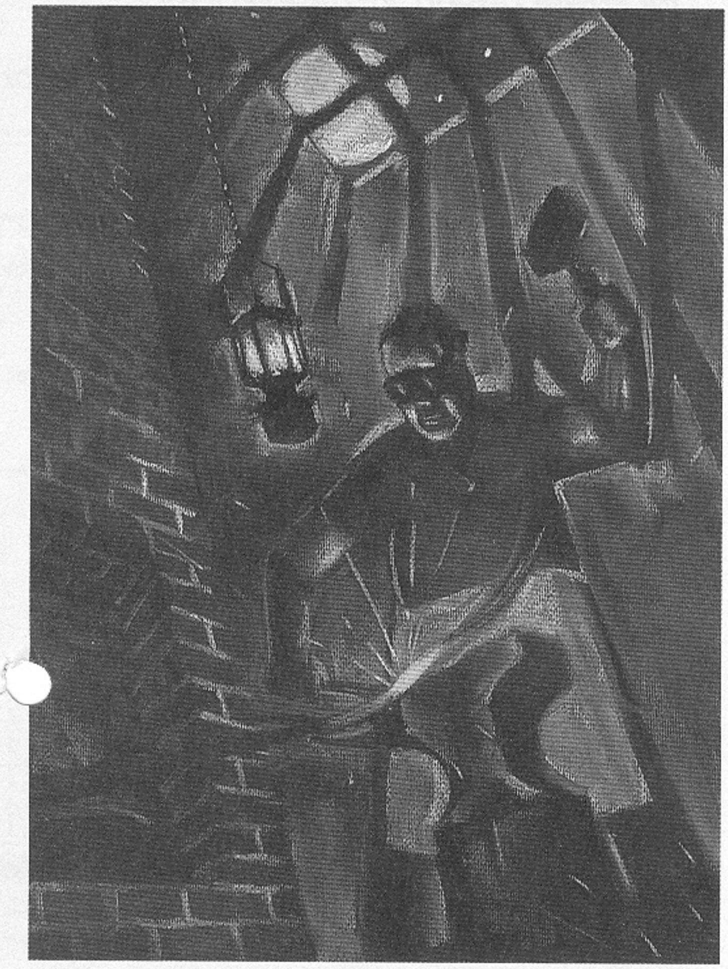


Mike J. Renardson's simple enhancement of a standard class-B output stage dramatically reduces crossover distortion. It can also remove the need for accurate setting and thermal compensation of quiescent current – making the design desirable for volume production.

Class B in a new class

My new idea involves using one half of the class-B output stage as a feedforward error correction amplifier for the other half. It may seem surprising that this is possible, because in class-B each half is normally switched off for most of one half-cycle. The usual requirement for an error amplifier is that it should remain linear at all times.

In this circuit, however, one side can remain in class-A throughout the whole signal cycle. Consider first a widely used circuit giving an output across its load equal to the difference between its inputs, **Fig. 1**. This arrangement is used as the top half of the class-B circuit in **Fig. 2**. In this case op-amps are used to drive output power transistors, but the technique can also be applied using discrete transistors.

Vout = Vin

The top half of the output stage subtracts the output of the other half, V_3, from the input voltage V_1. It produces a voltage $V_2-V_0=V_1-V_3$ across its output resistor to compensate for the error from the bottom half.

Both halves are biased onto the linear parts of their characteristics in the quiescent state by V_{bias}, and so on negative half-cycles if the bottom half provides the entire output required with no error, i.e. $V_3=V_1-V_{bias}$, then the top half will not have any change in its output across the 1Ω output resistor, i.e. $V_2-V_0=V_{bias}$. It remains operating at a constant current determined by the bias voltage and will not be cut off as in a conventional class-B circuit. On positive half-cycles the bottom half will eventually cut off, at which point, the top half takes over to provide the whole output current.

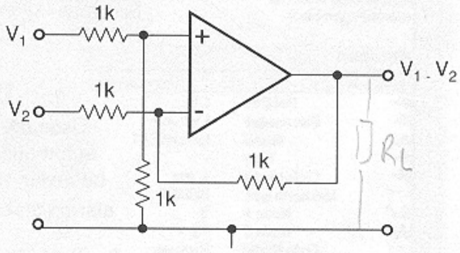


Fig. 1. This familiar circuit gives an output across its load equal to the difference between its inputs.

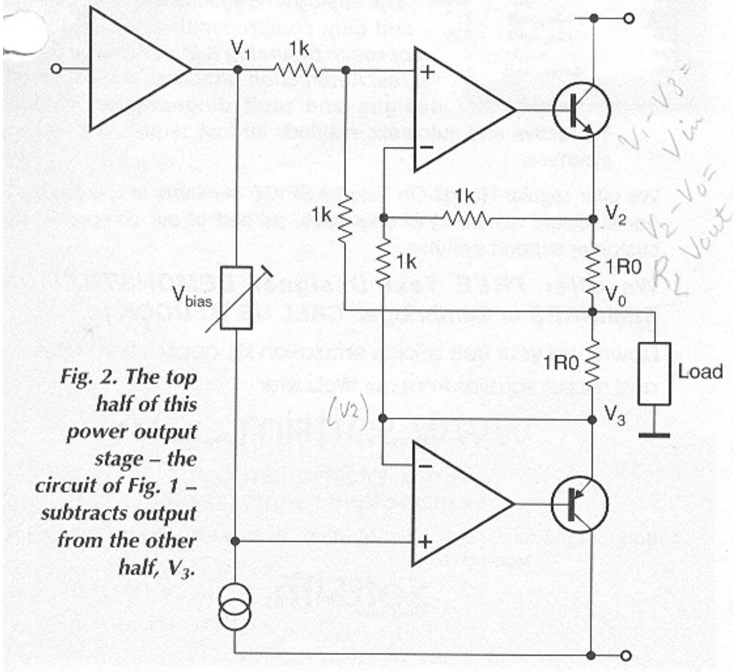


Fig. 2. The top half of this power output stage – the circuit of Fig. 1 – subtracts output from the other half, V_3.

A more convenient arrangement

There is another arrangement which is more convenient for a discrete component output stage, but again, for clarity, it is shown with op-amps in **Fig. 3**.

Operation of this configuration is perhaps more difficult to understand than in the previous example. One way to understand how it works is to observe that the top half functions as an inverting amplifier for the signal at the emitter of the lower, p-n-p power transistor.

The inverted signal is added to the original signal through the 1Ω resistors so that cancellation occurs. Output across the load is therefore independent of the output of the lower, class-B half, and is determined only by the top half of the stage which operates in class-A and can be made highly linear.

The lower half must of course still provide most of the output current on negative half-cycles, otherwise the top half will cut off in an attempt to correct the error. **Figure 4** shows how the currents vary in the two halves of the output stage with a sine-wave signal. The peak output current is I_P and quiescent current I_Q.

Figure 5 shows a complete circuit which has been built and tested. A switch is included which in one position, as shown in the diagram, gives the improved circuit, while in the other position it gives something not too far removed from a standard class-B arrangement for comparison purposes.

Distortion measurements were initially carried out at 1kHz, but in both configurations, with any quiescent current above about 10mA, the overall negative feedback was sufficient to reduce the distortion below the noise level of the test instrument used. This can easily be overcome by taking the feedback from the output of the op-amp so that the output stage is outside the feedback loop and open-loop distortion can be observed.

Doing this confirmed the successful reduction of crossover distortion in the improved circuit and the insensitivity to changes in quiescent current. The tests were repeated at 20kHz, and here the closed-loop distortion did become clearly visible giving the results shown in **Fig. 6**.

The tests were carried out with a 8Ω load, and a 20kHz, 100mV rms input signal. The distortion plus noise was extracted and displayed at various levels of output stage quiescent current for both circuit configurations. At 6mA both circuits produced similar crossover spikes shown in Fig. **6a**. The standard circuit distortion reduced to a minimum at around 10mA, as in Fig. **6b**, and increased at higher currents, and is shown in Fig. **6c** at 60mA.

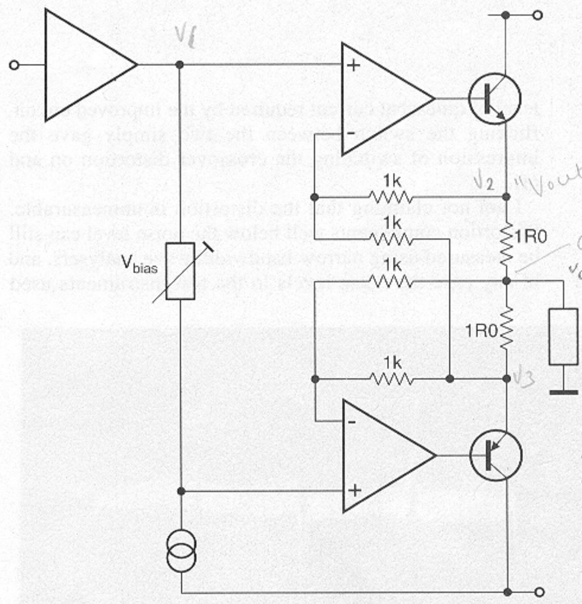
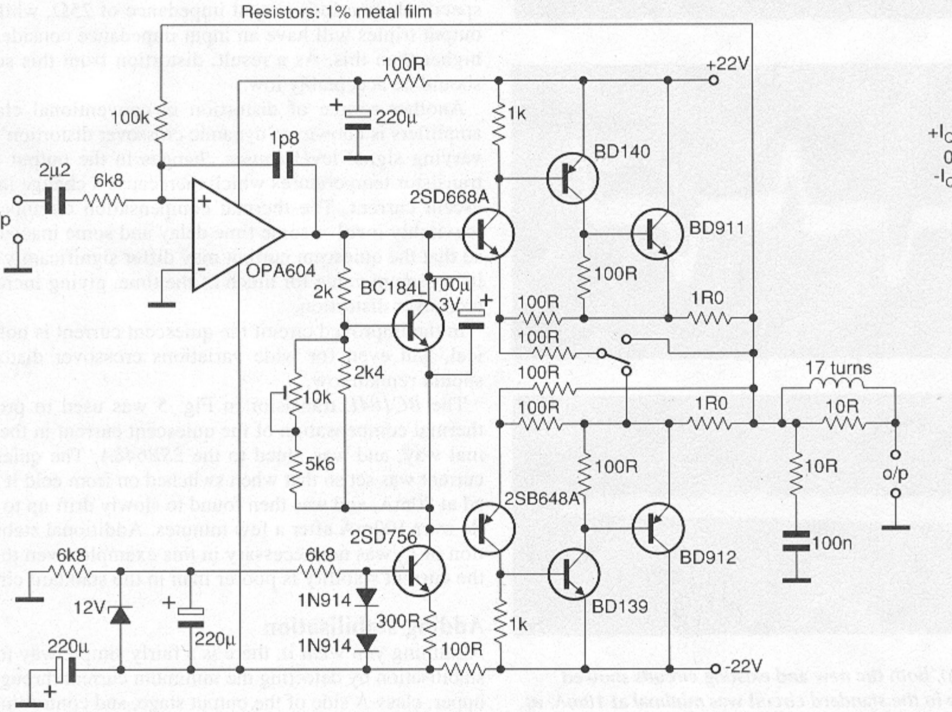


Fig. 3. This alternative arrangement lends itself to implementation in discrete components.

Adjusting for minimum distortion

The adjustment for minimum distortion was quite critical. Even a small variation from the optimum value gave an obvious increase. The improved circuit gave a similar result at 10mA, but at any quiescent current from 15mA upwards – a maximum of 120mA was used in the tests – the distortion fell out of sight below the noise level, as in Fig. **6d**.

Reducing the input signal to zero gave no visible change in the 'distortion' observed, which appeared to be entirely noise with or without an input signal present. The contrast with the standard circuit was dramatic. Above the minimum



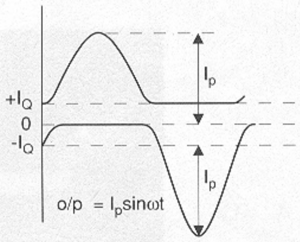


Fig. 4. How currents vary in the two halves of a class-B stage with a sine-wave signal.

Fig. 5. Complete circuit of the improved class-B stage. A switch is included so that you can compare performance of the improved configuration with traditional class-B.

level of quiescent current required by the improved circuit, flicking the switch between the two simply gave the impression of switching the crossover distortion on and off.

I am not claiming that the distortion is unmeasurable. Distortion components well below the noise level can still be measured using narrow bandwidth wave analysers, and in any case the noise levels in the test instruments used were far from ideal. My only intention was to demonstrate that crossover distortion really is significantly reduced, so more precise measurements or attempts to further improve or optimise the circuit were not made.

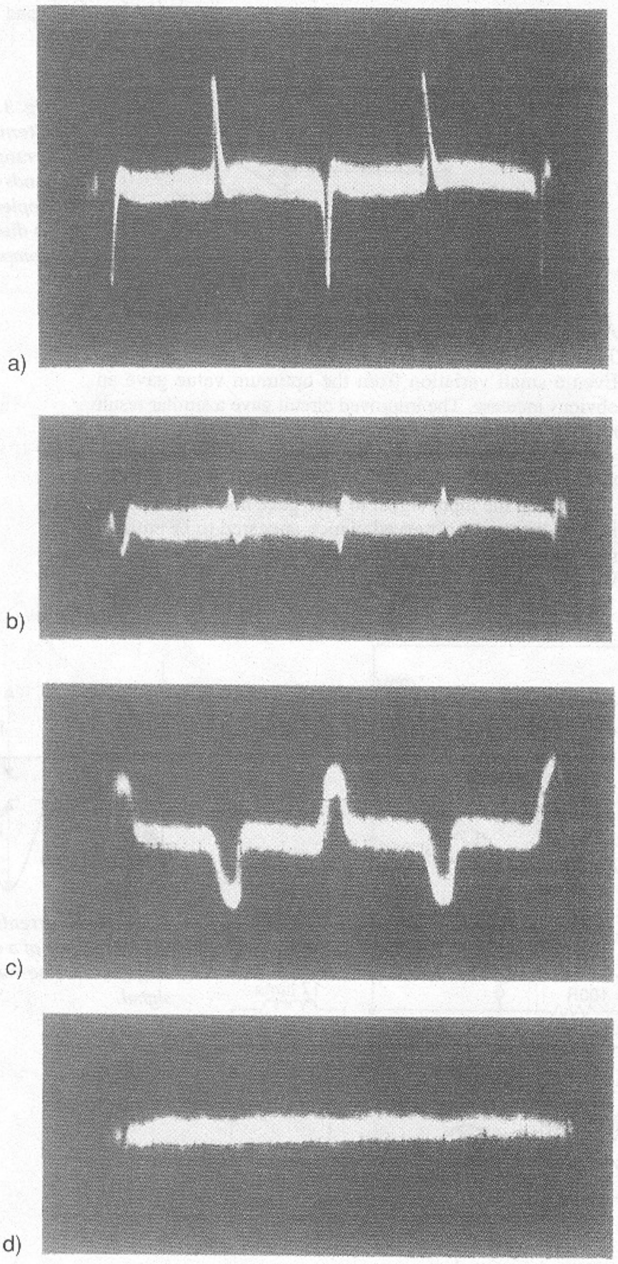


Fig. 6. At 6mA quiescent current, a), both the new and existing circuits showed similar crossover spikes. Distortion in the standard circuit was minimal at 10mA, as in b), but rose again as current increased, as is evident in c) at 60mA. For any quiescent current above 16mA, distortion with the new circuit remains below the noise level.

It may be worthwhile adjusting component values in the output stage to give accurate nulling of the distortion, but in the prototype low distortion was achieved using fixed 1% tolerance resistors. The component values shown are actually not theoretically correct for accurate nulling because the lower 1Ω resistor is in parallel with two 100Ω resistors in series and so more current is fed to the output via these resistors.

A 200Ω resistor connected in parallel with the upper 1Ω resistor would correct for this, but the error is less than the tolerance of the components used, so this is a fairly minor inaccuracy. The finite open-loop gain of the output triples adds further inaccuracy. The four 100Ω feedback resistors in the output stage could be reduced to increase the loop gain, and in a higher power version this may be necessary because of the fall in current gain in the output power transistors at high currents.

The 1.8pF capacitor determines the level of overall negative feedback, giving 34dB at 20kHz and increasing at 6dB per octave at lower frequencies. Square wave ringing with a 2μF capacitive load was considered just about adequate with this level of feedback.

Driving the output stage

One aspect of this design, which is also important in other class-B amplifiers, is that the output stage has a non-linear input impedance. If the driver stage has a high output impedance, the loading effect of this non-linear impedance may add significant distortion at this point in the circuit.

The *OPA640* op-amp used in the present design has a specified open-loop output impedance of 25Ω, while the output triples will have an input impedance considerably higher than this. As a result, distortion from this source should be acceptably low.

Another source of distortion in conventional class-B amplifiers is known as 'dynamic crossover distortion'. The varying signal level causes changes in the output stage transistor temperatures which then cause a change in quiescent current. The thermal compensation circuits used inevitably involve some time delay and some inaccuracy, so that the quiescent current may differ significantly from its optimum value for much of the time, giving increased crossover distortion.

In the improved circuit the quiescent current is not critical, and even for wide variations crossover distortion should remain low.

The *BC184L* transistor in Fig. 5 was used to provide thermal compensation of the quiescent current in the normal way, and was glued to the *2SB648A*. The quiescent current was set so that when switched on from cold it started at 80mA, and was then found to slowly drift up to a little over 100mA after a few minutes. Additional stabilisation of I_Q was not necessary in this example, even though the current stability is poorer than in the standard circuit.

Adding stabilisation

Assuming you want it, there is a fairly simple way to add stabilisation by detecting the minimum current through the upper, class-A side of the output stage, and controlling the quiescent current to keep this minimum value above a certain level. The use of such stabilisation circuitry can avoid the need for any setting up of quiescent current and make

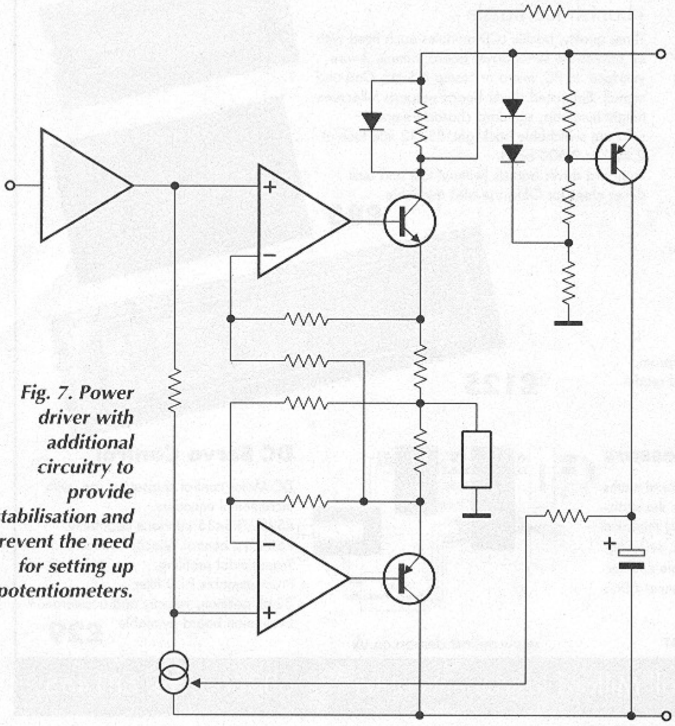


Fig. 7. Power driver with additional circuitry to provide stabilisation and prevent the need for setting up potentiometers.

possible an amplifier with no variable resistors requiring adjustment.

An example of the sort of stabilisation circuit possible is shown in **Fig. 7**. The controlled current source could be just a single npn transistor, but something a little more elaborate may be worthwhile so that the current is already set fairly accurately and the control circuit merely 'tweaks' it to keep it from drifting too far.

Although a quiescent current of 15mA was found to be adequate for low distortion in the prototype, a higher value is needed for two reasons. First, the observed drift from 80 to 100mA when the amplifier is warming up is not guaranteed to be the absolute maximum range of variation under all possible conditions, and some long term drift in component characteristics could add further to the range.

Secondly, even with 1% tolerance resistors in the output stage there could still be sufficient error on negative output currents to call for a little correction from the 'error amplifier', and the maximum correction current available in the negative direction is equal to the quiescent current.

A choice of 100mA seems a reasonable compromise. The maximum correction current required could be reduced by adjustment of the ratio of the two lower 100Ω resistors, i.e. those connected to the emitter of the *2SB648A*, but this is not a particularly simple adjustment to carry out and is unlikely be a great benefit to the performance.

Emitter resistor choice

The choice of 1Ω emitter resistors for the output power transistors is a compromise between quiescent current stability and power loss when feeding impedances below the nominal 8Ω. There are many loudspeakers available with highly inconvenient impedance characteristics, and general purpose audio amplifiers need to be able to cope with these without unacceptable deterioration in performance.

For such general use the present design may be considered inadequate, but being fortunate enough to use speakers with an undemanding impedance I chose to use 1Ω resistors. Even so, the resulting reduction in available output voltage at 4Ω load compared to 8Ω is under 1dB, so the effect is hardly a major concern.

For use with speakers with impedance falling much below 4Ω the resistors could probably be reduced to 0.5Ω without having to resorting to the sort of quiescent current stabilisation circuit mentioned earlier. Resistors with a value of 1Ω or 0.5Ω, 1% tolerance and a power rating of 2W or more are not readily available. Those used in my prototype were actually parallel combinations of higher values, i.e. four 3.9Ω, 0.6W 1% metal film components in parallel. Exact values of these two output resistors are of no importance – only their equality.

The inductor in series with the output is to reduce the effect of capacitive loads on loop stability. The component used was 17 turns, 8mm in diameter and 15mm long.

I chose the Burr-Brown *OPA604* because it has a maximum voltage rating of ±24V and I had a power supply available providing ±22V, giving maximum output power about 20W into 8Ω. I also find it a very good op-amp, designed for high-quality audio applications, with distortion rated at 0.0003% at 1kHz at unity gain. Its noise output is low, and it has a low open-loop output impedance as mentioned earlier. Gain bandwidth of the device is 20MHz.

In this application, output current is only taken from the op-amp in one direction, so the fact that it has a class-B output stage may not be a problem. No contribution to the distortion from this source was apparent in the tests.

The discrete option

A discrete input and driver stage might improve a little on the op-amp in some respects, but there seems little point in increasing circuit complexity to achieve even lower distortion if the distortion is of an innocuous variety which will have no audible effect. For higher output powers an op-amp input becomes less convenient and a discrete design more justifiable to achieve the required voltage swing.

The circuit presented here solves the most serious problems of class-B output stage design. I have only built a single prototype to demonstrate the operation of the output stage. Designing a commercial product would require more work, taking into account component tolerances to ensure repeatable results, and more detailed measurements.

One major advantage of the present design, which I hope any reader who knows otherwise will correct if I am mistaken, is that it is not the subject of any patent protection. It is therefore free to use by any amplifier manufacturer. As far as I am aware it was first published by myself in September 1996 in a low circulation magazine called 'Innovation and Speculation in Audio, Electronics and Physics', which regrettably is no longer available.

The fact that the design is so simple makes it hard to believe that it is a new idea, but at the very least it is not well known or in common use.

Why no listening tests?

Some of you may question the lack of listening tests. Well, the practical design was produced merely to demonstrate the success of the idea in reducing crossover distortion, rather than as a final commercial product. It is certain that if there is any audible difference between the two configurations tested it will be the improved version which will be the more correct. ■