about 20kHz. Thereafter, with increasing frequency, the phase angle will begin to shift until, at several hundred kHz, and especially when the amplifier has a high gain, sufficient positive feedback is present to cause sustained oscillation. To counteract this instability, small capacitors are suitably situated in the op-amp circuit to reduce gain at critical frequencies, and it follows that the use of such capacitors will place a limitation on the available frequency response of the amplifier.

C1 of Fig. 3.7 will block the unwanted high frequency content of incoming signals, and plays a major role in determining the bandwidth of the amplifier. If C1 is reduced in value, bandwidth will be increased, but so will the likelihood of instability. Needless to say, any form of instability will be highly detrimental to accuracy, and must be avoided at all costs. C2 works in a different way, by introducing negative feedback and consequent loss of gain at very high frequencies. Both capacitors act together to combat instability under the very varied conditions of operational amplifier use.

The measured frequency response of a representative UNIT "A" amplifier is given in Fig. 3.9, and is very linear up to the well-defined break frequencies of (a) open-loop, (b) with feedback resistor of 100 kilohm, and (c) when R_f = 10 kilohm.

DRIFT

If a d.c. amplifier is adjusted so that its output voltage is zero when there is no input signal, over an interval of minutes, hours, or days—depending on the amplifier, its power supply, and its surroundings—a spurious voltage will begin to appear at the output. A poor amplifier in adverse conditions will require frequent manual adjustments to keep its output at zero. Fortunately, drift errors are very small when an operational amplifier is used for summing and sign changing, due to the presence of a feedback resistor, and no adjustment of the amplifier will be called for during intervals of perhaps several hours, except in applications requiring a very high degree of accuracy. However, when the operational amplifier is being used as an integrator, with a capacitor in its feedback loop, it is quite possible for drift errors to exceed 1 per cent within a space of less than an hour if suitable precautions are not taken.

The figure quoted in Table 3.1 for drift is the amount of input voltage, either positive or negative, required at the amplifier summing junction to reset the amplifier output to zero after it has been allowed to drift for one hour following a preliminary computer warm-up period. In practical terms, a drift of about ±0·5mV per hour is not likely to prove to be too troublesome with most PEAC applications. Full scale analogue computers are sometimes installed in a temperature controlled computing room, and this considerably improves drift performance.

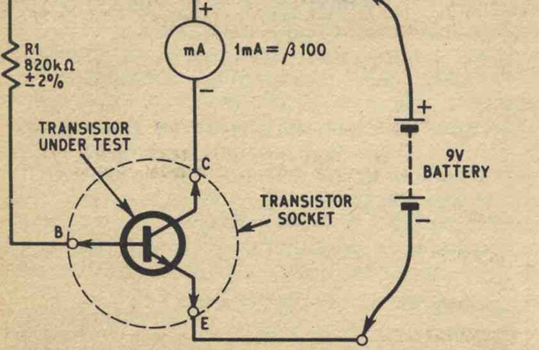
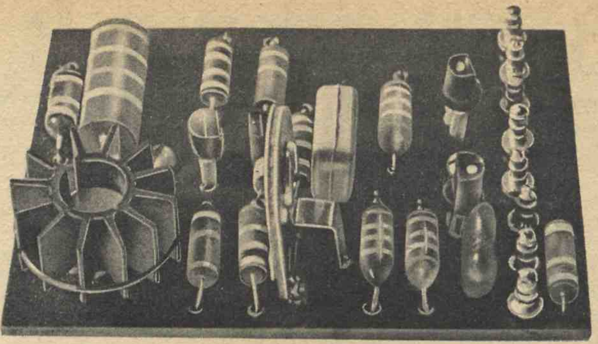


Fig. 3.10. Transistor test-rig. Note: reverse battery connections and milliammeter for pnp



TRANSISTOR SELECTION

Several prototype UNIT "A" amplifiers were constructed using non-selected transistors, and about one third of the amplifiers failed to meet the specification of Table 3.1. Defects were due entirely to "spreads" in semiconductor characteristics, and disappointment will be avoided if all amplifier semiconductors are tested before use.

It has already been mentioned that the long-tailed pair input stage transistors (TR1 and TR2 in Fig. 3.7) should be matched. In all nine transistors of the same type will be required for TR1, TR2, and TR3 in the three operational amplifiers, and it will assist the matching and selection process if, say, one dozen transistors are purchased at the same time. No wastage will be involved as "spare" transistors can later be used up in other PEAC circuits.

A simple test-rig circuit is given in Fig. 3.10 to facilitate the matching of TR1 and TR2, and the circuit can also be quickly adapted for checking other transistors. The test-rig could take the form of a transistor socket and resistor mounted on an odd piece of s.r.b.p., or Veroboard, with a testmeter employed as a milliameter.

Select each TR1–TR2 pair for near identical *betas* of 100 or more; this will dispose of six transistors. Do not attempt to pair off transistors of different types even if they do have the same *beta*. From the remaining transistors, choose three with the highest *beta* for TR3.

Although TR4 is a *pnp* transistor, it must be of silicon construction for low leakage drift. The majority of *pnp* silicon types at present on the market are unsatisfactory for use in the op-amp circuit because they exhibit almost no gain at all at very low collector current levels. Of all the types so far tested only the 2N3906 was found to be consistently good at low currents, therefore a suitable equivalent cannot be quoted. To check TR4, reverse the battery leads to the Fig. 3.10 test-rig, and switch connections to the milliameter before plugging in the *pnp* transistor. TR4 should display a *beta* of about 50 or more.

When handling plastic encapsulated transistors, which tend to look alike, take note that lead connections do not necessarily conform to a common pattern. In particular, notice the lead differences between types 2N2926 and its equivalent 2N3904, and remember that the 2N3906 is *pnp*. To avoid mishaps, always refer to Fig. 3.3 before applying current to the transistor.