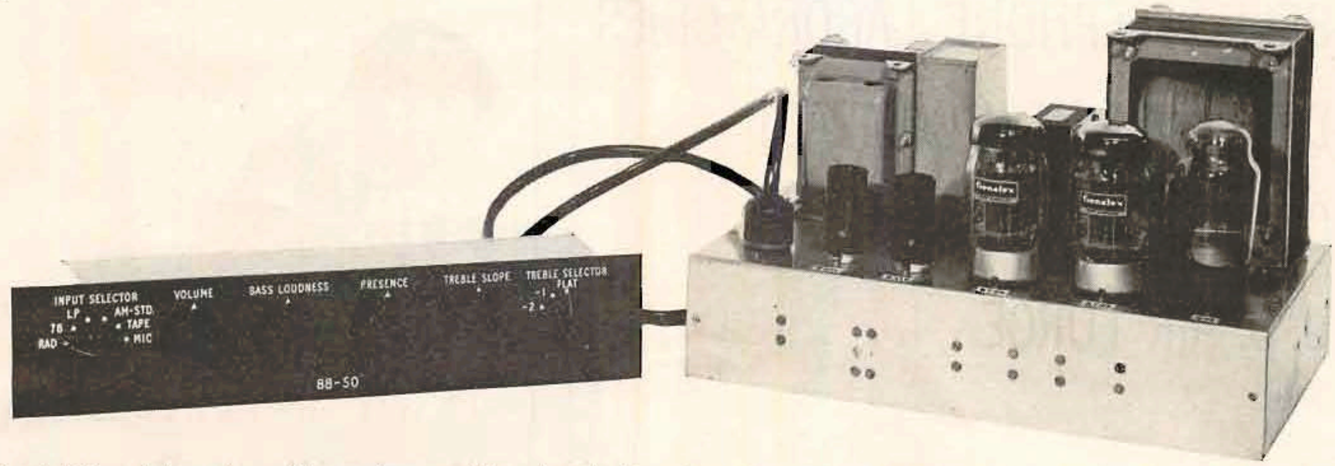


Fig. 1. External view of amplifier and preamplifier described by the author. This installment covers only the 50-watt power amplifier.

The 88-50—a Low-Distortion 50-Watt Amplifier

With harmonic distortion of less than 0.5 per cent throughout most of the audio spectrum, this 50-watt amplifier is comparatively simple in construction and requires only ordinary care in wiring.

W. I. HEATH* and G. R. WOODVILLE*

For audio amplifiers of medium power, the KT66 output tube became well known with the Williamson amplifier, and its reputation for reliability has made it much sought after in "off-the-shelf" high-fidelity amplifiers, as well as in home-built kits.

From the same stable there now follows a new tube, the KT88, a pentode with a higher plate-plus-screen dissipation of 40 watts, and a higher mutual lows a new tube, the KT88, a pentode with a higher plate-plus-screen dissipation of 40 watts, and a higher mutual conductance of 11 mA per volt (11,000 microhms.

The KT88 makes it possible to use familiar circuit techniques to build audio amplifiers giving the higher power output needed to handle the "peaks" in high-fidelity reproduction at home, or for public address equipment. This higher output is obtainable without using a plate voltage higher than that available from standard components. The KT88 achieves this by virtue of its lower plate impedance. For example with cathode bias, 30 watts of output power is obtainable with a plate supply of only 375 volts, compared with 425 volts required by the KT66. The maximum power obtainable with cathode-bias from a pair of KT88's is slightly over 50 watts with a supply voltage of 500 volts. This article describes the design and construction of such an amplifier; a second article will give similar details of a matching preamplifier. They are shown together in *Fig.* 1.

The complete amplifier, the "88-50," has been designed to give a high performance and a complete range of input and control facilities without complihas been designed to give a high performance and a complete range of input and control facilities without complicated networks or unusual components. It is therefore reasonably economical to construct. With its preamplifier it will reproduce from any programme source such as radio tuner, magnetic or crystal phonograph pick-up, microphone, or direct from a magnetic tape replay-head. A rotary switch selects the required input circuit and at the same time adjusts sensitivity and frequency correction to the required playback characteristic. The preamplifier is separate from the power amplifier and is connected to it by a flexible cable. Its controls include a loudness control, a presence control, and a treble-slope control, all these being continuously variable with a flat position around half-way. A wafer switch preselects the frequency at which the treble-slope control operates. To avoid one of the biggest gremlins of high-fi apparatus a rumble filter using an attractively simple circuit is incorporated in the preamplifier.

The Power Amplifier

The circuit of the power amplifier is shown in *Fig.* 2. A pair of KT88's is connected in an ultralinear output stage. They are driven by a push-pull double shown in Fig. 2. A pair of KT88's is connected in an ultralinear output stage. They are driven by a push-pull double triode (B329/12AU7) having a low plate impedance. A high-gain double triode (B339/12AX7) acts as the first stage and phase splitter. Over-all feedback of 22 db gives low distortion and good damping factor. The input sensitivity of the power amplifier is about 0.5 volt rms for 50 watts output. A U52/5U4G rectifier provides the 500-volt plate supply, and a thermistor[1] protects the electrolytic smoothing capacitors against excessive voltage during the warming-up period. The fact that all the plate cir-

* *The General Electric Company Ltd., Wembley, Middx, England.*

[1] A "thermistor" is a resistor having a large negative temperature coefficient of resistance. The type used here is about 3000 ohms when cold at switch-on, and gradually reduces to about 30 ohms in a minute or two when it has reached its running temperature under the influence of the combined plate and ripple currents.

cuits are in push-pull pairs enables the plate supply smoothing to be reduced to a minimum, with consequent economy of components.

The ultra-linear connection for output tetrodes and pentodes has become well known in recent years for its ability to provide the output power of pentodes at a distortion level as low as, or even less than triodes. As will be seen from *Fig.* 2, the screen grids are tapped down the primary winding of the output transformer so that the audio signal voltage on each screen is a fraction of the signal voltage at the corresponding plate. The screen-to-plate turns ratio may be anything from 20 per cent to slightly over 40 per cent for satisfactory results to be obtained. However, to avoid instability at very high frequencies when feedback is applied, the output transformer must have tight coupling between the various sections, and this is easier to achieve with a screen-to-plate turns ratio around 40 per cent, that is, each half primary is tapped 40 per cent (turns ratio) from the Bt. end. The ultra-linear circuit provides a low output impedance, roughly equal to the load, and a good damping factor is, therefore, easily obtainable with feedback.

The push-pull double-triode driver stage gives symmetrical drive to the output stage and prevents unbalanced operation even when grid current flows during overload. The B329/12AU7 was selected for the driver stage because of its low plate impedance, about 10,000 ohms. This makes sure that phase shift due to the input capacitance of the output stage is moved to frequencies above 50,000 cps. Combined with the symmetry of the circuit, this greatly assists in ensuring freedom from high-frequency instability when feedback is applied overall.

A high-gain double triode in the first stage (B339/12AX7) provides self-balancing in the phase-inverter circuit and adequate over-all sensitivity after feedback is applied.

Balancing Circuits

The push-pull signal at the plates of the phase inverter stage is balanced to about 2 per cent provided that the 1-megohm resistors R_8 and R_9 are equal. More perfect balance may be obtained if R_9 is about 2 per cent higher in value than R_8, the actual value being unimportant. If a comparison meter is available, a good compromise is to use 5 per cent tolerance resistors, making R_9 the one having the higher value. Stabilizing capacitors C_5 and C_6 should also be of similar tolerance.

The balance is improved somewhat by the use of an unbypassed cathode resistor, R_{18}, in the driver stage. The power stage uses close-tolerance individual cathode bias resistors, R_{27} and R_{28}, and this tends to equalize any slight inequalities in the output tube characteristics.

The over-all push-pull balance achieved by the above precautions in circuit design will give a performance which is absolutely satisfactory for most purposes. However, where an audio generator and 'scope are available, adjustment can be made which will give a minimum distortion figure. For this a preset wire-wound potentiometer, R_{39}, must be incorporated in the plate circuit of the driver stage as shown inset in *Fig.* 2. The audio generator should be set to a frequency between 200 and 2000 cps and should be reasonably free from second harmonic distortion. It should be adjusted to give a signal which drives the KT88's up to full power output into a dummy load resistance; this will be indicated by a slight flattening of one or both peaks of the output waveform, due to the onset of grid current. The balance control, R_{39}, should then be adjusted so that both KT88's reach the onset of grid current simultaneously as the signal voltage is increased. It has been found

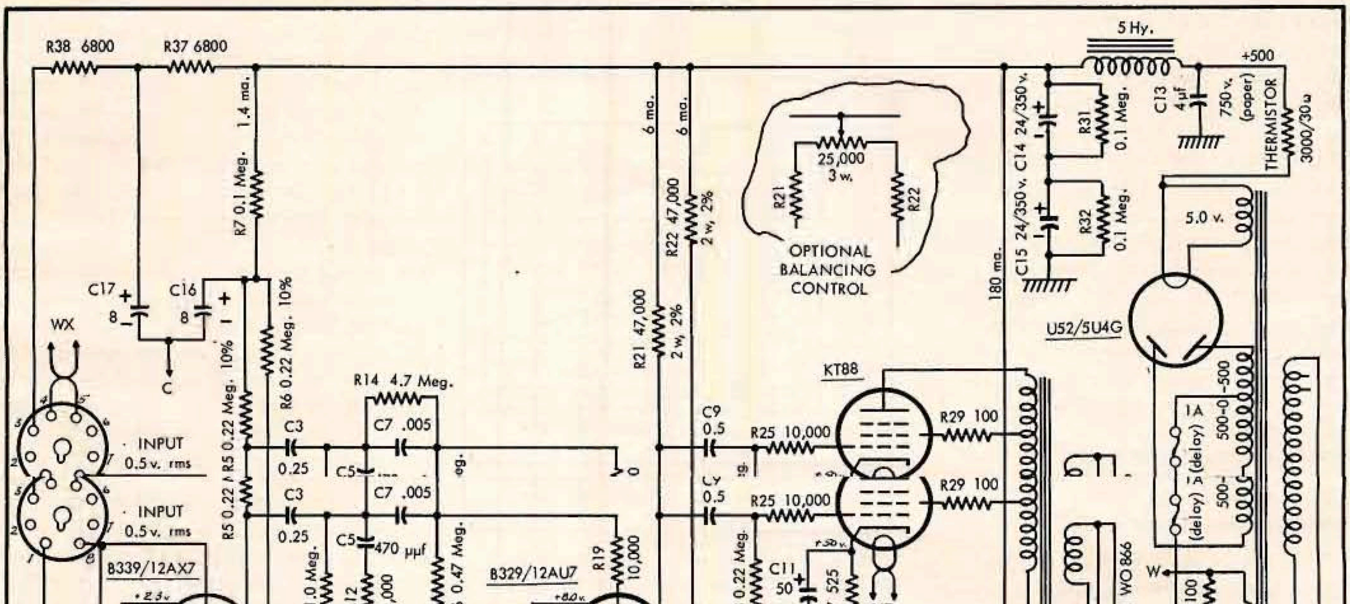


Fig. 2. Complete schematic of the power amplifier unit.

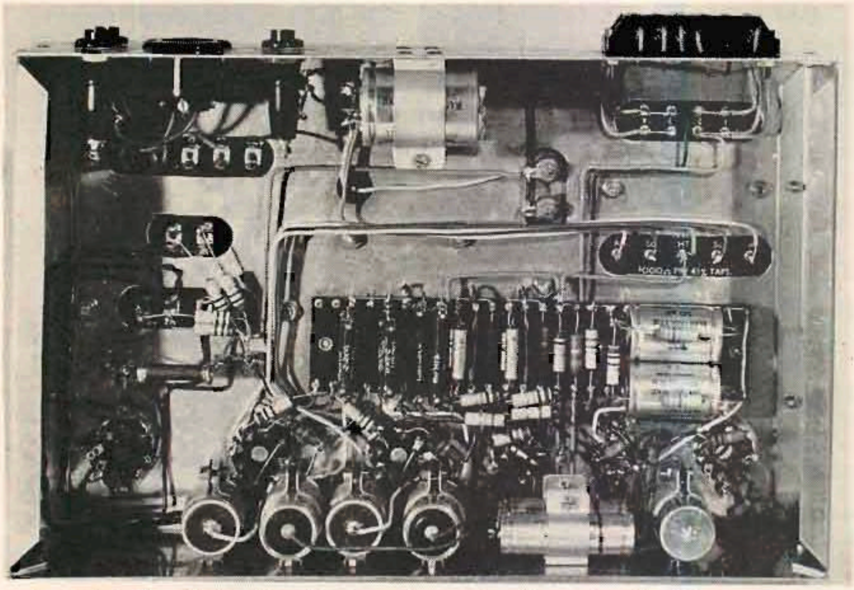


Fig. 3. Underside of chassis, showing placement of parts and wiring arrangement.

that this adjustment gives minimum distortion with a pair of output tubes that have not been specially matched.

Stabilizing

The feedback applied to an amplifier must be negative over the whole frequency range fed to the amplifier. Outside this range, the feedback must be either negative or inoperative. If this is not so, the final frequency response will show peaks, and a slight variation in feedback or load conditions may cause oscillation at these "peak" frequencies. This tendency for feedback amplifiers to oscillate is due to phase shifts in the coupling circuits, and in the output transformer itself. These peak frequencies are usually just above and below the audio band, and the technique for dealing with them is to remove them to as high or as low a frequency as possible, and then reduce the over-all feedback at very high and very low frequencies.

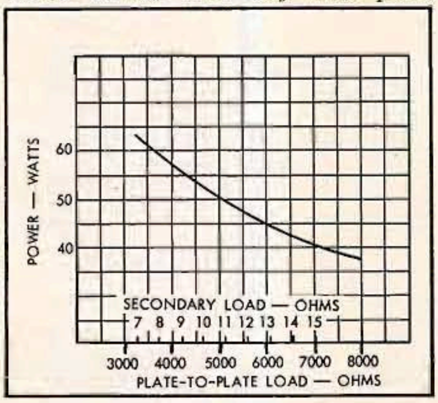
Low-Frequency Stabilizing

very high and very low frequencies.

Low-Frequency Stabilizing

The low-frequency peak occurs only when feedback is applied. It results from the combined phase shifts of (1) the coupling capacitors and associated grid leaks and (2) the primary inductance of the output transformer combined with the load and tube impedances. The peak occurs below 20 cps and often results in motorboating when a preamplifier is connected to the same plate supply. The peak is minimized by making the time constants of all the coupling circuits different, by suitable choice of capacitors, and the shortest time constant is consequently that of the output transformer itself. For complete elimination of the peak, the amplifier gain before feedback is connected should be reduced at the peak frequency without introducing additional phase shift. For a flat frequency response, the reduction in gain required is approximately equal to the feedback that is to be applied.

In practice, this is achieved by inserting a "step-circuit" in an early coupling circuit. This consists of a small series capacitor shunted by a high resistor, before the grid leak. Thus, the gain is reduced as the signal frequency is lowered and at the very low frequencies is reduced by a substantially resistive potential divider with very little phase



3000 4000 5000 6000 7000 8000
PLATE-TO-PLATE LOAD — OHMS

Fig. 4. Curve showing maximum power output of KT88 output stage delivered to load on secondary of transformer at frequency of 500 cps.

shift. For a 20-db (10:1) gain reduction, the shunt resistor should be ten times the grid leak. The capacitor should be sufficiently small to have, at very low frequencies, an impedance equal to or higher than that of the shunt.

As the "88-50" is push-pull throughout, such a circuit has to be incorporated on each side. In *Fig.* 2, this consists of C_7 shunted by R_{14} and followed by grid leak R_{16} on the one side, with C_8, R_{15} and R_{17} on the other. The values chosen will give low-frequency stability with any output transformer capable of delivering the full power output down to 40 cps. An advantage of this type of stabilization is that the response of the power amplifier is devoid of peaks, and falls sharply at very low frequencies with the result that there is no tendency for motorboating to occur when the preamplifier is connected on the same plate supply. This enables economy to be exercised in the smoothing for the preamplifier supply, to the extent that it is merely required to give adequate reduction of ripple.

High-Frequency Stabilizing

Before feedback is applied, peaks may be detected in the response of most amplifiers at frequencies up to 100 or 200 kc owing to resonances in the output transformer. With the output transformers used in designing the prototype 88-50, leakage inductances between the various windings were low and the first high-frequency peak was detected about 100,000 cps. Such a peak is always exaggerated when feedback is applied, and may cause instability under certain conditions. Accordingly, a stabilizing step circuit, comparable to that used at the low frequencies, is incorporated. This circuit (*Fig.* 2) consists of C_5 with R_{12} in series, and to maintain symmetry C_6 and R_{13} on the other side.

Location of Stabilizing Circuits

The early stages of the amplifier have been chosen so that the high-frequency phase shifts due to Miller effect are slight, and with the component values given the stabilization is substantially independent of output transformer and load. The stabilizing circuit has been inserted in an early stage in the amplifier to remove the risk of overloading the preceding tube. With such a circuit it is undesirable to use additional capacitors across the output transformer, or across the feedback resistor, and in any case the use of such capacitors is critically independent on the particular type of transformer and load used.

The component values were chosen to
critically independent on the particular
type of transformer and load used.

The component values were chosen to give the best results with transformers of the characteristics described below, but it was found that a simple transformer with slightly higher leakage inductances was quite stable in operation. With a transformer of the preferred specification, the overshoot on a 10,000-cps square wave was about 10 per cent with a resistive load, and there was reduction of 6 db in the effective feedback at 40 and 10,000 cps.

Output Transformer

Desirable requirements for an ultra-linear transformer for use with negative feedback are adequate primary inductance and low leakage inductances. Primary inductance should be adequate for full power performance down to at least 40 cps. Leakages between primary and secondary, between each half primary, and between each plate tapping of the half primaries and its associated screen tapping should not exceed 6 millienries each.

The output transformer used for the prototype amplifier was the WO866 made by R. F. Gilson Ltd., St. Georges Road, London, S.W.19 using grain oriented silicon iron. Although designed for operation at lower power outputs than those obtainable from the KT88, it gave very good results, as the curves show, over the frequency range from 40 to 20,000 cps. Excellent results have also been obtained with a Partridge Type 5353, and a Savage 4N1, the latter giving full power output down to about 20 cps. All these transformers had the necessary low leakages, and a resonant frequency around or above 100,000 cps.

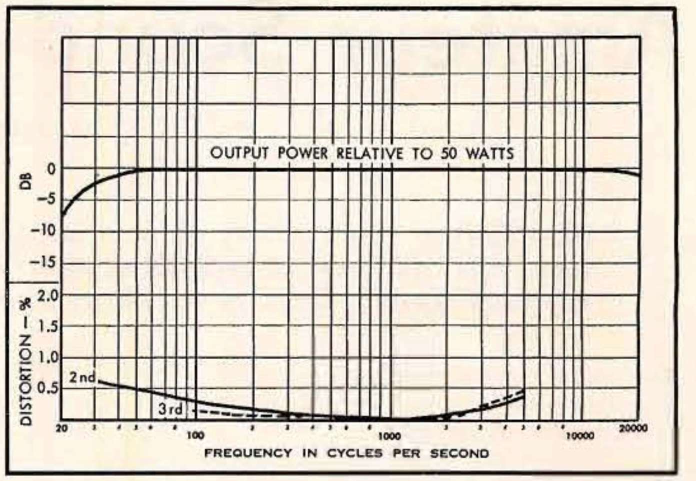


Fig. 6. Maximum output power, relative to 50 watts, over entire frequency spectrum, together with distortion curves at rated output.

Construction

Figure 3 shows the underside of the power amplifier chassis. The prototype was constructed on a chassis measuring 14 in × 9 in. × 3 in. The assembly plan follows an "in-line" strip layout with *one* ground terminal near the *input* socket and first tube, (B339/12AX7). If larger transformers are used the chassis may need to be increased in size but the layout is important and must be followed. It was thought advisable to mount the transformers with terminals down for safety.

The power transformer is as far as possible from the input to prevent hum and its orientation should be noted. (*Fig.* 1).

A mounting board is used for all smaller components. The larger coupling capacitors and the later cathode bypass capacitors are clipped direct to the side of the chassis, and this provides screening, with the exception of C_{14}, which must be insulated. For ease of servicing almost no wiring is beneath the tagboard.

The heater wires should be laid in first, with twisted twin wires along the bend of the chassis and the tube sockets oriented to avoid heater wiring crossing grid wiring. The heater supply for the preamplifier should also be laid in to the octal socket connection. Both supplies must have a center-tap grounded to chassis, or an artificial center-tap using two equal resistances, as shown. The ground point mentioned above should be placed near the first tube and a 'star' lug bolted down with a lock washer for good contact. All grid, plate, and intertube coupling circuits must be returned by insulated wiring to this one chassis point.

The signal input (pin 8 on the octal socket) should be wired as directly as possible to the grid of the 12AX7. The ground connection (pin 1 on the octal) and the grid leak should be connected to the 'star' lug. The cathode bypass capacitor C_1 with the series feedback resistor R_4 should be wired between the cathode pin and the 'star' lug, as close to the grid input lead as possible. The cathode bypass capacitor of the second half of the 12AX7 should be wired in an equally compact manner. The grid, fed from the phase-splitting network, should also be wired as compactly as good mechanical location of the components will permit.

Throughout, grid and plate leads should be short and separate as far as possible. 'Dead' wiring, such as plate-supply leads returning to a smoothing capacitor or cathode bias resistors which are bypassed, may be longer, if necessary. Grid stoppers R_{19}, R_{20}, R_{25}, R_{26}, R_{29} and R_{30} must be wired direct to the tube socket with very short leads.

The ground point of each tube should be insulated, connected back to the corresponding point on its predecessor and so on to the star lug. Similarly, the grounded end of the output transformer secondary should be returned to this point, as this circuit is part of the feedback. The grounded side of the plate supply and heater center tap may, however, be wired to the chassis. The output transformer is, of necessity, near the input circuits, and the live plate and screen wiring should be bound to-
the input circuits, and the live plate and screen wiring should be bound to-
gether and positioned well away from the mounting strip.

Connecting the Feedback

When completed and checked, a dummy resistance load should be connected, and the amplifier first switched on with the feedback disconnected by an open circuit at R_{11}. If the voltages measured across the cathode bias resistors approximate to those shown in *Fig.* 1 (some voltmeters will give a lower reading) a test signal may then be connected to the input of about 100 mv, and a loudspeaker tapped across the dummy load. If an audio oscillator is not available, a phonograph pickup having a high output, such as a crystal type, can be connected to the input via a temporary volume control. An extra

(*Continued on page 73*)

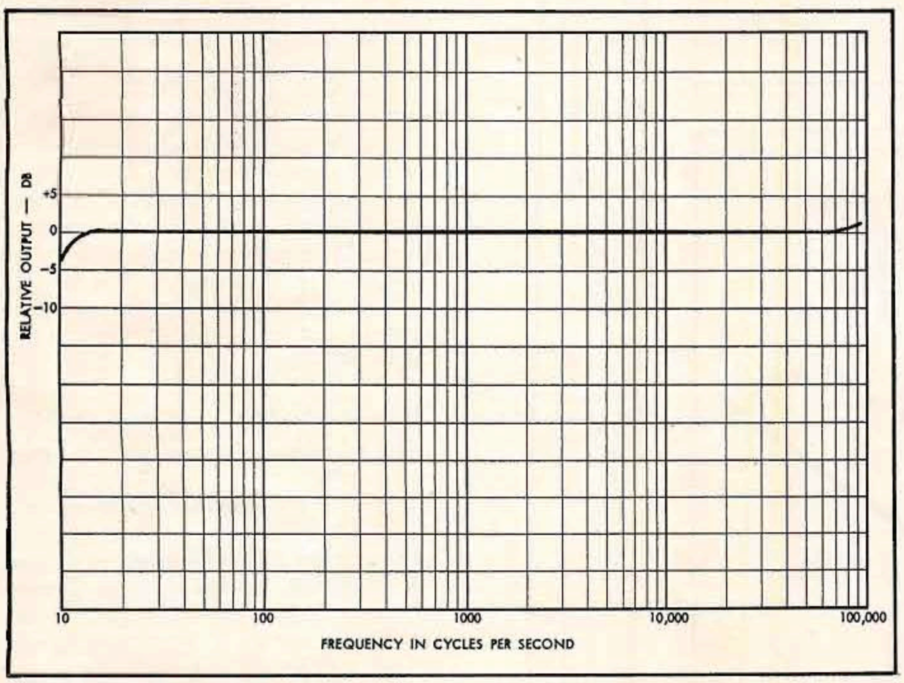


Fig. 5. Frequency response of amplifier at 1-watt output.

50-WATT AMPLIFIER

(from page 23)

resistance of about 47,000 ohms should be connected in series with R_{11}.

With the test signal audible, the feedback should be connected, and a note made of whether the output is increased or decreased. If the feedback increases the output, the connections to the output transformer must be reversed. If the feedback decreases the output, then the connections are correct, and the feedback may be permanently connected with the extra resistance removed. This method removes the risk of oscillation and possible damage to the output tubes and transformer.

Performance

The maximum power output of an R-C coupled amplifier may be defined as the maximum power obtainable without driving the output tubes to grid current, and this is easily observable on a 'scope. Under these conditions, the output measured across various dummy resistance loads on the secondary of the

playing in this performance is just plain

WO866 transformer, is shown in *Fig.* 4. An output of 50 watts is obtained with an equivalent plate-to-plate load of 5000 ohms, and this corresponds with this transformer to a secondary load resistance of 10.7 ohms. For a 15-ohm secondary load, the WO866 transformer ratio gives a primary load of 7000 ohms, and into this load 40 watts can be obtained. With two 15-ohm speakers in parallel an output of about 60 watts would be obtained, with somewhat greater distortion. Plate-to-plate loads below 4000 ohms give increased distortion and are not recommended. At frequencies above and below 500 cps the speaker impedance is usually greater than the nominal value, and the effective load is, therefore, higher.

Figure 5 shows the frequency response at a power output of about 1 watt into a load of 10.7 ohms. The level response with the absence of peaks over the whole frequency range from 10 to 100,000 cps indicates that the stabilizing circuits are very satisfactory with an output transformer having the characteristics described earlier. In consequence the amplifier is completely free of any tendency to parasitic oscillation under drive. The tendency for the response to fall below 10 cps is typical of a stabilized amplifier with feedback, and greatly assists low-frequency stability when a preamplifier is connected to the same plate supply.

Maximum power is obtainable over the audio band from 30 cps to over 20,000 cps, (*Fig.* 6). The same figure shows that at maximum power, second and third harmonic distortion are each less than 0.1 per cent at 500 cps. The increases at 100 and 5000 cps are the results of the stabilizing circuits reducing effective feedback at high and low frequencies. This, however, is a small price to pay for the clean performance resulting from good stability. The harmonic distortion was measured up to 15,000 cps, and listening tests confirmed the merits of the results shown. It should also be noted that these figures for distortion are measured at full power over the whole frequency range.

Maximum power output is obtained with an input drive of 0.5 volt rms, and the hum level is −73 db with the input open-circuited, or better than −90 db with the input short circuited. The feedback is 22 db at 500 cps with a 10.7-ohm secondary (24-volt output). For use with load impedances other than this, the feedback resistor R_{11} (4700 ohms) should be altered in proportion to the resulting output voltage.

Acknowledgements

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REFERENCES

Thomas Roddam, "Stabilizing feedback amplifiers. *Wireless World*, Vol. 57, March 1951, p. 112–115.

D. M. Leakey and R. B. Gilson, "U.L. output transformers." *Wireless World*, Vol. 62, January 1956, p. 29–32.