PART 3. PERFORMANCE OF PRACTICAL CIRCUITS

Designing Silicon-Transistor Hi-Fi Amplifiers

General considerations for conservative design using readily available silicon power transistors. Practical circuits of 10-, 25-, and 70-watt amplifiers and their performance are given.

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IN addition to the consideration that must be given to the achievement of performance objectives and the selection of the optimum circuit configuration (discussed in the previous two parts of this series), the circuit designer must also take steps to insure reliable operation of the audio amplifier under varying conditions of signal level, frequency, ambient temperature, load impedance, line voltage, and other factors which may subject the transistors to either transient or steady-state high stress levels. Some of these steps are relatively straightforward. For example, it is necessary to insure that the power dissipation ratings are not exceeded at high line voltage and under worst-case signal conditions. For class-A amplifiers, the maximum power dissipation occurs at zero signal. For an ideal class-B push-pull stage, maximum power dissipation occurs when the drive signal is 64 percent of that required for maximum output power. The corresponding output power for this condition occurs at 42 percent of the maximum output power, and the dissipation in each transistor is 20 percent of the maximum power output. Also, for class-AB transformer-coupled amplifiers, the appropriate transistor breakdown-voltage rating must be greater than twice the d.c. collector voltage that is employed.

Thermal Stability Requirements

One serious problem facing the design engineer, not only in the quasi-complementary circuit but in all the circuits thus far discussed, is the ability to design a circuit which is thermally stable at all temperatures to which the amplifier might be exposed. Ideally, the quiescent current of an output stage should remain constant at all temperatures of interest. At low current levels however, the base-to-emitter voltage (V_{BE}) of a transistor decreases with increases in the junction temperature for a given collector current (I_C). If V_{BE} is held constant, then I_C will increase as the temperature rises. This behavior may lead to thermal runaway.

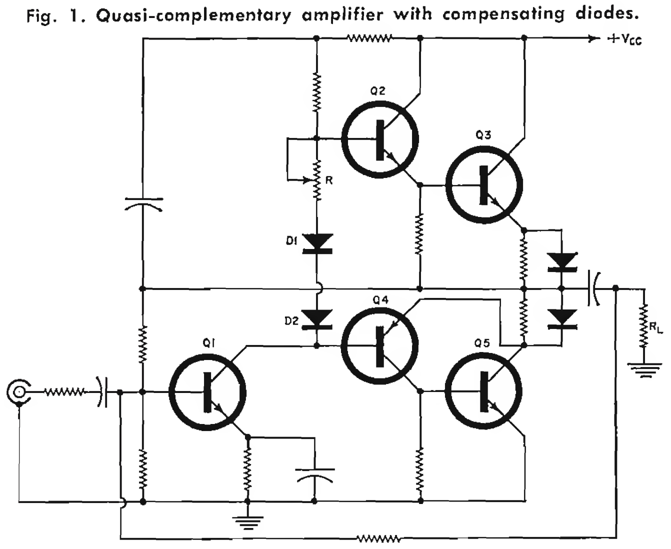
The effect of increasing temperature on collector current can be reduced by the use of an emitter resistor which will provide some local d.c. feedback. At high signal levels, the over-all saturation voltage of the device will be increased because of the voltage drop across this resistor. One solution to the saturation-voltage problem is to bypass the emitter resistor with a capacitor. In high-power amplifiers, however, the emitter resistors employed usually have a value of about 1 ohm, and the size of the capacitor required to bypass the emitter adequately at all frequencies of interest makes this approach economically impractical. A more practical solution is to increase the value of the emitter resistor and shunt it with a diode. With this technique, sufficient degeneration is provided to improve circuit stability, but the maximum voltage drop across the emitter resistor is limited to the forward voltage drop of the diode.

Thermal stability can be further improved by the addition of devices such as thermistors or bias diodes, the characteristics of which are such that they will tend to reduce the base drive voltage of the output transistor as temperatures rise. When these types of devices are used, it is possible to reduce or even eliminate emitter networks completely and thereby to reduce substantially the circuit losses at high power levels. It is interesting to note that a simple emitter diode itself will provide some improvement in circuit stability. The static resistance of a diode is fairly high at low currents (about 30 ohms at 20 milliamperes for a 1N1612). A disadvantage of this technique is that the forward voltage drop of this diode decreases with increasing temperature and, therefore, reduces the stabilizing effects of the high dynamic resistance.

It should be noted that at high current levels, the base-to-emitter voltage of silicon transistors increases with a rise in the junction temperature. This characteristic is the result of the increase in the small base resistance that is produced by the rise in temperature. The increase in base resistance with temperature has two beneficial effects: First, it helps to stabilize the transistor against thermal runaway because higher temperatures now require an increase in V_{BE} to cause an increase in I_C. Second, the increased resistance causes a portion of the transfer characteristic to be linear. A lower distortion is therefore possible at high temperatures.

The quasi-complementary amplifier shown in Fig. 1 incorporates the stabilization techniques just described. A

Fig. 1. Quasi-complementary amplifier with compensating diodes.



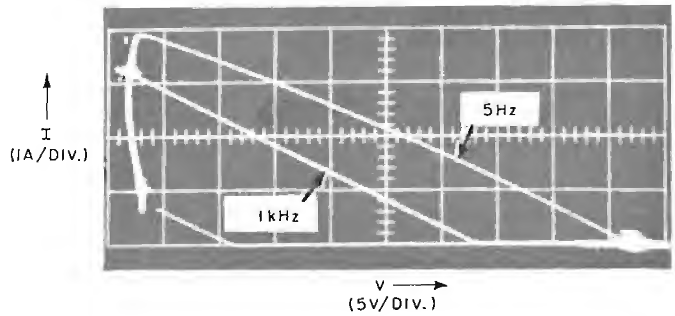


Fig. 2. Note load-line shift at very low operating frequency.

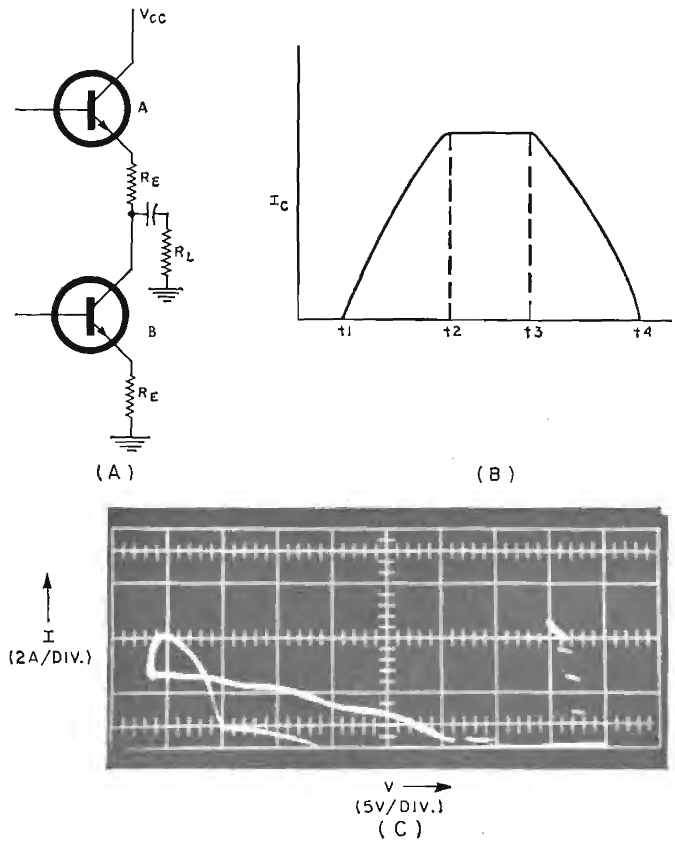


Fig. 3. (A) Output circuit which is overdriven. (B) Transistor A collector-current waveform. (C) Load line of circuit shown at operating frequency of 100 kHz and power output of 30 watts.

resistor-diode network is used in the emitter of transistor $Q3$, and another such network is used in the collector of transistor $Q5$.

Previous discussion regarding the *p-n-p* driver and *n-p-n* output combination ($Q3$ and $Q5$) revealed that the collector of the output device becomes the "effective" emitter of the high-gain, high-power *p-n-p* equivalent, and *vice versa*. Therefore, in order to provide maximum operating-point stability, the diode-resistor network should be in the "effective" emitter of the *p-n-p* equivalent. Most quasi-complementary circuits employ the stabilization resistor in the emitter of the lower output transistor and thus do not improve the operating-point stability of the over-all circuit. The resistor, however, does provide some protection against thermal runaway of the lower output transistor. Such protection may be necessary unless it is provided by other means.

The circuit shown in Fig. 1 is biased for class-AB operation by the voltage obtained from the forward drop of two diodes, $D1$ and $D2$, plus the voltage drop across potentiometer R, which affords a slight adjustment in the value of the quiescent current. The current necessary to provide this voltage reference is the collector current of driver transistor $Q1$. The diodes may be thermally connected to the heat sink of the output transistors so that thermal feedback will be provided to further improve thermal stability. Because the forward voltage of the reference diodes decreases with increasing temperature, these diodes effectively compensate for the decreasing V_{BE} of the output transistors by reducing the external bias applied. In this way, the quiescent current of the output stage can be held relatively constant over a wide range of operating temperatures.

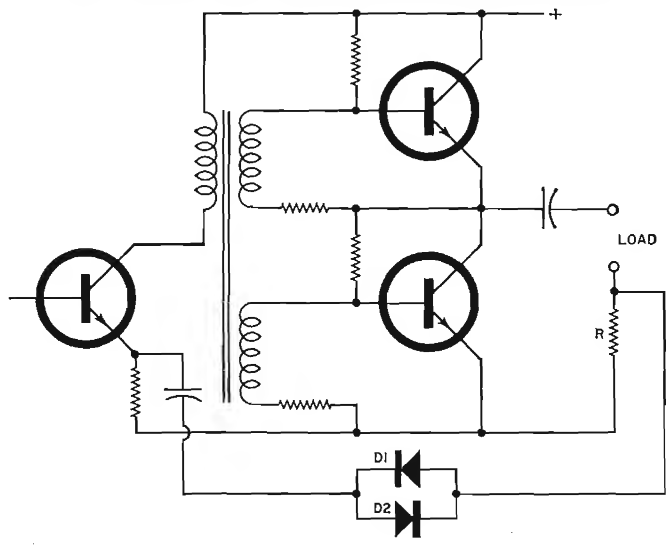
The value of the transistor operating parameters that affect thermal stability can be calculated to insure freedom from thermal runaway. In these calculations it should be realized that the temperature-dependent collector leakage-current limit specified by the transistor manufacturer actually consists of two components. One is related directly to the collector junction saturation current and is a strong function of temperature. In silicon transistors, this component is approximately doubled with each 7° C rise in junction temperature. At room temperature, however, it is on the order of only a few nanoamperes, so that a rise in case temperature of 140 C will cause the saturation current to rise only a few milliamperes.

The other component of collector leakage current is a surface leakage which is relatively independent of temperature. In fact, this leakage component may decrease as the temperature increases. The value of total leakage current (I_{CER}) specified by the transistor manufacturer is the sum of these two components. If the specified value is on the order of a few milliamperes, it will remain substantially constant with temperature. For example, in the published data for the *RCA*-40363, I_{CER} is given as 0.5 milliampere (maximum) at $T_c = 150°$ C. The transistor is, therefore, quite stable thermally with respect to any changes that might occur in the amount of leakage current.

Effects of Large Phase Shifts

The frequency-response characteristic is an important factor with respect to the ability of the amplifier to withstand unusually severe electrical stress conditions. For example, under certain conditions of input signal amplitude and frequency, the amplifier may break into high-frequency oscillations which can lead to destruction of the output transistors, the drivers, or both. This condition is particularly a problem in transformer-coupled amplifiers because the characteristics of transformers depart from the ideal at both low and high frequencies. The departure occurs at low frequencies because the transformer inductive reactance decreases and, at high frequencies because the effects of leakage inductance and of transformer wind-

Fig. 4. Push-pull power amplifier with short-circuit protection.



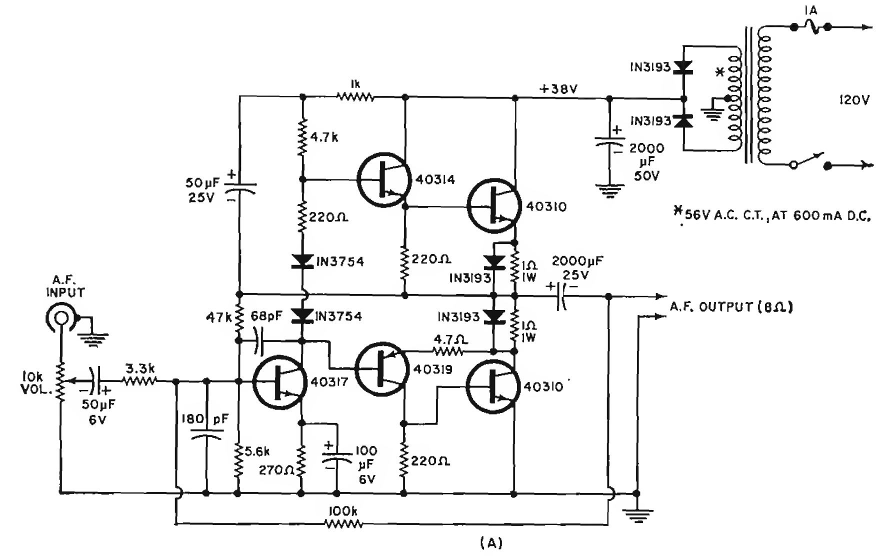
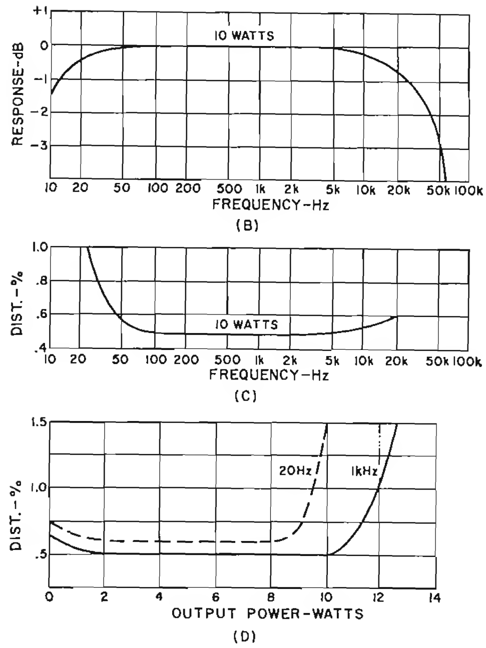


Fig. 5. Circuit diagram and performance of 10-watt amplifier.



ing capacitance become appreciable. At both frequency extremes, the effect is to introduce a phase shift between input and output voltage.

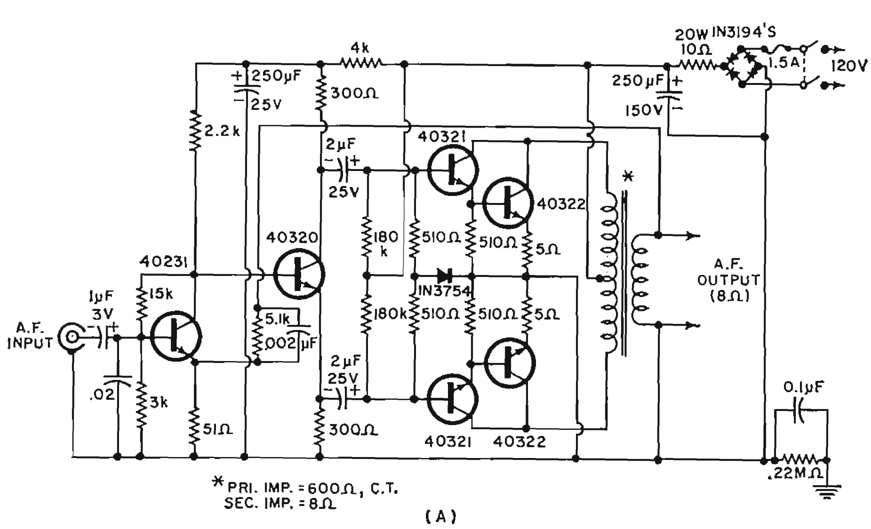
Negative feedback is used almost universally in audio amplifiers, and the voltage coupled back to the input by the feedback loop may cause the amplifier to be potentially unstable at some frequencies, if the additional phase shift is sufficient to make the feedback positive. Similar effects can occur in transformerless amplifiers because reactive elements, such as coupling and bypass capacitors, transistor junction capacitance, stray wiring capacitance, and inductance of the loudspeaker voice coil, are always present. The values of some of the reactive elements (*e.g.*, transistor junction capacitance and transformer inductance as the core nears saturation) are functions of the signal level, and coupling through wiring capacitance and unavoidable ground loops may also vary with the signal level. As a result, an amplifier which is stable under normal listening levels may break into oscillations when subjected to high-level signal transients.

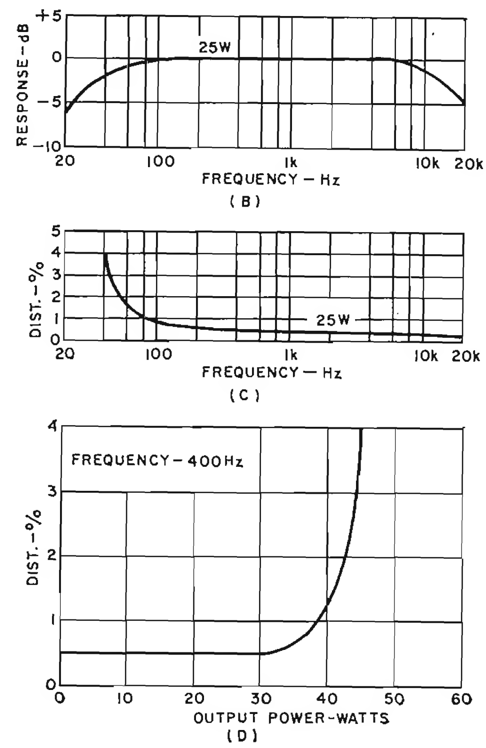
A large phase shift is not only a potential source of amplifier instability, but also results in additional transistor power dissipation and increases the susceptibility of the transistor to forward-bias second-breakdown failures. The effects of large signal phase shifts at low frequencies are illustrated in Fig. 2, which compares the load-line characteristics of a transistor in a class-AB push-pull circuit, similar to that shown in Fig. 1, for signal frequencies of 1000 Hz and of 5 Hz. The phase shift is caused primarily by the output capacitor. In both cases the amplifier is driven very hard into saturation by a 5-volt input signal. The increased dissipation at 5 Hz compared to that obtained at 1000 Hz results from simultaneous high-current and high-voltage operation. The transistor is required to handle safely a current of 0.75 ampere at a collector voltage of 40 volts for an equivalent pulse duration of about 10 milliseconds; it must be free from second breakdown under these conditions of operation.

Excessive Drive Levels

Simultaneous high-current and high-voltage operation may also occur in class-B amplifiers at high frequencies when the amplifier is overdriven to the point where the output signals are clipped. For example, assume that the input signal applied to the series-output push-pull circuit shown in Fig. 3A is large enough to drive the transistors into both saturation and cut-off. During a portion of the input

Fig. 6. A 25-watt a.c./d.c. transformer-coupled amplifier.





cycle, therefore, transistor A will be driven into saturation, and transistor B will be cut off. Fig. 3B shows the collector-current waveform for transistor A under these conditions.

During the interval from $t2$ to $t3$, transistor A operates in the saturation region, and the output voltage is clipped. The effective negative feedback is then reduced because the output voltage does not follow the sinusoidal input signal. Transistor A, therefore, will be driven even further into saturation by the unattenuated input signal. When transistor B starts to conduct, transistor A cannot be turned off immediately because the excessive drive has resulted in a large storage time. As a result, transistor B is required to support essentially the full supply voltage (less only the saturation voltage of transistor A and the voltage drop across the emitter resistors, if used), as its current is increased by the drive signal. For this condition, a large input signal is required when the frequency is high enough so that the storage time is greater than one-quarter cycle.

Fig. 3C shows the type of load line obtained under such conditions. The duration of the high-current, high-voltage condition is usually short enough so that forward-bias second breakdown does not occur. For example, the load line shown is for a 2N3878 transistor operated at a frequency of 100 kHz; no second breakdown failure occurred.

Transistor A in Fig. 3A is also subject to forward-bias second breakdown if the d.c. supply voltage and a large input signal are applied simultaneously, because of the charging current through the output coupling capacitor.

If the load of a transformer-coupled amplifier is disconnected during operation, the transistor then sees an inductive load (the transformer primary inductance). When the transistor is turned off, reverse-bias second breakdown may occur. Direct- or capacitive-coupled circuits, on the other hand, are quite stable with the load removed.

If the amplifier high-frequency response is limited by the high-frequency capability of the output transistors, then the driver transistors may be unduly stressed under high-frequency, high-drive conditions. This stress is produced because the reduction in output voltage, as amplifier gain decreases, results in a smaller negative feedback voltage. The effective over-all amplifier gain is therefore increased, thereby causing the current in the driver transistors to increase. At sufficiently high frequencies, failure may then result because the drivers become overloaded.

This potential cause of failure can be avoided by the deliberate introduction of a frequency roll-off at the input, or by the use of high-frequency output transistors. The 2N3878, which has a typical gain-bandwidth product of 100 MHz, is well suited as an output for very wide band amplifiers. This transistor has been used in a low-distortion amplifier to obtain a frequency response which is down only 1 dB at 15 Hz and at 200 kHz at 20 watts output.

Short-Circuit Protection

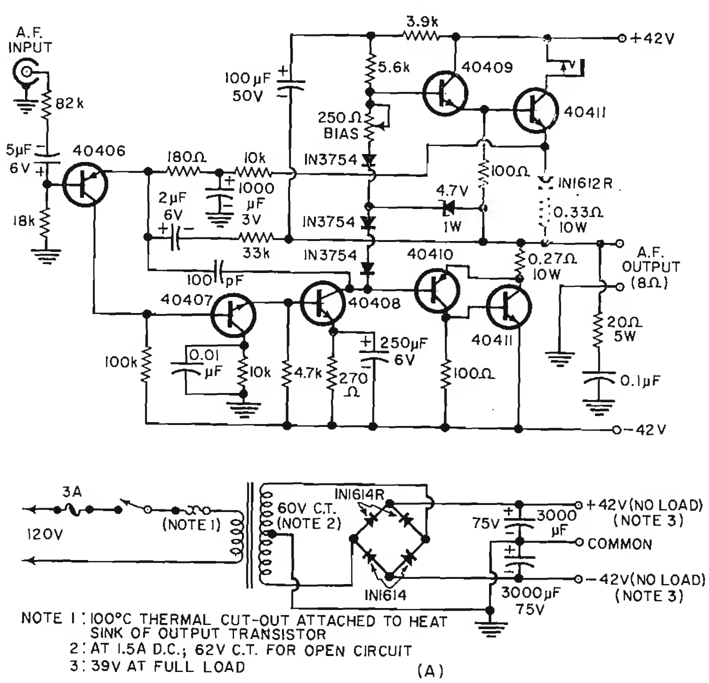
Another important consideration in the design of high-power audio amplifiers is the ability of the circuit to withstand short-circuit conditions. When the output terminals of an amplifier are shorted, the feedback becomes ineffective, and the open-loop gain is such that overdrive conditions result in disastrously high currents and excessive dissipation in both driver and output stages. Generally, before the output fuse can blow, the transistors are destroyed. Obviously, some form of short-circuit protection is necessary.

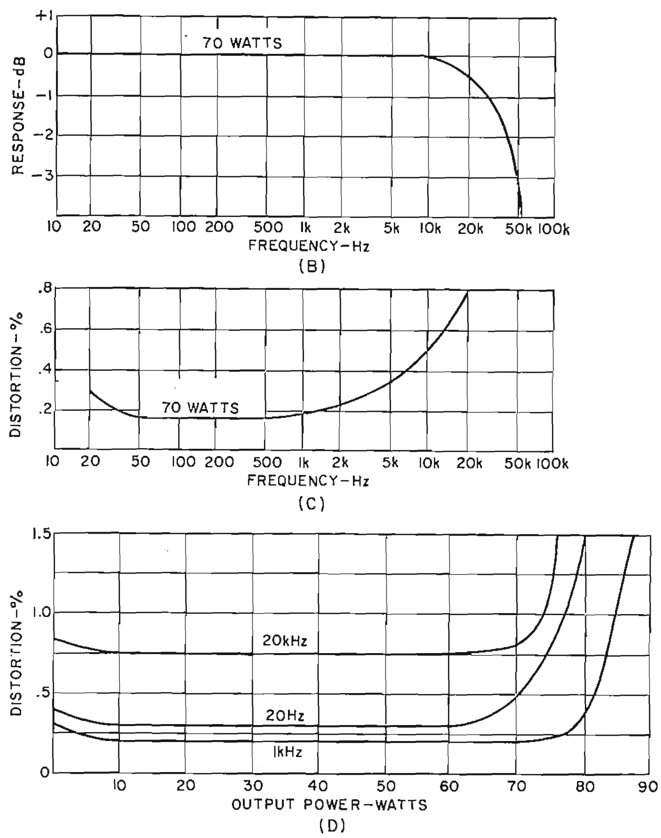
One such technique is shown in Fig. 4. A current-sampling resistor R is placed in the ground leg of the load. If any condition (including a short) exists such that higher-than-normal load current flows, diodes $D1$ and $D2$ conduct on alternate half cycles and, thereby, provide a high negative feedback which effectively reduces the drive of the amplifier; however, this feedback should not exceed the stability margin of the amplifier. Notice that this technique does not in any way effect the normal operation.

10-Watt, Class-AB Audio Amplifier

The advantages of using silicon power transistors in the driver and output stages of high-power audio amplifiers are shown by the typical performance of three practical circuits designed to operate at widely different power-output levels (10 watts, 25 watts, and 70 watts). The performance data shows that silicon transistors can be used to develop high levels of audio output power in circuits that exhibit the wide frequency response, high sensitivity, and low distortion levels required in high-quality audio systems. Moreover, because of the high-tempera- (*Continued on page* 80)

Fig. 7. A 70-watt direct-coupled audio power amplifier.





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ture capabilities of the silicon transistors, the performance of the amplifiers remains essentially the same over a wide variation in ambient temperature.

Fig. 5A shows a schematic of a practical 10-watt quasi-complementary audio amplifier. This circuit employs the same stability techniques as those used in the circuit of Fig. 1. Two 1N3754 diodes are used in the input of the driver stage to compensate for the effect of high-temperature variations of the output transistors. Two 1-ohm resistors are placed in the output stage to provide the degeneration required for circuit stability. These resistors are shunted by 1N3193 diodes to reduce losses when the amplifier is operated at full rated output power.

The use of direct-coupled stages and local d.c. feedback results in very stable quiescent operation at ambient temperatures up to 71°C. With an over-all negative feedback of 5 dB, the amplifier has a response that is flat within 1 dB from 15 to 20,000 Hz. Performance curves for the 10-watt amplifier are shown in Figs. 5B, 5C, and 5D.

25-Watt, Class-AB Audio Amplifier

Fig. 6A shows the schematic of a 25-watt a.c./d.c. transformer-coupled audio amplifier intended primarily for public-address systems and other applications for which economy and flexibility with respect to load impedance are important considerations. The high breakdown voltage of the silicon power transistors used in the output and driver stages permit the amplifier to be operated directly from a 120-volt a.c. or d.c. line. The negative-voltage terminals of the amplifier (*i.e.*, circuit ground) is isolated from chassis ground by a 0.22-megohm resistor to reduce the risks of electrical shock. The signal input should be transformer-coupled to the power amplifier to avoid shock hazard from the signal-source ground. A 0.1-μF capacitor provides a low impedance connection between circuit ground and chassis ground at r.f. frequencies to prevent high-frequency oscillations.

Each driver transistor is connected to the associated output transistor in a Darlington arrangement; the output is transformer-coupled to the speaker. Drive-signal phase inversion is provided by a transistor phase-splitter circuit. The small amount of forward bias required for class-AB operation is provided by the 180,000 and 510-ohm resistors and the 1N3754 diode. The diode also provides the temperature compensation required so that the quiescent current will remain relatively constant for wide variations in temperature. With the 10 dB of over-all feedback from the output to the emitter of the first stage, the amplifier has an input impedance of 2500 ohms. Performance curves for the 25-watt unit are shown in Figs. 6B, 6C, and 6D.

70-Watt, Class-AB Audio Amplifier

Fig. 7A shows the schematic of a high-quality 70-watt direct-coupled series-output audio amplifier in which unique techniques are used to obtain stable and reliable performance. The three 1N3754 diodes in the driver stage are thermally connected to the output transistor heatsinks so that the thermal feedback required to maintain a preset 20 milliamperes of quiescent output current is obtained at all case temperatures up to 100°C. Small-value emitter resistors are employed in the output stage because additional stability is not necessary and output losses must be held to a minimum. A 1N1612R diode is placed in the emitter of one output transistor to cancel the offset voltage of the input transistor and thereby maintain the quiescent output voltage near zero.

Short-circuit protection is provided by the 0.27- and 0.33-ohm emitter resistors and the zener diode. If any condition exists which will cause higher-than-normal current (5 amperes) to flow through these resistors, the voltage potential across the zener diode will be such that the diode conducts in the forward direction during the negative output half cycle and exceeds the diode breakdown voltage during the positive half cycle. In this way, the driver is clamped below the 5-ampere level, and no increase in output current above this value is allowed. The drivers and output transistors, therefore, are protected from high currents and excessive power dissipation that may result from a reduced load resistance or, in the worst case, a short-circuit. In addition, a 100°C thermal cut-off is attached to the output transistor heatsink which will turn off the amplifier when these abnormal conditions cause sustained higher-than-normal output dissipation.

The frequency response of the amplifier is flat within 1 dB from 5 to 25,000 Hz. The input sensitivity of the amplifier is 0.8 volt r.m.s. for full rated output. The input resistance is 100,000 ohms. The performance curves for the 70-watt amplifier are shown in Figs. 7B, and 7D.

(Editor's Note: The three amplifier circuits shown in this article are not intended as construction projects. We have no information on sources for any of the special parts required. Rather the circuits were included to illustrate the various design principles discussed in this three-part series of articles.) ▲