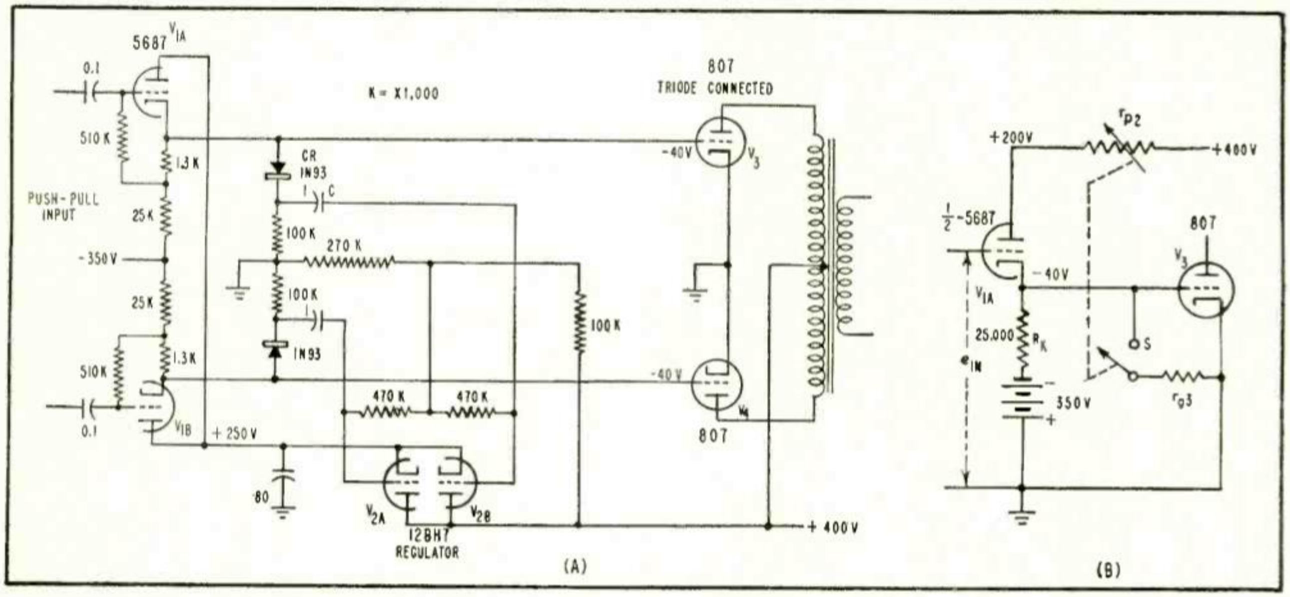


FIG. 1—Kicker circuit gives improved grid regulation for AB_2 operation from cathode-follower driver stage (A). Equivalent circuit of one side of push-pull circuit aids analysis of regulating action (B)

Circuit Design Factors for

SUMMARY —— New amplifier circuits feature high power output with low intermodulation distortion. Kicker-type circuit closely regulates plate supply of cathode-follower driver stage. Improved versions of Williamson and ultra-linear amplifiers are included

WHILE setting up a development program for a line of audio amplifiers, several new design configurations were evaluated, using both triode and beam power tubes.

Standard output and power transformers were used. To obviate use of a special grid-driving transformer, a cathode follower was employed to drive the output stage into the positive grid voltage region.

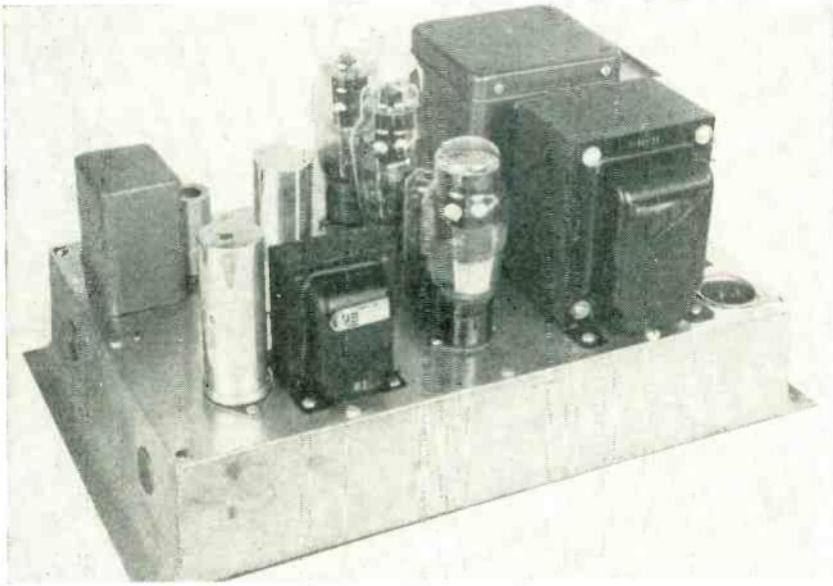
When a cathode follower drives the following stage into the grid-current region, flow of grid current is from the driven-stage cathode or filament to its grid, through the cathode of the driver stage to the plate of the cathode-follower driver and back through the plate supply of the driver stage to ground. The plate supply to the cathode-follower plate circuit must supply all the grid current which appears on the grid of the driven stage. This means the cathode-follower plate supply must have perfect regulation if the cathode-follower is to provide a low-distortion signal.

Regulation

To keep costs to a minimum, it is generally possible to have only one well-regulated, positive high-voltage supply. Low cost, high g_m, high-perveance tubes suitable for cathode-follower use in this function are limited in dissipation and plate-to-cathode voltage so some type of voltage-dropping circuit is required to secure the necessary 200 to 250 volts from the high-voltage plate supply. An R-C filter has poor regulation characteristics. Better regulation is available with a voltage-regulator tube used with an L-C filter or a cathode-follower type of degenerative regulator, but a more positive type of regulator was required for these amplifiers.

The kicker circuit of Fig. 1A was devised to obtain the required regulation of the cathode-follower plate supply. The cathode-follower stage supplied by this circuit is capable of driving the output stage grids into the positive grid current region with good linearity and excellent stability. The regulation circuit may be analyzed with reference to Fig. 1B, which is an equivalent circuit showing one side of the push-pull circuit of Fig. 1A.

Prior to the time V_3 is driven positive, the plate current through cathode follower V_{1A} and regulator tube V_{2B}, whose dynamic plate resistance is shown as r_{p2B}, is constant and the voltage at the plate of V_{1A} is steady. When V_3 is driven positive, S is effectively closed and the grid-cathode dynamic resistance shown as r_{g3} (which may drop as low as several hundred ohms) is thrown into the circuit, which for



Typical prototype chassis for 11, 24 and 33-watt amplifiers described in text; power supply is built on same chassis

Audio Amplifiers

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a given value of e_{IN} requires a greater plate current through V_{1A} to attain equilibrium. This normally results in a drop of plate voltage at V_{1A} with attendant positive-peak flattening off of the driving voltage to the grid of V_3. In Fig. 1A, however, diode *CR* immediately senses the instant when V_3 starts to go positive.

As a result of the connection of *CR* through *C* to the grid of V_{2B}, r_{p2} of V_{2B} may be simultaneously decreased to maintain the plate of V_{1A} at a constant voltage to permit driving V_3 to large positive voltages while maintaining excellent linearity. The origin of the kicker cognomen is thus seen.

Use of cathode-follower drivers may also reduce component costs and/or help the frequency response and phase shift performance of the driving circuit, if full advantage is taken of the high-input-impedance characteristic of the cathode-follower connection. Figure 2 illustrates the proper connection of this interstage circuit for maximum value of the input time constant *RC*.

Low-Impedance Driver

The apparent input-circuit time constant is 0.56 sec compared to 0.056 sec for conventional circuits.

To obtain the best possible driven grid-voltage waveform (and lowest driving impedance) it is possible and desirable to employ feedback over several of the preceding stages. Another advantage in doing this is establishment of equal gains, independent of tube characteristics, on each side of the push-pull circuit provided that R_1 R'_1 and R_2 R'_2 in Fig. 3 are carefully balanced. This permits the use of feedback from the primary of the output transformer to preceding push-pull stages. This also permits feedback to be applied across the sides of the push-pull circuit, which reduces cross-modulation and distortion to a very low value.

The cross-coupled push-pull pri-

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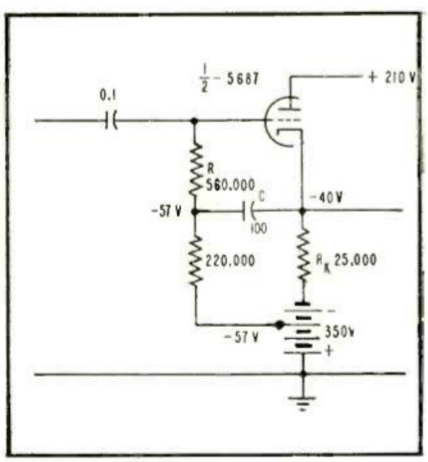


FIG. 2—Input coupling for large *R-C* time constant: output impedance is 225 ohms and maximum output 180 v peak to peak.

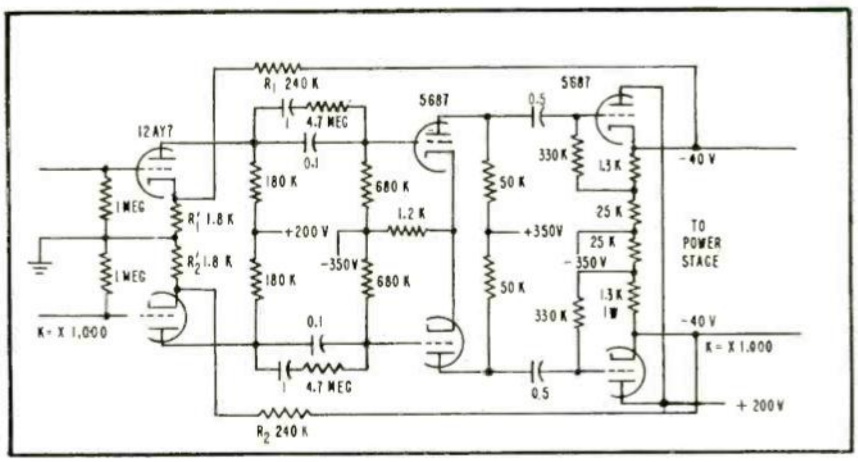


FIG. 3—Low-impedance push-pull driver amplifier has gain of 40 db with 12-db feedback. Resistors R, R', and R2R'2 must be balanced. Sufficient drive is available for operation of push-pull 807 tubes.

mary feedback amplifier (where a low leakage reactance transformer is used) is a special feedback case analogous to the situation where a tertiary transformer winding is used in a single-ended amplifier. Its equivalent circuit is shown in Fig. 4.[1]

Use of feedback in audio amplifiers operated in part over a nonlinear portion of the output tube characteristic may improve the overall performance of push-pull amplifiers.[2]

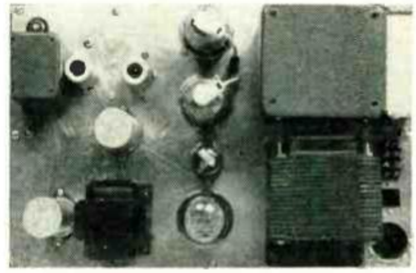
Tests indicate that use of the kicker circuit and 12 db of feedback from the driver grids, with an additional 12 to 20 db of cross-connected feedback from the output tube plates to an earlier stage, will permit design of an efficient amplifier which will supply a large output with low distortion. This arrangement is shown in Fig. 5.

Automatic Balancing System

To maintain the output stage in a statically balanced condition, the d-c servo type of automatic balancing system shown in Fig. 6 has been devised. This circuit employs a d-c differential sampling amplifier, each section of which is followed by a cascode stage for securing the proper phase relationships and maximum servo gain while permitting ready static adjustment of the output stage through adjustment of the cathode-follower driver bias voltages. In addition to the self-balancing feature, this circuit may be adjusted and operated to permit automatic control-bias variation[8] to secure optimum output-stage operation at all power levels. The kicker modification may also be used.

Modified Williamson

In the past, the basic Williamson circuit has been widely followed. Care must be used in the operation of this unit because of the severe distortion that occurs when the grids of the power output stage are driven positive. An improved version of the Williamson type amplifier is described in the literature.[4] Since then, simplification and improvements have been made for the purposes of further reducing distortion, minimizing the effects of the wide range of tube



Top view of chassis for amplifiers of Fig. 7, 8 and 9 shows component layout

characteristics normally encountered, simplifying construction and reducing the cost of the amplifier system.

The new amplifier shown in Fig. 7 employs parallel 5V4 tubes in the power supply to provide automatic time delay for the high voltage while maintaining the low power-supply impedance necessary for such a wide-band amplifier. Low-frequency performance is aided by improved decoupling circuitry and longer time constants in some networks. Low-frequency stability characteristics have been improved by reducing interstage time constant between the 12AY7 and the 5687.

Intermodulation Distortion

Since publication of the improved Williamson circuit, greater attention has been paid to optimizing the intermodulation characteristics of the input and driver stages by employing circuit values which will tolerate normal variations in tube characteristics as will occur from one lot of tubes to the next. Also, tests indicate that the 12AX7 may

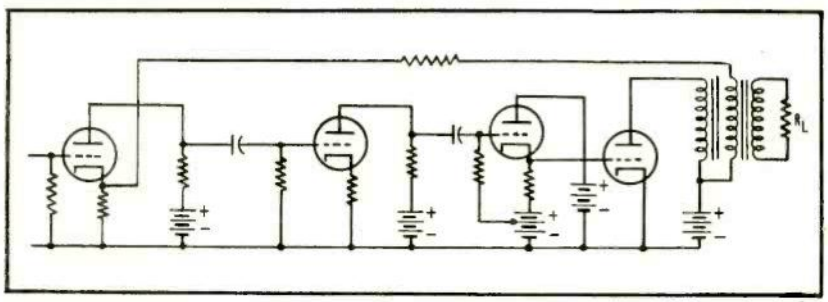


FIG. 4—Equivalent circuit of one side of cross-coupled push-pull feedback amplifier

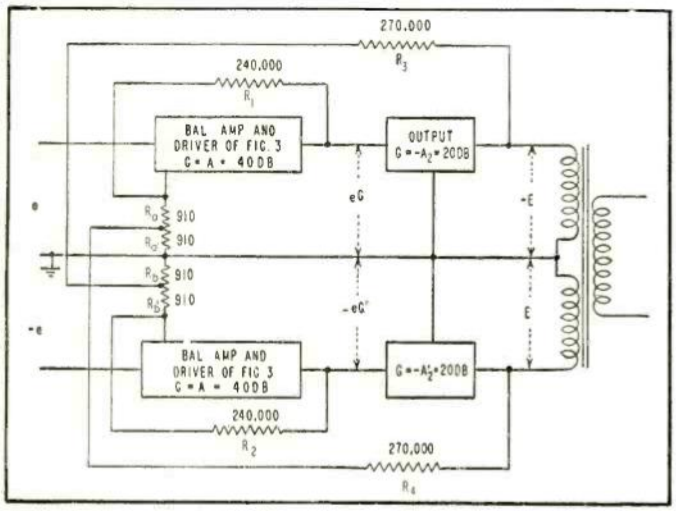


FIG. 5—Low i-d push-pull amplifier has balanced feedback and balanced output

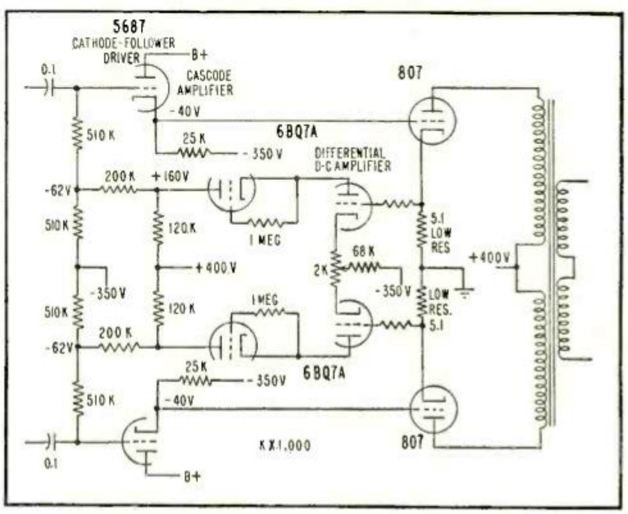


FIG. 6—Servo-balancing system automatically keeps output stage in static balance

serve as a replacement for the 12AY7, with but slight deterioration in performance. Circuit values for this improved input circuit are shown in Fig. 7.

It was found that the inverter section of the 12AY7 makes a large contribution to the intermodulation distortion of the amplifier. This results from too low a plate-supply voltage being generally employed in this stage. If the i-d is to be kept low in the first stage, the optimum cathode resistance should be approximately 270 ohms.

Cross checks were made with a 6SN7 in this part of the circuit and exactly the same results were experimentally verified. Accordingly, the new circuit employs a higher voltage for the plate supply to the inverter section of the 12AY7 and utilizes a 270-ohm resistor in the cathode of the input section. It was possible to get 3 volts rms out of each side of the inverter without measurable i-d, even when four sets of tubes from three manufacturers were interchanged.

Hum Reduction

A 2-ohm resistance in series with the filaments of the 12AY7 input stage helps to stabilize the d-c coupled operation of this stage and reduces hum susceptibility over a considerable variation in tube characteristics.

The 5687 driver stage was checked next, but the original circuit values proved to be optimum from the i-d point of view.

After evaluation of the driver stage, the triode output stage was examined carefully and adjustments were made to determine the optimum bypass point on the cathode resistor. This was found to be at a point 140 ohms down from the cathodes. This value applies only to the triode circuits of Fig. 7. The entire cathode must be bypassed in the tapped beam-power connection of Fig. 8.

The output transformer was next investigated. Two outstanding units were found, General Radio 942-A and the Freed 18777. The Peerless S-268Q, the ACRO, UTC and probably others would exhibit similarly excellent characteristics had they been available for test. These units all have low distortion, reasonably high primary inductance, low leakage reactance and good power-handling capability at both ends of the spectrum. Tight coupling is particularly required to minimize switching transients.

These modifications bring the Williamson circuit of Fig. 7 up to its finest point and provide an amplifier with i-d held to 0.1 percent at 7-watt equivalent single-signal output, to 1.0 percent at 11 watts. Like all amplifiers drawing grid current, the distortion goes to high levels as the grids are driven positive.

When the 807 power-stage grids are driven positive, the driving-point (source) impedance of the 5687 is approximately 1,000 ohms on positive peaks with consequent flattening off of the positive peaks. Matters are made even more acute when the 1,000-ohm series parasitic resistors are considered. An amplifier of this type will only exhibit extraordinary cleanness provided it is never required to deliver a high energy peak.

Ultra-Linear Circuit

A modification of the circuit of Fig. 7 to utilize the ultralinear connection is shown in Fig. 8. At an i-d level of 0.1 percent a power output of 13.7-watt equivalent single

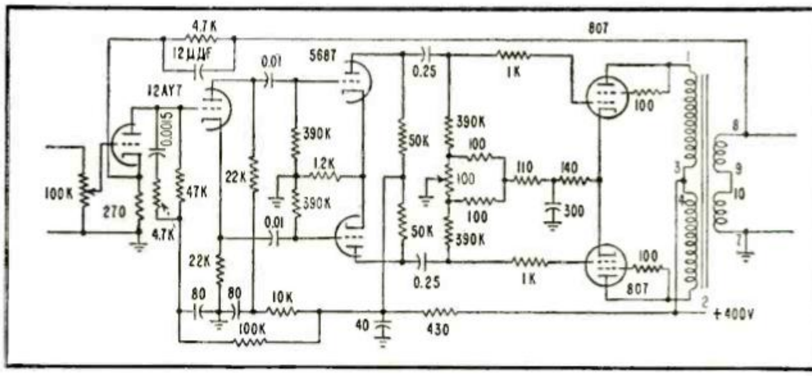


FIG. 7—Improved Williamson amplifier has 11-watt output. Output transformer is Peerless S-265-Q

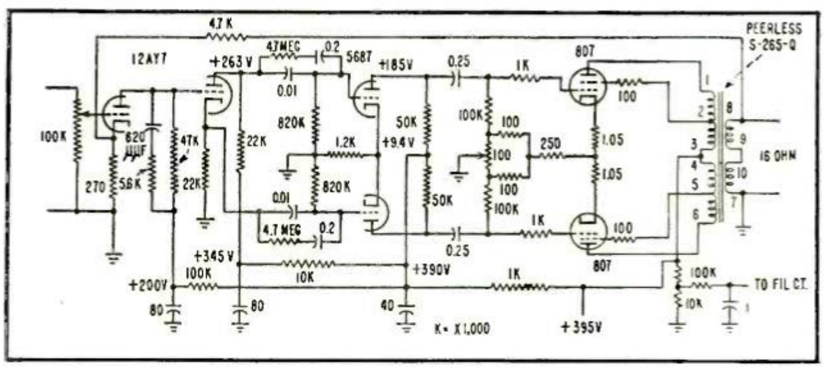


FIG. 8—Improved ultralinear amplifier has 24-watt output. Tube heaters are biased about 35 volts above ground to reduce hum modulation

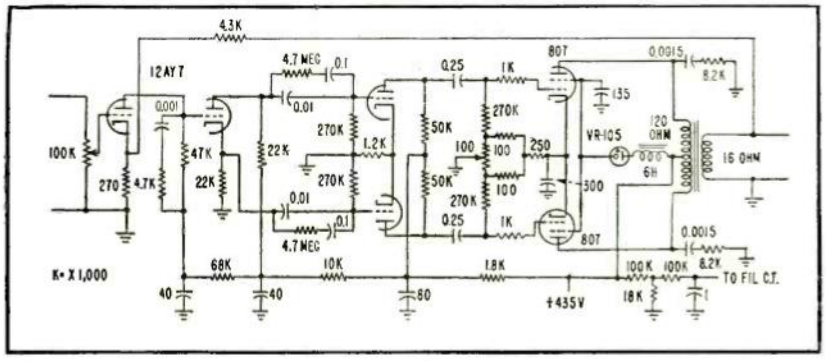


FIG. 9—Thirty-three-watt beam-power amplifier has gas-tube screen-voltage regulation. Output transformer is Peerless S-265-Q

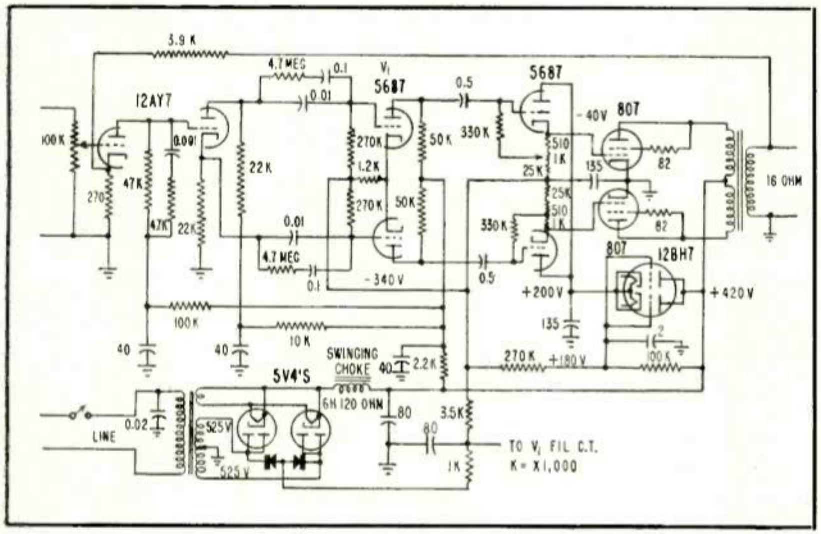


FIG. 10—Forty-five-watt amplifier uses kicker regulation circuit shown in Fig. 1

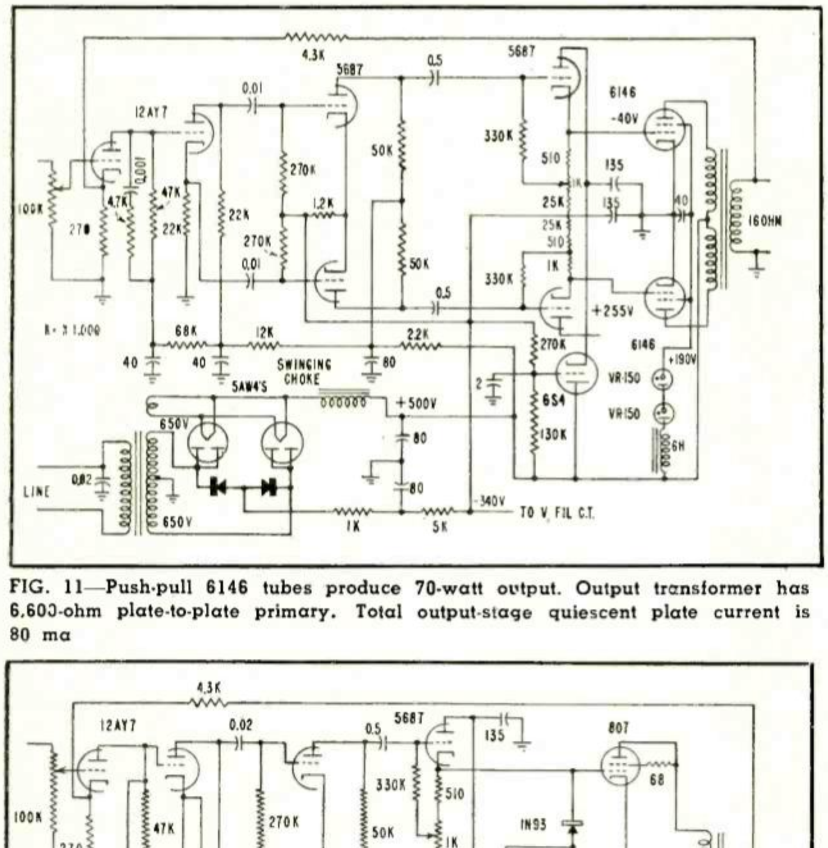


FIG. 11—Push-pull 6146 tubes produce 70-watt output. Output transformer has 6,600-ohm plate-to-plate primary. Total output-stage quiescent plate current is 80 ma

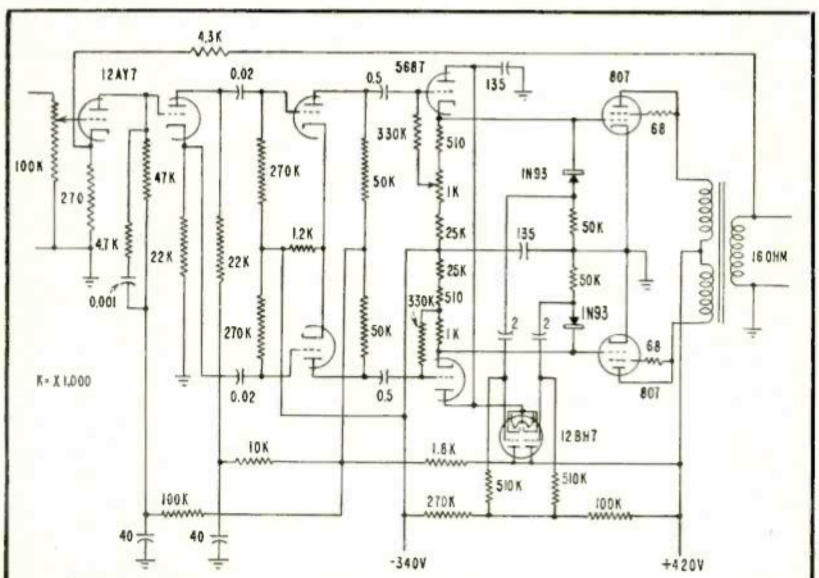


FIG. 12—Sixty-five-watt amplifier uses power supply similar to that in Fig. 10. Total output transformer primary impedance is 2,800 ohms. Second tube is 5687

signal is obtained while at an i-d level of 1.0 percent a power output of 24 watts is obtained, a very real gain in performance.

Approximately 20-db feedback is utilized in the triode version and approximately 24 db with the ultralinear version. The ultralinear version has greater gain because of the quasi-beam-power connection, but also a slightly increased amount of feedback because the feedback resistors are left unchanged. In this case the net circuit gain is about equal to the original triode circuit. Under these conditions, the following comparison of mid-range output damping was measured with a 15-ohm load, 6-volt level at 500 cps: 807 tubes triode connected, output = 0.54 ohm; 807 tubes ultralinear connected, output = 0.39 ohm.

The circuit of Fig. 8 was next modified to use a straight beam-power connection as shown in Fig. 9. At an i-d level of 0.1 percent, a power output of approximately 14 watts equivalent single signal was measured while at an i-d level of 1 percent a power output of 33 watts was obtained. The 24 db of feedback did not cause instability and the output damping was just as satisfactory as in the other two cases.

New Amplifiers

A new series of amplifiers was investigated and carried to a point near completion. Power output, simplicity and cost were the design objectives in this evolutionary program. In each case, care was taken to provide excellent i-d performance as well as output-damping characteristics in the range of 20 or 30 to 1.

The first amplifier built under this program is shown in Fig. 10. This unit employs a cathode-follower driver. Fixed biasing of the output stage combined with a negative high-voltage supply provide approximately 650 volts for the plate supply to the high-level voltage-amplifier driving stage. This amplifier provides 15 watts output at a i-d level of 0.1 percent and 45 watts at the 1.0 percent i-d level.

Fig. 11 shows a beam-power connected counterpart of the amplifier of Fig. 10. In this case, approximately 14 watts are available at a 0.1-percent i-d level and 70 watts at the 1-percent i-d level.

To check more closely the grid-regulation problem and the desirability of the triode connection, the configuration of Fig. 12 was evaluated and provisions made to use the kicker circuit of Fig. 1A. The improved grid regulation was apparent. At a power level of approximately 21 watts the i-d was 0.1 percent, while 65 watts were available at the 1.0-percent i-d level.

Figure 13 embodies a number of the circuit techniques previously discussed. This design pushes the output, from only two conventional tubes operated at rated levels, to about the maximum power level available from these tubes when operated at nominal receiver voltages and in conventional circuits. It is essential that the high-voltage power supply have good regulation so that peak plate currents of 290 ma, from a static level of 135 ma, will entail only a negligible drop in high-voltage supply. A beam-power connection was used due to the lower grid voltage required and greater gain available with this connection.

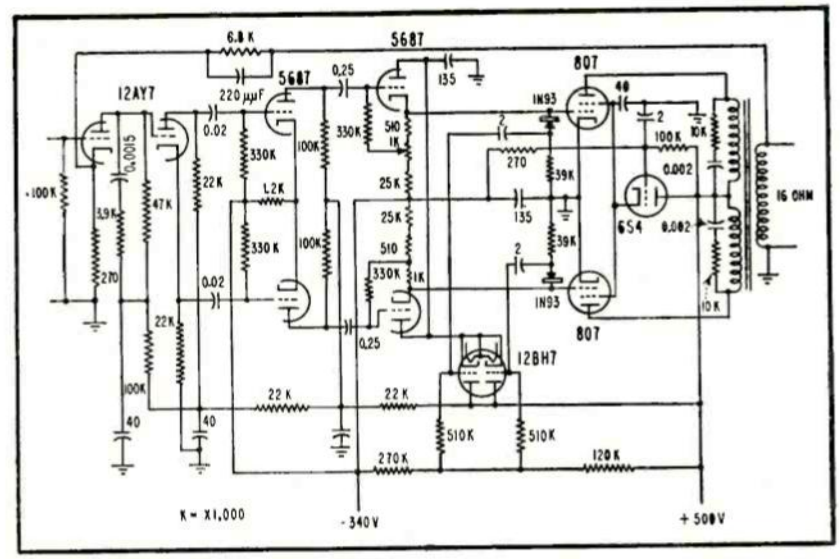


FIG. 13—Push-pull 807 tubes deliver their maximum power output of 87 watts. Total output-transformer primary impedance is 4,800 ohms

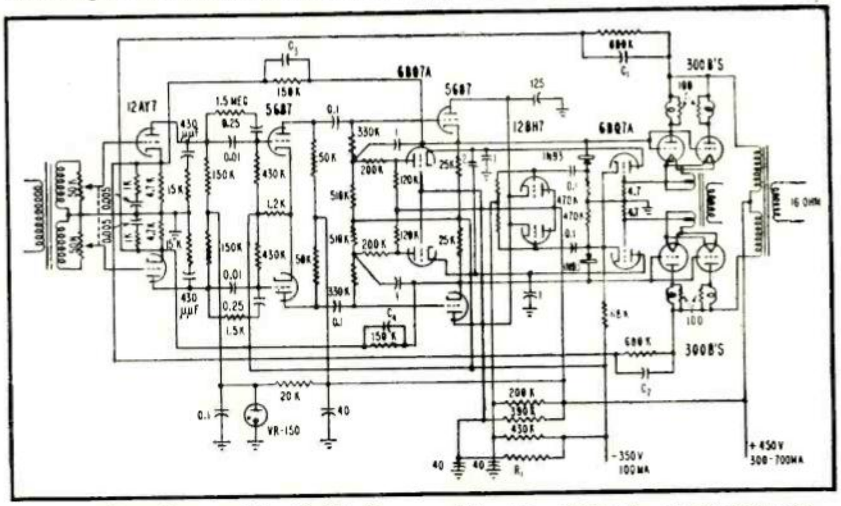


FIG. 14—Recording and/or distribution amplifier has 100-watt output and will deliver 200 watts on instantaneous peaks. Output transformer has total primary impedance of 1,650 ohms

Recording Amplifier

As a result of a meeting with BBC engineers and the acquisition of one of their acetate cutters, which required 87 volt-amperes to obtain a cutting level which was still about 10 db below direct cutting levels ordinarily employed in this country, it was necessary to design an amplifier of greater output capability.

This amplifier, shown in Fig. 14, has a normal rated output of 100 watts, but is capable of putting out 200-watt instantaneous peaks with negligible intermodulation distortion. The output stage efficiency is maintained at a relatively high level over a wide power range as the output stage gradually changes from class A operation to class AB_2 operation with an electronic, servo type of automatic balancing of the output stage static plate currents and simultaneous automatic optimum-bias adjustment.

Resistor R_1 is adjusted for total final-output quiescent plate current of 300 ma. Parasitic-suppression chokes in final-output-tube plate circuits are 20 turns of 32 wire on each associated 100-ohm, ½-watt resistor. Values of C_1, C_2, C_3 and C_4 depend on circuit wiring and transformer characteristics. The stability of this circuit is affected by the wiring and the power supply impedance.

The Freed 18777 transformer was specifically designed for use in this amplifier.

In the design of high-level audio equipment one important point becomes apparent. Cathode emission of cathodes or filaments is quite sensitive to operating temperature (voltage) if distortion is to be held to reasonable levels on peaks. At a point about two to four percent below rated voltage, emissivity starts to limit on peaks. Overvoltage reduces tube life and may give difficulty as a result of increased grid current.

Conclusion

The foregoing covers a considerable range of equipment. For home use, however, there seems to be no need or justification for an amplifier with an output rating in excess of 10 to 20 watts at an i-d level of 1 percent or less.

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