	**8.0**	**1.0**
0.06	**0.06**	**0.138**	**0.0**	**8.0**	**0.0**
0.03	**0.09**	**0.138**	**-0.06**	**8.0**	**-1.0**
0.0	**0.12**	**0.138**	**-0.12**	**8.0**	**-2.0**
0.0	0.15	0.1725	-0.15	8.0	-3.0 *
0.0	0.18	0.207	-0.18	8.0	-4.0 *
0.0	0.21	0.2415	-0.21	8.0	-5.0 *
0.0	0.24	0.276	-0.24	8.0	-6.0 *
0.0	0.27	0.3105	-0.27	8.0	-7.0 *
0.0	0.30	0.345	-0.30	8.0	-8.0 *

Table 1: Shared Cathode Resistor with Bypass Capacitor

I_{A1} and I_{A2} are the anode currents of the two pentodes working in push-pull. I_K is the combined cathode current ($I_K = I_{A1} \times 1.15 + I_{A2} \times 1.15$). I_L is the current which will be transformed to the loudspeaker ($I_L = I_{A1} - I_{A2}$). (Actually, by following the load line shown earlier, we are inherently assuming the load is resistive.) V_K is the cathode voltage to ground. V_{G1} is the control grid voltage, relative to ground, required at the first pentode to obtain the tabulated anode currents. It is obtained by reading the required V_{GK1} from figure 1 and adding V_K (i.e. $V_{G1} = V_{GK1} + V_K$). (The control grid voltages labelled * in the table are not strictly required as the valve is cut off for any grid voltage less than -2.0 volts in this case.)

The relationship between V_{G1} and I_L is the input/output relationship of the push-pull stage and if expressed as a ratio $\Delta I_L / \Delta V_{G1}$ is a transconductance, which could very loosely be described as the 'g_m' of the entire push-pull stage including its load. (Strictly speaking g_m is a well defined parameter of a single valve.) It can be seen from the table that increasing the (transformed) loudspeaker current (I_L) from 0.0 to 0.12 amps requires a change in control grid voltage (ΔV_{G1}) of 2.0 volts, whereas a further 0.12 amp increase in (transformed) loudspeaker current would require a ***further*** change in control grid voltage of 4.0 volts. This shows the inherent non-linearity in class AB due to 'g_m doubling', which has been discussed in references [1] and [2].

Case 2: Shared Cathode Resistor without Bypass Capacitor

At the quiescent point the combined cathode current (I_K) for both valves is again 0.138 amps, and the shared cathode resistor is 57.97 Ohms, as previously. Cathode voltage $V_K = I_K \times 57.97$. Now that the cathode voltage is not being held constant by a bypass capacitor, we have created local negative feedback from the anode current (combined with the screen current) to the control grid voltage. We can obtain the following table:

I_{A1} (amps)	I_{A2} (amps)	I_K (amps)	I_L (amps)	V_K (volts)	V_{G1} (volts)
0.30	0.0	0.345	0.30	20.0	20.0
0.27	0.0	0.3105	0.27	18.0	17.0
0.24	0.0	0.276	0.24	16.0	14.0
0.21	0.0	0.2415	0.21	14.0	11.0
0.18	0.0	0.207	0.18	12.0	8.0
0.15	0.0	0.1725	0.15	10.0	5.0
0.12	**0.0**	**0.138**	**0.12**	**8.0**	**2.0**
0.09	**0.03**	**0.138**	**0.06**	**8.0**	**1.0**
0.06	**0.06**	**0.138**	**0.0**	**8.0**	**0.0**
0.03	**0.09**	**0.138**	**-0.06**	**8.0**	**-1.0**
0.0	**0.12**	**0.138**	**-0.12**	**8.0**	**-2.0**
0.0	0.15	0.1725	-0.15	10.0	-5.0 *
0.0	0.18	0.207	-0.18	12.0	-8.0 *
0.0	0.21	0.2415	-0.21	14.0	-11.0 *
0.0	0.24	0.276	-0.24	16.0	-14.0 *
0.0	0.27	0.3105	-0.27	18.0	-17.0 *
0.0	0.30	0.345	-0.30	20.0	-20.0 *

Table 2: Shared Cathode Resistor without Bypass Capacitor

Note that the local negative feedback does not occur in the class A region, where the combined cathode current remains constant. In this case, increasing the (transformed) loudspeaker current from 0.0 to 0.12 amps requires a change in control grid voltage of 2.0 volts as before, whereas a further 0.12 amp increase in (transformed) loudspeaker current now requires a ***further*** change in control grid voltage of 12.0 volts. The inherent non-linearity has been greatly increased. Within the class A region the 'g_m' value is now ***six times greater*** than in the class B region (g_m sextupling!). The push pull output stage in this case behaves exactly the same as case 1 while it is in the class A region, but once one of the valves reaches cut-off there is much less gain and we now need a higher swing in grid voltage to overdrive the stage.

Case 3: Individual Cathode Resistors without Bypass Capacitors

At the quiescent point the individual cathode current (I_{K1}) for one valve is 0.06 x 1.15 = 0.069 amps. To obtain our stated bias voltage we need an individual cathode resistor (R_{K1}) of 8 / 0.069 = 115.94 Ohms. We can now obtain the following table:

I_{A1} (amps)	I_{A2} (amps)	I_{K1} (amps)	I_L (amps)	V_{K1} (volts)	V_{G1} (volts)
0.30	0.0	0.345	0.30	40.0	40.0
0.27	0.0	0.3105	0.27	36.0	35.0
0.24	0.0	0.276	0.24	32.0	30.0
0.21	0.0	0.2415	0.21	28.0	25.0
0.18	0.0	0.207	0.18	24.0	20.0
0.15	0.0	0.1725	0.15	20.0	15.0
0.12	**0.0**	**0.138**	**0.12**	**16.0**	**10.0**
0.09	**0.03**	**0.1035**	**0.06**	**12.0**	**5.0**
0.06	**0.06**	**0.069**	**0.0**	**8.0**	**0.0**
0.03	**0.09**	**0.0345**	**-0.06**	**4.0**	**-5.0**
0.0	**0.12**	**0.0**	**-0.12**	**0.0**	**-10.0**
0.0	0.15	0.1725	-0.15	0.0	-15.0 *
0.0	0.18	0.207	-0.18	0.0	-20.0 *
0.0	0.21	0.2415	-0.21	0.0	-25.0 *
0.0	0.24	0.276	-0.24	0.0	-30.0 *
0.0	0.27	0.3105	-0.27	0.0	-35.0 *
0.0	0.30	0.345	-0.30	0.0	-40.0 *

Table 3: Individual Cathode Resistors without Bypass Capacitors

In this case, increasing the (transformed) loudspeaker current from 0.0 to 0.12 amps requires a change in control grid voltage of 10.0 volts, whereas a further 0.12 amp increase in (transformed) loudspeaker current requires a ***further*** change in control grid voltage of 20.0 volts. We have low overall gain due to the local negative feedback, but are back to the usual g_m doubling effect.

Case 4: Individual Cathode Resistors with Bypass Capacitors

From the point of view of this analysis, the behaviour in this case is the same as in case 1.

Impact in Practice

The above cases are perhaps interesting from a technical point of view, but what is the practical impact for guitar tone? Firstly, it should be noted that global negative feedback will reduce the g_m multiplying effects, but perhaps the effect would be audible in amplifiers without global negative feedback (VOX AC30, Marshall 18W, and many others). Secondly, the non-linear behaviour of a real pentode, in which the 'grid lines' bunch closer together (i.e. the real g_m of the valve reduces) as I_{A1} approaches cut-off, would also tend to mask the effect. The g_m multiplying effect is a change in slope of the input / output characteristic of the stage, which will be much less audible than clipping. Nevertheless, the drastic change in slope in case 2 could well produce audible results. Listening tests would need to be rather subtle, as the effect would be absent when the amplifier is operated at low power (class A operation) and would be swamped by clipping at full overdrive.

Output Impedance

The local negative feedback under AC conditions, which is a consequence of removing bypass capacitor(s), will also result in an increase in the output impedance of the push-pull stage. The amount of this increase is unlikely to be very significant, however, as the output impedance of a pentode push-pull stage is already relatively high.

Self Balancing Effects

It is worth mentioning the effect of shared and individual cathode resistors on quiescent current balancing. If the two output pentodes are not perfectly matched then a shared cathode resistor ensures that both valves receive the same bias voltage, but their quiescent currents will be different. For poorly matched valves this could result in one running 'too cool' and the other 'too hot'.

Individual cathode resistors apply local negative feedback to each valve separately. This feedback is effective for the DC quiescent condition whether a bypass capacitor is present or not. Each pentode will tend to bias itself close to the desired current, but for mismatched valves the bias voltages will be different. (We are assuming that the cathode resistors are closer to each other in tolerance than the valves are.) A benefit of good quiescent current balance, between the push and pull sides, is that quiescent DC in the output transformer is reduced. The transformer has very low input resistance to DC and will be saturated magnetically if the quiescent DC is too high.

Bias-Shift in Continual Overdrive Conditions

Whenever operation repeatedly enters the class B region over a period of time, the average cathode current increases, and if a bypass capacitor is present the bias voltage will increase (in accordance with the time-constant of the cathode resistor and bypass capacitor). If the stage is continually over-driven, the bias voltage will increase still further, due to additional cathode current contributions from higher screen current and grid current. The shift of bias voltage under continual overdrive conditions can be very significant and can 'cool' the bias of the stage to such an extent that class C operation occurs, resulting in significant cross-over distortion. This type of bias shift cannot happen if bypass capacitors are absent. (Bias shift associated with grid blocking can still occur, however.)

Push-Pull Quartets

If there are four pentodes in push-pull parallel pairs we have an even wider range of cathode biasing options. Labelling the 4 valves: $Push_1$, $Push_2$, $Pull_1$ and $Pull_2$,we note the following:

- All four pentodes sharing a cathode resistor will either be similar to case 1 (if there is a bypass capacitor) or case 2 (no bypass capacitor). All four valves would need to be well matched to avoid unbalanced quiescent currents.

- Sharing one cathode resistor between $Push_1$ and $Pull_1$ and sharing a second cathode resistor between $Push_2$ and $Pull_2$ would also be similar to case 1 or case 2.

- Sharing one cathode resistor between $Push_1$ and $Push_2$ and sharing a second cathode resistor between $Pull_1$ and $Pull_2$ is similar to case 3 or case 4.

- Sometimes, if only one or two valves of a quartet need replacing, we may wish to purchase a 'matched pair' rather than a 'matched quartet'. The question then arises whether to use one matched pair for $Push_1$ and $Pull_1$ and the other matched pair for $Push_2$ and $Pull_2$ (which would seem natural) or we could use one matched pair for $Push_1$ and $Push_2$ and the other for $Pull_1$ and $Pull_2$. The first option is best for output waveform balance. However, if we have a cathode resistor on the push side and a separate cathode resistor on the pull side, then the second option may be better for overall quiescent current balance.

- Individual cathode resistors for each pentode would provide well balanced quiescent currents, even with poorly matched valves.

Conclusions

It is easy to see which of the above cases would be preferred for hi-fi; actually none of them! Pure class A and/or significant global negative feedback would be the way to go. However, for guitar amplifiers, where distortion (ranging from 'very subtle almost inaudible' to 'outrageously fuzzy') is generally welcome, the choice is not so clear. Bench and listening tests would be needed to evaluate the impact of g_m multiplication, balancing to reduce transformer quiescent magnetisation, bias shift, etc. It is hoped that the present article helps to clarify some of the technical aspects and presents 'food for thought' for designers and experimenters.

References

[1] 'Distortion in Class AB without Negative Feedback', (Irving Amplification website to appear)

[2] 'Distortion in Class AB – Diagrammatic Explanation', (Irving Amplification website to appear)