High Power Transistor Audio Amplifiers*

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Several models of high power audio amplifiers have been developed; each is capable of delivering 45 watts output. These amplifiers use a ribbon chassis for cooling and operate over an ambient temperature range of -10°C to +50°C. One amplifier uses a series type circuit and the other a quasi-complementary symmetry type circuit. Amplifier size and weight are reduced since neither circuit employs driver or output transformers.

INTRODUCTION

IN GENERAL, transistors offer the advantages of size and weight reduction, conservation of supply power, and greater reliability.

Until quite recently most transistor circuit development has been limited to low power applications and low transistor dissipations (in milliwatts). With the advent of higher power audio transistors, it became desirable to investigate the use of these devices in high power audio amplifiers where the transistors are operated at higher power dissipations and correspondingly higher junction temperatures. Under these conditions, techniques quite different from those used in low-power amplifiers had to be established. This paper will describe various design principles that enable newly available high power audio transistors to be utilized. (It should be pointed out that, since this project was a feasibility study, the transistors were occasionally used somewhat above their established ratings. In a commercial application, it is recommended that the transistors be used below their maximum ratings.)

Both the thermal and/or the electrical limitations impose an upper limit on the power handling capabilities of the transistor. When the transistors operate at high junction temperatures, the thermal considerations become quite important. Briefly, the thermal limitations are as follows: (1) For reliability considerations, the maximum junction temperature, as specified by the manufacturer, should not be exceeded; (2) The circuit must be stable thermally; that is, the chassis or other cooling facility employed must be capable of removing the heat generated by the transistor so as to maintain an equilibrium condition.

In essence, by providing a good thermal path from junction to air, and by maintaining a relatively stable dc operating point with temperature, the condition for stability may be met. Operating point stability may be obtained by stabilization (dc feedback) or temperature compensation (use of temperature-sensitive circuit elements).

The two power amplifier circuits to be discussed employ various techniques of stabilization and compensation which allow stable operation up to ambient temperatures of 50°C. Each amplifier can deliver 45 watts to a 4 ohm load. Of particular significance is the fact that neither a driver nor output transformer is employed in these circuits. The elimination of transformers in itself usually makes possible a considerable saving in size and weight, and often results in an improvement of the overall frequency response. Moreover, a greater amount of negative feedback is generally possible in the absence of transformers. Another interesting property of these circuits is their exclusive use of pnp transistors in the output stage.

QUASI-COMPLEMENTARY SYMMETRY AMPLIFIER

The first power amplifier circuit to be described is the quasi-complementary symmetry amplifier.[1] This is a convection-cooled amplifier designed to deliver 45 watts into a 4 ohm load over a temperature range of -10°C to +50°C. A photograph of the amplifier is shown in Fig. 1 and the circuit schematic is shown in Fig. 2. The amplifier has outside dimensions of 8½ x 6½ x 6½ inches and weighs about 10 lb.

The circuit consists of three stages: a *pnp* class-A driver stage; a complementary transistor pair, which acts as a phase splitter; and a power output stage, consisting of two *pnp* transistors in single-ended push-pull operation, capaci-

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[1] H. C. Lin, "Quasi-Complementary Transistor Amplifier," *Electronics*, September 1956, pp. 173-175.

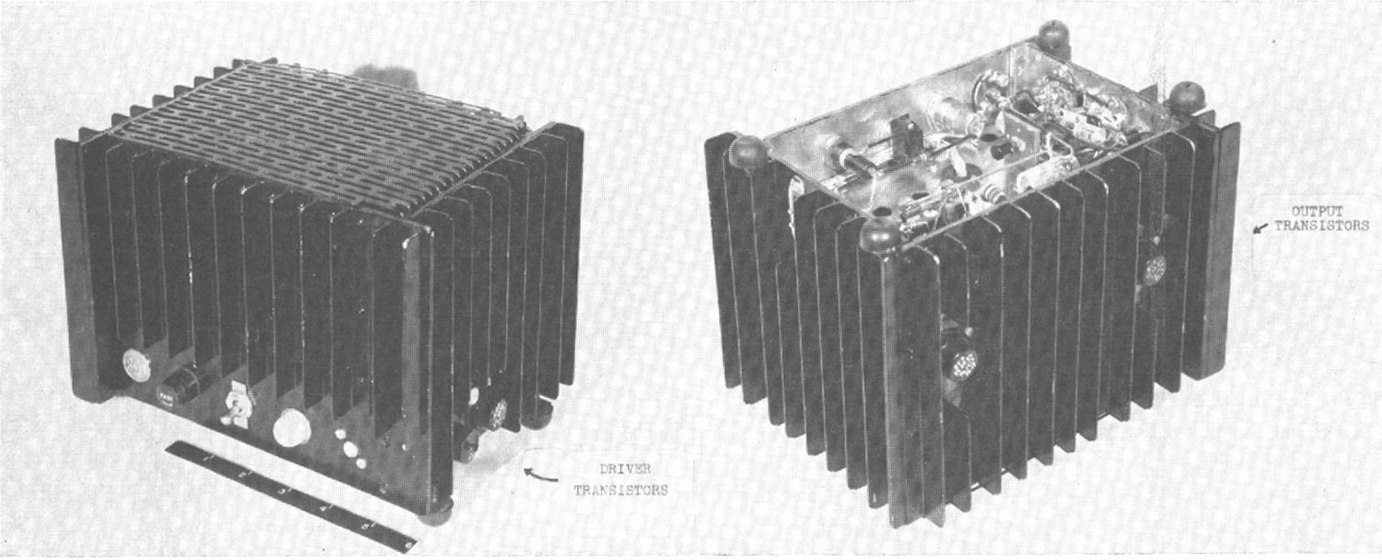

FIG. 1. 45-watt Quasi-complementary Amplifier. Left: Front view showing driver transistors. Right: Bottom view showing output transistors.

tively coupled to the load. The last two stages operate class B.

X_2 and X_4 operate as common collector amplifiers. When these transistors are conducting, the output current is B_2B_4 times the current supplied by the first stage, where B_2 and B_4 are the effective current gains of the phase-splitter and output stages. Similarly, the output current when X_3 and X_5 conduct is B_3B_5 times the current supplied by the first stage, where B_3 and B_5 are the effective current gains of the phase splitter and output stages. If $B_2B_4 = B_3B_5$, the input resistance presented to the first stage is equal to $B_2B_4R_L$, and the circuit is in balanced operation.

1. Output Stage

Fig. 2 shows the output stage which uses two RCA 2N301A transistors connected in series with the dc supply. For proper operation of the amplifier, these transistors should possess certain characteristics.

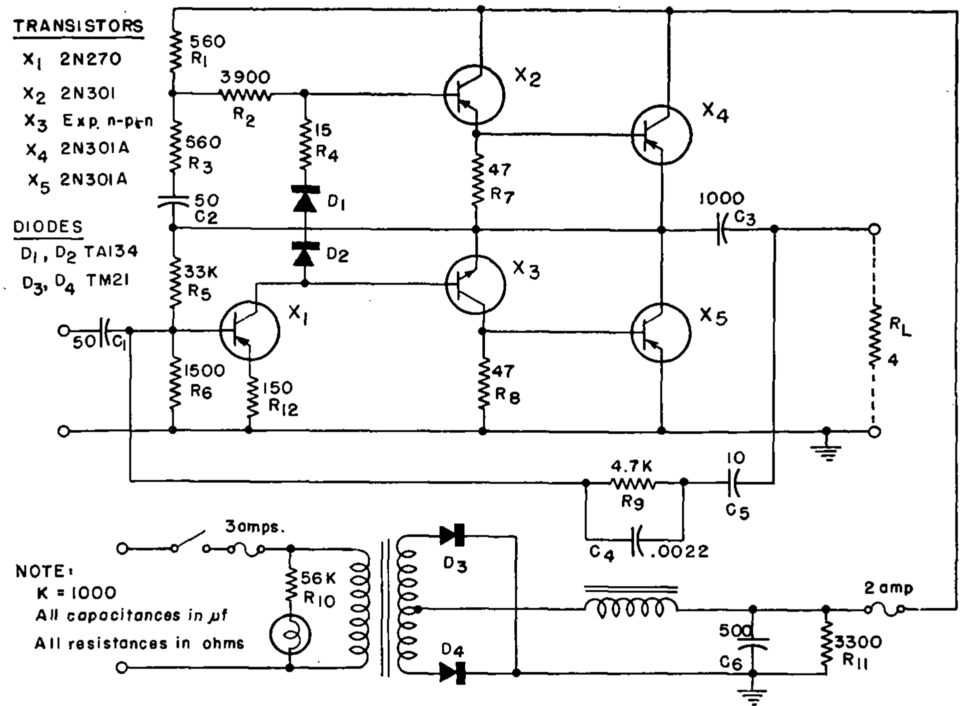

FIG. 2. Circuit diagram of 45-watt Quasi-complementary Amplifier.

One important property of these transistors is that they have a thermal resistance from junction to case of less than 1.3°C/watt. By close thermal coupling to the chassis, achieved by mounting the transistor on a Mylar insulator coated with silicone oil, a total thermal resistance from junction to air of about 3.0°C/watt is obtained. This resistance is sufficiently low so that the 10 to 12 watts dissipation (most severe condition) from each transistor may be stably transferred to the air. The low chassis thermal resistance of about 1.6°C/watt is obtained both by convection and radiation cooling from the large surface area of the ribbed chassis configuration, as shown in Fig. 1. The amplifier chassis is painted a dull black to aid heat transfer by radiation.

Another important property of the output transistors is their maximum collector-to-emitter breakdown voltage. This voltage which is dependent upon both the resistance connected between base and emitter and the junction temperature, decreases as the junction temperature is raised, and as the emitter-base resistance is increased (up to about 1000 ohms). The output transistors used were selected from stock such that their breakdown voltage exceeded 60 volts (at room temperature) with 47 ohms connected between base and emitter. This insures that the transistors operating in the actual circuit will not break down at higher temperatures. At peak signal swing the maximum inverse voltage applied to each output transistor is slightly less than the supply voltage (which is about 41 volts at full sinewave power output). Under normal operating condition, a good dc balance exists, and the center-point voltage, at the collector of X_5, is approximately equal to one-half the supply voltage.

The voltages appearing across resistors R_7 and R_8 provide a small forward bias to the base-emitter junctions of X_4 and X_5, as shown in Fig. 2. The resistors were chosen to be 47 ohms, since this provides a bias of about 0.15 volt (at 25°C) which is necessary to minimize the non-linear crossover region in the composite transfer characteristic of the class-B amplifier. It should be noted that the bias voltage is ultimately determined by the voltage drops across R_4, D_1, and D_2. D_1 and D_2 are RCA TA-134 developmental temperature-compensating diodes whose forward voltage drops decrease with increasing temperature and thus tend to hold the transistor emitter currents constant. This compensation is necessary because less forward base-emitter bias is required as the junction temperature is increased. A relatively constant operating point increases the thermal stability of the amplifier. For optimum temperature stability, three biasing diodes should be used in this circuit rather than two, since there are three emitter junctions in series.

It should be recognized that a penalty is paid in order to provide proper transistor bias and to obtain a lower distortion. This arises because of the selection of a small value of

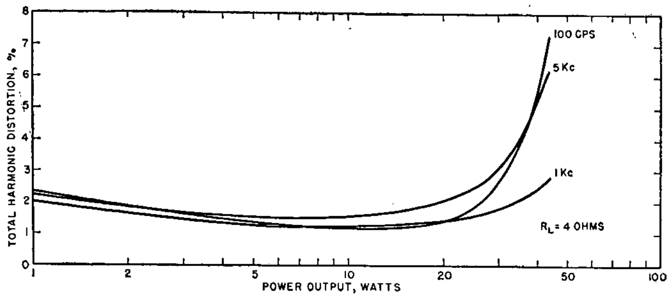

FIG. 3. Distortion vs. Power Output for 45-watt Quasi-complementary Amplifier.

resistance for R_7 and R_8. Some signal power is lost (about 1 watt at maximum power output) in these resistors since they are in shunt across the base-emitter junctions of the output transistors, which have a large-signal input impedance of approximately 20 ohms.

A further property required of the output transistors is that they possess a large-signal current gain of at least 25 at 4 amperes of collector current. This requirement arises due to distortion considerations since the peak collector current that flows in the transistors is between 4 and 5 amperes. Because the output impedance of the driver stage is relatively low, variations of the transconductance for the output stage also are important. Measurements have shown that 2 to 1 variations in this characteristic may be tolerated.

The harmonic distortion of the amplifier at various power outputs is shown in Fig. 3. The distortion increases at higher power output because of the β falloff of the output transistors at high collector currents. The reactance of C_3 gives rise to an elliptical load line at low frequencies, and as a result clipping occurs at high power outputs. At higher frequencies, transistor phase shift (due to the low transistor cutoff frequencies) causes nonlinearities and increases the distortion.

2. Complementary Phase-Splitter Stage

As shown in Fig. 2, X_2 is a *pnp* (2N301A) transistor and X_3 is an experimental *npn* transistor. Each operates class B and serves to split the phase of the incoming signal from X_1. In order to allow the amplitude of the peak signal swing to approach the supply voltage, bootstrapping is applied by way of C_2 and R_3 across R_1. Without the bootstrap

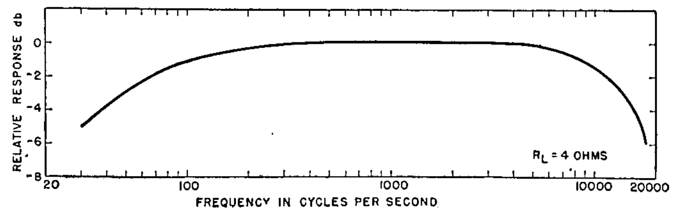

FIG. 4. Frequency response of 45-watt Quasi-complementary Amplifier.

action, the output voltage swing is limited to a value less than the supply voltage by virtue of the voltage drops in X_2 and X_4, and unsymmetrical clipping will occur at high power outputs. The value of R_3 was selected such that clipping was symmetrical at maximum (sine-wave) power output. Under this condition, the maximum collector efficiency of the output stage was increased to about 70% at room temperature.

The frequency response of the amplifier is shown in Fig. 4. The 3 db points are about 50 cps and 14 kc. The relatively low β cutoff frequencies of the power transistors used in the circuit limit the high frequency response of the amplifier. The low frequency response is limited primarily by the coupling capacitor C_3.

3. Driver Stage

X_1 is a medium power transistor (2N270) which acts as a class-A driver. Since the biasing of the following stages is strongly dependent upon the direct current flowing in the collector of this transistor, the temperature stability of this stage is important. The transistor is biased through resistor R_5 which is connected to the midpoint of the output stage, and thereby provides both dc and ac negative feedback. The temperature stability of this stage is further increased by virtue of emitter current stabilization provided by the emitter resistance R_{12} in conjunction with R_6.

The source impedance driving this amplifier should nominally be 500 or 600 ohms for proper performance. About 9 db of negative feedback is applied through R_9 around the entire amplifier to the base of X_1. C_4 is connected in parallel with R_9 to give a step-response in the feedback loop for stability.

At full power output, the power gain of the amplifier is about 41.8 db. The input impedance of the amplifier is about 200 ohms at 1000 cps, and the output impedance is about 1.6 ohms.

4. Power Supply

The power supply occupies about one-half the physical volume of the overall amplifier. This is necessary because of the large supply currents required to produce the high power outputs obtained. Full-wave rectification of the 60 cycle ac supply voltage is obtained by the use of silicon rectifiers followed by a choke-input filter which provides relatively good regulation and filtering. At full-signal output, the direct current is approximately 1.6 amperes at about 41 volts. The quiescent direct current at room temperature is about 70 ma, with no-signal voltage of about 54 volts. The hum at maximum signal output is approximately −15 dbm.

SERIES AMPLIFIER

The second high-power transformerless circuit to be described is the series amplifier, which is shown in Fig. 5. The

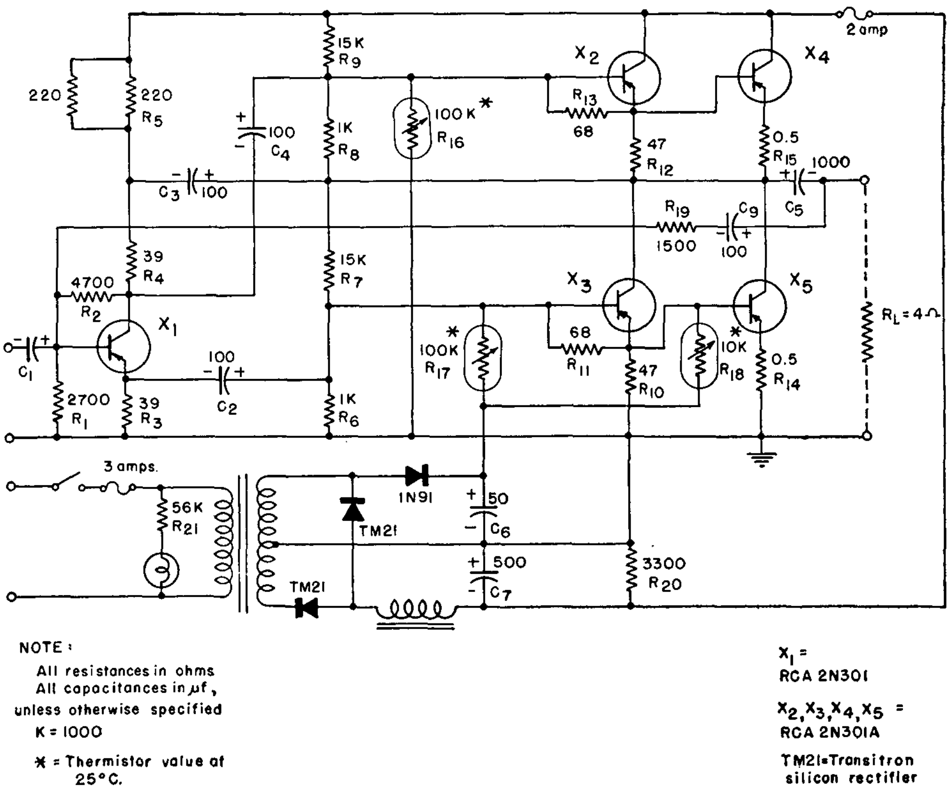

FIG. 5. Circuit diagram of 45-watt Series Amplifier.

circuit uses all transistors of like conductivity and requires no driver or output transformers. The series amplifier consists of a split-load phase inverter, capacitively coupled to a class-B common-collector driver, which, in turn, is direct coupled to the class-B common emitter power output stage. The driver and output stages are each in series for the dc collector supply.

This amplifier also weighs about 10 lb and is quite similar in size and physical layout to the quasi-complementary amplifier described above. The series amplifier is convection-cooled, uses 2N301 and 2N301A transistors throughout, and can deliver 45 watts to a 4 ohm load.

1. Power Output Stage

The series circuit, shown in Fig. 5, uses a pair of 2N301A transistors in the output stage. X_4 and X_5 operate in the common-emitter mode and are capacitively coupled to the load. The output stage operates class-B; therefore, with oppositely phased voltages applied to the bases of these transistors, the ac collector currents are additive in the load. Hence, X_4 and X5 are in series for the dc collector supply and in parallel for the ac signals.

The output transistors employed in this circuit were selected for the same properties as the corresponding transistors used in the quasi-complementary amplifier. These properties are: (1) a junction-to-case thermal resistance less than 1.3°C/watt, (2) a collector-to-emitter breakdown voltage (with a base-emitter resistor of 47 ohms) in excess of 60 volts, (3) a large-signal current gain of at least 25 at 4 amperes of collector current, (4) a variation in transconductance not to exceed 2 to 1.

It might be pointed out again that the reasonably acceptable linearity of the transconductance characteristic for these power transistors shows the desirability of driving large signal amplifiers from a low-impedance source, i.e., a voltage source. Lower distortion will result under this condition of drive than will occur if the transistors are driven from a high source impedance, i.e., a current source. This is true because of the relative nonlinearity of the current transfer characteristic caused by β-falloff. In the series circuit, a relatively low source impedance is provided for transistors X_4 and X_5 by virtue of the low output impedance provided by the common-collector driver stage.

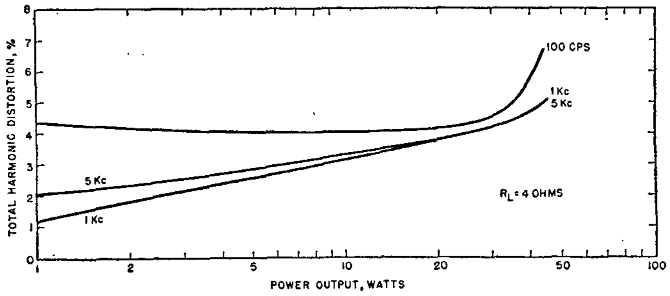

FIG. 6. Distortion vs. Power Output for 45-watt Series Amplifier.

The resultant distortion characteristics for this amplifier are shown in Fig. 6. The distortion may be reduced at low frequencies by increasing the values of C_2, C_3, and C_4. The ½-ohm resistors in series with the emitter of each output transistor improve the dc circuit stabilization for the output stage and also reduces distortion, but at the expense of a decrease in power gain and power output. The overall collector conversion efficiency (including the power lost in these resistors) is still about 65% at maximum power output.

The frequency response of the amplifier is shown in Fig. 7.

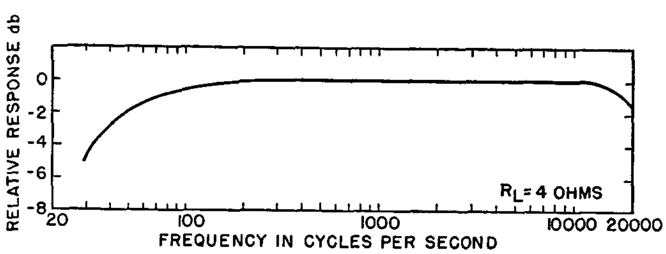

FIG. 7. Frequency response of 45-watt Series Amplifier.

The 3 db points are about 40 cps and 30 kc. The high-frequency response is limited by the β-cutoff frequency of the transistors and is highly dependent on the source impedance and the r'_{bb} of the transistors. The best frequency response for a common-emitter stage is obtained when it is driven from a low source impedance. Therefore, it is also desirable that r'_{bb} be as low as possible. The 2N301 and 2N301A transistors used in the circuit have an r'_{bb} of about 20 or 30 ohms. The preceding stage, being common collector, provides the desired low source impedance for the output stage. The low-frequency response is limited mainly by coupling capacitor C_5.

2. Series Driver Stage

The driver stage also uses a pair of 2N301A transistors which are connected in an emitter-follower (common-collector) configuration. This stage operates class-B and is direct-coupled to the output stage. Direct coupling eliminates a type of crossover distortion that occurs with capacitor coupling. This distortion would arise because the time constants of the charge and discharge paths of the coupling capacitor would be different during conduction and non-conduction. This difference would cause a reverse dc bias to be applied to the base-emitter junction, and this bias would then be dependent upon the signal level. The result would be an increase in distortion, since the forward base-emitter bias, normally applied to minimize crossover distortion, would be nullified.

This problem is encountered in the use of coupling capacitors C_2, C_3, and C_4 but is greatly reduced in the driver stage by resistors R_{13} and R_{11}, connected between the base and emitter of X_2 and X_3, respectively. The effect of these resistors[2] is to linearize the input impedance presented to the phase inverter, both during conduction and non-conduction. With a low impedance discharge path provided for these capacitors during non-conduction, the tendency for a charge to develop on the capacitor and to produce crossover distortion is reduced.

3. Phase Inverter

Transistor X_1 is a 2N301 transistor and is used as a split-load phase inverter which feeds driver transistors X_2 and X_3. This stage operates class-A and is biased at approximately 160 ma collector current, with 35 volts between the collector and emitter. This permits sufficient signal to be applied to the driver stage without introducing clipping at maximum power output. With no signal, this transistor dissipates about 5.5 watts and is closely coupled thermally to the ribbed chassis which acts as the heat dissipator.

Resistors R_3 and R_4 insure a low source impedance for the driver transistors. The impedance (for transistors of similar characteristics in the upper and lower halves) presented by the upper half of the driver-output transistor combination is essentially equal to that presented by the lower half, since, in each case there is a common-emitter stage preceded by a common-collector stage. This means that variations in the load impedance will be reflected to the phase inverter in a similar manner for the upper and lower halves, and the amplifier will thereby be in balanced operation. By virtue of splitting the collector load, and feeding the upper half of the amplifier from R_4, an essentially balanced output voltage is obtained.

Inherent negative feedback exists in the amplifier by virtue of the phase splitter configuration, the common collector driver stage (100% negative voltage feedback), and the unbypassed emitter resistors in the output stage. In addition, about 8 db of negative feedback is applied through a resistor R_{19} in series with a capacitor C_9 around the entire amplifier. (The amplifier should be driven from a source having an impedance of about 500 to 600 ohms.) In order to be able to drive the upper half of the amplifier close to the collector supply voltage, bootstrapping is employed in a manner similar to that used in the quasi-complementary amplifier. This is accomplished through the action of capacitor C_3 which is returned from the output to the junction of R_4 and R_5.

At full power output, the power gain of the series amplifier is about 30.6 db. The input impedance of the amplifier is about 113 ohms at 1000 cps, and the output impedance is about 2.5 ohms.

4. Bias Considerations for the Driver and Output Stages

In order to eliminate the effects of crossover distortion caused by the non-linear transfer characteristics of transistors at low signal levels, a small forward quiescent dc base-emitter bias voltage is required. Optimum bias voltage is obtained for the driver stages by the voltage divider action of resistors R_8 and R_9 in conjunction with R_{12} and R_{13} for the upper transistor and resistors R_6 and R_7 in conjunction with R_{10} and R_{11} for the lower transistor. At room temperature (28°C) the quiescent current for the driver stage is about 8 ma. Bias for the output transistors is obtained from the voltage drop across the emitter resistors R_{10} and R_{12} which are in series with emitters of X_3 and X_2, respectively. This bias is strongly dependent upon the quiescent current of the driver stage and the voltage divider network previously described. Quiescent current in the output stage is about 50 ma at room temperature.

As ambient temperature is increased, the operating points of the driver- and output stage change, since both the saturation current and the input conductance increase.[3] The problem of dc stabilization for the output stage is further complicated by virtue of direct coupling of the driver output stages. As temperature increases, the driver I_{co} increases, thereby increasing the forward voltage bias for the output stage. Simultaneously, the output transistor I_{co} is increasing and causes the quiescent current for the output stage to increase further. The ½-ohm resistors, R_{14} and R_{15}, in the

2 A. I. Aronson, "Transistor Audio Amplifiers," *Transistors I*, RCA Laboratories, pp. 515-535.

3. H. C. Lin and A. A. Barco, "Temperature Effects in Circuits Using Junction Transistors," *Transistors I*, RCA Laboratories, pp. 369-402.

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While an undergraduate, Mr. Herscher was employed by the Frankford Arsenal in Philadelphia under a co-operative training program. After graduation, he joined the circuit development group of RCA Defense Electronic Products, working primarily on transistor noise studies. He left RCA in 1954 for two years of active duty in the Signal Corps Engineering Laboratories at Fort Monmouth, New Jersey. In 1956, he returned to RCA, and resumed his work on transistor audio and pulse circuitry. He is presently working on advanced communication systems.

Marvin Herscher is a member of the Institute of Radio Engineers, the American Institute of Electrical Engineers and the Eta Kappa Nu and Tau Beta Pi fraternities.

output stage aid in stabilization of this stage by providing a negative current feedback that tends to maintain the output quiescent collector current constant. In the common-collector driver stage, degenerative direct current feedback is obtained by virtue of resistors R_{10} and R_6 in the lower transistor, and resistors R_{12} and R_8 for the upper transistor.

The dc operating point of the output stage is further stabilized by use of thermistor compensation. These thermistors are mounted on the chassis near the output transistors so as to compensate more closely the change in junction temperature rather than ambient temperature. Thermistors R_{16}, R_{17}, and R_{18} are connected in the circuit to provide a base-to-emitter voltage for the driver transistors which decreases with temperature. This action tends to maintain the driver emitter current constant with temperature. A positive bias supply is used to compensate the transistors at higher temperatures, since it is actually necessary to apply a reverse bias to the base-emitter junction to maintain a relatively constant operating point at elevated temperatures. The use of thermistors reduces the tendency for the quiescent collector current in the output stage to change with temperature, with the result that the amplifier performs satisfactorily throughout a temperature range of –10°C to +50°C. At low temperatures, cross-over distortion is increased due to the inability of the thermistor networks to adequately compensate the output transistors.

5. Power Supply

The power supply for the series amplifier is essentially the same as that used in the quasi-complementary amplifier. It consists of two silicon rectifiers in a full-wave circuit and a choke input filter. An additional positive supply for bias compensation is obtained from a IN91 diode half-wave rectifier. The no-load voltage for the collector supply is about 58 volts. The supply voltage drops to about 45 volts at full power output with a direct-current of about 1.55 amperes. The power-supply ripple in the load with maximum signal is about –15 dbm.