TRANSISTOR D.C. MULTIMETER

By W. CLELAND

A VALVE voltmeter, or a transistorised version, such as the multimeter described here, has an increased power sensitivity that gives it a useful role in circuit testing.

In the transistorised d.c. multimeter, the sensitivity of a moving-coil milliammeter is increased up to 100,000 times by preceding it with a solid-state amplifier, and at the same time the moving-coil meter is protected against overload. The amplifier uses silicon planar transistors throughout, and has an input current of picoamps.

Silicon planar transistors are less affected by temperature than field-effect transistors—the nearest solid-state counterpart to valves—and are more uniformly matched in their temperature variation. The completed instrument has a temperature drift of something like 15 microvolts per degree centigrade, making measurement possible in the millivolt and nanoampere region.

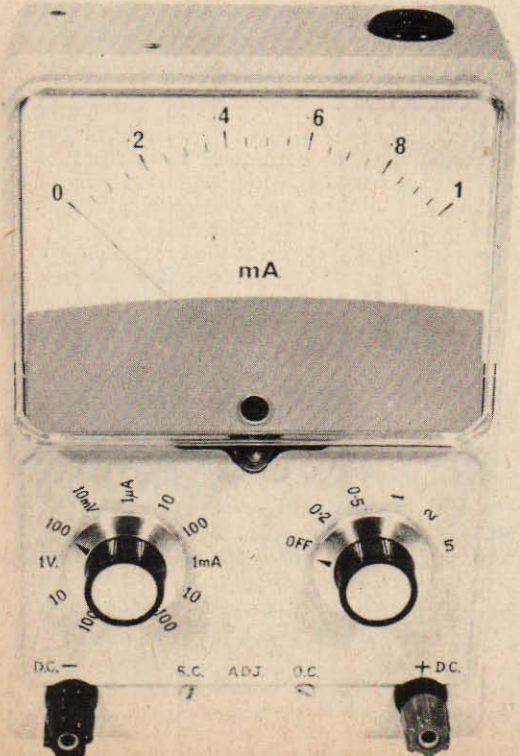
RANGES

One advantage of the large number of ranges (as listed in Table 1) is that most readings can be taken on the upper half of the scale, and this enables measurements to be made with a more consistent accuracy. Only a single scale is available for all ranges, but the basic ranges increase in powers of ten, and the multiplying factors are 0·2, 0·5, 1, 2 and 5, so that only doubling or halving the reading is required on ranges where the factor is not unity.

The scale of the meter is marked in even digits only, and these become consecutive when halved. Separate scales would be better, but it is not too awkward to halve or double the readings.

Direct currents and voltages can be measured on a total of 40 different ranges. There are also 18 superfluous ranges, shown in white panels in Table 1, differing only in impedance, that are not included in the total of 40. On ranges of from 0·2 volt to 500 volts f.s.d., an input impedance of 20 megohms is obtainable; sufficiently high not to disturb conditions in almost all circuits. On lower ranges, the input impedance reduces to 2 megohms, and on the millivolt ranges to 200 kilohms.

Ranges of current are also included, and extend down to 10 nanoamperes f.s.d., using the 2 millivolt range for the purpose.



VARIATIONS AND APPLICATIONS

The analogue testmeter is intended as a d.c. instrument, but an external adaptor for a.c. measurement could be added, using diodes or a thermocouple; a calibration curve might then be required.

Resistances can be measured over a very wide range using an external battery and potentiometer. Although there is no ohmmeter scale, the input resistance increases in steps of ten times on the current ranges from 0·1 ohm to 10 kilohms, and then on the voltage ranges from 200 kilohms to 20 megohms. Mid-scale readings of from 0·1 ohm to 20 megohms should therefore be obtainable, and insulation resistance could be measured with suitable circuit arrangements.

As a high-impedance millivoltmeter, the analogue testmeter can be used as a null detector to compare resistances accurately in a bridge circuit, and this method was used in making the 0·1 ohm resistance for the 100 mA range (R27).

INPUT/OUTPUT RATIO

A meter amplifier must include some form of feedback loop. Precision amplification depends upon feedback and is closely equal to the feedback ratio. The amplification without feedback is much greater, and is utilised in reducing the error margin. Feedback, applied over the amplifier is thus able to establish a definite ratio between input and output. The accuracy of this relationship can be tested by switching the milliammeter between the output and input circuits, with resistances included to keep the loading on the input source unchanged.

Table 1. MULTIMETER RANGES

RANGE SWITCHES S1 ▼ / S2 ▶	FULL SCALE DEFLECTION ON EACH RANGE (Accuracy—within ±5% on all ranges) 0·2	0·5	1	2	5	INPUT IMPEDANCE
100V	20V	50V	100V	200V	500V	20·2MΩ
10V	2V	5V	10V	20V	50V	20MΩ
1V	200mV	500mV	1V	2V	5V	20MΩ
100mV	20mV	50mV	100mV	200mV	500mV	2MΩ
10mV	{2mV / 10nA}	5mV	{10mV / 50nA}	{20mV / 100nA}	50mV	200kΩ
1μA	0·2μA	0·5μA	1μA	2μA	5μA	10kΩ
10μA	2μA	5μA	10μA	20μA	50μA	1kΩ
100μA	20μA	50μA	100μA	200μA	500μA	100Ω
1mA	200μA	500μA	1mA	2mA	5mA	10Ω
10mA	2mA	5mA	10mA	20mA	50mA	1Ω
100mA	20mA	50mA	100mA	200mA	500mA	0·1Ω

BASIC ARRANGEMENT

A simplified diagram, Fig. 1a, shows the basic feedback arrangement. Actually the differential arrangement of Fig. 1b is used in the analogue testmeter. This is completely symmetrical, and if only half is considered, the action is similar to Fig. 1a.

Corresponding to the large current amplification in the feedback loop, the input current to the amplifier is extremely small, and most of the current from the input terminal, through R_i, will flow past the input of the amplifier to become feedback current in the feedback resistor, R_f. This is equivalent to subtracting the feedback current from the input current to leave a small amplifier input. The output current in R_L is a multiple of the current from the input terminal, nearly equal to R_f/R_L.

In terms of voltages, the action is like tipping a balance; as one end goes up, the other end comes down, and similarly a voltage at the input produces a voltage of opposite polarity at the output. The amplifier input voltage is automatically reduced to bring it nearly to the fulcrum or zero position, although always short of zero by a small residual that is amplified to give the output. The input and output voltages will be in the ratio R_i/R_f, and the input impedance will be R_i.

In Fig. 1b, two of the Fig. 1a systems are, in effect, combined in a push-pull version, and the action is like two balances tipping equally in opposite directions at the same time.

CIRCUIT DESIGN

In the version of Fig. 1b, with a direct-coupled amplifier, feedback is applied symmetrically. There is a doubled input impedance, and both terminals are floating. To fix the potential of one terminal would unbalance the feedback and considerably increase drift. Offset is much less of a problem when the system is completely symmetrical, both terminals tending to remain at the same zero-signal potential. The effects of stray capacitances also tend to cancel.

A differential output stage overcomes any uncertainty about the value of R_L. Intermediate stages of this type also have advantages, and a differential input stage is essential to overcome offset and temperature drift.

Each stage in the amplifier thus consists of a pair of transistors, and by making the impedance in the emitter circuit as large as, or preferably much larger than, the collector load impedances, amplification of common-mode inputs can be avoided. A third transistor can be added in the emitter circuit of a differential stage to act as a high effective impedance, or constant current generator, keeping the total collector current constant. This gives a high common mode rejection ratio and makes the stage largely independent of voltage levels elsewhere in the amplifier, although still sensitive to differential inputs.

AMPLIFIER OPERATION

The amplifier is formed of three differential stages, together with emitter-followers. A configuration of five *npn* transistors is repeated, and between these two

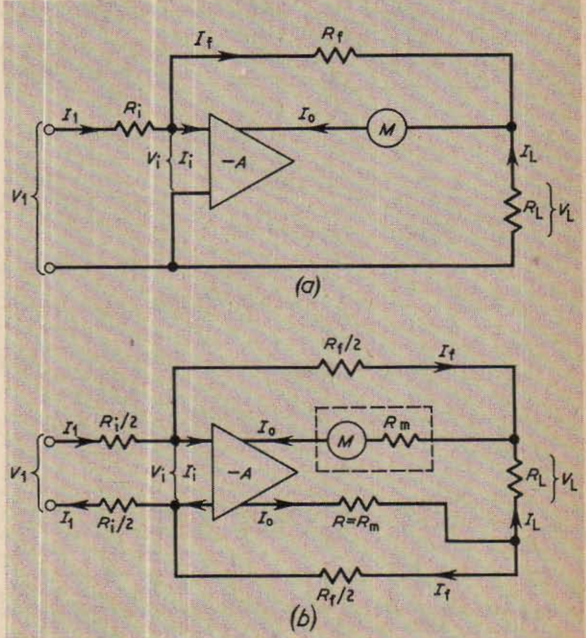


Fig. 1. Principle of the transistorised d.c. multimeter. (a) Basic arrangement of an inverting d.c. amplifier as a current or voltage follower. (b) Differential system incorporating a fully differential d.c. amplifier

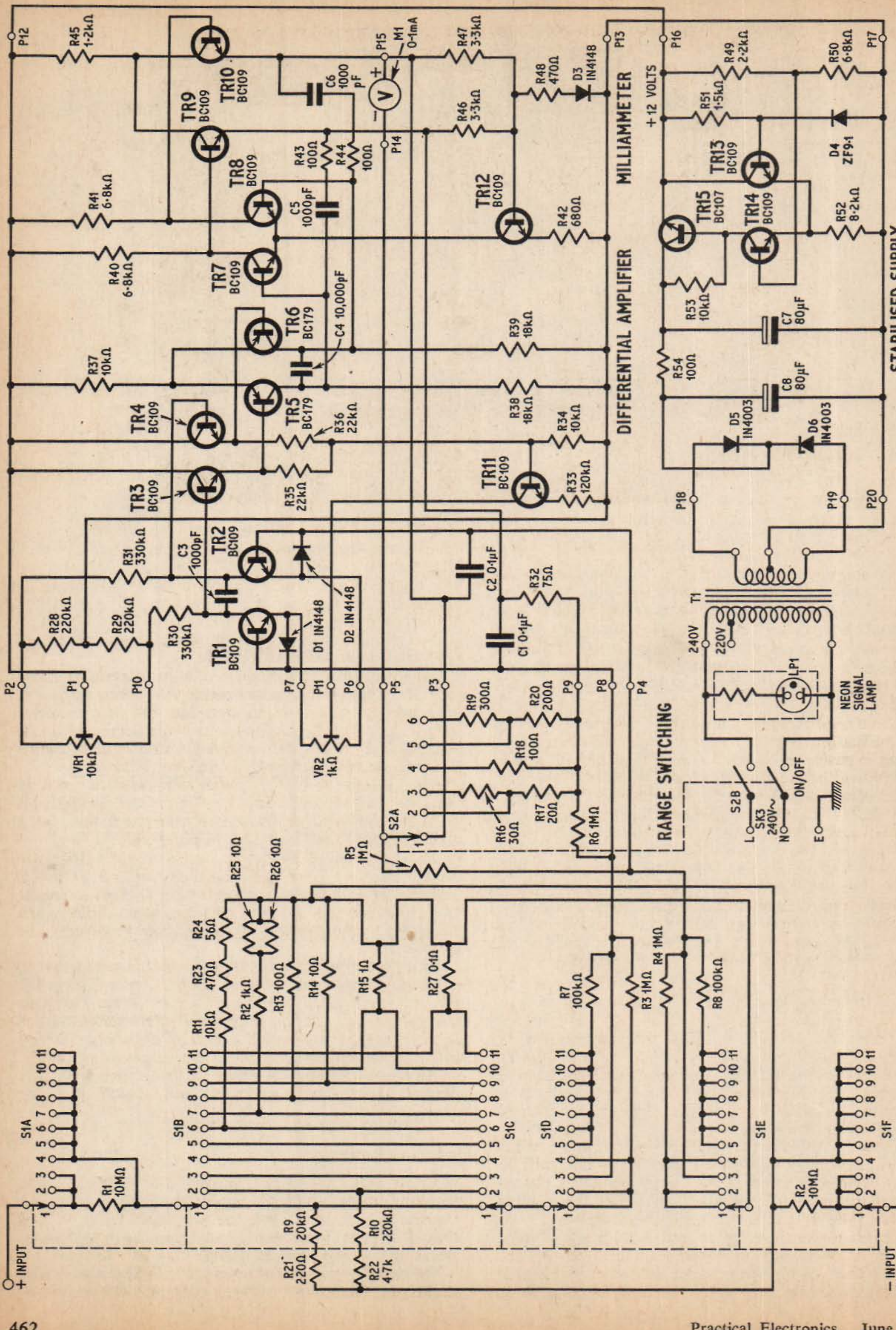
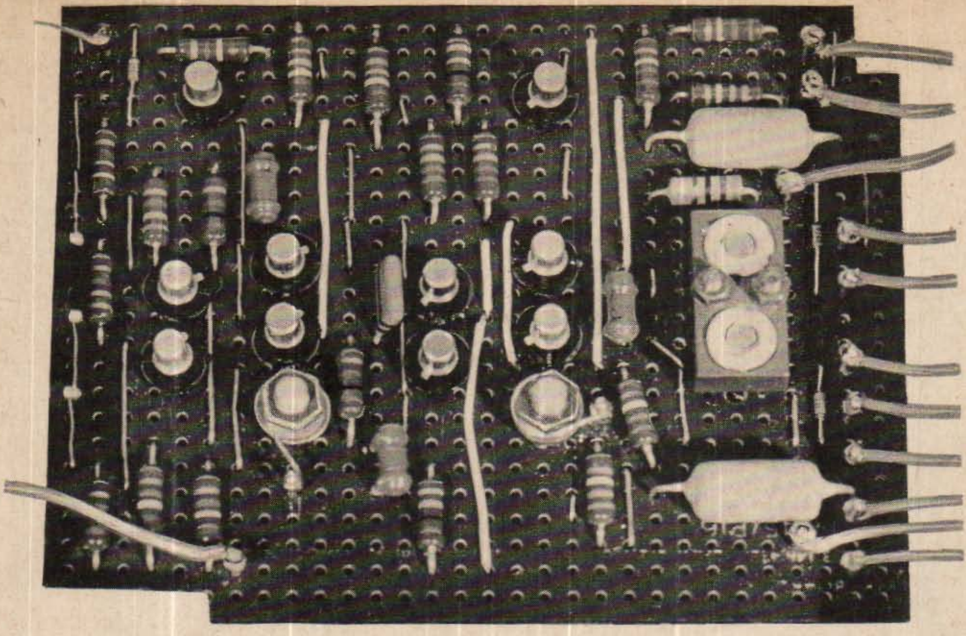


Fig. 2. The circuit diagram of the transistorised d.c. multimeter



Completed amplifier board with connecting wires attached

sections, a *pnp* stage is included (see Fig. 2) to reverse the stage by stage increase in voltage levels that usually occurs in a direct coupled amplifier, enabling d.c. feedback to be more readily applied between the output and input. In the *npn* configurations, the small amplification round the minor stabilising loop, helps to fix the voltage levels, and improves the symmetrical response to signals.

Amplification is only required at a low frequency, making it easier to achieve a very high amplification. The bandwidth is restricted to exclude mains frequency by including capacitors in the feedback network. Phase shift in the rest of the amplifier could produce oscillation, and to prevent this, two networks, each consisting of a 100 ohm resistor in series with 1,000 pF capacitor, are connected from the emitters of the output stage to the bases of the preceding stage. These effectively suppress oscillation at a low radio frequency, but v.h.f. oscillation can still occur, and must be prevented by connecting an additional capacitor of 10,000 pF between the collectors of the *pnp* stage.

VOLTAGE LEVEL VARIATION

Some variation in voltage levels is to be expected every time an amplifier is constructed because of component tolerances. The ratios of resistances associated with the constant-current stages will have the main effect, but the variations will not be amplified in successive stages because of the high common-mode rejection in the amplifier stages.

A diode in the second constant-current stage is for temperature compensation, to avoid a small shift in voltage level with temperature which would be passed back to the input of the amplifier. The diode adds slightly to the tolerance spreads in the amplifier.

A transistorised voltmeter will not check voltage levels in its own amplifier because of feedback effects. A simple form of high-impedance voltmeter will enable approximate checks to be made on amplifier conditions.

AMPLIFIER PANEL

The amplifier panel is shown in Fig. 3, and consists of 0·15 inch pitch veroboard.

An insulated backing sheet of thin material is fitted behind the amplifier panel, separated from it by the thickness of the 2 B.A. nuts on the milliammeter terminals. This is intended to provide some additional insulation between the amplifier and the neon mains indicator situated under the amplifier board.

The holes for the 2 B.A. meter terminals are carefully positioned as shown in Fig. 3. Two of the perforations on the Veroboard are drilled to take the 8 B.A. bolts that hold the small heat sink in position.

The positions of the breaks in the copper strips are shown in Fig. 3. Additional links are of 24 s.w.g. tinned copper wire,this gauge is thin enough to enable two links to be inserted in the same hole when necessary; the longer links should preferably be sleeved.

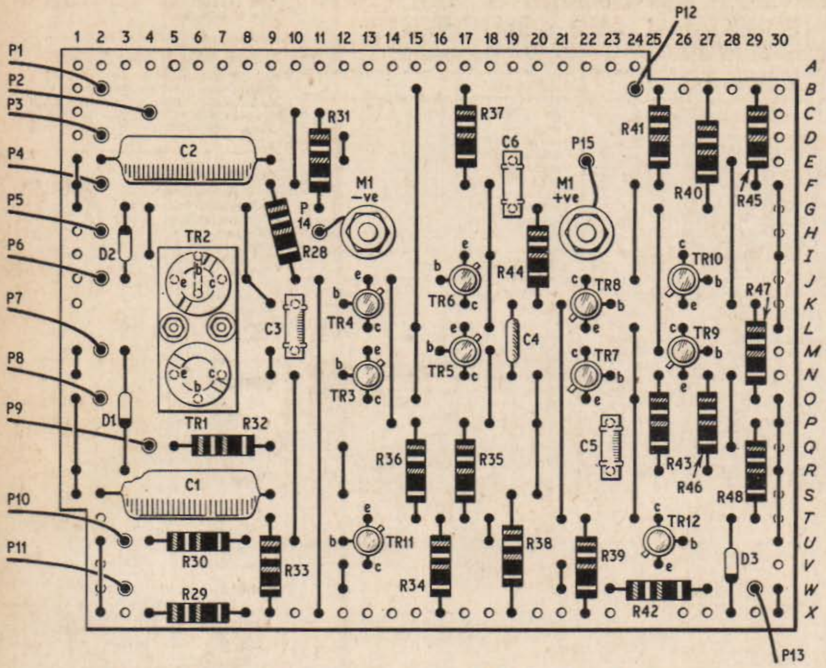
Veropins inserted into the amplifier board serve as soldering points for external connections. Those for the 0·15 inch pitch Veroboard are of larger diameter than those for the 0·1 inch pitch Veroboard that is incorporated in the range-switching assembly detailed later. The veropins are put in on the component side, soldered to the copper strips on the other side, and clipped short so that they do not project into the backing sheet.

TRANSISTORS

There are altogether a dozen transistors on the amplifier board, all of TO18 construction. Two of the transistors, TR5 and TR6, are *pnp* types (BC179) and should be kept carefully separate from the others which are all of the *npn* type (BC109).

The two *pnp* transistors form the intermediate voltage amplifying stage, and provide a convenient means of

AMPLIFIER BOARD



Pin numbers on the lead-out wires will be explained in the final wiring diagram

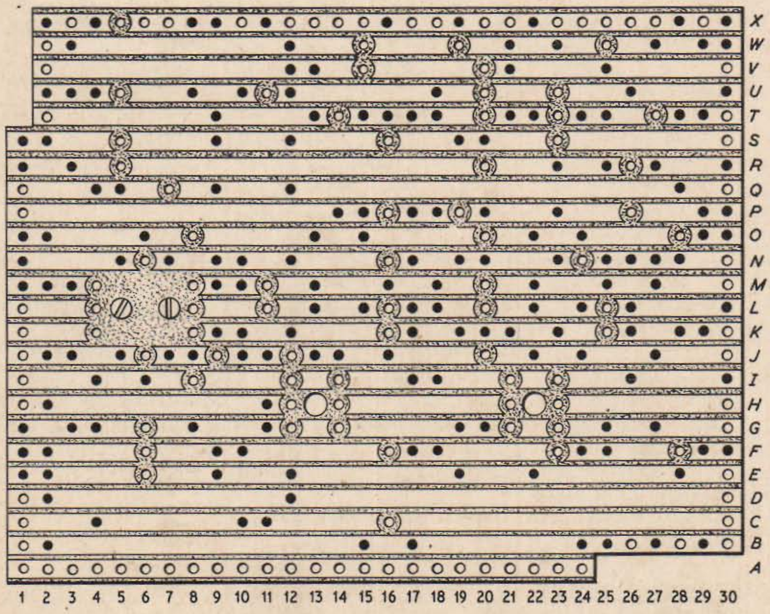


Fig. 3. Amplifier panel layout and wiring

COMPONENTS . . .

AMPLIFIER

Resistors

R28 220kΩ
R29 220kΩ
R30 330kΩ
R31 330kΩ
R32 75Ω
R33 120kΩ
R34 10kΩ
R35 22kΩ
R36 22kΩ
R37 10kΩ
R38 18kΩ
R39 18kΩ
R40 6·8kΩ
R41 6·8kΩ
R42 680Ω
R43 100Ω
R44 100Ω
R45 1·2kΩ
R46 3·3kΩ
R47 3·3kΩ
R48 470Ω

All ±5% ½W carbon film

Capacitors

C1 0·1μF polyester
C2 0·1μF polyester
C3 1,000pF ceramic
C4 10,000pF polyester
C5 1,000pF ceramic
C6 1,000pF ceramic

Semiconductors

D1–3 1N4148 (3 off)
TR1–4 BC109 (4 off)
TR5–6 BC 179 (2 off)
TR7–12 BC 109 (6 off)

Miscellaneous

Veroboard 4⅝in × 3¾in, 0·15in matrix
Veropins
Heatsink 2 × TO18 (Redpoint 18DC/HA)
S.R.B.P. 4⅝in × 3¾in (backing panel)

STABILISER BOARD

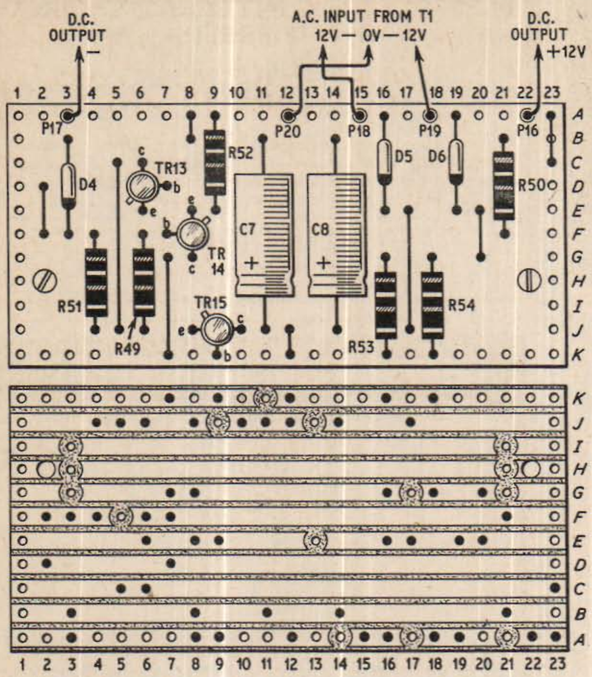


Fig. 4. Stabiliser board layout and wiring

COMPONENTS . . .

STABILISER

Resistors

R49 2·2kΩ	R52 8·2kΩ
R50 6·8kΩ	R53 10kΩ
R51 1·5kΩ	R54 100Ω

All ±5% ½W carbon film

Capacitors
C7 80μF elect. 25V
C8 80μF elect. 25V

Semiconductors
TR13, 14 BC 109 (2 off)
TR15 BC 107
D4 ZF 9·1
D5, 6 1N 4003 (2 off)

Miscellaneous
Veroboard 3¾in × 2½in, 0·15in matrix
Veropins
S.R.B.P. board 3¾in × 2½in (backing board)

bringing down the output to the same voltage level as the input, without introducing potential dividers or zener diodes.

In a feedback amplifier, temperature variation in the base-emitter potential of the input transistors is likely to be the only significant temperature variation causing drift, and its effect can easily be reduced by making the input circuit of high impedance, and by using a differential pair of transistors. There is considerable uniformity as regards the base-emitter temperature characteristic, so unmatched transistors can be used in differential stages. It is probably worthwhile, however, to sort out the BC109 transistors into pairs, and to use the best matched pair for the input stage. The transistors should be from the same production batch, and can be matched in β at a current of about 10μA. Transistors matched at 1mA may not be so well matched at a lower current.

HEAT SINK

Very constant conditions are maintained in the input stage, and the completed instrument has a sufficiently stable zero even on the 2 millivolt range. If the temperature characteristics of TR1 and TR2 are not alike, a rise in junction temperature will produce unequal effects, and drift will occur from switching on. However, the dissipation is very small, as the collector current is only 10 microamperes, and this should help to reduce the initial drift. Short term drift is very undesirable, as it can occur during a measurement. Long term drift takes place through changes in room temperature, and will be about 15μV per degree Centigrade.

If the two transistors were mounted separately, a slight difference in heating would cause a shift of zero position on the meter. It is necessary, therefore, to equalise the temperatures by mounting them close together in a heat sink.

Before insertion, the transistors should be turned so that the leads are in the correct position to pass through the perforations on the amplifier board. Both transistors require the same orientation, with the small lugs parallel, and with the base lead of each transistor on the centre line of the heat sink.

The heat sink is raised sufficiently from the amplifier board to allow for the spread of the transistor leads. A small piece of insulating material serves as a spacer.

STABILISER

It is just as necessary to overcome drift due to mains voltage variation, and this can be done by stabilising the 12 volt supply with a three transistor circuit (TR13 to 15 in Fig. 2). A high degree of stabilisation can easily be achieved, since the amplifier requires only a few milliamperes of current.

Positions of the components on the stabiliser board is shown in Fig. 4, this also shows the breaks in the copper strips. The two electrolytic capacitors are mounted centrally.

The finished board is mounted vertically at the side of the amplifier nearest to the miniature mains transformer T1, by means of an aluminium bracket to which it is fastened by 6 B.A. bolts. These also pass through the insulated backing piece from which it is spaced by insulating washers, case details and board positioning will be given later.

Next month: Further construction details