Project 477

MOSFET power amplifier **Part 1.**

Employing recently released Hitachi MOSFETs, this power amplifier features a 'no compromise' design, is rated to deliver 150 W RMS maximum and features extremely low harmonic, transient and intermodulation distortion. As the circuit techniques and design problems will be unfamiliar to many readers, a thorough discussion of the theory and problems is included.

David Tilbrook

THE ENORMOUS SUCCESS of the series 4000/1 four-way loudspeaker has surprised even us. They were originally intended to be the 'flagship' of a range of loudspeakers and quite frankly we expected the biggest demand to be for the cheaper loudspeakers further down the range. This has proved not to be the case as sales of four-way kits continue to rise. It is evident that there is a big demand for the higher quality audio projects. We recognised this demand and eight months ago began the development of the Series 5000 power amp and preamp. The objective was to design an amplifier for home construction of the highest possible quality. The cost of the project was a secondary consideration, although in real terms the cost saving in "doing it yourself" is considerable.

discussion

Defining the problem

Of all the stages in the amplifier the output stage is subjected to the worst operating conditions: varying load impedance, heating due to the large power levels necessary to drive loudspeakers, and the occasional short circuit produced by the careless connection of loudspeaker cables or perhaps even loudspeaker failure.

The output stage is also the site of three distinct sources of gross non-linearity, that of amplitude overload (clipping), crossover distortion and slew rate limiting. All three generate a very large number of distortion products and are therefore particularly noticeable and fatiguing forms of distortion.

In order to understand the causes of these types of distortion it is helpful to look at the circuit shown in Figure 1. This is a very simple output stage using two transistors. The output to the loudspeaker normally sits at 0 volts, exactly half way between the positive (+V) and the negative supply (−V) rails. Now, if

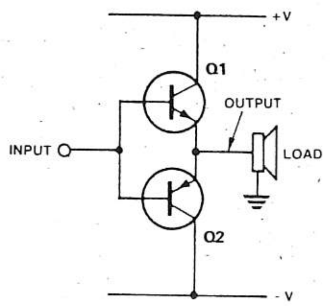


Figure 1. **Simplified circuit of a bipolar output stage.**

Q1 is turned on by a positive-going signal voltage the impedance between the output and the positive supply decreases and the output approaches +V. Similarily, if Q2 is turned on the impedance between the output and the negative supply rail decreases and the output approaches −V. When either output transistor is turned fully on, the output voltage will be equal to the supply voltage minus whatever voltage drop occurs across the output transistors. Any signal peak that exceeds this maximum output voltage will be amplitude limited or clipped (see Figure 2). It is possible to compress signal peaks that may otherwise cause clipping, but inevitably, the non-linearity still occurs. The large supply voltages associated with high powered amplifiers help reduce this problem and are one of the reasons that high power amps almost always sound better than low power ones . . . even at relatively low operating powers. In some respects

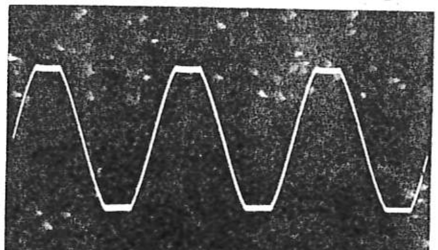


Figure 2. **An amplitude-limited waveform — "clipping".**

SPECIFICATIONS

Power output
100 W RMS into 8 ohms
(±55 V supply)

Frequency response
8 Hz to 20 kHz, +0 −0.4 dB
2.8 Hz to 65 kHz, +0 −3 dB
NOTE: These figures are determined solely by passive filters.

Input sensitivity
1 V RMS for 100W output

Hum
— 100 dB below full output (flat)

Noise
−116 dB below full output
(flat, 20 kHz bandwidth)

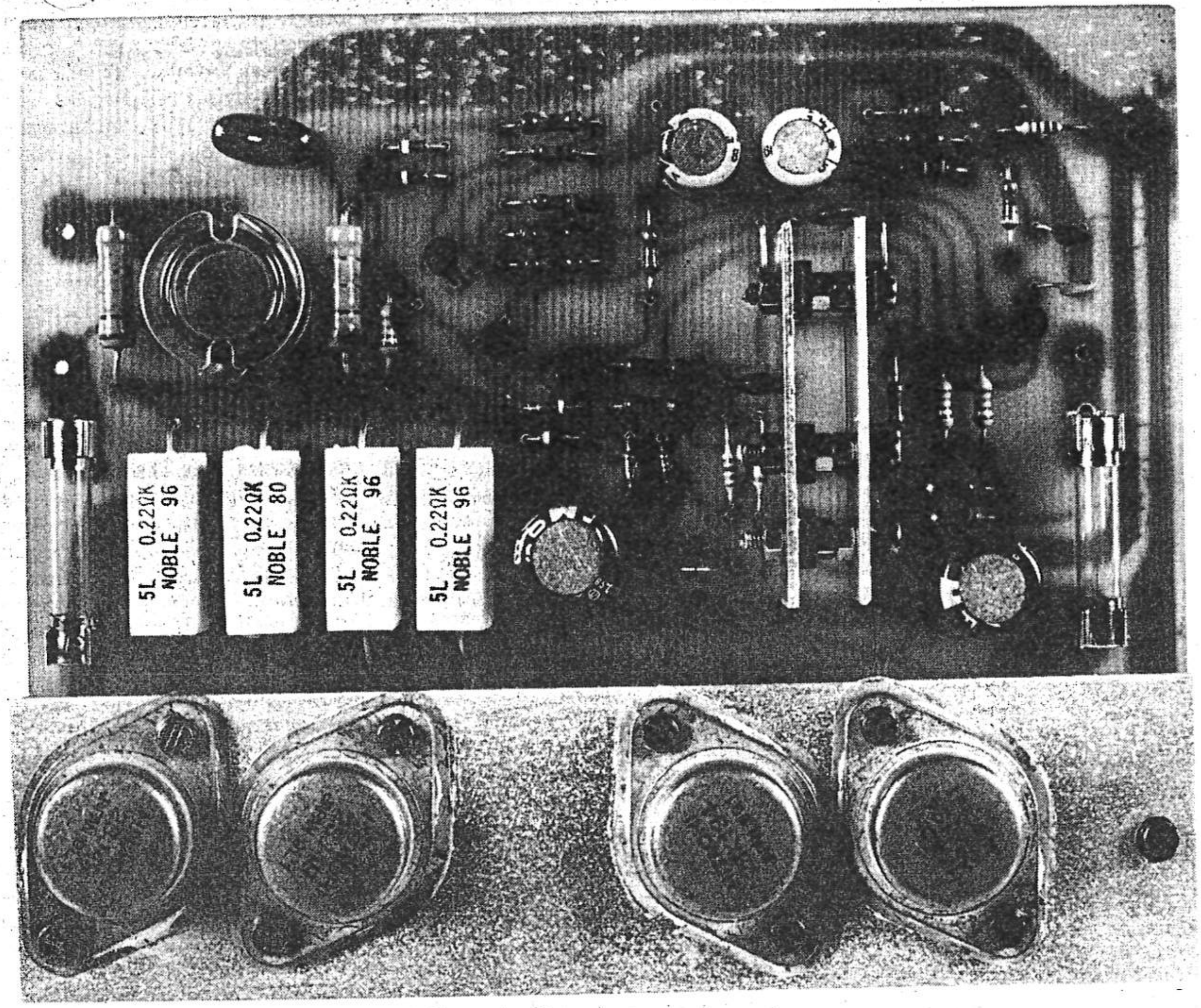
2nd harmonic distortion
< 0.001% at 1 kHz
(0.0007% on prototypes)
at 100 W output using a
±56 V supply rated at 4 A
continuous.
< 0.003% at 10 kHz and 100 W

3rd harmonic distortion
< 0.0003% for all frequencies
less than 10 kHz and all powers
below clipping.

Total harmonic distortion
Determined by 2nd harmonic distortion
(see above).

Intermodulation distortion
< 0.003% at 100 W.
(50 Hz and 7 kHz mixed 4:1)

Stability
Unconditional — see accompanying oscilloscope photographs.



it is unfortunate that output power is measured using a continuous sine wave. This certainly tests the power amp power supply combination under continuous conditions but does not give any indication of the transient power capability. A modern, good quality record can easily cause transient signal peaks of the order of at least 20 dB above the average music level. A typical 50 watt power amplifier for example, with a supply voltage of approximately ±30 V unloaded could be driven into clipping by transients when the average music level is only 3 V RMS, i.e: slightly more than a watt into eight ohms. If on the other hand, the unloaded supply voltage is increased to ±50 V while keeping the loaded voltage the same as before (approx. 28 V) then the continuous power rating will still be 50 watts but the average music level before clipping is increased to 5 V RMS or 3 W into eight ohms. The difference between the continuous power output of an amplifier and its transient power capabilities is called *dynamic overload margin* or dynamic headroom and is given by the equation

Dynamic Headroom (in dB)

$$= 10 \log \frac{P_T}{P_c} \qquad (1)$$

where P_T is transient power (RMS) and P_c is the continuous power rating (RMS)

An amplifier with a good supply regulation like the first of the two amplifiers discussed above, will have a low dynamic headroom figure (approx 0.6 dB). The second of the two amplifiers with poorer supply regulation will have a higher dynamic headroom figure (approx. 4.4 dB), and could sound superior to the first amplifier. Of course, the poorer supply regulation would have to be taken into account when designing the amplifier. The supply rejection would have to be higher to ensure the same distortion characteristics as the first amplifier, and the output transistors must be capable of handling the higher supply voltage.

Crossover distortion

When a bipolar transistor is used as an emitter follower the relationship between the output and the input is a function of the load impedance and the forward transfer admittance of the output transistors. Specifically:

$$\frac{e_o}{e_i} = \frac{R_L}{(R_L + 1/y_{fs})} \qquad (2)$$

where e_o is the output signal voltage
e_i is the input signal voltage
y_{fs} is the forward transfer admittance
and R_L is the load impedance.

It is the non-linear component of y_{fs} that causes distortion in the output stage. Equation (2) shows that if y_{fs} is large the value of $1/y_{fs}$ will be small and $(R_L + 1/y_{fs})$ will approach R_L. Therefore, for y_{fs} sufficiently large e_o/e_i will approach unity, and this is the ideal situation. ▶

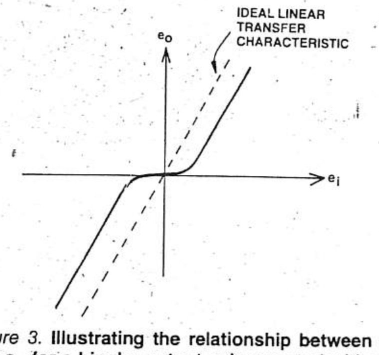


Figure 3. **Illustrating the relationship between e_i and e_o for a bipolar output pair operated without bias, as shown in Figure 1. The result is 'crossover distortion'.**

The problem with bipolar transistors is that, although their forward transfer admittance is high (approx. 40 Siemens for a typical output transistor and a current of 2 A) it drops dramatically if the base-emitter voltage drops below 0.6 V. In an output stage like that in Figure 1 the output signal voltage swings both positive and negative with respect to ground potential, with the transistor Q1 responsible for positive excursions and Q2 responsible for negative excursions. Whenever the voltage on the base of Q1 drops below 0.6 volts, or the voltage on the base of Q2 gets above −0.6 volts, (i.e: closer to 0 volts) the forward transfer admittance decreases rapidly, and the transfer characteristic of the output stage becomes grossly non-linear. This non-linearity produces crossover distortion (see Figure 3).

There are several methods commonly employed to overcome the problem of crossover distortion. Most make use of the concept of bias or quiescent current. With this technique, a fixed dc voltage of around 0.6 V is applied to the bases of the output transistors. In the output stage shown in Figure 4 this voltage is derived across the two diodes D1 and D2. If the diodes and the value of the resistor R3 are chosen correctly, then both output transistors are just turned on. With no signal voltage applied, the output of the stage is at 0 V so none of this dc current will flow in the load. Instead, this bias current flows directly from the positive to the negative rail and ac signal voltage is superimposed on this dc voltage. The base signal voltage must now reach −0.6 V to completely turn Q1 off. Since this region is now in the positive half cycle, Q2 has turned on and, with relatively high y_{fs}, will react essentially in a linear way to the input signal.

The same occurs when Q2 is turning off. It enters its low y_{fs} state in the region between 0 V and +0.6 V and being in the positive half cycle, Q1 will

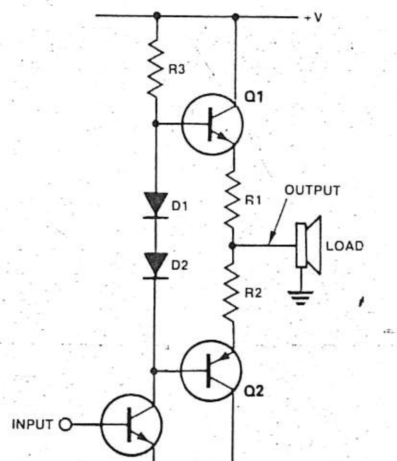


Figure 4. **A common method of linearising the relationship between e_i and e_o in an output stage is to apply bias using two diodes (D1 and D2).**

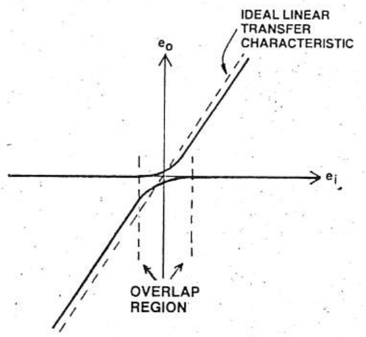


Figure 5. **How the application of bias to the output devices affects the relationship between e_i and e_o — the 'transfer characteristic'.**

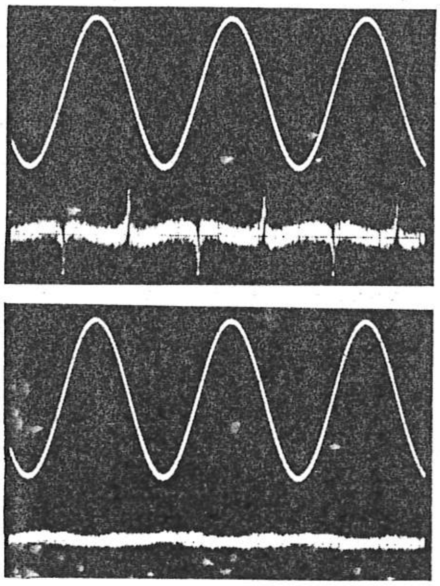


Figure 6. **Oscilloscope photographs taken from the ETI-477 module in operation: upper trace in each pic is output at 5 kHz, 10 V RMS; lower traces shows distortion analyser output. TOP: crossover distortion, reduced bias. BOTTOM: bias correctly set, distortion below resolution of analyser (0.003%!).**

have high y_{fs} and maintain the linearity of the stage. The graph in Figure 5 illustrates the effect of bias current. The curves shown in Figure 3 have moved parallel to the e_i axis and are now closer to the ideal linear characteristics. Figure 6 shows actual CRO photographs of an amplifier with and without bias current applied. The bottom waveform is the distortion obtained simply by filtering out the fundamental frequency of the input sine wave. Note that the distortion waveform has peaks that correspond to points where the sine wave crosses 0 V.

The use of bias current to decrease crossover distortion has its disadvantages also. The dissipation in the output stage is increased, causing heating of the output devices. An amplifier with a 50 V supply and a quiescent current of 50 mA must dissipate 2.5 W in each of the output devices so the output stage will run warm even with no input signal. Furthermore, bipolar transistors have a positive temperature coefficient. If the base-emitter voltage is held constant but the output transistor temperature increases, then the bias current will increase due to a decrease in the emitter-collector resistance. This increase in bias current causes a further increase in temperature and consequently a further increase in bias current. This condition is called *thermal runaway* and if left unchecked will destroy the output devices. In practical power amplifier circuits the temperature is sensed by a temperature sensitive element, like another transistor or a diode, and the bias current is adjusted accordingly.

The positive temperature coefficient of bipolar transistors also causes another problem that limits the maximum power handling of the output transistors. Since it is impossible to ensure that the heating produced in the transistor chip is perfectly homogeneous, some areas of the chip will heat up more than others. These areas will decrease in resistance, conducting more current and heating further. This effect is called *secondary breakdown* and causes hot spots on the chip surface that can destroy the device.

Slew rate limit

The third source of non-linearity normally associated with the output stage is *slew rate limiting*. Just as the output stage is limited in its maximum output voltage it is also limited in the time taken to change from one voltage to another. The time taken for the output stage to swing over a certain voltage range is called the *slew rate* of the output stage. Furthermore since the output transistors have the biggest chip areas they are usually the slowest devices in the amplifier. If the signal slope (instantaneous rate of change of input signal voltage with respect to time) approaches the slew rate of the output transistors (or any other stage in the amplifier) distortion will be produced that is analogous to the distortion due to amplitude limiting. This distortion is sometimes called *transient intermodulation distortion* (TIM or TID) but it is important to realise that it is a slew rate limited phenomenon.

There are only two ways to eliminate this type of distortion, either by decreasing the signal slope of the input waveform or by increasing the slew rate of the output stage.

Decreasing the maximum signal slope implies decreasing the frequency response of the power amplifier. So if a good frequency response is to be obtained, the problem of slew induced distortions must ultimately be solved through the use of faster output transistors.

The MOSFET output transistor

The power MOSFET overcomes many of the problems discussed above. Hitachi are the first company to make available MOSFETs at a realistic price and with sufficient power handling for use in the output stage of audio power amplifiers. We have chosen the 2SK134 and the 2SJ49 devices for this project. These have a maximum power dissipation rating of 100 W, maximum drain to source voltage of 140 V and a maximum current of 7 A, which is a very formidable specification!

The first major advantage of MOSFETs over bipolar transistors is their very high input impedance. Figure 7 shows an equivalent circuit for a typical MOSFET.

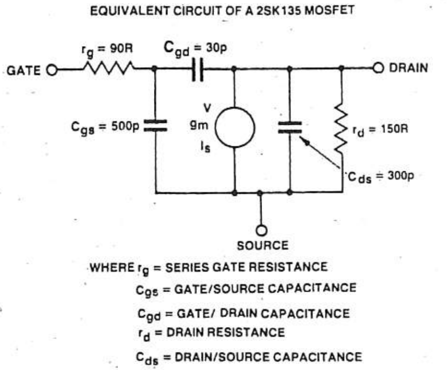


Figure 7. **Equivalent circuit of a typical power MOSFET (2SK135).**

The gate appears as a 90 ohm resistance in series with a 30 pf capacitance to the drain and a 500 pf capacitance to the source. At dc, the input resistance is the resistance of the two effective capacitors — essentially an open circuit. The equivalent circuit also gives us insight into another of the MOSFET's great advantages. The combination of the series gate resistance and the total equivalent gate capacitance determines the cut-off frequency of the device at around 3 MHz! When driven correctly, the MOSFET is capable of excellent frequency response linearity and its slew rate is *unmatched* by any bipolar device of similar power. The speed of the MOSFET is attributable to the absence of an effect called *minority carrier storage* and it can therefore switch a current of 2 A in roughly 3×10^{-8} seconds or *30 nanoseconds!* This is around *100 times* the capability of most bipolar transistors.

This very fast response, coupled with the high input impedance and gate capacitances make the devices prone to oscillation, although they are not difficult to tame if care is taken with the pc board layout and a few fundamental precautions are taken. The best approach is to ensure that all gate wiring is kept as short as possible and to increase the value of the series gate resistance. This increases the r_gC_{gs} time constant and limits the frequency response, greatly improving the device stability.

Figure 8 shows the frequency response of a typical power MOSFET and its relationship to the value of gate resistance. It is important that the distance between this resistance and the gate is kept to a minimum.

The extremely high slew rate of the MOSFET devices makes it possible to limit the maximum signal slope of the input signal while not affecting the frequency response of the amplifier inside the audio passband. In this way, the maximum signal slope cannot approach the slew rate of the output stage. Assuming no other stage in the amplifier slew rate limits this will overcome the problem of transient intermodulation distortion, but more about this later. ▶

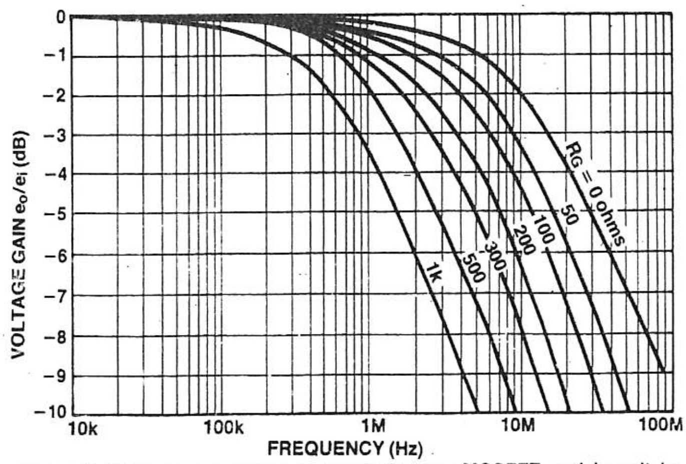
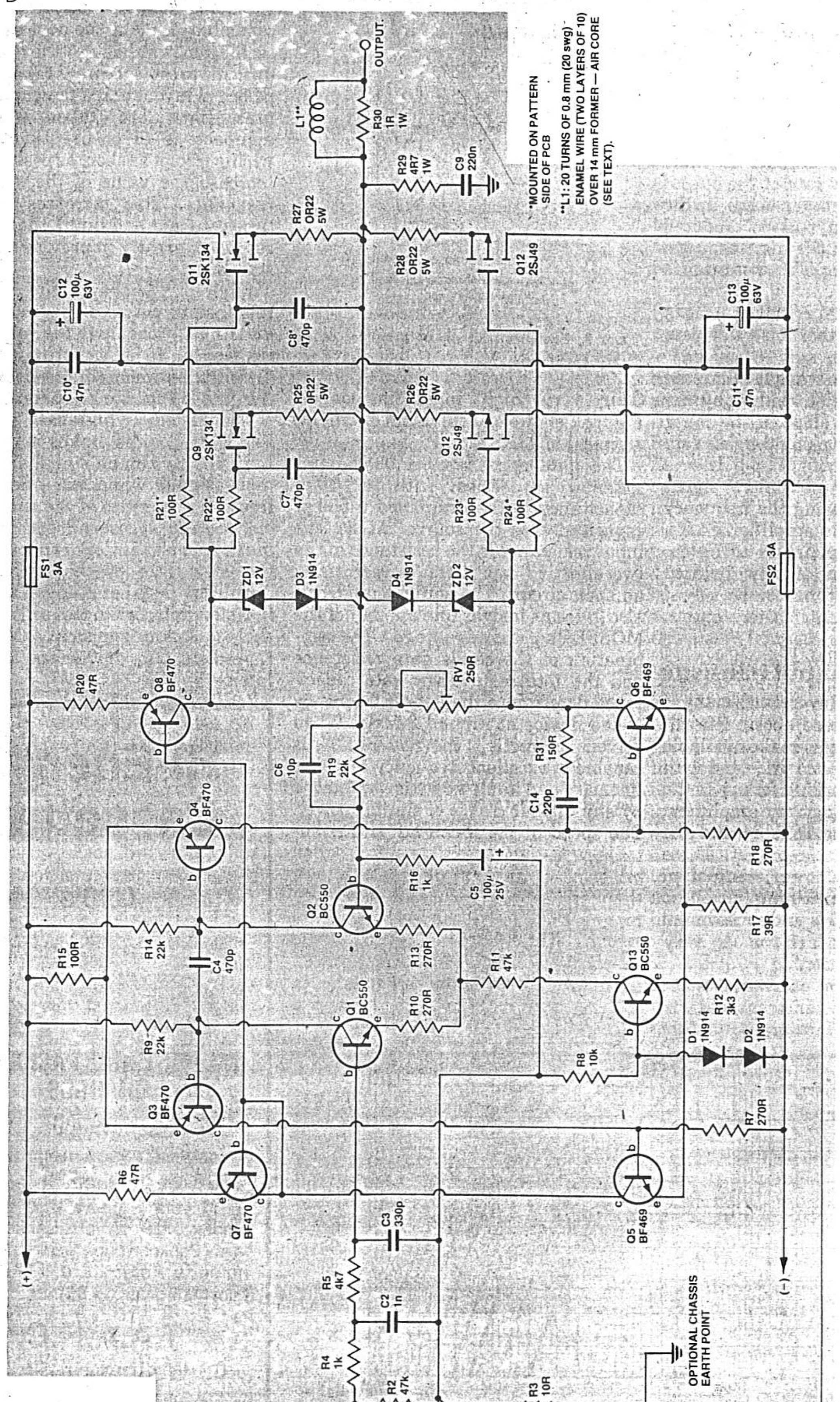


Figure 8. **Frequency response of a typical power MOSFET and how it is affected by series gate resistance.**



Circuit diagram of the ETI-477 MOSFET power amplifier module. A complete 'How It Works' description will be given next month.

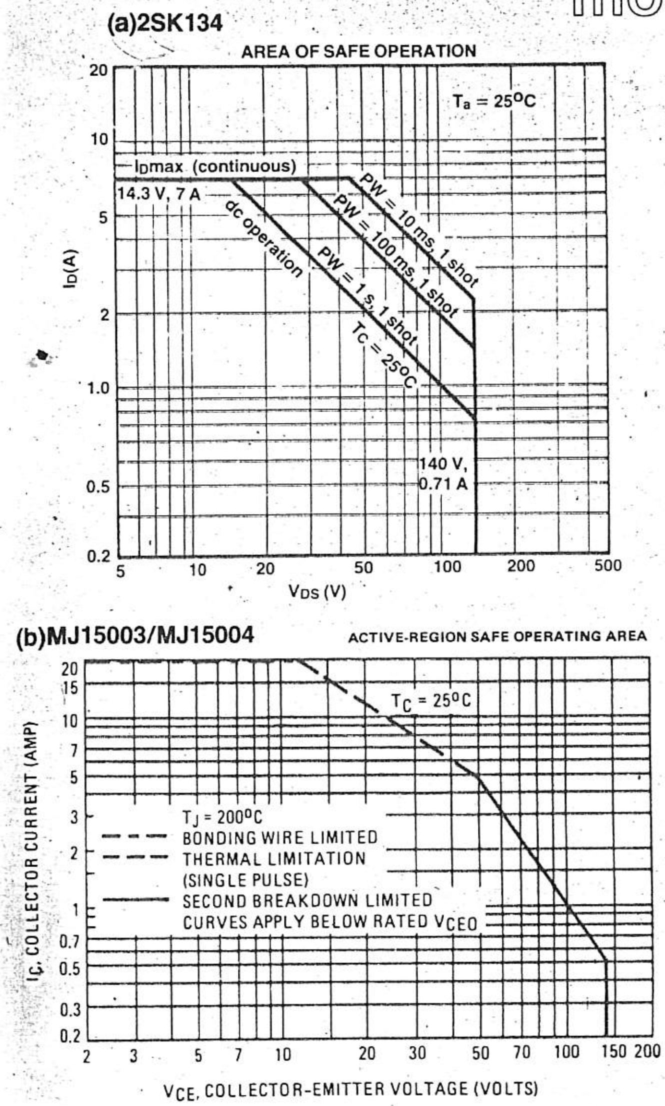


Figure 9. (a) SOAR curves for a 2SK134 power MOSFET. Compare with (b), the SOAR curves for a bipolar power transistor (MJ15003/MJ15004).

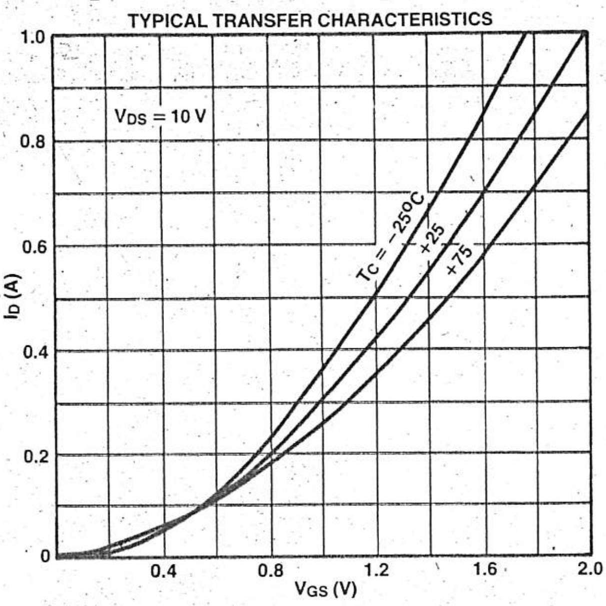


Figure 10. Typical transfer characteristics of a power MOSFET. Note that the greatest non-linearity occurs at low drain-source currents.

Another advantage of MOSFETs over bipolar transistors is their temperature characteristics. While the temperature coefficient of the bipolar device is *positive* the MOSFET has a *negative* temperature coefficient for drain source currents in excess of 100 mA. Heating of the devices causes an increase in the drain-source resistance and the current decreases. Furthermore, if one part of the chip surface heats more than any other, the increasing resistance in this area distributes current over the rest of the chip surface until the temperatures across the chip surface are equalised; so secondary breakdown is eliminated.

A look at the safe operating curves in Figure 9 shows a comparison between a MOSFET SOAR (Safe Operating ARea) and that of a good bipolar output transistor. Note that the bipolar has four limiting lines where the MOSFET has only three.

Crossover distortion and MOSFETs

It has been stated in a number of journals that one of the advantages of MOSFETs lies in the elimination of crossover distortion. Their argument relies on the fact that the variation in the forward transfer admittance of a bipolar transistor is exponential, while that of a MOSFET is more linear. The problem with this argument, as I see it, is that the MOSFET's greatest non-linearity still occurs for low drain-source current (see Figure 10) and certainly the Hitachi devices never achieve the high value of y_{fs} attainable with bipolar transistors. The specification for forward transfer admittance of the 2SK134 for example is approximately 1 Siemen, and this is only a fraction of the 40 S quoted earlier for bipolar devices. Remember that it is the non-linear component of y_{fs} that gives rise to distortion, and as a result, a MOSFET output stage with these characteristics could be expected to cause ten times the distortion of a bipolar design.

Although the bipolar turn-on characteristic is more severe, it is restricted to a smaller range of emitter current and once overcome by the application of bias current, the higher y_{fs} will actually yield a stage *with lower distortion*. The CRO photographs in Figure 6 were obtained using a MOSFET power amp and the crossover distortion is clearly evident.

In order to reduce crossover effects to satisfactory levels with these MOSFETs it is necessary to apply at least 100 mA of bias current, and for really good results approximately 200 - 300 mA would be needed. If the supply voltage is around ±50 V, each output device will dissipate five to ten watts with no input signal applied, substantially more than most bipolar output stages. This is not really a problem considering the MOSFET's negative temperature coefficient, but you should expect a MOSFET power stage to run warmer than bipolar output stages.

Another problem caused by the relatively low value of forward transfer admittance is the voltage drop between the gate and the source, which can be in the order of several volts increasing at high power levels; see Figure 10. The Hitachi devices have a maximum allowable gate to source voltage of 14 V and care must be taken in the design to ▶

ensure that this limit cannot be exceeded.

The minimum drain to source on-resistance for the Hitachi devices is around 1.7 ohms so that a drain current of 7 A continuous can be expected to cause a voltage drop between the drain and source of approximately 12 V. In order to get the same power as a bipolar stage a higher supply voltage is necessary to compensate for the higher voltage drop across the output devices. In order to make a power amplifier conservatively rated at 100 W into 8 ohms it is necessary to be able to deliver in excess of 28 V RMS to the load. This is equivalent to around 39 V peak. Adding the drain-source voltage drop of around 12 V gives 51 V, and allowing a margin for supply regulation of around 5% increases this to 56 V. Adding a further 20% for ac mains supply regulation implies that the output stage must be able to handle a supply voltage of around ±65 V. This is well within the maximum voltage specification of the 2SK134 and 2SJ49.

Examination of the SOAR characteristics of these devices reveals that it will be necessary to use two MOSFETs in parallel to achieve 100 W into 8 ohms and still not exceed the maximum power dissipation ratings of the devices. If we could guarantee that the amplifier would always be used with purely resistive loads the SOAR requirements could be relaxed substantially. If the amplifier had supply rails of ±50 V the maximum voltage swing across the load will be approximately ±40 V, giving a maximum load current swing of ±5 A, into an 8 ohm load. The maximum dissipation in the output devices will occur when the load current is around half the maximum current, i.e: 2.5 A and the voltage drop across the operating output transistor is approximately 30 V. So the power dissipation in the output devices would be less than 30 x 2.5 = 75 W.

A single pair of output transistors would suffice.

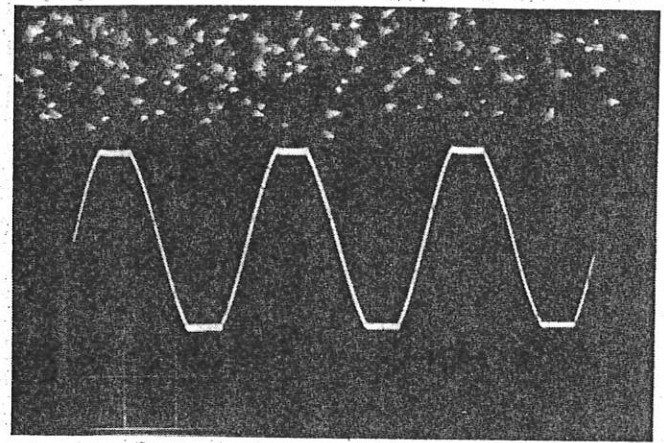
Unfortunately, loudspeakers are not purely resistive loads. In some electrostatic loudspeakers for example, the amplifier load is actually the primary of a step up transformer, needed to supply the high signal voltage for the electrostatic elements. This can represent a highly inductive load and the output stage must be able to handle the associated phase shift. Similarly, it is not uncommon for the load to have a substantial capacitance, especially in loudspeakers with poorly designed crossovers. Under these conditions the charged capacitive or inductive reactance will supply energy back into the output stage. If, for example, in an amplifier with ±50 V rails an effective load capacitance is charged to the maximum negative voltage of, say, −40 V by a large negative going signal voltage, this potential will remain on the load when the output is subsequently driven to the maximum positive voltage of around +40 V. If the resistive component of the load impedance is not less than 8 ohms the maximum current in the load is now 10 amps. The worst case power dissipation in each half of the output stage will be around 5 A when the voltage drop across the operating output device is 40 V. The maximum power dissipation will therefore be around 200 W, so two pairs of output transistors will be necessary to ensure reliable operation.

Since this problem is caused by the 'imaginary' (or reactive) component of the output load, these large signal currents will only exist momentarily while the load is charged or discharged to the new signal voltage. It is therefore possible for this load line to be marginally outside the dc safe operating area. Even taking this into account, a single pair of 2SK134/2SJ49s would not be sufficient. During the development of this power amplifier the output stage using two pairs of MOSFETs has been driven into hard overload, short circuits and even full power oscillation at over 10 MHz. Under these conditions the output device temperature was consistently measured in excess of 130°C. The MOSFETs are still performing perfectly, so these are extremely robust devices.

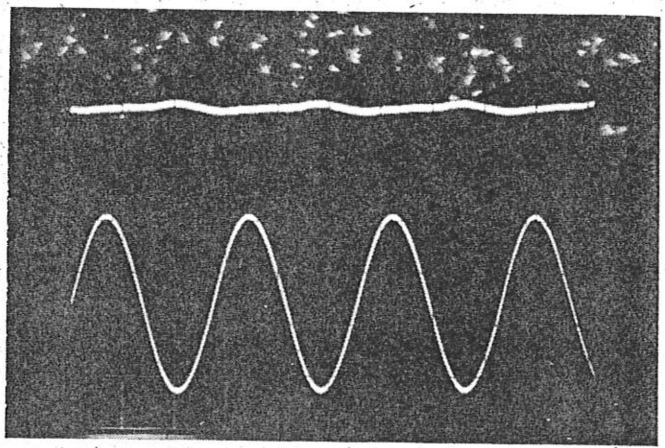
In summary, MOSFETs have both advantages and disadvantages when used in the output stage of an audio power amplifier. They are superior in speed and input impedance and are extremely robust. On the other hand, their higher distortion due to lower forward transconductance will necessitate an overall increase in the amount of negative feedback, so phase response will need to be carefully controlled to ensure stability. In general, the advantages outweigh the disadvantages, however, and it is for this reason that we have chosen these devices for the ETI-477 power module.

Discussion continued next month. Turn over for construction details for the module. ▶

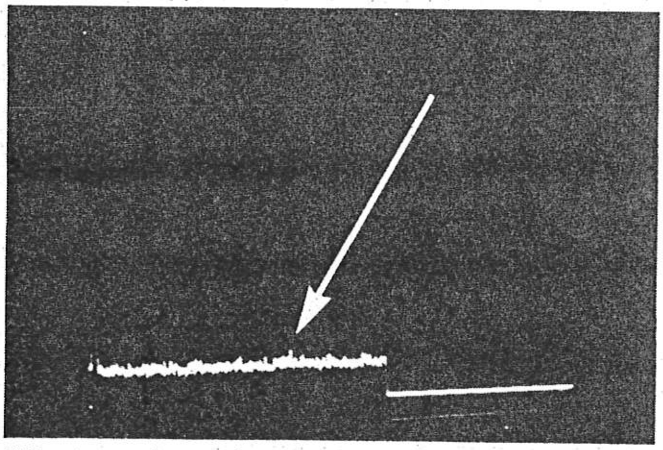
PROTOTYPE



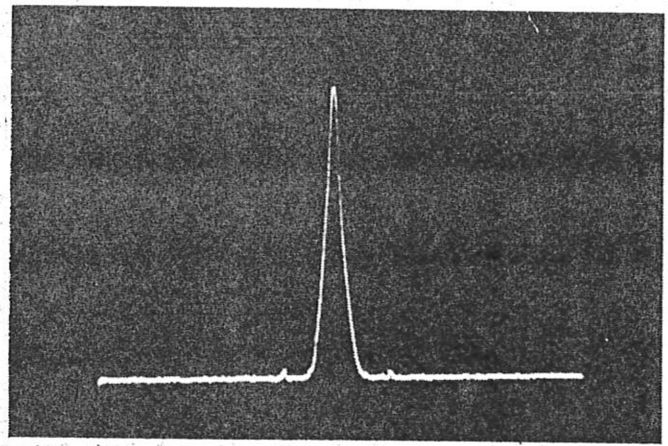
A) Overload recovery test. A 1 kHz sine wave input driving the module into amplitude overload (clipping). Note the amplifier remains stable when going into and coming out of overload.



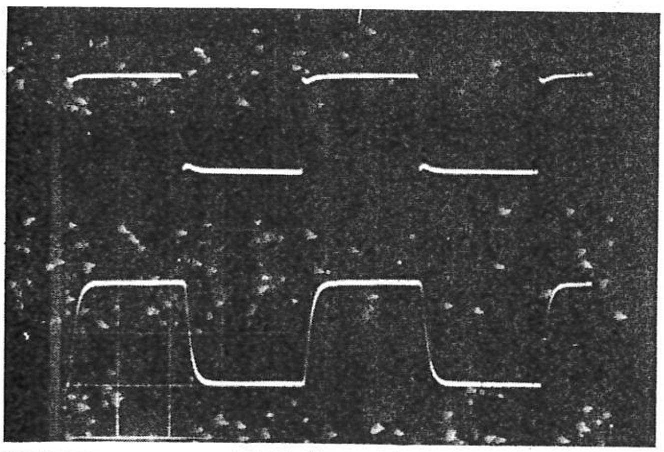
B) Total harmonic distortion measurement (AWA model F242A N. & D. meter). Lower trace is the 1 kHz, 10 W RMS output from the module. Upper trace shows output of the F242A, which in this case is at the limit of resolution (around 0.002% THD).



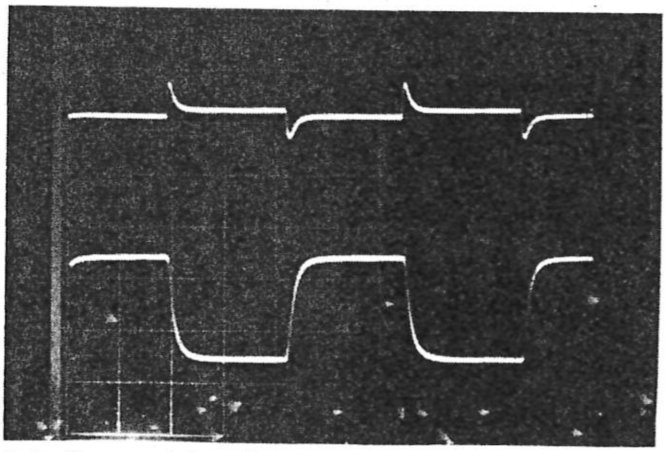
E) Spectrum analyser again. The peak on the left shows the fundamental: 20 kHz, 10 W RMS sinewave from the module. The second harmonic distortion is just visible above the noise (arrowed).



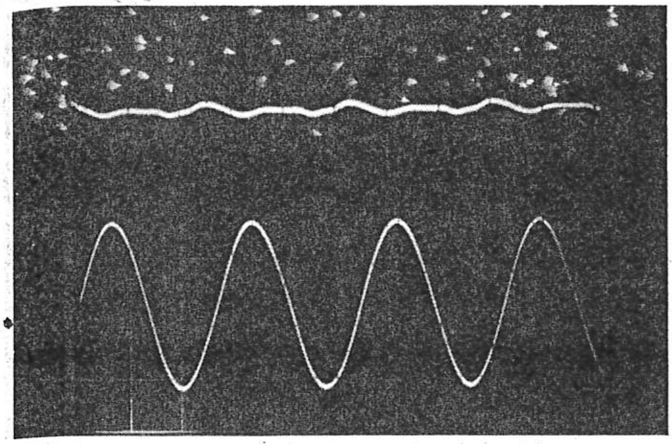
F) Intermodulation distortion proved as difficult to measure as THD, being below the resolution of most test equipment. A 50 Hz sine wave was mixed with a fundamental frequency in a 4:1 ratio. The fundamental was then varied over the audio range. Intermodulation products were not apparent for all frequencies below 7 kHz; i.e: less than 0.002%. This photo shows the IM products produced around a 7 kHz fundamental. Note they are just visible above the noise. This represents an IMD figure of around 0.004%.



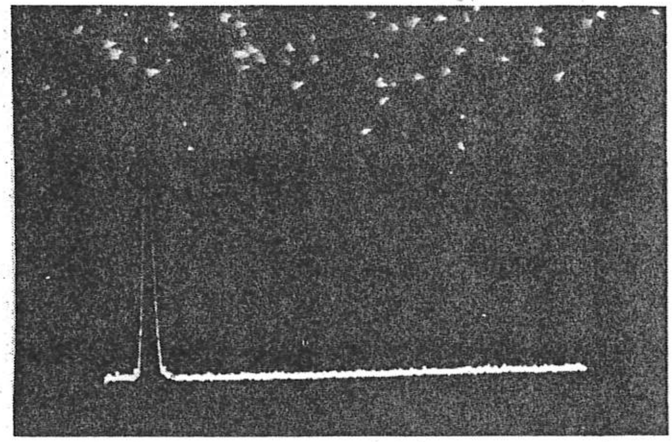
I) Square wave response at 10 kHz. Top trace is the input. The glitch after the rising and falling edges is due to a fault in the square wave generator. The harmonics produced, however, are well above the cutoff frequency of the input RC filter on the module. As a result, the output is a perfect band-limited square wave (lower trace).



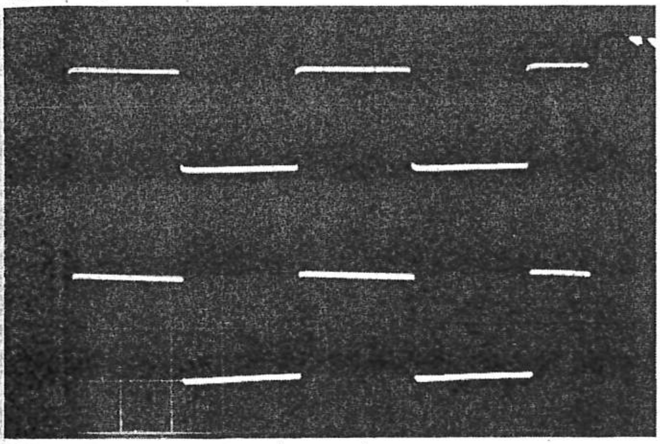
K) Oscilloscope photograph showing the error signal (top trace) in the negative feedback loop in response to a 10 kHz square wave drive producing 20 V p-p into an 8 ohm resistive load. Note that the error signal does not clip. This is a good qualitative indicator that the amplifier is free of transient-induced distortion. Scale for the error signal is 200 mV/division.



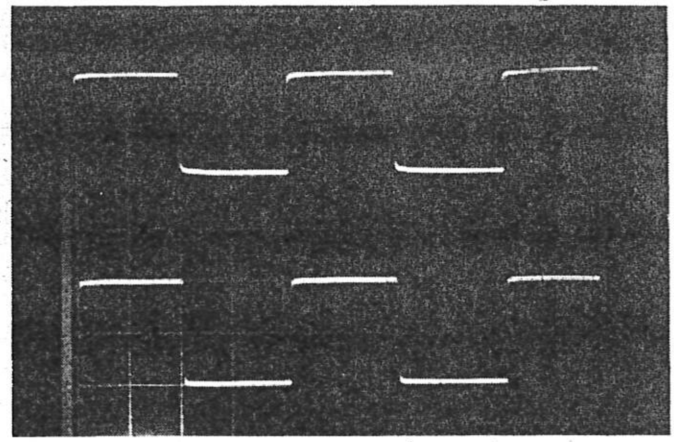
C) Total harmonic distortion, this time at 20 kHz, 10 W RMS output. The amplifier distortion is just becoming discernible above the resolution of the F242A. Note the difference between the distortion waveform shown here and that shown in B. THD here is around 0.004%.



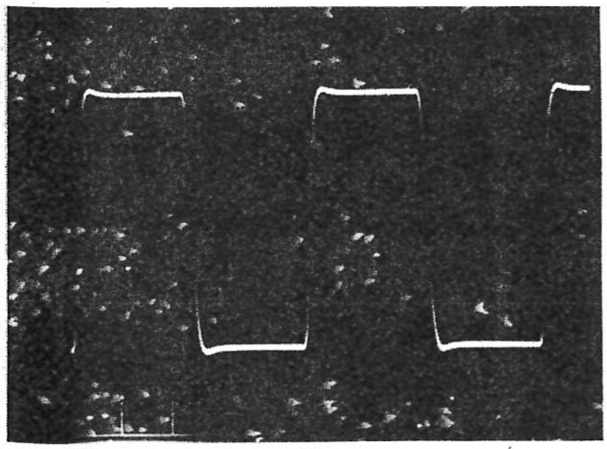
D) In order to measure the distortion products of the module it was necessary to use a Hewlett Packard 3580A spectrum analyser. This instrument can display a dynamic range of 90 dB on screen. The noise on the bottom of the trace here is around 0.002% of the fundamental. This photo shows the fundamental 1 kHz, 10 V RMS input from the module at far left. Notice that the distortion products are not visible above the noise. The THD/frequency curve shown elsewhere was obtained by fitting passive notch filters to the input of the 3580A analyser to increase its sensitivity. The limit of resolution of this technique obtained in ETI's laboratory is around 0.0003%, being the distortion generated by our AWA G233 sine wave oscillator!

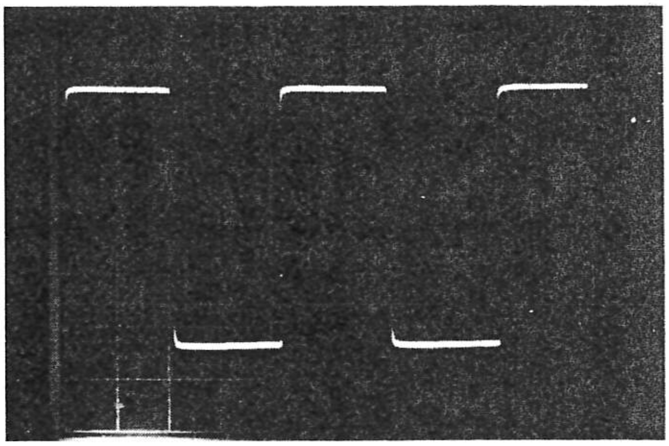


G) Square wave response of the ETI-477 module. Top trace is the 100 Hz input. Bottom trace is the resulting 20 V p-p output into an 8 ohm resistive load. The slight tilting of the output square wave occurs because of the high pass filter on the module's input and is therefore not a fault.



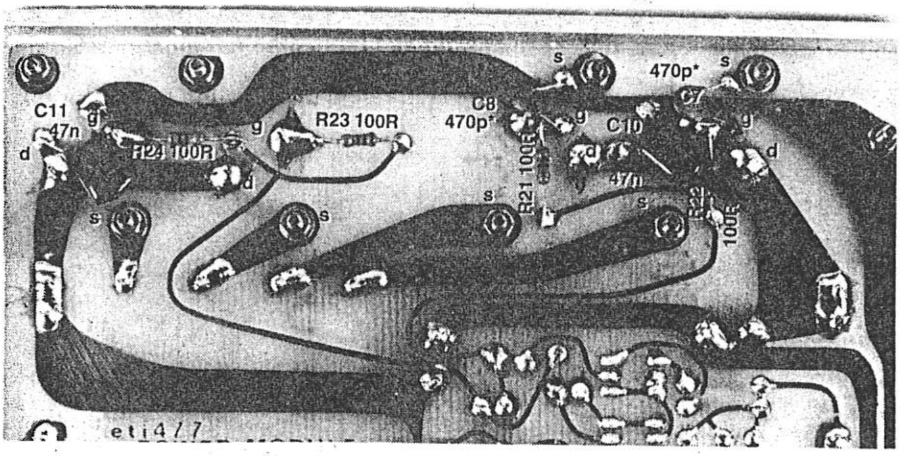
H) Square wave response of the ETI-477 with a 1 kHz input.



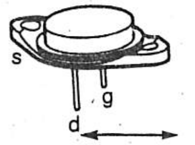


J) Oscilloscope photograph showing the module's performance into a reactive load. At left is the output waveform of the module, driven with a 10 kHz square wave. Output load is 2 uF in parallel with 8 ohms. Note that there is no sign of oscillation or instability. This is a very strenuous test as normally the reactive load would exhibit a series resistance which limits the charge and discharge times for the capacitance.

The photo on the right shows the output waveform from the module, again driven with a 10 kHz squarewave, the load this time being a 3 mH inductor. Again, the amplifier is totally stable.

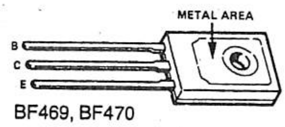


Overlay for the copper side of the pc board showing components mounted on this side.



MOSFETs

BC550



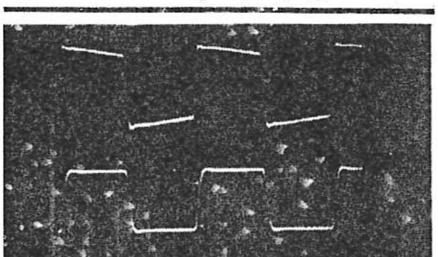
BF469, BF470

DIODE ORIENTATION

Construction

The construction of the power amp module is not difficult since all the components are mounted on a single pc board. Since the design employs a fairly large amount of negative feedback, the pc board pattern is a critical factor in attaining the maximum theoretical performance. It would be virtually impossible to achieve the same performance if the pc board pattern were altered, without recourse to a distortion analyser with a sensitivity of at least 0.005% and a very good spectrum analyser. The pc board pattern shown ensures freedom from earth path interaction and therefore does not degrade the distortion performance of the design — but more about that next month.

Commence construction by soldering all the resistors onto the circuit board. The OR22 (0.22 ohm), 5 W source resistors in the output stage get warm if the amplifier is operated for extended periods at high power. They should never get hot enough to burn the circuit board, since any fault capable of causing this much power dissipation should blow the supply fuses first. Nevertheless, it is good construction practice to space these resistors a few millimetres off the surface of the board. The 4.7 ohm, 1 W resistor R29 should *definitely* be spaced off the board since it will overheat if a fault condition should cause oscillation of the amplifier at high frequencies. Do not mount the four 100 ohm resistors R21, R22, R23, R24 at this stage. These are mounted on the rear of the circuit board and are best left until after the MOSFETs are mounted.



L) A more rigorous test shows the magnitude of the error signal with 10 kHz drive giving 20 V p-p output across a 2 uF capacitive load. As before, lower trace is the module's output. The upper trace shows that, as expected, the error signal is much greater than with a resistive load, but still does not clip. This could safely be considered the worst realistic load from the point of view of TIM production. Scale for the error signal is again 200 mV/div.

Solder the four pc board fuse clips into the board next. Now mount all of the capacitors, with the exception of C7, 8, 10 and 11. Once again, these mount on the rear of the board. Make sure the electrolytic capacitors C1, C5, C12 and C13 are inserted with the correct orientation as these are polarised components. Mount the 1N914s and zener diodes, taking care to orient them correctly. Solder the trimpot RV1 into place and then the small-signal transistors, Q1, Q2, and Q13.

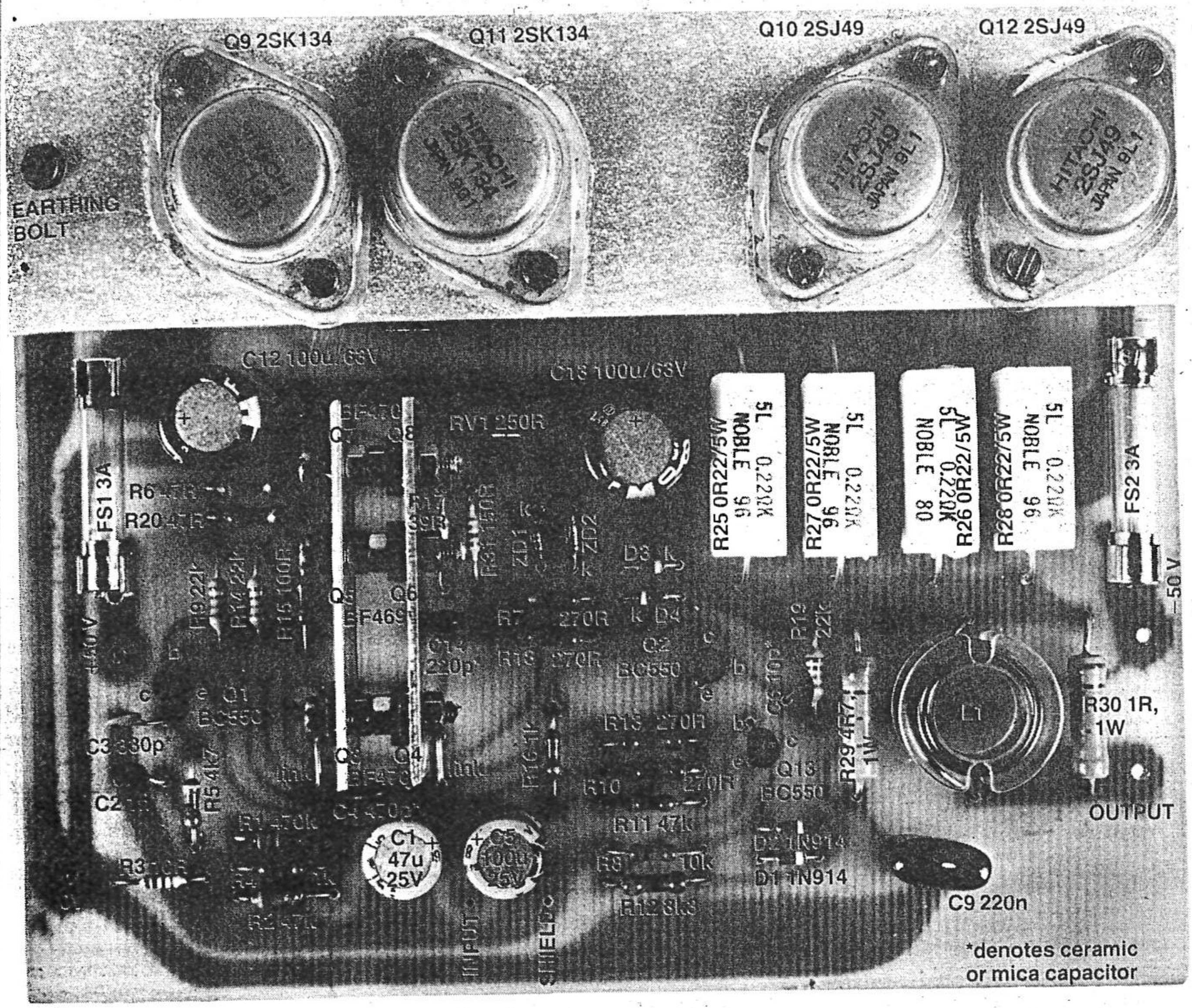
Next step is to mount the six voltage amp transistors, Q3 through Q8. These are situated on the pc board in two parallel rows, each row with three transistors. In the prototype modules, these heatsinks were constructed from two pieces of aluminium, as can be seen from the photographs. The transistors are mounted using 6BA bolts, each passing through a pair of transistors. This forms a very strong assembly which can then be soldered onto the pc board. Insulating mica or plastic washers should be used between the metal side of the transistors and the heatsink strip, using a small quantity of heatsink compound between each mating surface. When this transistor-heatsink assembly is completed, but before soldering it into the circuit board, check that each transistor is effectively insulated from the heatsink. Using a multimeter on the resistance range, check for shorts between the centre lead (collector) of each transistor and the heatsink strip. Note that the bolts through the six transistors are automatically insulated from the metal rear of the transistor by the plastic body of the device so no additional insulation of the bolts should be necessary.

Before mounting the MOSFET output devices it is necessary to make the heatsink bracket. This is cut from a suitable aluminium extrusion. The pc board has been designed to suit extrusions with one of the sides at least 40 mm wide. The transistor mounting holes have been placed so that the heatsink brackets used in the ETI-466 300 W module are compatible, although there will be some unused holes.

If you are making your own heatsink bracket, drill the holes according to the drilling template and make sure that no aluminium chips or burrs remain around the holes. This is best done with the use of an oversize drill bit (about 13 mm). A couple of twists with the drill bit will put a slight chamfer around the hole and remove any rough spots.

The extrusion used really needs to be selected to be compatible with the particular heatsink that suits your application. Next month we will use two of these modules as the basis for a high quality stereo power amplifier with the ▶

mosfet power amp module



Overlay for the component side of the pc board. Artwork for the pc board appears on page 113.

PARTS LIST — ETI 477

Resistors all ½ W, 5%

- R1 .... 470k
- R2, R11 .... 47k
- R3 .... 10R
- R4, R16 .... 1k
- R5 .... 4k7
- R6, R20 .... 47R
- R7, 10, 13, 18 ...... 270R
- R8 .... 10k
- R9, 14, 19 .... 22k
- R12 .... 3k3
- R15, 21 - 24 .... 100R
- R17 .... 39R
- R25 - 28 .... OR22, 5 W
- R29 .... 4R7, 1 W
- R30 .... 1R, 1 W
- R31 .... 150R
- RV1 .... 250R trimpot

Capacitors

- C1 .... 47u, 25 V electro
- C2 .... 1n greencap
- C3 .... 330p ceramic or mica
- C4, 7, 8 .... 470p ceramic or mica
- C5 .... 100u, 25 V electro
- C6 .... 10p ceramic or mica
- C9 .... 220n greencap
- C10, 11 .... 47n greencap
- C12, 13 .... 100u, 63 V electro
- C14 .... 220p ceramic or mica

Semiconductors

- D1, 2, 3, 4 .... 1N914 or similar
- ZD1, ZD2 .... 12 V, 400 mW zener
- Q1, 2, 13 .... BC550
- Q3, 4, 7, 8 .... BF470
- Q5, 6 .... BF469
- Q9, 10 .... 2SK134
- Q11, 12 .... 2SJ49

Miscellaneous

ETI-477 pc board; four pc mount fuse clips; two 3 A type 3AG fuses; one plastic bobbin (from P26/16 potcore, or similar); one metre of 0.8 mm dia. enamelled copper wire; two strips of 20g aluminium, each 15 mm wide by 47 mm long (for voltage amp heatsink — see text); 155 mm length of 40 x 12 mm aluminium extrusion for heatsink bracket (see text); assorted nuts, bolts, hookup cable etc.

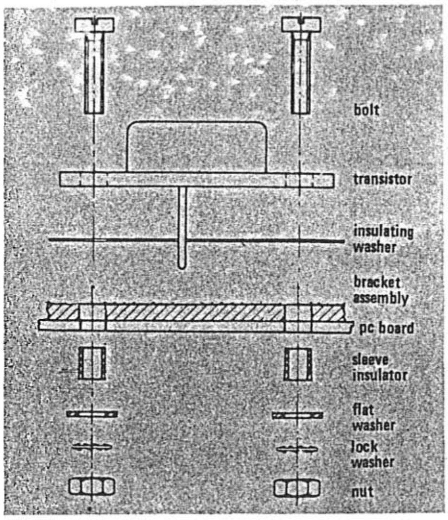
Price estimate

We estimate that the cost of purchasing all the components for this project will be in the range:

$62 - $68

(excluding heatsink and power supply)

Note that this is an **estimate** only and **not** a recommended price. A variety of factors may affect the actual price of a project, whether bought as separate components or made-up as a kit.



General diagram for mounting a TO3-cased device to a heatsink bracket and pc board assembly.

final specifications for the heatsink bracket. We will also discuss the problem of power supplies and the special precautions that should be taken to ensure good earthing to obtain maximum performance from the modules.

After the heatsink bracket has been drilled, the MOSFETs can be mounted onto the pc board. The bracket is held in place by the output devices and an 'earthing' bolt that connects the bracket to the 0 V rail (see overlay photo). The bolts holding the MOSFETs in place make the electrical connection to the source of each device, which is connected internally to the case. The bolts must be insulated from the heatsink bracket. Use a piece of spaghetti or heatshrink tubing cut to length such that the bolt will nowhere touch the heatsink bracket (see the accompanying TO-3 assembly diagram). Slip these into the holes in the heatsink bracket before assembling the MOSFETs.

Smear heatsink compound on one side of each of four mica or plastic TO-3 insulating washers and put them in place on the heatsink bracket. Smear heatsink compound on the under side of each MOSFET and put each in the correct place and secure them with bolts.

The output assembly should now be checked for shorts. Remove the earthing bolt first. The resistance between the case of each MOSFET and the bracket should be checked with a multimeter. If any device shows a short to the bracket it should be disassembled and the short found. Usually it is necessary to replace the TO-3 insulating washer as most faults of this type are the result of small metal burrs cutting through the washer when mounting the device.

Once the MOSFETs are mounted, the last passive components — resistors R21, R22, R23 and R24 plus capacitors C7, C8, C10 and C11 can be mounted on the rear of the circuit board. These are positioned on the rear of the board so that lead length is kept as short as possible. Cut the leads just short enough to mount the components in place. The accompanying photograph shows a close-up of these components on one of the prototype modules.

Set-up procedure

The recommended supply voltage for the modules is around +/− 55 V. With this voltage and reasonable supply regulation, the module will deliver around 100 W RMS into a nominal 8 ohm load. The power supply will be dealt with in more detail next month, but before applying power to the modules the following set-up procedure should be carried out.

First, re-check that the output devices are not shorted to the heatsink bracket. This is best done with the earthing bolt removed as mentioned earlier. If no shorts are found, replace the earthing bolt.

Do the same check for shorts between the six voltage amp transistor collectors and their heatsinks.

Check the polarity of all polarised components. It is often difficult to tell one end from the other on diodes since the markings are easily rubbed off. If in doubt, check these with a multimeter. Wind the wiper of the trimpot RV1 fully *counterclockwise* (least resistance). This ensures no bias is applied to the output stage. Now, remove the fuses from the pc board if they have been fitted and replace them with 10 ohm, ½ W resistors.

The module can now be connected to a power supply.

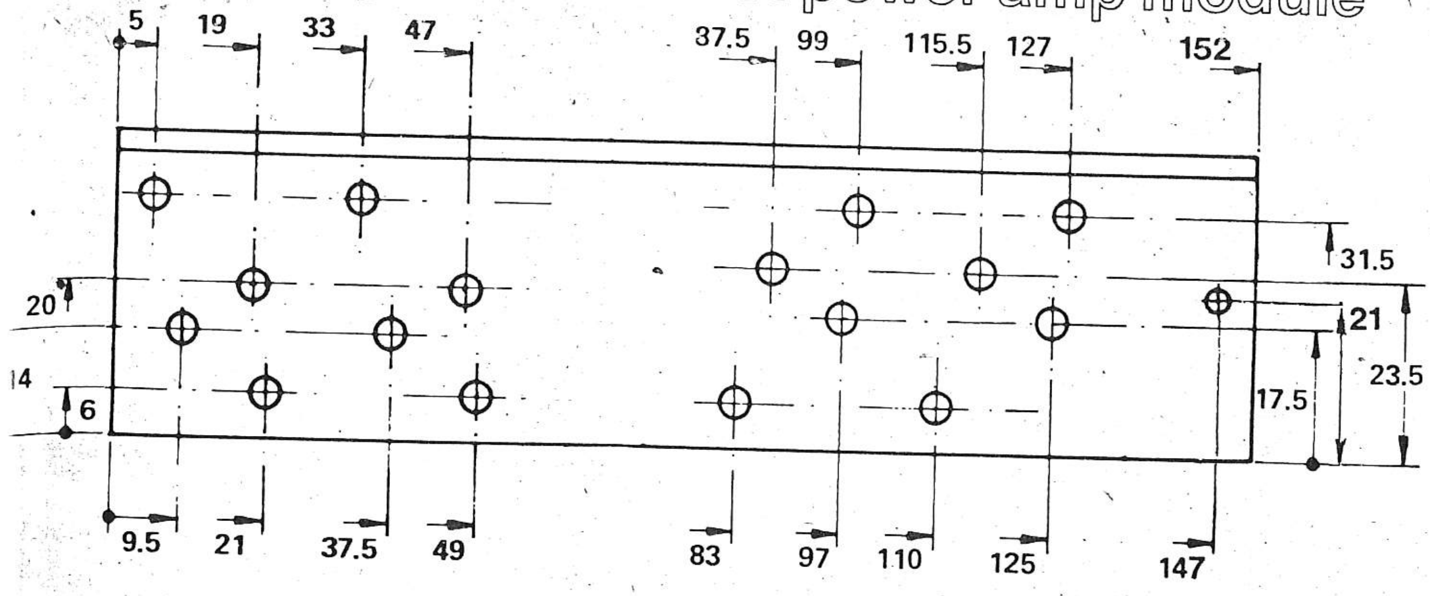
Make sure the power supply connections are sound, with good solder joints. If you have access to a current-limited bench supply it is best to connect the module to this for the set-up and initial test. If you can do this, set the current limit to around 200 mA. *Do not* connect a load to the output of the module at this stage.

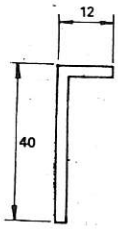
If the power is now turned on, the current through the two 10 ohm resistors replacing the fuses should be low. If these resistors start to smoke, this indicates a fault condition — turn the power off immediately.

If all is well, connect a multimeter across the 10 ohm resistor in the positive rail fuse holder and slowly wind the trimpot RV1 clockwise until the voltage measured is 1 V. This will set the bias current in the output stage at 100 mA. If the current sets up correctly, measure the voltage between the speaker output and 0 V on the power supply. You should see around ±25 mV. If you only have an analogue multimeter, this voltage may be too low to measure; in this case it is sufficient to show that the output is at 0 V.

If there is a fault in a direct-coupled amplifier like this, the output will usually be driven hard toward one of the supply rails and this is the reason the load should not be connected until these initial tests are done. Remember that 50 Vdc across an 8 ohm load equals a power dissipation in excess of 300 W, which would instantly destroy any loudspeaker!

If the module passes all these tests, it is safe to replace the fuses and connect a load. Make sure the power is off before removing the 10 ohm resistors from the fuse holder and allow time for the power supply electrolytics to discharge. There is 100 V between the fuses and *this is sufficient to cause electrocution.* Be *careful* when working with high power amplifiers.





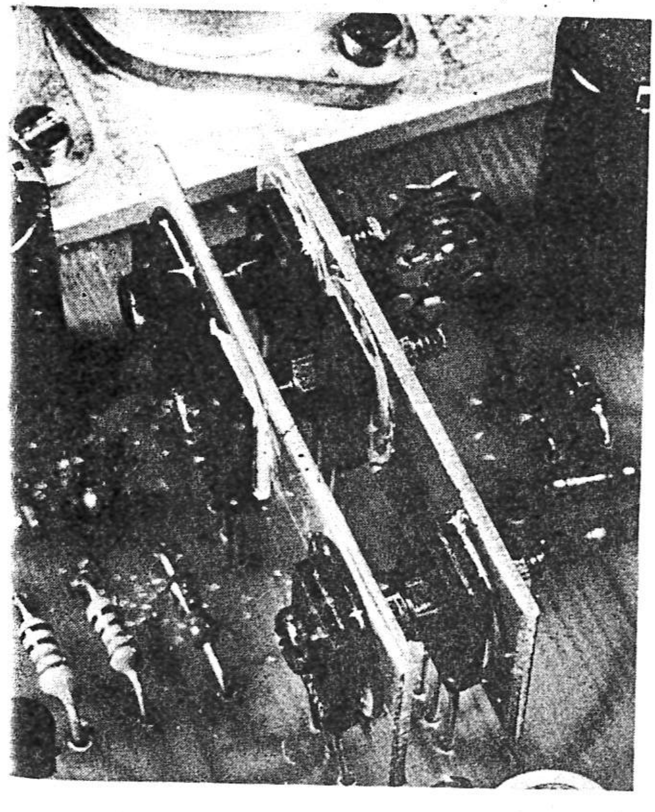
ALL 4mm DIA

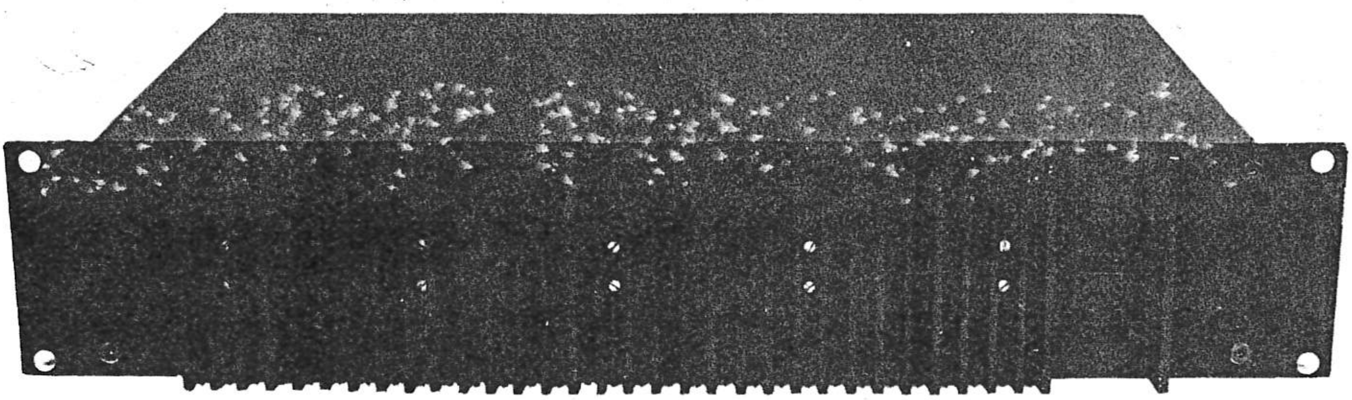
MATERIAL 40 x 12 x3 ALUMINIUM ANGLE EXTRUSION

Drilling details for the heatsink bracket assembly. All dimensions are in millimetres. Suitable aluminium angle stock is available from Alcan Handyman stores.

Next month we describe how to attach a power supply so as to achieve the performance we obtained along with a complete description of how to build a stereo power amplifier. This will use a heatsink as a front panel, manufactured exclusively for ETI — don't miss it.

View of the voltage amp transistors and heatsinking assembly. In the prototypes we used two 20g strips of aluminium, each 47 mm long by 15 mm high. This is the minimum size we would recommend and brackets measuring 50 mm long by 30 mm high are preferred. Centre-to-centre drilling dimensions can be taken from the pc board (page 113), measuring between the collector pins of each transistor.





Series 5000 MOSFET stereo amp

This is it! A 100W/channel stereo power amplifier featuring 0.001% distortion.

David Tilbrook

IN LAST MONTH'S ISSUE we gave details for the construction of a stereo power amp module suitable for mounting to the ETI front panel heatsink. All that remains to complete construction of the 100 W/channel Series 5000 power amplifier is to assemble the chassis, build in a power supply and see to the earthing details.

Housing the Series 5000 Stereo Power Amplifier presented a few headaches. Heatsinking presented the biggest headache. Barry Wilkinson, once ETI's project manager, has a saying: "If you can't hide it, make a feature of it"! So we did. We designed a heatsink/front panel. It consists of a special aluminium casting, designed to conform to one of the standard 19-inch (430 mm) panel sizes. A chassis assembly is readily attached to the rear, consisting in this case of four 10 mm square-section aluminium bars, each about 230 mm long, supporting the rear panel.

Construction is clear from the photographs. A U-section aluminium top plate plus a flat bottom plate completes the case. Attach feet and you have a stand-alone unit.

The ETI heatsink/front panel will be available from kit and component suppliers as well as directly from us, via mail order. (See the end of this article.) We have designed it to be a 'universal' component and intend to use it in other projects in the future.

The power supply shown last month is suitable for a single ETI-477 module. Two of these could be used as independent supplies in the stereo amplifier but in the final assembly we have elected to use two power transformers to form a single, higher current power supply. The advantage normally associated with independent power supplies is the reduction of crosstalk between channels. In the case of the ETI-477 module however, the high supply rejection of the design reduces crosstalk to a level that is completely insignificant (i.e: around the noise level), so independent supplies offer no real advantage. On the other hand the use of two PF4361/1 power transformers in a single power supply yields a supply capable of more than 100 V at over 7 A continuous. On page 32 is the circuit diagram for the Series 5000 power amplifier. The Ferguson transformer specified has two, independent 35 V windings. These are connected in parallel to produce a single 35 V RMS winding capable of supplying 5 A RMS. The two transformers then have these secondaries connected in series to provide the centre-tapped supply. When paralleling the windings of a transformer it is essential that they are connected together in the correct way. In the Ferguson transformer the start of the two windings are the black and red wires which should be connected together to form one terminal connection. The finish of the windings are the orange and yellow wires. These are connected together to form the other terminal. If the windings are connected in any other way the power transformer will be damaged when switched on.

One terminal of each transformer is connected to the bridge rectifier, a 35 A type. The filtering for the power supply is done with two 8000 μF capacitors to form a total of 16 000 μF across each half of the dc supply rails. The resulting dc supply voltage should be approximately $\pm$52 V, unloaded. At full power this will drop to around $\pm$50 V. With a 10 V drop across the output devices the peak signal voltage before clipping is around 40 V, which gives 100 W into an eight ohm load. In reality, the voltage drop across the MOSFETs is not as high as this since the ETI-477 module uses two devices in parallel. The maximum output power of the prototype unit using the power supply shown was 112 W single channel and 105 W both channels driven.

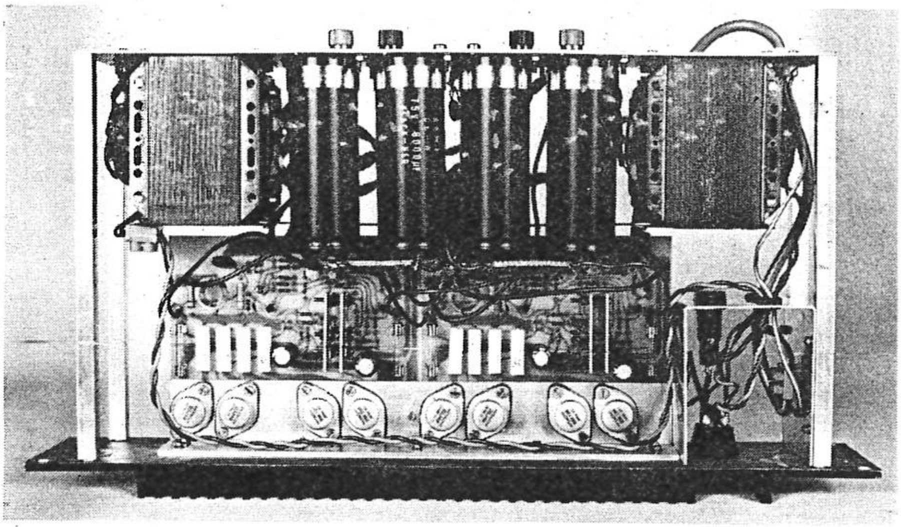
By far the biggest problem in the design and construction of any amplifier is that of earthing. If maximum performance is to be obtained from the ETI-477 modules great care must be taken to ensure complete isolation of high current earths from low current ones such as the input signal earth. If this is not done the large currents flowing in the speaker return earths, for example, will interact with the input and distortion results. Similarly, if the earth current from the electrolytic capacitors is allowed to interact with any low current signal earth the amplifier will have degraded hum figures and may even be unstable. The pc board layout has been designed to overcome these problems through the use of a *single-point* earthing arrangement. Earth lines from the output devices and power earth lines from the on-board electrolytic capacitors are kept separate until they reach the 0 V point on the circuit board.

The main input signal earth is the most critical.

The power amplifier will regard as a valid input any voltage difference between the input and the input earth terminals. So any hum present on this earth will be treated as an input and amplified accordingly. In order for the hum level to be inaudible from a 100 W power amplifier it must be at least 90 dB below the full output voltage, which is around 0.9 mV. Since the voltage gain of the ETI-477 is approximately 23, the equivalent input signal voltage is 0.9 mV/23 ≑ 39 uV! It is clear that even a *minute* hum level at the input will produce an audible hum at the output. To overcome this problem the input earth is isolated from the 0 V track on the circuit board by the 10 ohm resistor R3, shown on the ETI-477 circuit diagram in last month's issue. The input wiring to the module is done with a twisted pair of 10 amp hookup cable and the connection for the input earth is done at the input RCA sockets. This is shown in the circuit diagram for the Series 5000 amp assembly and in the wiring diagram on page 32. The 10 amp hookup cable is used instead of the more usual shielded cable, since in this application the lower resistance of the hookup cable results in better hum rejection.

The remaining earth problem is the possibility of hum loops caused by the fact that both the power amplifier and the preamplifier used to drive it must be connected to the same chassis ground point via their power cables. If the chassis of both the preamp and the power amp are connected to the 0 V point on their respective power supplies and the two 0 V points are connected together via the shielded cables between the preamp and power amp, a closed circuit is formed. Any hum currents induced into the earth lead of the three-core power cable, for example, can flow through the chassis of the power amp to the power amp 0 V point, down the shielded cable at the power amp input, to the 0 V point in the preamp and via the preamp chassis around the loop again. The presence of this hum current in the power amp input earth will be seen as an input by the power amp and output hum results. The cure is to open-circuit this loop so that hum current cannot flow in the input signal earth line. The best way to do this is to break the connection between the chassis of the power amp and the 0 V point on the power supply. In this way the power amp still has a valid earth reference at its input but the possibility of a hum loop is eliminated.

The disadvantage of this technique is that the chassis can no longer act as an effective shield to external electrical noise sources, but this problem can be overcome by capacitively coupling the chassis to the 0 V track at selected places in the power amplifier. The relatively high impedance of these capacitors at 50 Hz still maintains an effective open circuit to prevent the hum loop problem.



Internal view of the amplifier showing general construction. Note the twisted lead running from the transformer at left, around the front panel, to the 'mains termination box' at front right. The two transformers are mounted using brass washers between the panel and their mounting brackets.

The earthing procedure outlined above has consistently given good results both in the prototype Series 5000 amp and in numerous other power amps, and provides the power amplifier with good earthing that is not affected excessively by the earthing configuration used in the preamp.

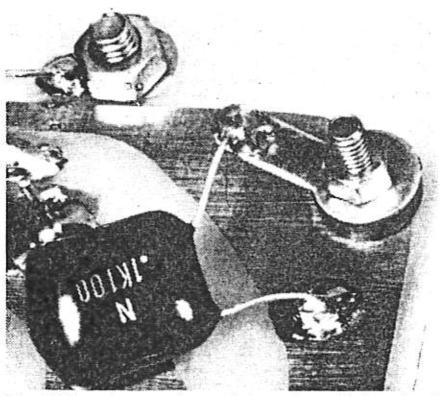
Construction

If you are using the ETI front panel heatsink it can be drilled at this stage according to the details shown on the front panel drilling diagram. This diagram assumes that the single double-length heatsink bracket is used (see last month's issue). The pc board assemblies can now be mounted to the front panel using 6 BA nuts and bolts. The heads of the 6 BA bolts should fit snugly between the heatsink fins. It is essential that there is good thermal contact between the heatsink bracket and the heatsink and for this reason the entire mating surface of the heatsink bracket should be coated in heatsink paste before bolting to the heatsink.

When you come to drilling the holes for the rack mounting bolts you'll notice dimples in the front of the casting indicating the hole centres. It would be preferable to use a drill press when drilling these holes as the rack standard leaves little room for error. If drilling by hand, drill a small pilot hole first.

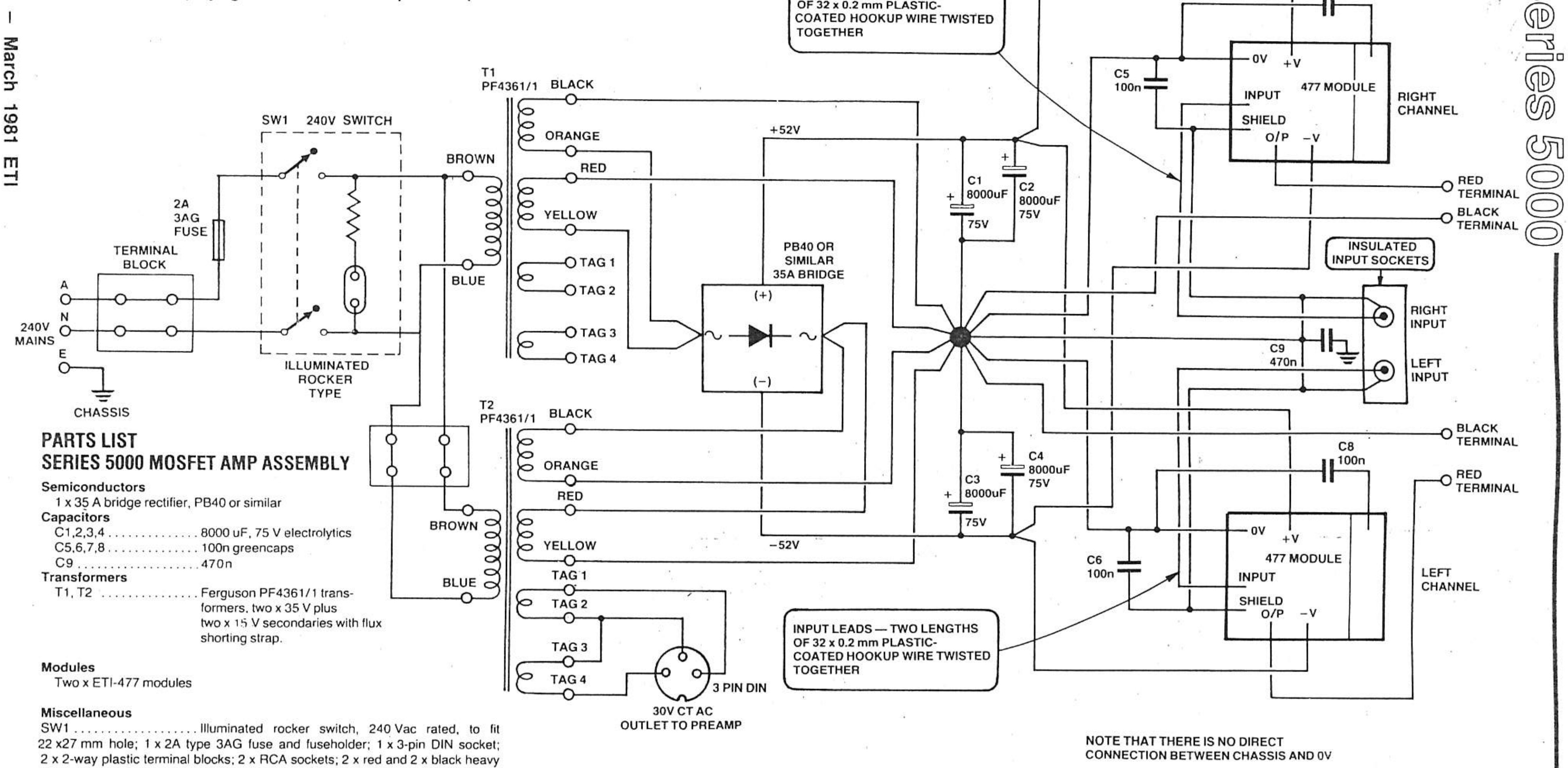
The input wires to each module should be attached at this stage. We used a twisted pair of 32 x 0.2 mm plastic-coated hookup wire. This is superior to standard shielded cable for this application. The input wiring must be kept away from the 240 V wiring at the rear of the power switch. To achieve this the input wiring to both modules is taken to the left hand side of the amp, passing beside the left hand power transformer and then going to the input (see accompanying photographs).

The input leads to the left module should be around 250 mm long while those for the right channel module should be around 400 mm. This allows for trimming in the final assembly. The input 'earth' on each board has to be ac-coupled to the 0 V line on each board for the reasons discussed earlier. This is done by soldering a 100n greencap on the rear of each pc board, immediately beneath R3. The 'earthing bolt', which makes connection to the heatsink bracket, is assembled with a transistor mounting insulator on the underside of the pc board so that the bolt is insulated from the 0 V line on the pc board. A solder lug is placed under the nut. A 100n greencap is then soldered between this lug and the 0 V track adjacent. The accompanying photograph and drawing make this clear. ▶



The 0 V track on each module pc board is 'earthed' via a 100n greencap to the earthing bolt, which is first insulated from the board using a transistor mounting insulator. (See also page 34).

WIRING DIAGRAM of the Series 5000 MOSFET Stereo Power Amplifier, employing two ETI-477 MOSFET power amp modules.



NOTE THAT THERE IS NO DIRECT CONNECTION BETWEEN CHASSIS AND 0V

PARTS LIST
SERIES 5000 MOSFET AMP ASSEMBLY

Semiconductors
1 x 35 A bridge rectifier, PB40 or similar

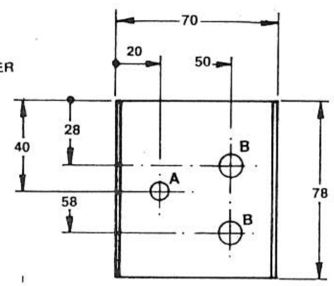
Capacitors
C1,2,3,4 .... 8000 uF, 75 V electrolytics
C5,6,7,8 .... 100n greencaps
C9 .... 470n

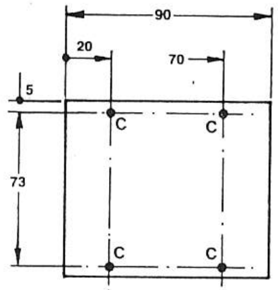
Transformers
T1, T2 .... Ferguson PF4361/1 transformers, two x 35 V plus two x 15 V secondaries with flux shorting strap.

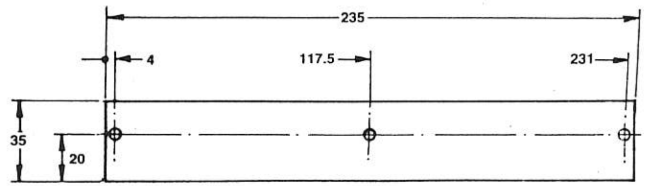
Modules
Two x ETI-477 modules

Miscellaneous
SW1 .... Illuminated rocker switch, 240 Vac rated, to fit 22 x27 mm hole; 1 x 2A type 3AG fuse and fuseholder; 1 x 3-pin DIN socket; 2 x 2-way plastic terminal blocks; 2 x RCA sockets; 2 x red and 2 x black heavy duty screw terminals; clamp grommet and sundry rubber grommets; hookup wire; nuts, bolts etc; Heatsink/front panel, metalwork etc.

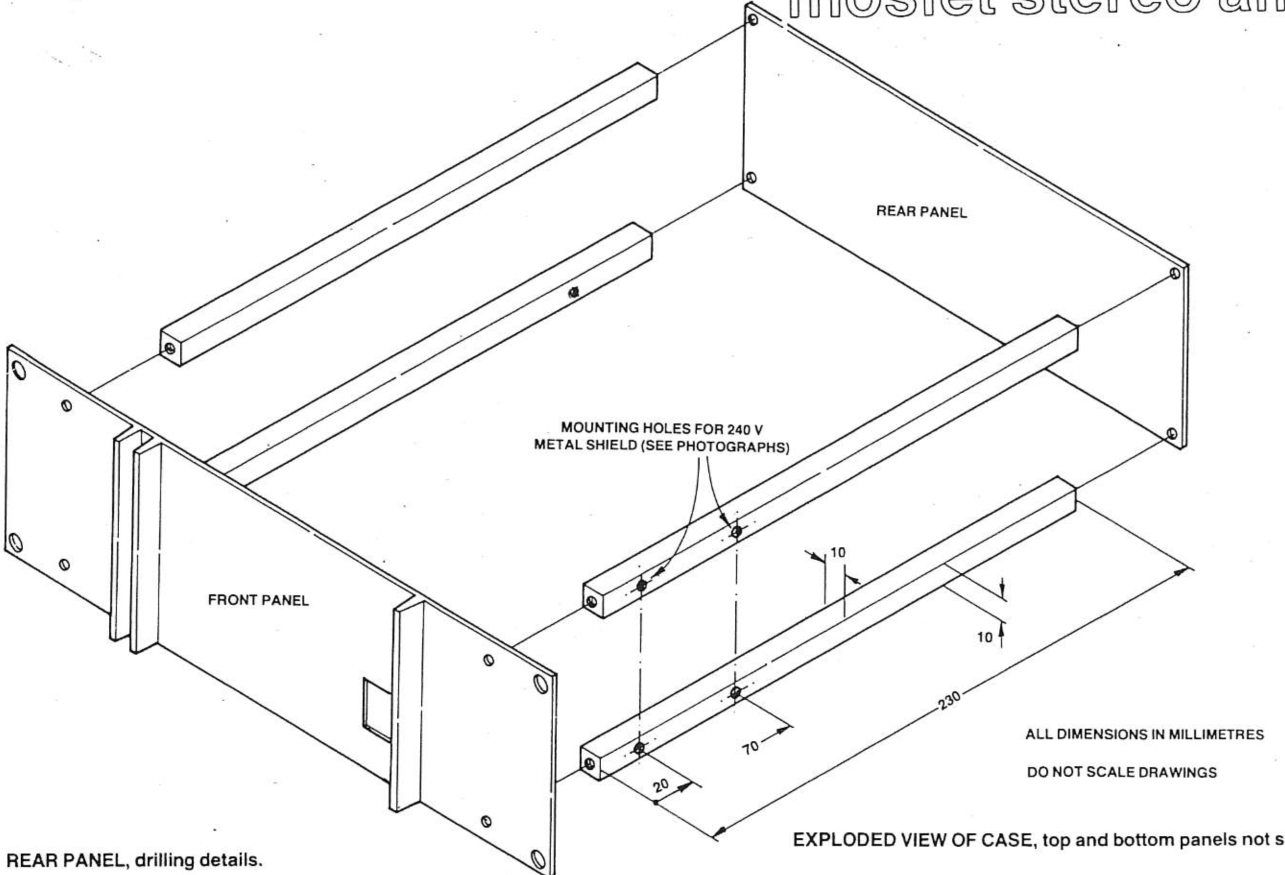
HOLES MARKED 'A' DRILL TO SUIT FUSEHOLDER
HOLES MARKED 'B' 10 mm DIA.
HOLES MARKED 'C' 3 mm DIA.
ALL DIMENSIONS IN MILLIMETRES
DO NOT SCALF DRAWINGS





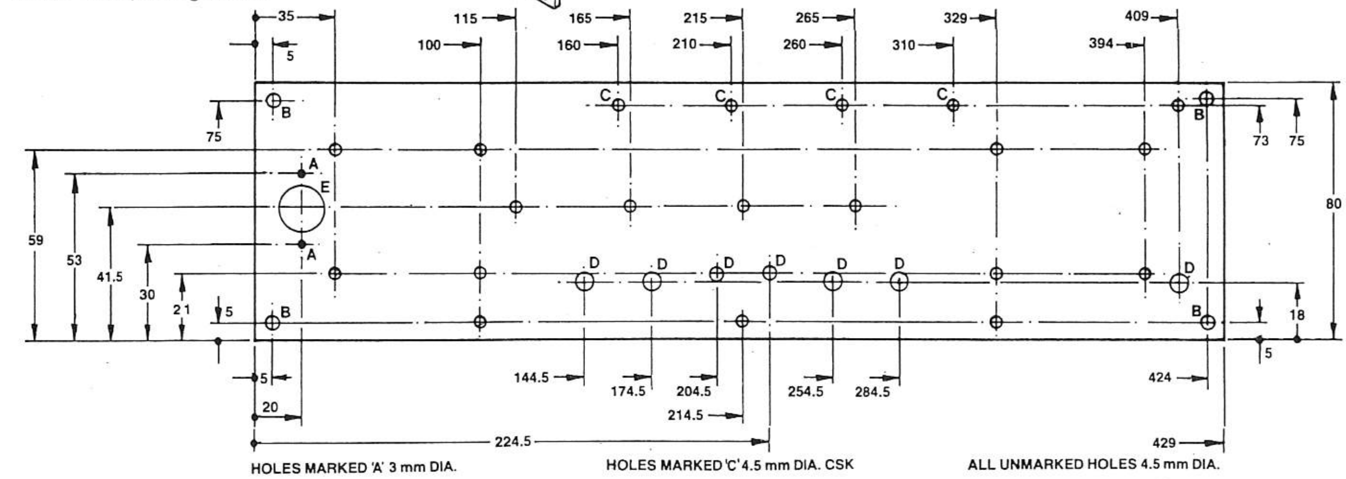


DRILL ALL HOLES 4.5 mm
ALL DIMENSIONS IN MILLIMETRES
DO NOT SCALE DRAWINGS

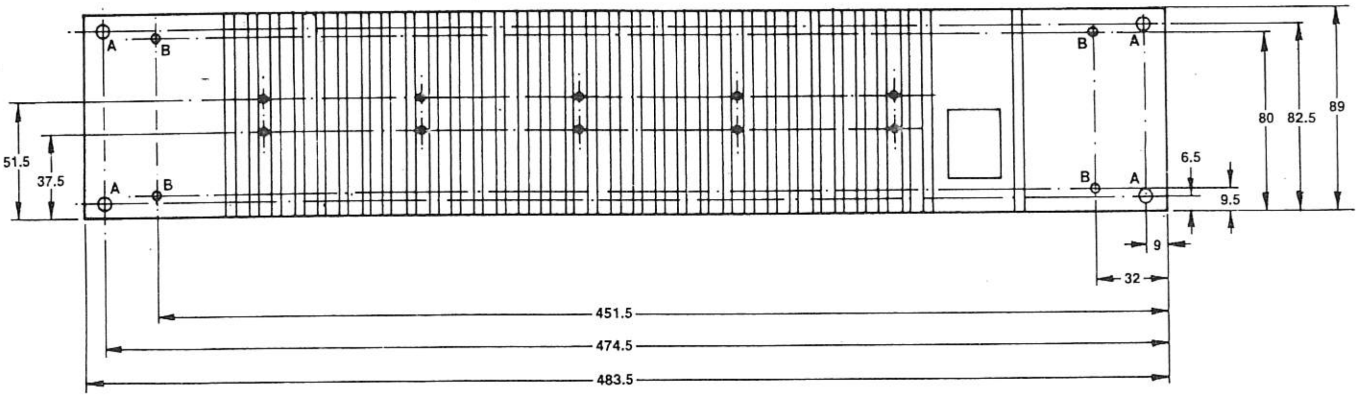


EXPLODED VIEW OF CASE, top and bottom panels not shown.

REAR PANEL, drilling details.

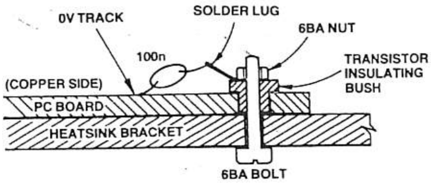


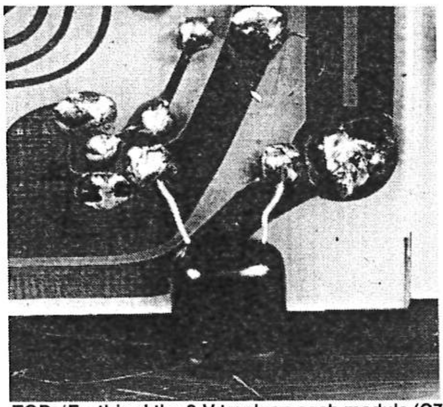
HOLES MARKED 'A' 3 mm DIA.
HOLES MARKED 'B' 5 mm DIA.
HOLES MARKED 'C' 4.5 mm DIA. CSK
HOLES MARKED 'D' DRILL TO SUIT
HOLES MARKED 'E' DRILL TO SUIT DIN SOCKET
ALL UNMARKED HOLES 4.5 mm DIA.
ALL DIMENSIONS IN MILLIMETRES
DO NOT SCALE DRAWINGS



HOLES MARKED A 8 mm DIA.
HOLES MARKED B TO TAKE 2BA COUNTERSUNK BOLT

HEATSINK/FRONT PANEL drilling details.



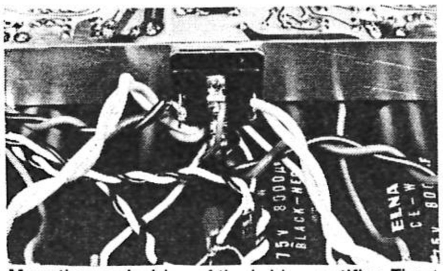


TOP: 'Earthing' the 0 V track on each module (C7, C8). LOWER: Capacitors C5, C6 mount beneath R3 on each module and couple the input earth to the board 0 V.

Next step is the rear panel assembly. Once the panel is drilled, the two input RCA sockets and the four output terminal posts should be assembled. Note that the two RCA sockets are mounted using small rubber grommets in the holes so as to insulate the outer connection (shield) from the chassis. See the accompanying photograph. Grommets having a 6 mm diameter hole are perfect for the job. Alternatively a two-way insulated RCA input terminal panel could be used. Mount the three-pin DIN socket next (ac output for preamp).

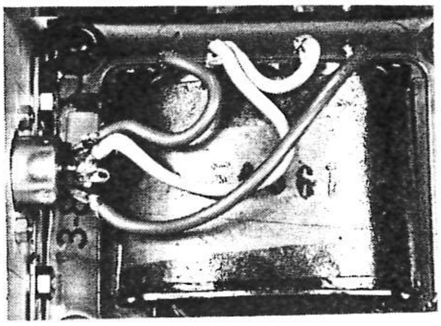
Next mount the power transformers. Place them with the solder terminals and primary leads facing *outwards*. The four filter capacitors come next. Note that the four holes for the capacitor mounting brackets along the top edge of the rear panel are countersunk so that the lip of the top panel for the case is not obstructed. Looking from the front panel, the left hand pair of capacitors is mounted with their negative terminals uppermost, the right hand pair positive terminals uppermost.

To mount the bridge rectifier, and provide some heatsinking for it, a 35 mm wide by 235 mm long strip of 20 gauge aluminium is mounted between the two transformers, running beneath the capacitors. The bridge is mounted in the centre of this strip towards the bottom so that it clears the capacitors. A bolt at each end secures the strip to the end cheeks of the respective transformers. The bridge rectifier is mounted with its + terminal down.



Mounting and wiring of the bridge rectifier. The + terminal is uppermost here.

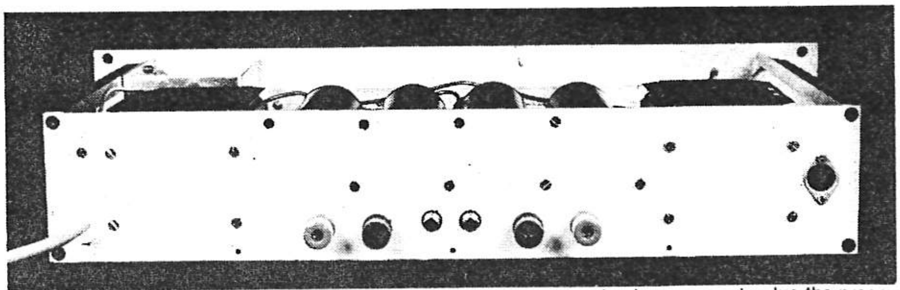
Now you can commence the wiring (a complete wiring diagram is reproduced on page 32). Do the bridge rectifier — transformer wiring first. Then do the capacitors. The lower terminals of all four capacitors are connected together using heavy braid stripped from a piece of RF type coax cable. The centre of this buss becomes the central 0 V return point (refer to the photograph). The two right hand capacitors also have their positive terminals bridged by a length of braid, as do the two negative terminals of the left hand capacitors. The positive output terminal from the bridge rectifier then connects to the positive terminal of the innermost right hand capacitor. The negative terminal of the bridge rectifier connects to the negative terminal of the innermost left hand capacitor. Two wires from each transformer secondary are wired directly to the central 0 V point (see wiring diagram).



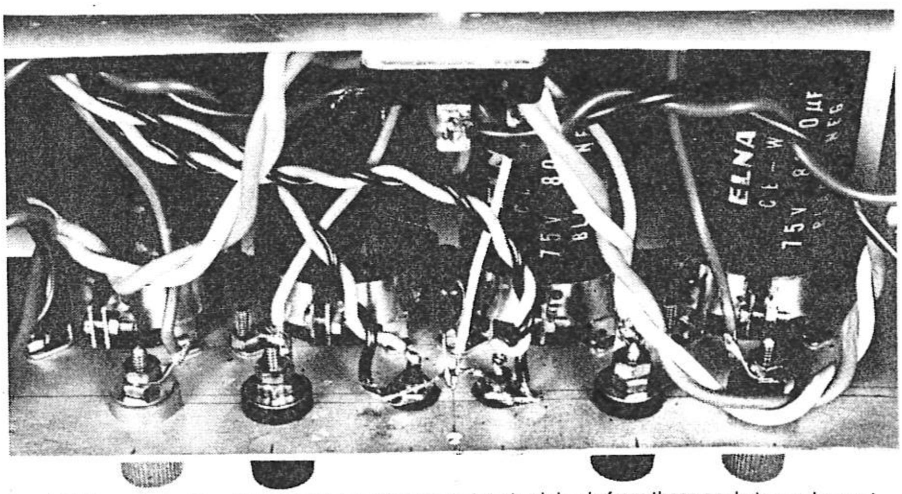
Wiring of the preamp ac supply DIN socket. The transformer tags are numbered 1, 2, 3, 4 from the left.

The preamp ac supply output socket (oh yes, a preamp is on the way . . . Ed.) may now be wired to the transformer adjacent to it. Wiring is clearly seen in the photograph here. The two 15 Vac transformer secondaries are series connected to provide a centre-tapped supply.

The two RCA input socket shield connections are wired together and a 470n/250 V greencap capacitor wired from this connection to a panel ground lug. The latter is secured under a nut on the capacitor mounting bolt immediately adjacent to the input sockets. A separate earthing lead is then run from the common shield connections from each input socket, back to the 0 V point.



Rear view of the chassis. Note the RCA input sockets are mounted using grommets plus the preamp supply DIN socket at right.



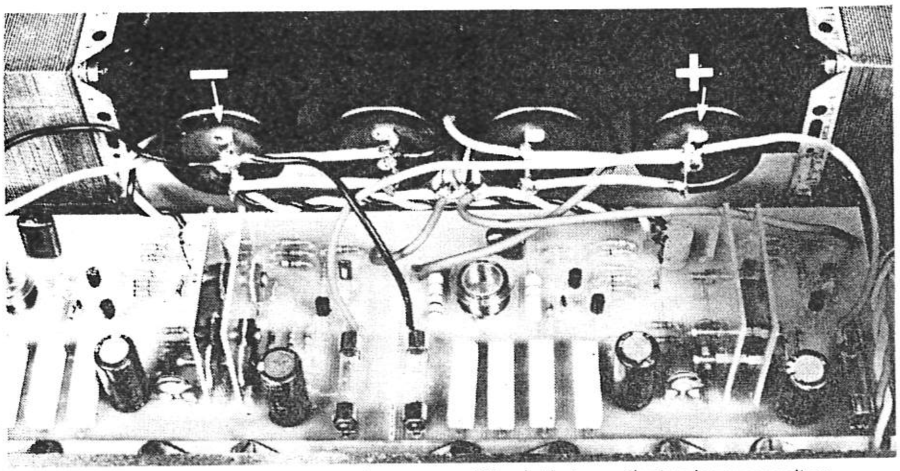
Input RCA socket wiring. Note which direction the twisted pair leads from these sockets are dressed.

The two speaker negative terminals, mounted either side of the input RCA sockets, are individually wired to the central 0 V point next.

Incidentally, if you're worried that the + terminal of the bridge rectifier may short to the bottom panel, bend it in a little and sleeve the connection.

The four 10 mm square aluminium bars may now be attached to the rear panel assembly. There are two 'upper' bars and two 'lower' bars and don't forget that the bars at the right hand end are drilled to take the mains termination and fuse assembly. The front panel assembly (with the two modules mounted) can be attached now. We placed 4 BA steel washers between the front panel and the four bars to accommodate the depth of the top cover we used, but this may be unnecessary in your case.

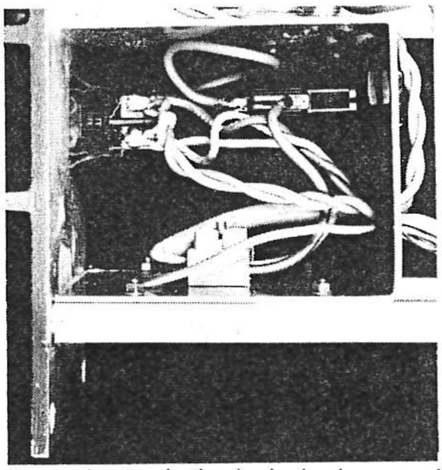
With the chassis assembled and tightened up, the wiring may be completed. Do the power supply to module wiring first. *We recommend you use 32 x 0.2 mm plastic-coated hookup wire;* anything less will probably degrade performance. The negative rail of each board connects to the uppermost (negative) terminal of the left hand



Wiring of the four filter capacitors. Note the common 0 V point between the two inner capacitors.

capacitor, while the positive rail of each board connects to the uppermost (positive) terminal of the right hand capacitor. This is visible in the photograph of this portion of the assembly. *Use separate leads; do not connect one board to the other, then to the capacitors.* The 0 V rail of each board is wired, *using separate leads*, to the central 0 V point, visible between the two innermost capacitors. Each speaker output lead is wired to its respective output terminal.

Now we come to the 240 Vac wiring. The mains switch is a DPDT illuminated rocker type that has a push-in,



The 'mains termination box', showing general assembly and wiring.

snap-lock mounting arrangement. There are several makes available and these fit the 22 x 27 mm hole provided in our panel. If you prefer something different an escutcheon may be fitted in this section of the panel. We noticed that the rocker switch sold by Dick Smith stores (cat. no. S-1506) has snap-lock flutes designed to hold the switch to a thinner gauge panel. You will need to trim them — carefully — to get this switch to fit our panel.

A U-shaped sub-assembly is mounted behind the mains switch, secured to the adjacent bars which run between the front and rear panels. This mains cable terminates at a two-way plastic terminal block mounted on the outer side. The mains fuse holder is mounted on the rear side. Also on the rear side are two grommetted holes. The lower and larger one provides an entry for the mains cable. The mains cable itself enters the cabinet via the back panel, secured with a clamp grommet (see rear photograph). The smaller, upper hole provides passage for the mains earth lead, which returns to an earth lug on the rear panel. The ac wiring to the transformer primaries also passes through this hole.

The active (brown) mains lead is wired to one pole of the mains switch via the fuse. The neutral (blue) is wired to the other pole of the mains switch. A twisted pair is taken from the mains switch terminals to another two-way plastic terminal block mounted on the left hand transformer. This cable is routed around the front panel, secured with cable ties held by several of the module heatsink bracket bolts. The right hand transformer is wired directly to the output terminals of the mains switch, the wires passing through the smaller grommetted hole.

That should complete the wiring. But, before proceeding to test the amplifier, *check all your wiring thoroughly.*

Getting it going

Having satisfied yourself that all is well, remove the fuses on each pc board, arm yourself with a multimeter, hold your breath ... and switch on. Assuming no disasters occur, measure the supply rail voltages. They should be around 52 V. If you have previously set up your modules then you can replace the four fuses and proceed with listening tests. Before replacing the fuses allow sufficient time for the electrolytic capacitors to discharge. This will take several minutes.

The general set-up procedure was discussed on page 32 of the January issue.

Once you have completed the set-up procedure, your amplifier is ready for listening tests.

The top and bottom covers can be screwed in place once you've confirmed all is well. We recommend you use aluminium for these items as steel plates will react with the field of the transformers and produce quite a loud hum.

We trust you enjoy your Series 5000 Stereo Power Amplifier.

The second project in the Series 5000 range will be a high quality control preamp that is already in the prototype stage.

Performance

The objective of this project has been to design a power amplifier module of the highest possible performance. Ideally the power amp should produce an amplified version of its input signal and contribute no sound of its own. In order to design a practical amplifier that will come as close as possible to this ideal, it is necessary to 'define' limits on the input signal characteristic and then ensure that the power amp exceeds these limits.

The problem of amplitude overload cannot be eliminated, since no practical power amplifier has access to infinite supply voltage. In order to overcome this problem, the ETI-477 module has been designed to handle in excess of ±50 V rails, giving it a conservative power rating of 100 W RMS into 8 ohms. The output stage has been designed so that the MOSFETs will not operate outside their safe operating area on any load in which the effective series resistance does not drop excessively below 8 ohms.

Similarly, since no power amp has an infinite slew rate or infinite frequency response, the input signal has been limited by a passive input filter. It can be easily demonstrated by experiment that the introduction of a passive filter that does not excessively affect the frequency response within the audio passband will not affect the sound of the input signal. This filter will define a maximum possible input slope. It is therefore only necessary to design the amplifier with a slew rate that exceeds this by a sufficient margin to ensure freedom from slew-induced distortion. Since the amplifier is operated below its slew rate limit, the application of negative feedback will decrease distortion produced as a result of the signal slope approaching the slew rate (TIM).

Differential pairs have been used throughout the design to form not only the input stage but also the voltage gain stage. This ensures that the distortion characteristics of the input and voltage gain stages are low enough so that the open loop characteristics of the amplifier will be determined by the output stage. The improved frequency and phase linearity of the differential pair make it considerably easier to ensure that the amplifier meets the Nyquist stability criterion. Another advantage of the differential pair is its relatively high supply rejection, a parameter which is often not given sufficient attention in power amp design.

Careful control of the feedback loop and the use of a passive filter/load on the output of the module, coupled with the design points mentioned above, have yielded an amplifier with particularly low dynamic distortion characteristics. An amplifier that has been designed with these objectives in mind will automatically have low THD and TID figures. The ETI-477 is no exception, with a THD at 1 kHz and 10 W RMS of less than 0.001%, rising slightly to around 0.003% at 10 kHz (top end distortion figures are a function of bias current). It should be remembered, however, that obtaining low THD figures should not be the prime objective of a good power amplifier design, but results from the reduction of dynamic distortion mechanisms already discussed.

The ETI-477 module has been tested exhaustively and all prototypes have performed with negligible differences.

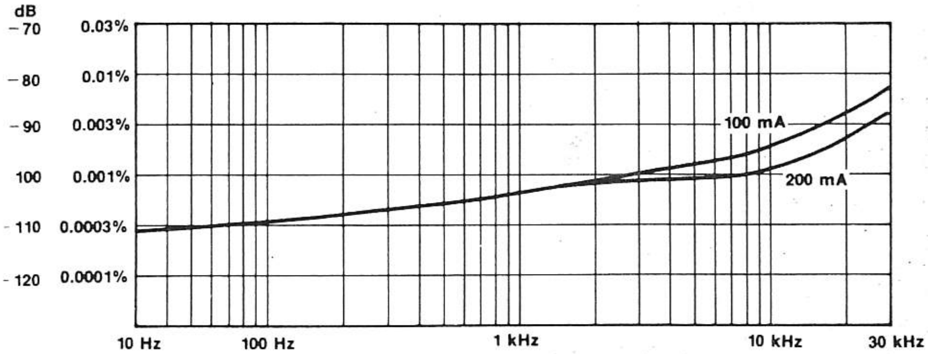
When attempting to measure distortion figures as low as these, great care must be taken with the earthing arrangement to the test equipment. The amplifier module will give its lowest distortion figures only when measured with respect to the correct earth. It may be necessary to remove the connection between mains earth and signal earth inside some distortion analysers. This problem will not arise when the amplifier is connected to a loudspeaker. This condition is not unique to the ETI-477 module, but will occur whenever an alternative earth path is provided to the output signal earth.

The subjective performance of the 477 module has confirmed for me the validity of the basic design approach. The sound is clean with no sign of the aggressive high frequency performance common to many transistor amplifiers. There are some amplifiers that give the subjective impression of being 'over-smooth'. By this I mean that the amplifier on first listening sounds clean and unobtrusive. Further listening tests reveal, however, that these amplifiers lack detail, and complex sounds like a symphony orchestra tend to become a single mass of sound rather than being rendered as single instruments. The ETI-477 does not suffer from this problem. When connected to my system (ETI Series 4000 Four-way Loudspeaker, Nakamichi MC1000 moving coil cartridge, Linn Sondek turntable, Stax tone arm, ETI-473 MC head amp), the result is one step closer to a system that has no sound of its own. ●

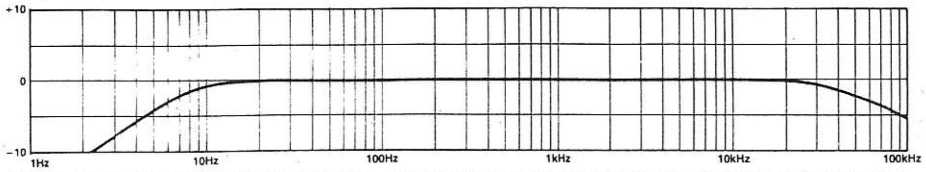
QUIESCENT CURRENT SETTING

With the quiescent current of each module set at 100 mA (1 V across 10 ohm resistors inserted across the fuse holders) the heatsink temperature will rise to typically 40°C after warm up. In use it will rise perhaps a further 30° or more, depending on programme material.

If you wish the unit to operate a little cooler, the quiescent current can be set to 75 mA on each module — adjust each RV1 for 0.75 V across 10 ohm resistors inserted across the fuse holders.



This graph shows the measured distortion versus frequency for two values of quiescent current in the output stage.



The measured frequency response of the amplifier (single module). Roll-off points are defined by the input filter (low end) and output compensation network (high end).

SERIES 5000 HEATSINK/FRONT PANEL

This will be available through a variety of suppliers and we suggest you check your usual source for price and availability. However, if you are unable to obtain one locally you may order it direct from us.

Cost is $42.50 each, post paid within Australia. Send your cheque or money order, to cover the number you require, to:

Series 5000 Heatsink/Front Panel
ETI Magazine
15 Boundary St
Rushcutters Bay NSW 2011

Please allow up to four weeks for delivery.

Bridging adaptor converts Series 5000 Power Amp into 300 W mono amplifier

Here's how to operate the two ETI-477 MOSFET power amplifier modules in the Series 5000 amp in bridge configuration with the addition of a simple, inexpensive module.

Geoff Nicholls
David Tilbrook

THE AMOUNT of power an amplifier can deliver into a certain load is determined by the simple equation:

$$P = V^2/R$$

where V is the supply voltage and R is the resistance of the load. To achieve more power we must either decrease the resistance of the load or increase the supply voltage. Either of these will cause an increase in the amount of current to flow, and this must be catered for in the design. Unfortunately, power transistors are limited by the maximum voltage they can withstand so the supply voltage cannot be increased indefinitely. An amplifier with a supply voltage around 50 V is probably capable of supplying around 40 V peak to the load, the remaining 10 V being dropped by the output transistors, driver transistors and the power supply. This corresponds to a power level of around 100 W RMS into an 8 ohm load. In order to increase this the load could be decreased to 4 ohms, for example. The simple equation above predicts a power level twice that of the 8 ohm case. In practice this ideal is never met since the increased current causes increased voltage drops. In the case of a MOSFET output stage such as the ETI-477, the relatively high on resistance will cause quite a high voltage drop, decreasing the maximum output power to around 150 W for a 4 ohm load.

In order to increase the power of audio amplifiers it would seem we must increase the supply voltage and design the amplifier so that it is capable of withstanding higher signal currents. A closer inspection of Figure 1, however, reveals another alternative. The conventional power amplifier consists of the amplifier itself and a power supply, as shown in the diagram. The power supply is represented by the pair of capacitors. These correspond to the main storage capacitors in the power amp. The rest of the power supply has been omitted since its purpose is simply to maintain the necessary dc voltage differential between the ends of the capacitors. In a class B output stage only one of the output capacitors is supplying energy to the load at any given time. The arrows in the diagram indicate the direction of the current flow when the power amp is delivering a positive-going output signal. As can be seen, the large signal current flows from the positive supply capacitor to the power amplifier, through the load and via an earth return path to the electrolytic capacitors. Every wire in this current path has resistance, so voltage drops occur at all points in the circuit. These voltage drops can be extremely significant in the performance of the power amplifier. The distortion figure for the ETI-477 module, usually around 0.001%, can be degraded to worse than 0.3% if the resistance in the power supply leads exceeds a small fraction of an ohm. If extremely low distortion figures are required the entire heavy current path and earth leads should be wired with one of the very *low resistance* speaker cables available.

We have seen above that at any given time in a class B power amp only one of the capacitors is supplying power to the load. So the load has access to only one of

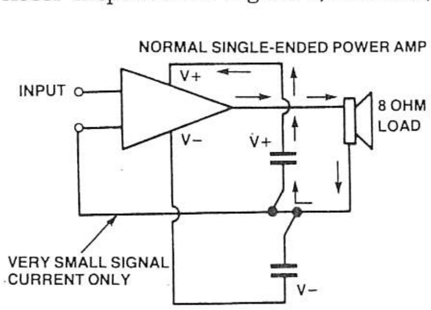


Figure 1. **Single-ended power amp showing how current flows in the power supply and the load.**

SPECIFICATIONS OF BRIDGED SERIES 5000 AMPLIFIER

Power output
300 W RMS into 8 ohms
(at onset of clipping)

Frequency response
8 Hz to 20 kHz, +0 −0.5 dB
(determined by passive filters)

Input sensitivity
1 V RMS for 100 W output

Hum and Noise
−100 dB below full output, or better

Total Harmonic Distortion
less than 0.003%

Stability
Unconditionally stable.

the supply rails. If both supply rails could be used at the same time the voltage available to the load would be doubled without having to redesign the amplifier, so long as the resulting current were within its capabilities. This is the purpose of the bridge configuration with power amps, sometimes referred to as 'bridging'. The principle is shown in Figure 2. Two identical power amplifiers have been used here, the output of each going to opposite ends of the load. The input signal is fed to the input of the first amp in exactly the same way as in the more conventional approach. The arrows indicate the direction of current flow for a positive-going signal voltage. At the same time, the input signal is fed to the second power amp via a unity gain phase inverter. A positive-going input signal voltage becomes a negative-going signal at the input of the second amp. While the output of the first power amp is swinging positive the output of the second amp is swinging negative, so the load experiences double the supply voltage (neglecting for a moment the increased voltage drop due to increased signal current).

In the 4 ohm case discussed earlier the signal current is doubled, while the supply voltage remains much the same; the maximum power is therefore doubled. In the bridge case, however, the maximum signal voltage is doubled, increasing the current. Since power is given by the product of voltage and current the power increases by a factor of *four*. In a real amplifier, of course, this power is never achieved. Once again the voltage drops across the output transistors, etc, will decrease the power considerably, and this is especially true when using MOSFET output devices. To make a closer estimate of the power that can be expected of an amplifier when connected in bridge, determine the power delivered into a load of half that used in the bridge and double this value. If the bridge is to be used with an 8 ohm load, for example, determine the power delivered by one amplifier into a 4 ohm load and double this figure. In the case of the ETI-477 module the power into 4 ohms is around 150 W RMS, so the power achieved by two 477s in bridge should be around 300 W RMS. Measurements carried out with the bridging adaptor gave power figures between 280 and 300 W RMS, in good agreement with the estimate.

There are also limitations, however, which must be considered for successful operation of a bridge amplifier. Firstly, since each amp is effectively driving a load half that of the real load, the load resistance connected to a bridge amplifier must be twice the minimum load specified for individual power amps. Since the minimum load recommended for the ETI-477 module is 4 ohms the minimum load used in bridge should be 8 ohms.

Another problem associated with bridging is that both power amps used should share the same power supply to ensure the integrity of the earthing system. If this condition is not met, the distortion figure and stability margin of the amp will almost certainly be degraded. In Figure 2, two independent power amplifiers are connected in bridge. This is done by joining their earth reference points together and driving the loudspeaker with out-of-phase signal voltages. Current resulting from a positive-going signal voltage flows from the positive supply through the first power amp and through the loudspeaker to the second power amp, and then to the negative supply rail of the second power amp. The circuit is completed by the connection between the two earth points. The problem is that, since this connection has a finite resistance, a voltage drop will occur across it, varying with the signal voltage and modulating the earth current for the second power amp. The solution is to operate both power amps from a single power supply. Figure 3 shows a pair of amps connected in bridge and using a common supply. Once again, the arrows show the direction of current resulting from a positive-going signal voltage. Notice that in this case the connection between earth reference points has been eliminated and both power amps ▶

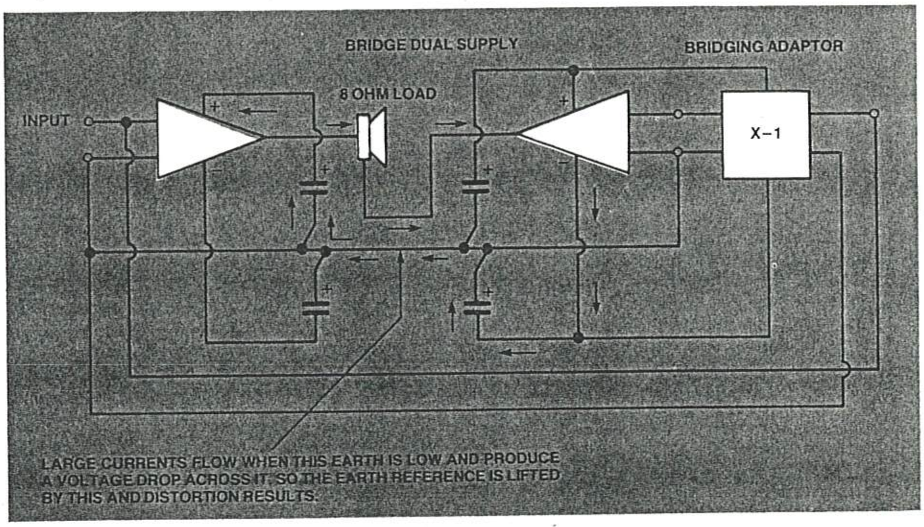


Figure 2. **Two separate power amplifiers in 'bridge' configuration showing how the individual power supply currents and the load current flows.**

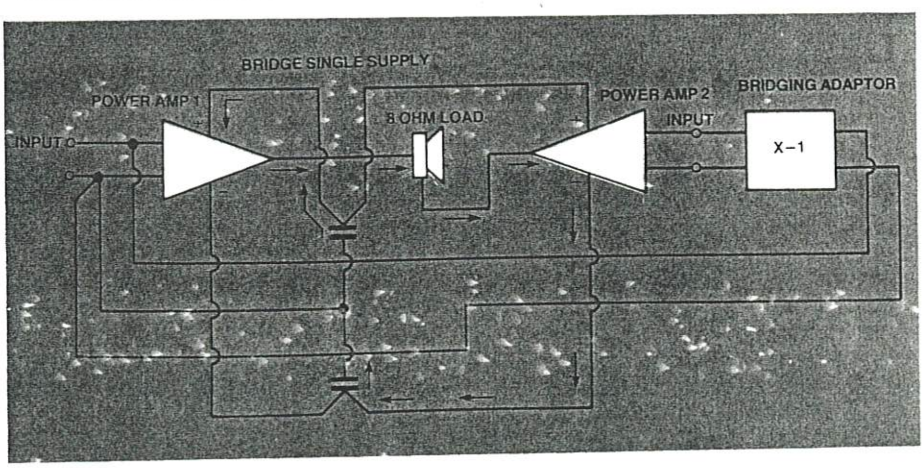
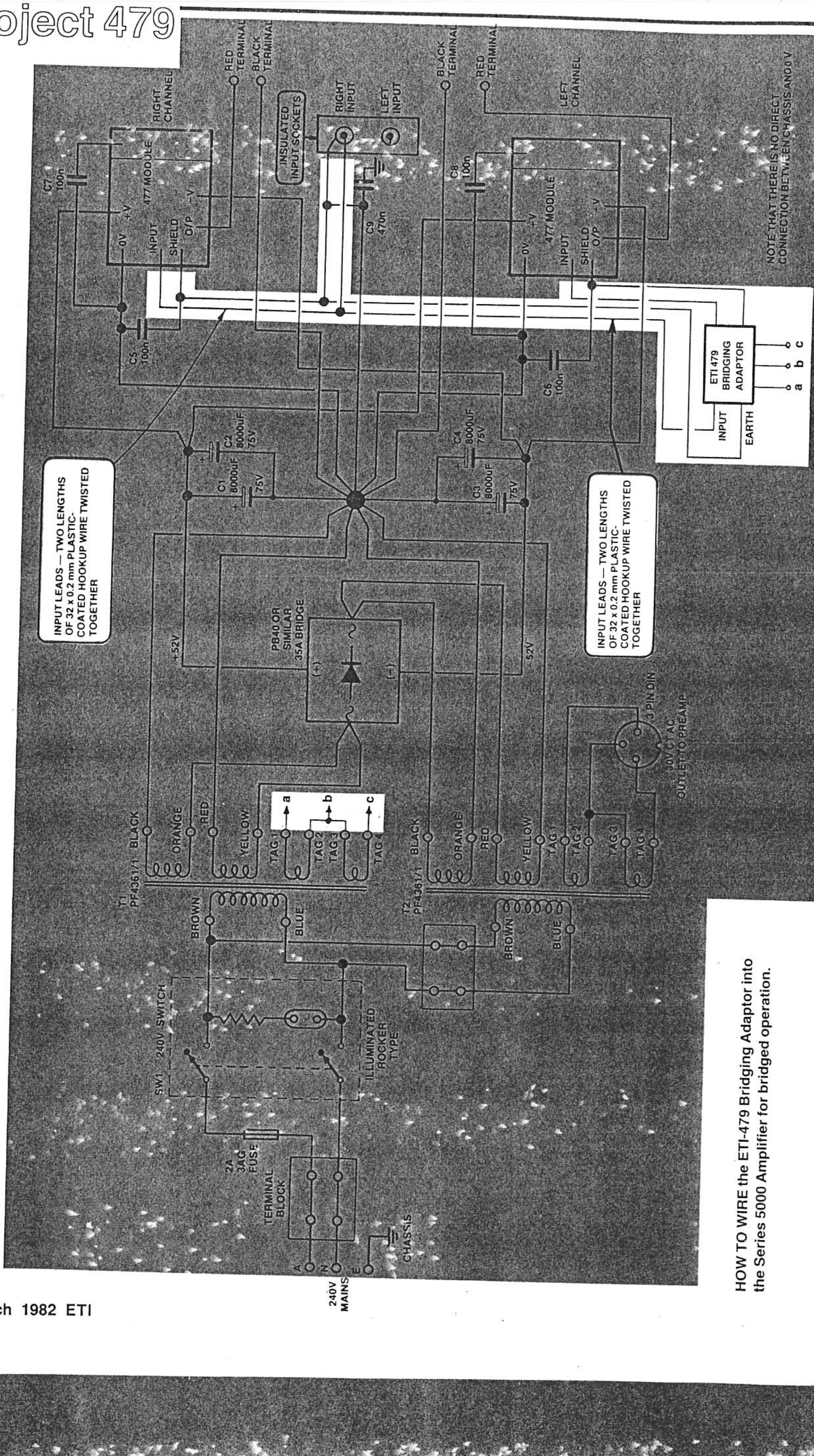


Figure 3. **Bridged power amplifier and single supply showing load and supply current flow.**



HOW TO WIRE the ETI-479 Bridging Adaptor into the Series 5000 Amplifier for bridged operation.

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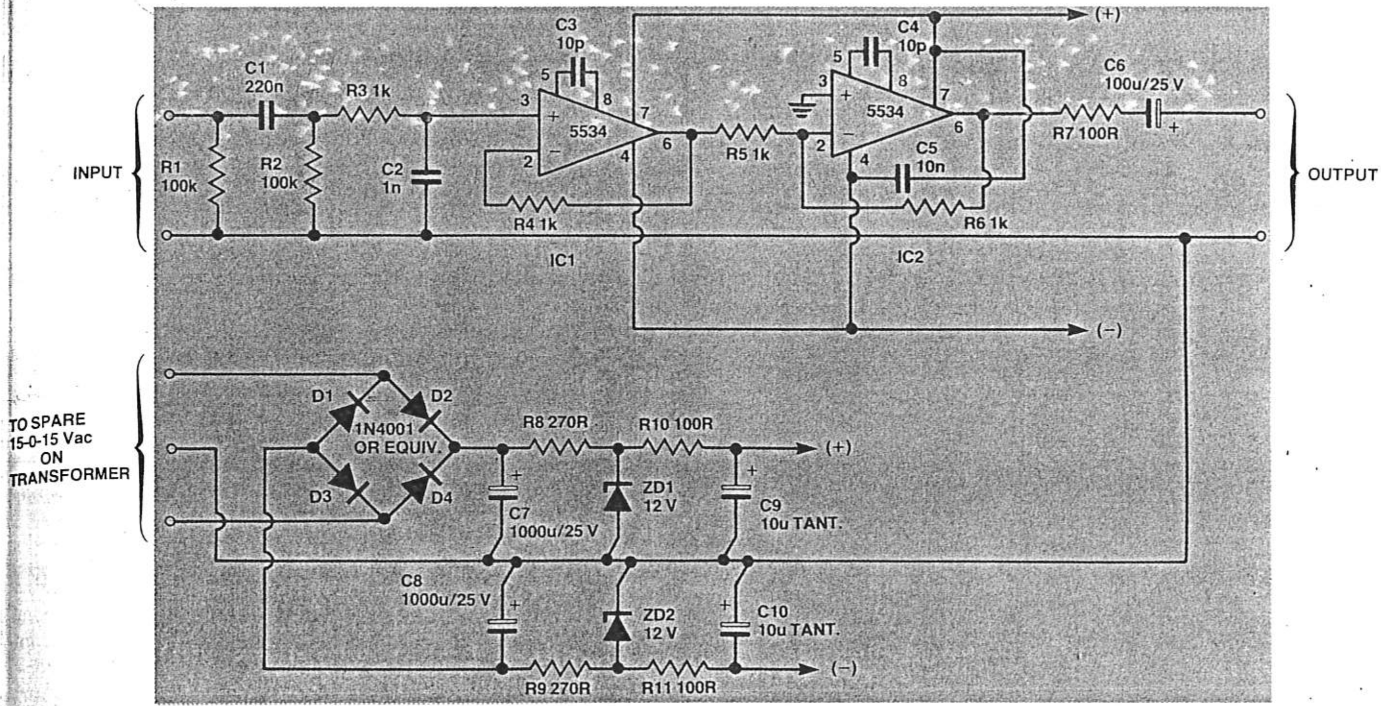


have access to the same single reference point. This is one of the reasons the Series 5000 power amplifier was configured with a single supply even though two power transformers and a total of four electrolytics were used. The two channels in a stereo power amp should be bridged, forming a mono power amp. For stereo operation two such amplifiers are required.

Bridging adaptor

This project consists of a unity gain phase inverter that can be installed within the Series 5000 power amp. The input to one of the power amps is disconnected from the input socket and is wired to the output of the bridging adaptor. The input of the bridging adaptor is connected in parallel with the input of the other channel. This leaves one of the input sockets unused, although it could be connected to the other input socket if required.

The bridging adaptor must not degrade the distortion figures of the amplifier to which it is connected. Similarly good noise figures and freedom from slew-induced distortions must be ensured through careful design of the unity gain amplifier stages. Unfortunately, amplifiers with a gain of one tend to be the most difficult to stabilise because of the relatively high amounts of negative feedback. To overcome this problem and to maintain good noise figures, NE5534N op-amps were used in the design. The conventional way to achieve an inverting amplifier is to ground the non-inverting input and insert the input signal into the inverting input via a resistor. In this configuration the inverting input is also connected to the output of the op-amp through another resistor and forms a virtual earth point. The input resistor therefore forms the input resistance of the stage. Since this is connected to the output of the preamplifier the value of this resistor must be high, i.e: around 10k-100k. Unfortunately, this would seriously degrade the noise performance. To overcome this problem the bridging adaptor has been broken into two stages. The first is simply a unity gain buffer. This stage has low noise figures and an output impedance low enough to drive the following inverter stage. Since the input resistor has been kept to a small value in the second stage a good noise figure results.

HOW IT WORKS — ETI-479

The Bridging Adaptor is a unity gain (i.e: gain of 1x) inverting stage that has its input in parallel with one power amplifier module and its output driving the other power amplifier module. Thus the power amp module it drives operates out of phase with the other power amp module.

The bridging adaptor has two stages — a non-inverting input buffer stage and an inverting output stage. The active device in each stage is an NE5534 high performance op-amp. A rectifier on-board provides dual supply rails regulated by two zeners.

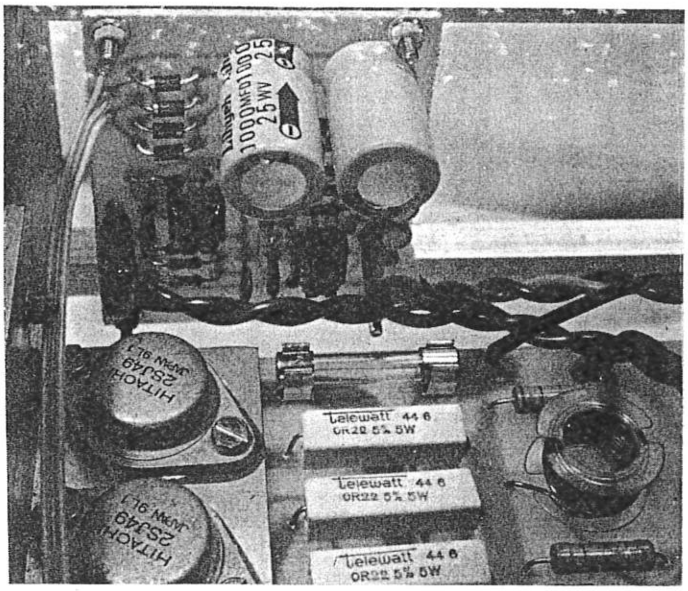
Input is coupled to the non-inverting input of IC1 via an RC network consisting of C1, R2, R3, and C2. Resistor R1 provides a dc return for the input line. Resistor R3 is a low value to ensure good noise performance for IC1, and together with C2, a lowpass filter is established to limit the slew rate of incoming signals to prevent slew-induced distortions. Feedback for IC1 is provided by R4, connected between the output and the inverting input. The output of IC1 drives the inverting input of IC2 via R5. Feedback around IC2 is provided by R6. The feedback constants for both IC1 and IC2 are arranged so that each stage has a gain of one.

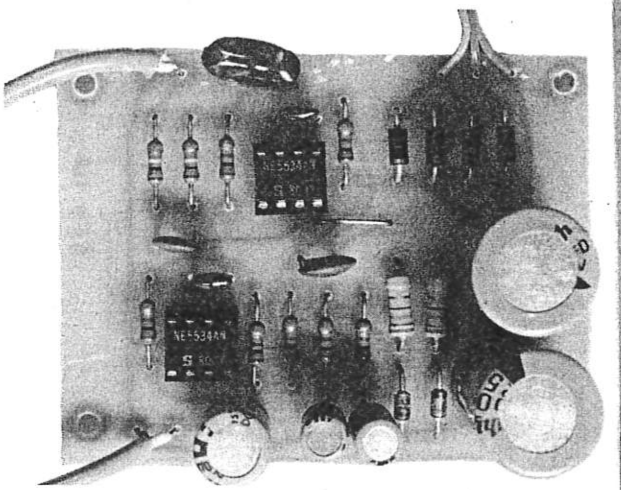
The output from IC2 is coupled via R7 and C6, which provide a low frequency rolloff, C6 also providing dc blocking.

The bridging adaptor is powered from the unused 15-0-15 Vac winding on one of the Series 5000 amplifier power supply transformers. Diodes D1 to D4 form a bridge rectifier providing about ±20 Vdc with respect to the winding centre tap. Capacitors C7 and C8 provide smoothing. Two zener diodes, ZD1 and ZD2, are used to provide regulated positive and negative 12 Vdc supply rails for the two ICs. Resistors R8 and R9 provide current dropping for the two zeners and R10/C9, R11/C10 provide further filtering. Capacitor C5 provides a high frequency bypass for the supply rails. Capacitors C3 and C4 provide frequency compensation for IC1 and IC2 respectively.

Construction

Construction of the bridging adaptor is not difficult since all components are ▶





ABOVE: The bridging adaptor board. Note that we did not use screened cable to install the board in the Series 5000 Stereo Amp.

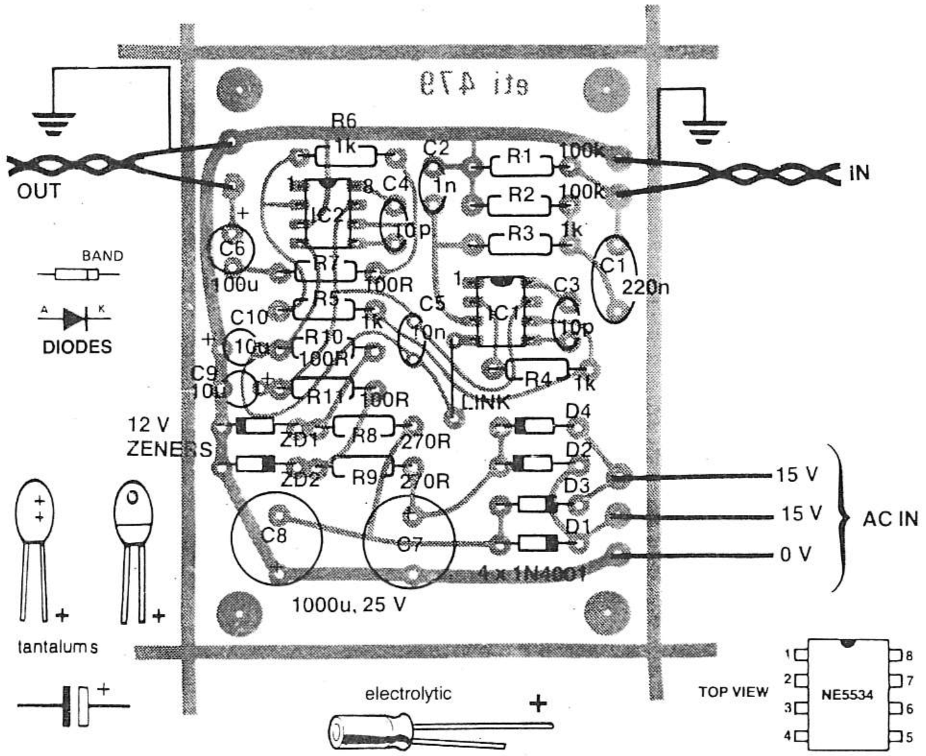
LEFT: The board is installed in the Series 5000 Stereo Amp at the left hand end of the chassis.

mounted on the pc board. The components can be mounted on the board in any order, although it is probably best to leave the two large electrolytic capacitors until last. As usual, be careful of the orientation of all polarised components such as the electrolytic capacitors, ICs and diodes.

Solder input and output leads to the board and bolt to the side bars on the left hand side of the power amp, as viewed from the front, as shown in the accompanying photograph. Use twisted pairs of 32 x 0.2 mm plastic-covered hookup wire, as with the existing input wiring. Solder the output directly to the input of the power amp closest to the bridging adaptor. Solder the input leads of the bridging adaptor to the input socket of the other power amp. Included here is the block diagram of the Series 5000 power amplifier showing suitable modifications to incorporate the bridging adaptor.

Performance

The prototype bridged Series 5000 amp performed favourably and gave distortion figures around the resolution of our THD analyser (approx. 0.003%). Similarly, noise figures were not degraded and the adaptor tested was free of slew-induced distortion. The power output achieved was around 300 W RMS when connected to an 8 ohm load. Connection to a 4 ohm load is *not* recommended for the reasons given earlier in this article.



PARTS LIST — ETI-479	
Resistors	all ½ W,5%
R1,R2	100k
R3,R4,R5,R6	1k
R7,R10,R11	100R
R8,R9	270R
Capacitors	
C1	220n greencap
C2	1n greencap
C3,C4	10p ceramic
C5	10n greencap
C6	100u/25 V electrolytic
C7,C8	1000u/25 V electrolytic
C9,C10	10u/20 V tantalum
Diodes	
D1-D4	1N4001 or equivalent
ZD1,ZD2	12 V 400 mW zeners
Integrated Circuits	
IC1,IC2	NE5534N
Miscellaneous	

ETI-479 printed circuit board; assorted mounting hardware; hookup wire.

Price estimate

We estimate the cost of purchasing all the components for this project will be in the range:

$12-$14

Note that this is an **estimate** only and **not** a recommended price. A variety of factors may affect the price of a project, such as — quality of components purchased, type of pc board (fibreglass or phenolic base), type of front panel supplied (if used), etc — whether bought as separate components or made up as a kit.