equa amplifier

Literally thousands of circuits for transistor-amplifiers have been developed, all of which were later marketed under the banner of hifi. The brands that meet the Equa-standards laid down in this issue can, however, be counted on the fingers of one — possibly two — hands.

A feedback loudspeaker system ('electronic loudspeaker') places very strict requirements on the associated amplifier. This consideration, among others, led the editors to develop an equa-amplifier, with a circuit that could be easily adapted to give any output power up to 100 Watts.

A high quality amplifier must meet several requirements that are not laid down by the DIN standard for so-called hifi-amplifiers. With present techniques it is not very difficult to build an amplifier to satisfy these requirements.

Quality requirements

In the first place, the amplitude-frequency response curve of an amplifier should be flat over the entire audio-range, say from 30 to 20000 Hz. Outside this range the curve must remain 'smooth', which is actually the result of meeting a requirement placed upon the phase-frequency response inside the range. (This latter point is the vital one; but the amplitude curve is easier to measure). A rolloff slope of, say, 12 dB/octave below 30 Hz and above 20 kHz will not in itself influence the quality. (It will frequently prevent subsonic or ultrasonic overdriving, and produce an audible improvement.)

Secondly, the distortion must be so low that it cannot be detected by ear. The threshold for this is typically 0.5 to 1%. A problem here is that our hearing responds to the amplitude (i.e. peak level) of a distortion component and not to its RMS level. Therefore, the amplitude of any distortion component must remain below 0.5%. The usual distortion measurement gives the RMS result of all unwanted components; this does not always give a meaningful, never mind accurate, impression. We will return to this point in a moment.

Finally, we must also set up a requirement about reliability. This can be summed up in general terms as follows: the amplifier must be unconditionally stable, with any load; it must also be protected internally against overdriving, excessive loading and voltage surges by inductive loads.

The output stage

In principle, output stages can be built in many ways. With two or more transistors, a super-emitter-follower, the so-called Darlington pair, can be made. In figure 1a this is shown for two NPN transistors; figure 1b shows the perfectly complementary arrangement using PNP transistors.

Another possibility is to use complementary transistors in each half of the output stage. This principle is shown in figure 2a with an NPN power transistor, and in figure 2b with a PNP power device. These circuits can be seen as amplifiers with fairly high open-loop gain, using 100% negative feedback to achieve a voltage gain of unity. This behaviour resembles that of an emitter-follower; the performance is however rather better, particularly with small signals.

A very popular output stage configuration is the combination of figure 1a with figure 2a to form the 'quasi-complementary' arrangement. This has the advantage that the power transistors are identical NPN types, which are usually easier and cheaper to get hold of than their PNP complements. It has the serious disadvantage, however, that the two halves are not really complementary — which invariably causes increased distortion.

The half stages of figures 1a and b — two Darlington arrangements — can be combined to provide a perfectly complementary circuit. The combination of figures 2a and 2b is, however, the preferred arrangement. The individual circuits themselves are better than Darlingtons, and the complete output stage is also complementarily symmetrical. This arrangement therefore was chosen for the Equa-amplifier.

The Law of Cussedness requires that this circuit should also have objectionable aspects. Well, is has. One practical objection is that the output is taken from the power-transistor collectors, which means that the device cooling surfaces carry audio voltage. To avoid stability problems the transistor must be insulated by mica washers, and the heatsink itself should be connected to circuit earth.

Crossover distortion

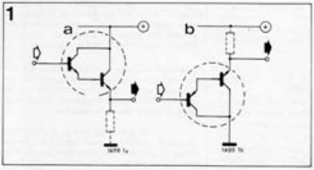
The distortion in a power amplifier is usually determined by the output stage. One well-known effect is (primary) crossover distortion. This occurs with class B output stages in the neighbourhood of zero-crossing of the signal waveform. Both halves of the stage are then operating in the non-linear area close to cut-off. To avoid distortion it must be arranged that the stage-gain (actually its transconductance) does not vary with the position on the signal waveform. At greater excursions one half of the output stage is amplifying and the other is cut off. The active half will show its ultimate value of transconductance (or 'slope') over most of its working range.

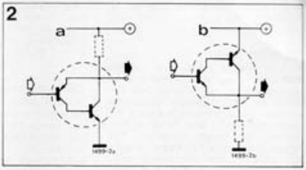
If the stage is sufficiently symmetrical, the ultimate slope will be essentially the same for both directions of swing. In the 'crossover' region near the zero-crossings both stage halve will conduct. This can lead to three situations (see figure 3): the sum of the two slopes can be greater, less than or equal to the ultimate slope of one half stage during greater excursions. Clearly, it is the third situation that is required for minimum distortion. This condition is most closely approached by arranging that both sections amplify with half their ultimate slope at the actual point of zero crossing. This is achieved by, among other things, setting the correct value of standing ('quiescent') current.

Secondary crossover

Less well-known is the so-called secondary crossover distortion. This is caused by charge-storage in the bases of, mainly, the output transistors. The effect is that the output sections 'cut off too late' and 'turn on too late'. It produces short distortion notches, shown for one half stage in figure 4 (exaggerated for clarity). This distortion is virtually ignored by the 'normal' distortion measurement!

The DIN standard specifies a measurement of the RMS value of the total of distortion products. Suppose now that the amplitude of these notches is 5% (!) of the signal amplitude. This is distinctly audible. During each cycle there will be only two notches, which are very short. Suppose now that the total notchtime is one fiftieth of a cycle.





An RMS measurement now gives the effective value as a proportion of the total effective value – less than 0.1%. Such an amplifier therefore meets the hifi-standards and may be sold as a hifi instrument. But a high-quality amplifier it is not! In the Equa-amplifier certain precautions are taken to keep this kind of distortion as low as possible.

A first good step in this direction is to introduce low-value resistors between base and emitter of the output transistors. This allows the charge to flow off more quickly.

After this, compensation networks are inserted in the emitter circuits of the driver transistors. These networks are designed to simulate the output transistor's base-emitter junction with its shunt resistor.

One half of the output stage then has the circuit shown in figure 5. The choice of diode and other components depends on the properties of the associated power transistor. The idea is to select the values so that, provided an output transistor of the specified type is used, the worstcase total amplitude of the distortion will be less than 0.1%. Using good instruments it is possible to trim up an individual amplifier to about 0.01%! One must, however, have access to a good distortion-

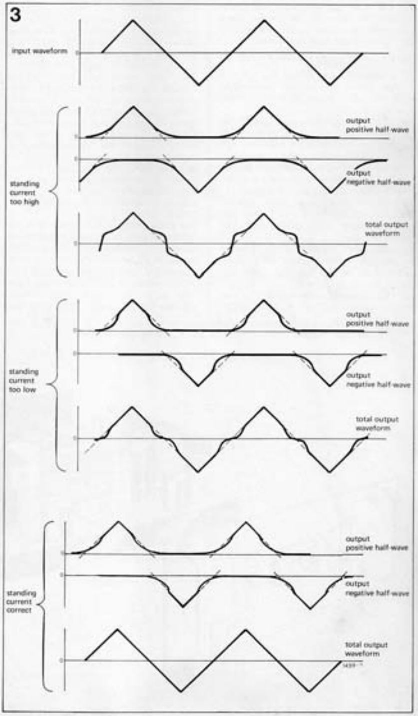


Figure 1. The Darlington circuit for one half of an output stage. It can be built up using two NPN (a) or two PNP (b) transistors.

Figure 2. An alternative circuit for output stage-halves. One half is built up using a PNP followed by an NPN, vice versa.

Figure 3. Three possible cross-over characteristics, depending on how the output transistors are biassed. The output signal is always the sum of the signals from the two stage-halves.

meter, a low-distortion oscillator and an oscilloscope. We hope to publish designs for such instruments shortly.

Protection circuits

Each half of the output stage is fitted with a protection circuit. Figure 6 shows the arrangement for the upper half. The circuit has three functions. Overdriving the input and/or excessively loading the output will cause a large current to flow through the output transistors. The voltage drop across the emitter resistor R_{16} appears between the points B and C. If this voltage drop exceeds about 1 volt, T_6 will start to conduct. This short-circuits the drive to the output stage and limits the output current swing. The maximum output current is about

$I_{max} = \frac{1}{R_{16} \text{ (or } R_{17})}$ ampères for positive (or negative) swing. Taking $R_{16} = R_{17} =$ 1 ohm makes this current about 1 A; with the values $R_{16} = R_{17} = 0.22$ ohm it approaches 5 A.

The third function is connected with the experience that back e.m.f.s. produced by inductances at the output can blow out the driver transistors; the base-emitter junction is exposed to an excessive reverse bias and the resulting breakdown destroys the transistor. In this amplifier, when the base-emitter voltage of T_8 goes negative, the base-collector junction of T_6 becomes forward-biassed. This safely limits the reverse bias on T_8.

For high-power versions it is advisable to add 1 k series resistors in the base connections of T_5 and T_6. These are shown dashed in figure 8.

An extra protection by means of a fuse in the supply rail is not just luxury. Strictly speaking it is unnecessary, but it does provide a convenient measuring-point for the standing current. The milliammeter can be simply connected in place of the fuse.

The complete amplifier

Figure 8 shows the complete circuit of the amplifier. Several details meet the eye that have not been discussed as yet. The four capacitors C_4, C_5, C_6 and C_7 are included to control and improve the high-frequency performance of the circuit (stability and impulse response in particular).

The feedback resistors R_5 and R_6 determine the amplification. This is set by the specified values at about x20. Reducing the value of R_5 is allowed; it will increase the gain (and therefore the input sensitivity!) but will also increase the distortion. For this reason a minimum value of 100 ohm is specified for R_5. The distortion is then still acceptable while the gain is in the order of 100.

Transistor T_2 controls the output stage standing current; the required value is set by adjusting P_2. Before switching the amplifier on for the first time, P_2 should be set at minimum. The amplifier can then be switched on and the correct quiescent current set in accordance to table 2.

The circuit around T_4 is unusual in this application. It is shown separately in figure 7a. Fundamentally it is a combination of a current-source and a gyrator, providing a fairly high impedance for the collector load of T_3. This enables T_3 to fully drive the output stage without 'running out of current'. The usual way

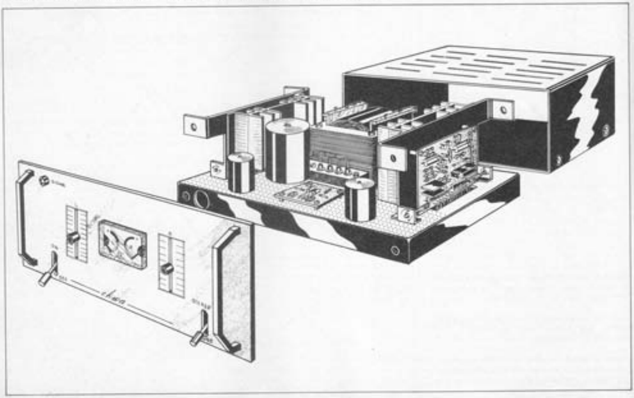
Figure 4. The signal from one half of an output stage. The secondary crossover distortion is clearly visible as small notches superimposed on the half-sinewave. A 'normal' distortion-measurement virtually ignores this effect.

Figure 5. The same circuit as figure 2, but now including the compensation-networks. The correct component values depend on the characteristics of the power transistors. This arrangement is used in the equa-amplifier.

Figure 6. The protection circuit. A network of this kind is added to each half of the output stage. It protects the amplifier against overdriving, excessive loading and inductive back-voltages at the output.

Figure 7. To achieve a high collector feed-impedance for the pre-driver transistor T_3 the combination of gyrator and current-source shown in figure 7a may be used. The classic solution is 'bootstrapping' as shown in figure 7b. We believe the first circuit is preferable, but the circuit board can be used with either.

Figure 8. The complete amplifier. With the specified power transistors the maximum output power rating is about 100 watts into 4 ohms. The compensation network is designed to match these transistors.



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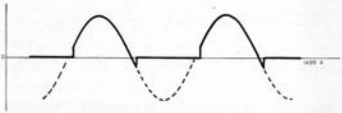
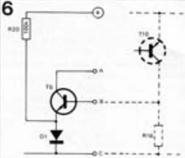
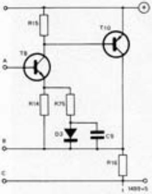

0
1499 4

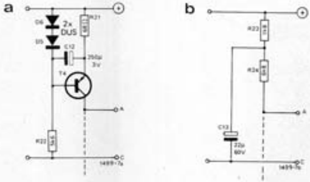
6


R20
T10
A
T6
B
D1
R16
C

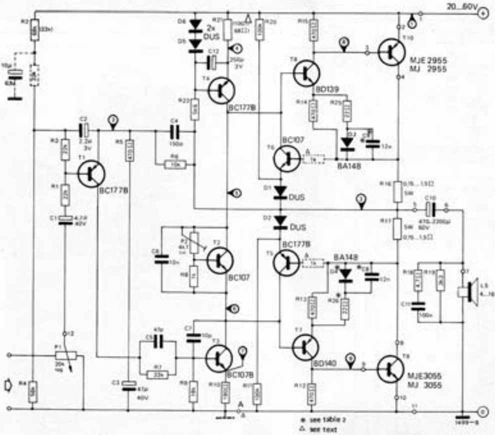
5


R15
T10
T8
A
R14
R25
D3
C9
B
R16
C
1499-5

7


a
D6
2x
DUS
D5
R21
C12
250µ
3V
T4
A
R22
C
1499-7a
b
R23
R24
A
C12
22µ
60V
C
1499-7b

8


R2
68k
(33k)
10µ
63V
R3
27k
C2
2,2µ
3V
T1
BC177B
R1
22k
C1
4,7µ
40V
P1
20k
log
R4
56k
R5
470Ω
C3
47µ
40V
C4
150n
R6
10k
C5
47p
R7
22k
C7
10p
R9
18k
T3
BC107B
R10
180Ω
A
D6
2x
DUS
D5
R21
(100Ω)
68Ω
C12
250µ
3V
T4
BC177B
R22
5k6
C6
10n
P2
4k7
lin
R8
1k
T2
BC107
R20
100k
R11
100k
R15
470Ω
T8
BD139
R14
470Ω
R25
27Ω
D3
C9
12n
T6
BC107
1k
BA148
D1
DUS
D2
DUS
T5
BC177B
1k
BA148
D4
C8
12n
R13
470Ω
R26
27Ω
T7
BD140
R12
470Ω
T10
MJE 2955
MJ 2955
R16
0,15 ... 1,5Ω
5W
C10
470...2200µ
60V
R17
5W
0,15 ... 1,5Ω
R18
4,7Ω
R19
3k3
C11
100n
LS
4 ... 16Ω
T9
MJE3055
MJ 3055
20 ... 60V
1
2
3
4
5
6
7
8
9
10
11
12
* see table 2
△ see text
1499-8

of providing this high impedance is the 'bootstrap' circuit shown in figure 7b. This latter circuit can be expected to have a greater instability-risk; but practical experience has yet to demonstrate any difference. The circuit board is suitable for either arrangement although, in our opinion, figure 7a is preferable.
Finally, the loudspeaker connection is parallelled by a network consisting of R_{18}, R_{19} and C_{11}. This guarantees the stability of the amplifier when it is operated without a load.

The proof of the pudding . . .

Several amplifiers were built according to this recipe, using randomly-chosen components. The worst-case measurement results were as follows:
Amplitude-frequency response curve flat within 1 dB from 20 Hz to 60 kHz.
Peak distortion level below 0.07% (typ. 0.03%).
Stability maintained for:
resistive load (all values from dead short to open circuit),
capacitative load from 10 pF to 1000 µF,
inductive load from 10 µH to 200 mH,
any combination of values.

Output power

The maximum output can be selected with the aid of table 1. As will be apparent, the absolute maximum is 100 watts (sine wave) into 4 ohms. For all normal listening in the sitting room how- ever, the 20 watt version is emphatically

Table 1. The required supply voltages and values of R_{16} and R_{17}, for various loudspeakers (nominal) impedances and output power ratings.

Output power (watt)	Loudspeaker impedance (ohm)	Supply voltage (volt)	R_{16}, R_{17} (ohm)
10	4 16	42	0.47
20	4 16	60	0.33
40	4 8	60	0.22
70	4 5	60	0.18
(100	4	60	0.15)

Table 2. A number of possible compensation networks, suitable for power transistors MJ(E) 2955/MJ(E)3055.

D_3,D_4	R_{25},R_{26}	C_8,C_9	Quiescent current	Remarks
1N4002	0 Ω	27 n	25 mA	recomm.
BA 148	22 Ω	12 n	25 mA	suitable
BY 127	10 Ω	x	40 mA	possible

Table 3.

Test points (Fig. 8)			
1	60	40	20
(R_{21}	100 Ω	82 Ω	68 Ω)
2	28	19	9.5
3	29	20	10.5
4		(+V_b – 0.7)	
5	30	21	11.5
6	28	19	9.5
7	1.25	1.5	1.85
8		(+V_b – 0.65)	
9	0.65	0.65	0.65

All voltages ± 10%

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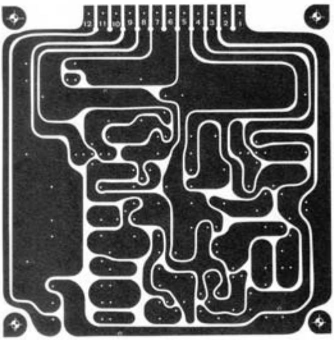

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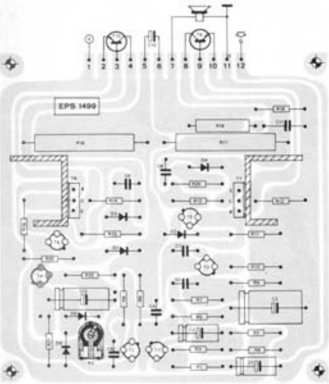


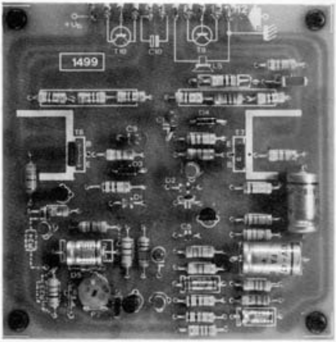
Figure 9. The printed circuit board for the amplifier.

Figure 10. The component layout for the amplifier, when the arrangement of figure 7a is used.

Figure 11. The component layout using the circuit in figure 7b.

recommended. It has been extensively tested with electrostatic loudspeakers and as the driver for the 'electronic' (feedback) loudspeaker, easily producing more than enough sound level.

The various voltages, currents, loudspeaker impedances etc. can be found from the output power nomogram, elsewhere in this issue. As will be obvious, the input sensitivity is equal to the output voltage V_{eff} divided by the amplification. For the 20 watt/8 Ω version for instance, V_{eff} is found to be 12.5 volts. The input sensitivity is therefore approx. $\frac{12.5}{20}$ = 625 mV.



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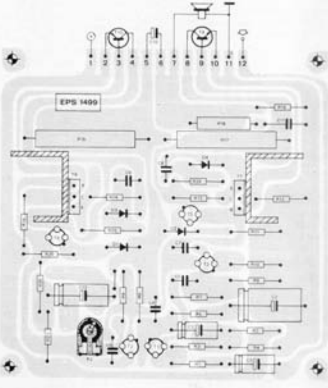

Parts list

Resistors:
R_1, R_3 = 22 k
R_2 = 68 k
R_4 = 56 k
R_5 = 470 Ω
R_6 = 10 k
R_7 = 33 k
R_8 = 1 k
R_9 = 18 k
R_{10} = 180 Ω
R_{11} = 100 k
$R_{12}, R_{13}, R_{14}, R_{15}$ = 470 Ω
R_{16}, R_{17} = 0.15 . . . 1.5 Ω
(see text and table 1)

R_{18} = 4.7 Ω
R_{19} = 3k3
R_{20} = 100 k
R_{21} = 68 . . . 100 Ω
R_{22} = 5k6
R_{23} = 1k8
R_{24} = 6k8
R_{25}, R_{26} = 22 Ω*
P_1 = 20 k log.
P_2 = 4k7 lin. (trim.)

* see text and table 2

Capacitors:
C_1 = 4.7 . . . 6.8 µ (40 . . . 70 V)
C_2 = 2.2 . . . 2.5 µ (2.5 . . . 70 V)
C3 = 47 µ (40 . . . 70 V)
C_4 = 150 p
C_5 = 47 p
C_6 = 10 n
C_7 = 10 p
C_8, C_9 = 12 n*
C_{10} = 470 . . . 2200 µ (60 . . . 80 V)
C_{11} = 100 n
C_{12} = 220 . . . 250 µ (2.5 . . . 16 V)
C_{13} = 16 µ (60 . . . 80 V)

Semiconductors:
T_1, T_4, T_5 = BC 177b
T_2, T_3, T_6 = BC 107
T_7 = BD 140
T_8 = BD 139
T_9 = MJ(E) 3055
T_{10} = MJ(E) 2955
D_1, D_2, D_5, D_6 = DUS
D_3, D_4 = BA 148*