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LB-1072

CIRCUIT CONSIDERATIONS FOR AUDIO-OUTPUT STAGES USING POWER TRANSISTORS

RADIO CORPORATION OF AMERICA
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Approved

Stuart Wm Seeley

Circuit Considerations for Audio-Output Stages Using Power Transistors

Recent advances in the semiconductor field have resulted in the commercial availability of transistors designed specifically to handle large amounts of power. These "power transistors" are capable of dissipating up to several watts and are particularly suitable for use in audio-frequency power amplifiers. This bulletin presents circuit-design considerations for the application of p-n-p alloy-junction power transistors to audio-frequency power output-stages. Both class A single-ended and class B push-pull circuits are discussed. The effects of the source and load impedances on distortion are also discussed. Methods of obtaining a desired degree of bias stability with temperature variations are outlined. Although a specific application is described, sufficient general remarks are made which are applicable to a wide variety of transistor power amplifiers.

RCA Power Transistors

The new RCA germanium p-n-p alloy-junction transistors 2N301 and 2N301-A, shown in Fig. 1, are designed specifically for use in class A and class B audio-output stages in automobile broadcast-band receivers and other medium-to-high-power applications. These transistors are characterized by low thermal resistance and extremely low leakage currents. The low thermal resistance, i.e., high heat-transfer efficiency from the transistor's collector junction to the external case, is achieved by direct connection of the collector junction to the external mounting flange.

Choice of Mode of Operation for Power Amplifiers

The choice of the mode of operation (i.e., class A or class B push-pull) depends upon several factors, including the amount of power output and power efficiency required. In the design of power amplifiers, the object is to obtain as much power output as possible with a minimum amount of distortion. When moderate amounts of power output are required, a single power transistor can be used in a class A circuit. In class A transistor power amplifiers, the output is developed under such conditions that collector current flows continuously throughout the cycle. Because maximum power is dissipated in the transistor at zero-input-signal condition, the maximum possible output power is one-half the maximum rated dc power dissipation, P_{max} (dc).

When considerably more power output and power efficiency are required, class B operation is used. In the class B amplifier, the transistors are biased approximately at cutoff so that amplification occurs over only one-half cycle of applied input-signal waveform. The class B push-pull amplifier is characterized by high collector-circuit efficiency and relatively high output power in proportion to the average dissipation in the transistors. During periods of zero signal, the power-supply drain and collector dissipation are very low. The maximum possible power output is equal to $N_p/(1-N_p) \times P_{max}$ (dc) where N_p is the output-circuit efficiency.

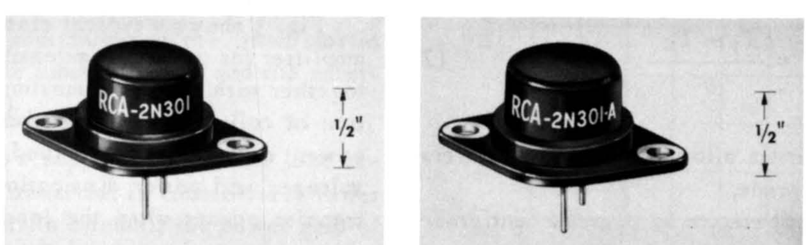

Fig. 1 – Photograph of RCA germanium p-n-p alloy-junction power transistors 2N301 and 2N301-A.

Power-Dissipation Considerations

In the design of audio power amplifiers, the most important characteristic to be considered is the power-dissipation capability of the transistor. The maximum power that can be dissipated before "thermal runaway" occurs depends on a number of factors, of which the most important is the ability to remove the heat generated within the transistor. When heat is removed by conduction, this ability is measured by the thermal resistance, i.e., the internal temperature rise per unit of power dissipation. The lower this thermal resistance, the greater the power-handling capability. Other factors which determine the maximum power-dissipation capability are the collector-voltage rating, reverse collector saturation current, circuit stability factor, and maximum ambient temperature. The maximum permissible dissipation, P_{max}, of a germanium transistor is given by:[1,2]

$$P_{max} = \frac{12.5}{\theta} \times \ln \frac{12.5}{\theta s_f V_{ce} I_{cs}} - \frac{(T_a - T_{25})}{\theta} \quad (1)$$

where θ is the total thermal resistance of the transistor and chassis in degrees centigrade per watt,
V_{ce} is the collector-to-emitter voltage in volts,
I_{cs} is the reverse collector saturation current at 25 degrees C,
s_f is the circuit stability factor, and
T_a is the maximum operating ambient temperature in degrees centigrade.

The value P_{max} obtained from Eq. (1) is the maximum theoretical power that can be dissipated before thermal runaway occurs. In circuits having low values of $s_f V_{ce}$, this value may be greater than the power which can be obtained in practical circuits. The actual power dissipation possible in a practical circuit design is also limited by the maximum safe collector-junction temperature at which the power transistor can be operated without appreciable alteration in its electrical characteristics or a decrease in its life expectancy. For most germanium transistors this temperature limit is below 100 degrees C. The maximum power-dissipation capability can be expressed in terms of the allowable junction temperature as follows:[3]

$$P_{max} = \frac{T_j - T_a}{\theta} \quad (2)$$

where T_j is the maximum allowable junction temperature in degrees centigrade,
T_a is the ambient temperature in degrees centigrade, and
θ is the total thermal resistance of chassis and transistor in degrees centigrade per watt.

The two equations for P_{max} can be used together to obtain power-rating curves for a given transistor provided the following conditions are imposed.

(1) When the allowable power dissipation obtained from Eq. (1) is greater than that calculated from Eq. (2), the maximum allowable collector-junction temperature rise is the limiting condition for dissipation.

(2) If the allowable power dissipation calculated from Eq. (1) is less than that found by Eq. (2), then thermal runaway is the limiting factor.

Fig. 2 shows a set of maximum power-dissipation curves for the 2N301 or 2N301-A power transistor. The horizontal lines represent the maximum power dissipation for various ambient temperature when the limiting factor is maximum collector-junction temperature rise. The sloping portion of the curves represents the maximum power dissipation before runaway occurs. The maximum power dissipation can be obtained for any value of $s_f V_{ce}$. These curves are extremely useful in the design of class A power amplifier in which stabilization is effected by the use of linear dc feedback methods.

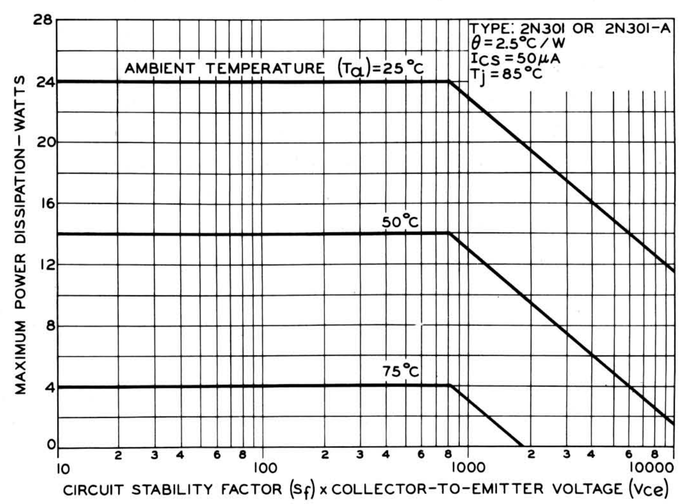

Fig. 2 – Maximum power-dissipation curves for power transistor 2N301 or 2N301-A for three different ambient temperatures.

Circuit Considerations for Class A Power Amplifiers

Fig. 3 shows a typical class A audio-frequency power amplifier for use in an automobile receiver output stage, together with curves of maximum power output as a function of collector load impedance. Although the maximum power output is determined by the collector-current, voltage, and power dissipation ratings, maximum power transfer occurs when the load impedance is matched to the output resistance of the transistor. For the supply voltages shown, however, the load impedance must be kept low if large amounts of power output are to be ob-

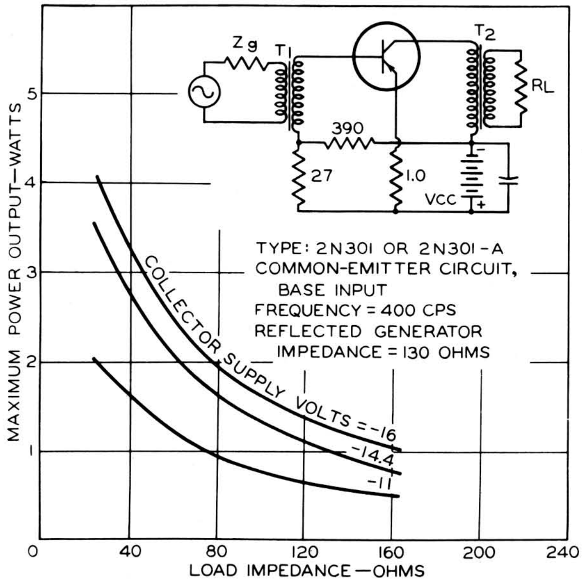

Fig. 3 – Typical class A audio-frequency power amplifier using 2N301 or 2N301-A, together with curves of maximum power output as a function of collector load impedance.

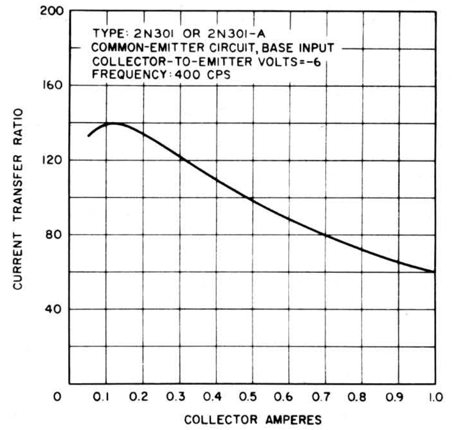

Fig. 4 – Current transfer ratio of 2N301 or 2N301-A power transistor as a function of dc collector current.

tained. Consequently, the possibility of impedance matching for maximum power transfer is eliminated, and distortion becomes the limiting and determining factor in the selection of the desirable output load value. The selection of maximum allowable percentage distortion is arbitrary, depending on subjective factors, In the case of output stages for automobile receivers, a maximum value of 10 percent total harmonic distortion is usually acceptable. The curves shown in Fig. 2 represent a total harmonic distortion of 10 percent. As the load impedance is increased, there is an appreciable reduction in power output.

The power gain of a junction-transistor class A amplifier is a function of input resistance, load impedance, and ac large-signal current transfer ratio, and can be expressed as follows for the common-emitter circuit:

$$\text{Power Gain} = \alpha_{cb}^2 \frac{R_L}{R_{IN}} \qquad (3)$$

where α_{cb} is the ac large-signal current transfer ratio, R_L is the collector load impedance in ohms, and R_{IN} is the ac input resistance of the transistor in ohms i.e., $r_{bb'}$ plus the product of α_{cb} and the external emitter resistance).

In operation with a low supply voltage, the load impedance presented to the transistor is considerably lower than its output resistance. As a result, the power gain of the transistor will be low unless the mismatch condition is minimized by use of the highest feasible value of load impedance.

At high values of emitter current, the resistance of the emitter junction is very low and the input resistance of the transistor is approximately equal to the resistance $r_{bb'}$. When an unbypassed external emitter resistor is used, the resultant input resistance of the transistor is approximately equal to $r_{bb'}$ plus the product of the current transfer ratio (α_{cb}) and the emitter resistor. If the resultant input resistance is greater than the load impedance, the power gain of the class A stage will again be low unless the transistor has a high current transfer ratio (α_{cb}). Fig. 4 shows the variation of α_{cb} with dc collector current. As the collector current increases, there is an appreciable reduction in α_{cb}. Fig. 5 shows the variation in power gain with collector load for one watt of power output. The power gain increases as the load impedance is increased. In general, the maximum power output is specified for a given circuit design and a compromise is made in power gain.

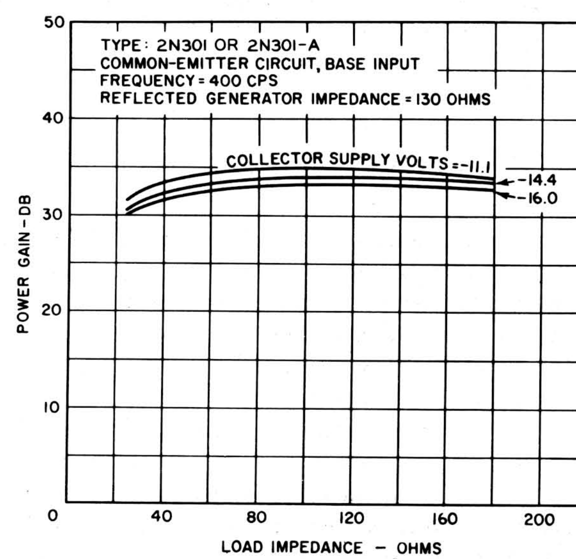

Fig. 5 – Power gain as a function of collector load impedance at a power output of one watt.

Efficiency of a Class A Power Amplifier

The efficiency of a class A transistor power amplifier is defined as the ratio of the power output that can be developed with only moderate distortion to the dc power supplied to the collector circuit. A class A power amplifier has a maximum theoretical efficiency of 50 percent. In practice, the over-all efficiency depends upon the efficiency of the output transformer and the amount of power lost in the bias network. The collector-circuit efficiency is greatest at full rated power output and decreases as the power output is reduced.

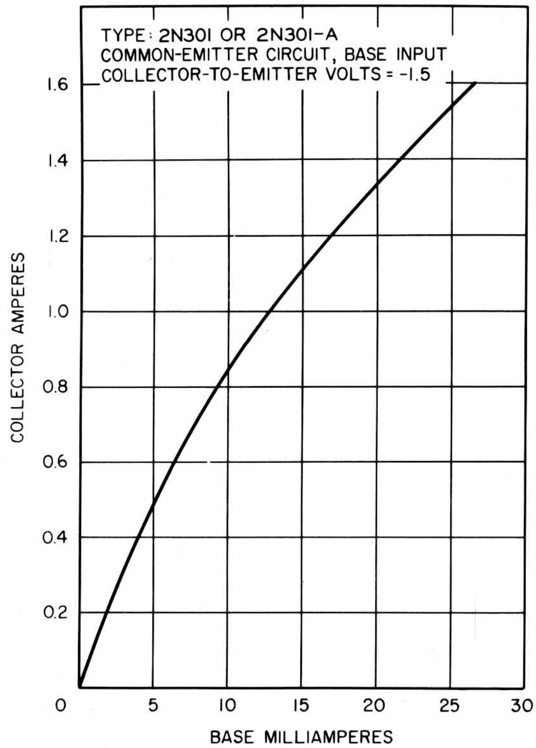

Fig. 6 – Base-to-collector transfer characteristic of a 2N301 or 2N301-A power transistors.

Distortion In Class A Power Amplifiers

Distortion in transistor class A amplifiers is primarily a function of supply voltage, power output, nonlinearity in transfer characteristics, and source impedance. Fig. 6 shows the base-to-collector current transfer characteristic for a 2N301 or 2N301-A power transistor. When the input (base) current is sinusoidal, the nonlinearity in the current transfer characteristic is small at low signal levels. The output current is fairly linear and low in harmonics. As the signal level increases, the input current traverses a greater portion of the nonlinear region of the transfer characteristic and the harmonic content of the output current increases considerably. Fig. 7 shows

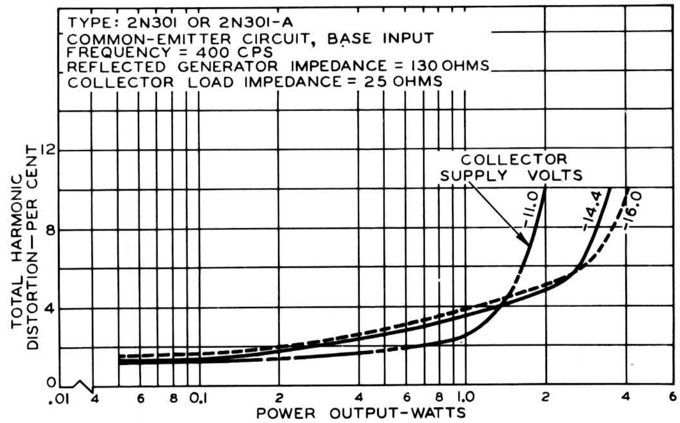

Fig. 7 – Total harmonic distortion in class A circuit as a function of power output for different supply voltages.

the total harmonic distortion as a function of power output for different supply voltages. The increase in distortion with increasing power output is due primarily to the nonlinearity in the base-to-collector current transfer characteristic. The rapid change in slope of the distortion curve at high power-output levels is due to "clipping" in the output circuit.

Effects Of Source Impedance On Distortion In Class A Power Amplifiers

The source impedance presented to the input of a class A power amplifier stage which uses an interstage transformer depends on the type of driving device used and the impedance transfer ratio of the driver transformer.[4] When the transferred driver output impedance is much less than the input resistance of the transistor, the class A stage is considered to be operated from a constant-voltage source. When the reflected driver output impedance is much greater than the input resistance of the transistor, the stage is considered to be operated from a constant-current source. Fig. 8 shows the variation in total harmonic distortion as a function of the ratio of reflected source impedance (Z_g) to the input resistance of the transistor. The total harmonic distortion increases appreciably as the ratio Z_g/R_{IN} is increased, partly because of the higher degree of nonlinearity in the current transfer characteristic. The lowest feasible value of source impedance should be used in a class A power amplifier to minimize distortion.

In some applications, it may be necessary to use negative feedback to reduce the total harmonic distortion. One method of obtaining degenerative feedback is by the insertion of resistance in the emitter lead. The amount of emitter resistance that can be used is normally limited by the power-gain requirements of the output stage.

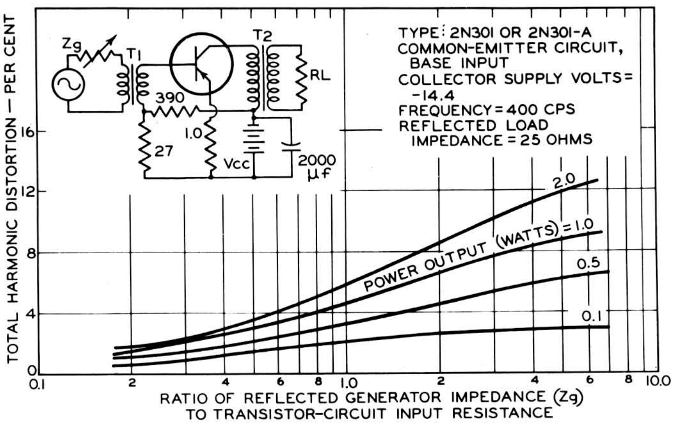

Fig. 8 – Total harmonic distortion as a function of the ratio of reflected source impedance to the input resistance of the transistor.

Temperature Considerations for a Class A Power Amplifier

The effects of temperature changes on transistor behavior are due primarily to changes in reverse collector current, I_{CO}, and the dc input conductance. These parameters are highly sensitive to temperature changes, and may cause a shift in operating point. In a class A circuit having low dc load resistance, such as a transformer-coupled stage, the collector voltage is relatively constant. The collector current in such a circuit will increase with temperature due to variations in I_{CO} and dc input conductance. The resulting increase in dissipation may cause operation beyond the maximum power ratings of the transistor. For satisfactory operation over a wide range of temperatures, some form of stabilization must be used.[5,6,7]

The transfer characteristic curves shown in Fig. 9 illustrate the effects of temperature upon the transistor in a stabilized common-emitter class A circuit. The operating point is designated by point A on the 25 degrees C curve. If this common-emitter circuit were operated with a constant base-to-emitter bias voltage, an increase in temperature would cause an appreciable increase in quiescent collector current and a consequent increase in power dissipation. In the circuit shown, however, the bias voltage is determined by the voltage drops across the emitter resistor, R_E and the parallel combination of R_1 and R_2. The voltage drop across the emitter resistor is essentially proportional to the collector current, and tends to stabilize the collector current by applying a reverse bias to the transistor. For a given value of emitter resistance, therefore, the stability of the operating point is largely dependent on the resistance of the parallel combination of R_1 and R_2. Decreasing the resistance of the parallel combination of R_1 and R_2 results in an increase in stabilization.

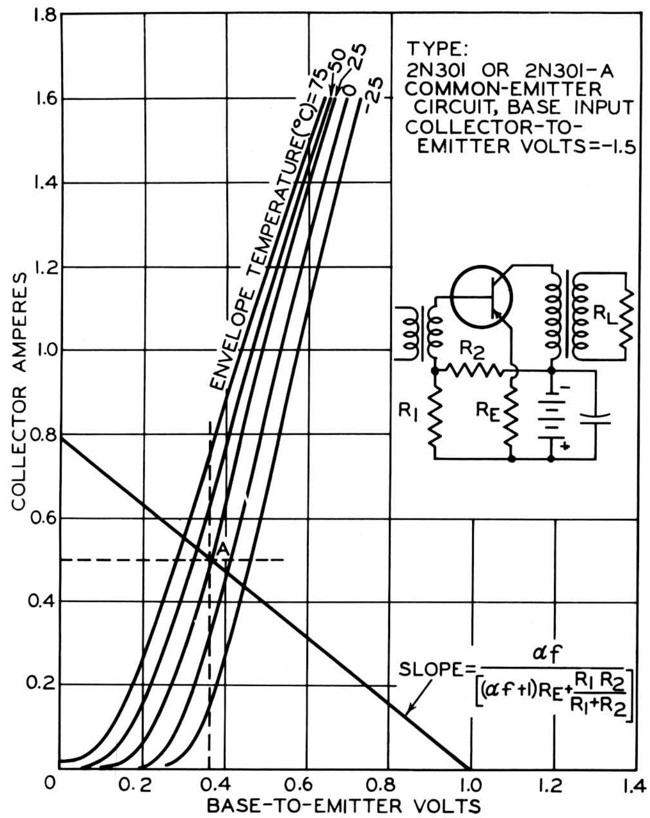

Fig. 9 – Curves showing effect of temperature on transistor performance in a stabilized common-emitter class A circuit.

Class B Push-Pull Power Amplifiers

Considerably more power output or power efficiency can be obtained from power transistors in class B operation than in class A operation. In a class B push-pull audio-frequency amplifier, the transistors are biased approximately to cutoff so that amplification occurs over only one-half cycle of the applied input-signal waveform. This type of amplifier is also characterized by high collector-circuit efficiency and relatively high power output in proportion to average dissipation in the transistors. During periods of zero signal, power-supply drain and collector dissipation are very low.

In the design of class B push-pull amplifiers, the following transistor characteristics are of importance to the circuit designer:[8,9]

(1) maximum collector dissipation,
(2) maximum peak collector current,
(3) maximum collector voltage,
(4) input characteristics, and
(5) base-to-collector current transfer characteristics.

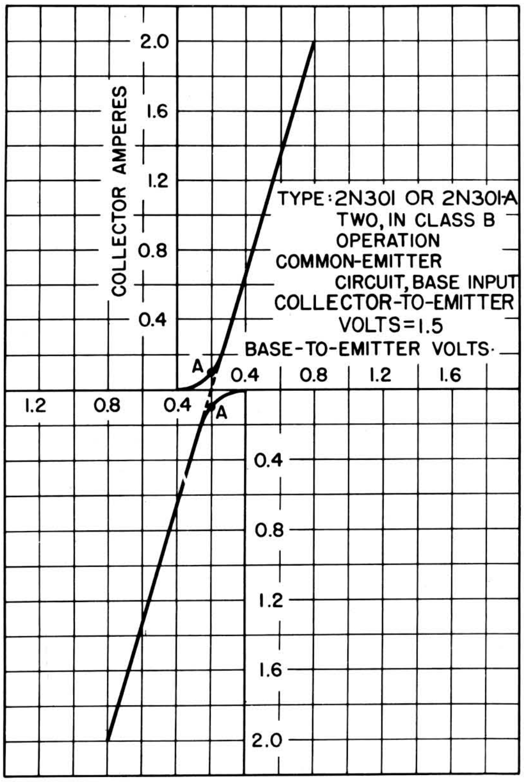

Fig. 10 – Composite transfer characteristic for two 2N301 or 2N301-A power transistors in class B operation.

Design Of Class B Power-Amplifier Stages

In most cases, the supply voltage, power output, power gain, and maximum distortion limits are specified for a particular application (e.g., the output stage of an automobile receiver). The first step in the design of the class B amplifier, therefore, is the choice of the zero-signal operating point for the transistors. Class B operation implies that the transistors are biased to cutoff so that the static operating collector current and collector dissipation are reduced to zero. It is impractical to use zero bias, however, because the nonlinearity in the small-signal region causes a high percentage of cross-over distortion, especially at low signal levels.

For a given transistor type, there is a particular value of base bias that results in a good balance between cross-over distortion and collector-circuit efficiency. Fig. 10 shows the composite transfer characteristic for two 2N301 or 2N301-A transistors in class B operation. As shown on the curve, a convenient method for determining the operating point is to project the main part of the transfer characteristic curve in a straight line to the cutoff point. The use of this projected cutoff bias appreciably reduces crossover distortion. The remaining distortion can then be reduced by the use of negative feedback.

Choice Of Load Impedance

For a given supply voltage, the factors which influence the choice of the load impedance are the maximum power-dissipation and peak-collector-current ratings. The optimum value of collector load impedance should be used to achieve high power gain and good output-circuit efficiency.

Fig. 11 shows a class B push-pull audio power-amplifier stage which uses two RCA-2N301 or 2N301-A p-n-p junction transistors in the base-input, common-emitter circuit configuration. This amplifier stage has high power gain and power efficiency. The transistors used in the circuit must have fairly well matched large-signal characteristics. The average input resistance is very low and is extremely nonlinear over the operating range. With a collector supply voltage of -14.4 volts, low values of load impedance must be used to produce appreciable power output. The minimum value of load impedance is determined by the maximum peak-collector-current ratings of the transistors.

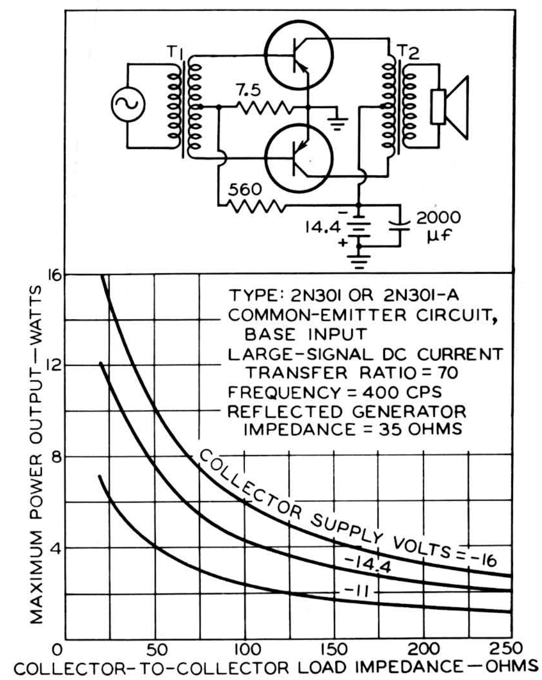

Fig. 11 – Class B push-pull audio-amplifier stage using 2N301 or 2N301-A power transistors, together with curves showing maximum power output as a function of collector-to-collector load impedance.

Fig. 11 also shows the maximum power output for various values of collector-to-collector load impedances. The maximum power output is essentially independent of all transistor characteristics except the peak-collector-current capabilities of the transistors. The power gain of junction-transistor class B amplifiers is a function of the input resistance, the load impedance, and the large-signal current transfer ratio. Fig. 12 shows the variation in

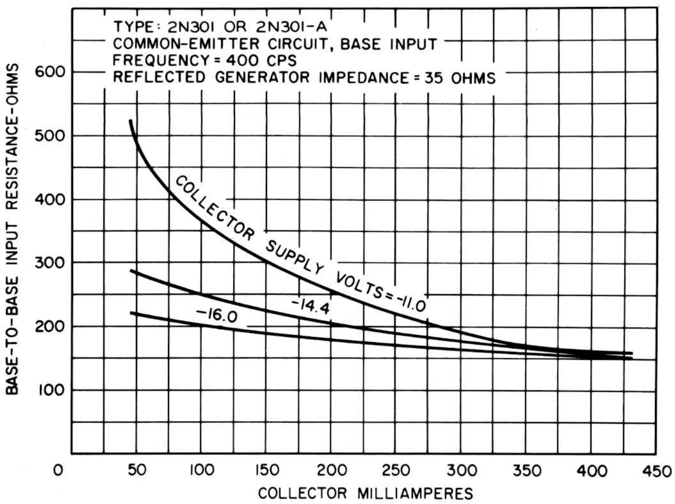

Fig. 12 – Base-to-base input resistance of class B circuit as a function of dc collector current.

base-to-base input resistance as a function of dc collector current. Although there is considerable variation in the input resistance, the power gain may not vary appreciably because the magnitude of the large-signal current transfer ratio increases at low values of collector current. This increase tends to offset to some extent the reduction in power gain which results from an increase in input resistance at low signal levels. The power gain of the common-emitter circuit depends to a large extent upon the load impedance and the large-signal amplification factors. As the load impedance is increased, the power gain increases, as shown in Fig. 13.

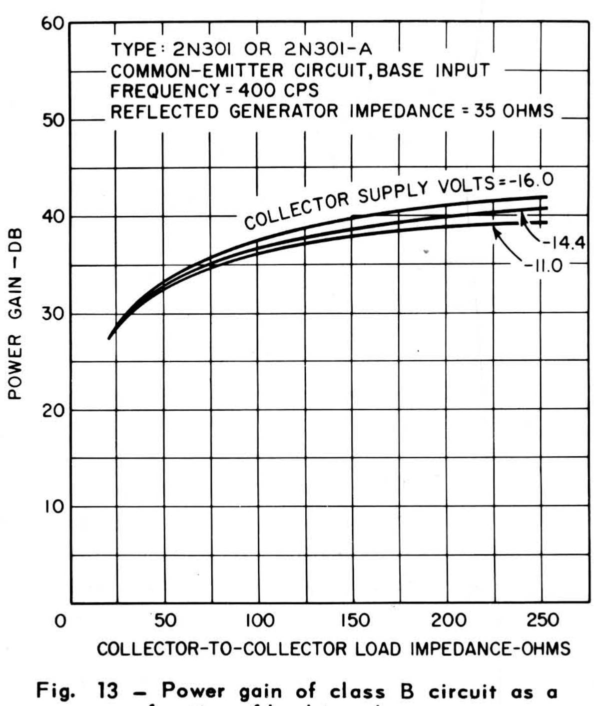

Fig. 13 – Power gain of class B circuit as a function of load impedance.

Efficiency Of A Class B Push-Pull Amplifier

The efficiency of a common-emitter class B circuit has a maximum theoretical value of 78 percent. In practice, the efficiency depends upon the quiescent value of collector current, the supply voltage, the efficiency of the output transformer, and the level of power output. The collector-circuit efficiency is greatest at full rated power output and decreases as the power output is reduced, as shown in Fig. 14. For constant values of power output, the efficiency decreases for decreasing values of load.

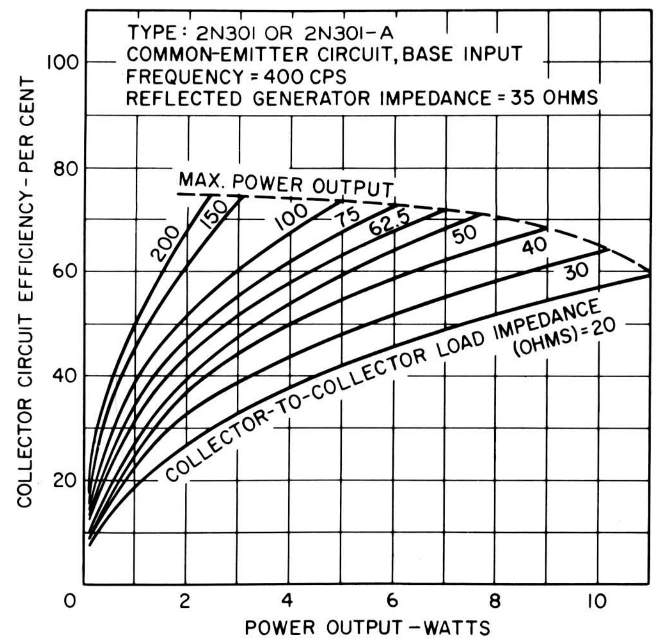

Fig. 14 – Collector-circuit efficiency of class B circuit as a function of power output.

Distortion In Class B Push-Pull Amplifiers

Distortion in transistor class B amplifiers is a function of the power output, the supply voltage, the driving source, the load impedance, and the large-signal current transfer ratio of the transistor. The effects of these factors are more severe in common-emitter circuits which employ no internal degeneration. Fig. 15 shows the variation of total harmonic distortion with power output. The low-power-level distortion depends primarily on the zero-signal operating point. If the bias point is not chosen properly, the distortion will increase considerably, as shown by the curve for a collector supply of -11 volts. The extent to which the distortion increases at high power levels depends on the degree of mismatch in the current transfer ratio of the transistor, the load impedance, and the collector supply voltage.

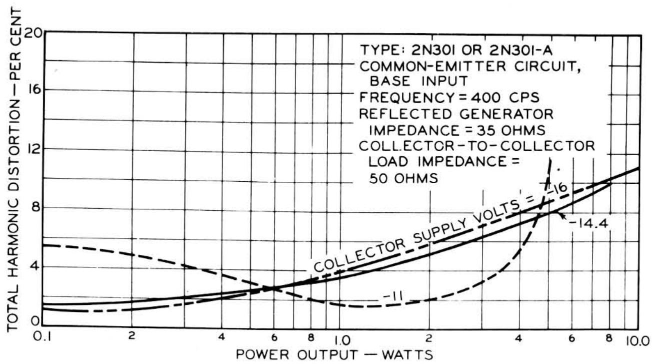

Fig. 15 – Total harmonic distortion of class B circuit as a function of power output.

Effects Of Source Impedance On Distortion In Class B Push-Pull Amplifiers

The source impedance presented to the input of the class B stage is determined by the type of driving device and the impedance transfer ratio of the driver transformer used. Fig. 16 shows the variation in total harmonic distortion as a function of the ratio of the reflected source impedance and input resistance of the transistor. As the source impedance is increased, the total harmonic distortion increases considerably. The effects of driving-source impedance on distortion in class B push-pull amplifiers is minimized by the use of a low value of reflected source impedance.

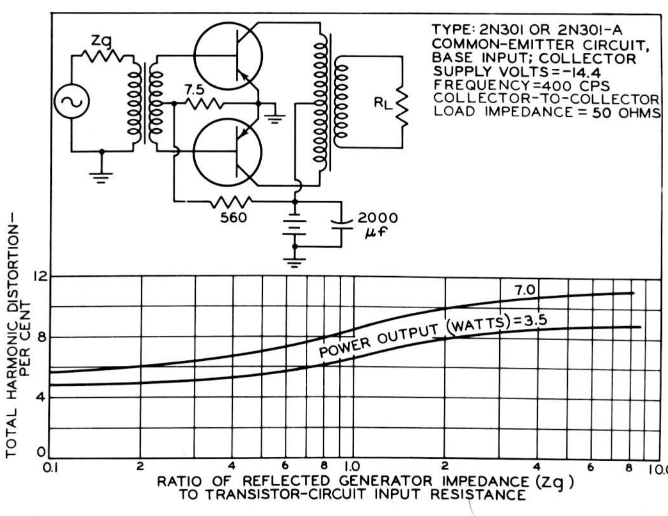

Fig. 16 – Total harmonic distortion as a function of the reflected source impedance and the input resistance of the transistor.

Effects Of Temperature On Zero Signal Operating Conditions

The transfer characteristic curves shown in Fig. 17 illustrate the effects of temperature upon transistors in the common-emitter class B circuit. The operating point is designated by point A on the 25 degrees C curve. If the common-emitter circuit is operated with a constant base-to-emitter bias voltage, an increase in temperature causes an appreciable increase in quiescent output current and a consequent decrease in the maximum power output and output-circuit efficiency. As the temperature decreases, the quiescent collector current decreases almost to zero. Although there is an increase in maximum power output and a slight increase in efficiency, the crossover distortion becomes appreciable at low signal levels because the transistor operates over the nonlinear portion of the transfer characteristics.

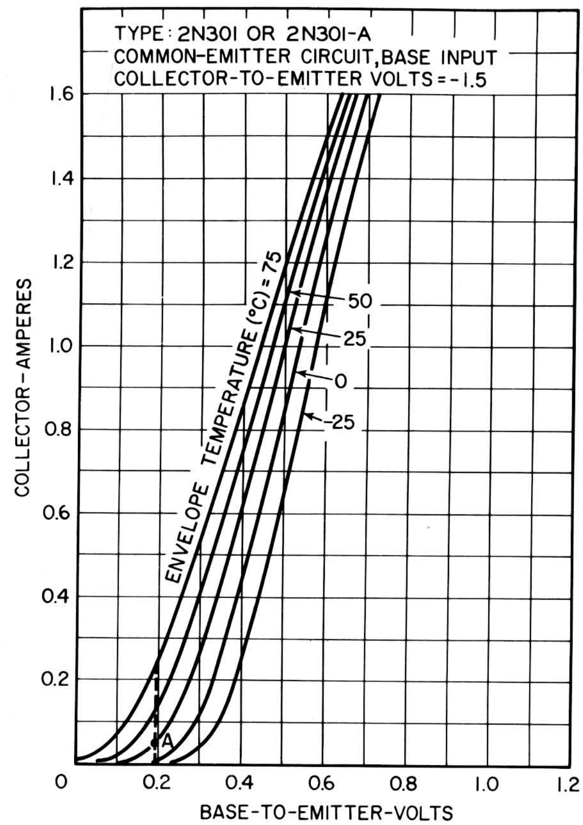

Fig. 17 – Curves showing effects of temperature on transistor performance in class B circuit.

Fig. 18 shows three practical methods of establishing the bias voltage for transistors in class B operation.[10] The resistive bias network of circuit A maintains a constant base-to-emitter voltage which does not vary with temperature changes. In this circuit, the quiescent collector current increases, with an increase in temperature as shown by curve A. For optimum performance from a class B power-amplifier circuit over a wide temperature

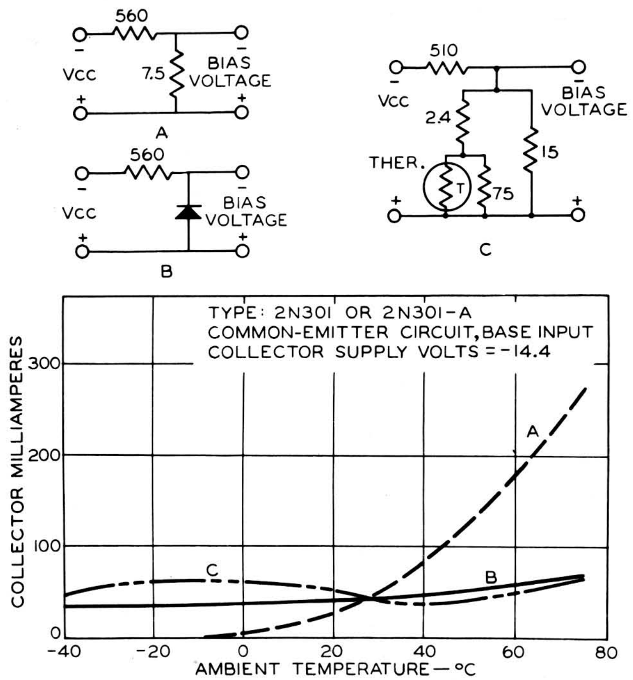

Fig. 18 – Three practical methods of establishing bias voltage for transistors in class B operation.

range, some means must be provided to adjust the base-to-emitter bias voltage so that the collector current will remain constant. A temperature-sensitive element may be used in the bias network so that the required change in bias voltage is obtained with changes in temperature.

Circuit B incorporates a germanium junction diode designed to provide the required change in bias voltage. This diode has a resistance-versus-temperature curve whose slope approximates that of the transistor input characteristic. Curve B shows the variation in collector current with temperature for a class B stage using the "compensating" diode in the bias network.

The bias network of circuit C uses a thermistor in conjunction with other resistive components.[11] The desired change in bias voltage is obtained when the resultant network resistance of the bias circuit provides a resistance-versus-temperature curve having a slope approximating that of the transistor input characteristic. The diode used in circuit B provides a higher degree of stability than the thermistor used in circuit C, and has good bias-voltage regulation for variations in collector supply voltage.

Frequency Response Of Transistor Power Amplifiers

The frequency response of class A and class B power amplifiers is determined primarily by the characteristics of the transformers and the transistors. The low-frequency response depends on the primary inductance of the transformer. The high-frequency response depends on the leakage reactance and winding capacitance of the transformers, and the frequency at which the current transfer ratio of the transistors drops to 0.707 times the 1000 cycle value. Because of the high currents and low supply voltages used, the dc resistance of the primary of the output transformer should be as low as possible to retain high efficiencies.

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