

30-watt High Fidelity Amplifier

Output stage using complementary transistors

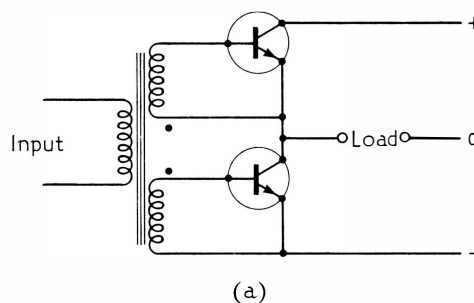
by Arthur R. Bailey*, M.Sc., Ph.D., M.I.E.E.

It is only recently that matched complementary output transistors, capable of high dissipation, have been available at a reasonable price. In the past this has had the effect of concentrating high power amplifier design into two main streams. The first uses a driver transformer with a pair of identical output transistors in a series connection. The use of a driver transformer is undesirable mainly on account of the cost, as the bandwidth of a well designed component may well extend from the sub-sonic region up to several megahertz. Nevertheless a circuit that does not require the use of such a component will obviously be an advantage.

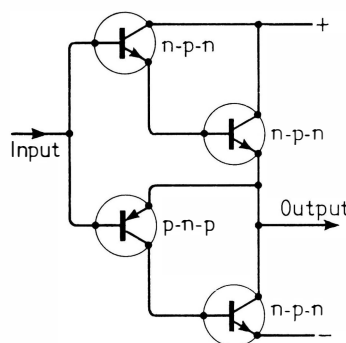
The alternative circuit that has been used by many designers is the quasi-complementary output stage. In this design identical output transistors are used and a complementary pair of driver transistors is arranged so as to give phase-inversion to the bases of the two output transistors. These two circuits are shown in Figs. 1(a) and 1(b) respectively. A correctly designed fully complementary output stage (Fig. 1(c) shows the basic arrangement) is capable of better performance than either of these common circuits and the reasons for this will be examined.

Compared with the quasi-complementary amplifier, the transformer-driven amplifier has the great advantage that the input impedances to the two sides of the output circuit are identical. This means that if a suitable quiescent current is used in the output transistors, cross-over distortion will be almost completely absent.

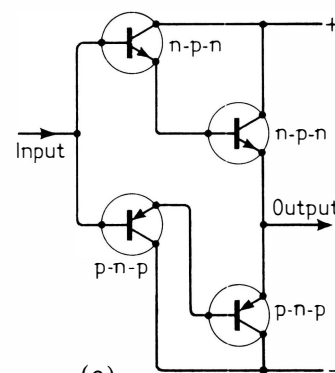
The quasi-complementary amplifier, however, gives greater overall distortion even if identical output transistors are used. This increase is due to the different input impedances of the two halves of the output stage in the quasi-complementary circuit. In the upper half of Fig. 1(b) the input impedance is due to two emitter-base junctions in series, whereas in the lower half the signal feeds into only one transistor. The effect of this is an extremely marked asymmetry between the input impedances of the upper and lower halves of the output stage.



(a)



(b)



(c)

Fig. 1. Direct-coupled output stages: (a) with driver transformer; (b) quasi-complementary; (c) fully complementary.

Unfortunately the two input impedances cannot be equalized by the use of a series resistor as the curvature of the two stages is completely different. This dissimilarity of curvature can be seen in Figs. 2 and 3, these being the transfer characteristics of the upper and lower halves of an output stage using matched transistors.

The dissimilarity in input impedance is most marked at low values of collector current. Hence in the case of a class B output stage there is an abrupt change in slope at the cross-over point, giving rise to the well known phenomenon of cross-over distortion. This distortion may not be particularly serious when measured on an r.m.s. basis, but as it unfortunately occurs mainly within a small part of the overall output swing, the peak value of the distortion can be surprisingly high. Also the distortion does not normally decrease appreciably as the output swing is reduced, since the effect is occurring at small signal levels. The overall effect is quite serious, therefore, and the ear seems to be very sensitive to such types of distortion.

This then is perhaps the reason why two amplifiers may sound quite different even though their "paper" performance may be identical on the basis of normal amplifier measurements. Very few valve amplifiers suffer from cross-over

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Specification

Sensitivity	1.0 volt for 30 watts into 8-ohm load 0.8 volt for 20 watts into 16-ohm load
Rise time	approximately 0.7 microsecond
Distortion	below 0.1% over the whole of the audio-frequency range at rated power outputs
Load stability	unconditional
Abnormal load protection	provided adequate heat sinks are used the amplifier will not be damaged by operation into incorrect loads
Noise	better than 80 dB down on full power output
Hum	depends on layout if stray hum fields exist. Negligible hum in output if normally smoothed supplies are used.
Distortion generated	predominantly third harmonic, cross-over distortion being absent.

distortion, and this may be the reason why the best valve amplifiers are difficult to evaluate on subjective tests. Certainly there are much greater subjective differences between the performances of current transistor amplifiers.

If cross-over distortion is present it would appear that the common 0.1 per cent harmonic distortion rule for an acceptable limit at peak output is no longer valid, and at least one manufacturer is working on the basis of far lower distortions being necessary.

There appear to be two ways of tackling this problem. The first is to use a larger value of overall feedback so as to reduce the effect to inaudible proportions. The main drawback with this method is that high values of overall feedback make the amplifier closer to instability, and it may be difficult, if not impossible, to achieve a reasonable stability margin. Stability may then be obtained by decreasing the cut-off frequency of a stabilizing step-network, but this has the effect of decreasing the available power at high frequencies as well as degrading the distortion characteristics at high frequencies.

Complementary Symmetry Output Stage

In view of these considerations the author decided that the best line of approach was to use a fully symmetrical output stage based on complementary transistors. With such a symmetrical system, there is no difference between the input impedances in the upper and lower halves of the circuit. From the basic circuit in Fig. 1(c) it will be seen that both halves of the circuit have the same input impedance characteristics because of their identical configurations. By a suitable choice of standing quiescent current, cross-over distortion can be reduced to levels where it is extremely difficult to detect. This absence of cross-over distortion means that perfectly satisfactory results will be obtained if the overall distortion factor of the amplifier is similar to that commonly found in valve amplifiers, i.e. about the 0.1 per cent mark. In fact lower distortions than this are possible while maintaining both unconditional load stability and good high-frequency performance.

During the development of this amplifier it was discovered that the overall performance was not as good as might have

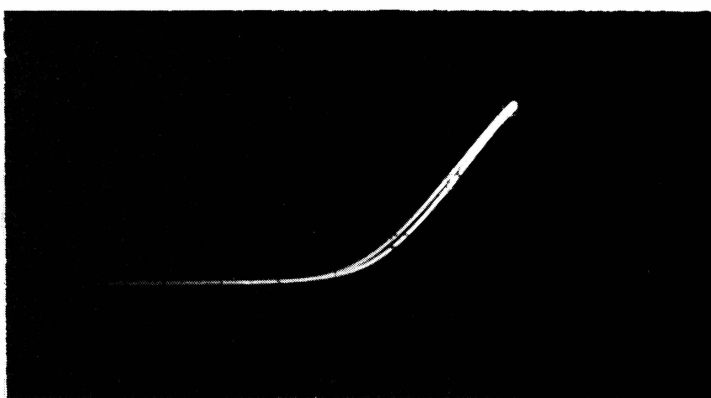


Fig. 2. Transfer characteristic of upper half of Fig. 1(b).

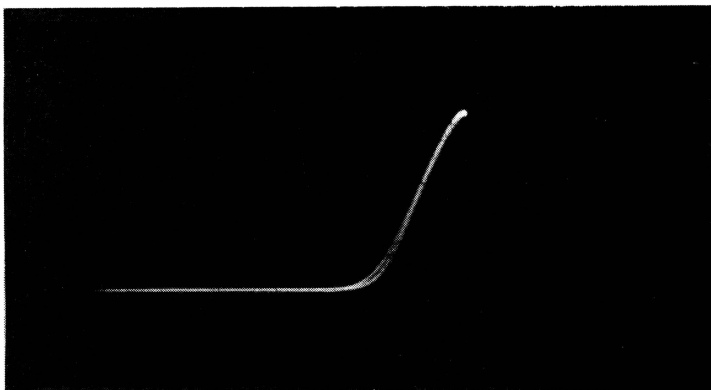
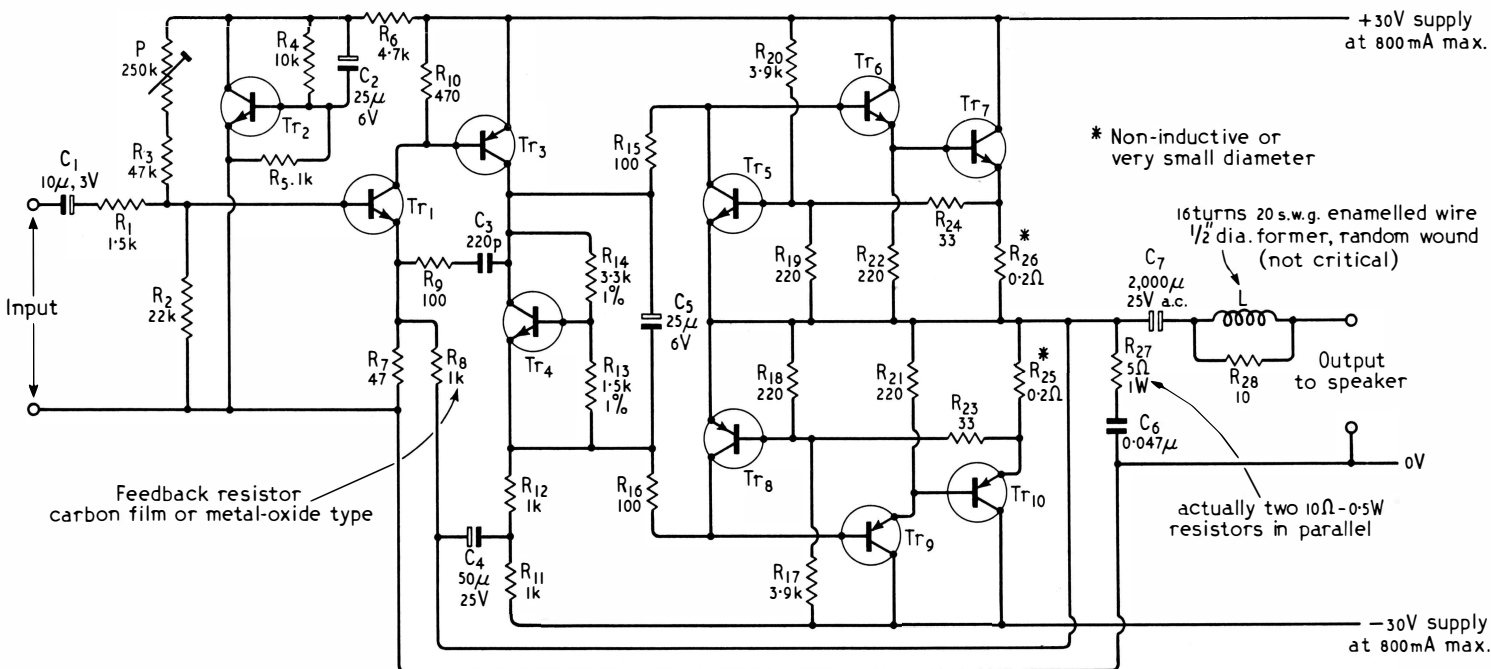


Fig. 3. Transfer characteristic of lower half of Fig. 1(b).

been expected from the output stage characteristics. This distortion increase was traced to the common-emitter amplifier stage that drives the output stages. This is transistor Tr_3 in the complete amplifier circuit shown in Fig. 4. The effect was found to be caused by "Early effect", the high collector voltage swing modulating the gain of the stage. In fact the overall distortion was approximately three times that which would have been expected. As this effect depends entirely on

Fig. 4. Circuit of complete power amplifier. The transistors used are: Tr_1 —40361 (R.C.A.); Tr_2 —BC109 (Mullard); Tr_3 —40362 (R.C.A.); Tr_4 —BC107 (Mullard); Tr_5 —BC125 (Fairchild); Tr_6 —40361 (R.C.A.); Tr_7 —M7481 (Motorola); Tr_8 —BC126 (Fairchild); Tr_9 —40362 (R.C.A.); Tr_{10} —M7491 (Motorola). Note that C_7 is a reversible electrolytic and could be made up of two 4000- μ F polarized electrolytics connected "back-to-back".



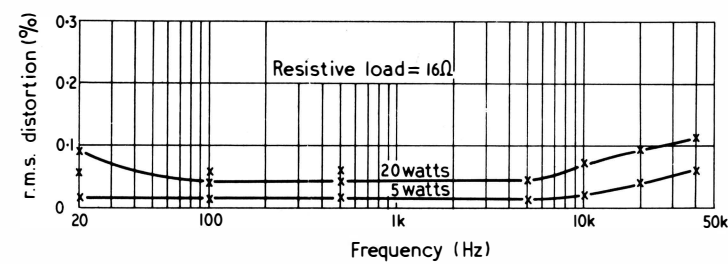


Fig. 5. Distortion characteristics of amplifier with 16-ohm load.

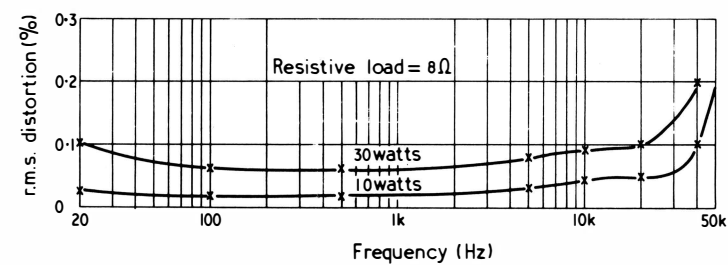


Fig. 6. Distortion characteristics of amplifier with 8-ohm load.

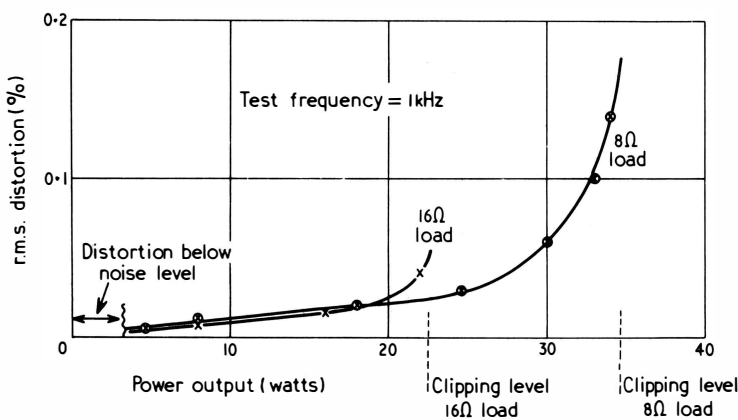


Fig. 7. Variation of distortion with output power level.

the design of the transistor in use, it was necessary to select a suitable transistor type for this position in the amplifier. This source of distortion seems to have been largely overlooked in the past, but it is obviously a possible source of extremely bad distortion. In addition, the high-frequency distortion was found to increase more rapidly than was expected and this was traced to the modulation of the collector-base capacitance of this transistor. The high collector voltage swing was causing non-linear capacitive feedback, and this in turn was increasing the high-frequency distortion. Again the only cure is by transistor selection. The type used appears to be the best currently obtainable, and the distortion introduced by these effects is below that of the output stage proper, over the whole of the audio-frequency range.

For low distortion at high frequencies, it is essential that the transistors should have, as high a cut-off frequency as possible. Planar transistors are used in all but the output stage to give this bandwidth. The output transistors used have a cut-off frequency of several megahertz and this enables low distortions to be obtained at 20 kHz at full power output.

The design of the remainder of the amplifier circuit is fairly straightforward. The input stage is a common-emitter amplifier, but the current and voltage swings associated with it are very small, so there is little difficulty in the operation of this stage. To correct for the emitter-base voltage change of this input stage with temperature, a transistor is used to regulate the base supply current. This transistor Tr_2 , operates as a rather crude temperature-sensitive Zener diode and also as a hum filter. The net effect is to stabilize the d.c. base current of the

input transistor, the supply voltage to the base of this transistor or decreasing with increased temperature. This stabilization of the d.c. operating conditions enables the amplifier to deliver full output over a wide temperature range.

The bias for the driver and output transistors is produced by means of a transistor, Tr_1 , rather than a string of diodes as is commonly used. This is mounted in the heat sink of one of the output transistors, being as close to the output transistor as possible. This method of compensation works extremely well, and the transistor type is not critical provided a silicon one is used. The standing current in the output stage can easily be adjusted to its correct value (which is not critical) by slightly adjusting the ratio of the two resistors in the base circuit of the transistor.

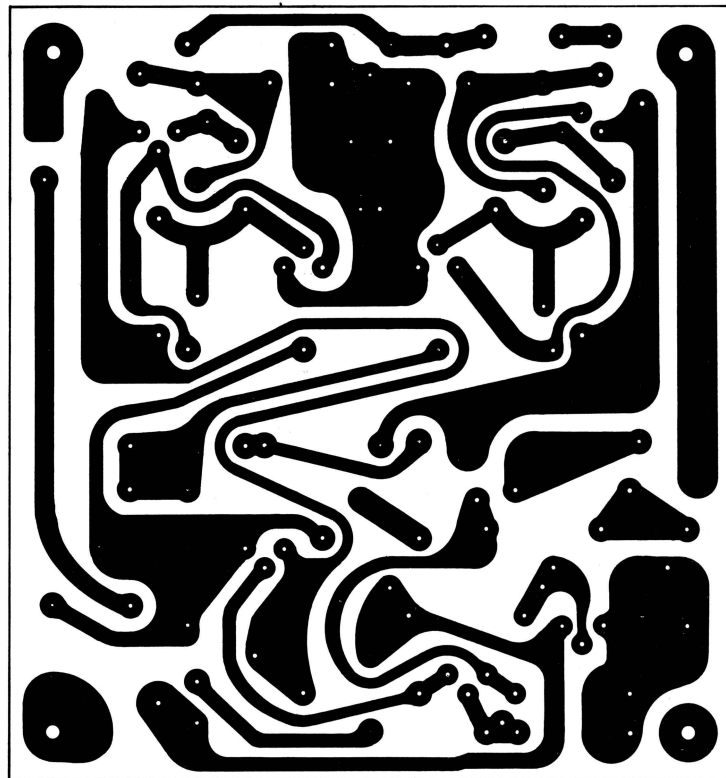
For full power output from the amplifier the d.c. potential existing at the output of the amplifier proper should be as low as possible. This can be adjusted by the potentiometer in the base of Tr_1 . If this is not done the amplifier will not be able to swing equally in the two output polarities.

The quoted figures for the amplifier were obtained using regulated supplies. Unless the amplifier is to be called on to deliver large sustained outputs, this is not really necessary. On the other hand, reduced mains voltage will severely restrict the power output of an amplifier with unregulated supplies. Commercially, a thyristor regulated supply is being utilized, and this has the two advantages of small heat dissipation and saving in components.

Constructional Points

The overall bandwidth of the amplifier is extremely wide and the stabilizing step-network necessary only becomes operative in the ultrasonic region. Equally the inductor in series with the output lead, which improves the stability with capacitive loads, need have only a very small inductance. This wide bandwidth gives exceptional high-frequency performance as can be seen from the distortion figures in Figs. 5, 6 and 7. Unfortunately, however, wideband amplifiers are very susceptible to layout,

Fig. 8. Layout of suitable printed-circuit board, actual size. (Courtesy Radford Audio Ltd.)



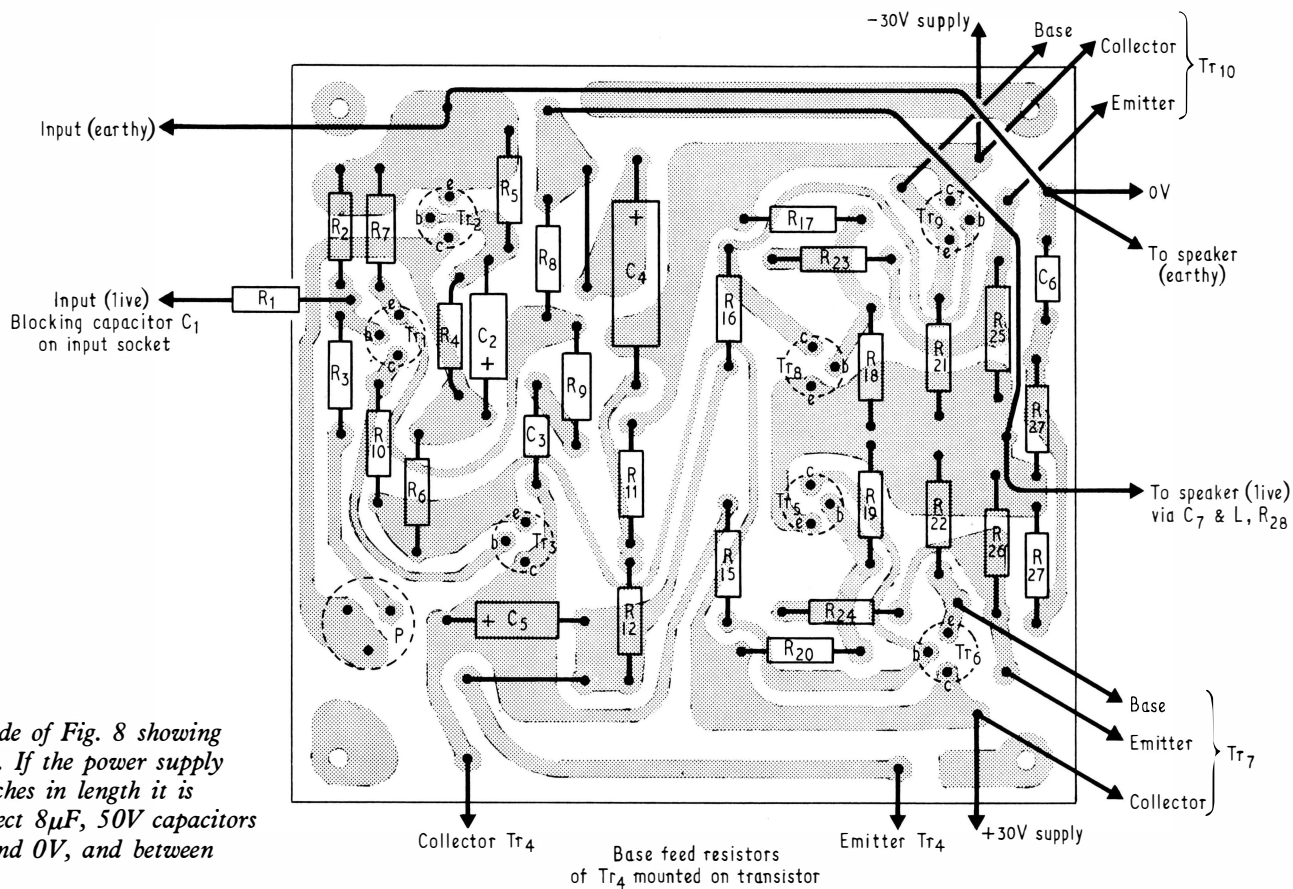


Fig. 9. Reverse side of Fig. 8 showing component layout. If the power supply leads exceed 6 inches in length it is advisable to connect $8\mu\text{F}$, 50V capacitors between $+30\text{V}$ and 0V , and between -30V and 0V .

particularly common coupling leads. Provided lead lengths are kept *very* short there should be no difficulty, but the author experienced tremendous variations in high-frequency stability when "rats-nest" construction was used. For this reason the safest course is to use a printed-circuit, so that the strays can be kept to a minimum. The design of a suitable board along with its component layout is shown in Figs. 8 and 9. The performance details given were measured using this particular layout. The leads to the output transistors should be as short as possible, preferably no longer than 3 to 4 inches. The size of the heat sinks for the output transistors is a matter of personal choice, the author having used sinks of finned aluminium about 4in. by 4in. square. This size is not really necessary for high-fidelity use, and sinks of half this size would be adequate provided that extended periods of testing were not undertaken.

The overall performance of the amplifier is very good, considerably better in fact (on paper) than the best valve amplifiers. Unfortunately, listening tests have shown that the performance of the amplifier is only slightly, if any, better than the best valve amplifiers. Extensive listening tests indicate only a very slight improvement in audible results, the subjective effects being almost identical. It would therefore appear that any further improvement will be of no real benefit for high-fidelity applications, the main need for work here definitely being in the field of loudspeakers, discs, etc.

Owing to the absence of cross-over distortion, the distortion at low levels is very difficult to measure and the curves appear in Fig. 7. The wide bandwidth can be seen from the curves in Figs. 5 and 6, where it will be observed that the amplifier will deliver full power output from 20 Hz to 20 kHz with less than 0.1 per cent of distortion. Indeed it is possible to obtain about 15 watts of power at 200 kHz. The square-wave tests are far better than with any known valve amplifier. Even with pure capacitive loads there is no tendency whatever towards instability. The waveforms are shown in Figs. 10, 11, 12, and 13.

The protection circuits of the amplifier operate very satisfactorily, short-circuits and 50 microfarad capacitors giving no

distress to the amplifier whatever. One word of caution is necessary however; extended tests on low impedance reactive loads and short-circuits can cause high junction temperatures in the output transistors because of the finite heat-sink size. Unless one uses very large heat sinks, it is therefore undesirable to run the amplifier at full drive for extended periods when applying such abnormal load conditions. If 16-ohm load opera-

Fig. 10. Square-wave response, 1kHz and 8-ohm load.

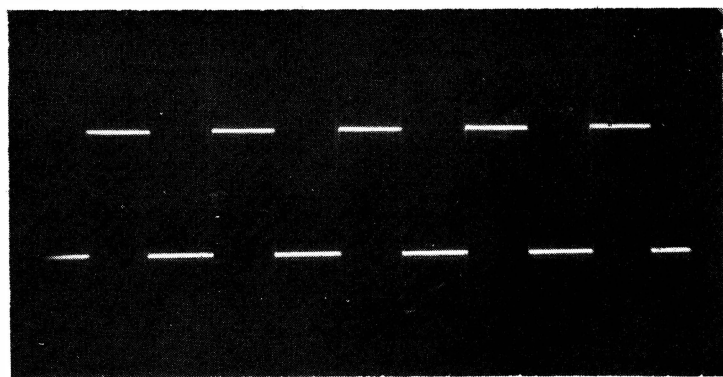
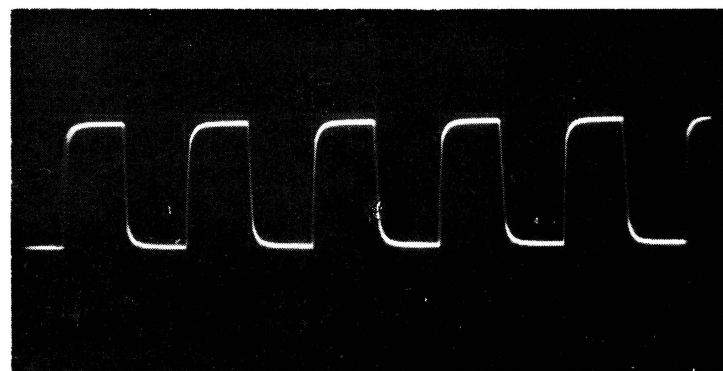


Fig. 11. Square-wave response, 50kHz and 8-ohm load.



Announcements

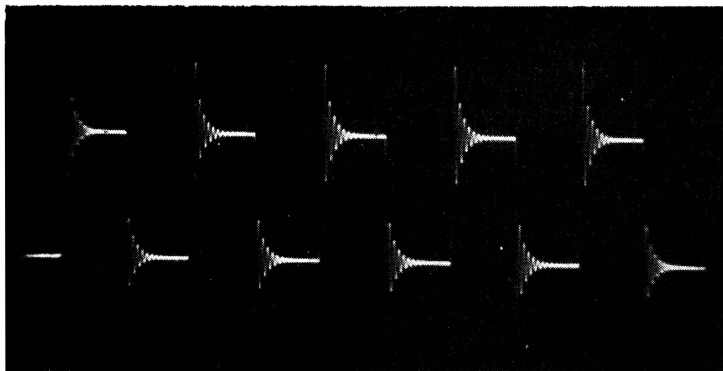


Fig. 12. Square-wave response, 10kHz and 0.1- μ F load.

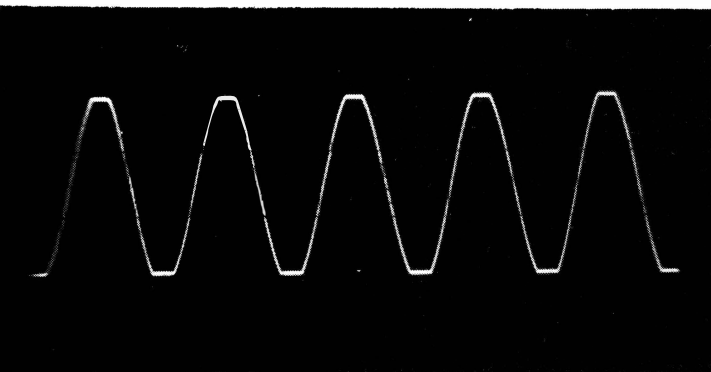


Fig. 13. Overdrive with sine-wave input, showing clean limiting (1kHz and 8-ohm load).

tion only is to be used, then the emitter resistors in the output stage can be increased up to 0.4 ohm, with a corresponding halving of the transistor dissipation under abnormal load conditions.

The specification is shown on page 94. The overall sensitivity may be either doubled or halved by doubling or halving the value of the 1000-ohm feedback resistor. This has the effect of increasing the sensitivity at the expense of distortion if the increased amplification is felt to be necessary. With the increased feedback the overall distortion is halved, and even with this value of overall feedback the amplifier is still unconditionally load stable.

When the amplifier is operated in the reduced feedback condition for 500-millivolt sensitivity, the author cannot hear any difference in performance as compared with the halved distortion characteristic obtained with the 2-volt sensitivity. It appears therefore that no further improvement in amplifier performance will be detectable until other limiting factors are greatly improved. In fact the author has a sneaking suspicion that this may be the end of the road so far as amplifier design for sound reproduction is concerned, further improvements being limited to power and cost.

In conclusion the author would like to acknowledge the interest and comments of the many readers who wrote to him after the publication of the previous article on transistor amplifier design. There were often delays in replying, but short of employing a full-time secretary such delays are sometimes inevitable. One obvious question is whether the earlier germanium circuit sounds as good as the one just described. Personally the author cannot hear any appreciable difference, but on such a controversial point it is unwise to be dogmatic!

Reference

1. "The Transistor" by E. Wolfendale. Heywood & Co., London (1963), p. 24.

A special course entitled "Tape Transport and Systems" has been organized by the Department of Electronics and Communications Engineering, Northern Polytechnic, Holloway Road, London, N.7. The course comprises twelve lectures to be held each Thursday from 6.30 to 9 p.m. commencing 25th April.

The I.E.E. and I.E.R.E., in collaboration with the University of Southampton, are arranging a conference on **computer aided design**. It will be held under the aegis of the United Kingdom Automation Council at Southampton University from 15th to 18th April 1969.

Home Radio (Components) Ltd, of 187 London Road, Mitcham, Surrey, have been appointed as **retail stockists for Lektrokrit** electronic rack and chassis construction systems manufactured by A.P.T. Electronic Industries Ltd.

Cole Electronics Ltd., Lansdowne Road, Croydon, Surrey, have been appointed U.K. distributors for **Bosch television test equipment**. The range of equipment includes level oscilloscopes, video test signal generators, group delay test sets, colour bar generators etc.

The Ever Ready Company (Great Britain) Ltd has acquired from the receiver of Royston Industries the factory and assets relating to the telecommunications section of **Burddept Electronics Ltd**, at Erith, Kent. The company will continue under the name Burddept Electronics (E.R.) Ltd.

Aveley Electric Ltd, of South Ockenden, Essex, have been appointed U.K. representatives for **Systron Donner products**, previously handled by Dynamco Ltd.

A marketing agreement has been signed between the **Decca Navigator Company** and **Atlas Electronik**, of Bremen, whereby Decca will handle the non-European sales of the Atlas AN 6014 survey echo sounder. This instrument is unusual in that two frequencies are employed, 30 kHz and 210 kHz, giving very high penetration and an accurate narrow beam.

Radial S.A., of Paris, have formed a new company to market their products in the U.K. The company, Radial Microwave Components Ltd, will operate from Station Approach, Grove Park Road, Chiswick, London, W.4.

Add-a-Vision, the electronic viewfinder for film cameras developed originally by the Livingston Group which recently went into liquidation, is now being produced and marketed by Prowest Electronics Ltd, of Maidenhead.

T. J. Sas & Son Ltd, of Victoria House, Vernon Place, London, W.C.1, have been appointed U.K. distributors for the COBEM range of motors manufactured in Belgium.

Greenray Industries Inc., the American manufacturers of oscillators, have appointed G. A. Stanley Palmer, Island Farm Avenue, West Molesey Trading Estate, Surrey, as U.K. agents for their products.

The Copenhagen firm **Radiometer A/S** have appointed Omega Laboratories Ltd., 57 Union Street, London, S.E.1, as sales and service agents in Britain for their range of test equipment. This follows the recent collapse of the Livingston Group who used to fulfil this function.

Semicomps Ltd., have added semiconductors produced by **Motorola** to the range of products marketed by them.

The American company, **Electro Scientific Industries** have appointed D. A. Pitman Ltd, of Mill Works, Jessamy Road, Weybridge, Surrey, as U.K. representatives for their complete range of precision laboratory standard measuring instrumentation.

The Marconi Company have signed an agreement with the Sylvania Division of G.T. & E. International for marketing their microelectronic microwave devices in the U.K.

S.C.E.E. Ltd, of Reddicap Trading Estate, Sutton Coldfield, Warwickshire, have changed the name of the company to Cressall Printed Circuits Ltd.

The West German company **SABA Gmbh** and **General Telephone & Electronics International**, of the U.S.A., have agreed on a programme of technical and economic co-operation aimed at providing research and export facilities for SABA and further European engineering facilities for GT & E.