60W NDFL AMPLIFIER

Following last month's article on nested differentiating feedback loops, here is a practical amplifier design, presented as a module, with very low distortion. Design by Edward M. Cherry, Associate Professor, Dept of Electrical Engineering, Monash University.

This amplifier will perhaps be of most interest to home constructors who want to rebuild an existing system and upgrade its performance without the expense of new major components. The power output transistors employed are the well-known types MJ802 and MJ4302 which have been around for several years and have proved their reliability. Indeed, the whole design is mature and home constructors should have no difficulty in making it work.

The theoretical basis for this amplifier was discussed in last month's ETI.

Grounding

In any amplifier where the basic distortion has been reduced to a few parts per million, several distortion mechanisms not ordinarily considered may become significant. One such mechanism is associated with currents circulating in the ground leads and power-supply wiring.

Figure 1 explains the origin of this distortion. The current in each power transistor of a class B stage is a half-wave rectified version of the output. The two currents, drawn in

![Fig. 1 Circulating even-harmonic current in a Class-B output stage.](image)

HOW IT WORKS

Figure 2 is the complete circuit of one channel of the amplifier; equations referred to in this explanation refer to last month's feature. The circuit is clearly based on Fig. 10 (last month's ETI), with major parameters

\[ 1/B = 32.9 \]

\[ R_1 = 800 \text{ R} \]

The value of the overall feedback resistors R11 and R12 (470k and 1k — see Equation 13), is set by:

a) R4 and R5 (3k8R) plus C6 and C8 (68pF) in conjunction with the chosen value of \( b \) (see Equation 13);

b) R15 and C7 (1k8 and 470p — see Equation 14);

c) R12 and C4 (4k52 and 100n) plus the 8 ohm nominal load and L3 (6uH);

d) R12 and C4 (15k and 33p) via the other constants in Equation 15.

The first stage requires little comment. Q1 and Q2 operate at 1.5 mA each, Q3 is a current source, Q4 is a common-base stage to equalize the quiescent voltages on Q1 and Q2. Q5 and Q6 constitute a current mirror. R1 and C2 form a 200 kHz low-pass filter against RF interference.

The Rush current amplifier operates at 3 mA, set by R18, and it incorporates a catching diode (D1) to accelerate recovery from overdrive. The pre-driver, Q10, operates at 8 mA; Q9 protects the stage against damagingly large currents under fault conditions. Driver quiescent current is 25 mA, set by R28.

Transistors Q12 and Q13 provide short-term protection for the power transistors. Short-circuit current is limited to about 4 A, and peak signal current is limited to 7 A. Long-term protection is provided by 2 A fuses in each supply rail: these should be "ordinary" types, rather than delay or quick-blow.

In the unlikely event of transistor failure, these fuse the loudspeaker current to 2 A, corresponding to 32 W into 8 ohms.

The common alternative of a single fuse in the loudspeaker lead is less satisfactory: it provides less protection for the amplifier: it provides less protection for the loudspeaker as the fuse must be rated to carry the full signal current, and it introduces distortion on large-amplitude, low-frequency signals.

LOW FREQUENCY COMPENSATION

A feature of Fig. 2 not discussed so far is a low-frequency compensating circuit, R13 and C5. Amplifiers of the basic circuit topology of Fig. 2 (last month) have a group delay which is different for different signal frequencies. Some frequencies take longer or shorter times than others to pass through the amplifier. High-frequency group delay in NDFL amplifiers can be corrected, as described last month, by a small capacitor in the feedback network (see Equation 15). Errors in low-frequency group delay, in both Figures 2 and 10 (last month) are associated with the input coupling capacitor and the capacitor in series with R4. Low-frequency square-wave inputs are reproduced with a "lift" as in Fig. 3a.

One approach to this problem is to use a truly direct-coupled amplifier, with no capacitors in series with the signal path: commercial audio power amplifiers of this type appeared in the 1970s. Unfortunately, such amplifiers are prone to drift. A DC voltage may appear at the output even when there is no input. Although it is possible to reduce drift in a power amplifier to an acceptable level, it is not possible with today's technology to build a system that is truly direct-coupled from pick-up input, through the RIAA network and the power amplifier.

In the last few years a generation of amplifiers has appeared which include some form of servo amplifier to correct the drift. All circuits known to the author re-introduce the problem of group delay, albeit in a lesser form.

The approach adopted in the design is to retain the coupling capacitors and thereby eliminate drift, but include a group-delay correcting circuit. Figure 4 shows the outline. Group delay is optimally compensated if:

\[ R_0 = 2 \frac{R}{R+R_C} \quad (16) \]

\[ R_C = \frac{R}{R+R_C} \quad (17) \]

Figure 3b shows the improvement in square-wave response.

Low-frequency group-delay compensation could well be included in audio power amplifiers and preamplifiers other than NDFL types.
Fig. 2 Circuit diagram of the 60 W power amp. Components marked with a single asterisk are not mounted on the PCB.

Fig. 3a Square wave response of the amp without group-delay compensation.

Fig. 3b Square wave response of the amp with group-delay compensation — note the improvement over Fig. 3a.

Fig. 4 Circuit for compensating low frequency group delay: (a) basic uncompensated circuit; (b) compensated circuit.

alternatively from the positive and negative supplies, are equivalent to a circulating full-wave rectified current and this is basically an even-harmonic distortion of the signal output. If there is any mutual inductance between the powersupply wiring (including the grounds) and the signal wiring (also including the grounds), then an even-harmonic distortion is induced in the amplifier and feedback is powerless to correct it.

The circuit board has been laid out so as to minimise this effect. The areas enclosed by some tracks are critical, and home constructors making their own PCBs are cautioned to follow the layout exactly; use the foil pattern on page 84, or, better still, purchase a ready made board.

Note that the circuit uses three distinct ground symbols.

a) is the quiet ground track on the circuit board (one per channel).

b) is the noisy ground track on the circuit board (one per channel).

c) is the metal chassis ground (there are six connections to the chassis in total).

Each channel is connected to chassis ground at two points. The input socket is connected to the chassis (rather than insulated from it); the input lead from socket to circuit board is screened, and the quiet ground track is connected to chassis ground at the input socket via the screen. Similarly, the ground output terminal is screwed into the chassis, the leads from the circuit board to the output terminals are a twisted pair and the noisy ground track is connected to chassis ground at the output terminals via the ground output lead. The remaining two connections to chassis are in the power supply (Fig. 5).

Note that a 10 ohm resistor, R31, links the quiet and noisy ground tracks. This resistor is short circuited at low frequencies by the input screen and neutral output wiring to chassis ground. However, the resistor takes over at high frequencies where wiring inductance become significant.

Fig. 5 Suggested PSU for the amplifier. Alternatively, see next month’s ETI for a better choice.
The 15pF filter inductors in the supply rails are also for suppressing circulating currents (R6 and R7 represent the winding resistances of L1 and L2). This amplifier employs only two nested differentiating feedback loops and its distortion is not down to the ultimate limit. The benefit of including the filter inductors is therefore marginal. The author is not blessed with ‘golden ears’ and cannot hear the effect of removing the filters, although the difference is clearly measurable. The filters should certainly be included in amplifiers that use three or more NDPLS. As the inductors must be home-made, and therefore cost nothing but time, and as they do make a measurable (if small) improvement, most home constructors will probably wish to include them. Winding data is given in Table 1.

The precise values of inductance and resistance are not important — ±50% is good enough — but do not use the 1.25 mm wire from L3 as something like 0.1 ohm series resistance is essential. For a similar reason, do not parallel the 470µF bypass capacitors C9 and C10 with high-frequency types. Brass or steel mounting screws are perfectly satisfactory for the filter inductors, as linearity is not important.

Critical Components

The majority of the components in this amplifier are not critical. Almost any small-signal diodes will do, such as the 1S44, 1N914, and 1N4148. Q1 and Q2 should be high-gain, low-noise types — BC109 and BC549 are among the cheapest available. The others could be almost any small signal types: BC107 and BC547 are readily available NPN types, the BC177 and BC557 are suitable PNP. The driver and output transistors should be the types shown: BD139 and BD140 for the drivers, MJ802 and MJ4502 for the power transistors. The biasing transistor, Q11, could be any NPN in a TO-126 can that can be mounted on the heatsink: the BD135 and BD139 are readily available types that would suit. Unless the contrary is indicated on the Parts List, resistors can be standard 3W types and the capacitors can be the lowest available working voltage. A few components, however, do require special mention. A feedback amplifier cannot be more linear than its feedback network, so the various components that constitute the feedback network should have small voltage coefficients. Specifically:

- a The overall feedback resistors R11 and R12 should be high-stability types, such as metal oxide or metal film;
- b) C4, C6 and C8 should be NPO ceramics, not high-K types (NPO means negative-positive-zero, a low-K capacitor with a very low temperature coefficient; metallised plate ceramics, for example. Silvered mica capacitors are also suitable;
- c) C5 and C14 should be polycarbonate, polystyrene or polypropylene types, but not polyester (eg mylar types);
- d) C3 should be an ordinary cheap aluminium electrolytic, definitely not one of the relatively expensive resin-dipped tantalum types (this is not a misprint).

TABLE 1

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Rated output</th>
<th>20 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>19 ppm</td>
<td>5 ppm</td>
</tr>
<tr>
<td>3rd</td>
<td>14 ppm</td>
<td>3.5 ppm</td>
</tr>
<tr>
<td>4th</td>
<td>2.5 ppm</td>
<td>2.5 ppm</td>
</tr>
<tr>
<td>5th</td>
<td>3.0 ppm</td>
<td>1.5 ppm</td>
</tr>
<tr>
<td>6th</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>7th</td>
<td>1.8 ppm</td>
<td>1.8 ppm</td>
</tr>
<tr>
<td>8th</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>9th</td>
<td>1.0 ppm</td>
<td>1.0 ppm</td>
</tr>
<tr>
<td>10th</td>
<td>1.0 ppm</td>
<td>1.0 ppm</td>
</tr>
</tbody>
</table>

Notice how the harmonics drop away at small signal amplitude. In this regard a class-B NDPL amplifier is more like a conventional class-A amplifier than a class-B amplifier.

1 ppm = 0.0001%.

HARMONIC ANALYSIS AT 6 kHz

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Rated output</th>
<th>20 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>115 ppm</td>
<td>40 ppm</td>
</tr>
<tr>
<td>3rd</td>
<td>100 ppm</td>
<td>25 ppm</td>
</tr>
<tr>
<td>4th</td>
<td>32 ppm</td>
<td>15 ppm</td>
</tr>
<tr>
<td>5th</td>
<td>40 ppm</td>
<td>9 ppm</td>
</tr>
</tbody>
</table>

Harmonics higher than the 3rd are ultrasonic and hence inaudible.

BUYLINES

Amongst the semiconductors, only Q16 (MJ802) and Q17 (MJ4502) could possibly present problems: these are both available from Bradley Marshall, Cricklewood and Technomatic. Some care will be needed in ordering the capacitors mentioned as critical, though the types should not be that hard to find. The PCB is available through the ETI PCB service on page 87.

PATENT PROTECTION

The principle of nested differentiating feedback loops, on which this amplifier depends, is patented in Britain and principal overseas countries. Commercial enquiries should, in the first instance, be directed to the Legal Office, Monash University, Clayton, Victoria 3166, Australia.
The 6u8 H inductor (L3) needs to be home-made. Winding data is given in Table 1. The bobbin should be mounted on the circuit board with a nylon screw; brass or steel must not be used, because of non-linear eddy current losses.

Construction
Assembly of the PCB is quite straightforward. It is probably best to commence by soldering all the resistors in place. Note that R32 could be either a 2 W type (not common) or two 1 W resistors (15R and 18R) in parallel. Note that the emitter ballast resistors of Q16 and Q17 (R29 and R30) should have very low inductance and if you have trouble with high frequency instability, these resistors are likely to be the culprit. The best solution may be several carbon resistors in parallel. Mount R29 and R30 a few millimetres above the board.

Assemble the diodes next, making sure you get them all the right way round. Install the links next. Follow with the capacitors. Note that C3 and C14 must be polycarbonate types and C4, 6 and 8 must be NPO ceramics. None of the other ceramic capacitors should be hi-K types, as mentioned earlier. When mounting C9 and C11, see that there is three or four millimetres between the capacitor body and the adjacent 5 W resistors (R29 and R30) to allow for.
convection around the latter.

The transistors may be mounted now. See that each is oriented correctly, 60N13 next and mount it on the board. Details are given in Table 1. It is not necessary to strictly follow the former dimensions given, but the inductance needs to be close to 6uH and wound from 1.25 mm wire at least, for low resistance.

Assembly of the components mounted to the heatsink comes next. The heatsinks in the original were a standard type sold by many companies and masquerading under such names as type 6W-1 (Maplin) or RS 401-807. Each heatsink has a thermal resistance to ambient of about 1°C/W, and other types could, of course, be substituted. The specified thermal resistance permits continuous operation at full power: smaller heatsinks (up to 2°C/W) could be substituted if the amplifier is to be used only for domestic sound reproduction. Use one heatsink per channel.

Three small components are mounted on the heatsink adjacent to the transistors to keep certain leads short: R28, C12 and C13. Construction is very much simplified if a 4-way panel is installed under one of the collector mounting bolts of Q16 and a 5-way strip under one of Q17's mounting bolts. Figure 8 shows details.

The collector and emitter leads from each power transistor to the circuit board should be twisted. The base leads to Q14 and Q15 could be twisted in with the corresponding collector and emitter leads (although this is not necessary) and the base lead of Q11 can be kept separate. Note that all transistors must be insulated from the heatsink. Note also that the BD140 specified for Q10 needs its leads dressed to fit the board.

Quiescent current in the power transistors should be set to 40-60 mA by PR1. Be warned that this quiescent current is almost zero until PR1 is about three-quarters of its maximum resistance, after which the current increases very rapidly; be sure that PR1 is set to minimum resistance when the amplifier is turned on for the first time.

A convenient way to check the quiescent current is by means of the voltage drop across R29 and R30; this should be 40-60 mV (total) for zero signal input to the amplifier.

See the June ETI for details of a complete NDFL amplifier system.
PCB FOIL PATTERNS

ETI BALANCED DIFFERENTIAL INPUT PREAMP

ETI NDNL

ETI DUAL PSU

ETI SINGLE PSU

Above: the elusive meter scale artwork for last month's Max/Min Thermometer.

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