Phase-Splitting in Push-Pull

DEVELOPING THE
QUALITY AMPLIFIER

THE use of push-pull amplification with resistance coupling is now firmly established for ultra-high quality reproduction. Its popularity was established in large measure by *The Wireless World* Push-Pull Quality Amplifier, and although it is now five years since it was described no improvement in performance has yet been possible, nor would it be necessary if it were possible.

The frequency response is even, within the limits which the ear can detect, over a range wider than the audible, and the amplitude distortion is exceedingly low up to the rated output. The phase characteristics are also good, although it is still doubtful whether these are of importance. The output was originally 4 watts, but an alteration in the rating of the PX4 valve enabled this to be increased to 7 watts by increasing the anode voltage.

Since the performance cannot be improved, development has lain chiefly in the direction of obtaining as good results with less material. Experience has shown it to be permissible to omit certain by-pass condensers and decoupling components and a simpler version was produced for the Pre-tuned Quality Receiver.[1]

The next step was to increase the output to 7 watts by taking advantage of the increased rating of the output valves. The changes which this necessitated were chiefly to the mains equipment, for the output stage needed some 350 volts at

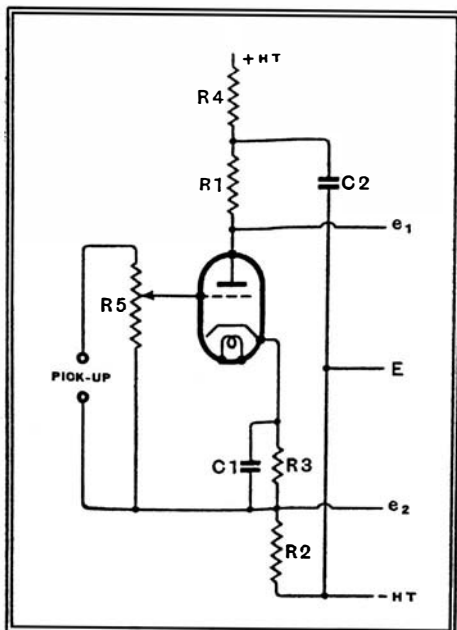[1] *The Wireless World*, Sept. 25th and Oct. 2nd, 1936.

Fig. 1. – This phase splitter is simple and gives high gain, but neither input terminal can be earthed.

100 mA. instead of 285 volts at 70 mA.

Originally, provision was made for energising the field winding of a loud speaker from the mains equipment, the field being inserted in series with the main HT supply and also acting as a smoothing choke. The resistance of the field was 1,250 ohms, and at 120 mA. the drop across it was 150 volts. This made an HT supply after the first choke of 435 volts necessary.

With the increased current consumption of the output valves under the new rating it proved very difficult to retain the field winding in the HT supply and at the same time have an economical supply. It was consequently decided in a later amplifier[2] to make no provision for energising a speaker field,

Fig. 2.—The arrangement of Fig. 1 can be applied to a grid detector, but the whole input circuit is floating.
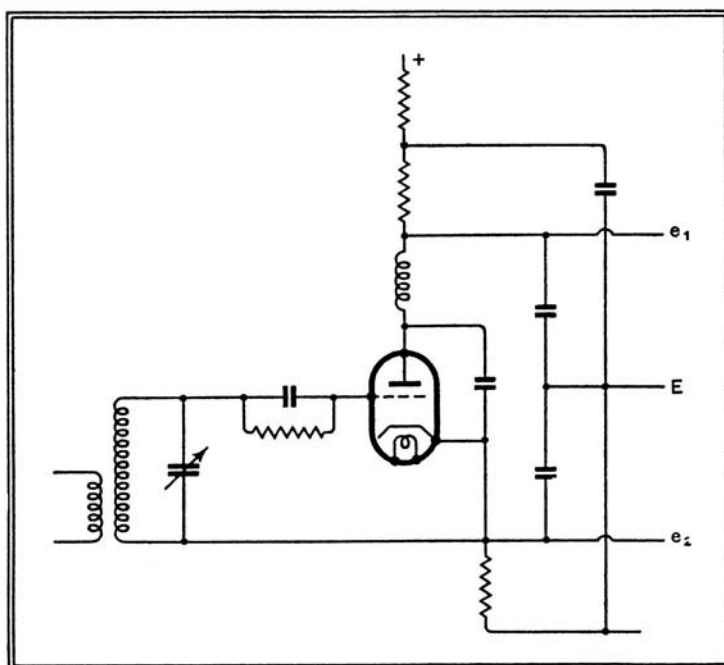
and this decision was arrived at after taking two further points into account First, permanent-magnet speakers were widely used, and, secondly, the field requirements of energised speakers varied enormously.

The power needed varied from 6 watts to 20 watts and the resistance from 500 ohms to 5,000 ohms. No standard method of connection could be devised, therefore, which would meet all requirements with even reasonable economy.

The H.T. Supply

Although connected as a smoothing choke and acting as such, the smoothing provided by the field in early models was not really necessary. No audible increase in hum was found to result from its omission, and there was also the saving of a smoothing condenser.

Instead of having to provide 435 volts after the first choke, only 350 volts were needed for the full rating of the valves, so that the voltage rating of the HT winding on the mains transformer could be reduced

[2] *The Wireless World*, Communication Receiver, Aug. 18th, 25th, Sept. 8th, 1938.

and the current rating increased. The lower voltage made it possible to use the cheaper electrolytic type of condenser for the reservoir capacity instead of the paper-dielectric condenser of the earlier models.

So far, the general arrangement of the amplifier proper had been retained; that is, a pair of push-pull PX4 valves were used in the output and preceded by a pair of push-pull MHL4 valves, or their equivalent, with resistance coupling. The preceding stage, however, had to be a phase-splitter, and considerable development took place here. As it is in connection

with phase-splitting that the newest development occurs, it is of interest to trace the various methods adopted and to see their advantages and disadvantages.

The original arrangement used for gramophone is shown in Fig. 1. Equal resistances R_1 and R_2 are connected in the cathode and anode circuits of a triode and equal voltages e_1 and e_2 are developed across them; e_1 and e_2 are in opposite phase, however.

The valve gives its normal stage gain, just as if R_1 and R_2 were both in the anode circuit. There is the minor disadvantage of a potential difference between heater and cathode of 50-100 volts, but the main drawback is that neither of the input terminals can be earthed.

The input terminal connected to R_2 and R_3 fluctuates with respect to earth by the output voltage e_2, and the other terminal by $e_2 + e_{IN}$, where e_{IN} is the input voltage. This is inconvenient, in practice, and although it can be made to work well, it is more liable to hum pick-up than other arrangements.

For radio, a similar method can be used with the valve functioning as a grid

Amplifiers

By W. T. COCKING

MANY of the more important methods of feeding a resistance-coupled push-pull amplifier are discussed in this article with particular reference to the Push-Pull Quality Amplifier. The application of a new circuit is treated and is shown to lead to a simplification of the amplifier.
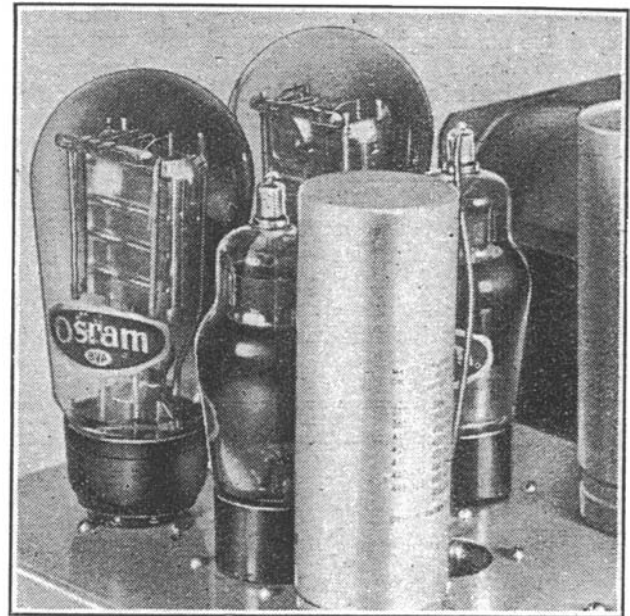
detector, as shown in Fig. 2, or else with a diode preceding Fig. 1. In either case, no point on the detector circuit can be earthed. This normally rules out its use in a straight set with ganged tuning, and in any case it makes it more difficult to secure RF stability. Nevertheless, very good results can be secured, and the method has been used in several receivers.

The next method to be used is shown in Fig. 3. The valve V1 is a normal first-stage amplifier and its output e1 across R1 + R2 is fed to one side of the push-pull amplifier. A portion of the output is tapped off across R2 and fed to V2 through the C1 R4 combination. The voltage e2 developed across R3 is in the opposite phase and feeds the other side of the push-pull amplifier.

For equality of the two outputs (e1 = e2) it is necessary that R2/(R1 + R2) be equal

This self-balancing action makes very precise setting of the input control to V2 unnecessary, and it is often satisfactory to feed it from a fixed tapping point as shown in Fig. 3. It should, however, be pointed out that we do not necessarily want perfect equality of the outputs, for the push-pull stages themselves may not be perfectly balanced. A deliberate inequality of output may be needed to obtain the correct overall balance.

However, if the pairs of push-pull valves are operated with a common un-by-passed bias resistance, there is a self-balancing action in each stage. This is not always a possible condition in the output stage, for a by-pass condenser may be desirable for other reasons.

The balance on a signal in Fig. 3 is only good over a range of frequencies. At very low and very high frequencies it fails because of the circuit capacities. The voltage e1 is produced from e_IN without any frequency discrimination or phase shift at low frequencies. The input to V2, however, and hence e2, is taken from e1 through the coupling C1 R4.

Inevitably, e2 falls off in respect to e1 at low frequencies and is no longer 180 degrees out of phase with it. By making the product C1 R4 large enough, we can push the frequency at which the departure from balance occurs as low as we like, but we cannot avoid it.

Similarly, at high frequencies the stray capacities across R1 + R2 make the ratio of e1/e_IN fall off; e2/e_IN falls off more rapidly, however, because V2 is fed with a fraction of e1 and its anode circuit produces its own additional attenuation. Matters are made still worse by the input capacity of V2, which acts to make the input voltage to this valve less than the normal fraction of e1. By suitable design the frequency at which these effects

become important can be kept very high.

A normal push-pull stage is balanced as regards disturbances in the HT supply; that is, any hum or feed-back voltage affects both anodes equally and in the same phase. The circuit of Fig. 3, however, is not balanced from the point of view of the HT supply, for although equal voltages are applied to the anodes a portion is also applied to the grid of V2.

Decoupling of the HT supply is consequently necessary and is provided by R6 and C2. This reduces the voltage applied to the valves and so restricts their output.

Negative Feed-back

It should be noted that these two valves do not operate in true push-pull, because the input of V2 is derived from the output of V1. If V1 introduces distortion the
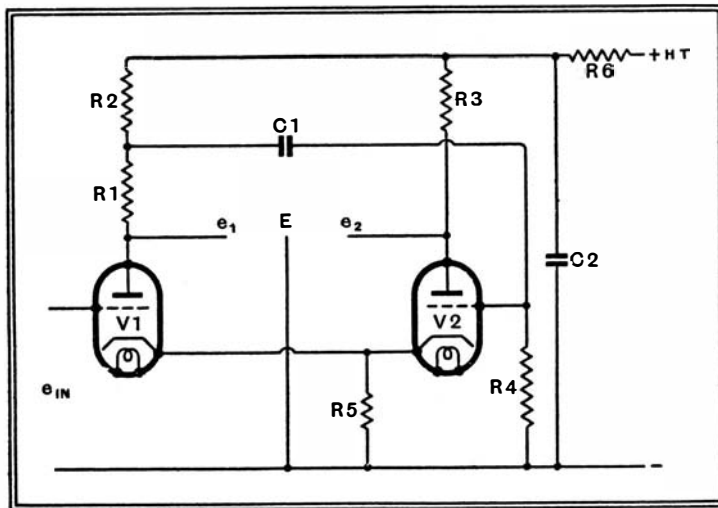
Fig. 3.—A well-known arrangement is shown here. V2 is fed from a tapping on the coupling resistance of V1.

to the gain of V2. It is usual, therefore, to make the tapping point variable and to adjust it under working conditions. When R3 = R1 + R2, the valves are similar, and e1 = e2, the alternating components of the anode currents through R5, are equal and opposite. No by-pass condenser is consequently needed to prevent negative feed-back.

If the stage is not properly balanced, however, there is feed-back which tends to restore balance. Thus, if the anode current of V1 is greater than that of V2, so that e1 is greater than e2, the voltage developed across R5 gives negative feed-back on V1 and positive feed-back on V2. It thus acts to reduce e1 and increase e2.
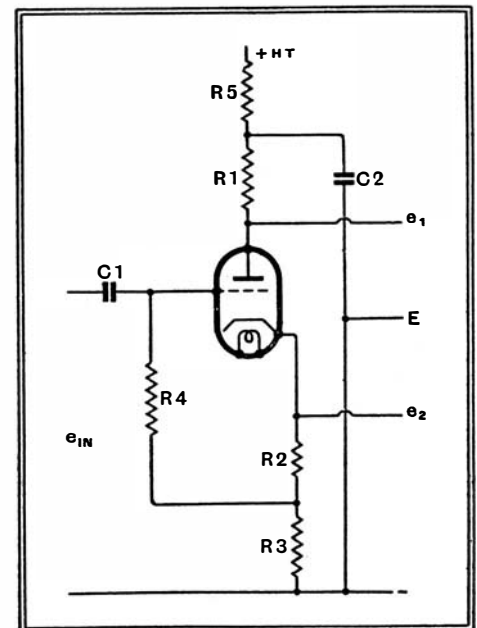
Fig. 4.—This circuit is similar to that of Fig. 1, but the input is applied between grid and earth. There is then heavy negative feed-back and the stage gain is very low.

Phase-Splitting in Push-Pull Amplifiers—
input of V2 is not a true copy of the input to V2.

The method of phase-splitting which has probably been most widely used in conjunction with the Push-Pull Quality Amplifier is a modification of Fig. 1. It is shown in Fig. 4, and the only essential difference is that the input is applied between grid and earth instead of between grid and cathode. The phase-splitting action remains unchanged, but there is now heavy negative feed-back along the
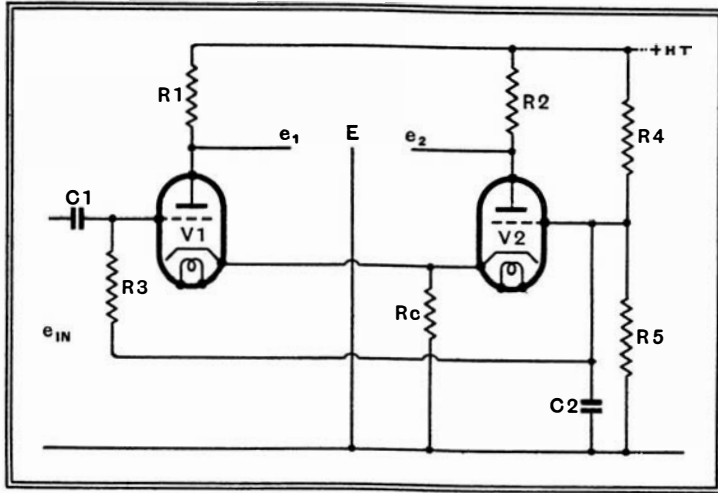

Fig. 5.—A new phase-splitting circuit is shown here. V2 derives its input from the cathode circuit of V1. There is some negative feed-back on V1.

cathode resistance, with the result that the gain is only about 0.8—0.9 per side; that is, $e_1/e_{IN} = e_2/e_{IN} = 0.8$ to 0.9.

The feed-back results in great linearity and quite a large output can be obtained; it is not sufficient to feed the output stage directly, however, so that this valve precedes the push-pull MHL4 stage. For balance $R_1 = R_2 + R_3$, or if R_2 is shunted by a 50-μF. condenser, $R_1 = R_3$.

Perfect balance is not obtained at very low frequencies because of the impedance of the decoupling circuit; at very low frequencies e_1/e_2 tends to rise somewhat. If the stray capacities across R_1 equal those across $R_2 + R_3$, the balance will be maintained at high frequencies, but if the cathode circuit capacity is higher than the anode e_1/e_2 will increase with frequency.

A New Circuit

As with the circuit of Fig. 1, there is a difference of potential of 50-100 volts between heater and cathode, but this is usually unobjectionable. The circuit is unbalanced as regards the HT supply, for although a ripple on the supply affects e_1 and e_2 in the same phase, it does not affect them in equal magnitude. Hence, the necessity for thorough decoupling.

Now it will be apparent that the obvious step in simplifying the Quality Amplifier is to obtain the phase-splitting in the stage immediately preceding the output valves. If this can be done without affecting the performance a valve will be saved. The circuits of Figs. 1, 2 and 4 are hardly suitable, because they will not give sufficient

undistorted output with a reasonable HT supply and allowing for decoupling. The arrangement of Fig. 3 has the disadvantages already pointed out.

A new circuit[1] offers distinct possibilities, however, and its basic arrangement is shown in Fig. 5. R_4 and R_5 are provided for grid bias purposes; for the moment ignore them and consider the grid of V2 as being returned to earth, as it is effectively for alternating currents. The input is applied to the grid of V1 and causes variations in its anode current which produce e_1 across R_1; the variations also produce voltage variations across R_c, which are applied to the grid of V2 and cause anode current changes in this valve, and hence produce e_2.

The operation is more easily understood by assuming a small definite change of grid potential on V1 and following its results. Suppose the grid potential changes in a positive direction. This causes a rise in anode current in V1, and consequently a rise in cathode potential and a fall in anode potential e_1. The rise in cathode potential means that the cathode voltage of V2 rises with respect to the grid, which is at a fixed potential. This is equivalent to a fall in the grid potential of V2 relative to its own cathode, and so the a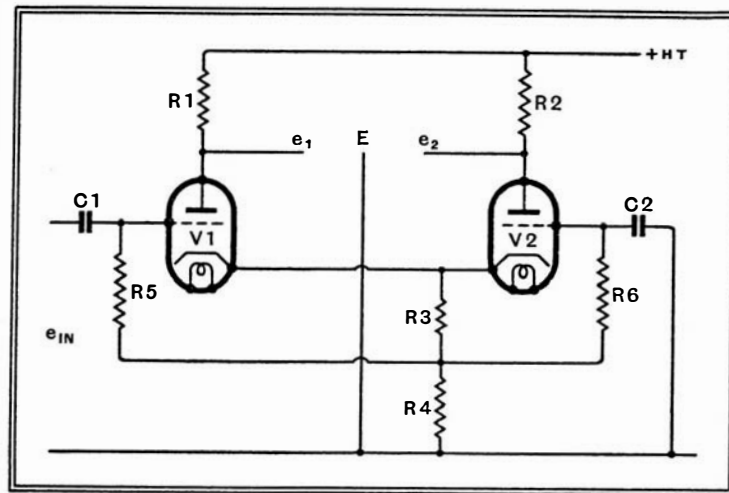node current of this valve decreases. This fall in anode current causes a fall in cathode potential and a rise in anode potential e_2. e_1 and e_2 thus change in potential in opposite directions. www.keith-snook.info

If R_1 and R_2 are equal, then for e_1 and

[1] *Journal of Scientific Instruments*, March, 1938.

e_2 to be equal it is clear that the alternating anode currents of the two valves must also be equal. They flow in opposite directions through R_c, however, so they will set up no voltage drop across it; consequently, V2 will have no input and be unable to produce an alternating anode current.

This is impossible, and if the valves are identical and R_1 and R_2 are equal, e_1 and e_2 cannot be equal. To make the outputs the same R_2 must be greater than R_1, for to obtain an input to V2 the alternating anode current of V1 must be greater than that of V2.

Accuracy of Balance

Although with $R_1 = R_2$ perfect equality of output cannot be secured, the balance can be made as nearly perfect as we like by increasing R_c sufficiently. Then the input to V2 is very nearly equal to the grid-cathode voltage of V1. So far as V1 is concerned the voltage across R_c acts as a negative feed-back voltage and the stage gain of V1 is very nearly one-half of what it would be if R_c were absent. The input required for a given total output $e_1 + e_2$ is almost the same as that needed by the same two valves in normal push-pull, but instead of the input voltage being balanced to earth it has one terminal earthed.

If we express the balance as the ratio e_1/e_2, then the value of R_c for a given degree of balance is given by $R_c = (R_a + R_1)/(1 + \mu)$ $(e_1/e_2 - 1)$, where R_a and μ are the AC resistance and amplification factor of the valves, assumed identical. With valves of the MHL4 type R_a is about 10,000 ohms and μ is 20, then if we permit 10 per cent. unbalance $(e_1/e_2 = 1.11)$ and R_1 is 25,000 ohms, R_c should be 15,000 ohms. If R_c is made 20,000 ohms, then the error becomes 8.3 per cent.

The cathode resistance R_c cannot be increased indefinitely because of the voltage drop across it set up by the steady anode current of both valves. If the current is 7 mA. and R_c is 20,000 ohms, the voltage drop is 140 volts and the effective operating voltage of the valves is reduced by this amount.

As the cathodes are at a high voltage with respect to earth, the grids cannot be returned to earth, but must be taken to a positive point. This is provided by the voltage divider R_4 R_5. With the cathodes at +140 volts the valves might need −4 volts grid bias with respect to cathode, so in this case the potential at the junction of R_4 and R_5 must be +136 volts.

Fig. 6.—This modification of Fig. 5 shows a simpler way of obtaining grid bias by the voltage drop across R3.

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For a given anode current it is desirable to make Rc as small as possible, for then the voltage lost across it is a minimum. The factors which affect Rc are the amplification factor of the valves, their AC resistances and the values of the coupling resistances. In general, R1 must be roughly proportional to Ra to obtain reasonable stage gain and good linearity. As the current taken is also likely to be roughly proportional to Ra, the voltage drop across Rc will be nearly independent of valve resistance for constant unbalance.

The only way to reduce the cathode voltage, therefore, is by increasing the amplification factor μ. In fact, Rc and

rent of 5 mA. ; therefore, R3 = 600 ohms. As R3 + R4 is to be 15,500 ohms, R4 should be 14,900 ohms. Actually, 15,000 ohms is quite near enough.

We thus find the following values suitable for Fig. 6 : V1 = V2 = Mullard 354v. or equivalent ; R1 = R2 = 50,000 ohms, R3 = 600 ohms, R4 = 15,000, R5 = R6 = 2 megohms ; C1 = C2 = 0.01 μF. The total current is 5 mA. at 350 volts and the output is just sufficient to load a PX4 push-pull stage. The stage gain $e_1/e_{IN} = 14.5$ and $e_2/e_{IN} = 13.1$. These are calculated, not measured, values and allow for 0.25 megohm grid leaks in the following stage.

The circuit of Fig. 6 is perfectly balanced at all frequencies as regards disturbances in the HT supply so long as V1 = V2, R1 = R2, C1 = C2, R5 = R6, and the output impedance of the preceding stage is negligibly small. The arrangement of Fig. 5 is not quite so well balanced in this respect.

As regards the signal path the balance in Fig. 5 is substantially independent of frequency, but in Fig. 6 there is the extra coupling C2 R6 which upsets the balance

A balanced output can be secured by making R2 somewhat larger than R1. If this is done the circuit is no longer perfectly balanced as regards the HT supply.

Fig. 8.—The input-output curve of the amplifier is linear up to 7 watts or slightly more.

The error is small, however, and if an adjustable balance is provided any lack of balance in the output stage can be corrected.

Measured Performance

The difference of potential between heater and cathode is a disadvantage, but most valves will withstand 80 volts between the two without harm. The Mullard 354v. is rated for a maximum of 50 volts, however. The difference of potential can be avoided by using a separate heater winding for these valves and connecting it to cathode. The capacity of this winding, and of the associated wiring to earth, then appears across Rc, but owing to the very low output impedance of the stage viewed across Rc, it does little harm. Even at 20,000 c/s the effect of shunting Rc by 0.001 μF. is barely measurable.

In order to check the performance of this phase-splitter the amplifier shown in Fig. 7 was set up. No special precautions in the choice of valves or components were observed ; resistances, for instance, were picked at random and might differ from their nominal values by the usual tolerances. No effort was made, either, to
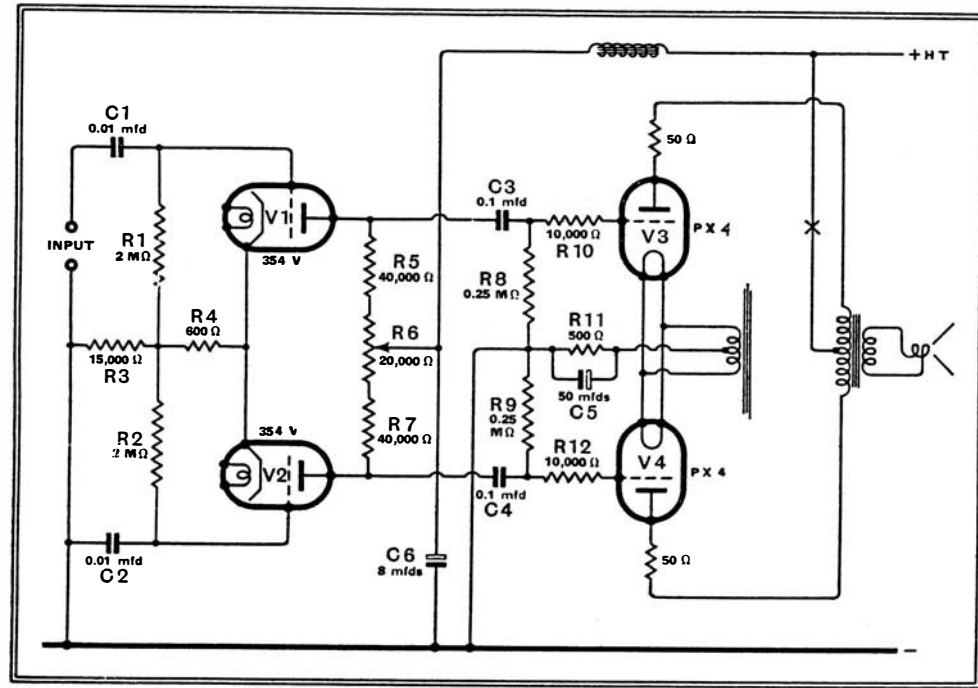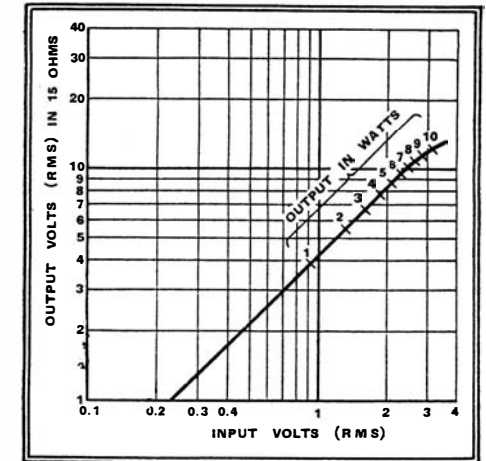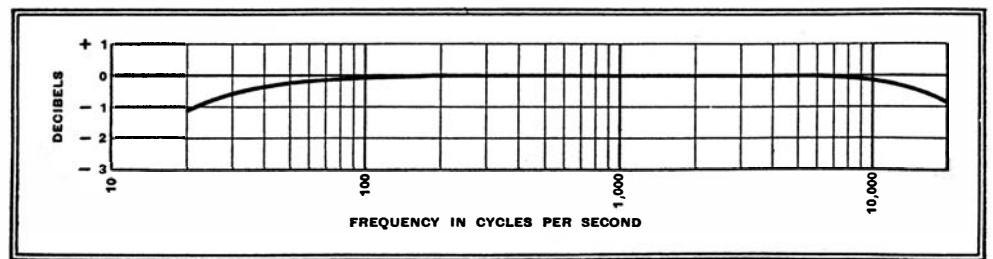

Fig. 7.—This diagram shows a phase-splitter feeding the output stage. This was the arrangement used for measurement purposes.

the cathode voltage are roughly inversely proportional to μ, assuming the other values to be constant. Valves of high mutual conductance are, therefore, desirable. The MH4 class should consequently be preferable to the MHL4.

Operating Conditions

The AC resistance Ra of the 354v. under normal working conditions for RC amplification is about 15,300 ohms and μ is about 37. Suppose we make R1 = 50,000Ω, then for 10 per cent. unbalance Rc = 15,500 ohms. This is little lower than before, but the valves take less current, so the cathode potential is lower.

With 350 volts HT and grid bias of -3 volts each valve takes 2.5 mA., so that the cathode potential is $+77.5$ volts ; the grids, therefore, must be returned to a point 74.5 volts above earth. The potentiometer for grid bias is rather inconvenient, and its use can be avoided by taking the grid return leads to a tapping on Rc as shown in Fig. 6. Here Rc is split into two parts, R3 and R4.

In the particular case we are considering we need 3 volts across R3 with a cur-

at very low frequencies. This is not important in many applications, however, and the method of biasing adopted here is the more convenient.

Fig. 9.—The frequency-response, including the output transformer, shows a drop of about 1 db. at 20 c/s and 20,000 c/s.

obtain matched valves, and the conditions were consequently such as one might expect in practice. In view of the possible variations one cannot expect very close

Phase-Splitting in Push-Pull Amplifiers—

agreement between the measured performance and the calculated.

The input-output curve of Fig. 8 shows that for 7 watts output the input to V_1 is 2.45 volts RMS, or 3.46 volts peak. The amplifier was, of course, balanced by means of R6. This is easily done by inserting a 50-ohm resistance in series with the HT lead to the output transformer at the point X in Fig. 7 and connecting a pair of 'phones or an oscilloscope across it. An AF oscillator, or a pick-up with a constant frequency record, is connected to the input, and R6 is adjusted for *minimum* output in 'phones or oscilloscope. With a small input the balance is quite sharp. The test frequency should be of the order of 400-1,000 c/s. www.keith-snook.info

The overall frequency response is shown in Fig. 9; at 20 c/s the response is -1.2 db. and at 20,000 c/s it is -0.9 db. The maximum deviation over the range of 20-20,000 c/s is thus ± 0.6 db. It should be noted that this includes the output transformer which has itself a variation of about ± 0.5 db.; the amplifier alone thus is likely to vary by only ± 0.1 db. Such variations are quite unimportant and are, in fact, near the limit of accuracy of the measuring gear.

The input-output curve of Fig. 8 also includes the output transformer, so that the 7 watts output is available on the secondary. The component used was a Sound Sales Type SS036, with a resistance for the secondary load.

Comparative Advantages

Comparing this new arrangement with the amplifier of *The Wireless World* Communication Receiver, we find that one valve less is used and that for the same output the input required is 3.46 volts peak, or, say, 3.5 volts, as compared with 2.35 volts peak. The total anode current consumptions are about the same—105 mA.—but the heater current of the extra valve is saved. There is also a saving of four fixed resistances, one tubular condenser, one 8 μF. electrolytic condenser and one valve-holder, against which must be offset the potentiometer R6. For the same accuracy of balance, this would be needed with the earlier circuit, however.

The saving effected is thus a worthwhile one, and if it lives up to its promise during extended tests it will undoubtedly be employed in future ultra-high quality apparatus described in *The Wireless World*. It should, perhaps, be pointed out that the amplifier of Fig. 7 does not give enough gain for many purposes; usually an additional stage will be needed. As a gain of some 4-7 times would be adequate for radio and for most pick-ups, there is the possibility of making this stage of the tone-control type.

PROBLEM CORNER—15

An extract from Henry Farrad's correspondence, published to give readers an opportunity of testing their own powers of deduction:—

"Radiovilla,"
Hackbridge.

Dear Mr. Farrad,

I have been making up a dynatron oscillator for experimental work, but so far have had no success. The valve seems all right; in fact I have taken a characteristic curve of it which I enclose. As I wanted to make use of the downward slope to the maximum advantage, I decided to work at an anode voltage of about 45, which, as you see, is about half-way down the slope. I am running the screen off a 90-volt battery (see circuit diagram), and to avoid tappings the anode is supplied through a voltage-dropping resistor. The anode current being $2\frac{1}{4}$ mA at the working point, I think I am correct in using a 20,000-ohm resistor to drop 45 volts. The grid bias is supplied by a small separate cell as I believe it is advisable not to run the valve without bias.

Well so far I have not succeeded in get-

ting anything to oscillate. I have checked over all the connections many times and tried tuned circuits that I know should oscillate easily with the slope of this valve. Having heard that you are good at solving these little mysteries, I am writing in the hope that you will do me this favour.

Yours sincerely,
Ray Lea.

The circuit diagram and valve characteristic curve enclosed with Mr. Lea's letter. Do they disclose the reason for the failure to oscillate?

SCREEN VOLTS = 90
GRID VOLTS = -1½

ANODE CURRENT IN MILLIAMPERES

ANODE VOLTS

The Elements of Radio Communication.

By O. F. Brown, M.A., B.Sc. (Oxon.), B.Sc. (Lond.), B.Sc. (Lond.). University Press, Amen House, Warwick Square, London, E.C.4. 16s. net.

THIS book is at once recognisable as outstanding among elementary textbooks on radio communication, for it is one of the very few that give the general reader a really comprehensive and authoritative survey of the underlying principles without recourse to mathematical treatment. In the preface the authors point out that particular attention has been paid to lucid explanation of the principles and reasons underlying radio phenomena, and every effort made to treat the subject comprehensively, rather than with great depth.
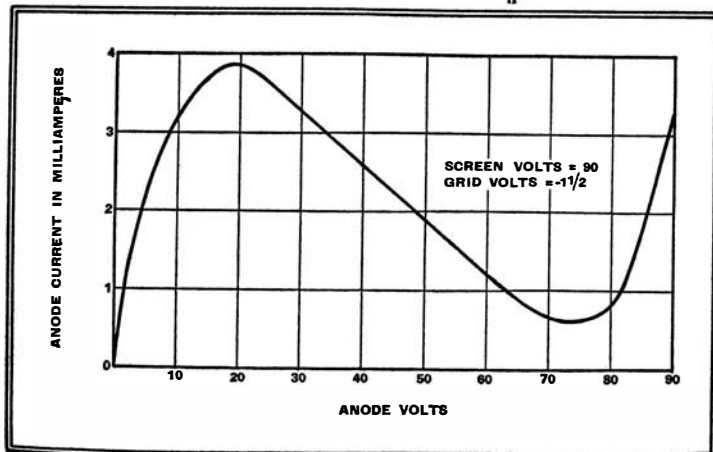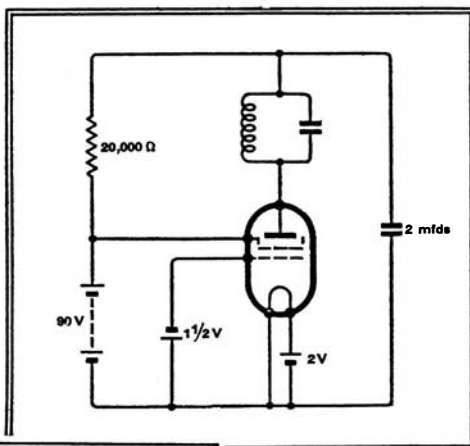
Each branch of the subject is treated from the beginning, early methods and historical stages being considered first, and then followed up by modern developments. No attempt has been made to describe in detail all the modern devices of transmitting and receiving equipment, for, as the authors say, "countless existing works do this very completely." But the fundamental principles and the reasons for the various phenomena are very fully explained in a style easily read and understood by the beginner. The reader is given a sound general knowledge of his subject, enabling him subsequently to study the more highly specialised and technical works without loss of perspective.

The introductory chapter is a survey of historical aspects, from Maxwell's predictions to present-day achievement. Then follow chapters on high-frequency alternating currents, electrical oscillations and radiation, thermionic valves, etc. Where electrical formulæ have to be introduced, free use is made of that most useful expression: "It can be shown that . . ." and the small amount of AC theory required is very simply expounded. There are very few statements open to criticism.

It may be somewhat unexpected to find a whole chapter on the now obsolescent method of spark transmission, but this has been included as a convenient theoretical introduction to other systems, apart from its historical interest. The sections on valves, detection, amplification, selectivity and reception in general, taken as a coherent whole, give the reader a survey which is remarkably complete and detailed for a non-mathematical treatment.

Due prominence has been given to television in the last two chapters, covering no fewer than 65 pages. Basic principles and early methods are treated at somewhat great length in the first section, the second and shorter section being devoted to the principles of modern electronic television.

For the benefit of those studying for examinations in radio communication, selections of past examination questions have been appended to each chapter.   O. P.