TRANSFORMERLESS TECHNIQUE RESULTS IN GOOD PERFORMANCE, ALLIED WITH SIMPLICITY AND COMPACTNESS

Transistor Audio Power Amplifier

By R. TOBEY, M.A. and J. DINSDALE, B.A.

THE object of this design is to produce a transistor amplifier comparable in performance with good modern practice using thermionic valves, but with all the advantages of transistorized equipment.

This object is best achieved by the elimination of all transformers from the design, when the following advantages are obtained:—

(i) Smaller size and weight, since transformers account for a large portion of the bulk and weight of a conventional power amplifier.

(ii) Better frequency response.

(iii) Greater efficiency.

(iv) Less distortion without feedback.

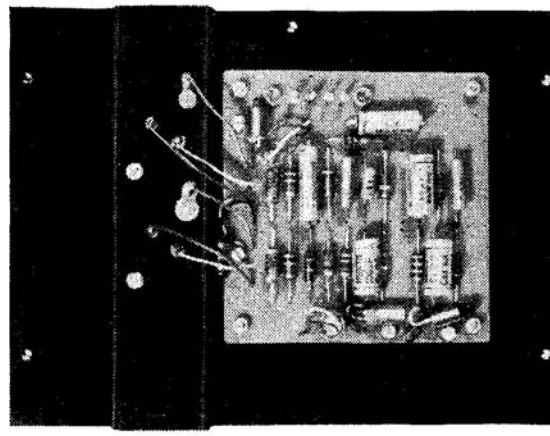
(v) More feedback may be used to reduce this distortion still further, without causing instability.

(vi) One expensive component less required.

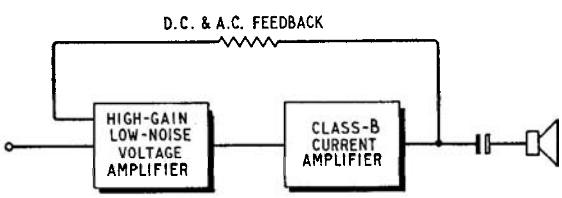
The basic circuit is shown in block diagram form in Fig. 1. It consists of a high-gain, low-noise, voltage amplifier, directly coupled to a current amplifier, with overall d.c. negative feedback to stabilize the working points of the transistors, and a.c. feedback to reduce distortion to a sufficiently low level.

Current Amplifier.—This matches the low impedance of the loudspeaker to the output of the voltage amplifier. Two stages are needed to give the required current gain of about 1,000.

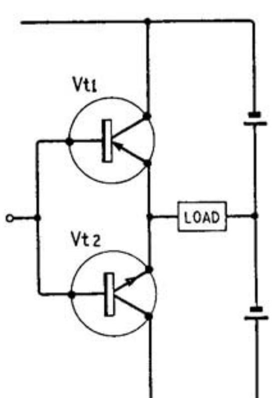
There are various ways of matching a Class-B push-pull output stage to a loudspeaker load without incorporating transformers. These all hinge round the use of complementary symmetry, i.e. a p-n-p/n-p-n pair of transistors.



Power amplifier showing components mounted on a printed circuit plate.



Above: Fig. 1. Block diagram of amplifier.



Left: Fig. 2. Push-pull Class-B emitter follower.

Fig. 2 shows a single stage of what may be considered as a Class-B emitter follower. Vt1, a p-n-p transistor, acts as an emitter follower for the negative half cycles of the input, while Vt2 is cut off. Similarly, Vt2, an n-p-n transistor, emitter follows the positive half cycles.

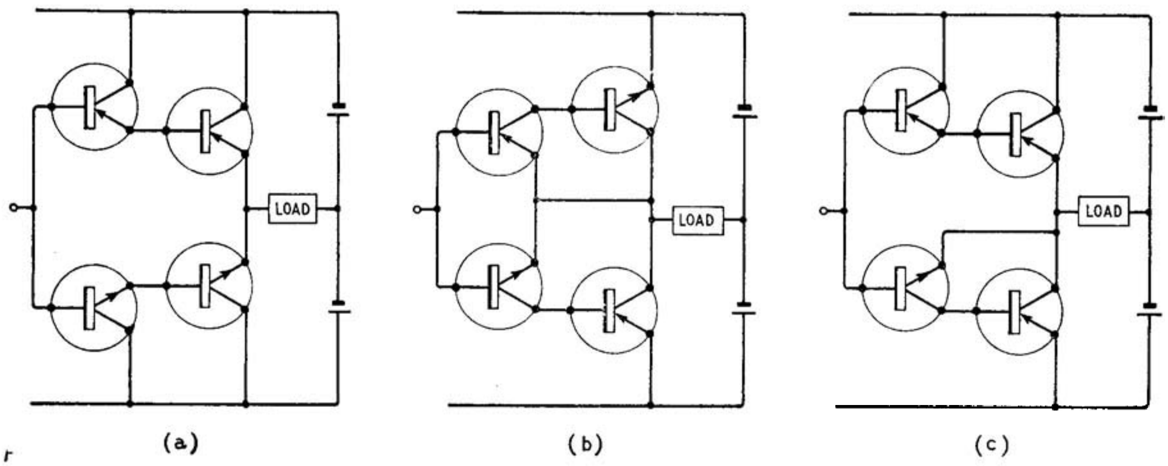
Fig. 3a shows a two-stage Class-B emitter follower having a total current gain equal to the product of the current gains of the individual stages. The voltage gain is slightly less than unity, as would be the case with the analogous cathode-follower circuit, each stage having 100 per cent voltage feedback.

A different arrangement of the same transistors giving the same result is shown in Fig. 3b. This consists of two grounded-emitter stages with 100 per cent voltage feedback over the two stages together (as opposed to over each stage separately as in Fig. 3a). The voltages, currents and dissipations of the various transistors are the same at any point of the waveform in both arrangements.

From Figs. 3a and 3b is derived the arrangement of Fig. 3c which has the advantage that both output power transistors may be of the p-n-p type.

All three arrangements will give equally satisfactory results, however, with suitable transistors.

The voltage amplifier (see Fig. 4) consists of two directly-coupled grounded-emitter stages in cascade. Vt1 works with a low value of collector-



r

ig. 3 (a) Two-stage push-pull Class-B emitter follower. (b) Two-stage push-pull Class-B grounded-emitter amplifier with 100 per cent voltage feedback. (c) Hybrid circuit derived from (a) and (b).

emitter potential and with a small collector current, thus ensuring a low noise factor.

Complete Amplifier (Fig. 4).—The voltage and current amplifiers are d.c. coupled, and the complete amplifier has d.c. feedback around it via R_{16}, which stabilizes the working points of all the transistors. The quiescent current in the output stage Vt5, Vt6, is set by R_9, in series with the diode D1, about 10-20 mA being suitable. The d.c. working point of the output of the amplifier (Vt6 collector) should be half the supply voltage with respect to earth, and should be set up if necessary by varying R_1.

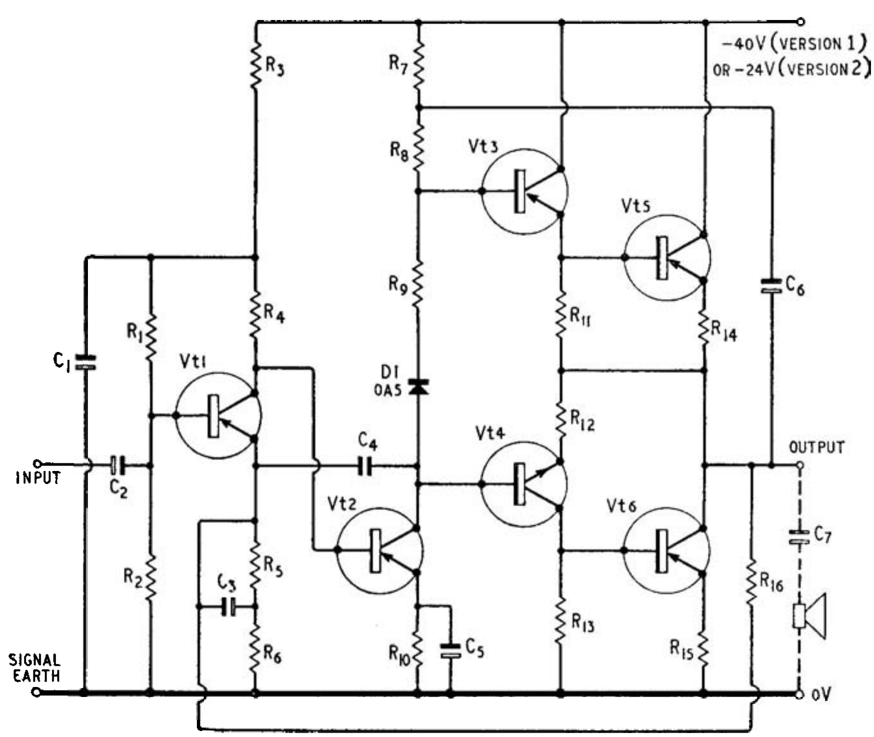


Fig. 4. Power amplifier circuit.

The diode D1, is biased in the conducting direction on a portion of its characteristic giving a high degree of voltage stabilization across it, with change of current through it (Fig. 5). This stabilizes the output stage quiescent current against supply voltage variations, and also reduces the effects of temperature on the output stage quiescent current, provided that the diode is attached to the same heat sink. R_{14}, R_{15} are included to give good thermal stability under adverse conditions.

Values of components are given for two typical versions of the amplifier (see Table 1). Version 1 is designed to give 10 watts into a 15-ohm speaker from a 40-volt supply. Version 2 is designed to give 10 watts into a 4-ohm speaker (or 3½ watts into a 15-ohm speaker) from 24 volts. The design is extremely flexible and easily adapted for other needs. Maximum theoretical power output is $V^2_{batt}/8R_L$ but in practice is only about $V^2_{batt}/10R_L$.

It might be thought that the use of a Class-B output stage in an amplifier for high fidelity applications is undesirable, and would lead to considerable distortion, especially high order harmonics. The distortion introduced at the cross-over point of the output stage characteristic may, however, be kept low by a suitable choice of quiescent current, and the total amplifier distortion may be reduced to any desired level by negative feedback. The application of the high values of

TABLE 1
Component Values for Power Amplifier

Component	*Version* 1: 40 volts 15 ohms		*Version 2:* 24 volts 4 ohms	
Resistor	*Value*	*Remarks*	*Value*	*Remarks*
R1	270kΩ	See Text	330kΩ	See Text
R2	56kΩ		56kΩ	
R3	68kΩ		22kΩ	
R4	22kΩ		22kΩ	
R5	220Ω		150Ω	
R6	33Ω	H.S.	33Ω	H.S.
R7	1kΩ		470Ω	
R8	4.7kΩ		1.5kΩ	
R9	22Ω	See Text	10Ω	See Text
R10	560Ω		270Ω	
R11	150Ω		150Ω	
R12	10Ω		3.3Ω	W.W.
R13	150Ω		150Ω	
R14	1Ω	W.W.	0.5Ω	W.W.
R15	1Ω	W.W.	0.5Ω	W.W.
R16	3.9kΩ	H.S.	2.2kΩ	H.S.

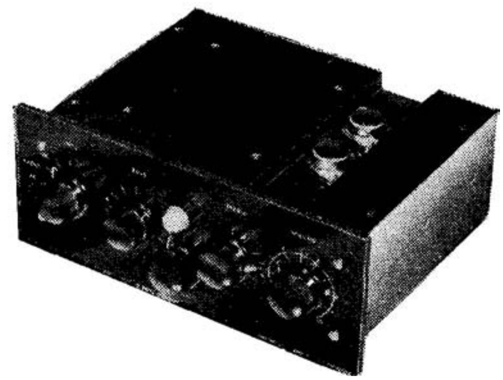
Capacitor	*Value*	*Remarks*	*Value*	*Remarks*
C1	1μF	25V wkg	1μF	25V wkg
C2	50μF	25V wkg	50μF	25V wkg
C3	100μF	6V wkg	100μF	6V wkg
C4	1000 pF		2200 pF	
C5	100μF	6V wkg	100μF	6V wkg
C6	25μF	50V wkg	50μF	25V wkg
C7	1500μF	25V wkg	2500μF	25V wkg
C8 (power supply)	1500μF	50V wkg	2500μF	25V wkg

feedback needed to produce low distortion is facilitated by the transformerless technique, and the absence of transformers removes one source of particularly objectionable cross-over distortion in Class-B amplifiers, which is produced by imperfect coupling between the two halves of the primary of the output transformer.

This amplifier has feedback totalling over 60 dB (34 dB via the main loop, 26 dB locally in the output stage), and the distortion is satisfactorily low (see Table 3) being predominantly third harmonic, as would be expected in a normal well-balanced push-pull amplifier.

Advantages of Class-B Output Stage Operation.—By operating the output stage under conditions which approximate to Class B, important economies are possible in several directions, namely, in the design of the heat-sink and power supplies.

When used to amplify a speech or music input, the average dissipation in the output transistors is very small; they would, in fact, remain cool even without a heat-sink. However, with sine-wave drive (which is used for example in routine testing), a heat-sink of about 50 square inches of 16 s.w.g. aluminium bent to any convenient shape is required. A 10-watt amplifier with a Class-A output stage would require a heat-sink to dissipate at least 20 watts continuously, which would result in a large and cumbersome design. The prototype amplifier



Stereo power amplifier and pre-amplifier showing one pair of output transistors.

was built into an aluminium box which itself served as the heat-sink.

The amplifier is suitable for operation from a wide variety of power supplies. For permanent use a mains power unit may be used, which can, however, be quite rough and ready. Provided a large reservoir capacitor is used, further smoothing and

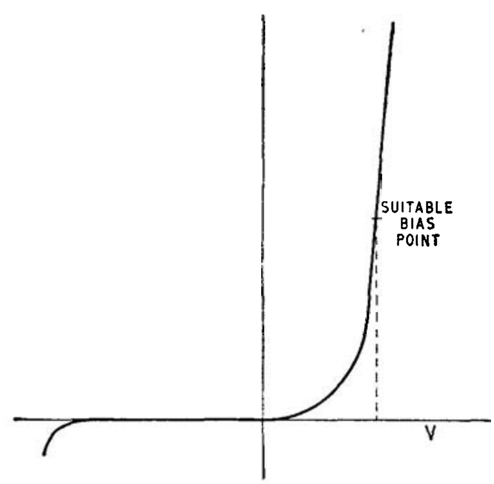


Fig. 5. Diode current/voltage characteristic.

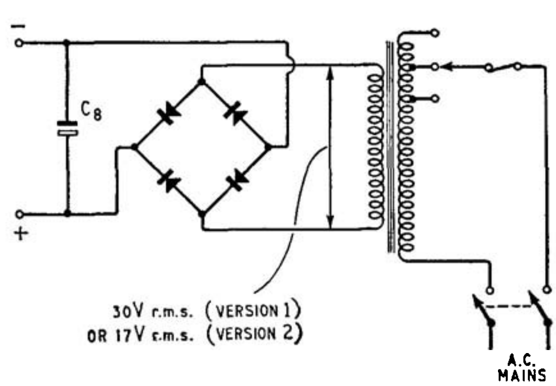


Fig. 6. Simple mains power supply circuit.

TABLE 2
Guide to suitable types of transistor for power amplifier

Transistor Number	Type	Gain (Typical)	Version 1		Version 2	
			Voltage wkg	Typical Types	Voltage wkg	Typical Types
Vt 1	p-n-p Small signal high frequency	High (100)	6	GET874 OC44 XA102	6	GET874 OC44 XA102
Vt 2	p-n-p	Medium (50)	40	GET111 XB121	24	GET102 OC71 XB103
Vt 3	p-n-p	Medium (30 at 100mA)	40	GET111 XB121	24	GET102 OC72 XC121
	n-p-n	Medium (30 at 100mA)	40	2N385A 2N388A SYL1750	24	XA702 2N385 SYL1750
Vt 5 } Vt 6 }	p-n-p Power	Medium (30 at 3A)	40	OC35 GET573 2N257 2N457 XC141	24	OC35 GET572 2N257 2N457 XC141

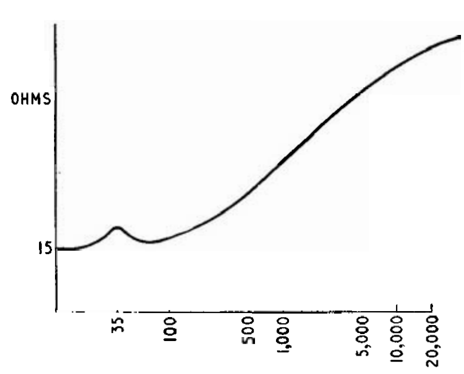
a high degree of regulation are not necessary (see Fig. 6), since under zero or low signal input, when hum is most noticeable, the quiescent current drawn by the amplifier is small, and hence the hum producing ripple on the reservoir capacitor is low.

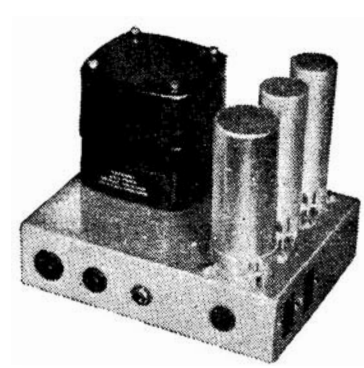
Battery supplies may also be utilized, and a surprisingly long life can be obtained from ordinary dry batteries (e.g. grid-bias batteries), especially if the quiescent current of the amplifier is reduced, at the expense of a slight increase in distortion, by shorting out R_{10}. The amplifier will operate satisfactorily down to less than half nominal voltage without component alterations, but with a reduction in power output, which is proportional to V^2_{batt}.

Transistor Characteristics Required.—The choice of transistors used in the amplifier is not critical, but the basic requirements of each part of the circuit must be satisfied.

It will be seen from Table 2 that ordinary p-n-p power transistors are used in the output stage, whose current gain falls appreciably at the high end of the audio-frequency band. However, this does not cause a corresponding reduction in performance because the impedance of a typical moving-coil speaker increases with frequency, see Fig. 7, (and hence the current it draws falls) at a rate which, in fact, more than offsets the decrease in current gain of the output transistors. The amplifier is designed to work into an inductive lead, as given by a normal speaker or speaker combination.

Fig. 7. Impedance characteristic of typical moving-coil loudspeaker.





Power supply for stereo power amplifier and pre-amplifier.

If, however, an amplifier is required to work into a resistive or capacitative load (e.g. an electrostatic speaker) the use of power transistors having a high α cut-off frequency, such as the Mullard OC23, would be worth-while.

Transistors Vt2 to 6 must be able to stand the full supply voltage in the cut-off condition.

Stability.—Even though the feedback loop does not contain a transformer, care is needed if the

(*Continued on page 569*)

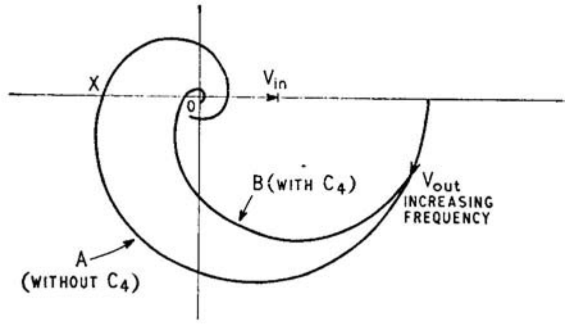


Fig. 8. Open-loop Nyquist diagrams of amplifier with (curve B) and without (curve A) the stabilizing capacitor C_4.

TABLE 3

Performance of Power Amplifier

Power output	10 watts at 400 c/s
Total harmonic distortion ..	0.25 per cent
Second harmonic distortion ..	0.1 per cent
Third harmonic distortion ..	0.2 per cent
Fourth harmonic distortion ..	0.05 per cent
Fifth harmonic distortion ..	0.04 per cent
Sixth harmonic distortion ..	0.02 per cent
Distortion for harmonics higher than the sixth	Less than 0.01 per cent
Output impedance	Less than 0.25 ohm
Input impedance	33 kilohms
Input voltage for 10 watts output	100mV
Voltage gain constancy	Within ± 1dB from 40 c/s to 20 kc/s. (The bass response can be extended if desired by increasing C_3)

amplifier is to have an adequate margin of stability under all conditions, since the transistors give appreciable phase shift at frequencies where high loop gain is needed for good performance.

The amplifier contains two subsidiary feedback loops within the main feedback loop, both of which contribute to maintaining stability. One loop consists of the output stage and driver stage, which have 100 per cent voltage feedback, thus reducing the phase shift at high frequencies due to these two stages. The voltage amplifier stages Vt1, Vt2, have feedback around them at high frequencies, via C_4, so that the voltage amplifier approximates to a single active dominant lag.

In Fig. 8 Curve A shows the open-loop Nyquist diagram of the amplifier without the stabilizing capacitor, C_4. From the length of the intercept OX, on the X axis it will be seen that very little overall loop gain is required to make the amplifier unstable. The addition of C_4 gives Curve B, which is much more satisfactory.

Earthing.—The correct connection of earths (see Fig. 9) is essential if distortion is to be avoided, since the earth wire to the output stage carries large asymmetric earth currents, from the Class-B output stage, which can produce appreciable voltages across quite short pieces of wire. If these voltages are coupled into the input of the amplifier even harmonic distortion will be produced.

Noise.—The performance of the amplifier with regard to noise, and, when used with a mains unit, hum, is extremely good, being better than 85 dB down on full output.

A word of warning however: the noise depends almost entirely on Vt1, and, although the conditions of operation are chosen to minimize noise, the occasional specimen may be found unsatisfactory in this respect, when it should be changed. In fact, transistors are extremely variable in this parameter—the author has found variations of 50 dB in noise factor between transistors of the same type from the same packet. Transistors with a doubtful past history of use (or abuse) are particularly to be avoided on this account.

Layout.—The layout of the power amplifier is not at all critical, and with suitable screening they may be mounted in close proximity to the pre-amplifiers. Thus, for the prototype, two of the 40-volt, 10-watt amplifiers were made up on printed circuit boards, and used in conjunction with a four-transistor stereophonic pre-amplifier. The complete unit has a front panel 8½in × 3½in and is 6in deep. (Power supplies were kept separate, as the unit is very suitable for operation from batteries.)

The power amplifiers are mounted on the top and base plates of the unit, and a channel in each of these housed the output transistors (see photographs). This heat-sink is quite adequate for the output dissipation, even on short-term sine-wave testing at full output power.

As with all transistor apparatus, a little care when first switching on the newly-built equipment will often save an expensive catastrophe. The voltage should be applied slowly, preferably from a dry battery, so that the presence of any fault current is discovered before damage is done.

Associated Equipment.—While the amplifier is sensitive enough to work directly from a crystal

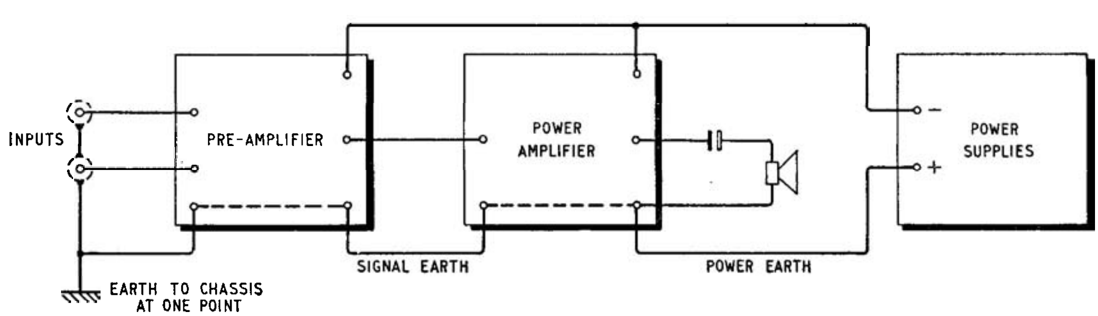


Fig. 9. Earthing diagram for power amplifier and associated equipment.

pick-up, it must be driven from a low impedance source (i.e. less than 10 kilohms) if the full value of feedback is to be operative.

The design of a suitable pre-amplifier, incorporating all the usual refinements, will be the subject of a future article.

Performance.—The performance of the amplifier has proved very satisfactory, and subjective listening tests have confirmed the results obtained in the laboratory (see Table 3). It is possible to apply more feedback to the amplifier and reduce the distortion still further, but it is doubtful if any worthwhile benefit would result, and the lower sensitivity would complicate the design of the pre-amplifier.

High frequency tests on the amplifier should be carried out using a dummy load simulating the impedance of a loudspeaker, i.e.: for a 15 ohms loudspeaker: 15 ohms+1 mH; and for a 4 ohms loudspeaker: 4 ohms+0.25 mH.

Putting the Computer to Work

SEQUENCE OF OPERATIONS ILLUSTRATED BY A SIMPLE ELECTRICAL CALCULATION

By WILLIAM McMILLAN*

Although readers of this journal have been kept up to date on the electronic elements of digital computers, they may be less clear about what people do with the complete machine when it is assembled and ready for use. This article describes a computer installation and illustrates its use by a familiar example.

THE upsurge of interest in computers, accelerated to some extent by the recent Electronic Computer Exhibition, has caused many electronic engineers and businessmen to take a fresh look at the subject. Unfamiliar terms used by logical designers and programmers have perhaps tended to make computer operation appear more difficult than it is. This article is intended to help dispel this illusion.

The various units which make up a typical computer installation are shown in Fig. 1. The particular installation shown here consists (reading from left to right) of:—

1:—The computer cubicle, which contains the electrical circuits and storage medium. The computer draws its special power supplies from a separate cubicle which is not shown in this picture. The power cubicle is about half the size of the computer cubicle.

2:—Two high-speed tape readers.

3:—The computer input control panel.

4:—The "on-line" teleprinter.

5:—Two "on-line" high-speed tape punches.

6:—The "off-line" tape reader.

7:—The "off-line" teleprinter.

8:—The keyboard tape perforator (for the preparation of the "programme" and "data" tapes).

From this it will be obvious that although the computer is the heart of the installation, a great deal of other equipment is needed to make full use of its capabilities.

These "Input" and "Output" devices are necessary to put information into a form which is usable by the computer and to reconvert the computer output signals—electrical pulses—into printed form.

The Computer — What's Inside?—The most important feature of an electronic computer is its ability to store numbers. In many computers a magnetic drum is used for this purpose, there being many

* Standard Telephones and Cables Ltd

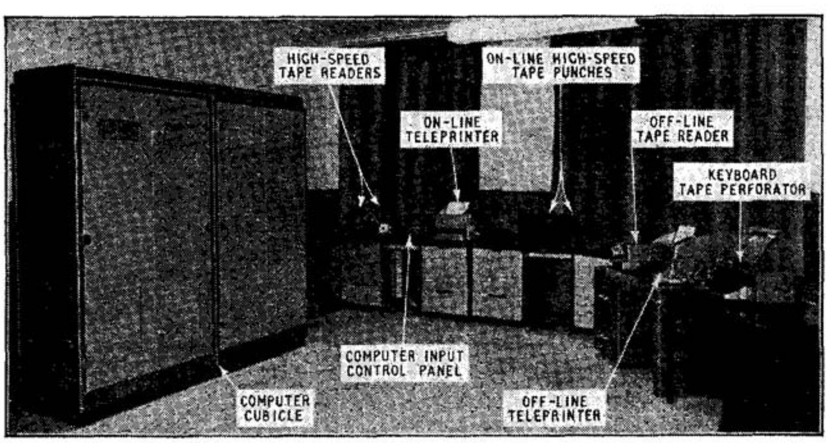


Fig. 1. Typical Stantec Zebra installation showing the computer and peripheral equipment.