LB-1022

TRANSISTOR AUDIO AMPLIFIERS

RADIO CORPORATION OF AMERICA
RCA LABORATORIES
INDUSTRY SERVICE LABORATORY

RADIO CORPORATION OF AMERICA

RCA LABORATORIES

INDUSTRY SERVICE LABORATORY

LB-1022

Transistor Audio Amplifiers

Approved

Transistor Audio Amplifiers

Transistors applied to audio amplifiers have the expected advantages of smaller size, reduced weight and power consumption as compared to vacuum-tube amplifiers. In addition, transistor audio amplifiers have very low hum levels and with proper circuit design a smaller number of components.

In this bulletin, three audio amplifiers using transistors are described: a +20 dbm (100 mw) pre-amplifier, and two five-watt power amplifiers. The pre-amplifiers, for use with microphones, tape playback heads, or phonograph pickups, meets broadcast standards with respect to frequency response, distortion, and noise figure. One five-watt power amplifier uses a conventional push-pull output stage with an output transformer but means are provided for eliminating the driver transformer often used with transistor power amplifiers. The other five-watt amplifier, utilizing the complementary symmetry principle, employs no audio iron-core components and is suitable for high-fidelity sound reproduction.

Introduction

The use of transistors in audio circuits has resulted in devices that perform comparably with their tube counterpart at much greater efficiencies, and in some cases have resulted in applications that were not possible with tubes.

Some transistor audio devices, the pre-amplifier described here for example, are now ready for commercial use. Audio transistors that can perform most audio functions are commercially available, and indications are that audio circuits will be one of the first major areas using this new electronic device.

The +20 dbm pre-amplifier, power amplifier, and the complementary symmetry amplifier decribed here represent practical applications of transistors to common audio devices. The circuits cover a range of functions from low-noise, low-level input stages to power output stages, and include such elements as volume control, driver, temperature-stabilizing and tone-equalizing circuits. An attempt has been made to use the inherent low-impedance characteristics of transistors to eliminate the audio transformers, a source of problems in high-fidelity amplifiers, used in the tube counterpart of these amplifiers.

The +20 dbm pre-amplifier described is characterized by very low distortion, low noise, wide frequency response and high efficiency. The amplifier should find wide application in audio systems requiring a +20 dbm output to a 600 ohm load.

The five-watt power amplifier is characterized by less than 1 percent distortion at mid-frequencies and a wide frequency response. The driver transformer, generally used in transistor circuits of this type, has been eliminated.

The five-watt complementary symmetry amplifier is characterized by low distortion over the entire audio spectrum. No audio transformers are used and the output is directly coupled to a standard 15-ohm speaker. The amplifier is equalized for use with a standard variable-reluctance phonograph pickup. The pre-

Table I

AUDIO AMPLIFIER PERFORMANCE

	+20 db Preamplifier	5-Watt Power Amplifier	5-Watt Complem. Symmetry Amplifier
Input			
Source Impedance	500-ohm microphone		RCA SPC-1 Phonograph Cartridge
Input Impedance	3000 ohms	2700 ohms	Figure 16
Input Voltage to Obtain Rated Output-1000 cycles	0.3 mv.	45 mv.	15 mv.
Output			
Load Impedance	600 ohms unbalanced	15 ohms	15 ohms
Output Impedance (1000 cycles)	25 ohms	3 ohms	1 ohm
Power Output vs. Distortion	Figure 5	Figure 9	Figure 13
Distortion vs. Loading		Figure 8	Figure 14
Feedback	15 db	17 db	15 db
Frequency Pesponse	Figure 4	±2 db, 20 cy. to 20,000 cy.	Figure 15

formance of this amplifier is high enough for use in high-fidelity applications, and a model of this unit has been used in a home music system to replace a high quality 10-watt tube amplifier with no noticeable degradation of sound quality.

The characteristics of these three audio amplifiers are summarized in Table I.

+20 DBM Pre-Amplifier

General Description

The pre-amplifier shown in Fig. 1 uses six commercially available transistors. No audio iron-core components are used. The pre-amplifier will provide a 20 dbm (100 mw) output at low distortion over a range of frequencies from 50 cycles to 15,000 cycles. Using low-noise transistors for the input stages, noise figures less than 3 db can be obtained. This performance is sufficiently good for broadcast application and for operation with microphones, tape play-back heads and low-impedance phonograph pickups.

The power drain of the amplifier is very

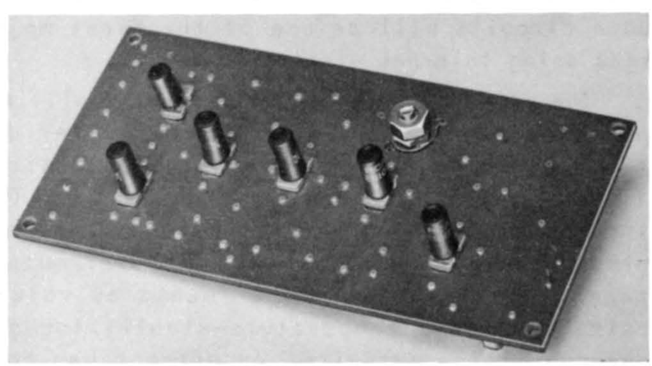


Fig. 1 - A +20 dbm Pre-amplifier.

low, making it attractive for a remote amplifier in portable audio equipment. The total power drain is 280 mw, idling, and about 500 mw under full signal condition.

Circuit Description

Fig. 2 is a complete circuit diagram of the pre-amplifier. Transistor X-1 is a low noise input stage with X-2 and X-3 serving as common-emitter amplifiers. X-4 is a class A driver amplifier direct coupled to a complementary symmetry class B output stage, X-5 and X-6.

Input Stage

Noise is the most important consideration in low-level audio amplifier input stages. Transistors make ideal low-noise amplifiers because the absence of a heater winding removes hum sources always troublsome with tubes. The transistor is relatively free from microphonic tendencies, and low-impedance circuitry associated with transistors makes them less susceptible to electrostatic noise pickup. Finally, the inherent noise of present transistors is low enough to enable audio amplifier designs in some applications to approach the theoretical minimum noise limit with a given source. Fig. 3 shows the output signal of the pre-amplifier with a one-microvolt input signal

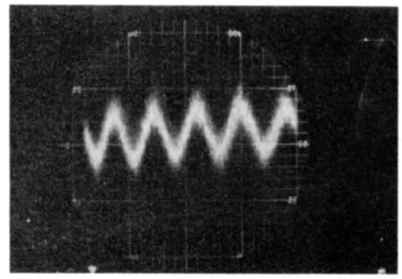


Fig. 3 - Output signal of the +20 dbm amplifier with a one microvolt 1000 cycle input signal. Source impedance is 10 ohms, effective bandwidth is 60 kc.

to illustrate the low-noise capability of modern transistors.

To achieve low noise with a transistor amplifier requires a careful selection of source impedance and d-c operating point.[1] Measurements indicate that the minimum noise figure for present junction transistors occurs with a source impedance in the range from 200 to 1000 ohms. This impedance range matches that of many broadcast microphones so that the microphone can be directly coupled to the input.

[1] P. M. Bargellini and M. B. Herscher, "*Investigations of Noise in Audio Frequency Amplifiers Using Junction Transistors*", *Proc. IRE, Vol.* 43 *pp.* 217-226, *Febuary,* 1955.

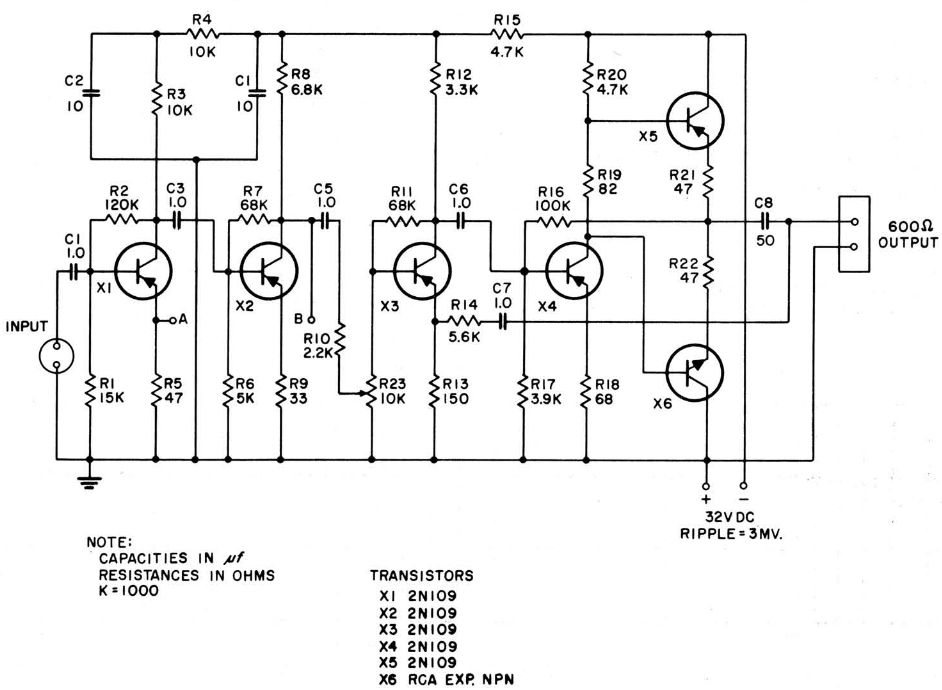


Fig. 2 - 20-dbm preamplifier schematic.

Transistor noise has been shown to increase with collector current, and to be relatively independent of collector voltage to values as high as 20 volts. This is true with transistors having low collector-base leakage. Low noise operation can be obtained with collector currents in the range from 0.2 to 1.0 milliampere. With a given source impedance, and the same d-c operating point, the noise figure is substantially the same for the common-emitter, common-collector, or common-base connections, but the common emitter should be used for maximum gain to mininize second-stage noise.

The amplifier has a flat frequency response, shown in Fig. 4, and can be used directly with low-impedance microphones with 250 or 500-ohm impedances. At maximum gain control setting, a 0.3 millivolt signal will drive the amplifier to a +20 dbm output.

For use with tape playback heads or magnetic phonograph pick-ups, a suitable series R-C feddback network can be connected between points A and B in the circuit of Fig. 2 to provide for proper low-frequency equalization. The specific R-C value will depend on the particular magnetic transducer used. For typical values with a variable reluctance cartridge refer to the first two stages of the five-watt complementary symmetry amplifier described in a later section.

Intermediate Amplifiers

Transistors X-2 and X-3 are conventional common-emitter amplifiers. Stabilization of operating point[2] with ambient temperature change and transistor variation is accomplished by collector-to-base voltage feedback and current feedback in the emitter circuit.

[2] Lo, Endres, Zawels, Waldhauer, Cheng, "TRANSISTOR ELECTRONICS" Prentice Hall. 1955, pp. 134 ff, 152, 165 ff.

Driver-Ouptut Stage

A class A driver stage, X-4, is direct-coupled to a class B complementary symmetry output stage with transistors X-5 and X-6 connected in a common-collector configuration.

The complementary symmetry configuration was used to eliminate the output transformer and phase inverter generally needed with push-pull stages. The elimination of reactive elements permits a more liberal use of negative feedback for distortion reduction.

The N-P-N and P-N-P transistor in the output stage was connected common collector for the following reasons:

A. The 100 percent voltage feedback inherent in this configuration balances the complementary transistors so that low distortion can be obtained with unselected pairs. Transistors with an α_{cb} range of 20 to 100 will work in this circuit provided they have the peak current capability.

B. Zero-signal biasing can be achieved in a more straightforward manner compared to a common-emitter version of this circuit.

C. Power-supply ripple effects are reduced, compared to common-emitter.

D. Stabilization against ambient temperature rise can be achieved more easily.

A great disadvantage of the common collector connection is the low voltage gain (unity or less) making drive requirements difficult when a common d-c supply is used for the driver-output stage.

The peak current required from each output transistor when driving a 600 ohm load at 20 dbm output is about 25 milliamperes. The distortion

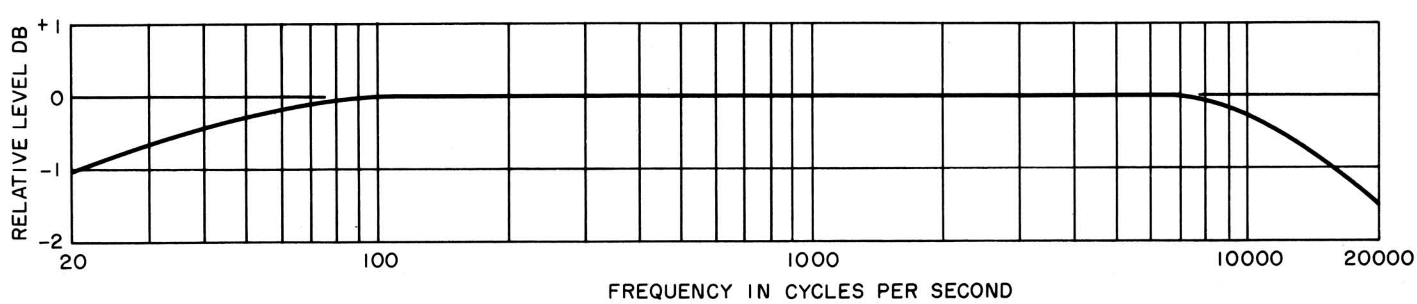


Fig. 4 - Frequency response +20 preamplifier

as a function of power output is shown in Fig. 5. This low distortion results from the inherent linearity of the output stage and an additional 15 db of negative feedback applied from the load to R-13.

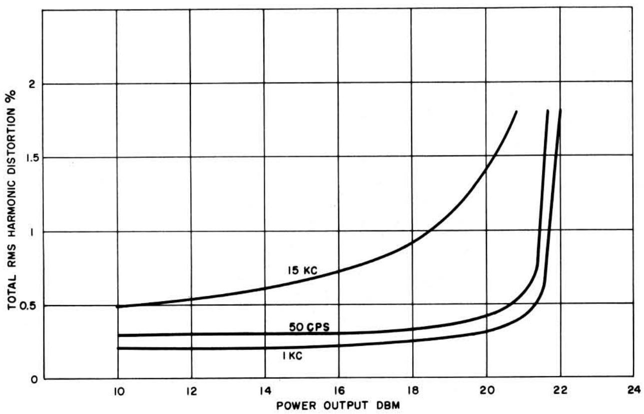


Fig. 5 - +20 dbm preamplifier power output vs. distortion

The output transistors are connected in series across a single polarity 32-volt power supply with capacity coupling to the load. To operate properly in this circuit, the transistors should divide the supply voltage equally, and this is accomplished by biasing the base circuit with resistor R-19 at about 16 volts with respect to ground. The half-supply voltage point will reflect to the emitter circuit by the emitter follower action of the output stage so that the proper collector-to-emitter potential of 16 volts per output transistor will be established. Forward bias voltage to remove any remaining crossover distortion in the class B stage is provided by the collector current flowing in X-4, thus providing a 400 millivolt drop in R-19. The reference for this bias voltage applied between the bases of X-5 and X-6 will be midpoint of R-19 so that the effective bias for each output transistor will be 200 millivolts.

Stabilization of the output stage for temperature effects is accomplished by emitter feedback due to R-21 and R-22 in addition to the inherent stability of the common-collector configuration. A portion of the available output power is lost in R-21 and R-22, but the amount is small compared to the stabilization achieved. This amplifier is stable up to at least 60 degrees C. The temperature range can be extended if necessary, by substituting a thermistor for R-19.

5-Watt Power Amplifier

General Description

Fig. 6 is a photograph of the power amplifier showing a top and bottom view of the chassis. The two experimental p-n-p power transistors can be seen; the output transformer is also shown. The bottom of the chassis shows the wiring of the subassembly board with the power transformer and filter capacitor representing the two largest components.

A unique feature of this amplifier is the absence of the driver transformer often used in transistor power amplifiers. The elimination of this component helps achieve lower distortion performance, which in this amplifier is limited mainly by the quality of the output transformer.

Circuit Description

Fig. 7 is a complete schematic of the power amplifier. The circuit consists of two common-emitter amplifiers, X-1 and X-2, coupled to a split-load phase-inverter. The phase-inverter is capacity-coupled to a class B push-pull common-collector driver which is finally direct coupled to the class B power stage. The circuit may most conveniently be discussed by sections.

Driver -- Power Output Stage

The driver-power stage consists of a push-pull class B common-collector driver direct coupled to a push-pull class B common-emitter output stage.

In order to achieve wide frequency response (about 50 cps to 15 kc) at low distortion with a practical amplifier, it is desirable to eliminate the driver transformer used to couple signal to the power transistors. Driver transformers tend to become bulky when good low-frequency response below 100 cps is desired and the added phase shift introduced by this element limits the amount of stable negative feedback that can be employed.

Replacing the driver transformer with a resistance-coupling driver stage requires that the driver source present a low d-c path between the base-emitter circuit of the power transistors. This is necessary to bypass the I_{CO} current from the base circuit to avoid amplification of this thermally-dependent current. The incremental d-c output resistance of the drivers is 47 ohms per side. The 2N109 trans-

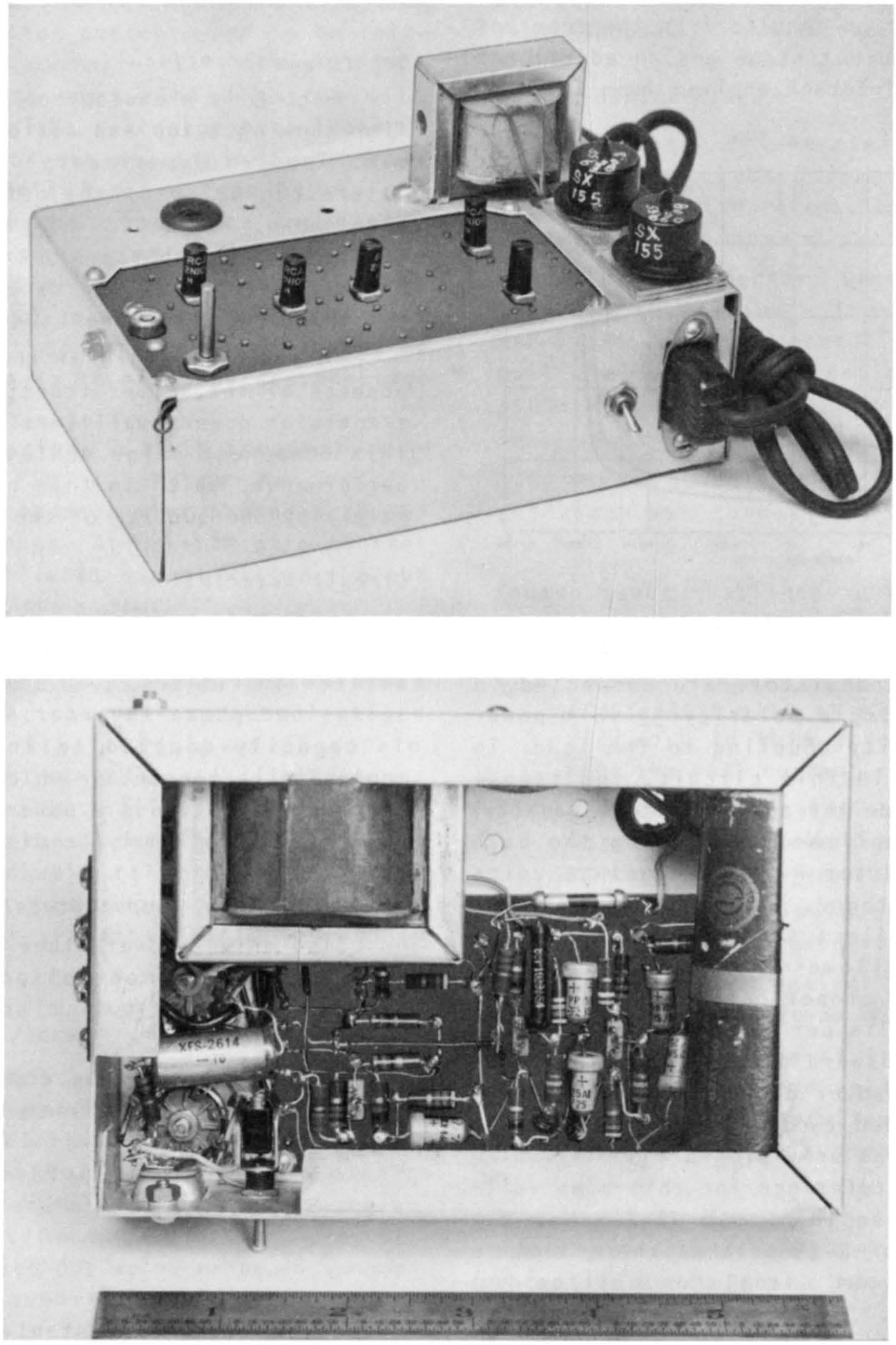


Fig. 6 - Five-watt power amplifier

istors connected common-collector make ideal drivers for this application. Direct coupling the driver to the output stage also permits one bias supply to bias both the driver and power stage simultaneously. Also, with this direct-coupled arrangement, the coupling capacitors to the power transistor bases are eliminated, thus avoiding a difficult crossover distortion problem caused by bias changes in class B circuits due to charging coupling capacitors.

The peak driver output current required will depend on the large-signal gain (beta) of the power transistors. For this particular amplifier, at five watt output, the power transistors should have a minimum beta of 20 at a collector current of 1 ampere. The 2N109 drivers

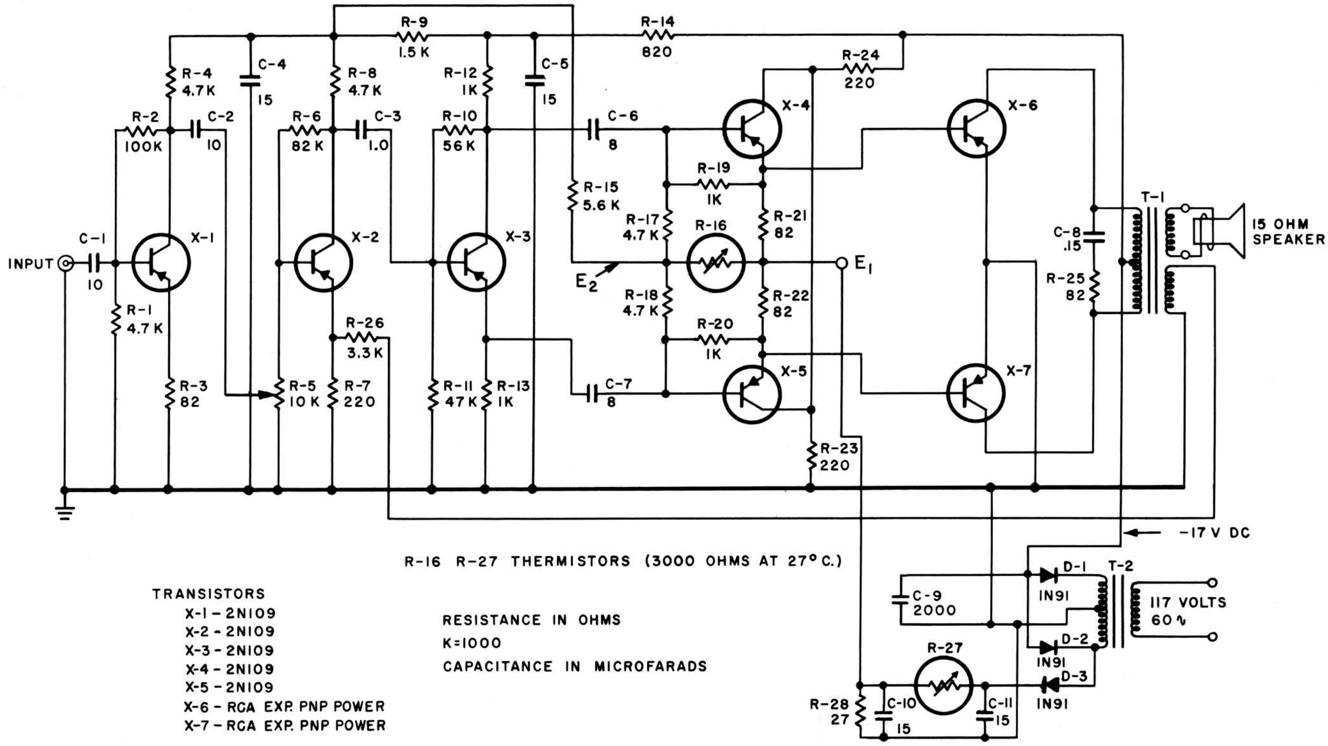


Fig. 7 - Five-watt power amplifier schematic

have sufficient peak current capability and gain to drive the output stage to 10 watts if a supply voltage of 28 volts is used for the power transistors. The purpose of the voltage divider R-23, R-24 is to reduce the collector voltage on X-4 and X-5 for reduced dissipation.

The collector-to-collector loading on the output stage is 96 ohms with a 15-ohm secondary load. Distortion vs. loading for the amplifier, is shown in Fig. 9.

Seventeen db of tertiary feedback is applied to the emitter resistor, R-7, of X-2, which reduced mid-frequency distortion to less than 1 percent. Distortion increases at low and

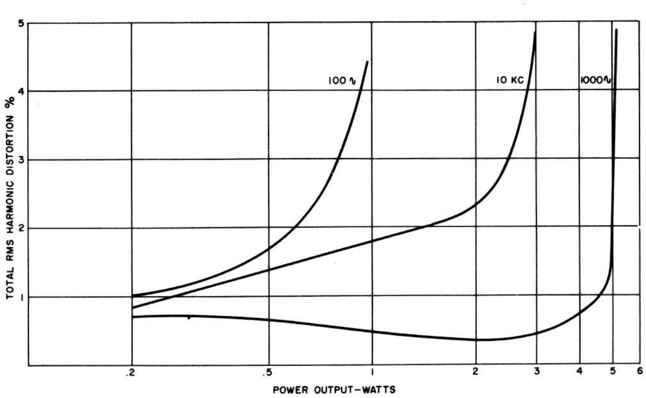


Fig. 8 - Five-watt amplifier distortion vs. power output

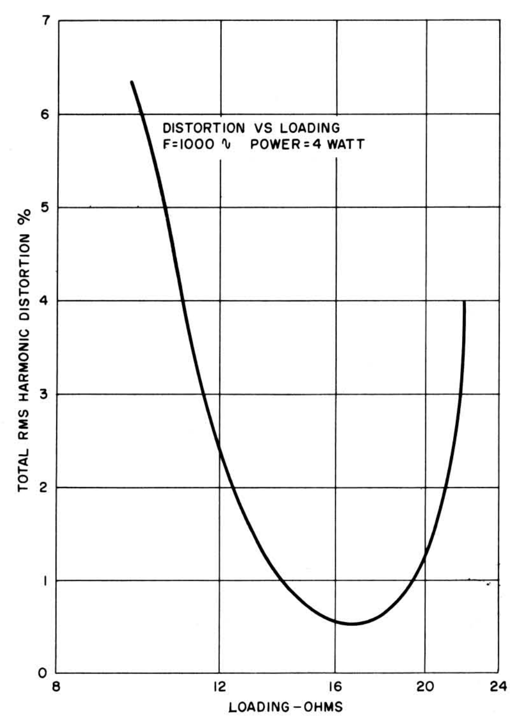


Fig. 9 - Five-watt power amplifier - distortion vs. loading

high frequencies, as shown in Fig. 8, because of insufficient primary inductance and high leakage reactance in the output transformer. The network C-8, R-25 across the primary of the output transformer maintains a high-frequency load on the amplifier to provide for feedback stability on removal of the external load.

Phase Inverter-Driver

Transistor X-3 is used as a split load phase inverter feeding the drivers, X-4 and X-5. Minimum distortion of the phase inverter output signal and elimination of the charge on coupling capacitors C-6 and C-7 (which would cause cross-over distortion) is desired. This is accomplished by linearizing the input impedance of the class B drivers, by means of R-19 and R-20 connected between base and emitter of X-4 and X-5. How this works can be seen by analyzing the input impedance of driver stage X-4, (identical for X-5).

During conduction:

$$Z_{in} \cong \frac{R_{19}\, R_{in\,x-4}}{R_{19} + R_{in\,x-4}} + \beta\, \frac{R_{21}\, R_{in\,x-6}}{R_{21} + R_{in\,x-6}}$$

where:

$$\beta = \alpha_{cb}$$

R_{in} X-4 = Input impedance of X-4.

R_{in} X-6 = Input impedance of X-6 (which will vary with signal)

During cutoff:

$$Z_{in} \cong R_{19} + R_{21}$$

(neglecting shunting effects of R_{in} X-4 and R_{in} X-6)

By equating these relationships, values for R-19 and R-21 can be obtained to achieve a relatively constant input impedance during drive and cut-off of the output stage.

With conduction maintained for the full cycle of signal flow, the tendancy for a charge to develop on capacitors C-6 and C-7, producing cross-over distortion, will be reduced.

Heat Dissipation and Temperature Compensation

A primary consideration in the design of a reliable transistor power stage is to maintain low collector junction temperatures, which for germanium transistors should not exceed 80-100 degrees C, and for silicon transistors, 100-150 degrees C. Maintaining low junction temperatures with signal power output, can be achieved by mechanically clamping the power transistor to a heat sink (chassis). With the transistor shell electrically at collector potential, suitable insulation must be provided between the shell and chassis.

Even if great care is exercised in heat dissipation of the power transistors, there still exists the temperature-controlled variations in collector current which at high ambient temperatures tend to become regenerative with eventual thermal runaway. Temperature compensation can be employed to maintain a constant zero signal collector current with ambient temperature change. This compensation is accomplished by two thermistor-controlled bias supplies shown in Fig. 10. With this arrangement, a positive bias voltage is applied to the bases of the SX-155A and a negative voltage applied to the 2N109 bases. The negative voltage is adjusted at room temperature, with signal, until the crossover distortion just disappears. This voltage is varied as shown in Fig. 10 by means of the thermistor R-16 to maintain a constant zero-signal collector current with temperature change. The positive bias voltage is used to

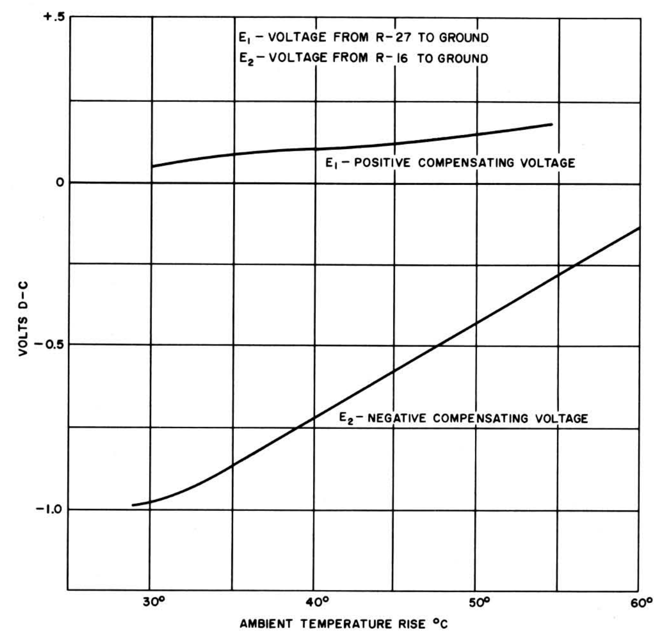


Fig. 10 - Five-watt power amplifier temperature compensating voltages

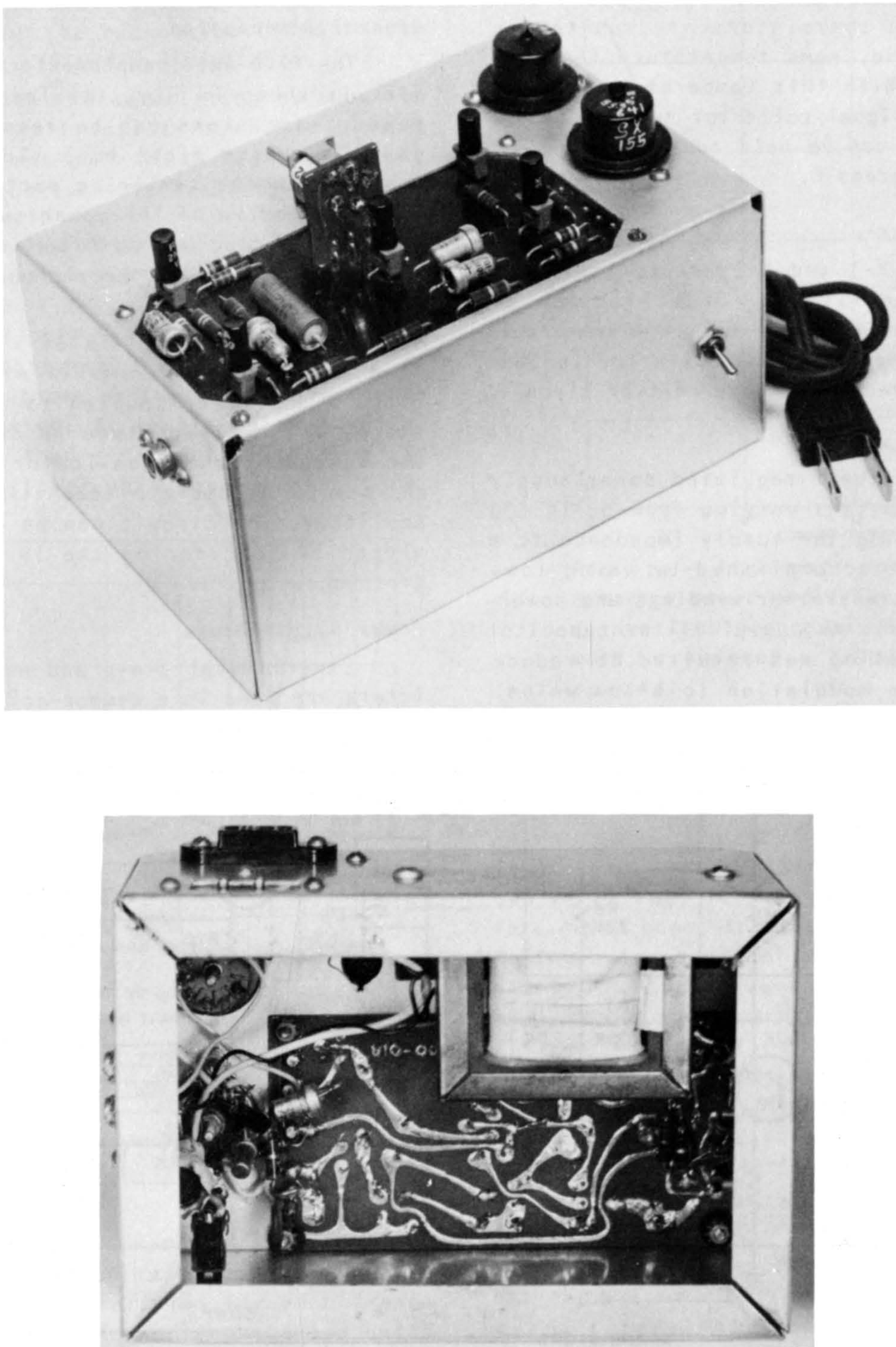


Fig. 11 - Five-watt complementary symmetry power amplifier

maintain a reverse bias on the power transistors, which is desirable at high ambient temperatures. If the thermistors are mounted on the transistor stud, some temperature feedback can be achieved. With this temperature compensation, the zero signal collector current of the power transistors can be held constant from -40 degrees to +60 degrees C.

Low Level Amplifier

Transistors X-1 and X-2 are conventional common emitter amplifiers. Stabilization against operating point drift with temperature is obtained by d-c feedback from collector to base and d-c current feedback in the emitter circuit.

Power Supply

Maintaining a well regulated power supply with the supply current varying from 50 to 500 ma involves reducing the supply impedance to a few ohms. This is accomplished by using low-resistance power-transformer windings and power-junction rectifiers. A 2000-µf filter capacitor with a 15-volt rating was required to reduce ripple and ripple modulation to a low value.

Complementary Symmetry Power Amplifier

General Description

The five-watt complementary symmetry amplifier is shown in Fig. 11. The n-p-n and p-n-p power transistors can be seen mounted on the chassis at the right hand side of the photograph, with the remaining portions of the circuit, exclusive of the power supply, mounted on a printed wiring board. A view of the under side of the chassis shows the wiring and power-supply components.

The circuit consists of a two-stage equalized phonograph pre-amplifier, followed by a class A amplifier coupled to a class A driver stage. This driver stage is direct-coupled to two cascaded common-collector stages. Fig. 12 represents a complete schematic diagram of the amplifier. The circuit can be conveniently analyzed by considering the invididual circuit groupings.

Power Output Stage

Experimental p-n-p and n-p-n power transistors are used in a common-collector connection

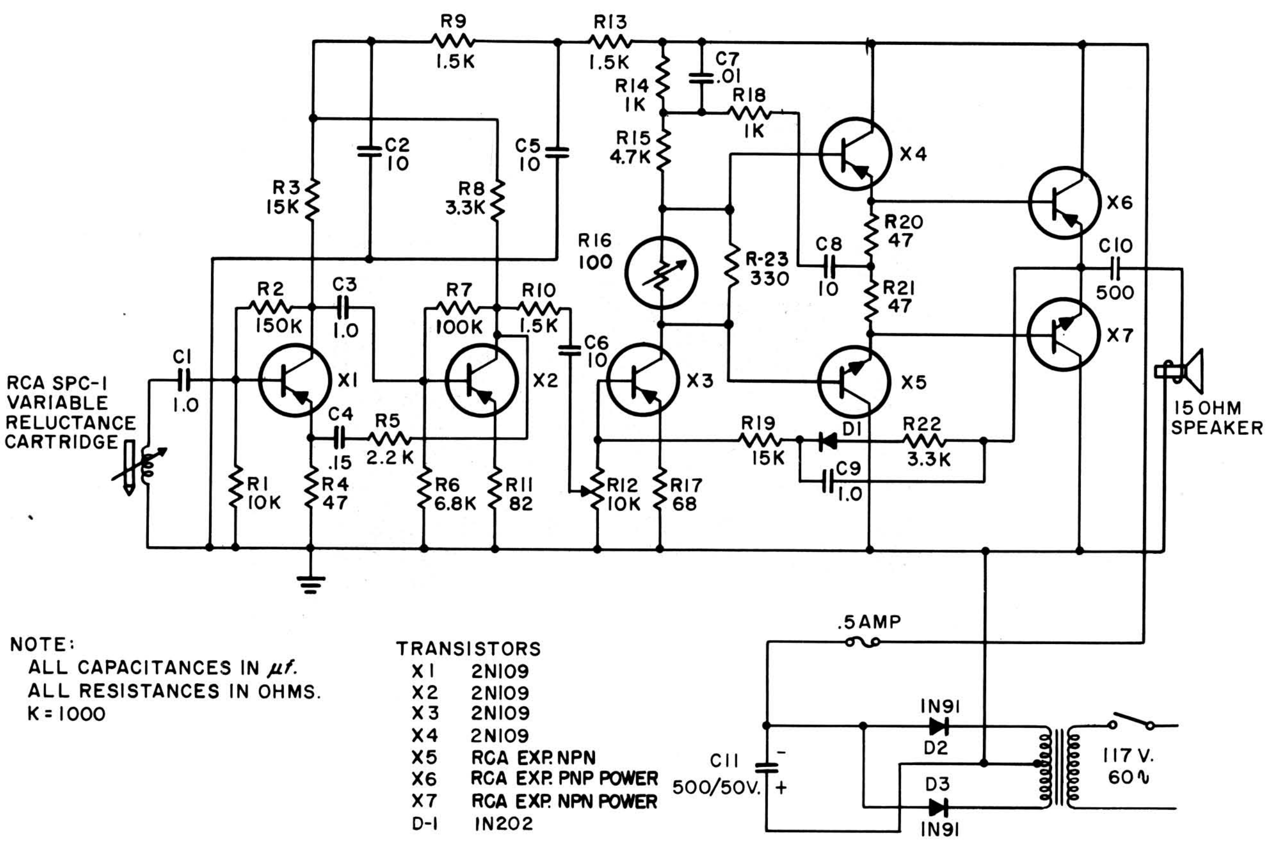
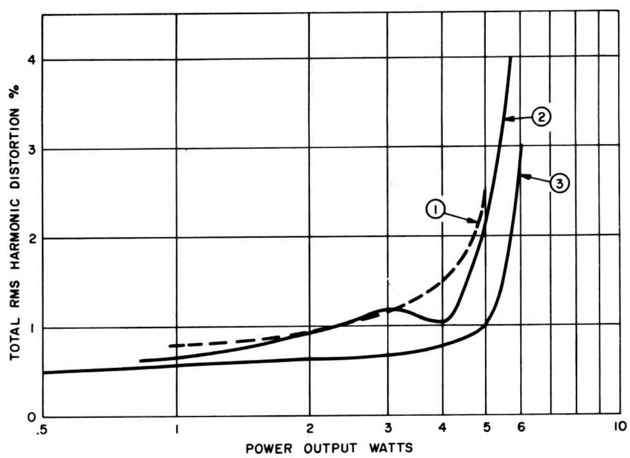


Fig. 12 - Five-watt complementary symmetry power amplifier schematic

for the output stage. The common-collector connection was used in preference to common-emitter or common-base for the reasons outlined in the discussion of the +20 dbm pre-amplifier.

For distortion characteristics as shown in Fig. 13, the power transistors should have a large signal current gain of at least 30 at one ampere of collector current. Peak collector currents at rated output will be on the order of one ampere with a collector loading of 15 ohms. Distortion vs. loading characteristics are shown in Fig. 14. The amplifier will function normally with power transistors having less than the desired beta characteristics, if an increase in distortion after three or four watts power output can be tolerated. At levels below 4 watts, output with less than 1 percent distortion can be obtained with lower gain power transistors.



POWER OUTPUT VS DISTORTION
15 OHM LOAD

CURVE	FREQ.CPS
1	100
2	20,000
3	1,000

Fig. 13 - Five-watt complementary symmetry power amplifier

A single polarity power supply is used for both the NPN and PNP transistors. Proper collector-emitter bias polarities for each transistor are obtained by connecting the two units in series across the power supply, without a conductive path to the load, and biasing the base circuit with approximately half the supply potential. This base voltage will appear at the power transistor emitters because of the common collector connections.

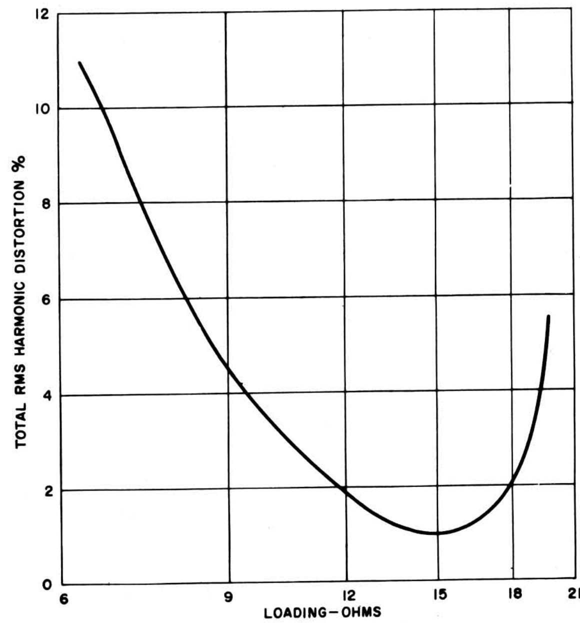


Fig. 14 - Five-watt complementary symmetry power amplifier. Distortion versus loading, power output = five watt, frequency = 1,000 cycles per second.

Complementary Symmetry Class-B Driver Stage

The driver stage consists of an experimental n-p-n and a 2N109 transistor connected in a common-collector configuration. The circuit is similar to that described for the power stage and it is used for the advantages outlined before. With power transistors in the output stage having a large signal current gain of approximately 30, the drivers supply approximately 35 milliamps peak current for full power output. This peak current requirement is within the capability of the drivers, but with lower gain power transistors, the drivers will be unable to supply the peak current and will contribute to the overall distortion. Also, the dissipation in the drivers may become excessive with low gain power units in the output stage.

Quiescent d-c base-emitter bias voltage for the driver-output stages to eliminate crossover distortion is obtained by the voltage across the thermistor R-16 in the collector circuit of the class A driver, X-3.

Class A Driver

The class A driver, X-3, is direct-coupled to the class B driver stage, X-4 and X-5. Because of the cascaded common-collector configuration of the driver and output stages, with voltage gains less than unity, the driver voltage requirements of the class A stage, X-3, are rather stringent. Because the driver, X-3, controls the d-c operating point of the remaining stages, stabilization of this circuit is important, and is discussed further in the following section.

Temperature Stabilization and Heat Dissipation

The amplifier is stable up to 70 degrees C with full signal. Temperature stability is achieved:

A. Providing for heat removal from the collector junction.

B. Providing circuit means for maintaining the d-c operating point constant with temperature change.

C. Insuring that maximum transistor ratings are not exceeded.

Heat removal from the power transistor collector junction is accomplished by clamping the shell (on which the collector is mounted) to the chassis which acts as an effective heat sink. With the transistor shell electrically at collector potential, suitable means must be provided for insulating the collector from the chassis while still maintaining good thermal contact. For the SX-155A, insulation is provided by a 0.001-inch mylar film sandwiched between the transistor mounting base and the chassis. Silicone oil is used between the transistor and heat sink for improved thermal contact. The n-p-n power-transistor collector is at ground potential in the circuit and it is mounted directly without insulation.

The power transistors, X-6 and X-7, tend to stabilize each other. With the transistors in series and capacity coupled to the load, the emitter currents for both units must be equal. The low resistance of R18 and R19 between X-6 and X-7 bases provides a low resistance d-c path for I_{co} currents that tends to avoid amplification of this thermally dependent current in the collector circuit.

The class B drivers, X-4 and X-5, have the same stability as the power stage with an additional measure of stability afforded by current feedback in R-20 and R-21. Signal is coupled from the drivers to the output such that no drive power is wasted in these resistors.

The zero-signal d-c operating point from collector to emitter of both the class B driver and output stage is controlled by the collector voltage and current of the driver, X-3. This class A driver stage requires extremely good temperature stabilization because a small change in operating point at X-3 is amplified by direct-coupling to the output stage and can cause thermal runaway.

Stabilization of X-3 is accomplished by the d-c feedback path consisting of R-19 and R-22, and the zener diode, D-1. The zener diode is operated in the reverse direction and has a voltage breakdown of approximately 12 volts. When connected as shown, the diode permits the stabilization feedback resistor to be 15,000 ohms while maintaining an effective bias resistance of 150,000 ohms. This provides a 10-to-1 increase in the d-c stability of X-4 over the use of a 150,000-ohm resistor in a conventional collector to base voltage feedback arrangement.

The 100-ohm thermistor, R-16, is used to compensate for the slight increase in the collector current of X-3 as the temperature increases. The voltage across R-16 due to the collector current flowing in X-3, provides about 400 mv of forward bias for the driver-output stage to eliminate cross-over distortion in the output signal.

Stabilization of the remaining low level circuits is accomplished by conventional collector-to-base voltage feedback and emitter feedback.

Signal Feedback

Approximately 15 db of negative feedback is applied from the output load to the base of X-3. This negative feedback is accomplished by partially bypassing the d-c stabilization network with C-9. The 100 percent voltage feedback inherent in the common collector configuration of the drivers, X-4 and X-5, is reduced by C-8 so that the drive available from the preceeding, class A stage, X-3, is sufficient. C-7 improves the high frequency stability margin.

Phonograph Pre-amplifier

Transistors X-1 and X-2 are used for an equalized pre-amplifier to operate from a variable-reluctance phonograph pickup. The circuit consists of cascaded common-emitter stages with second-stage collector to first-stage emitter feedback to provide for low-frequency equaliza-

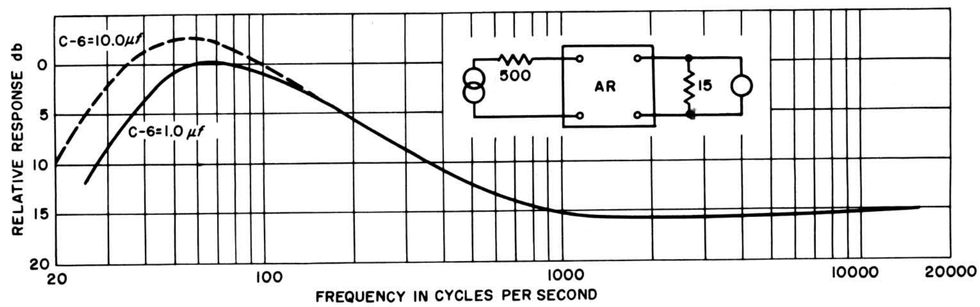


Fig. 15 - Five-watt complementary symmetry power amplifier. Frequency response 500 source to 15-ohm load.

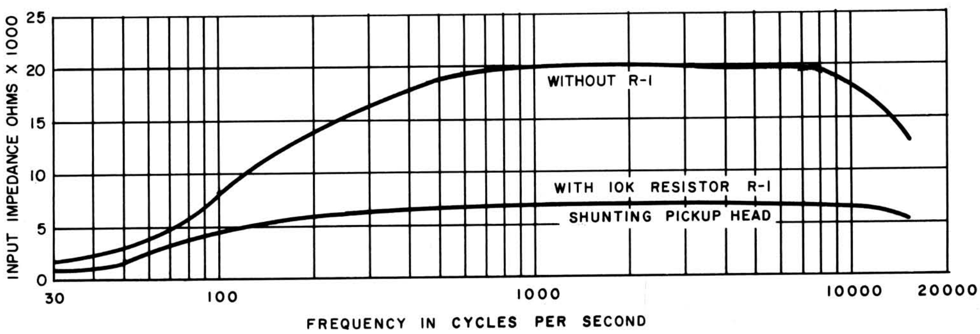


Fig. 16 - Five-watt complementary symmetry power amplifier. Input impedance versus frequency.

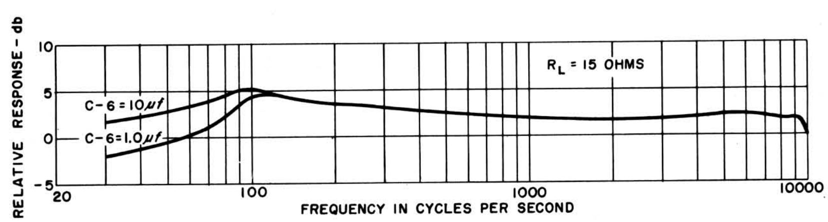


Fig. 17 - Five-watt complementary symmetry power amplifier. Frequency response with SPC-1 cartridge reproducing RCA 12-5-49 test record.

tion and a high input impedance at high frequencies for the pickup. Fig. 15 shows the frequency response of the amplifier. A 10,000-ohm resistor, R-1, at the input of the amplifier shunts the pickup as shown in Fig. 16 to provide the proper high-frequency deemphasis necessary for flat playback of the R1AA (Orthophonic) recording characteristic as shown in Fig. 17. The voltage from the pickup at full groove modulation is about 10 millivolts, so considerations for low noise performance become important. The input circuit can be modified for use as a flat amplifier by removing the bass boost network.

Albert I. Aronson

RCA Engineering Products