LB-1021

DESIGN CONSIDERATIONS IN CLASS B COMPLIMENTARY SYMMETRY CIRCUITS

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Design Considerations in

Class B Complementary Symmetry Circuits

Approved

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The potentialities of the complementary symmetry exhibited by p-n-p and n-p-n transistors were explored in *LB-906, Symmetrical Properties of Transistors and Their Application.* This bulletin discusses design considerations for transformerless complementary-symmetry circuits providing class B push-pull audio output at medium power levels. The relative significance of the various transistor parameters is considered, and three circuits are described in detail.

Transistors For Complementary Symmetry

Experimental transistors which might be considered for developmental complementary-symmetry circuits have been described[1]. Many transistors which might be considered for low-level stages, and a number of alloy-junction transistors intended for high-current, medium-power applications may presently be obtained. In addition, several available "radio-frequency" alloy-junction transistors, while not intended for high-current service, do exhibit respectable performance. (This is not entirely fortuitous, since several of the factors that enhance high-frequency operation, e.g., close junction spacing and low base-lead resistance, enhance high-current performance as well.) The circuits herein described employ transistors which were obtained in small quantities without consideration of cost or future availability.

The transistor parameters that most directly influence performance in complementary-symmetry output circuits are current gain and transconductance. Loosely speaking, current gain describes the relation between base or emitter current and short-circuit collector current. The base-to-collector current gain, α_{cb} (also sometimes designated β), is the ratio of an increment in collector current to an increment in base current for some specified operating conditions. Since α_{cb} diminishes at higher collector currents, a second parameter, "large signal current gain," or "d-c alpha," may be specified. This refers to a collector-current to base-current ratio at some relatively high value of collector current. One of the factors that influences α_{cb} and large signal current gain is minority carrier type; that is, whether the transistor is n-p-n or p-n-p. Other things being equal, one might expect the n-p-n to excel both in α_{cb} and in large-signal current gain, but even with mechanically similar transistors, many other factors enter, and either the n-p-n or p-n-p may excel. The factors that influence current gain, and its dependence on current level are described in *LB-916* and *LB-966, The Variation of Current Gain with Junction Shape* and *Surface Recombination in Alloy Transistors* (parts I and II) and *LB-917, The Variation of Junction Transistor Current Amplification Factor with Emitter Current.* The differences in current gain between n-p-n and p-n-p units that can be tolerated in complementary-symmetry applications depend upon the circuits, and will be discussed later.

Transistor transconductance is usually not specified directly. At low current levels, the incremental emitter current change with incremental base-to-emitter voltage usually follows the relationship for an idealized transistor, $\frac{\partial Ie}{\partial Vbe} = \frac{KT}{q} Ie$, where $\frac{KT}{q} = 38.9 \text{ volts}^{-1}$ at 25 degrees C. At higher currents, the incremental voltage drop produced by base current flow in the base-lead resistance becomes appreciable, and the transconductance no longer increases linearly with emitter current; in fact, it ultimately decreases with increasing emitter current. The presence of any emitter-lead resistance also reduces the transconductance from the ideal value. A "large-signal transconductance" may be inferred when the required base-to-emitter voltage is specified for some relatively large value of collector current.

Generally, the impedance levels in complementary-symmetry output circuits are relatively low, and signal voltage developed at the collector has little direct effect on collector current. An important exception occurs when the collector "bottoms," that is, when the reverse bias at the collector junction becomes too small for collection to take place. A parameter which describes the minimum

1. For example, see *LB-868, Germanium PNP Junction Transistors, LB-900, A Germanium NPN Junction Transistor by the Alloy Process,* and *LB-1010, Recent Advances in Power Junction Transistors.*

collector-to-emitter voltage for collection at some relatively large collector current is then of interest. The ratio of this minimum voltage to the collector current may be thought of as an effective series resistance which the transistor exhibits.

All of these parameters may be derived from sets of characteristics such as those shown in Fig. 1. These characteristics were photographed on the curve tracer described in *LB-882, A Transistor Curve Tracer.* Representative curves for any transistor type are usually available from the manufacturer.

The transistor voltage and dissipation limits specified by the manufacturer must be taken into account in circuit design. The range of ambient temperature over which performance is satisfactory is intimately related to circuit design, as discussed in *LB-979, Temperature Effects in Circuits Using Junction Transistors,* and will be considered in conjunction with some representative circuits.

Basic Circuits

When a single-ended amplifier employing a p-n-p transistor is connected in parallel (for signal frequencies)

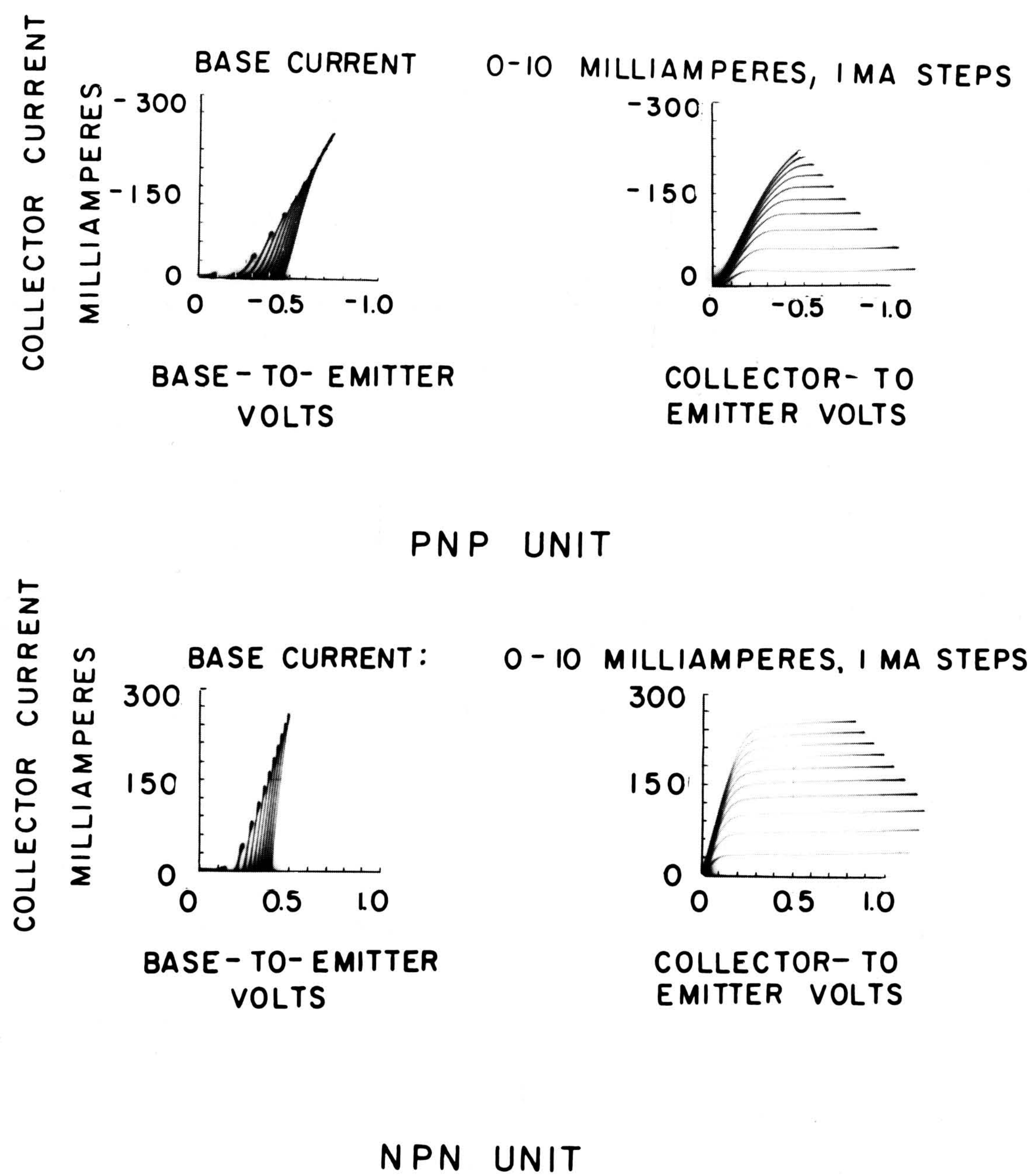
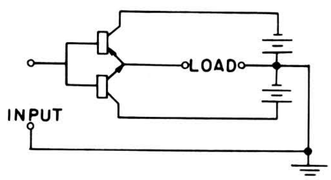
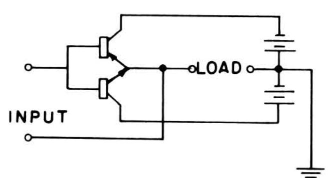


Fig. 1. Representative transistor characteristic curves.

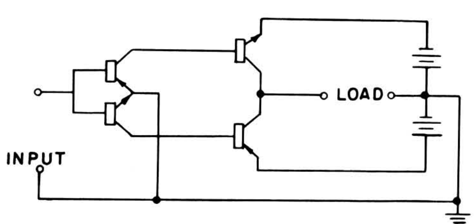
with the same type of single-ended amplifier employing an n-p-n transistor, a rudimentary push-pull complementary-symmetry amplifier is born. The circuit becomes something more than rudimentary when advantages in biasing and coupling are exploited, e.g., in class B operation without transformers. Basic complementary-symmetry circuit types reflect the single-ended circuit types from which they are derived. One of the simplest is the "common-collector" or emitter-follower circuit, shown diagrammatically in Fig. 2a. When the paralleled bases swing negative, the p-n-p conducts and the paralleled emitters follow; for positive swing the n-p-n conducts, and again the emitters follow the bases. The voltage gain of this circuit is necessarily smaller than unity; the current gain is equal to the base-to-emitter current gain (α_{cb} + 1) of the transistors.



a) COMMON COLLECTOR



b) EMITTER LOADED



c) CASCADE COMMON EMITTER

NOTE: IN COMPLETE CIRCUITS, THE BATTERY CENTERTAP MAY IN SOME CASES BE ELIMINATED.

Fig. 2. Basic complementary symmetry circuits.

A modification of this circuit, the *emitter-loaded* amplifier, is shown in Fig. 2b. In a sense, this is a common-emitter circuit, since the signal source and load are both returned to the paralleled emitters. However, note that in this circuit the *common* point does not correspond to the amplifier *ground*. The voltage gain of this circuit (the product of the transistor transconductance and the load impedance) may be quite large; the current gain is equal to the base-to-collector current gain (α_{cb}) of the transistors.

A two-stage cascaded common-emitter amplifier is shown in Fig. 2c. Here, the signal source, the load, and the various emitters are all returned to a-c ground. The separate collectors of the first stage drive the separate bases of the second stage, and the paralleled collectors of the second stage are connected to the load. The voltage and current gains of this amplifier are greater than single-stage common-emitter gains by a factor equal to the second stage current-gain.

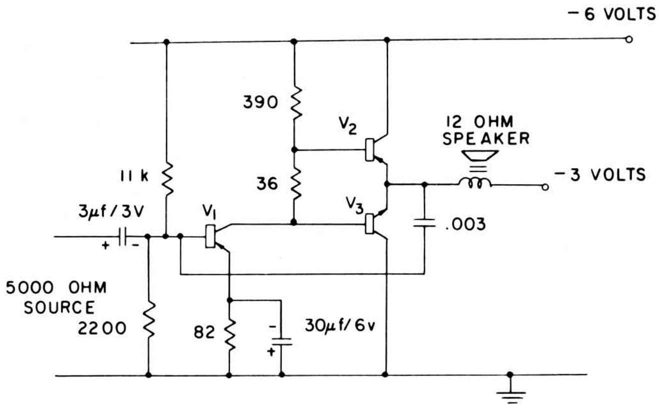
Some Illustrative Circuits

Common Collector

An audio amplifier employing a common-collector output stage and a single-ended class A driver stage is illustrated in Fig. 3. This amplifier, which might be employed in a portable receiver, provides a nominal 75 mw maximum output. The driver is direct-coupled to the output stage. A by-passed emitter-return resistor stabilizes driver current and the voltage developed by driver collector-current flowing through a 36-ohm resistor connected between the output-stage bases provides threshold bias for the output transistors. The 12-ohm voice-coil is direct-driven by the output stage emitters, and returns to the centertap of the -6 volt supply. A 0.003 μfd capacitor controls high frequency response by introducing negative feedback at frequencies above 3 kc. The sensitivity of the amplifier is 80 μa rms input for 75 mw out.

The driver stage, which is biased at 7.5 ma, is direct coupled to the output stage. With no signal present, the driver collector current develops about -2.88 v and -3.12 v at the n-p-n and p-n-p bases respectively. Since the paralleled emitters of the output stage are returned, via the voice coil, to the -3v tap, each of the output transistors is provided with a small forward bias, so that about 2 ma emitter current flows serially through the emitters. This "threshold" bias minimizes nonlinearity in the cross-over interval when current shifts from one output transistor to the other. The total quiescent current drain of the amplifier, then, is slightly more than 9.5 ma.

The driver stage is "constant emitter-current" biased by means of the bypassed emitter-return resistor. The efficacy of this type of bias with respect to changes in ambient temperature may best be understood by reviewing *LB-979, Temperature Effects in Circuits Using Junction*



V1 : LOW LEVEL P-N-P

V2 : HIGH CURRENT P-N-P *

V3 : HIGH CURRENT N-P-N *

ALL RESISTORS CARBON, 5%

* SEE FIG. I FOR REPRESENTATIVE CHARACTERISTICS

Fig. 3. Amplifier employing common-collector output stage.

Transistors. The most important consequence of the shift in driver collector current with change in ambient temperature is the unbalancing of the quiescent currents in the output transistors. For example, at reduced ambient temperatures, driver collector current is reduced, and the bases of each of the output stage transistors become more negative. The p-n-p quiescent current increases, and the n-p-n quiescent current diminishes, resulting in unbalanced battery drain, and direct current flow through the speaker. A second important effect of ambient temperature change occurs in the output transistors. While the quiescent voltage developed between the output stage bases does not change significantly with temperature change, the corresponding threshold currents change rather rapidly, as pointed out in *LB-979*. This results in the appearance of cross-over distortion at low ambient temperatures, and in increased battery drain at high temperatures. The substitution of a suitable thermistor-resistor combination for the 36-ohm threshold-bias resistor essentially eliminates this second effect by developing a threshold-bias voltage which exhibits the proper variation with ambient temperature. An example of thermistor compensation is shown for a subsequent circuit.

Signal current, after amplification by the driver stage, is shared by the bases of the output stage and the collector-return resistance (coupling resistance) of the driver, while the collector-return resistance alone carries essentially all the static driver current. Hence, the dynamic impedance at the driver collector is smaller than the static resistance; this means that a 7.5 ma peak signal swing produces a voltage swing at this point which is necessarily smaller than 3 v peak. Maximum output is limited by the onset of clipping, which occurs due to current limitation in the driver. In the amplifier illustrated, a 1.8 v maximum peak signal is developed at the driver collector, about 4.5 ma peak flowing in the coupling resistance, and about 3 ma peak into the output bases. The corresponding peak base-to-emitter voltage is about 0.45 v and peak emitter current is about 110 ma, producing 75 mw maximum in a 12 ohm load. The voltage at the driver collector for peak maximum collector current is about -1.2 v. This margin is exploited by the driver stage bias arrangement, which requires that the driver emitter be somewhat negative with respect to ground.

The common-collector connection is degenerative since signal voltage developed across the load diverts driver signal current into the coupling resistance. Increased negative feedback for the same load may be obtained by reducing the coupling resistance. However, since appreciable signal voltage appears from base-to-emitter of the

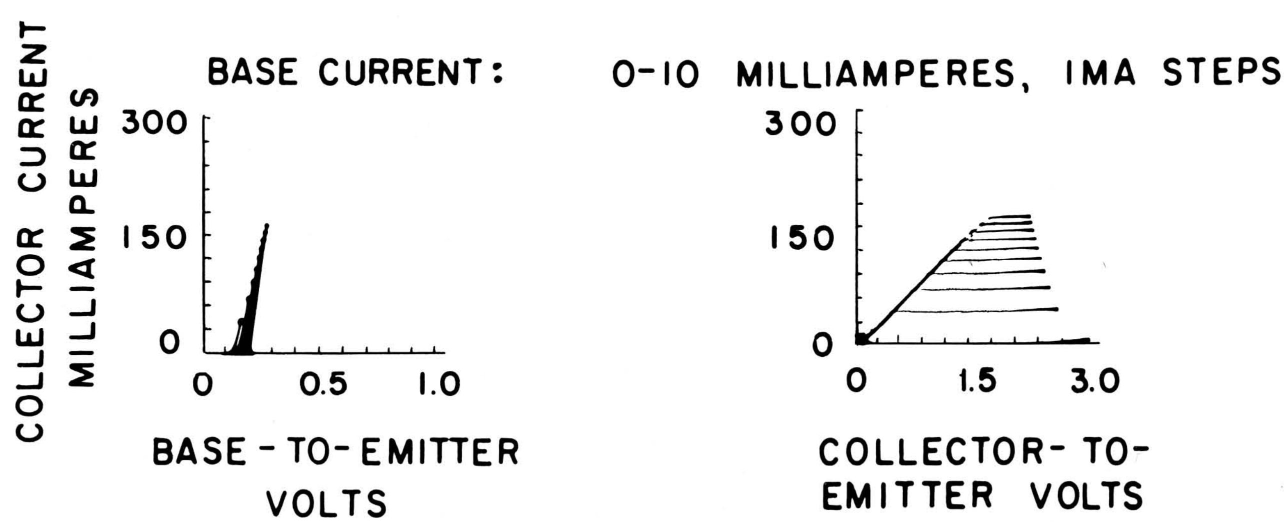
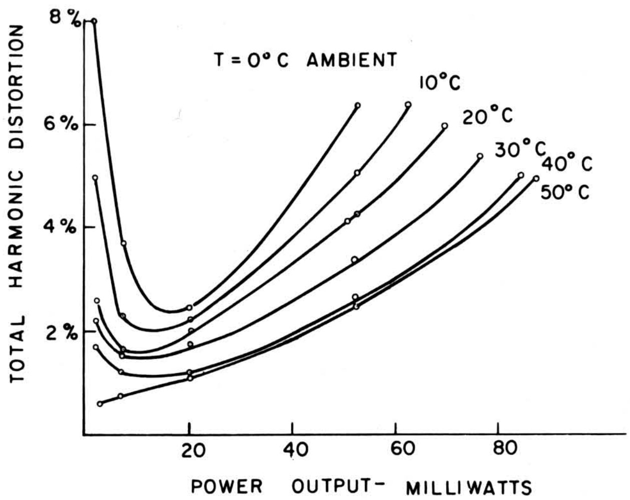


Fig. 4. Transistor characteristic curves for a transistor exhibiting high "series collector resistance".



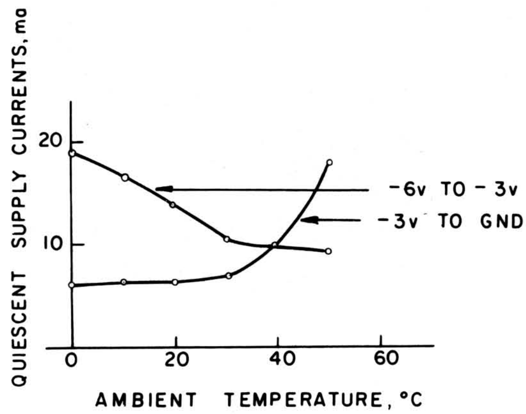


Fig. 5. Common-collector amplifier performance as a function of ambient temperature.

output transistors, it may be shown that the stage gain decreases more rapidly than the negative feedback increases. For instance, the negative feedback, for the circuit values shown, is 5.2 db; increasing the feedback to 8.2 db would require reducing the coupling resistance to 137 ohms with a resultant gain reduction of 6.7 db, and an increase is quiescent driver current to about 22 ma. The negative feedback may be increased much more efficiently by introducing current feedback from the load to the base of the driver. No increase in driver current is required, and the gain reduction is essentially equal to the increase in negative feedback. Capacitive current feedback, which is employed to control the high-frequency response of this amplifier, ameliorates any residual crossover distortion. Low frequency response is controlled by the magnitude of the driver emitter-bypass capacitor.

Increasing the magnitude of the coupling resistance would increase the gain, reduce the negative feedback and the driver quiescent current, but also reduce the maximum power output capability, since the peak driver current, and hence, the peak voltage applied at the output bases necessarily would be smaller. For instance, increasing the coupling resistance to 780 ohms increases the output stage gain by 3 db and requires a reduction in driver current to about 3.8 ma, but reduces the negative feedback to 3.4 db and the maximum power output capability to 40 mw.

The performance data of the circuit of Fig. 3 over the ambient temperature range 0 degrees C – 50 degrees C is illustrated in Fig. 5. The data shown applies for output transistors that are fairly well matched. Considerable unbalance can be tolerated, especially if the unbalance is in the direction of increased current gain or transconductance. For example, if the "bogey" n-p-n is replaced by one which exhibits twice the large signal current gain, the theoretical total harmonic distortion introduced from the mismatch alone is something less than 7 per cent, mostly second harmonic. In practice, less than the theoretical distortion is introduced, due largely to the smooth current transition provided by the threshold bias. Asymmetrical clipping reduces the maximum power out to about 60 mw, and an unbalance current of about 12 ma d.c. flows through the speaker at maximum power out.

The substitution of an output transistor of higher or lower large-signal transconductance increases or decreases, respectively, the output signal level required for clipping in the substituted transistor. In addition, an increase in transconductance acts like an increase in current gain, in that the stage current gain increases somewhat. In this circuit, collector bottoming does not normally occur, so unbalance in this parameter is of no significance. In extreme cases, however, such as that for the transistor for Fig. 4, collector bottoming limits the maximum output signal.

Emitter Loaded

An amplifier employing an emitter-loaded output stage and a single-ended class A driver stage is illustrated in Fig. 6. The configuration of this circuit is similar to that of the common-collector circuit, with the following distinctions: the driver stage bias is stabilized by *d-c* feedback from the output stage, the voice-coil is capacitively coupled to the output stage and returned to -6 v rather than to a centertap, and the driver coupling-resistance is returned to the "high" side of the voice-coil. This circuit offers some advantages over the common-collector amplifier: the output peak-to-peak voltage may approach the *d-c* supply voltage without a concomitant large decrease in gain and increase in driver current, negative feedback and gain may be traded equally, the *d-c* supply is not centertapped, thus there is no problem of unbalanced battery drain and no appreciable direct current flows in the speaker. At the same time, some signal voltage is developed across the load-coupling capacitor, reducing the output efficiency and limiting the low-frequency response. (The series resistance as well as the capacitive reactance of this capacitor must be low compared to the voice coil impedance, and the manufacturer's r.m.s. cur-

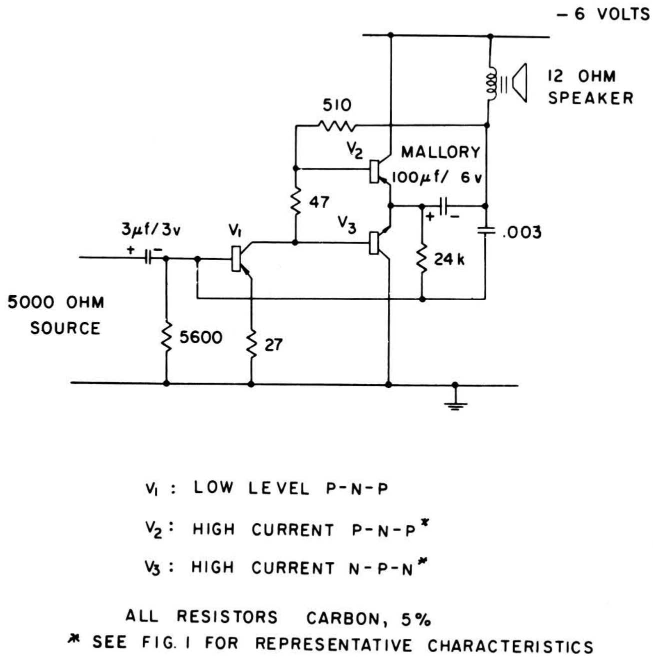


Fig. 6. Amplifier employing emitter-loaded output stage.

rent limit must be observed.) The amplifier illustrated provides a nominal 130 mw maximum output into a 12-ohm speaker for a 100 microampere rms input, operating from a -6 v supply.

The driver stage is biased at 5 ma, and provides threshold bias for the output stage in the same manner as in the previously discussed amplifier. However, since the speaker is capacitively coupled to the paralleled emitters,

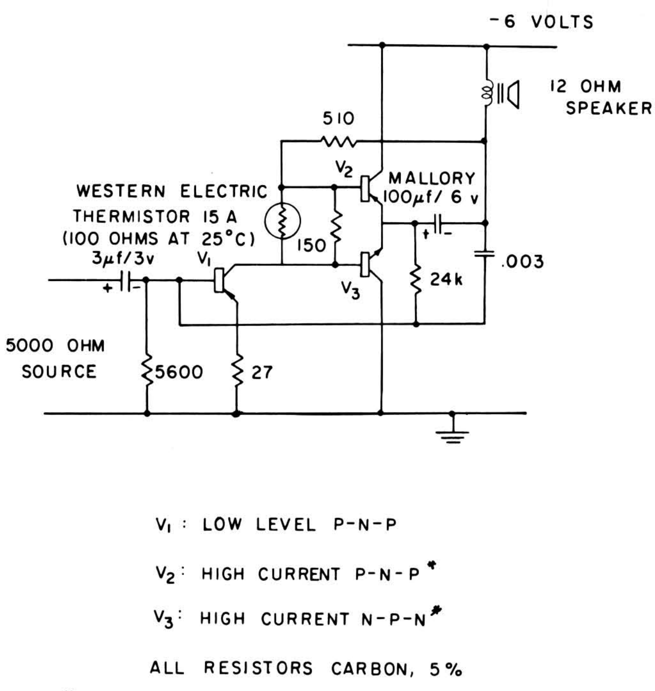


Fig. 7. Temperature-compensated emitter-loaded amplifier.

a shift in driver current produces no unbalanced output current, but only a change in the quiescent voltage at the emitters, with a corresponding asymmetry in clipping and reduction in maximum power output capability. The total quiescent current drain of the amplifier is slightly more than 7 ma.

The driver bias is stabilized by *d-c* feedback from the paralleled output emitters to the driver base and by the

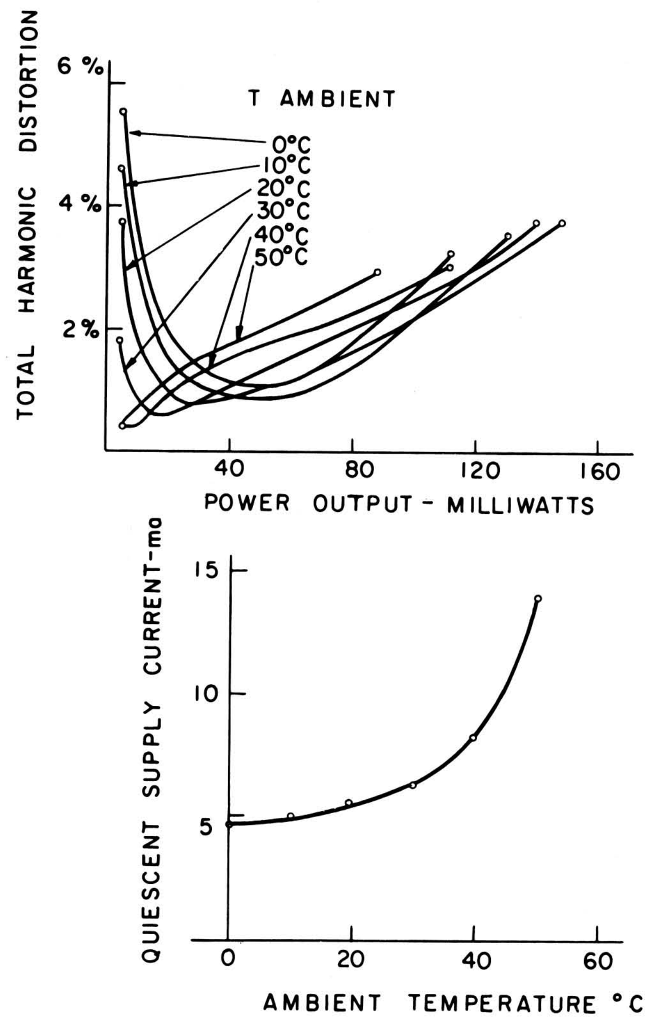


Fig. 8. Emitter-loaded amplifier performance as a function of ambient temperature. (circuit of Fig. 6)

emitter-return resistor. These function in essentially the same manner as collector-to-base stabilization, as discussed in *LB-979*. The variation of threshold current with ambient temperature for this amplifier does not differ appreciably from the previously discussed circuit. The emitter-loaded amplifier may be modified for greater temperature stability by the incorporation of thermistor compensation in the output stage, as illustrated in Fig. 7.

Operating principles of the circuits, with or without thermistor compensation, are essentially identical with respect to signal. Signal current, after amplification by the driver stage, is shared by the bases of the output stage and the coupling resistance. Since the coupling resistance is returned to the *high* side of the load, the emitter-loaded connection is not degenerative; only the sum of the signal voltage from base-to-emitter and the signal voltage developed across the load-coupling capacitor need be developed across the coupling resistance. The signal voltage at the driver collector is the sum of the above voltages and the

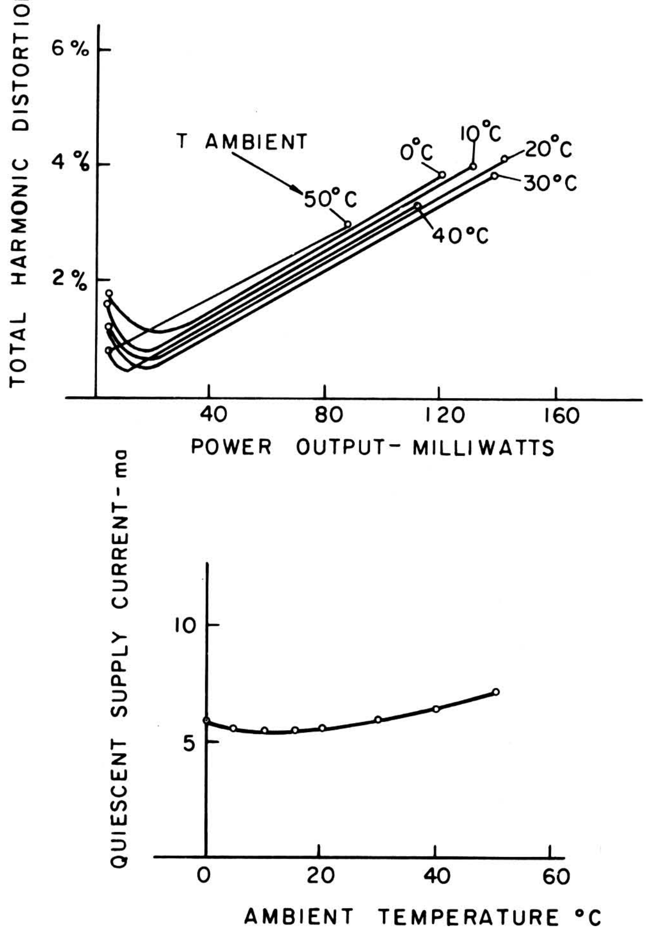


Fig. 9. Temperature-compensated emitter-loaded amplifier performance (circuit of Fig. 7).

output voltage. The magnitude of the dynamic impedance at the driver collector actually somewhat exceeds the coupling resistance; for this condition the coupling resistance is made slightly lower than the product of the output-transistor current gain and the load impedance. Clipping occurs, then, due to collector bottoming in the driver stage on positive signal peaks, and due to collector bottoming of the p-n-p output transistor on negative signal peaks. The peak-to-peak voltage at the driver collector is approximately equal to the *d-c* supply voltage; the output voltage is smaller than the supply voltage by the sum of the base-to-emitter voltages and the signal developed across the load-coupling capacitor.

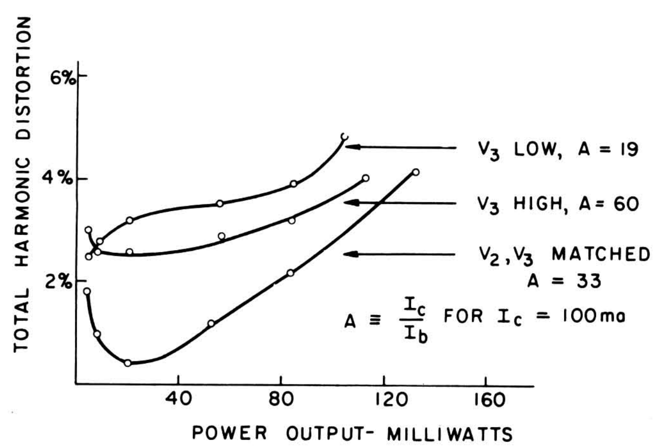


Fig. 10. Emitter-loaded amplifier performance at 25°C for unbalanced output transistor current gains.

The feedback resistor from the output emitters to the driver base introduces negative feedback for signal (in this case, 6 db) as well as for *d.c.* An R-C network may be employed here if less signal feedback than d-c feedback should be required. High-frequency response is controlled by capacitive-current feedback.

The consequences of unbalanced current gain in the output transistors in this circuit are essentially the same as in the previous circuit, except that large signal unbalance can produce no *d-c* shift in the load. At the same time, the driver *d-c* feedback brings about a shift in the driver operating bias which tends to "recenter" the signal, minimizing asymmetrical clipping.

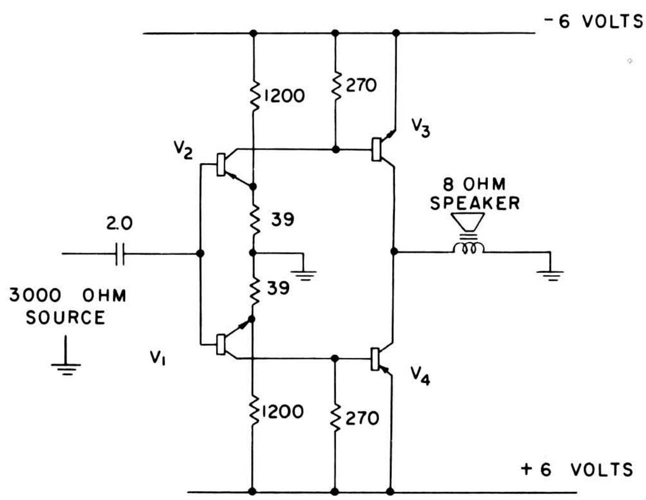
The situation with respect to unbalance in transconductance does not differ from that in the common-collector circuit, but collector bottoming becomes significant for the emitter-loaded circuit, since the peak-to-peak signal voltage is more nearly equal to the supply voltage.

The performance of the circuits of Figs. 6 and 7 over the ambient temperature range 0 degrees C – 50 degrees C is illustrated in Figs. 8 and 9. Performance of the unmodified circuit at 25 degrees C with current gain unbalance in the output stage is illustrated in Fig. 10.

An audio amplifier employing an emitter-loaded complementary symmetry output stage which is direct-coupled to the speaker is described in *LB-957, A Developmental Pocket-Size Broadcast Receiver Employing Transistors.*

Common Emitter

The cascaded common-emitter circuit is employed in the amplifier shown in Fig. 11. In this circuit, both driver and output stages operate push-pull, and direct coupling is used throughout. This amplifier, which might find application in a portable phonograph or table model radio, provides a nominal 2.0 watts maximum output into an



V1 : LOW LEVEL N-P-N

V2 : LOW LEVEL P-N-P

V3 : MEDIUM POWER N-P-N

V4 : MEDIUM POWER P-N-P

ALL RESISTORS 1/2 W CARBON, 5%

Fig. 11. Cascade common-emitter amplifier.

8 ohm speaker for 1.5 ma rms input, operating from a 12-volt centertapped supply.

The sum of the threshold currents of the driver-stage transistors is stabilized by the emitter-return resistor networks in a manner analogous to "constant-emitter-current bias," i.e., sufficient emitter current flows out of the junction of the 39-ohm and 1200-ohm resistors so that only the sum of the base-to-emitter voltages of the two driver stage transistors is developed across the 39-ohm resistors. The ratio of the n-p-n to p-n-p emitter currents is equal to the ratio of the respective current gains, since the static base current that flows out of the p-n-p flows into the n-p-n. The sensitivity of this bias arrangement to the increase in base-saturation current that occurs at elevated temperatures depends upon the similarity of the n-p-n and p-n-p units with respect to saturation current, any difference in saturation current of the two units producing an unbalance in the two emitter currents. The driver stage collectors are direct-coupled to the output stage bases, and returned via 270-ohm resistors to the respective output-stage emitters.

Driver stage collector current, about 2 ma at 25 degrees C., develops threshold bias for the output stage transistors, biasing them to about 12 ma emitter current at 25 degrees C. Due to the nonlinearity of the base voltage-current characteristic, these resistors do not materially shunt the output bases for large signals.

For output signals larger than a few milliwatts, each cascaded pair of transistors works essentially half the time. Any unbalance of signal peaks arises from differences in the product of the stage current gains for each pair. Since the n-p-n driver works into the p-n-p output transistor and vice versa, any systematic difference in current gain between p-n-p and n-p-n units tends to be balanced. The maximum output voltage obtainable is limited by collector bottoming. This amplifier will tolerate output transistors which exhibit relatively low large-signal transconductance, since this parameter does not here affect the maximum output power, and since the coupling resistors can be adjusted so that no significant reduction in output stage current gain is incurred.

The performance of this amplifier over the ambient temperature range 0 degrees C to 50 degrees C is illustraded in Fig. 12. Negative feedback is not incorporated in this amplifier, so the performance characteristics represent the maximum gain, maximum distortion mode of operation. Low-frequency response is limited only by the input-coupling capacitor, and high-frequency response by the transistors. The response is down 1 db at 20 cps, 3 db at 10 kc. Feedback, applied, for example, by connecting suitable admittances from the output to each of the input stage emitters, could be expected to effect an exchange of gain for improved distortion performance. Additional

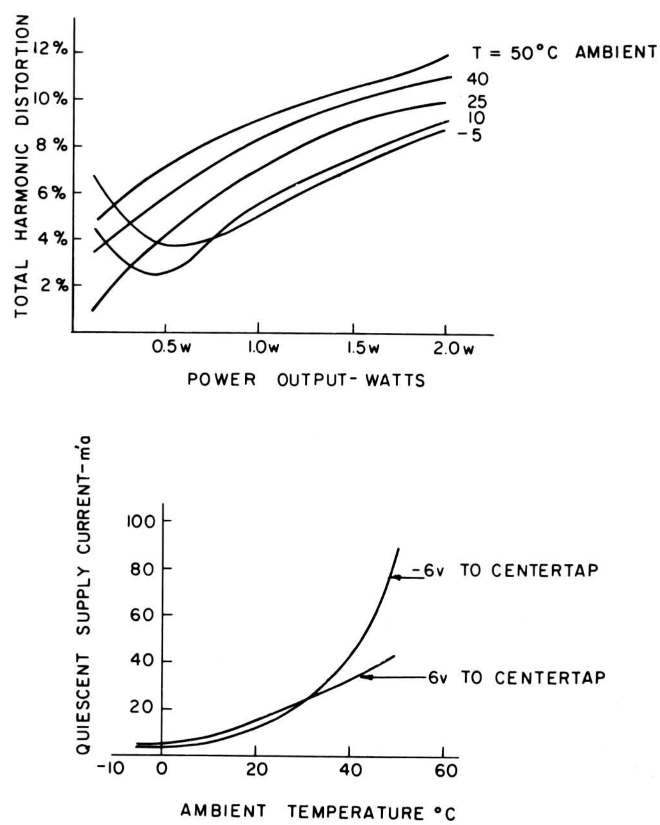


Fig. 12. Cascade common-emitter amplifier performance as a function of ambient temperature.

stabilization of the *d-c* operating point can be obtained at the same time, by providing a *d-c* path to ground for the paralleled input stage bases. An amplifier of this type employing 100 per cent voltage feedback is described in *LB-906 Symmetrical Properties of Transistors and Their Applications.*

Generalizations and Conclusions

Among the performance criteria by which an audio amplifier might be judged are gain, linearity, output power capability, stability with respect to ambient temperature changes, and tolerance of variation in transistor parameters. By means of negative feedback, gain and linearity can usually be traded. Achieving greater temperature stability, on the other hand, can require that some fraction of the *d-c* supply voltage be sacrificed for bias purposes, with a resultant reduction in output power capability and gain. The degree of variation in transistor parameters for which the transistors can be said to be interchangeable in the foregoing circuits can generally be increased by the application of increased signal and *d-c* feedback. On the other hand, the circuits may be revised for increased gain if a wide range in transistor parameters need not be tolerated (for example, it may be possible to eliminate signal feedback). The output power capability of the amplifiers described depends fundamentally on the speaker impedance and the supply voltage, the upper limit on maximum output power being $[(V_{supply})^2/8]$ x (load resistance), that is, for the peak-to-peak signal across the voice coil equal to the supply voltage. The nominal voice-coil impedances of small speakers fall into the 10 to 16 ohm range (No. 40 wire for the voice coil); fabrication becomes increasingly difficult at higher impedances where finer wire for the voice coil must be employed. Larger speakers offer greater latitude in this respect. Thus, for small speakers, power-output requirements usually dictate the supply voltage employed, and emphasis is placed on the output transistors as low-impedance, low-voltage devices.

Comparison of the complementary-symmetry amplifiers with transformer-coupled push-pull amplifiers reveal certain basic differences, the most prominent difference being the elimination, in the complementary-symmetry amplifier, of the interstage and output transformers. This becomes particularly significant where minimum size and weight, or a wide frequency response is important. (An intermediate arrangement, permitting the elimination of the output transformer, but not the interstage, is described in *LB-1012, A 20-Watt Transistor Audio Amplifier.)*

Basic differences that affect performance exist in both the output and driver stages. The maximum peak-to-peak signal between collector and emitter of either complementary-symmetry output transistor is necessarily somewhat smaller than the supply voltage; in the transformer-coupled output stage, the peak-to-peak collector-to-emitter voltage is more nearly twice the supply voltage. For the same supply voltage, then, and the same output power, the peak collector currents in the complementary-symmetry stage must be more than twice those in the transformer-coupled stage. This difference is slightly offset by the larger insertion loss of the output transformer, compared to the loss for the capacitively- or direct-coupled complementary-symmetry circuits. As a consequence, there is more nearly a two-to-one ratio in collector currents required for the same load power. Due to the curvature of the transistor current-gain characteristic, the distortion (for no inverse feedback) for the complementary-symmetry output stage may be somewhat greater than for the transformer-coupled amplifier, and the required peak currents into the output stage bases are more than twice as large.

The current gain of the driver-stage-and-interstage-transformer is larger than the current gain of the complementary-symmetry driver stage by a factor equal to the turns ratio of the interstage transformer. The gain of the complementary-symmetry amplifier, then, from driver-base to speaker is lower than the gain of the transformer-coupled amplifier (for the same supply voltage and output performance) on three counts: (1) the 2:1 difference in output stage peak base currents, (2) the current gain of the interstage transformer, and (3) the likely application of somewhat more negative feedback in the complementary-symmetry amplifier to insure the same output performance. This difference in gain might be on the order of −18 to −24 db. An important additional consideration arises upon the incorporation of the amplifier into a receiver. The input presumably would be driven from a detector; the detected audio levels being on the order of a few microwatts and a few hundredths of a microwatt, for standard output, for the complementary-symmetry and transformer-coupled amplifiers respectively. This difference in level should materially affect detector performance. For example, a detector of the general type described in *LB-957, A Developmental Pocket-Size Broadcast Receiver Employing Transistors,* adjusted at each level to provide the same distortion, affords a conversion gain approximately proportional to the input power level. The difference in receiver gain effected by the two amplifiers, then, is more nearly −9 to −12 db.

There is little fundamental difference in the bias requirements for the two amplifiers. In each case, the output stage requires threshold bias, which can be temperature-compensated as required by the application. The driver stages in the complementary-symmetry amplifiers discussed are direct-coupled to the output stages. The operating-current stability required for these driver stages, therefore, is typically more stringent than that required for a transformer-coupled stage; the required stability being achieved by d-c feedback.

Complementary-symmetry, then, affords the radio receiver designer the option of eliminating two audio transformers if he can accommodate this 9 to 12 db gain reduction.

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