

NEGATIVE FEEDBACK

1. Some of the Awkward Points Explained

By "CATHODE RAY"

SUCH a lot has already been written about negative feedback that the thought of expecting anybody to read much more seems at first mildly revolting. But in spite of all the explanations that have been given (no, I would hate to say *because* of them) I personally have found the subject remarkably confusing. For example, some articles say feedback reduces hum, while others utter a warning about the increased smoothing needed to prevent hum when feedback is applied. Then, what is the real difference between "voltage" feedback and "current" feedback? A cathode follower looks rather like a "current" feedback circuit, but behaves in the opposite manner. And when one reads that voltage feedback reduces the internal resistance of the valve, but that this holds good for some purposes but not for others, what does it mean? Is the resistance reduced or isn't it? So, in case there are others who are not quite clear about all this, here are some of the shafts of daylight that eventually penetrated my mental gloom.

The general idea of feedback is simple enough ("negative" is understood from now on). Some or all of the output voltage of an amplifier is fed back to the input in such a way as to oppose the input voltage, thus reducing the amplification. To prevent the output from falling, then, the input voltage has to be increased, which is a disadvantage. But it is often worth it, because distortion and other unpleasant things are reduced too, and it is generally much easier to organise a higher input voltage than to obtain equal benefits in any other way. In fact, in designing a receiver to include AVC, the output from the detector is often more than is needed as an input to the audio amplifier, and part would have to be thrown away anyhow. So feedback was a discovery like those of manufacturers who suddenly find that what they had to pay men to cart away or stack into

unsightly heaps is a by-product with a good market price.

Although I don't intend to fall back on mathematics in order to dodge saying things plainly in words, I think it is a mistake to fight shy entirely of symbols. So A will hereinafter stand for the voltage amplification obtained without feedback, and B for the fraction of the output voltage fed back. Some writers call these α and β respectively. The amplification factor and internal anode resistance of the valve will be μ and r_a as usual. R_L will indicate

R_c doesn't come into the signal question at all, because it is short-circuited to alternating currents by a very high-capacitance by-pass. So $v_{gc} = v_i$; and of course $v_o = Av_{gc}$. If v_{gc} is 1 volt, v_o is 20 volts.

Now suppose we feed back 20 per cent. of this output voltage (i.e., 4 volts); in other words, we make $B = 0.2$. In symbols, the voltage fed back is Bv_o or ABv_{gc} . In order to keep the output at its original level, v_{gc} must be kept constant; so it is necessary to increase v_i by the same amount as the voltage fed back, making it $v_{gc} + ABv_{gc}$, or $v_{gc}(1 + AB)$.^{*} This, in the present example, is $1[1 + (20 \times 0.2)] = 5$ volts, which

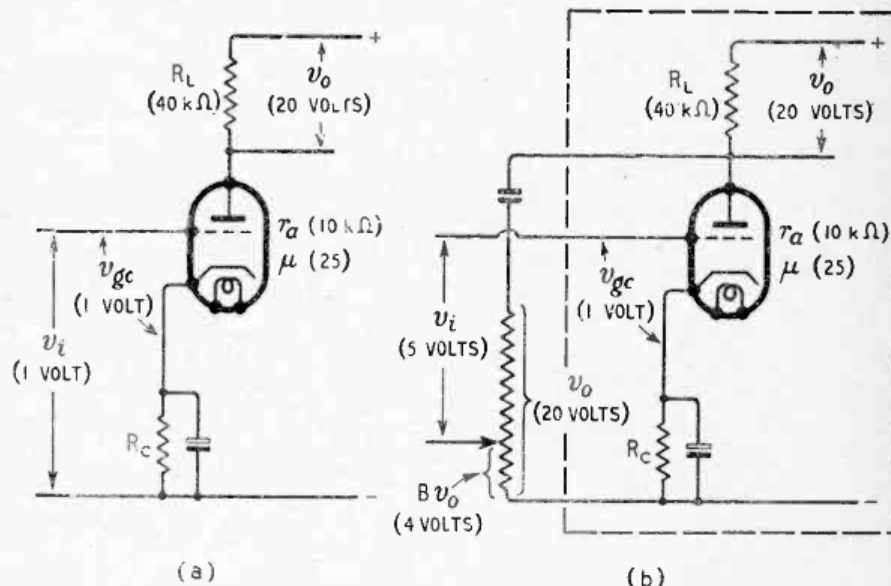


Fig. 1. Typical example of a simple amplifier stage (a) without negative feedback, and (b) with 20 per cent. feedback.

the load resistance and R_c the cathode resistance, if any. And v_{gc} will be the signal voltage applied between grid and cathode; v_i the total signal voltage input; and v_o the signal voltage output. They will do to be going on with, I think; and to make sure that the meanings of these symbols are clear let us take a simple example, illustrated by Fig. 1(a). Assume the valve has a μ of 25 and an r_a of 10,000 ohms. The amplification A , is $\mu R_L / (R_L + r_a)$; so if R_L is, say, 40,000 ohms, A is 20.

result you have of course already arrived at without bothering about formulae, because I chose easy figures. If you count only what is in the dotted box in Fig. 1(b), the valve is still giving a gain of 20; but as regards the whole circuit

^{*} The position at the input is rather like that of a man with a net salary of £500 a year. If his expenses are £200, his gross pay must be made up to £700. Strictly speaking, v_i should be $v_{gc}(1 + AB)$, and B should be $-B$ to indicate that it is negative feedback; but as this article is about negative feedback exclusively it seems a waste of time putting in a minus every time just to be cancelled by another minus, and is one more thing to have to remember if mistakes are not to be made.

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the gain is reduced by negative feedback to v_o divided by the new v_i ; that is to say $20/5$, or 4.

The general formula for the overall gain with feedback (call it A') is quite easily derived in the same way as the above example was worked out:

$$A' = v_o/v_i = Av_{gc}/v_{gc}(1 + AB) = A/(1 + AB)$$

So the gain with feedback is equal to the gain without feedback (or the gain inside the dotted line in Fig. 1(b)) divided by $1 + AB$. If 100 per cent. feedback is employed—i.e., all the output voltage is fed back, as in the cathode follower— B is 1 and A' is $A/(A + 1)$ or slightly less than 1, as we saw in the November, 1945, issue when considering the cathode follower.

Now to clear up the little mystery about "voltage" feedback and "current" feedback (seeing that in both cases it is voltage that is fed back!). The difference is important, because in one case the valve is made to behave as if its r_a were lower and in the other as if it were higher.

Fig. 1(b) is one of the many ways of obtaining voltage feedback. The voltage fed back is a proportion of the signal voltage across the load, R_L . Fig. 2(a) is the simplest form of current feedback,

voltage proportional to the signal current through the load.

The easiest way of seeing what this difference has got to do with r_a is to suppose that the load resistance (say, a loudspeaker) is reduced (by connecting another loudspeaker in parallel). The signal current rises because of the reduced resistance, and the output voltage falls because of the increased "drop" in r_a . If the valve is a pentode, in which r_a is generally much greater than the load resistance itself, the current is only slightly more than before; and as it has to divide between the two loads the voltage across them falls by nearly 50 per cent. But if voltage feedback is in use, the voltage fed back falls in the same proportion, and releases an equal quantity of v_i from its job of neutralising the feedback. There is therefore that much more v_i available to increase the output of the valve, thus wiping out most of the fall in signal voltage. The balance between these opposite tendencies leaves the output signal voltage much less reduced than it would have been without feedback. So one result of voltage feedback is to make the valve behave as if it had a smaller r_a , so far as constancy of output with varying load resistance is concerned.

current flowing through R_C , and is nearly proportional to it if R_C is much less than R_L . As the signal current is increased (if only slightly) the fed-back voltage increases, entirely at the expense of v_{gc} , which is thus unable to maintain the signal to the valve even at its original level. The tendency for the output current to rise is therefore checked, just as if the valve had a huge r_a . For operating loudspeakers this is the last thing one wants, so current feedback is avoided in such cases. In fact, unless stated to the contrary, "feedback" will hereafter mean "voltage feedback."

If it were not for R_L , Fig. 2(a) would be a picture of a cathode follower circuit. The position of R_L , however, is the essential thing in deciding what sort of feedback is happening; and in a cathode follower (Fig. 2b) R_C is R_L . So the result is 100 per cent. voltage feedback.

But what are we to say about Fig. 3? This is the "concertina" phase-splitter circuit, used in the *Wireless World* Quality Amplifier. As it is required to provide two equal outputs it has two load resistances, one of which serves as a current feeder-back for the other and a voltage feeder-back for itself. So, as it appears to be both sorts of circuit at once, what happens to r_a ? Well, it is not like the chameleon in the story, that blew up when it was put on a Scotch tartan; it does manage to be two opposite things at the same time. It all depends on which way you look at it. Output No. 1 sees a high-resistance valve, because the voltage delivered to it is practically proportional to R_L (combined with any other load impedances in parallel). Output No. 2, on the contrary, is certain the valve has a very low resistance, because its voltage is only slightly affected by alterations in the load impedance. If these two were human they would undoubtedly go to war to uphold their sovereign rights to the truth about r_a . As they are not, however, they co-operate quite amicably and deliver the goods.

All the same, there is obviously something rather queer about a resistance that can have three entirely different values (counting

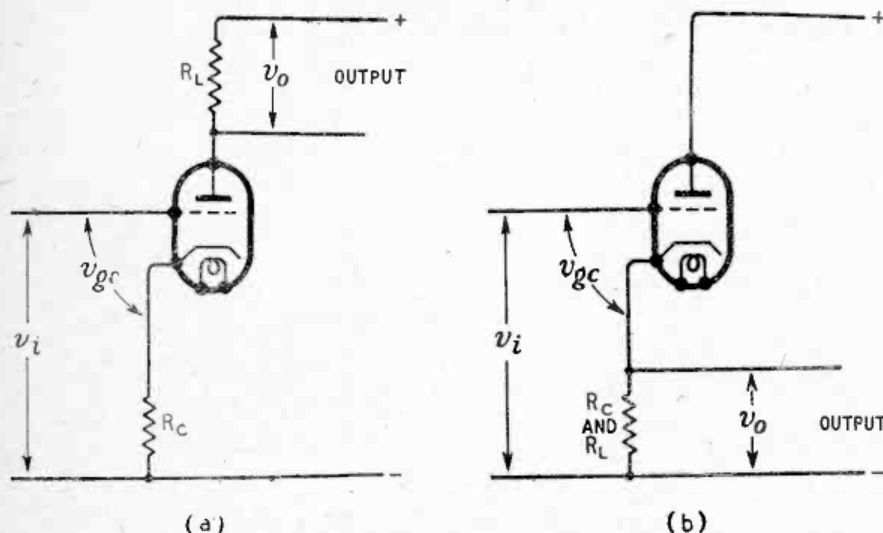


Fig. 2. (a) Simplest example of "current" feedback. (b), although apparently rather similar, is actually a "voltage" feedback circuit.

obtained by forgetting to connect a by-pass condenser across the bias resistor, R_C . Here, again, a voltage is fed back, but it is a

Compare with this the result of reducing the load resistance in Fig. 2(a), where the voltage fed back is that due to the signal

the original, proper, r_a) at the same time, same place, same current, and even the same frequency; and this should put one on guard against indiscriminate use of these "apparent resistance" values. The thing to remember—and which Fig. 3 brings out well—is that the apparent r_a due to feedback holds good only from the point of view of the load concerned. The valve itself is quite unaware that its own internal affairs are anything out of the usual.

Before investigating the problem of when to use the apparent r_a value (let us call it r'_a) and when to use the real r_a , it would be a good thing to know what r'_a is in relation to r_a . This in itself is a trap into which surprisingly learned people have sometimes fallen. We have already worked out that the effect of feedback is to divide the gain by $1 + \mu B$. It can be shown (but don't ask me to do it just now) that distortion, noise, hum, etc., are, within certain limits, reduced in the same proportion. But the catch is that r_a is divided (apparently) by $1 + \mu B$. With a triode there may not be much difference between A and μ . In the example with which we started this story, A was $4/5$ ths of μ . But in a pentode A is likely to be only a small fraction of μ . The result is that r_a is reduced (apparently) far more than the gain or the other things mentioned. In fact, a pentode's μ is so large that even if B is only a moderate fraction, μB is much larger than 1, so r'_a is approximately equal to $r_a/\mu B$, or $1/g_m B$, g_m being the mutual conductance of the valve. The largest possible B (achieved in the cathode follower, for example) is 1; in which case r'_a is very nearly $1/g_m$. In a high-conductance valve, g_m may be as much as 0.01 amps. per volt, making r'_a only 100 ohms. This for a valve with an r_a perhaps getting on for a megohm! So it makes rather a difference which value one uses for one's calculations.

So far we have reckoned that voltage feedback makes the valve behave as if it were an imaginary valve with a lower anode resistance, as regards its "regulation," i.e., the extent to which the output voltage varies due to changes

in the output current drawn (or what is the same thing, changes in load impedance); and have called the imaginary valve's internal resistance r'_a . To complete our dream picture it is necessary to give it an imaginary μ , too (call it μ'), which is the real μ divided by the same factor as we have used for r'_a , namely, $1 + \mu B$. So the imaginary g_m is the same

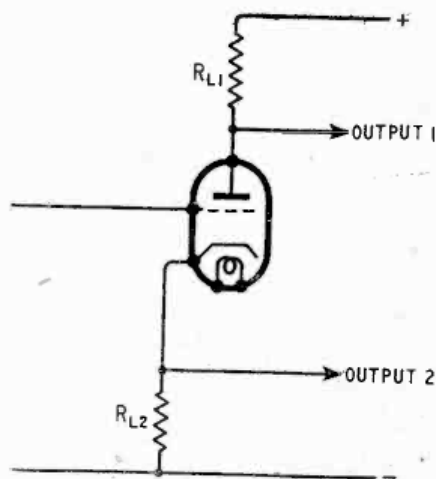


Fig. 3. This phase-splitter circuit is an interesting and instructive case, so far as apparent valve resistance is concerned.

as the real one and needs no new symbol. The real valve with feedback, then, can be replaced in imagination, and in calculations, by one with characteristics μ' and r'_a each $1 + \mu B$ times less than μ and r_a . I am not going to waste the Editor's space by copying out a textbook proof of this; but let us try it on our original example, Fig. 1(b). Here the dividing factor is $1 + (25 \times 0.2)$, or 6. So μ' is $25/6$, or $4\frac{1}{6}$, and r'_a is $10,000/6$, or 1,667. Suppose an input of 5 volts is applied to a valve of these characteristics (without feedback). Then the output, $v_i \mu' R_L / (R_L + r'_a)$, is $(5 \times 4\frac{1}{6} \times 40,000) / (40,000 + 1,667)$ or 20 volts, which is what we have found the real valve with feedback gives.

Now see what happens to this output voltage when R_L is halved, say, by adding another 40,000 ohms in parallel. The new output is $(5 \times 4\frac{1}{6} \times 20,000) / (20,000 + 1,667)$, or 19.2 volts. (Check it by the "real" way if you wish.) Compare this with the drop in volts that would occur

in the Fig. 1 (a) circuit; $(1 \times 25 \times 20,000) / (20,000 + 10,000)$ or 16 $\frac{2}{3}$ volts — a drop of 3.3 volts instead of 0.8. It is clear that feedback is a great help in a system where, for example, varying numbers of extension loudspeakers are used. The improvement is even more marked with pentodes, which have a much higher r_a .

Moving coil loudspeakers have a mechanical resonance usually in the region of 80 c/s. If you give the coil a flick it vibrates several times at that frequency before coming to rest. The same thing is liable to happen whenever a sudden transient in speech or music occurs in whatever programme it is reproducing; and the resulting 80 c/s note, though short-lived, is something that doesn't belong to the programme. It is distortion that has found its way in, giving the reproduction a false 80 c/s "coloration" or boom. I said "liable to happen," because it will not do so if the loudspeaker has a comparatively low resistance shunted across it. The reason is that the coil vibrating in the powerful magnetic field generates an EMF, just like any other electric motor, and if it has a low resistance across its terminals the resulting current causes a force tending to oppose the motion of the coil. I don't think I need recite the rest of any elementary book on Electricity and Magnetism, and will merely mention that a visual demonstration of precisely the same phenomenon, called damping, can be obtained by shaking a moving coil milliammeter with and without its terminals short-circuited.

The anode-cathode path of the valve, having an AC resistance r_a , is virtually across the terminals of the loudspeaker (though the route may be a devious one, including a transformer, the power supply smoothing condenser and the bias by-pass condenser). So the extent to which this particular form of distortion occurs depends on r_a . Or r'_a ?

If a loudspeaker, or any other generator forming part of R_L , tries to pump current into the anode circuit, and voltage feedback is in operation, its own EMF is fed—not back, because it didn't come from there—to the

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grid. Suppose that at any particular moment the EMF is of the same polarity as the HT source, increasing the current through the valve. It is therefore fed positively to the grid, which makes the anode current increase more, for a given loudspeaker EMF, than if there had been no feedback. The valve therefore appears to the loudspeaker to have a lower resistance than r_a , and—yes, you are right!—what it appears to be is r'_a . [If you complain that the idea of anything appearing to a loudspeaker is too much like an *Æsop's fable*, you will prefer to say that the anode current generated by an EMF e caused by the coil of the loudspeaker vibrating is equal to $e/(r'_a + R_L)$ instead of $e/(r_a + R_L)$.]

By now the nature of this make-believe resistance may be becoming clearer. What we are doing is using Ohm's Law in a circuit where two EMFs are operating, and calculating the resistance of the circuit by dividing one of the EMFs (generally the smaller one at that) by the current. So, of course, we get a queer answer! In most cases this procedure would be just as silly as it sounds, but in a feedback circuit there is some method in the madness, because the neglected EMF, μv_{gc} , is itself rather of the "apparent" variety, and has for some time been the occasion for a lively technical dogfight, which I have no intention of joining. The point is that there is another voltage—the fed-back voltage is real enough, at least—controlling the anode current, and as this voltage is exactly proportional to the original EMF, it is sometimes simpler to consider the results as being due to a lower resistance instead. It is as if a Rich Uncle (this is a Tale of Long Ago) adopted the benevolent practice of contributing half a guinea for every 4s. 6d. saved by young Harry for the purpose of buying Savings Certificates. From young Harry's point of view—and from nobody else's—Savings Certificates would cost 4s. 6d. It would only be reasonable to express the situation in this way so long as Uncle's "EMF" was strictly proportional to Harry's smaller one.

Incidentally, exactly the same convention is adopted with regard to the apparently enormous input capacitance of a valve due to Miller effect. The large extra capacitance does not really exist at all; it just appears to do so because we leave out of the account a second and relatively large charging voltage because it happens to be proportional to the input voltage.

Reverting to our loudspeaker damping question, applying the optimum damping resistance is merely a matter of choosing the amount of feedback, B , which makes $r_a/(1+AB)$, which is r'_a , equal to that resistance. The only problem, then, is to decide what is the optimum. Mr. Amos recommends something of the order of half the mid-frequency loudspeaker impedance (referred to the primary of the output transformer).*

Bearing in mind that r'_a is what the valve looks like to the load, the same technique covers other problems in which it is desirable to match the impedance of the signal source to the load. For example, a transmission line. Here the source should be equal to the line impedance, and as that is generally quite low, a cathode follower is almost the only answer.

Do you think this sounds like the end of the valve-and-load story? That in all such questions it is on r'_a , not r_a , that the answer is based? If so, you must not miss the sequel next month.

* *Feedback and the Loudspeaker*, December, 1944 issue.

A SIMPLE OHMMETER

IN the July issue of *Wireless World* a description was given of a method of measuring resistance by means of a milliammeter and a voltmeter. The writer has been using a similar instrument requiring only one meter, and the following details may be of interest to readers.

The milliammeter R_m has a resistance of 100 ohms and a full-scale current consumption of 1 milliamp. A resistance R_2 equal to the resistance of the meter is connected as shown. R_3 is a wire-wound resistance of 10,000 ohms, correct to within ± 1 per cent. The resistance to be measured, X , is connected to terminals T_1 and T_2 .

With the switch down, the meter will be in series with the unknown

resistance X and will measure the current flowing through it; R_2 will be in series with R_3 and will simulate a voltmeter load. If the switch is thrown up the meter becomes a voltmeter reading 0-10 volts. The voltage indicated will be that across X and R_2 . As R_2 is equal to R_m it will compensate for the removal of R_m from the circuit; in other words, the voltage now indicated is that across X and R_m when the switch was down. Strictly speaking, R_3 should be 9,900 ohms to take into account $R_m = 100$ ohms, but the error will be very small.

The following ranges of resistances can be measured:—(1) With the switch down:—Vary R_1 to such a value that the milliammeter indicates 0.1 mA. Then throw the switch up and read the voltage. Then from Ohm's Law we get—

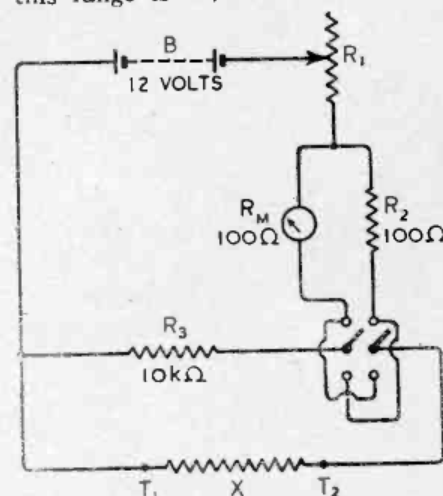
$$\text{Resistance } X = \frac{\text{Volts}}{0.0001} \text{ ohms}$$

In other words, the resistance equals the voltage multiplied by 10,000. For example, a reading of 6.3 volts means that $X = 63,000$ ohms. The maximum resistance which can be measured on this range is 100,000 ohms, corresponding to a reading of 10 volts.

With R_1 adjusted to give a current of 1.0 milliamp., on throwing the switch up the voltage is read, and we get:—

$$X = \frac{\text{Volts}}{0.001} \text{ ohms}$$

or, the resistance equals voltage multiplied by 1,000. The maximum resistance which can be measured on this range is 10,000 ohms.



The meter is switched for successive current and voltage readings without altering the load on the battery.

It should be clear that in each case the resistance of R_m (100 ohms) should be subtracted from the resistance obtained above, but in most cases, however, R_m can be neglected. "CALIBRATOR."