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 MJ4502 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

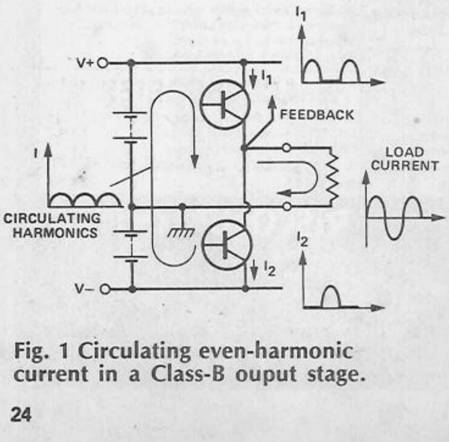

Fig. 1 Circulating even-harmonic current in a Class-B ouput stage.

HOW IT WORKS

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

$$1/\beta = 32.9$$
$$\tau_x = 800 \text{ nS}$$

The value of β is set by the overall feedback resistors R11 and R12 (470R and 15k — see Equation 1). τ_x is set by:

a) R4 and R5 (330R) plus C6 and C8 (68p) in conjunction with the chosen value of β (see Equation 13);

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

c) R32 and C14 (8R2 and 100n) plus the 8 ohm nominal load and L3 (6u8 H);

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 equalise 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 fuses limit 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 R_{F1}. Low-frequency square-wave inputs are reproduced with a 'tilt' 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 significant 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:

$$R_{F3} = 2\,R_{F2}\,, \qquad (16)$$
$$R_{F2}C_{F2} = R_{F1}C_{F1} \qquad (17)$$

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.

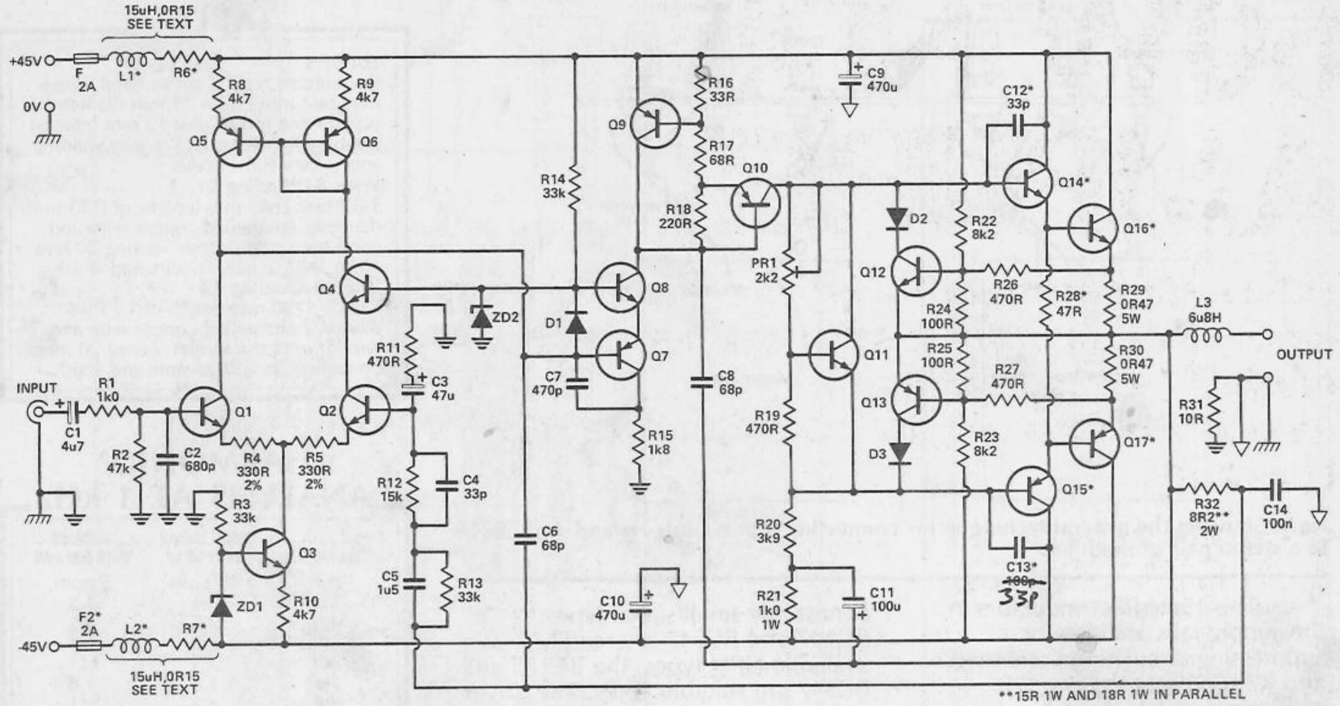

Fig. 2 Circuit diagram of the 60 W power amp. Components marked with a single asterisk are not mounted on the PCB.

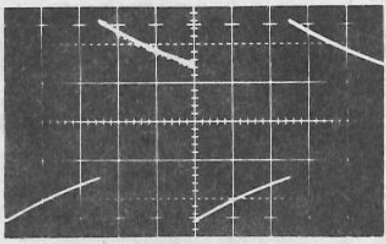

Fig. 3a Square wave response of the amp without group-delay compensation.

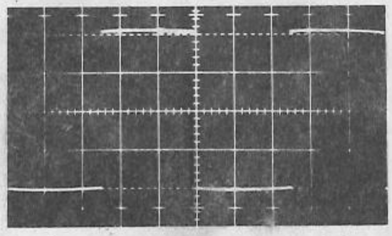

Fig. 3b Square wave response of the amp with group-delay compensation — note the improvement over Fig. 3a.

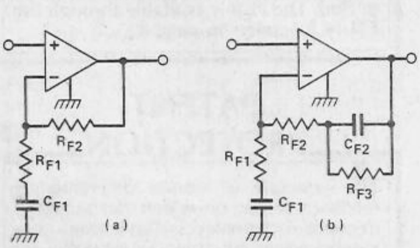

Fig. 4 Circuit for compensating low frequency group delay: (a) basic uncompensated circuit; (b) compensated circuit.

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 power-supply 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.

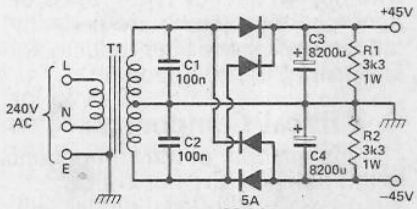

Fig. 5 Suggested PSU for the amplifier. Alternatively, see next month's ETI for a better choice.

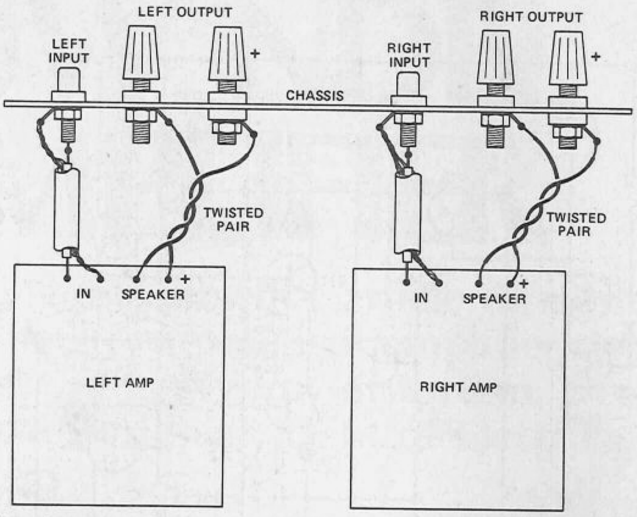

Fig. 6 Showing the general technique for connecting inputs, outputs and grounds to a stereo pair of modules.

The 15µH 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 NDFLs. 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 PNPs. 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 pack 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 $\frac{1}{2}$W 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

Formers
If a suitable type is not to hand, these may be turned from 25 mm diameter polystyrene rod to give 12 mm internal bobbin diameter with 7.5 mm winding space between cheeks.

Wire & Winding L1, 2
Take two 1680 mm lengths of 0.75 mm diameter enamelled copper wire and wind onto each former leaving 20 mm or so lead length at start and finish.

Wire & winding L3
Take a 1190 mm length of 1.25mm diameter enamelled copper wire and wind it onto the former. Leave 20 mm or so lead length at start and finish.

HARMONIC ANALYSIS AT 1 kHz

Harmonic	Rated output 21V9 60 W	– 20 dB 2V19 600 mW
2nd	19 ppm	5 ppm
3rd	14	3.5
4th	2.5	2.5
5th	3.0	1.5
6th	<1	<1
7th	1.8	1.8
8th	<1	<1
9th	1.0	<1
10th	1.8	<1

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

1 ppm = 0.0001%

HARMONIC ANALYSIS AT 6 kHz

Harmonic	Rated output 21V9 60 W	–20 dB 2V19 600 mW
2nd	115 ppm	40 ppm
3rd	100	25
4th	32	15
5th	40	9

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 3168, Australia.

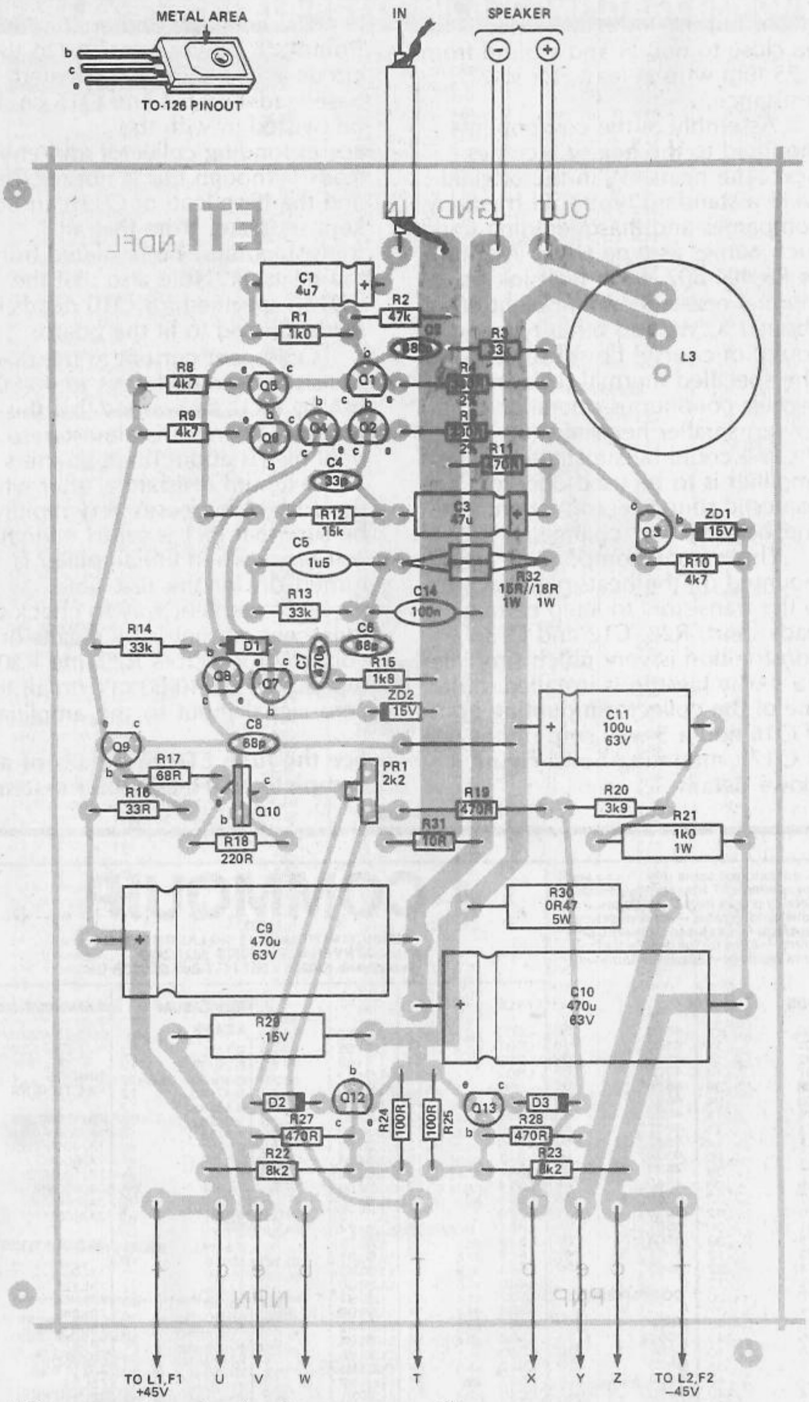

Fig. 7 Component overlay for the power amplifier.

PARTS LIST

Resistors (all ½W, 5% except where stated)	
R1	1k0
R2	47k
R3,13,14	33k
R4,5	330R 2%
R6,7	see text
R8-10	4k7
R11	470R metal oxide or metal film
R12	15k metal oxide or metal film
R15	1k8
R16	33R
R17	68R
R18	220R
R19,26,27	470R
R20	3k9
R21	1k0, 1 W
R22,23	8k2
R24,25	100R
R28	47R
R29,30	0R47, 5 W
R31	10R
R32	8R2, 2 W or 15R//18R, each 1 W
Potentiometer	
PR1	2k2 miniature vertical preset
Capacitors	
C1	4u7 axial electrolytic
C2	680pF ceramic
C3	47uF axial electrolytic
C4	33pF 100 V NPO ceramic
C5	1u5 polycarbonate
C6,8	68pF 100 V NPO ceramic
C7	470pF ceramic
C9,10	470uF 63 V axial electrolytic
C11	100uF 63 V axial electrolytic
C12,13	33pF 100 V ceramic
C14	100nF 100 V polycarbonate
Inductors	
L1, 2	15uH (see text and Table 1)
L3	6u8 H (see Table 1)
Semiconductors	
Q1,2	BC109, BC549 etc
Q3,4,8,12	BC107, BC547 etc
Q5-7,9,13	BC177, BC557 etc
Q11,14	BD139
Q10,15	BD140
Q16	MJ802
Q17	MJ4502
D1-3	1N4148, 1N914, 1S44 etc
ZD1,2	15 V 400 mW zener
Miscellaneous	
F1,2	2 A standard fuse
PCB (see Buylines); one 4-way and one 5-way tagstrip; heatsink to suit (see text); PCB stakes; bobbins for inductors; wire, etc.	

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 C5 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

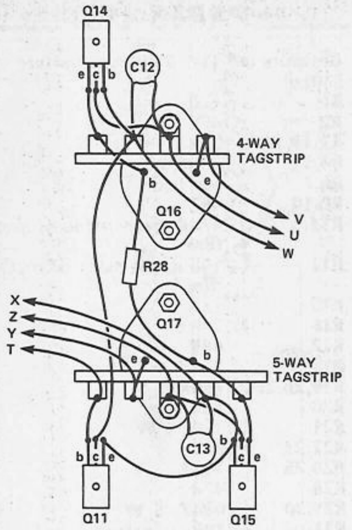

Fig. 8 Wiring diagram for the components mounted on the heatsink.

convection around the latter.

The transistors may be mounted now. See that each is oriented correctly. Wind L3 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 6u8 H 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 tagstrip 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. **ETI**

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709	25	LM3914	175
741	14	LM3915	195
748	35	LM13600	105
9400CJ	345	MC1496	68
AY-3-1270	710	MC3340	120
AT-3-8910	370	MF10CN	350
AY-3-8912	540	ML924	195
CA3046	60	NE529	225
CA3080	65	NE531	135
CA3089	190	NE544	180
CA3090AQ	370	NE555	16
CA3130E	85	NE556	45
CA3140E	36	NE565	110
CA3161E	100	NE566	140
CA3189	200	NE567	100
CA3240E	110	NE570	370
ICL7106	680	NE571	370
ICL7611	95	RC4136	55
ICL7621	180	RC4558	45
ICL7622	180	SL490	250
ICL8038	290	SL76477	380
ICL8211A	150	SP8629	250
ICM72224	775	TBA120S	70
ICM7555	80	TBA800	75
LF353	85	TBA810	95
LF356	90	TBA820	70
LM10	325	TBA950	220
LM301A	24	TDA1008	310
LM311	70	TDA1022	480
LM318	120	TDA1024	115
LM324	30	TL061	40
LM334Z	90	TL062	60
LM335Z	120	TL064	95
LM339	45	TL071	25
LM348	60	TL072	45
LM358	55	TL074	95
LM377	165	TL081	24
LM380	65	TL082	45
LM381	120	TL084	90
LM382	110	TL170	49
LM384	130	UA2240	115
LM386	65	ULN2003	75
LM387	120	ULN2004	75
LM393	95	XR2206	285
LM711	60	ZN414	79
LM725	325	ZN423	130
LM733	69	ZN424	130
LM747	60	ZN425E	340
LM1458	40	ZN426E	290
LM2917	185	ZN427E	575
LM3900	45	ZN428E	395

ZN459	285
ZN1034E	200

LOGIC ICs

AY-2376	590
MC1488	55
MC1489	55
MM5303	625
MM5307	1250
MM58174	700
TMS6011	365
ULN2003	75
8T26	99
8T28	120
8T95	90
8T97	90
81LS95	80
81LS96	80
81LS97	80
81LS98	85
6522	310
6532	675
6821	110
6845	650
6847	650
6850	110
6852	250
6875	485
8155	350
8212	110
8216	100
8224	110
8226	250
8228	220
8243	270
8250	865
8251	250
8253	400
8255	225
8257	400
8259	395
8279	385
8832	250
9602	220
Z80ACTC	260
Z80ADART	775
Z80ADMA	975
Z80AP10	270
ZN425E8	320
ZN426E8	320
ZN427E8	575
ZN428E8	395

CMOS

4000	11	4518	39
4001	11	4520	48
4002	11	4521	90
4007	14	4522	105
4008	34	4526	55
4009	24	4527	55
4011	11	4528	45
4011	11	4531	65
4012	14	4532	60
4013	20	4538	60
4015	39	4539	80
4016	20	4543	60
4017	32	4555	35
4020	42	4556	35
4021	39	4561	100
4022	39	4583	80
4023	12	4584	40
4024	32	4585	50
4025	12		
4027	20		
4028	37		
4029	43		
4035	45		
4040	40		
4042	38		
4043	40		
4044	40		
4049	21		
4050	22		
4051	42		
4052	48		
4053	48		
4066	22		
4068	14		
4069	13		
4071	13		
4072	13		
4073	13		
4075	13		
4076	44		
4078	13		
4081	12		
4082	12		
4093	23		
4099	70		
4502	50		
4508	110		
4510	45		
4511	45		
4512	42		
4514	110		
4515	110		
4516	50		

COMPUTER ICs

1802	650
2650A	1175
6502	320
6800	220
6802	250
6809	615
8035	345
8060	1090
8080A	250
8085A	345
Z80A	315

MEMORIES

2101	395
2114(220ns)	85
2532	295
2708	225
2564	1000
2708	225
2716(5V)	210
2764	750
4116(200ns)	80
4118-3	325
4164	420
5101(450ns)	150
5204	725
6116(150ns)	375
6514	330
6810	115

74LS

LS00	11	LS153	38
LS01	11	LS155	29
LS02	11	LS156	33
LS03	11	LS157	25
LS04	12	LS158	27
LS05	12	LS160	30
LS08	12	LS161	35
LS09	12	LS162	35
LS10	12	LS163	35
LS11	12	LS164	40
LS12	12	LS165	50
LS14	22	LS168	80
LS15	12	LS170	70
LS20	12	LS173	47
LS21	12	LS174	36
LS22	12	LS175	36
LS27	12	LS181	87
LS28	14	LS183	05
LS30	12	LS190	35
LS32	13	LS191	35
LS33	14	LS192	35
LS37	14	LS193	36
LS38	14	LS194	32
LS40	12	LS195	32
LS42	28	LS196	43
LS47	35	LS197	45
LS48	40	LS221	50
LS49	50	LS240	55
LS51	14	LS241	55
LS54	14	LS242	55
LS55	14	LS243	55
LS74	16	LS244	55
LS75	16	LS245	70
LS76	16	LS251	28
LS78	17	LS253	30
LS83	33	LS257	29
LS85	39	LS258	32
LS86	15	LS259	53
LS90	22	LS266	18
LS92	25	LS273	53
LS93	22	LS279	30
LS95	36	LS283	38
LS109	21	LS290	40
LS112	20	LS293	40
LS113	20	LS365	27
LS114	21	LS366	27
LS123	34	LS367	27
LS125	24	LS368	27
LS126	25		
LS123	29		
LS136	23		
LS138	24		
LS139	27		
LS151	30		

MICRO-MINI 100V CERAM PLATE CAPS

1pF 10nF	7

TANTALUM

BEADS

0.1/35	12
0.22/35	12
0.33/35	12
0.47/35	12
0.68/35	12
1.0/35	12
1.5/35	14
2.2/35	16
3.3/35	17
10/25	18
15/25	28
2.2/16	14
3.3/16	14
4.7/16	16
6.8/16	16
10/16	18
15/16	27
22/15	27
33/16	40
47/16	40
100/16	75
15/10	22
22/10	24
33/10	30
47/10	35
100/10	55
100/6.3	42

63V MINI MONOLYTHIC CERAMIC

10nF	10
22nF	10
33nF	10
47nF	10
68nF	10
100nF	14

DIODES

0A47	10
1N4001	4
1N4002	4
1N4003	5
1N4004	5
1N4005	6
1N4006	7
1N4148	2
1N5401	12
1N5404	14
1N5406	17
1N5408	19

ZENER DIODES

2V7-33V 500MW	7
5V1-75V 1.3W	14

BRIDGE RECTIFIERS

1A/100V	20
1A/200V	23
1A/400V	25
1A/800V	38
2A/100V	36
2A/200V	40
2A/400V	40
2A/800V	52

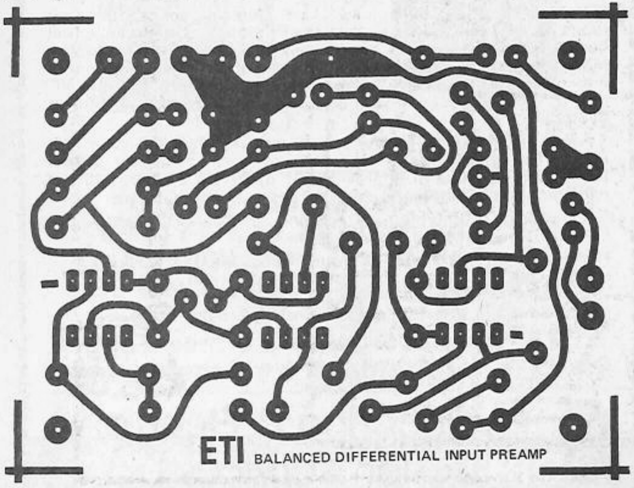
REGULATORS

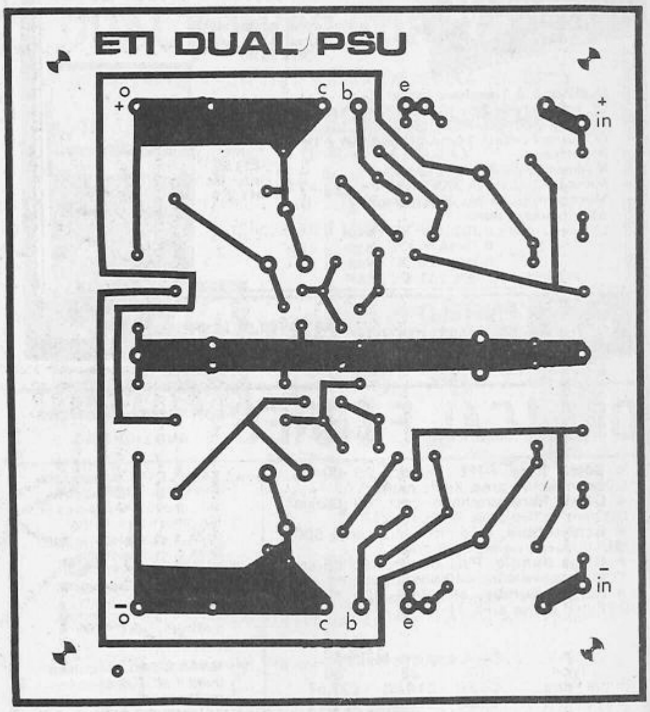
78L05	30
78L12	30
78L15	30
78L24	30
7805T	36
7812T	36
7815T	36
7824T	36
79L05	60
79L12	60
79L15	60
7905T	42
7912T	42
7915T	42
7924T	42
LM309K	130
LM317	270
LM317T	120
LM323K	350
LM723	35
78H05-5A/5V	550

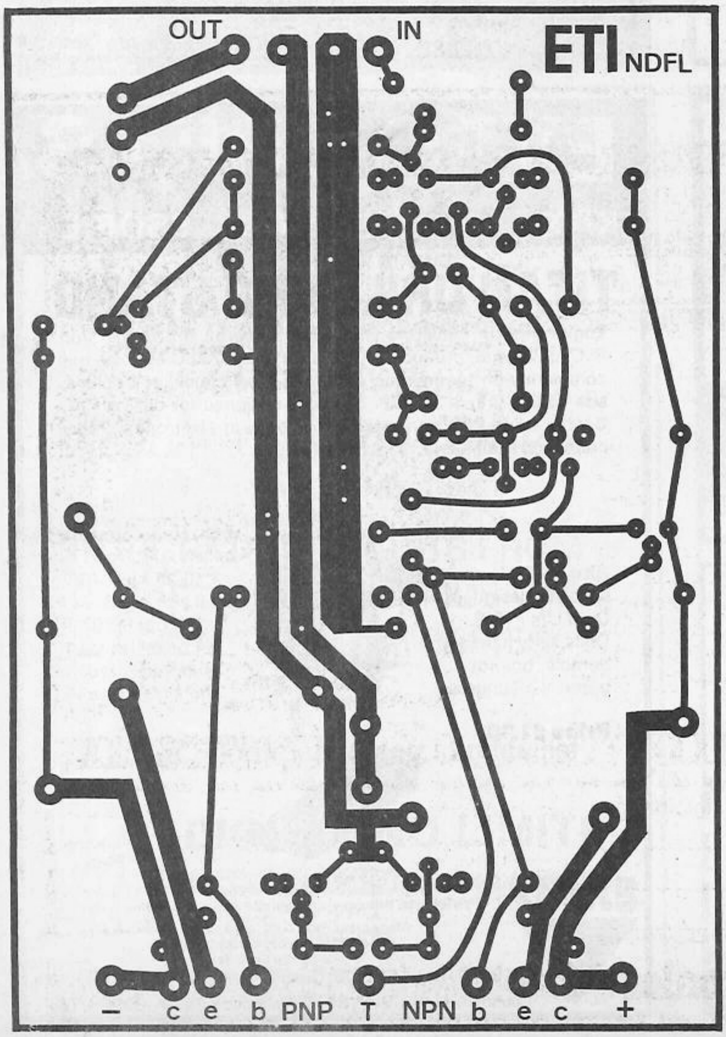
RESISTORS

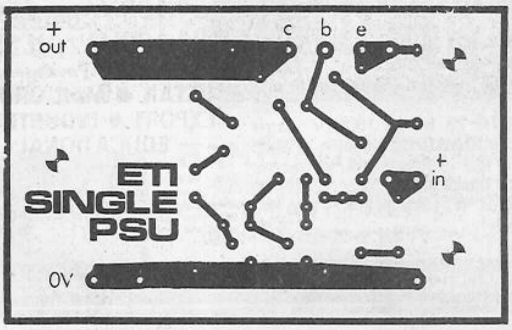
Carbon Film, High Stab 5%	
¼W 10-M	2
½W 10-10M	2
Metal Oxide/Film	
2% Met. Film E24	5
1% Met. Film E24	8

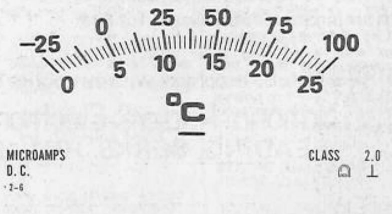
PCB FOIL PATTERNS











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