Use of the RCA-2N109 P-N-P Junction Transistor in Class B Audio Applications

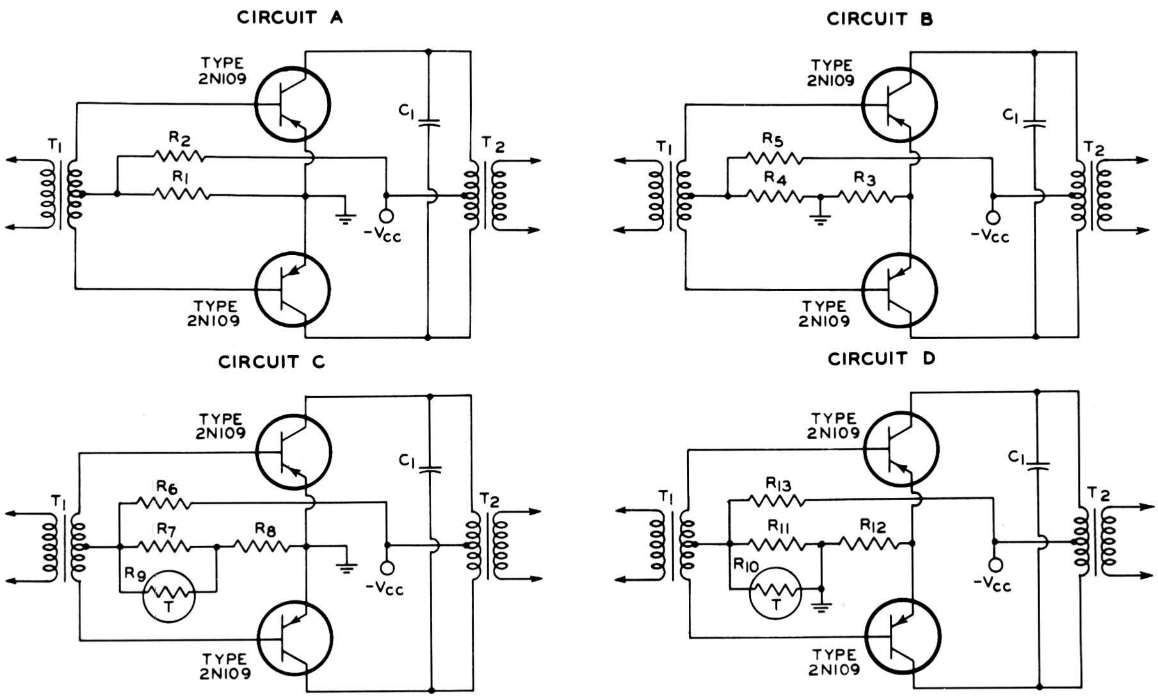
This Note describes the use of the RCA-2N109 p-n-p alloy-junction transistor in class B operation in the output stage of battery-powered portable radio receivers and other types of portable low-power audio amplifiers. This transistor features high audio gain, low distortion, uniform characteristics, and excellent life stability. Numerous combinations of the elements in four basic class B circuits utilizing the 2N109 are presented in tabular form, and circuit performance is evaluated for a range of supply voltages from 1.25 volts (average mercury-cell voltage throughout life) to 12 volts at power outputs from 20 to 300 milliwatts and a maximum total harmonic distortion of 10 per cent. The circuits shown provide stable operation at equipment ambient temperatures up to 50°C (122°F). In addition, they have low battery drains which contribute to high amplifier efficiency and long battery life.

CIRCUIT CONSIDERATIONS

The four basic class B circuits shown in Fig.1 use the common-emitter connection because it provides the highest power gain. A thermistor is included in the bias networks of circuits C and D to maintain essentially constant circuit performance with ambient-temperature variations. The use of thermistor compensation is also necessary to obtain stable operation at rated power-output levels in excess of 150 milliwatts. The same value thermistor is used in both basic circuits for purposes of standardization and for considerations of thermistor cost and availability.

In any practical class B circuit, either transistors or tubes must be biased at a zero-signal collector current or plate current on a fairly linear portion of the transfer characteristic. If the zero-signal current is too low, excessive cross-over distortion will result.[1] In a transistor circuit, if the zero-signal collector current is too high, the battery drain is increased significantly. In addition, there is danger of permanent damage to the transistor. Because the transfer characteristic of a transistor is extremely sensitive to temperature variations, the performance of the circuit over the anticipated ambient temperature range of the equipment must be considered. All the circuits shown have been designed to operate safely throughout the temperature range from 0°C (32°F) to 50°C (122°F). Performance variation as a function of temperature will be discussed further.

The basic circuits shown in Fig.1 differ only with respect to the secondary impedance of the driver transformer, the biasing network, and the use of emitter resistance to provide degeneration. The source im-



T_1 Primary – Determined by Driver
T_1 Secondary – Circuit A-3000 ohms Base to Base
Circuit B-9000 ohms Base to Base
Circuit C-1500 ohms Base to Base
Circuit D-4500 ohms Base to Base

T_2 Primary – See Fig.2
T_2 Secondary – Matched to Speaker
For Resistor Values – See Fig.3
For Capacitor Values – See Fig.4
Max. Permissible Ambient Temperature = 25°C

Fig.1 - Four basic class B circuits using the RCA-2N109 transistor.

pedance of the driver transformer is selected to provide the best combination of power gain and distortion, rather than to match the input. The chart given in Fig.2 specifies the collector-to-collector load impedance of the output transformer for each circuit for given values of supply voltage and power output. Because the efficiency of transformers varies considerably, the rated power output specified in this chart refers to the power delivered to the transformer. The rated power must be multiplied by the transformer efficiency^2 to determine the power delivered to the voice coil. The power supply should be adequately bypassed to realize the maximum efficiency. Because the impedance of the load is small, rather large values of bypass capacitors are required.

The total output that can be obtained from equipment under maximum drive, or "squawk" conditions, is often important in "listening" tests. Because the difference between rated power output and "squawk" power output is much smaller in transistor circuits than in tube circuits, it may be necessary to design transistor amplifiers for greater rated power

Collector-to-Collector Load Impedance (R_L)-ohms

Circuit	RATED POWER OUTPUT-MW	COLLECTOR SUPPLY VOLTS (V_{CC}) 1.25	1.5	2.5	3.0	3.75	4.5	6.0	7.5	9.0	10.5	12.0
A	20	110	180	600	900	1400	2100					
	35		100	330	500	800	1200					
	50			230	350	600						
	75				230	380						
B	20			500	800	1300	2000	3800	6000	9000	12000	16000
	35			250	400	750	1100	2200	3500	5000	7000	9000
	50			140	260	500	750	1500	2400	3500	5000	6500
	75					300	500	1000	1600	2400	3300	
	100							700	1200	1800		
	150							420	750			
C	20	110	180	600	900	1400	2100	4000	6000	9000	12000	16000
	35		100	330	500	800	1200	2200	3500	5000	7000	9000
	50			230	350	600	850	1500	2400	3500	5000	6500
	75				230	380	550	1000	1600	2400	3300	4500
	100					300	420	800	1200	1800	2500	3300
	150							500	800	1200	1600	2200
	200								600	900	1200	
D	20			500	800	1300	2000	3800	6000	9000	12000	16000
	35			250	400	750	1100	2200	3500	5000	7000	9000
	50			140	260	500	750	1500	2400	3500	5000	6500
	75					300	500	1000	1600	2400	3300	4500
	100							700	1200	1800	2400	3300
	150							420	750	1100	1600	2100
	200									800	1200	1600
	250										900	1200
	300											1000

Note: "Squawk" power output is equal to 1.5 times rated power output.
Unassigned blocks represent operating conditions not recommended.

Fig.2 - Collector-to-collector load impedance of the output transformer for the four basic circuits shown in Fig.1 for given values of collector supply voltage and rated power output.

output than is usually considered satisfactory for tube amplifiers to produce the same subjective effect. The relationship between "squawk" power output and rated power output for transistors is 1.5 to 1. "Squawk" power output, which is the maximum obtainable power output without regard to distortion, is produced when the circuit is considerably overdriven. The rated power output is measured at a total harmonic distortion level of 10 per cent.

Values for the resistive components and thermistor of circuits A through D are given in Fig.3. Information on the choice of the capacitor used in shunt with the output load is given in Fig.4. The value of this capacitor depends upon the collector-to-collector load impedance and the desired upper limit of frequency response. This capacitor is useful in minimizing the effects of nonlinear distortion, as will be discussed later.

Resistive Circuit Parameters-ohms

RESISTOR	COLLECTOR SUPPLY VOLTS (V_{CC}) 1.25	1.5	2.5	3.0	3.75	4.5	6.0	7.5	9.0	10.5	12.0
R_1*	91	91	100	100	91	91					
R_2*	750	910	1800	2200	2400	3000					
R_3	10	10	10	10	10	10	10	10	10	10	10
R_4*	75	75	82	82	75	75	75	75	75	75	75
R_5*	750	910	1800	2200	2400	3000	3900	5100	6200	7500	8200
R_6*	820	1000	1500	**	2400	3000	3900	5100	6200	7500	8200
R_7*	180	180	150	150	150	150	150	150	150	150	150
R_8	15	15	15	15	15	15	15	15	15	15	15
R_9*	150 at 25°C, 495 at 0°C, 54 at 50°C Thermal Rise <10°C/mw										
R_{10}*	Same as R_9										
R_{11}*	Same as R_7										
R_{12}	Same as R_3										
R_{13}*	Same as R_6										

All resistors are 0.5 watt. Tolerance is 20 per cent except as follows:
* Denotes 5 per cent.
** 2200, 5 per cent in parallel with 27000, 20 per cent.

Fig.3 - Values of the resistive components and the thermistor of the four basic circuits shown in Fig.1 for given values of collector supply voltage.

CIRCUIT PERFORMANCE

Information on battery current drain is given in Figs.5, 6, and 7. Fig.5 gives average battery drain under full drive from a waveform produced by speech or music, and is used in the calculation of battery life. Fig.6 gives battery drain under full drive from a sine waveform.

Fig.7 shows how the zero-signal circuit current (the total of the bleeder current necessary to supply transistor bias and the zero-signal collector current) increases with temperature in each of the four basic circuits. The uncompensated circuits have the greater change. Although the use of circuit A is limited to maximum collector supply voltages up to 4.5 volts because of its sensitivity to temperature changes, it has the advantages of lower cost, because of the absence of a thermistor,

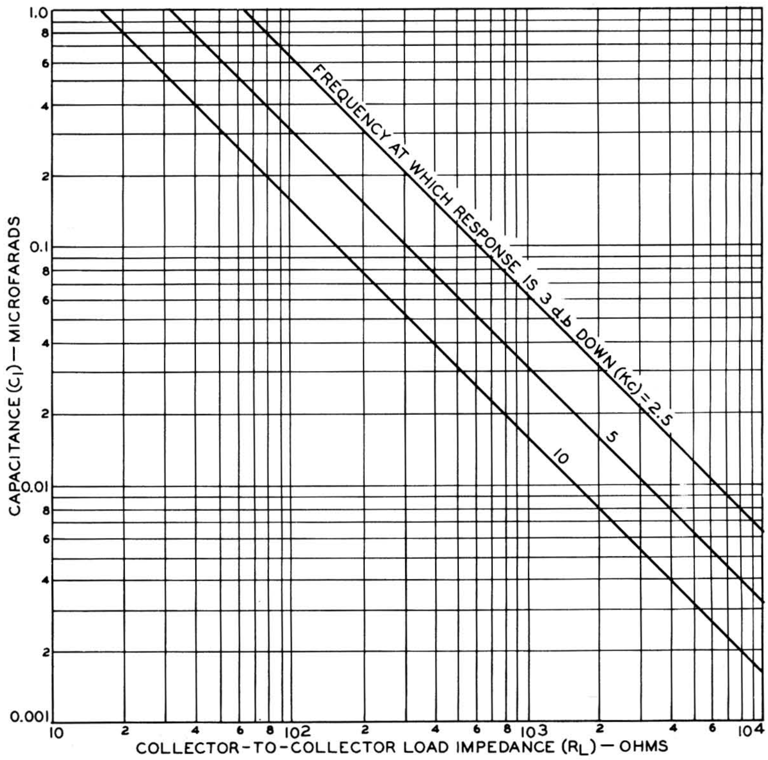


Fig.4 - Value of capacitor C_1 used in shunt with the output load as a function of collector-to-collector load impedance.

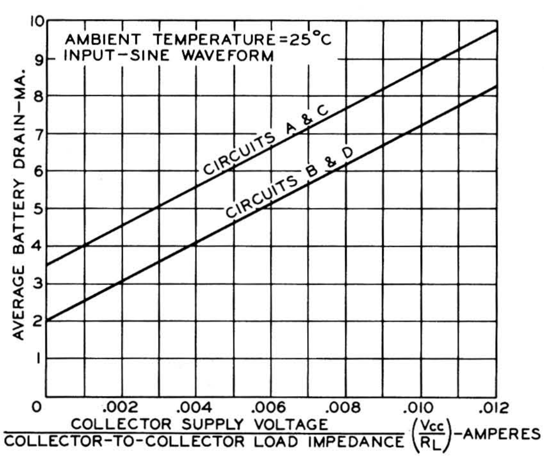


Fig.5 - Average battery drain under full drive from a waveform produced by speech or music as a function of the quotient of the collector supply voltage divided by the collector-to-collector load impedance.

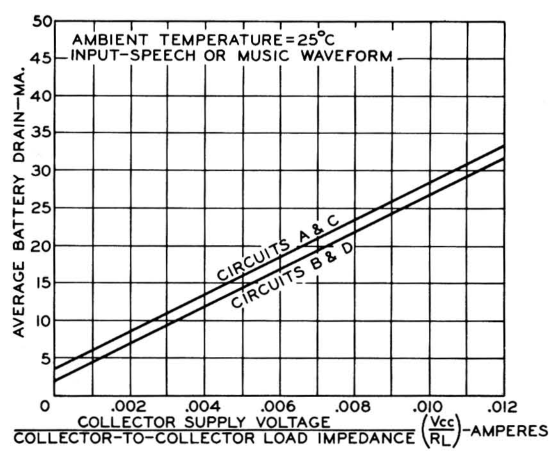


Fig.6 - Average battery drain under full drive from a sine waveform as a function of the quotient of the collector supply voltage divided by the collector-to-collector load impedance.

and of relatively high sensitivity. Other considerations which affect the choice of circuits and components will be discussed later.

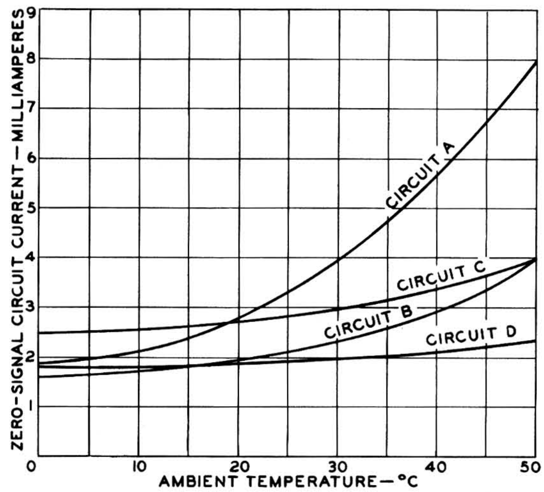


Fig.7 - Zero-signal circuit current (bleeder current necessary to supply bias plus zero-signal collector current) as a function of ambient temperature.

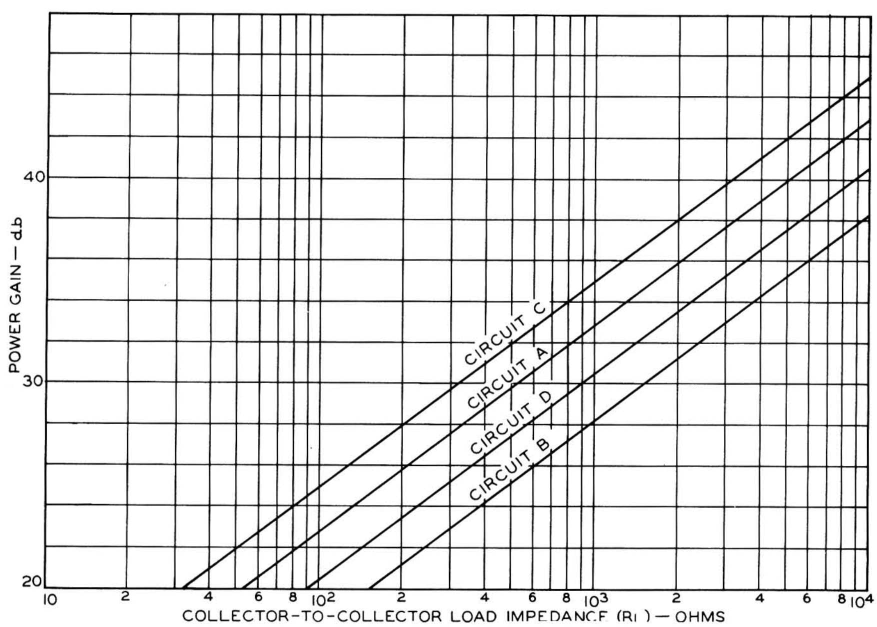


Fig.8 - Power gain as a function of collector-to-collector load impedance.

Power gain of the four basic circuits is shown in Fig.8 as a function of collector-to-collector load impedance. Relatively large values of power gain are obtained as a result of the excellent large-signal current-amplification characteristics of the RCA-2N109.

The relationship between driving power, power output, and power gain is shown in Fig.9. The available driver power should be about three times that shown in this figure to provide adequate reserve in accordance with safe engineering practice. Inefficiencies introduced by the driving transformer may require an additional slight increase in available driving power.

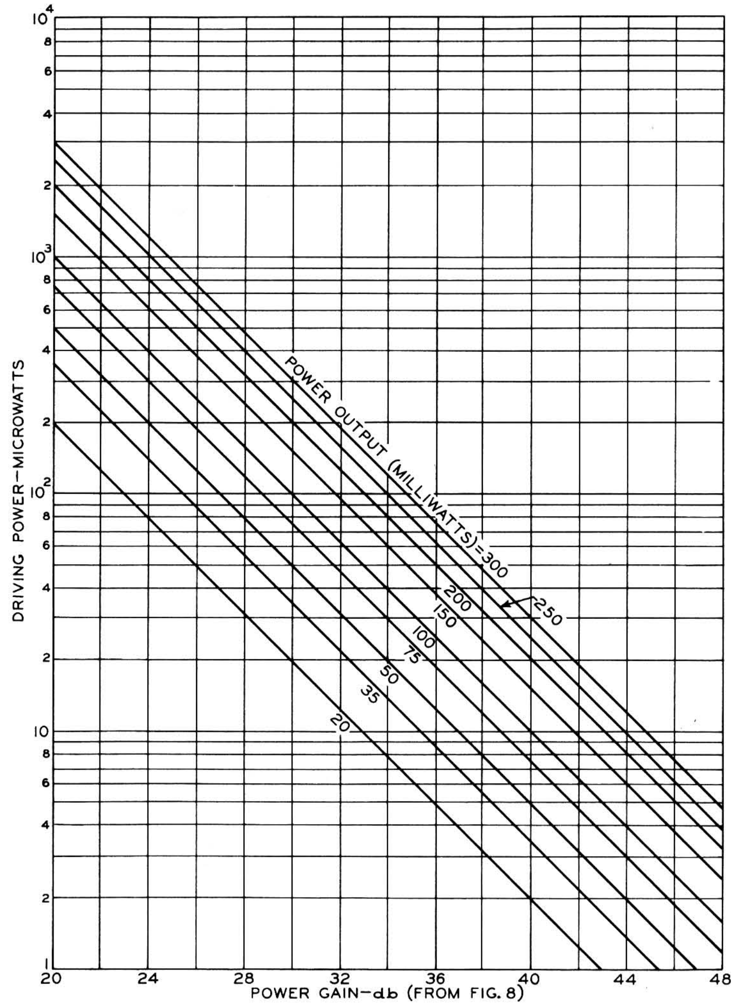


Fig.9 - Driving power as a function of power gain for given values of power output.

Figs.10 and 11 show the total harmonic distortion of the circuits as a function of ambient temperature. The curves shown in these figures cover a wide ambient-temperature range to illustrate the influence of temperature on transistor performance. Because of the absence of a temperature-compensating thermistor, circuits A and B show appreciably more performance variation with temperature. In class B operation, distortion is often more severe at low power levels than at power levels approaching rated power output because of cross-over effects. Information is presented in the curves, therefore, at power levels equal to approximately 5 per cent (low volume) and 20 per cent of maximum output.

The 20-per-cent value is considered representative of normal dynamic[3] listening levels. Distortion remains relatively low as power output is increased, until clipping occurs in the collector circuit. This distortion pattern is a beneficial aspect of transistor circuits. Beyond the clipping level, distortion rises rather rapidly.

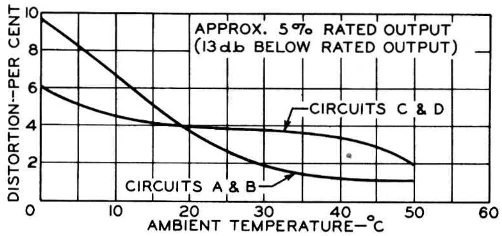


Fig. 10 - Total harmonic distortion of basic circuits shown in Fig. 1 as a function of ambient temperature at a power level equal to about 5 per cent of maximum output (low volume).

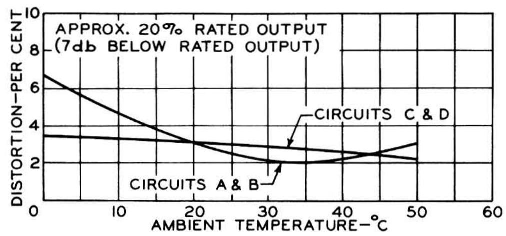


Fig. 11 - Total harmonic distortion of basic circuits as a function of ambient temperature at a power level equal to about 20 per cent of maximum output (normal dynamic listening level).

FACTORS INFLUENCING THE CHOICE OF CIRCUITS

1. *Cost.* The cost of the components of the four basic circuits shown in Fig.1 is approximately equal except that circuits C and D also require a thermistor. If the supply voltage for the circuits is not fixed, higher supply voltages may be used with higher load resistances to increase the power gain. The additional sensitivity may be sufficient to permit elimination or a reduction in cost of one of the earlier stages. This advantage may be off-set to some extent by the increased cost of the output transformer. A low-impedance transformer is usually less expensive than a higher-impedance transformer provided the low-frequency response of the system is held constant.

2. *Frequency Response.* The low-frequency response of the amplifier system is dependent upon the low-frequency performance of the transformers. The upper frequency limit of the system may be determined by the transistors, the transformers, or the value of capacitor C_1 in the basic circuits. If this capacitor is omitted, the upper frequency limit will be in the order of 12 to 20 kilocycles per second. In many applications, very little intelligence is conveyed in the upper portions of the audio spectrum. As an example, the FCC limits most standard broadcast-band AM radio transmissions to an upper limit of 5 kilocycles. In this application, the only audio energy delivered to the voice coil at frequencies above 5 kilocycles would be distortion components. It would be desirable, therefore, to select the value of C_1 in the circuit to limit the upper frequency response to 5 kilocycles, thereby reducing the total harmonic distortion of the receiver.

3. *Battery Life.* In normal usage, circuits B and D have less battery drain than circuits A and C. This normal battery drain includes the bleeder current necessary to provide transistor bias, the zero-signal collector current of both transistors, and the average ac current under

listening conditions. Provided the load impedance is varied to maintain a constant power output, the ac component of current is inversely proportional to the design supply voltage. Greater efficiency is obtained, therefore, at reduced supply voltages which reduce zero-signal collector power and bleeder power. Basic circuits B and D designed for use with low supply voltages approach ideal class B efficiency and, as such, require the least battery power. Because the zero-signal circuit current of circuit B increases appreciably with temperature, circuit D approaches ideal class B operation more closely at elevated temperatures.

4. *Sensitivity.* In any power amplifier, the load impedance is determined by the supply voltage and the required power output. The peak-collector-voltage rating of the 2N109 limits the maximum dc supply voltage, which, in turn, governs the maximum load impedance for a given power output. In all practical 2N109 power-amplifier circuits, as the load impedance is decreased the power gain is reduced proportionately. At the same time, the available power output is increased proportionately until the load impedance reaches a minimum permissible value determined by the peak-current rating of the 2N109. In Fig.2, several values of load impedance are shown for a given supply voltage. All of the values are selected to provide maximum sensitivity for the corresponding power output.

In most cases, in order to provide the best combination of power sensitivity and distortion, the driving source impedances shown are slightly higher than the values required for matching. This arrangement also permits the use of lower zero-signal collector currents and provides higher power outputs at maximum dissipation conditions.

The highest power gain is obtained from basic circuit C. Circuits A, D, and B are 2, 5, and 7 db less sensitive, respectively. When the supply voltage is not fixed, the use of higher voltages results in greater sensitivity because of the higher load impedances required.

5. *Distortion.* In circuits which do not include thermal compensation, the zero-signal collector current increases rapidly as the ambient temperature of the equipment is increased, resulting in an approach to class A operation. Conversely, the zero-signal collector current decreases rapidly as the temperature is decreased, resulting in an approach to class C operation. Circuits C and D exhibit good distortion characteristics through the temperature range from $0^{o}C$ to $50^{o}C$ ($32^{o}F$ to $122^{o}F$). Circuits A and B exhibit good distortion characteristics from $20^{o}C$ to $50^{o}C$ ($68^{o}F$ to $122^{o}F$). Subjective listening tests made with these two circuits indicate that performance is acceptable at temperatures well below $20^{o}C$.

CIRCUIT DESIGN PROBLEM

A typical example of the application of 2N109 transistors in class B operation is a small battery-powered amplifier in which low cost and high sensitivity are the chief design objectives. Battery voltage for the amplifier is 4.5 volts, and the desired power to the voice coil is 50 milliwatts. A frequency response of 5 kilocycles is adequate. The output-transformer efficiency is assumed to be 75 per cent. The rated power output of the amplifier is given by

$$\text{Rated Power} = \frac{\text{delivered power}}{\text{output-transformer efficiency}} = \frac{50}{0.75}$$

$$= 67 \text{ milliwatts}$$

The collector-to-collector load impedance for each basic circuit is determined from Fig.2 for a voltage of 4.5 volts and power outputs of 50 and 75 milliwatts:

Circuit A - 50 mw not recommended; 75 mw not recommended

Circuit B - 50 mw, R_L = 750 ohms; 75 mw, R_L = 500 ohms

Circuit C - 50 mw, R_L = 850 ohms; 75 mw, R_L = 550 ohms

Circuit D - 50 mw, R_L = 750 ohms; 75 mw, R_L = 500 ohms

These values indicate that circuits B, C, and D may be considered. As mentioned previously, circuit B is less expensive than circuits C and D by the cost of a thermistor. Because the supply voltage is fixed and high sensitivity is desired, other cost considerations discussed earlier do not apply. Because circuit C has the greatest sensitivity, the designer may choose between circuit B and circuit C. The choice is based on whether the 7-db additional sensitivity is worth the extra cost of the thermistor. If it is assumed that circuit C is chosen, the value of certain parameters must be established:

T_1 Primary - determined by driver (From Fig.1, Circuit C)

T_1 Secondary - 1500 ohms base-to-base (From Fig.1, Circuit C)

T_2 Primary - Because no data are given for the rated power output of 67 milliwatts established previously, the designer may interpolate the value of collector-to-collector load impedance or use the next higher power level, 75 milliwatts. For 75 milliwatts, the load impedance value is 550 ohms collector-to-collector (From Fig.2, Circuit C)

T_2 Secondary - matched to speaker (From Fig.1, Circuit C)

Undistorted power to the voice coil (10 per cent distortion) = 75 milliwatts times transformer efficiency = 75 x 0.75 = 56 milliwatts

"Squawk" power output = 1.5 times the rated power output times the transformer efficiency = 1.5 x 75 x 0.75 = 84 milliwatts (From Fig.2)

R_6 = 3000 ohms, 5 per cent (From Fig.3, 4.5 volts)

R_7 = 150 ohms, 5 per cent (From Fig.3, 4.5 volts)

R_8 = 15 ohms, 20 per cent (From Fig.3, 4.5 volts)

R_9 = thermistor (for complete specifications, see Fig.3)

C_1 = 0.05 microfarad for cutoff at 5 kilocycles (From Fig.4 using value of T_2 primary)

V_{cc} = 4.5 volts (given)

The battery drain may be determined from Figs. 5, 6, and 7. The value of V_{cc}/R_L is first calculated.

$$\frac{V_{cc}}{R_L} = \frac{4.5}{550} = 0.0082 \text{ ampere}$$

Normal battery drain at 25°C = 7.8 milliamperes (From Fig. 5, Circuit C)

Normal battery drain at 50°C = normal drain at 25°C plus the difference between the zero-signal drains at 50°C and at 25°C = 7.8 + (4.0 - 2.8) = 9.0 milliamperes (From Fig. 7, Circuit C)

Rated drain at full power = 24 milliamperes (From Fig. 6, Circuit C)

Power gain = 32 db (From Fig. 8, Circuit C)

Power required of the driver - As in the case of the output transformer, driver-transformer efficiency must also be considered. The driver power required is the power required for the transistor bases divided by the driver-transformer efficiency. If a transformer efficiency of 75 per cent is assumed, the power required of the driver = 48 microwatts/0.75 = 64 microwatts (From Fig. 9, 75-milliwatt curve). For conservative engineering practice, multiply by 3; 3 x 64 = 192 microwatts.

Total harmonic distortion is about 3 per cent at 15 milliwatts, and about 4 per cent at 4 milliwatts (From Fig. 10 and Fig. 11, Circuit C)

NOTES

[1] Another form of cross-over distortion, which appears as "ringing" in the cross-over region, is caused by excessive series inductance in the class B transformer. Physically, excessive series inductance is due to inadequate coupling from one half of the transformer winding to the other half.

[2] The efficiency of class B output transformers should be measured with the input connected from collector tap to center tap rather than from collector to collector. The single-ended efficiency is always higher than the class B efficiency. As an approximation, if the collector-to-collector dc resistance is 7 per cent of the transformer collector-to-collector impedance, the transformer efficiency in class B service will be about 65 per cent. A collector-to-collector dc resistance equal to 3.5 per cent of the transformer collector-to-collector impedance will result in a transformer efficiency of approximately 80 per cent. Because the impedance of the voltage supply also reduces the maximum output power, it should be low.

[3] Because of the relatively large amount of "dead" time in both speech and music, the average short-term signal level to be handled by the amplifier is usually higher than the average long-term signal level. The short-term level, which affects distortion, is called the normal dynamic listening level. The long-term level, which determines battery drain, is called the normal static listening level.