Audio Power Amplifier

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In this article the author puts forward a proposal for a transistor power output stage which does not claim the best possible performance but provides an economic configuration to achieve acceptable results. A circuit diagram for a 30W main amplifier with 0.1% distortion and a hum level of −50dBW is presented together with a description of the design philosophy.

The current-voltage relationship of a semiconductor junction is basically an exponential form. This curve has the property that moving it horizontally along the voltage axis is equivalent to a simple change of the scale of the vertical or current axis. There is an unfortunate consequence when it comes to trying to adjust two exponential curves back-to-back to make a class B output stage, Fig. 1. No matter how one juggles the two curves relative to each other the resultant, shown dotted, always has the same shape; it merely changes in scale. It is a hyperbolic sine and is far from linear. Semiconductor junctions are evidently bad starting material for a class B design.

Matters are somewhat better if a fixed resistance \( R \) is included in series with each junction. A few moments' work with pencil and paper shows that, for the nearest approach to a linear resultant characteristic, the resistance should have a value equal to the slope resistance of the junction at the standing or quiescent current. What happens when it does not have this value has been graphically illustrated by Gibbs.

There is an important practical consequence. If \( I_0 \) is the standing current and \( V_0 \) the corresponding voltage drop across the base-emitter junction, then the general equation relating current \( I \) and voltage \( V \) is,

\[
I = I_0 \exp\{K(V - V_0)\}.
\]

The slope resistance is \( dV/dI \), and when \( I = I_0 \) takes on the value \( 1/KI_0 \). If the series resistance has this value we get the particularly simple result that the standing voltage drop across it must be \( I_0 \times 1/KI_0 = 1/K \). So if \( I_0 \) is firstly chosen, the value of resistance follows and the circuit must be designed to maintain \( 1/K \) volts across the resistance under quiescent conditions.

Now \( K = q/kT \), where \( q \) is the charge on an electron, \( k \) is Boltzmann's constant and \( T \) is junction temperature. It is the same for all transistors n-p-n or p-n-p, germanium or silicon, and has the value \( 40V^{-1} \) at room temperature. Hence there is a universal rule which defines that, for class B operation of any transistor, the standing voltage drop across each series resistor should be 25mV at room temperature. Here lies the practical difficulty. The 25mV is in series with the much larger, and variable, 550mV, or so, voltage drop \( V_0 \) across the junction. It is small wonder that temperature compensating diodes and preset adjustments are required in class B designs. Added to this are the difficulties that the adjustment is critical, \( K \) is temperature-dependent (so that strictly the series resistance should vary with junction temperature) and the series resistance must include the internal emitter resistance of the transistor — about \( 1\Omega \) for type BD121. Therefore, only part of the 25mV is available outside the transistor for monitoring the standing current. All in all, it is surprising how well class B stages have been made to perform.

Class AB is a little better. Typical values are \( R = 1\Omega \) and \( I_0 = 100mA \), so that the standing voltage drop is 100mV. This voltage is still rather small compared with 550mV but unfortunately it cannot be increased much above this figure because, as \( I_0 \) is increased, there are problems of power dissipation in the transistors. On the other hand \( R \) is in series with the load so that if this resistance is increased, the peak voltage drop across it reduces the peak power available in the load. That is, \( R \) ideally should be small compared with the resistance of the load.

The new circuit to be described attempts to overcome these difficulties by putting the current monitoring resistor outside the main feedback loop.

\( \dagger \) By a similar argument one obtains another universal rule which defines the transfer conductance of all transistors to be 40mA/V per mA of emitter current at room temperature. It is strange that not many textbooks mention this valuable and easily-remembered fact.
Circuit operation

The basic circuit, shown in Fig. 2 has one of the output transistors, TR1, acting as a straightforward emitter follower. The current generator and the resistance R1 represent a transistor driving TR1 and R2 is a collector current monitoring resistance. In the absence of signal the standing current through TR1 is chosen to be 100mA so that the voltage drop across R2 is 390mV. The polarity and magnitude of this voltage is arranged to make diode D1 partially conduct, but not sufficiently to pass appreciable current.

Ignoring D1 for the moment, there is seen to be negative feedback round the loop TR2-TR3-TR1. The standing current through TR1 and TR3 (the second output transistor) is fixed in terms of the voltage drop across R2, which is applied to the emitter of TR2, and the fixed voltage applied to the base of this transistor from the chain D2-R3-R4. The diode D2 is included to compensate for variations in the base-emitter voltage of TR2 and the voltage across R3 is therefore approximately equal to the desired standing voltage drop across R2.

Now suppose TR1 is driven by a signal. Over positive half-cycles TR1 passes more current from the positive supply to the load. The voltage drop across R2 rises, reducing the collector-emitter current in TR2 and hence TR3. This does not matter if the conditions are correct because TR1, provided it has sufficient drive, should be capable of supplying all the current required by the load. What is important, however, is that R2 has a value which is comparable with an 8Ω loudspeaker load and, if measures were not taken to counteract the voltage drop, the peak output current would severely reduce the voltage at the collector of TR1 and would consequently restrict the positive excursions of output voltage available across the load. In this circuit the voltage drop across R3 is limited to about 600mV, when D1 fully conducts. Obviously D1 must be a small power type to carry the peak current.

Over negative half-cycles TR1 passes less current which reduces the voltage drop across R3 so that TR2 passes more current and TR3 conducts more to supply the required load current from the negative supply. Current through TR1, which is maintained by the negative feedback, still flows through the load. Thus TR3 supplies the load current on negative half-cycles but TR1 remains in conduction operating as an emitter follower to control the output voltage at all times.

Thus the circuit permits the use of a much higher current monitoring resistance than in a typical class AB amplifier, the resulting voltage drop under quiescent conditions being high enough to permit pre-set adjustments to be dispensed with, but because this resistance is outside the main amplifier feedback loop the peak voltage can be limited by a shunt diode.

Distortion

The distortion produced by this circuit is basically even-order and may be estimated as follows. In practice TR1 is a Darlington pair with a current gain of about 2500. On positive half-cycles, when TR2 is inoperative, an 8Ω load is therefore presented as a resistance of about 8 x 2500 = 20kΩ across R1. On negative half-cycles the extra gain round the TR2-TR3 loop makes the reflected resistance much higher. Therefore, assigning a value of 10kΩ to Rs creates the condition where on negative half-cycles the current generator works into approximately 10kΩ and on positive half-cycles it works into 10kΩ in parallel with 20kΩ, which is 6.7kΩ. The magnitudes of positive and negative half-cycle output voltage therefore differ by 13% second harmonic. The distortion is approximately half this value or 17%.

A loop gain of 170 round the main amplifier loop would reduce this to the target figure of 0.1%.

A practical audio amplifier incorporating the new output stage is shown in Fig. 3. It provides 30W into an 8Ω load and performance is as expected. Distortion is 0.1% at maximum output and is mainly second harmonic. Full output is available up to 15kHz with an input voltage of 600mV r.m.s. With conventional power supplies the hum is less than 10μW with a load of 8Ω.

The following points may be of interest. A minor extravagance seems to be the use of a zener diode D5 to couple TR4, to TR3. This has the effect of defining accurately the voltage drop across R4 and hence the current flowing through TR1 and R3. In turn, this defines the voltage drop across R3, which reduces variations in the output d.c. voltage to less than 100mV—with any pre-set adjustment. If the loudspeaker has a d.c. resistance of 8Ω, an output coupling capacitor can be eliminated. It appears that the use of D1 is not such an extravagance as it all.

An additional point is that TR4 does not need a collector load resistance connected to the negative supply. This eliminates not only a potential source of hum, but also the usual “boots trapping” capacitor. This means that this type of output stage is ideally suited for applications requiring an output down to d.c., such as control and servo drive systems.

References


Sixty Years Ago

The problems of obtaining what is now the basic function of a transmitter—the production of a continuous wave—were, sixty years ago, so formidable that many people were of the opinion that they just were not worth the trouble. In his evidence to the Postmaster-General’s Advisory Committee, G. Marconi said “... there has never been submitted here or elsewhere one scintilla of evidence to prove that the continuous or undamped waves have any advantage over intermittent or feebly-damped waves for long-distance telegraphy.” In an article on methods of obtaining these waves using rotary machines, Hubert Dodell mentioned the difficulty of maintaining a constant frequency, the speed of the machine being affected by the loading due to Morse modulation. “So serious is this difficulty, that the full load is kept permanently on the machine, and the dots and dashes are produced by varying the aerial wavelength so that at times it is in tune with the receiver, and at others it is so much out of tune that the receiver is not affected.”