against the fingers, pushing it from its central position, should steadily increase in both directions. Sometimes the spider develops an " oil-can " action, so that it avoids the centre position, travelling past it quickly; sometimes it is not as bad as that, but there is central zone of movement practically without any opposition due to the spider, and beyond this movement the spider suddenly begins to show greater opposition to further movement. Either of these cases produce considerable modulation distortion. Careful refitting of the spider can often improve such a speaker.

Intermodulation distortion is not easy to track down without special equipment, since it can originate almost anywhere in the chain. Any measurement to detect it relies on the use of equipment known to be free of it. The method used to check loudspeakers for intermodulation distortion consists of feeding in two fairly high frequencies at the same time from an amplifier known to be free of distortion, coupled to two pure tone audio signal generators. Distortion in the speaker shows up by an extra note of lower frequency, equal to the difference of the other two, although this frequency is not applied to the speech coil. Having checked that the distortion is due to the loudspeaker, it remains to see how it is caused; but since the reader may not possess either the facility to check for distortion in this way, or the means of altering the loudspeaker, no more will be said here.

9

MATCHING

THERE are two places in an amplifier where matching is important—the input and the output. The general idea of output matching is well known, but often only partly understood. The requirement of input matching is often not realised at all.

The formula for turns ratio in matching is well known,

$$\frac{Z_1^2}{Z_2^2} = \frac{T_1}{T_2} \text{ or } \frac{Z_1}{Z_2} = \sqrt{\frac{T_1}{T_2}}$$

The abac shown in Figure 27 on pages 32/33 is provided to facilitate this calculation. As an example of its use, to match 15 Ohms to 6,000 Ohms requires a ratio of 20/1.

Measuring Transformer Ratio

It is easy to find which windings of a transformer are the high and low number of turns respectively, by measuring their resistances with an ohm-meter. But the ratio of winding resistances does not necessarily give any indication of turns ratio, so if the ratio of a transformer is not known, another method must be used. The simplest is a check with input from the mains. A voltage should be connected to the high turns side, taking care that the voltage is not too high for the purpose of the transformer. Then the voltage is measured on both sides, and the ratio calculated directly from the voltages.

Input Matching

At the input end of the amplifier, the microphone or pick-up should have a transformer of the correct ratio to get best results. Use of too high a step-up ratio will result in loss of quality, although there may be greater gain: while use of too low a ratio will merely lose gain—there will be no deterioration in quality. However, too much loss of gain may mean that an amplifier, that otherwise would have sufficient gain, has not. This will appear from the examples that follow. The abac of Figure 27 may be used to find a good ratio for any specified microphone or pick-up impedance. If the impedance is matched to less than 50,000 Ohms, useful gain will be lost; but quality becomes poor if an attempt is made to match to over 200,000 Ohms. The best plan is to find a standard ratio that matches somewhere between these figures.

For example, a certain moving coil microphone has an impedance of 50 Ohms. A ratio of 40/1 will match it to 80,000 Ohms, or one of 50/1 to 125,000 Ohms, either of which would be reasonably suitable, only making a difference of 2 db. (There is a scale provided on the opposite side of the ratio line, giving db gain due to a step-up transformer.)

As another example, a ribbon microphone has an impedance of ½ Ohm (0·5). This requires a ratio of 400/1 to match it to 80,000 Ohms or 500/1 to match it to 125,000 Ohms. If this microphone were used with the same transformer as that used for the moving coil microphone, it would only match to 800 or 1,250 Ohms, and there would be 10/1 too little step-up—a deficiency in gain of 20 db. On the other hand, using a 400/1 or 500/1 transformer for the 50 Ohms microphone, would match it to 8 or 12½ Megohms, which would result in very poor quality indeed, giving an extremely " woofy " reproduction.

Input matching is not highly critical, but a very wide range of impedances is encountered, so that different transformer ratios are a definite requirement, according to purpose.

Output Matching

Output matching requires more careful attention, because incorrect ratio results in loss of output and considerable distortion. The problem is complicated by the fact that the impedance of a loudspeaker changes for different frequencies.

Figure 28 shows a typical moving coil loudspeaker impedance characteristic. The lowest value of impedance shown, at about 600 cycles, is not much more than the d.c. resistance of the speech coil. The rise in impedance at the low frequency end, shown centred at about 100 cycles, is due to the diaphragm resonance. If the diaphragm is clamped resonance disappears, and any alteration to cabinet design that alters resonance will alter the impedance characteristic at this end in a corresponding way. The steady rise at the high frequency end is due to the inductance of the speech coil. The question is: What value is to be taken as the loudspeaker impedance ?

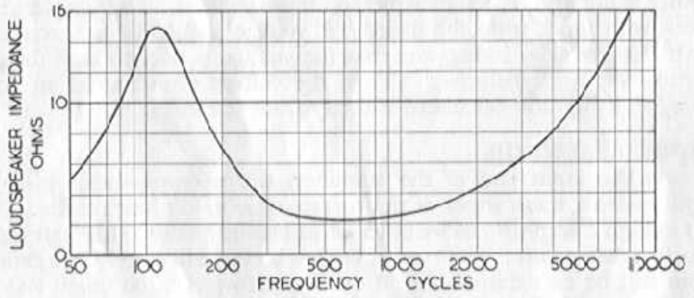

FIG. 28. IMPEDANCE CHARACTERISTIC OF A TYPICAL MOVING COIL LOUDSPEAKER.

The value usually given by the manufacturer of the loudspeaker is not much above the lowest reading—often its impedance at 1,000 cycles. It is quite a simple matter to measure the loudspeaker impedance at a few spot frequencies. It is connected to the output of an amplifier, with a resistor in series with it, of a value somewhere near to the expected impedances. A constant frequency disc, or an audio signal generator, provides a constant note input to the amplifier of several known frequencies, and at each frequency voltage readings are taken across both the resistance and the loudspeaker. Figure 29 shows the method. The loudspeaker impedance is given by

$$Z = R \times \frac{V_s}{V_r}$$

where R is the value of the series resistor of known value.

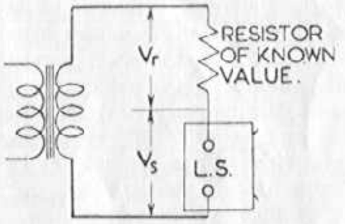

FIG. 29. METHOD OF MEASURING LOUDSPEAKER IMPEDANCE.

A fact often not realised is that the quality of a loudspeaker depends upon the output impedance of the amplifier, quite apart from the matter of matching. The ratio has been calculated so that when the loudspeaker is connected to the secondary of the transformer, the output valve(s) " see " their optimum load impedance in the primary, according to the formula

$$\frac{Z_1}{Z_2} = \sqrt{\frac{T_1}{T_2}}$$

where Z_1 is the optimum load impedance, and Z_2 that of the speech coil. But the extra factor determining the quality of the loudspeaker reproduction, even if the amplifier has a perfectly flat response and is matched into its correct load, is the a.c. resistance of the output valves.

Using pentodes or tetrodes the a.c. resistance of the valves is several times the optimum load resistance, usually about five times. Using triodes the a.c. resistance is usually between one-fifth and one-third of the optimum load impedance. This a.c. resistance is " matched " through the output transformer ; thus, if the a.c. resistance is one-quarter of the optimum load impedance, the speech coil impedance will " see," or be looking out of an impedance, on the secondary of the transformer, one-quarter of its own.

Figure 30 shows the effect of two typical types of output stage on the response of the loudspeaker whose impedance characteristic is shown in Figure 28. It is assumed that the loudspeaker gives a perfectly

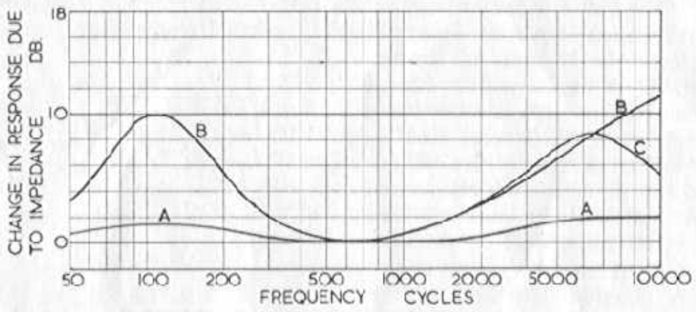

FIG. 30. EFFECT OF OUTPUT A.C. RESISTANCE ON FREQUENCY RESPONSE OF LOUDSPEAKER WITH IMPEDANCE CHARACTERISTIC OF FIG. 28.

flat response when fed with a voltage that is constant for all frequencies. Curve A shows the response when fed from a triode whose a.c. resistance is one-quarter that of its optimum load, while curve B shows the response fed from a tetrode whose a.c. resistance is five times its optimum load. In both cases the optimum load is matched for the value of loudspeaker impedance at 600 cycles. It will be noticed that the pentode over-accentuates both low and high frequencies. High note correction in the form of a capacitor from anode to cathode can modify the response to that shown in Figure 30, curve C.

At low frequencies in the region of resonance, the actual load resistance " seen " by the tetrode will be much larger than optimum, which, as seen in Chapter 1, will cause distortion. To get over this trouble the impedance of the loudspeaker at resonance should be matched to the optimum load value. This would mean that the load impedance at other frequencies will be even lower compared to a.c. resistance, further exaggerating the poorness of the response shown in Figure 30 for pentodes or tetrodes.

Damping

There is another aspect of this matching question closely related to this a.c. resistance/load impedance ratio, called " damping." It has been stated that the rise in impedance at the low frequencies is due to resonance, which means it is due to diaphragm movement. Since diaphragm movement has such a pronounced effect on impedance at these frequencies, it is not surprising to find that the impedance connected to the loudspeaker, resulting from the a.c. resistance of the amplifier output stage, matched down by the transformer, affects the movement of the diaphragm.

This fact can be verified fairly simply by disconnecting the loudspeaker altogether, and pushing the diaphragm in, and letting go suddenly; it will be seen to overshoot—perhaps it will oscillate a time or two at its resonant frequency before coming to rest; now short the speech coil terminals and repeat the action: the tendency to oscillate will be noticeably reduced, in fact there will probably be no overshoot at all. This difference in movement will occur whatever form the impedance connected to the loudspeaker terminals takes. When it is connected to an amplifier, the impedance is the a.c. resistance of the valve(s), matched down by the output transformer.

Thus if the a.c. resistance of the output valve(s) is low compared to the optimum load, the speech coil movement will be damped, so as not to overshoot. But if the a.c. resistance is high compared to the optimum load, the speech coil will not be damped appreciably, and overshoot will occur. The effect of insufficient damping on reproduction, as well as over-accentuating frequencies in the vicinity of resonance, will be to make the diaphragm " ring " on its resonant frequency, rather than play the true note, and, also, whenever a transient appears, the diaphragm will " ring " on resonance.

From this it is evident that triodes will give better reproduction than tetrodes or pentodes, although the latter are much more efficient types of valve. But much can be done to overcome their deficiency from the quality viewpoint by the use of negative feedback, which forms the subject of the next chapter.

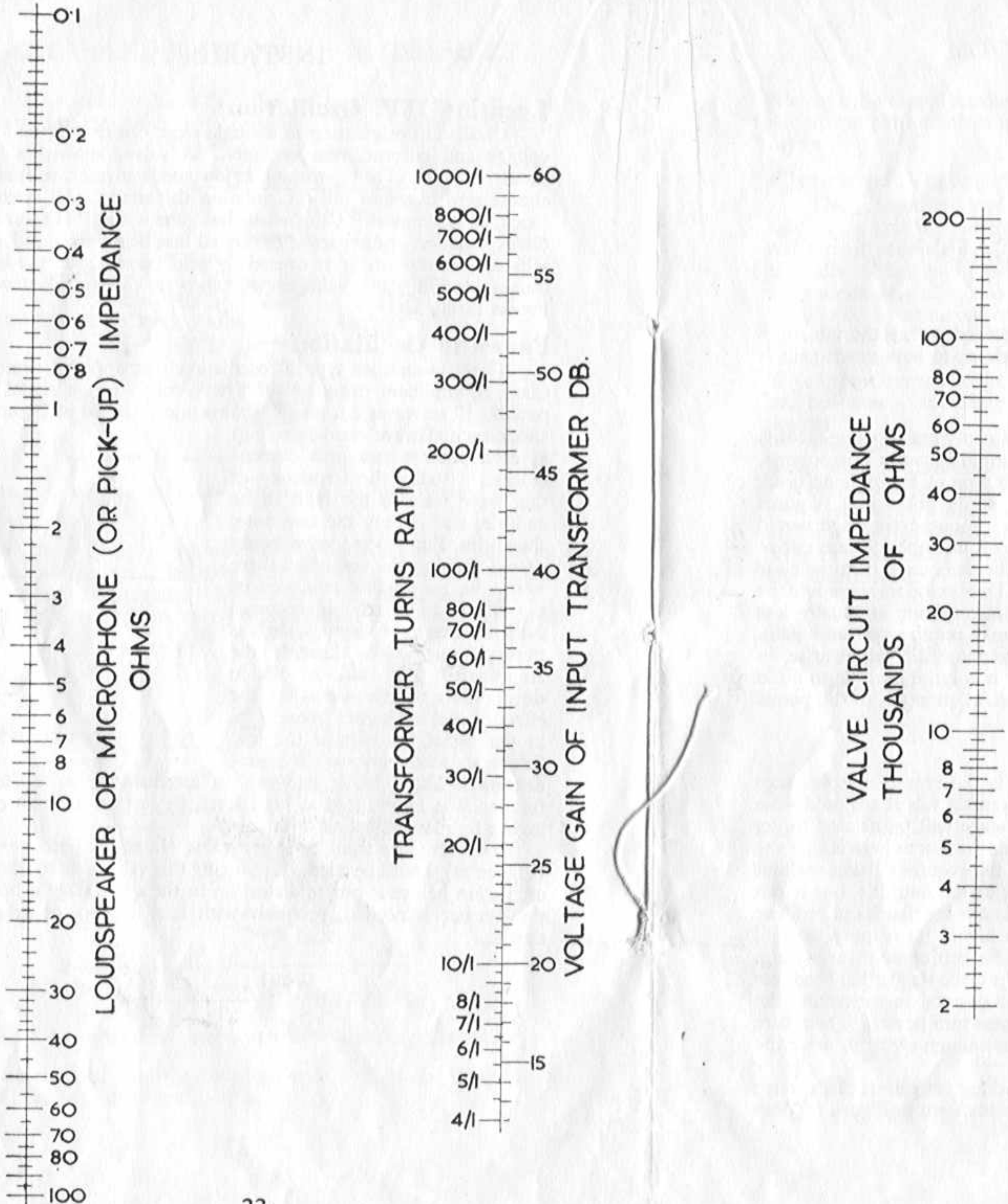

FIG. 27. AN ABAC FOR CALCULATING MATCHING RATIO.

(See page 49)

10

NEGATIVE FEEDBACK

This is a wide subject indeed, and is to have a separate book in this series devoted to it. The purpose of this chapter is to explain its effect on performance. Many claims have been made for negative feedback, most of which can be substantiated in appropriate cases; but the claims have often been presented in such a sweeping manner as to lead the reader without sufficient knowledge, to the conclusion that negative feedback provides the answer to all his problems, like a fairy godmother.

Claims for Negative Feedback

One claim that must be seriously limited concerns the ability of negative feedback to straighten out a poor frequency response. More accurately stated, negative feedback can make the response of a good amplifier better; but, applied to an amplifier with a poor response, it will more likely make it worse.

The next claim is that negative feedback reduces distortion. This is quite true; but it does not necessarily mean that it can make an amplifier give a bigger output. The effect of negative feedback on output depends on the way distortion builds up as output increases. This can best be understood by examining some typical waveforms.

Figure 31 shows: (a) the waveform at two different output levels, from an amplifier where negative feedback can increase output slightly; (b) shows a repeat of the higher level, distorted output of (a), and also the improved waveform produced by feedback.

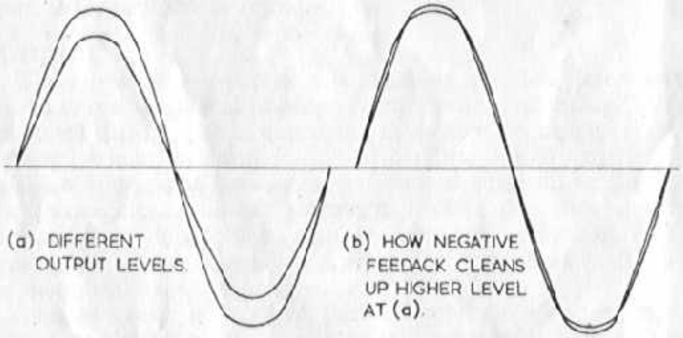

FIG. 31. SAMPLE WAVEFORMS FROM AN AMPLIFIER WHERE NEGATIVE FEEDBACK CAN IMPROVE MAXIMUM OUTPUT SLIGHTLY.

Figure 32 shows a case where negative feedback cannot increase output at all. Overloading occurs suddenly. Whatever happens, the output valves cannot be driven beyond certain limits, where the waveform completely flattens. Application of negative feedback could not extend this swing in the output, and so could only reduce the distortion until the output is at the same level as for the same distortion without feedback. Use of feedback will clean up any small distortion present before full output is reached; but when full output is reached—no bigger than without feedback —distortion comes in just as suddenly as without feedback.

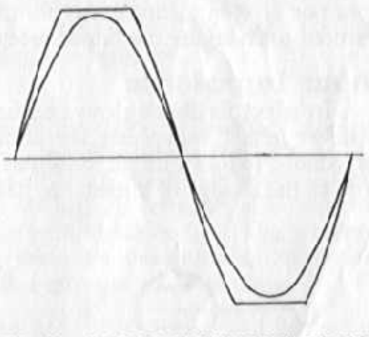

FIG. 32. SAMPLE WAVEFORMS FROM AN AMPLIFIER WHERE NEGATIVE FEEDBACK CANNOT IMPROVE MAXIMUM OUTPUT.

Negative feedback is useful for stabilising gain, especially when using high gain valves where the exact gain is dependent on operating voltages to a considerable extent. This application of feedback is rather specialised, and does not concern the commoner audio frequency applications, so further explanation does not find a place in this chapter.

Cathode Follower

The most important property of negative feedback from the viewpoint of this book, is its ability to alter input and output impedances. A well-known circuit that achieves both objects at the same time is the cathode follower, shown in Figure 33. R_2 is the self bias resistor required by the valve used. R_3 is the "anode" load transferred to the cathode lead. The input impedance, which if R_3 were in the anode would be R_1 in parallel with the effective grid-cathode capacitance of the valve, is multiplied by the gain of the valve using R_3 as anode resistor.

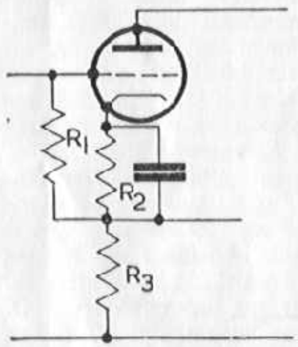

FIG. 33. CIRCUIT OF CATHODE FOLLOWER.

The output impedance (effective a.c. resistance) can be found approximately, in Ohms, by dividing the mutual conductance of the valve into 1,000. Thus a valve with a mutual conductance of 2 milliamps per volt will have an effective a.c. resistance of 500 Ohms as a cathode follower. The "anode" load, R_3, will be much higher than this, and so need not be taken into account from the viewpoint of output impedance.

The gain of a cathode follower stage is very nearly one. That means one volt input gives very nearly a volt output. So the valve does not give any gain in the normal sense of the word. Instead it is devoted to changing the impedance at which the voltage is provided.

Input Impedance

In effect feedback always exchanges one advantage for another—it never gets "something for nothing." To raise, or lower, input impedance requires negative feedback that will lose a gain of the same ratio as the change of impedance desired. Figure 34 shows methods of connection from the input viewpoint that result in increased input impedance, while Figure 35 shows a circuit that gives reduced input impedance.

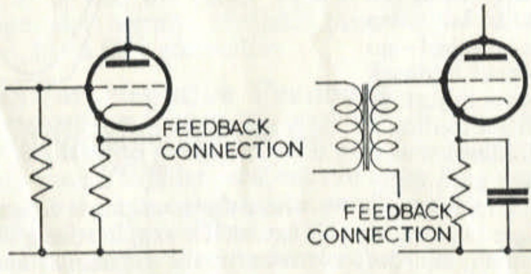

FIG. 34. FEEDBACK CONNECTIONS GIVING INCREASED INPUT IMPEDANCE.

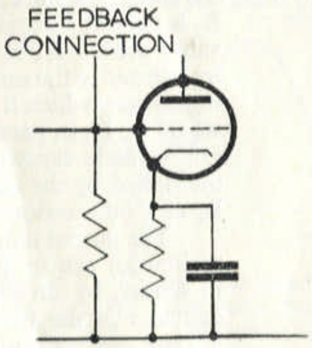

FIG. 35. FEEDBACK CONNECTION GIVING REDUCED INPUT IMPEDANCE.

Output Impedance, or A.C. Resistance

Use of negative feedback to reduce output impedance or a.c. resistance is probably its most important feature. From the output viewpoint, there are two kinds, known respectively as voltage feedback and current feedback. Voltage feedback always reduces effective a.c. resistance, while current feedback increases it, each by a ratio equal to the loss of gain caused by connecting the feedback.

Current Feedback

The simplest, and only popular form of current feedback, consists simply of leaving off the decoupling capacitor across the cathode bias resistor. It should be noticed that while the small negative feedback thus caused will reduce distortion slightly, it actually raises effective a.c. resistance, aggravating the effects described in the previous chapter. It is usually far better to leave the bias decoupling capacitor in, and use voltage feedback to *reduce* effective a.c. resistance.

Feedback and Valve Hiss

There is little point in applying negative feedback over the whole of a high gain amplifier. The earlier stages do not require feedback to reduce distortion, and there is the disadvantage that feedback does not reduce the effect of valve hiss caused by valves within the feedback section. As more gain must be provided to make up for that sacrificed in feedback, overall feedback will give more noise at the output than an amplifier without feedback having the same gain. Thus it is better to leave the early stages without feedback, and only use it over stages where the level is high enough to cause distortion and to swamp noise. Usually the last one or two stages are sufficient for this purpose.

Voltage Feedback

Figure 36 shows a variety of feedback circuits, all employing voltage feedback. The feedback connections are drawn blacker to simplify following the diagrams.

At (a) is a circuit suited for single pentode or tetrode output stages. The stage before may be a pentode or tetrode without involving any difficulty; but if a triode is used distortion may be caused, as the feedback reduces its effective anode load resistance.

At (b) is another circuit for a single output valve, having the advantage of including the previous stage in the feedback, and also the output transformer. Care must be taken to see that the transformer is connected the correct way round, otherwise the feedback will be positive and oscillation will occur, usually violently. Even connected the right way, oscillation may occur, if too much feedback is used. R_1 and R_2 determine how much there is. R_2 is fixed by being the bias resistor for the first stage of the pair. In some circuits there will not be too much feedback if R_1 is eliminated altogether.

At (c) is a well-known arrangement for push-pull output and

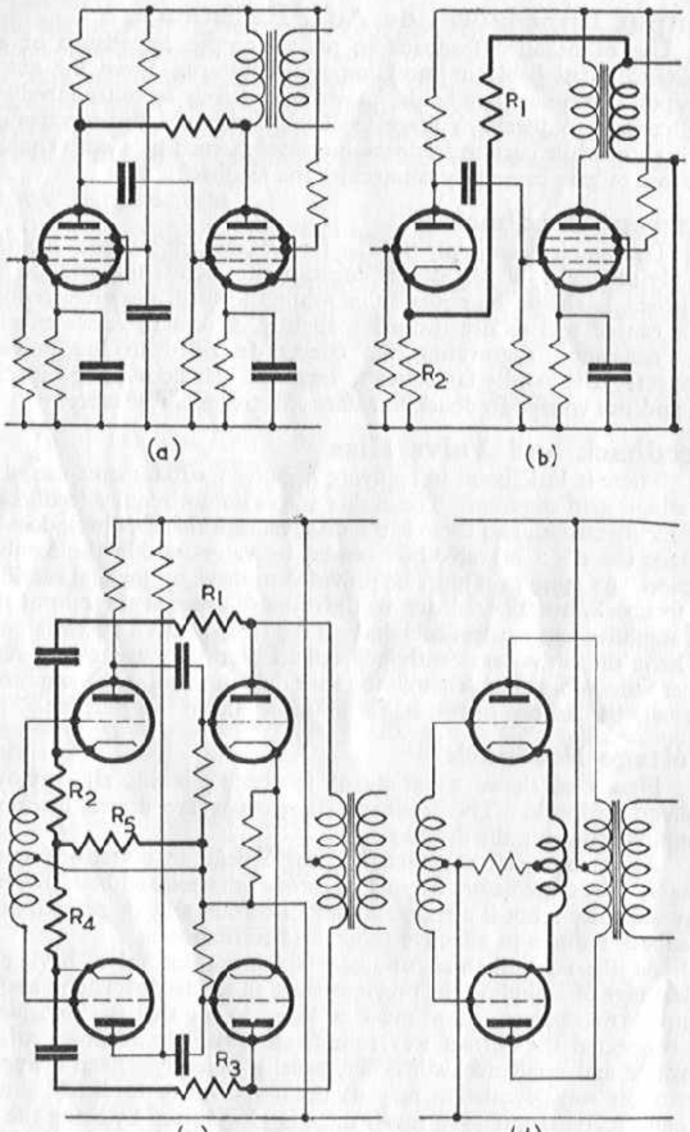

FIG. 36. NEGATIVE FEEDBACK CIRCUITS FOR REDUCING OUTPUT A.C. RESISTANCE.

drive stages. A special feature is the resistor R_5 which makes the circuit self-balancing, to compensate for inequalities in individual valves, so that " matched pairs " are unnecessary. The resistors R_1 to R_4 should all be 10% tolerance values, as the balancing action depends on their accuracy.

At (d) is a circuit that can be applied by winding extra turns of fine wire gauge on to an existing output transformer for the cathode windings. The two sets of turns must be equal in number, and again care should be taken to see they are connected the correct way round. One way will increase gain and maybe cause oscillation, while the other way will reduce gain. The latter is the required method of connection. Incidentally this is voltage feedback, not current feedback, because the voltage is fed into the cathode circuit instead of being taken from it. Another way of looking at the arrangement is to think of it as being partly a cathode follower, due to the cathode windings.

II

HOW MANY WATTS?

THE answer to this question depends largely on another: What kind of watts? The previous chapter explained how negative feedback can be used to reduce effective a.c. resistance so that tetrodes and pentodes can be used for output stages, giving quality very little inferior to that from triode stages. One point to be remembered in using negative feedback in this way, is that it does not really alter the valve's characteristics. All the while the part of the characteristics being used is reasonably near perfect (known as linear), negative feedback "does the trick." But as soon as the curved parts come into play, negative feedback ceases to be so wonderful.

Notice what happens when feedback is applied to tetrodes, particularly at the low frequency resonance of the loudspeaker. The load line is still too near horizontal, because of the rise in loudspeaker impedance. Negative feedback cancels some of the grid input at this frequency—more than it does at other frequencies—so that a shorter part of the load line is used. Negative feedback helps the damping problem, because when the diaphragm goes to move more than it should for the current passed to its speech coil, a voltage is caused by this movement which is fed back along with negative feedback voltages. This produces a current in the output opposing the movement and preventing overshoot.

But overloading still occurs very suddenly with tetrode or pentode type valves, especially when too high a value of load line occurs, as at loudspeaker resonance, due to the fact that grid voltage curves converge together at the "knee" of the characteristics. In a triode type valve, the effect of too much grid voltage input is to start grid current, or go round the anode bend. Neither of these produce such sudden stoppage of swing as does the zero grid end of a load line of too high value with a tetrode, so distortion does not start so suddenly. For this reason triode type output stages give "nicer watts" than tetrodes or pentodes with the same nominal output.

This affects the How many watts? problem. Sudden distortion gives the same effect as the speech coil knocking against a pole piece in the loudspeaker, which is very noticeable and annoying. Less sudden distortion can be tolerated more readily. Consequently, if the output is limited to a certain absolute maximum, as in Figure 32, the maximum should be sufficient to ensure that even sudden peaks do not "go over." If sudden peaks do not cause such drastic distortion, a large margin is not needed. This aspect, too, favours triodes for quality, although cost is against them. Even so, it is possible to get good quality in small amplifiers with tetrodes more cheaply than with triodes, but *a larger nominal output must be specified.*

TROUBLE TRACING GUIDE

No.	Symptoms	Possible Causes	See Chapter
1	Sound as of speech coil knocking against something at large outputs (having checked that it is not).	(a) Wrong bias. (b) Wrong load. (c) Feedback incorrectly applied.	1 1 10 & 11
2	As No. 1, but particularly at low frequencies.	Reactive load.	1
3	Harsh reproduction (sharp).	(a) Wrong bias. (b) Wrong load. (c) Feedback incorrectly applied.	1 1 10 & 11
4	As No. 3, but particularly at low frequencies.	Reactive load.	1
5	Distortion particularly of low and high notes (shrill).	Pentode or tetrode output with insufficient negative feedback.	9 & 10
6	Smaller output power available than expected.	(a) Wrong bias. (b) Wrong load. (c) Feedback incorrectly applied.	1 1 10 & 11
7	Motor-boating.	(a) Inadequate decoupling. (b) Impedance of h.t. supply too high.	2 2
8	Sound as if breaking through, only loudest sounds coming over.	H.F. blocking.	2
9	Reproduction goes dithery, particularly at high level low frequencies.	(a) Parasitic oscillation. (b) Intermodulation.	2 8
10	All reproduction dithery.	Insufficient smoothing to push-pull output.	5

[continued overleaf