The Cathode Follower and Its Weaker Siblings

This author's results confirm that cathode followers are even more capable of driving capacitive loads than equivalent common-cathode amplifiers.

By Christopher Paul

In a recent article ("Rehabilitating Cathode Followers," *aX* 5/06), I compared the abilities of the Cathode Follower (CF) and the Common Cathode Amplifier (CCA) to drive capacitive loads. I showed that CFs and CCAs made from identical triodes biased to identical plate voltages and currents and driving identical loads "disconnected" from their loads at the same peak currents and voltages—one on the load voltage downswing, and the other on the upswing. The article also discussed that the higher output impedance of the CCA left it at a disadvantage when it came to driving capacitive loads—that is, attenuation occurred more readily at higher frequencies for the CCA.

In a subsequent exchange of private letters, it was pointed out that the CCA could address this deficit by paralleling resistances across a capacitive load (thus extending bandwidth) and then increasing drive to reestablish the original level. However, it also became clear that these higher drive levels would increase distortion at the mid and low frequencies and limit the peak voltage across the load. It seemed that the CF still retained the advantage.

If the CF is the preferred driver for capacitive loads, it makes sense to more fully explore and understand its characteristics, which you should consider in comparison to those of CF-like circuits that nevertheless operate distinctly differently from a CF. Over the years, I have noticed that some people attribute CF-like characteristics to many CF-like circuits, apparently mainly because their outputs are cathodes. Recently, I found a manufacturer selling a preamp with an SRPP output stage that claimed to have a CF-like output impedance. The manufacturer subsequently confirmed by measurement, to his surprise, that the SRPP does not have the output impedance of a CF, and changed the specification accordingly. A similar assertion regarding an SRPP with a "low output impedance" was made even more recently in the pages of *audioXpress* (p. 10, 10/06.) I'd like to explore this and other differences between the CF and its variants in the rest of this article.

THE CIRCUITS UNDER INVESTIGATION

There's value both in performing circuit derivations and in building and measuring the circuit on the bench. There's no

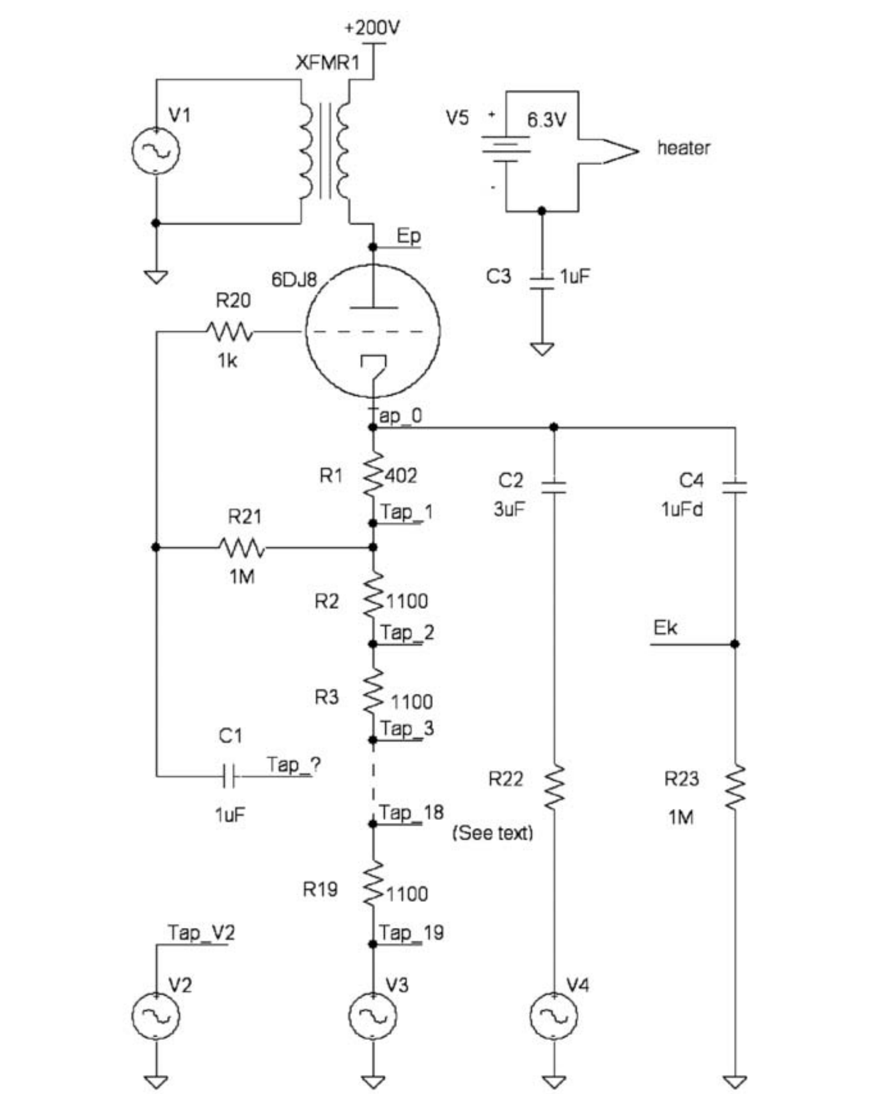

FIGURE 1: Circuit for testing a CF, and SRPP or an MF.

denying bench results, but a validated derivation is priceless when it comes to getting a feel for how a circuit works and for applying and optimizing it. So I'll start with a general-purpose schematic (**Fig. 1**) that illustrates the CF and its variants and how to test them.

I'll present measurements and calculations I made from them in **Tables 1** and **2** to determine certain circuit parameters of interest. I'll also provide calculations (**Table 3**) of the same parameters using the equations I derived in the sidebar. If you're not interested in the derivations, you can skip the sidebar, although I think you'll gain some insight if you review it. I'll compare and discuss the results of the measurements and the derived equations later.

In **Fig. 1**, 1100Ω resistors R2-R19 are strung together with 402Ω R1. You can conveniently connect each point between a connected pair of resistors to Tap_? (one side of C1), affording a means to test different cathode follower (CF) variants. A connection of Tap_? to Tap_V2 produces a cathode follower. A connection to Tap_1 yields the top of an SRPP (although in this case, C1 is not really needed). Connections to Taps 2-19 yield the top of a Mu Follower (MF), while a connection to Tap_0 provides a convenient means of measuring the r_p (plate resistance) of the 6DJ8, as I'll show.

For the SRPP and MF, think of V3 and the resistors between it and the connection to Tap_? as the controlled source and the resistance seen at the plate of the bottom triode in those two-triode configurations. With the CF, V3 is uniformly 0 (V2 is the active source), and the resistors from R1-R19 are simply cathode resistors. Note that the DC bias of the triode is fixed for all variants at a 5mA plate current and a 100V plate voltage with the 6DJ8 I used.

Only one of the very low impedance (under 10Ω) sources V1-V4 supplies a signal at any time; consider the remainder to be short circuits. These 1kHz signal sources are used to support the measurement of three important parameters of the circuits I'm examining.

GAIN, OUTPUT IMPEDANCE, AND POWER-SUPPLY REJECTION RATIO (PSRR)

These three parameters represent excellent figures of merit for a circuit. Consider the equations (derived in the sidebar) which determine them in the **Fig. 1** circuit. Capacitors are assumed to be AC shorts and the 1M resistors are AC open circuits. R_T is defined as the sum of R1 + R2 +. . . R19. For SRPPs and MFs, R_k is the value of that portion of R_T between Tap_0 and the selected connection (Tap_0, Tap_1,. . . Tap_19) to Tap_?. For CFs, $R_k = R_T$. r_p and g_m are the plate resistance and transconductance, respectively, of the 6DJ8.

Measure output impedance (Z_0) by first activating V4 and setting R22 to a finite, non-zero value (I used 1100Ω in my measurements, but its value is unimportant in the derivation). Other sources are off and E_p is shorted to +200V. De-

TABLE 1: MEASUREMENTS AND THE CALCULATIONS OF GAIN, ZO, AND PSRR FROM THEM.

Rk Ω	Ek, mV RMS (Z_0 test)	I_{R22}, mA RMS (Z_0 test)	$Z_0 = Ek/i_{R22}$Ω (Z_0 test)	Ek/V3 for MF & SRPP: Ek/V2 for CF (gain test)	Ep/Ek (PSRR test)	Comments
0	398.0	0.093	4292	0.217	1.3	test for r_p
402	364.0	0.124	2943	0.483	1.9	SRPP
1502	287.0	0.194	1483	0.727	3.5	MF
2602	240.0	0.236	1018	0.812	5.1	MF
3702	204.6	0.268	762	0.858	6.7	MF
4802	180.9	0.290	624	0.886	8.3	MF
5902	161.6	0.307	526	0.906	9.9	MF
7002	145.7	0.322	453	0.922	11.5	MF
8102	132.3	0.334	396	0.934	13.1	MF
9202	124.7	0.341	366	0.942	14.6	MF
10302	114.4	0.350	326	0.946	16.3	MF
11402	106.3	0.358	297	0.950	17.8	MF
12502	100.8	0.363	278	0.952	19.4	MF
13602	95.0	0.368	258	0.958	21.0	MF
14702	89.0	0.373	238	0.962	22.6	MF
15802	84.8	0.377	225	0.966	24.1	MF
16902	79.7	0.382	209	0.966	25.8	MF
18002	73.8	0.387	191	0.968	27.5	MF
19102	69.9	0.391	179	0.970	29.1	MF
20202	68.1	0.392	174	0.972	30.8	CF and g_m test
R_T = 20202				V2 = V3 = 500mV RMS	Ep = 1V RMS	

TABLE 2: CALCULATIONS OF RP AND GM FROM MEASUREMENTS USING

$Z_0 = 1/(1/R_P + (1 + G_M \times R_K)/R_T))$

R_TΩ	RkΩ	Ek, mV RMS (Z_0 test)	i_{R22}, mA RMS (Z_0 test)	$Z_0 = Ek/i_{R22}$ Ω (Z_0 test)	r_p Ω	g_m 1/Ω
20202	0	398	0.093	4292	5450	
20202	20202	68.1	0.392	174		0.00553

termine Z_0 by the ratio of the cathode voltage to the cathode current fed through R22 and C2, as was derived in the sidebar:

Z_0 (measured) = E_k/I_{R22}
Z_0 (derived) = $1/(1/r_p + (1 + g_m \times R_k)/R_T)$

The Power-Supply Rejection Ratio (PSRR) specifies how well power-supply noise is rejected at the circuit output. Measure it by first activating V1. Other sources are off and R22 is removed. PSRR is determined by the ratio of E_p/E_k (which is always greater than 1 and improves as it increases in value). I also derived PSRR in the sidebar:

PSRR (measured) = E_p/E_k
PSRR (derived) = r_p/Z_0

Measure gain by first activating source V2 for a CF or V3 for an SRPP or an MF. Other sources are set to 0, Ep is shorted to +200V, and R22 is removed. Gain is determined by the ratio of E_k to the level of the active source (V2 or V3) and was derived in the sidebar:

$Gain_{M,S}$ (measured) = $E_k/V2$
$Gain_{M,S}$ (derived) = $((1 + g_m \times R_k)/R_T) \times Z_0$

for the MF and SRPP and

$Gain_{CF}$ (measured) = $E_k/V3$
$Gain_{CF}$ (derived) = $g_m \times Z_0$

for the CF.

TABLE 3: CALCULATIONS OF GAIN, ZO, AND PSRR FROM THE SIDEBAR DERIVATIONS, USING TABLE 2 VALUES OF R_P AND G_M.

RkΩ	Z_0Ω	gain	PSRR	Comments
0	4292	0.212	1.3	
402	2916	0.465	1.9	SRPP
1502	1553	0.715	3.5	MF
2602	1059	0.806	5.1	MF
3702	803	0.853	6.8	MF
4802	647	0.881	8.4	MF
5902	541	0.901	10.1	MF
7002	466	0.915	11.7	MF
8102	408	0.925	13.3	MF
9202	364	0.933	15.0	MF
10302	328	0.940	16.6	MF
11402	298	0.945	18.3	MF
12502	274	0.950	19.9	MF
13602	253	0.954	21.5	MF
14702	235	0.957	23.2	MF
15802	220	0.960	24.8	MF
16902	206	0.962	26.5	MF
18002	194	0.964	28.1	MF
19102	183	0.966	29.7	MF
20202	174	0.968	31.4	CF

R_T = 20202

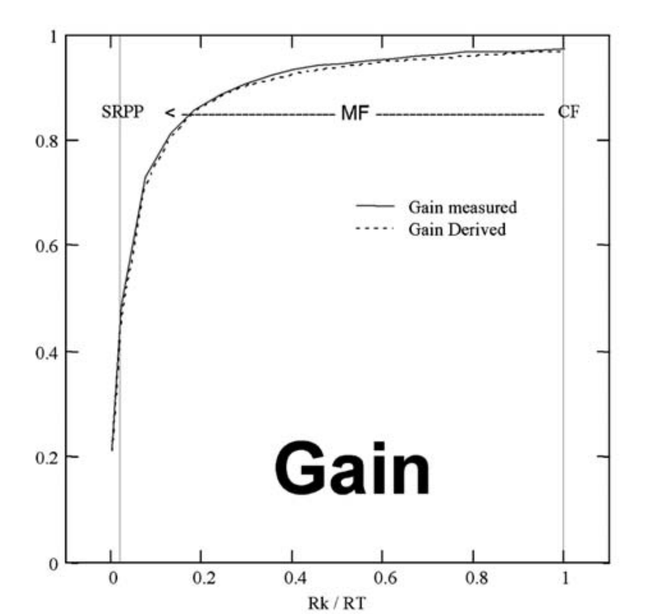

FIGURE 3: Measured and derived values of gain vs. R_k/R_T.

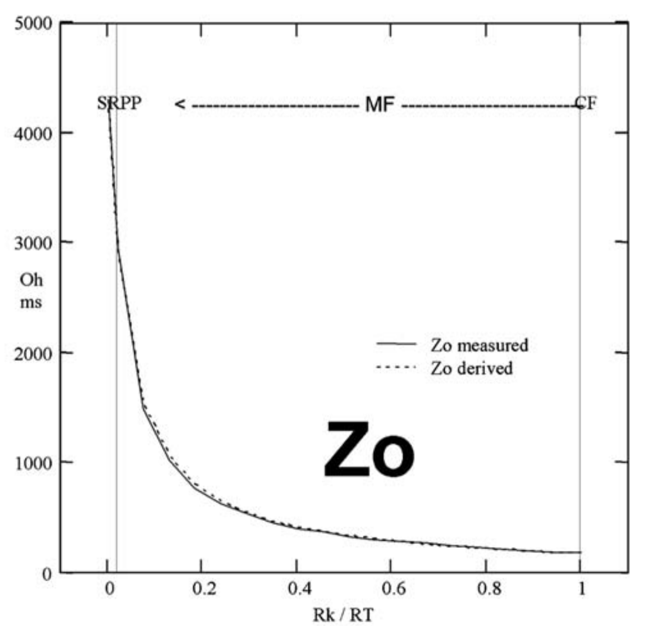

FIGURE 2: Measured and derived values of output impedance vs. R_k/R_T.

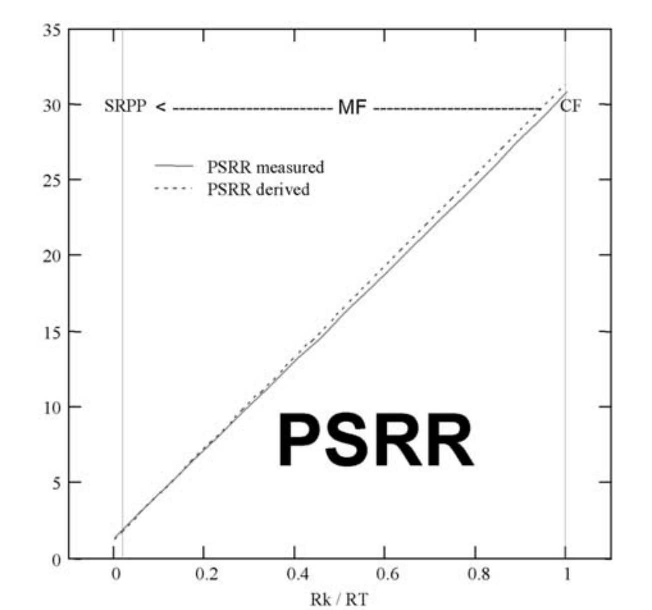

FIGURE 4: Measured and derived values of PSRR vs. R_k/R_T.

MEASUREMENTS AND CALCULATIONS

A summary of the measurements I made is given in **Table 1**, which also contains the values of the parameters Gain, Zo, and PSRR calculated from those measurements. You can also calculate those same parameters (**Table 3**) from their derivations if you first calculate g_m and r_p (**Table 2**) from certain measurements listed in **Table 1**. (You could read g_m and r_p from a chart of plate curves, but it is better to use the values of the tube under test to properly compare measured and derived results.) Comparing calculations from the measurements and the derivations validates both, and can be done graphically (**Figs. 2**, **3**, and **4**), or more tediously and precisely from **Tables 1** and **3**.

ANALYSIS

A glance at the three graphs tells the story. The gold standard for performance is the CF with the highest gain and PSRR and the lowest Z_0. The SRPP top is the worst, quite a bit poorer than the CF. The MF top occupies a range between the two.

Why is the SRPP so poor? Two words: positive feedback (from the cathode to the grid). The grid is so close to the cathode electrically that very little AC voltage develops between the two terminals to drive the transconductance, so Z_0 suffers. The desired source for the grid, V3, is not that much closer electrically than the plate, so the PSRR suffers. And the triode acts more like a simple resistive load than a controlled source, so the gain suffers.

The MF is an attempt to win back some of the CF's stellar AC performance by reducing the amount of positive feedback from the cathode to the grid. It does this by maximizing the ratio of R_k to R_T. The ratio can't get all that close to 1 because of the "plate resistance" (the part of R_T which is not R_k) of the "triode" (whose other part is V3). Practical factors limiting the ratio include 1) the voltage drop across R_k, which must be made up by the plate supply if the MF bias is to be maintained, and 2) heater-cathode voltage ratings if the entire MF is made from one dual triode. Fortunately, even modest voltage drops across R_k can make a big difference.

Consider the case where another 6DJ8 and R1 form the bottom part of an MF by replacing V3 and the portion of R_T which is not R_k. The resistance seen at the plate would be R1 × (1 + g_m × r_p) + r_p = 18K (see **Table 2** for values of g_m and r_p). This would be similar to an MF where Tap_? was connected to Tap_3, increasing R_k/R_T to about .13 from the .02 of the SRPP. The drop across R2 + R3 adds only 11V, but the MF's Z_0 improves over that of the SRPP by a factor of about 3, the PSRR improves by a factor of about 2.5, and the Gain almost doubles (see **Tables 1** or **3** or **Figs. 2–4**). It's easy to achieve even greater improvement by further modest increases in the value of R_k. You can see this yourself by substituting larger values for R_k into the derived equations.

But why not use the CF in place of the MF top? Because the MF provides a much higher impedance load to the plate of the "bottom" triode than would a plate resistor that would need to be used in its place along with a CF. And common cathode triode gain stages love high impedance plate loads for maximizing gain and PSRR and minimizing distortion. Also, the excellent PSRR of the CF is rendered useless by the poor PSRR of the resistively plate-loaded stage driving it. To make full use of the CF PSRR, you need to drive it from a low PSRR circuit such as cascade feedback pair with a good amount of open loop gain.

CONCLUSION

I believe this kind of result should make you think twice about using an SRPP. But if you still decide to use one, now you can calculate exactly what you're losing by doing so! *aX*

DERIVATIONS OF GAIN, Z0, AND PSRR

Refer to **Fig. 1**. Capacitors are assumed to be AC shorts and 1M resistors are AC opens. R_T is defined as the sum of R1 + R2 +. . . R19. R_k is the value of that portion of R_T between Tap_0 and the connection to Tap_? for SRPPs and MFs, or simply R_T for CFs. rp and gm are the plate resistance and transconductance, respectively, of the 6DJ8. All derivations start from the knowledge that the sum of all currents flowing out of a node is zero (else there would be net accumulation of charge).

Determine the equation for output impedance Z_0. Here, E_p is shorted to +200V, and V1, V2, and V3 are set to 0. I_{R22} is the current through R22. The sum of the currents out of node E_k are:

$$-I_{R22} + E_k/r_p + E_k/R_T - g_m \times E_k \times ((R_T - R_k)/R_T - 1)$$

$$E_k \times (1/r_p + 1/R_T + g_m \times R_k/R_T) = I_{R22}$$

$$E_k / I_{R22} = 1/(1/r_p + 1/R_T + g_m \times R_k/R_T)$$

Z_0 = Voltage across the output/Current into output = $E_k/I_{R22} = 1/(1/r_p + (1 + g_m \times R_k)/R_T))$

$$\mathbf{Z_0 = 1/(1/r_p + (1 + g_m \times R_k)/R_T))}$$

Determine the equation for the PSRR. Here V2, V3, and V4 are set to 0V and R22 is open (not used). The sum of the currents out of node E_k are:

$$(E_k - E_p)/r_p + E_k/R_T - g_m \times E_k \times ((R_T - R_k)/R_T - 1)$$

$$E_k \times (1/r_p + 1/R_T + g_m \times R_k/R_T) - E_p/r_p = 0;$$

$$E_k/Z_0 - E_p/r_p = 0$$

$$\mathbf{PSRR = E_p/E_k = r_p/Z_0}$$

Determine the equation for gain for the MF and SRPP. Here V1, V2, and V4 are set to 0, and R22 is open (not used). E_p is shorted to +200V. The sum of the currents out of node E_k are:

$$E_k/r_p + (E_k - V3)/R_T - g_m \times ((E_k \times (R_T - R_k)/R_T + V3 \times R_k/R_T) - E_k)$$

$$E_k \times (1/r_p + 1/R_T + g_m \times R_k/R_p) = V3 \times (1 + g_m \times R_k)/R_T$$

$$\mathbf{Gain_{M,S} = E_k/V3 = ((1 + g_m \times R_k)/R_T) \times Z_0}$$

Determine the equation for gain for the CF. Tap_? is connected to Tap_V3, V1, V3, and V4 are set to 0, and R22 is not used. E_p is shorted to +200V. The sum of the currents out of node E_k are:

$$E_k/r_p + E_k/R_T - g_m \times (V2 - E_k)$$

$$E_k/r_p + E_k/R_T + g_m \times E_k = g_m \times V2$$

$$\mathbf{Gain_{CF} = E_k/V2 = g_m/Z_0 = g_m/(g_m + 1/r_p + 1/R_T)}$$