THE CATHODE FOLLOWER

What It Does and How It Does It

By "CATHODE RAY"

> Radio Mech: "May I be excused Church Parade?"
> Sergt-Major: "Religion?"
> Radio Mech: "I'm a Cathode Follower."
> Sergt-Major: "One of the awkward ones, eh? Well, I suppose you'd better fall out."

ONE of the ways television and radar specialists have of creating an impression that theirs is real big medicine, too hard for the "ordinary" radio man, is to talk a lot about using cathode followers. Any explanations they condescend to give are generally wrapped up with sufficient mathematics to intensify that impression. So here are some—I hope—simple answers to such simple questions as: What is a cathode follower? Why is it so called? What does it do? And how does it do it?

Fig. 1a shows the familiar resistance-coupled amplifier, omitting all incidentals such as grid bias arrangements. Alongside for comparison is a cathode follower, also reduced to bare essentials. The only difference is that the load, the thing across which the output voltage comes, is on the cathode side of the valve instead of on the anode side. This apparently slight modification leads to remarkable differences in performance. But before we go on to that, I ought to mention that although resistance couplings, shown in these two circuits, are the commonest and (what is more to my point!) the simplest for purposes of explanation, it is possible to use other sorts of coupling—choke, transformer, etc.

Why is Fig. 1b called a cathode follower? That will emerge later. What does it do? Unlike Fig. 1a, it cannot amplify the signal voltage fed to it, but it can be used as a current amplifier over a very wide range of frequency, in particular, it is useful as a coupling between a high impedance and a low impedance, because a direct connection between them would cause signal loss and distortion A slight elaboration of the cathode follower used to be called the "infinite impedance detector." but I believe it is now more usual for the relationship to be openly acknowledged by naming it a "cathode follower detector." It all sounds very sleuthy.

Referring again to Fig. 1a, when a signal voltage (within the limits the valve can handle) is applied between the points marked INPUT, a magnified signal voltage is given at OUTPUT. The amount of the magnification (the number of times the output voltage is greater than the input) depends on the characteristics of the valve and on R; let us call it A. If it were practicable to make R such a high resistance that in comparison the resistance of the valve, r_a, was negligible, then A would be practically equal to the amplification factor, μ, of the valve. With a typical triode valve having a μ of 35 and r_a of 10,000 ohms, if R is 25,000 ohms A is 25, so one volt input would give 25 volts output. (The well-known formula connecting these is $A = \mu R/(R + r_a)$. Sorry about all this dull recapitulation, but, like an army of invasion, we must have a springboard)

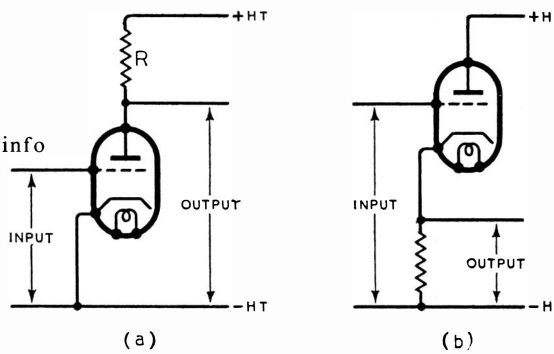

Fig. 1. Comparison between ordinary resistance-coupled amplifier (a) and the cathode follower (b).

Now reconnect this amplifier as a cathode follower, Fig. 1b. The points marked INPUT are no longer the effective input terminals of the valve. The only input voltage a valve takes any notice of is that between its own grid and cathode; and now we have both INPUT and OUTPUT voltages connected in series between those two points. As therefore we can't calculate the effective input until we know the output voltage, and that depends on the effective input, it begins to look like a vicious circle. To break it up let us suppose that 1 signal volt exists between grid and cathode, and see where it leads us. The fact that R is on the cathode side of the valve instead of on the anode side does nothing to prevent A volts appearing across it, exactly as in Fig. 1a. So we now know, for this particular case, the signal voltage between grid and cathode, and also that between cathode and − HT; and it is only necessary to combine them in order to get the voltage from grid to − HT, which is the required input voltage. The only possible catch is whether the output voltage must be added to that between grid and cathod or subtracted from it. To settle this, assume the grid is being driven in the positive direction. That causes more anode current to flow, increasing the voltage drop across R and making the cathode more positive. So the A volts across R are directly added to the 1 volt between grid and cathode, as in Fig. 2; and therefore the INPUT signal voltage necessary to deliver the assumed

1 volt to the valve must be A + 1. Therefore, however much the valve itself may amplify, the output (A) can't help being always less than the input (A + 1). With the valve and resistance assumed for Fig. 1a, reconnected as a cathode follower, it would be necessary to put in 25 volts in

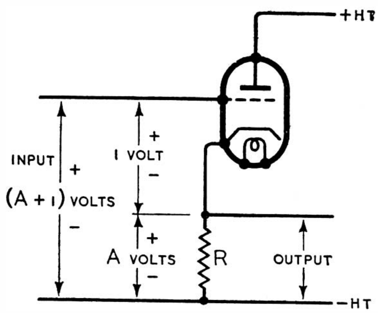

Fig. 2. If the valve, in conjunction with R, gives an A-fold amplification, used as a cathode follower its over-all "amplification" is A/(A+1), which is inevitably less than 1.

order to get 24 out; 1 volt actually to drive the valve, and 24 volts to neutralise the output voltage, which is being fed back in opposition to the INPUT. If A, the amplification of the valve, is 10, then 11 must be supplied to the cathode follower for every 10 to be taken out; and so on.

At first sight this may look a particularly silly way of using a valve. To understand the value of the cathode follower it is necessary to study it more closely. Up to the moment we have found out it differs from the ordinary resistance-coupled stage (Fig. 1a) in the following ways :—

(*a*) The voltage "amplification" is A/(A+1), instead of A.

(*b*) The "live" side of the output—the cathode—goes more positive when the grid is made more positive (and *vice-versa*); in other words, the output is in the same phase as the input, instead of being inverted as it is in Fig. 1a.

Following this up for our example in which A is 25 and the signal input is making the grid 1 volt more positive (reckoned from —HT as zero), compare the two systems again in Fig. 3. (Here, as everywhere in this story, only the signal voltages are counted. The steady voltage drop in R, and the grid bias voltage, although present, are ignored.) In (*a*) the 1 volt input is magnified by 25 and reversed at the anode, which is therefore —25 volts. So there is a difference of 26 volts between grid and anode. The dotted condensers in Fig. 3 represent the capacitances between grid and anode (C_{ga}) and grid and cathode (C_{gc}), made up of the valve electrode and connection capacitances, including the wires leading to the electrodes. Generally a valve itself contributes about 5$\mu\mu$F, and for illustration we shall take typical total values of 10$\mu\mu$F each for C_{ga} and C_{gc}. That is when the valve isn't working. When it is working, for every volt applied to the grid 26 volts appear between grid and anode. The amount of electricity that the source of the signal has to supply to charge up the grid-to-anode capacitance is therefore 26 times as great when the valve is working as when it is not; so this capacitance, for all practical purposes, is 26 times as great; namely, 260$\mu\mu$F. Believe it or not.

There is no such jiggery-pokery about C_{gc}, which has only the 1 signal volt across it, and so is 10$\mu\mu$F, live or dead. Total, 270$\mu\mu$F.

Now if the source of the signal is a high-μ valve, or a photo-electric cell, or any other high-impedance device, and the signal includes high frequencies, or sudden changes as in pulses (the same thing, really), this is serious 270$\mu\mu$F at a frequency of, say, 100 kc/s, is about 6,000 ohms. Shunted across a high impedance, it is going to cause serious loss of the high-frequency parts of a signal. The effect is a rounding-off of pulses or other sharp-cornered signals used in television, radar, and high-speed telegraphy. By the way, this capacitance-multiplying by-product of amplification is the celebrated Miller effect.

The position can be greatly eased by using a screened tetrode or pentode, having such a small C_{ga} that even when multiplied by A + 1 it is not likely to amount to much. It does introduce a C_{gs} however—capacitance from grid to screen—so that the grand total in a typical case might be 25$\mu\mu$F. But that is a vast improvement. The cathode follower does better still, because it has a sort of inverted Miller effect. Look at Fig. 3b. Putting +1 signal volt on the grid causes the cathode also to go all but 1 volt positive; twenty-five twenty-sixths of a volt in this case, to be exact. The potential of the cathode *follows* that of the grid pretty closely wherever it goes. For every one signal volt put on the grid of a cathode follower, the voltage across the grid-to-cathode capacitance is only the small difference between input and output voltages, 1/(A+1) volt—in our example one twenty-sixth, and the effective or working capa-

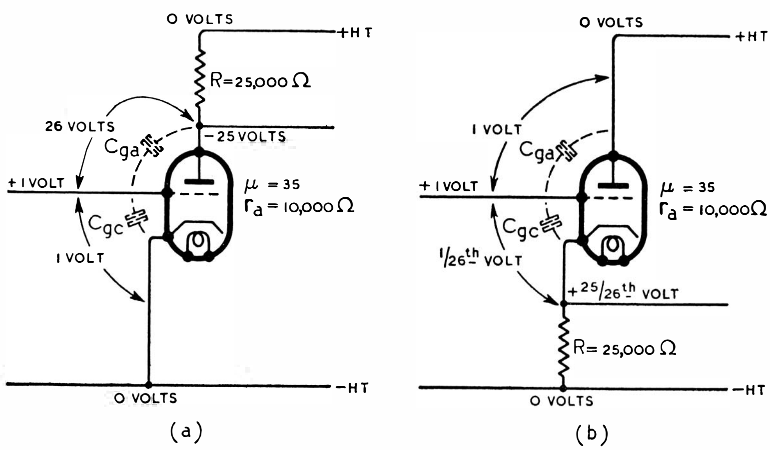

Fig. 3. More detailed comparison of cathode follower (b) with ordinary amplifier (a), showing the effect on the input capacitance in a typical example.

The Cathode Follower—

citance is in the same proportion; so we have $\frac{10}{26}$ or about $0.4\mu\mu F$. C_{ga} is its normal $10\mu\mu F$, so the total is $10.4\mu\mu F$. With a little care regarding C_{ga}, this figure could be improved upon. Whatever can be done by the other systems as regards minimising input capacitance, the cathode follower can beat it.

The same goes for stray resistance shunting, which is a rather more complicated subject. But it all adds up to this, that the cathode follower has an exceptionally high input impedance, and causes a minimum of loss or distortion in any circuit to which it is connected.

This alone is not so very helpful. If its own *output* impedance were also very high, nothing would be gained. The great value of the cathode follower is that its output impedance is extremely low—lower than that of any other high-impedance input system without a step-down transformer. And compared with a step-down transformer, the cathode follower throws away hardly any signal voltage, and can easily be made to cover a frequency range from zero up to megacycles per second.

Reducing Distortion

How this works can be seen by feeding a rather low-impedance load—a resistance of 500 ohms, say, from each of our Fig. 3 systems in turn. It makes very little difference whether the load is connected in parallel with R or substituted for it. (500 ohms in parallel with 25,000 is just over 490 ohms). For easy arithmetic let us substitute. Then in Fig. 3a, the new amplification—call it A′—is $(35 \times 500)/(500 + 10{,}000)$ or $1\frac{2}{3}$, a catastrophic fall from 25! If this amplifier is part of a system that has to work over a very wide range of frequency, it is likely that impedances may vary over such a range as 500 to 25,000, with consequent enormous variations in amplification; this result is commonly called frequency distortion.

Substituting A′ for A in Fig. 3*b*, we get an output of $\frac{5}{8}$ volt instead of $\frac{25}{26}$—a comparatively slight drop.

Even this will no doubt fail to sell the cathode follower idea to some readers, who will be pointing out that if the orthodox amplifier has a 500-ohm resistor permanently connected, the amplification will be tied down to something in the region of $1\frac{2}{3}$ over the very wide range of impedance it may have to feed into; and $1\frac{2}{3}$, although small, is at least bigger than the cathode follower's miserable $\frac{5}{8}$.

Part of the answer is that, whatever the range of impedance may be, the cathode follower's output

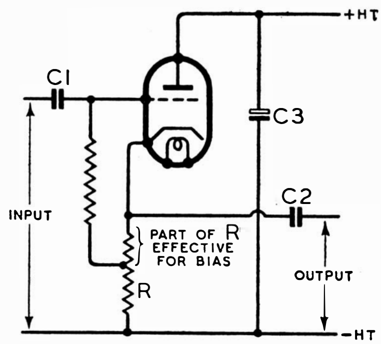

Fig. 4. Practical cathode follower circuit, showing tapping for reducing grid bias, blocking condenser (C2) to keep DC out of output, and by-pass condenser (C3) to keep anode potential steady.

varies less than the amplifier's on that account. This is not easy to prove other than mathematically, but it can be seen in a general way by considering what happens if the load resistance to which a cathode follower is connected is reduced. The amplification of the valve is reduced accordingly, so the output voltage drops. But in doing so it releases more of the input voltage to drive the valve, so largely offsetting the drop in valve amplification.

This is, in fact, a result of the cathode follower being an extreme case of *negative feedback*; one in which *all* the output voltage is fed back in opposition to the input. Great constancy of output voltage for a given input is one of the features of negative feedback. Another feature—reduction of distortion—supplies the more important part of the answer to the question of why the cathode follower is to be preferred for feeding low impedances. If an ordinary amplifier is used to feed a load of only a few hundred ohms, the amplitude of signal it can handle within reasonable limits of distortion is very small indeed. The reason is that nearly all the impedance in the anode circuit is the resistance of the valve itself, and that is non-linear—varies over each cycle of signal voltage. As regards the cathode follower, it may be enough to repeat that it uses negative feedback 100 per cent. If that is not enough to satisfy the curious, some idea of its anti-distortion properties may perhaps be seen by considering that any parts of the output wave introduced by the non-linearity of the valve are fed back in reverse to the input and thereby largely cancelled out. There are limits to this, of course, but the cathode follower in its particular job does score heavily over the ordinary amplifier.

CF Features

Summing up, the cathode follower has these features:—

(*a*) Output voltage slightly less than input.

(*b*) Output voltage in phase with input.

(*c*) Input impedance very high.

(*d*) Output impedance very low.

(*e*) Because of the foregoing, the cathode follower is able to reproduce very accurately across a low impedance a signal voltage derived from a high-impedance source, even if the signal waveform is complicated (i.e., composed of simple waves of a wide range of frequency).

As regards (*a*) and (*d*), the effect of connecting a valve as a cathode follower is to make it behave as if both its μ and its r_a were divided by $\mu + 1$.

A practical cathode follower circuit generally includes a large condenser —$40\mu F$ or so—across the HT to ensure that the anode voltage is undisturbed by the signal. Regarding grid bias, it is obvious that the load resistance R provides it. But it may provide too much. If so, a normal grid leak should be used to tap off the required bias voltage, as in Fig. 4. If the output is connected to something that has a variable or indefinite DC resistance, or if it is desired to keep the DC out of it, then a blocking condenser C_2 should be used, of sufficiently large capacitance to cause negligible drop of volts at any signal frequency.

As the effective output impedance is $r_a/(\mu + 1)$, which, for most valves, is nearly the same as r_a/μ, or $1/g_m$, other things being equal the best valve to use is the one with the highest mutual conductance.

Tetrodes or pentodes cannot be used as such; on account of the absence of anode load they revert to the habits of triodes. The screen is fed from a fixed positive voltage as usual, and the suppressor grid pin, if any, should be joined straight to the cathode.

For most purposes R may be 1,000 to 5,000 ohms. Unless there is any special reason to the contrary, it is good practice to make the resistance the greatest that is not too much for bias. If it is much less, it is likely to be too small as a load (or it shunts a parallel-connected load too heavily) and the anode current may be excessive; if it is larger it is too much for grid bias purposes and the complication of a tapping is necessitated. A high load resistance, especially with a small grid bias, may lead to trouble owing to the voltage between cathode and heater going beyond the safe limit—rated at 50 volts for most valves.

The cathode follower is not exclusive to television and radar engineers; at least three applications to the listener's gear have been discussed in *Wireless World*. One is as a final IF stage, with a view to dodging the various difficulties in designing a detector that can be attached to it without spoiling the selectivity and introducing distortion. Another is as the driver for a Class B output stage. Both of these were described by Cocking in the December 15th, 1938, issue. Then there is the idea of using the cathode follower, single or push-pull, as the output stage feeding a loud speaker, the object being to make sure that loud speaker resonances are thoroughly damped in the very low resistance of the stage. This problem was argued in every 1944 issue from April to September inclusive, and the conclusion I was left with was that the choice of cathode follower versus tetrode with negative feedback is made partly by what fits best on to the design of the rest of the set and partly just by the way one feels about it.

The cathode follower detector (still snooping in the background) is of course as much at home in the broadcast receiver street as anywhere else, but I do not intend to be drawn into a full account of it here and now. Its close resemblance to the cathode follower—the only difference is that R (Fig. 1b) is high in resistance and has a small condenser across it—is deceptive. Anything like a real explanation would take quite a lot of time and space. But the following clues may set interested readers on the way.

In the circuit, Fig. 5, the condenser C is the crux of the matter. It has to be of such a capacitance that to the radio frequency it is

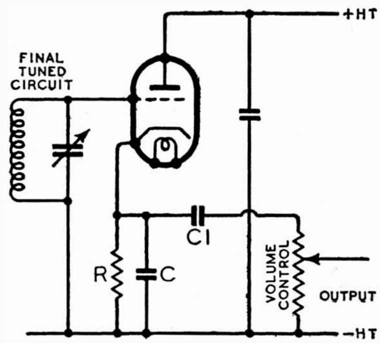

Fig. 5. Cathode follower detector or "infinite impedance" detector. The usual arrangement for volume control is included

an effective by-pass to R. The two together are just a device for giving the valve a steady bias. So far as the RF is concerned, then, the system is not a cathode follower at all. There is, or should be, no negative feedback, because there is no appreciable RF anti-phase voltage drop across C. R is high enough—about 50,000 to 250,000 ohms—to bias the valve well down on the "bottom bend"; and, as almost the only RF impedance in the anode circuit is the resistance of the valve itself, a relatively large rectified current flows in it when an RF signal is applied to the grid. This rectified current increases the charge on C and therefore the voltage across R. If the amplitude of the RF is varied at an audio-frequency rate—due to modulation by speech or music—this voltage drop varies accordingly, and the variations are passed on through C1 and become the output. But note that unless C is small enough to be negligible at all. audio-frequencies, it will tend to smooth out the audio-variations too. As the capacitance of C cannot be infinite for radio frequency and zero for audio frequency, it must be a well-chosen compromise between these extremes. With 0.1 megohm for R, a typical value is 100μμF.

Another reason why the value of C is important is apt to be overlooked because it depends on a condenser that does not figure on any component list — C_{gc} again (Fig. 3b). With C, this capacitance forms a potential divider across the RF tuned circuit feeding the detector, and the detector valve turns the whole show into a Colpitts oscillator circuit. Whether or not it actually oscillates depends mainly on the value of C. If it is equal to C_{gc} or not more than several times greater, the chances are that it will. The larger is C, the more stable the circuit. Making it smaller (which of course favours the audio-frequency performance) causes the input impedance to be less and less of a load on the tuned circuit; then to become an infinite impedance; and if reduced still further it begins to neutralise the losses of the tuned circuit, and finally to maintain oscillation. So if you use a pre-set condenser for C you ought to be able to arrive at a good compromise between your requirements for selectivity and high-note response. But don't try to use the drop across R for AVC—it comes the wrong way round!

CATALOGUES RECEIVED

A LEAFLET describing representative test equipment and electronic industrial control gear designed by the Dorland Electric Co., Ltd., 38, Brompton Road, London, S.W.3.

Two illustrated leaflets dealing respectively with public address equipment and automatic intercommunication telephones made by the Reliance Telephone Co., Ltd., Magnet House, Moor Street, Birmingham, 4.