As an extreme example, we might need a low noise low distortion cascode using half of a 6SN7 dual triode as the upper valve, so we might set its anode current to 8 mA (good linearity at this current). However, if the lower valve was a triode-strapped E810F, passing 45 mA, an additional 37 mA would be required. If $V_a = 100\,\text{V}$ for the E810F, and the HT $= 400\,\text{V}$, then:

$$R = \frac{V}{I} = \frac{400 - 100}{37} = 8.1\,\text{k}\Omega$$

All topologies that involve operating cathodes at voltages significantly above ground have problems because of heater/cathode leakage currents and the maximum allowable heater to cathode voltage V_{hk} (see Chapter 4). It is not uncommon for the cathode of a valve to be unbypassed and therefore have signal voltages on it. If, as in the cascode, the gain to the cathode of the upper valve is low, and we are using the device because of its good noise performance, then it is likely that the signal voltage on that cathode is very small, perhaps only a few millivolts. Leakage currents via the heater/cathode insulation become worse as V_{hk} rises, so the combination of $V_{hk} = 75\,\text{V}$, and a small signal voltage, means that the effects can be significant. The author once made a circuit using valves that were rated at $V_{hk(max.)} = 150\,\text{V}$, operated the valves at $V_{hk} = 120\,\text{V}$ and suffered low frequency noise, which was only cured by sitting the relevant heaters on a 150 V DC supply. There is an understandable reluctance to do this, because it means that we need two or more heater supplies, one connected to ground as normal, and another connected to an elevated voltage. We will return to this practical problem later.

The cathode follower

The circuits that we have considered up until now have been concerned exclusively with providing voltage gain. Sometimes we need a *buffer* stage that provides high input and low output resistance. The cathode follower[5] has a voltage gain of slightly less than 1, a low output resistance, typically $\leq 1\,\text{k}\Omega$, a high input resistance ($\approx 500\,\text{M}\Omega$ in valve microphones), and is non-inverting. We will consider the fixed bias version of the cathode follower first. See Fig. 2.26.

We have changed the position of the load resistor, so that the output is now taken from the cathode, but the circuit can still be analysed in the same way as before, using loadlines. See Fig. 2.27.

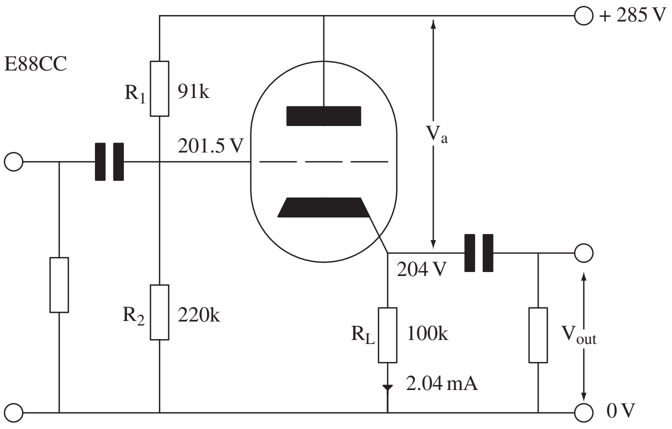

Fig. 2.26 *Fixed bias cathode follower*

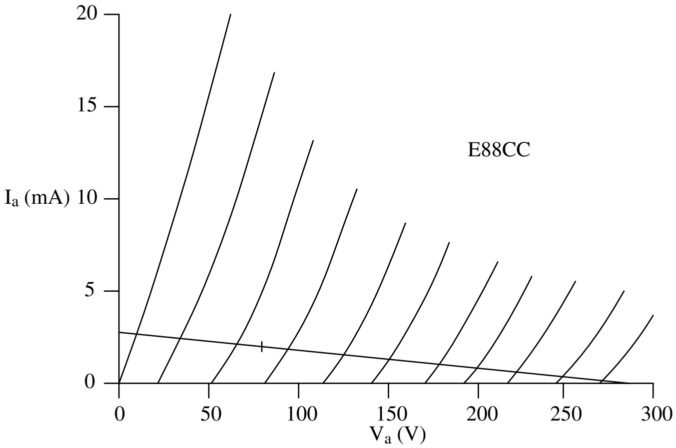

Fig. 2.27 *Operating point of fixed bias cathode follower*

$R_L = 100\,\text{k}\Omega$, and so we draw the appropriate loadline, $V_g = -2.5\,\text{V}$, with $V_a = -81\,\text{V}$, because of the excellent linearity in this region. Remembering that V_a is actually the *anode to cathode* voltage, the cathode is now at $285\,\text{V} - 81\,\text{V} = 204\,\text{V}$, and because $V_{gk} = -2.5\,\text{V}$, the grid must be at $201.5\,\text{V}$ to bias the valve to this condition. This voltage is set by the potential divider R_1, R_2.

The cathode follower is simply a special case of the common cathode amplifier with 100% negative feedback (parallel derived, series applied). To find the gain after feedback, we use our normal technique of measuring the gain from the loadline ($A_v = 28.5$), and apply the feedback equation:

$$A_{\text{fbk}} = \frac{A_0}{1 + \beta \cdot A_0}$$

Since we have 100% feedback, $\beta = 1$, and the gain of our example becomes $28.5/29.5 = 0.97$.

We saw earlier that the AC resistance at the cathode was:

$$r_k = \frac{R_L + r_a}{\mu + 1}$$

But for a cathode follower, R_L from the anode to the HT $= 0$, so this equation can be approximated to $1/gm$. From the anode characteristics, $gm \approx 5$ mA/V, this gives an output resistance of $\approx 200\ \Omega$. This is not a particularly accurate answer, since the method of determining *gm* was crude, but this does not matter, since it is usual to operate an audio cathode follower with *a* ≈ 1 kΩ resistor in series with its output to ensure stability – this then swamps the slight inaccuracy. Nevertheless, 1.2 kΩ is a low output resistance for a valve stage.

As shown, the stage does not have a high input resistance, although this configuration is useful for making Sallen & Key active filters (see Appendix). We need to rearrange our bias to achieve a high input resistance. See Fig. 2.28.

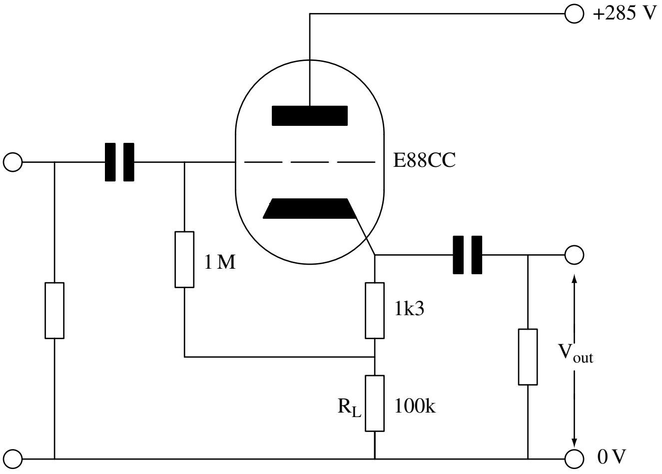

Fig. 2.28 *Cathode bias cathode follower*

We now have cathode or *self* bias provided by the 1.3 kΩ resistor, whose value is calculated in the normal way. You will note that by adding this resistor, we have slightly increased the value of R_L, and indeed this was also the case in the common cathode amplifier, but this ≈1% increase has a negligible effect on circuit conditions.

At first sight, this configuration is very little better than the fixed bias configuration, as the input resistance appears to be only 1.1 MΩ. However, the 1 MΩ grid leak resistor has been *bootstrapped*,[6] which is to say that the entire input signal does *not* appear across it.

It works like this. We have just calculated the gain A_v to the cathode as being 0.97. We can calculate the attenuation of the potential divider formed by the cathode bias resistor and R_L as being 0.987, therefore the proportion of input signal voltage at the lower end of the grid leak resistor is $0.96\,V_{in}$. Now, since the output of a cathode follower is *non-inverting*, this means that there is only $0.04\,V_{in}$ *across* the grid leak resistor. The *signal* current through this resistor will therefore be only 4% of what it would have been, had the grid leak resistor been connected directly to ground. It presents an input resistance equivalent to $1\,\text{M}\Omega/0.04 = 25\,\text{M}\Omega$. Formalizing this argument:

$$r_{\text{input}} = \frac{R_g}{1 - A \cdot \frac{R_L}{R_L + R_k}}$$

Note that A is the gain of the cathode follower, not the original loadline gain. A similar argument can be used to determine the input capacitance of the cathode follower:

$$C_{\text{input}} \approx C_{ag} + (1 - A) \cdot C_{g-k}$$

Note that this is an approximate value because there will be significant strays. Using our example with the E88CC:

$$\approx 1.4\,\text{pF} + (1 - 0.96) \times 3.3\,\text{pF} = 1.5\,\text{pF}$$

We should add a few pF for wiring strays, as we did before, which brings the likely input capacitance of the cathode follower to 4.5 pF, which is rather less than half the value of the cascode or pentode.

It has been suggested that the linearity of the cathode follower is questionable. It is hard to see how this accusation can be true, particularly if the operating point has been chosen carefully, as in the previous example, since the stage operates under 100% negative feedback. This means that any non-linearity will be reduced in proportion to the feedback factor $(1 + \beta A_0)$, which in our example gives a reduction of 30:1.

Nevertheless, it *is* possible to do even better. We mentioned earlier that μ was one of the more stable valve parameters, whereas r_a varies considerably with anode current. This is significant, because it is mostly the variation of r_a that causes distortion, and we can see why this is if we look at the equation for the gain of a common cathode amplifier:

$$A_v = \mu \cdot \frac{R_L}{R_L + r_a}$$

If we could make R_L very large, ideally infinite, r_a would become insignificant by comparison and could no longer cause distortion. Provided that we have chosen a sensible operating point where μ does not vary greatly, we will then have a very low distortion buffer. Unfortunately, if we simply make R_L very large, we find that there is such a voltage drop across it that we need an HT of over 2 kV! See Fig. 2.29.

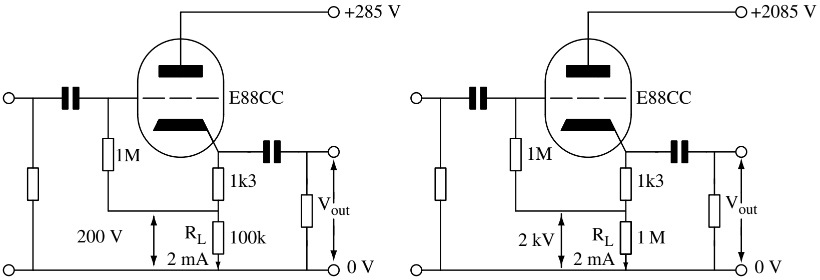

Fig. 2.29 *Effect of increasing R_L in a cathode follower*

We need a way around the problem of excessively large values of R_L, and to do this, we need to examine some definitions.

Sources and sinks: definitions

A current or voltage source is a supply of energy (such as a battery) capable of supplying energy into a load whose other terminal is connected to ground, whereas a sink may *control* the characteristics of an external source of energy, but provides none of its own. Audio electronics often needs real world approximations to these hypothetical devices in order to improve the AC