CIRCUITS FOR DIFFERENCE AMPLIFIERS, I.

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Pursuant to an article recently published in this journal, which dealt with difference amplifiers in general, part I of the present article gives details of circuits designed to achieve the very high rejection factors that are frequently required. Part II, to be published in the next number, will offer hints on the efficient use of difference amplifiers. Some cases will also be described where difference amplifiers can be used with advantage even where the object is not to amplify a potential difference between two points.

Introduction

The behaviour of a difference amplifier is largely governed, as discussed in an earlier article [1]), by the characteristics of the first stage. In dealing now with various circuits used for difference amplifiers, we shall therefore be primarily concerned with single-stage amplifiers. The problems that arise when stages are added, some of which will also be touched on here, are as a rule not difficult to solve.

It was shown in the previous article that difference amplifiers are mainly used for amplifying low-frequency or DC signals. Our considerations will therefore be confined to such amplifiers, and we shall disregard the problems encountered at higher frequencies, connected for example with the capacitances of valves and other components.

The nature of the applications of difference amplifiers makes it necessary to stipulate for the most important characteristics — the rejection factor and the discrimination factor — a lower limit which differs from case to case. *The circuits that we shall deal with have been designed so as to be able to guarantee these minimum values without readjustment of the amplifier, even when the parameters of the valves and other components, which always show some mutual disparity, have the maximum deviation from the normal value and these deviations are all operative in the same (adverse) direction.*

As explained at some length in the above-mentioned article [1]), the problem of the difference amplifier consists in amplifying the voltage between two points which may both have a much higher potential with respect to earth. An obvious method of amplifying the potential difference between the two points would be to connect them with the input terminal and the "earth terminal" of a normal single-ended amplifier. The latter terminal is then not connected to earth; it can be said that electrically the whole amplifier "floats". Without going into details, it may be noted that amplifiers made electrically floating in this way are usually complicated and unwieldy in construction, and moreover usually have to be screened against interfering induction voltages. The principle described in this article, of *a balanced amplifier with a very high common cathode resistance*, offers in almost every case a much simpler solution.

Circuit with common cathode resistance

It was shown in the article quoted [1]) that a balanced amplifier, consisting of two independently operating sections, cannot be used as a difference amplifier because its discrimination factor is equal to unity, whereas for most purposes a value of at least 100 is required. In principle, a circuit can be used where the two valves of a balanced amplifier are given a common cathode resistance without decoupling (*fig. 1*). As we shall see, this resistance, R_k, must be very much higher than that needed for giving the grid the normal negative bias. For
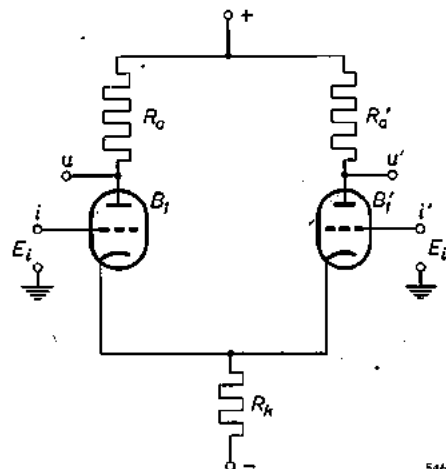

Fig. 1. Difference amplifier with a resistance R_k incorporated in the cathode lead common to both valves. Input terminals i and i', output terminals u and u'.

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[1]) G. Klein and J. J. Zaalberg van Zelst, General considerations on difference amplifiers, Philips tech. Rev. 22, 345-351, 1960/61 (No. 11).

this reason, R_k is not usually connected to earth but to a voltage source which supplies a negative voltage with respect to earth. In this way the grids of valves biased to their normal operating point can be more or less at earth potential, which simplifies connection to the points whose voltages are to be measured, especially in the case of DC amplifiers.

If both valves are perfectly identical, and identically biased, there will be no change in the current through R_k when two equal but opposite small changes [2]) are made to the two grid voltages E_i and E_i'. The resistance R_k then has no effect on the amplification of the two valves. If, however, the changes in E_i and E_i' have the same sign, the two valves function as if they were connected in parallel. The presence of R_k now gives rise to negative feedback. As a result the amplification of in-phase signals (see [1])) is smaller than that of anti-phase signals, and the discrimination factor F is therefore greater than unity. Assuming perfect symmetry, the value of F is easy to calculate. From the familiar expression for the gain of a triode the anti-phase gain is found to be

$$A = \mu \frac{R_a}{R_i + R_a}, \quad \ldots \quad (1)$$

where μ is the amplification factor and R_i the internal resistance of the valves, and R_a is the anode resistance. The in-phase gain C, where negative feedback due to R_k occurs, is given by

$$C = \mu \frac{R_a}{R_i + R_a + 2(1 + \mu)R_k}. \quad \ldots \quad (2)$$

The discrimination factor is thus

$$F = \frac{A}{C} = 1 + 2 \frac{(1 + \mu)R_k}{R_i + R_a}. \quad \ldots \quad (3)$$

In the circuits we shall be dealing with, the value of R_i is always large compared with R_a, and $2\mu R_k$ large compared with R_i. Since moreover the amplification factor μ is large compared with unity for normal valves, we can write F with negligible error as

$$F = 2SR_k, \quad \ldots \ldots \quad (4)$$

where S is the transconductance of both valves. Where the transconductance of the valves is not exactly the same, the discrepancy can be taken into account by inserting in eq. (4) the average value of

S for both valves. Small discrepancies in the values of R_i and R_a are found to have an entirely negligible influence on F.

To compute the rejection factor H we must start from differences between the parameters, which cause a degree of asymmetry in the amplifier. If the amplifier were perfectly symmetrical, the value of H would of course be infinite. To find the rejection factor of a circuit as in fig. 1, we should therefore assume that the two halves of the amplifier differ in the transconductance and amplification factor of the valves and also in the resistance in the anode leads. The result of this calculation [3]), provided the differences are not excessive, can be presented to a good approximation by the formula:

$$H = \frac{4}{\left(\dfrac{\Delta S}{S} + \dfrac{\Delta R_a}{R_a}\right)\dfrac{1}{SR_k} + \dfrac{1}{\mu}\left(\dfrac{\Delta\mu}{\mu}\right)\left(2 + \dfrac{R_a}{R_k}\right)}, \quad (5)$$

where ΔS, $\Delta\mu$ and ΔR_a are the differences in the transconductance, amplification factor and anode resistance of the valves respectively. Distinguishing the relevant values for the one valve from those for the other by a prime, we may write $\Delta S = S' - S$, $\Delta\mu = \mu' - \mu$ and $\Delta R_a = R_a' - R_a$.

From equation (5) we see that the smallest value of H occurs when $\Delta S/S$, $\Delta\mu/\mu$ and $\Delta R_a/R_a$ have the same sign (i.e. when S, μ and R_a of one valve are greater than those of the other valve), and moreover have the maximum values that can be expected from the normal tolerances of valves and resistors. The equation is greatly simplified if we assume that the maximum relative difference of the above three quantities have the same value, denoted by δ. (In practice, δ may for example be 0.1.) Inserting this in eq. (5) we find the minimum rejection factor that can occur for a given magnitude of δ:

$$H_{min} = \frac{4}{\delta\left\{\dfrac{2}{SR_k} + \dfrac{1}{\mu}\left(2 + \dfrac{R_a}{R_k}\right)\right\}}. \quad \ldots \quad (6)$$

From this expression we see that H_{min} is greater the larger the value of R_k in the common cathode lead. If the value of R_k is so high that R_a/R_k is negligible compared to 2, we can simplify eq. (6) to:

$$H_{min} = \frac{2}{\delta\left(\dfrac{1}{SR_k} + \dfrac{1}{\mu}\right)}. \quad \ldots \quad (7)$$

Equations (6) and (7) show that to obtain a high value of H_{min} it is necessary, though not sufficient,

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[2]) The changes must be small enough to prevent the curvature of the characteristics from playing any part.

[3]) See G. Klein, Rejection factor of difference amplifiers, Philips Res. Repts 10, 241-259, 1955.

to have a large R_k. If SR_k is of the same order of magnitude as μ, then R_k must be very considerably increased to achieve a relatively slight increase in H_{min}. For a particular value of H_{min}, both SR_k and μ must have a specific minimum value which is larger the larger is H_{min}. If SR_k is small compared to μ, the minimum rejection factor is given by:

$$H_{min} = 2SR_k/\delta, \quad \ldots \ldots (8)$$

or, putting $\delta = 0.1$:

$$H_{min} = 20\,SR_k. \quad \ldots \ldots (9)$$

From the expressions (4) and (9) we see that in this case F is roughly equal to $0.1\,H_{min}$.

It may also happen that SR_k is large compared to μ, in which case H_{min} is approximately given by:

$$H_{min} = 2\mu/\delta, \quad \ldots \ldots (10)$$

or, with $\delta = 0.1$:

$$H_{min} = 20\,\mu. \quad \ldots \ldots (11)$$

In order to guarantee a rejection factor of, for example, 10 000 one must — assuming that R_k is sufficiently large — use valves having an amplification factor of at least 500. Where SR_k is not large compared to μ, the latter value must be even higher. For instance, H_{min} can also be made equal to 10 000 when both SR_k and μ are equal to 1000. Given a transconductance of 1 mA/V [4]) for both valves, R_k must then be equal to 1 MΩ.

In certain cases where an even higher rejection factor is required, a much higher value of R_k is needed, e.g. 10 MΩ. The use of such a resistor of normal construction in the common cathode lead is invariably inadvisable, in view of the abnormally high negative biasing voltage then called for. It is a fortunate circumstance, however, that the only requirement imposed on R_k is that the quotient of the voltage change and the resultant current change should be high; in other words, a high *differential* resistance is wanted. The DC resistance (voltage divided by current) may permissibly be very much lower and indeed should be so, having regard to our remarks on the supply voltage needed.

In one of the following sections we shall consider circuits which in fact combine a very high differential resistance with a low DC resistance. First, however, we shall examine in more detail various problems arising from the necessity of using valves having a high amplification factor.

Difference amplifiers using pentodes

Most pentodes have a much higher amplification factor than conventional triodes. Where valves with a high amplification factor have to be used in a difference amplifier, our thoughts first turn therefore to the use of pentodes. The circuit diagram of a difference amplifier with pentodes is shown in *fig. 2*. (For the present it is sufficient to show a normal resistance R_k in the common cathode lead.)

The very high amplification factor of a pentode is only used to full advantage when, given a variable control-grid voltage, the potential difference between screen grid and cathode is kept constant and when changes in screen-grid current flow only partly or not at all through R_k. If the difference amplifier is intended solely for alternating voltages, this can be achieved by connecting a capacitor C between the screen grids and the cathodes in the usual way
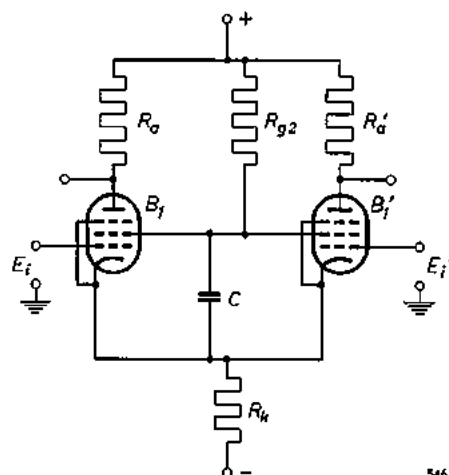

Fig. 2. Difference amplifier for AC signals, with two pentodes.

(see fig. 2). Where the amplifier is also required to deal with DC signals, a voltage-stabilizing valve can be used instead of a capacitor (see *fig. 3*). Since the operating voltage of such a valve is very little dependent on the current, a practically constant potential is maintained in this way between the screen grids and the cathode, and changes in screen-grid current do not flow through R_k to any significant extent.

The above two conditions are never entirely fulfilled, for which reason H_{min} is smaller than follows from equation (7). The denominator of the complete equation in fact contains two extra terms, the first of which is due to the fact that the control-grid voltage and the screen-grid voltage do not necessarily influence the anode current in the same ratio in both valves. The second term is due to the possible spread in the distribution of cathode-current changes over anode and screen grid.

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[4]) The valves are usually biased to obtain a low anode current, and hence a low mutual conductance, so that at the required value of R_k a lower negative supply voltage can be used. When the anode current is raised (and R_k correspondingly reduced) the mutual conductance increases relatively less, so that in spite of the higher S the product SR_k is no greater than when S is smaller.

A serious difficulty entailed by the use of pentodes arises from the flow of direct current to the screen grid. To obtain the required screen-grid potential the resistance R_{g2} must not exceed a specific value. (In fig. 3 the current of the voltage-
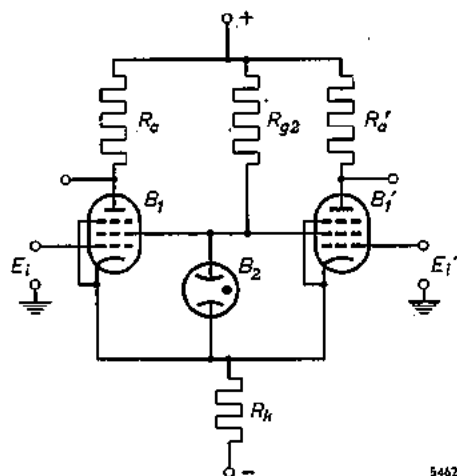

Fig. 3. Difference amplifier for DC signals, with two pentodes. A voltage-stabilizing valve B_2 is inserted between the screen grids and the cathodes.

stabilizing valve B_2 also flows through R_{g2}. In this case, therefore, the resistance in question must be even smaller than when a capacitor is used.) Since a constant potential difference is maintained between the screen grids and the cathodes, and also between the points marked $+$ and $-$, the resistor R_{g2} may be regarded as in parallel with R_k as far as voltage and current changes are concerned. The differential resistance between cathode and earth is consequently reduced, and this causes, as we have shown above, a smaller value for the guaranteed rejection factor and discrimination factor. Methods that largely overcome this drawback will be discussed in the following sections.

The use of cascodes

An amplifier stage giving an amplification factor much higher than that of a triode can also be obtained by connecting two triodes in such a way as to produce a "cascode" circuit. The principle of such an arrangement is shown in *fig. 4*. The cathode of triode B_2 is connected to the anode of B_1. Provided the biasing voltages are so chosen that the valves operate in the normal part of their characteristics, a cascode exhibits properties closely resembling those of a pentode. The grid of triode B_2 functions in the circuit very much like the screen grid of a pentode. An important difference, however, is that screen-grid current always flows in a pentode, whereas in the "upper" valve in a cascode circuit no more than the usual, very low, grid current

flows. This accounts for a marked advantage gained by using cascodes in difference amplifiers, to which we shall presently return.

A simple calculation shows that the transconductance of a cascode is practically identical with that of the "lower" valve:

$$S_{\text{casc}} = S_1. \quad \ldots \ldots \quad (12)$$

The amplification factor μ_{casc} of the whole circuit is given by

$$\mu_{\text{casc}} = \mu_1(\mu_2 + 1), \quad \ldots \ldots \quad (13)$$

where μ_1 and μ_2 are the amplification factors of the "lower" and "upper" valves, respectively. Since the amplification factors of normal valves are always very much larger than unity, we can write (13) to a very good approximation as

$$\mu_{\text{casc}} = \mu_1\mu_2. \quad \ldots \ldots \quad (14)$$

The amplification factor of a cascode is thus high compared with that of each of the two valves of which it is composed.

A higher amplification factor, if required, can be obtained by using a cascode with more than two triodes. *Fig. 5* shows an example using three triodes. The gain of the cascode in this case is

$$\mu_{\text{casc}} = \mu_1(\mu_2 + 1)(\mu_3 + 1),$$

or, to a close approximation,
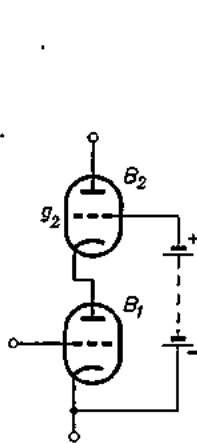
$$\mu_{\text{casc}} = \mu_1\mu_2\mu_3.$$

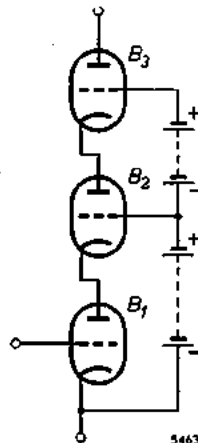Fig. 4   Fig. 5

Fig. 4. Cascode consisting of two triodes.
Fig. 5. Cascode consisting of three triodes.

To obtain an amplification factor as in (13) with a circuit as shown in fig. 4, the grid g_2 of B_2 must have a constant potential with respect to the cathode of B_1. This is represented in the figure, for simplicity, as being produced by a battery. As a rule, of course, the bias for g_2 will be derived from the anode-voltage source by means of a voltage

divider. *Fig. 6* shows a voltage divider for this purpose in a difference amplifier consisting of two cascodes. Because of the extremely low grid current flowing in the valves, the resistance R_1 can be given a very high value, e.g. a few megohms. To maintain
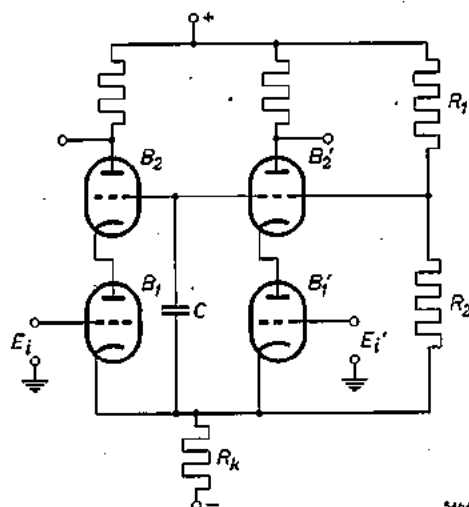

Fig. 6. Difference amplifier for AC signals, with two cascodes.

the required constant potential between the grids of B_2 and B_2' and the cathodes of B_1 and B_1' a capacitor C is introduced, the effect of which is to transfer practically all sufficiently rapid voltage variations from the lower cathodes to the upper grids. For alternating voltages, then, resistor R_1 can be regarded as being in parallel with R_k, so that the differential resistance in the common cathode lead is again smaller than R_k. In view of the fact, however, that R_1 can be given a very high value, this drawback is less serious here than with the screen grids of pentodes.

Cascodes are not so superior to pentodes when the difference amplifier is to be used for amplifying DC potential differences in the same way as the pentode circuit in fig. 3. The capacitor C will then be replaced by a voltage-stabilizing valve, and because of the direct current flowing in this valve the value of R_1 has to be made very much smaller. As in pentode circuits, arrangements can again be made that largely overcome this drawback. We shall touch on this under another heading.

It should be noted that the gain in H_{min} obtained by using cascodes instead of pentodes is less than would follow from equations (7) and (14). This is because the maximum spread in the amplification factor of a cascode is greater than that shown by the amplification factors for each valve individually. If μ_1 and μ_2 may each have a relative deviation δ from the nominal value, then the maximum relative deviation of μ_{casc} is equal to 2δ. When cascodes

are used, therefore, the minimum guaranteed value of H is given not by equation (7) but by

$$H_{min} = \frac{2}{\delta\left(\dfrac{1}{S_1 R_k} + \dfrac{2}{\mu_{casc}}\right)} \qquad . \quad . \quad (15)$$

The term accounting for the influence of the amplification factor on H_{min} is thus only reduced by half the ratio between the amplification factors when we change over from triodes to cascodes.

It should be remarked that equation (15), like equation (7) in the case of pentodes, is only valid on the assumption that there are no voltage variations between the grids of the upper valves and the cathodes of the lower ones. In order to allow for the fact that this is never the case, and assuming that the voltage variations on the grids are k times those on the cathodes ($k < 1$), the value for μ_{casc} to be inserted in (15) should not be calculated from (13) or (14) but from:

$$\mu_{casc} = \frac{\mu_1(\mu_2 + 1)}{(1-k)\mu_2 + 1}.$$

Since hardly any grid current flows in a cascode, H_{min} is not reduced by any spread in the distribution of the cathode current, as it is in the case of pentodes.

It may sometimes be regarded as a disadvantage of cascodes that the power-supply circuit has to deliver a higher voltage than for pentodes. This is a particular objection in multi-stage DC amplifiers with direct coupling between the stages (see part II of this article). It is even more of a drawback, of course, when cascodes consisting of more than two valves are used.

Circuits for obtaining a high differential resistance in the cathode lead

We have seen from a numerical example that the use of a normal resistance in the common cathode lead of the valves in a difference amplifier seldom deserves consideration, but that a component or circuit is required for this purpose whose DC resistance is low and whose differential resistance is very high. This requirement can largely be met by incorporating a pentode in the cathode lead (*fig. 7*). If the control
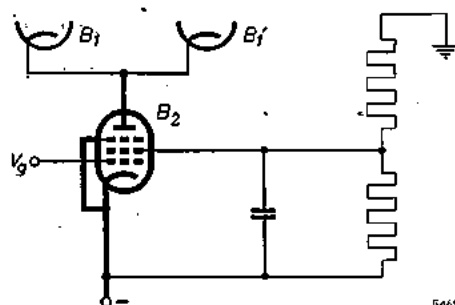

Fig. 7. Use of a pentode B_2 for producing a high differential resistance in the common cathode lead of the tubes B_1 and B_1'.

grid and screen grid are kept at the stipulated constant potentials with respect to the cathode, the differential resistance of a pentode is equal to its internal resistance, which may be more than 1 MΩ.

Another method of producing a high differential resistance in the common cathode lead is illustrated in *fig. 8*. The cathode lead of triode B_2 contains a resistance R_{k2}. If the grid of B_2 has a constant potential, the differential resistance R_d of the branch represented by thick lines in fig. 8 is given by

$$R_d = R_{i2} + (1 + \mu_2)R_{k2}, \quad . \quad . \quad . \quad (16)$$

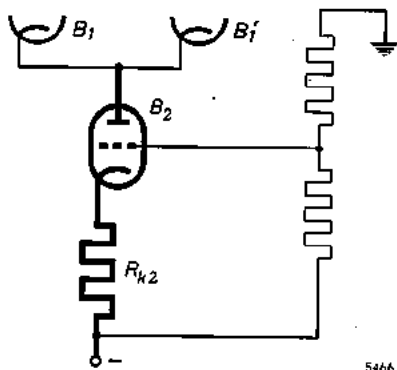where R_{i2} is the internal resistance and μ_2 the am-

Fig. 8. Use of a triode B_2 with cathode resistance R_{k2} for producing a high differential resistance in the common cathode lead of the tubes B_1 and B_1'.

plification factor of triode B_2. From eq. (16) we see that R_d is greater than $\mu_2 R_{k2}$. If, for example, the triode used has an amplification factor of 50 and R_{k2} is equal to 0.1 MΩ, then R_d will be greater than 5 MΩ.

A pentode has a much higher amplification factor than a triode, and therefore R_d can be given a higher value if the triode B_2 in fig. 8 is changed for a pentode. We should bear in mind, however, that equation (16) is only valid for a pentode provided the changes in the anode current are equal to the changes in the current through the resistance in the cathode lead. Since there is always some screen-grid current flowing in a pentode, the only way to fulfil this condition is to insert between the screen grid and cathode either a capacitor of sufficiently high capacitance or a gas-discharge tube. In many cases it is then simpler to use a cascode arrangement, where there is no grid current and therefore no need for the above measure.

Fig. 9 shows a cascode, formed from two triodes B_2 and B_3, incorporated in the common cathode lead of valves B_1 and B_1'. The cathode lead of B_2 contains the resistor R_{k2}, and the grid voltages are kept constant by a voltage divider R_1-R_2-R_3.

We have seen that the amplification factor of a cascode is greater than the product of the amplification factors of the two valves. For this reason the differential resistance of the branch represented by thick lines in fig. 9 is greater than $\mu_2\mu_3 R_{k2}$ (μ_2 and μ_3 being the amplification factors of triodes B_2 and B_3). Here too it is possible to use cascodes built up from more than two triodes, so that there is practically no limit to the value of the differential resistance which can be obtained in this way.

As explained above, the differential resistance in the common cathode lead of valves B_1 and B_1' does not consist solely of the thickly drawn branch in figures 7, 8 and 9, but also of a resistance in parallel with this branch and represented by R_{g2} in figures 2 and 3 and by R_1 in fig. 6. Since R_{g2} is much smaller than the required differential resistance (in DC amplifiers this also applies to R_1, as we have seen above), this is a severe obstacle to a high rejection factor. Two circuits that largely overcome this obstacle are represented in *figs 10* and *11*.

In fig. 10 the required constant potential difference between the cathodes and screen grids of B_1 and B_1' is not obtained by interposing a capacitor or voltage-stabilizing valve, but by means of a cathode follower B_3 and a coupling capacitor C. (Where the difference amplifier is also to amplify DC potential differences, a voltage-stabilizing valve should be substituted for the capacitor C.) If B_3 were an ideal cathode follower and the reactance of the capacitor C were negligible compared with the resistance R_{g2}, the voltage on the screen grids would completely "follow" the voltage variations on the cathodes. In reality, of course, this is never so. For that to be possible the differential resistance between the
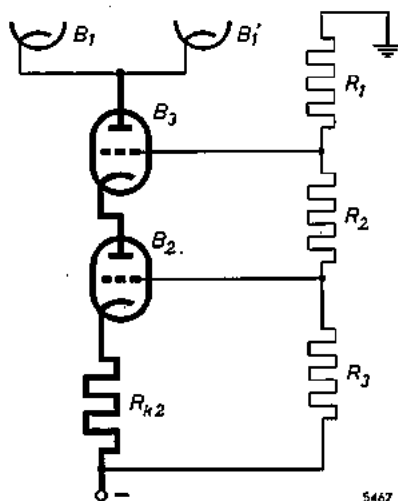

Fig. 9. Cascode with cathode resistance R_{k2} used for producing a high differential resistance in the common cathode lead of the tubes B_1 and B_1'.
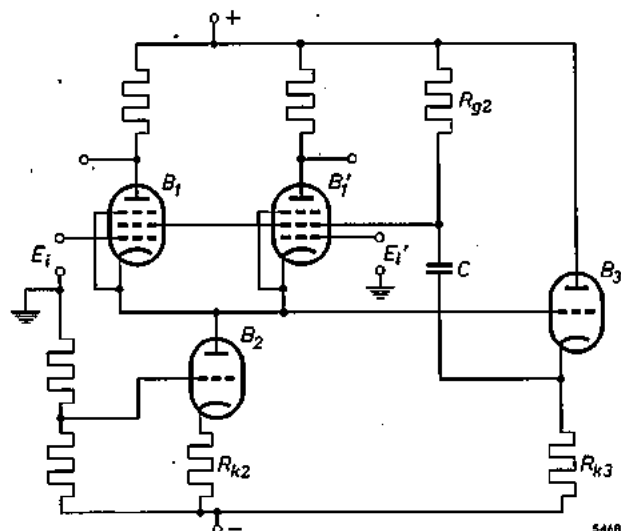
Fig. 10. Difference amplifier with pentodes B_1 and B_1'. The common cathode lead is given a high differential resistance by means of the triode B_2 and the resistor R_{k2}. The cathode follower B_3 enables the screen grids to follow the voltage fluctuations on the cathodes of B_1 and B_1'.

cathode of B_3 and earth would have to be infinitely high, and B_3 itself would have to have an infinitely large amplification factor. There will still, therefore, be slight voltage variations between the screen grids and the cathodes of B_1 and B_1', but owing to the fact that R_{g2} in fig. 10 has no influence on the common cathode resistance of these valves the cathode follower B_3 does in fact considerably improve the rejection factor and the discrimination factor.

The situation is even more improved if the cathode follower B_3 in fig. 10 is replaced by an amplifier whose gain approaches still closer to unity. In this way the influence of R_{g2} on the rejection and dis-
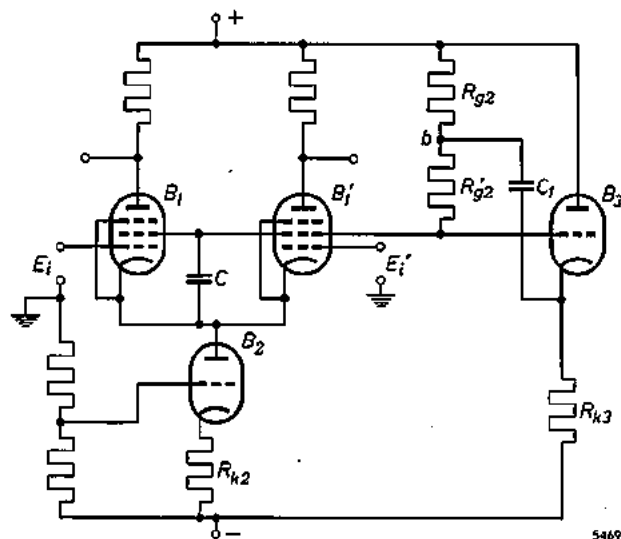

Fig. 11. Difference amplifier with pentodes B_1 and B_1'. The common cathode lead is given a high differential resistance by means of the triode B_2 and the resistor R_{k2}. The cathode follower B_3 raises the differential resistance between the screen grids and the anode-voltage source to a very high value.

crimination factors can be almost entirely eliminated.

In fig. 11 a capacitor C is again shown incorporated between the cathodes and screen grids of pentodes B_1 and B_1'. Given a high enough value of C, the voltage on the screen grids will almost completely follow the voltage variations on the cathodes. In that respect, then, this circuit has an advantage over that in fig. 10. The disadvantage, that the DC resistance of the screen grids reduces the differential resistance in the common cathode lead of B_1 and B_1', is largely overcome by the fact that the screen grids are here connected to the anode-voltage source by a circuit which has a very high differential resistance but a much smaller DC resistance. This circuit consists of the two resistors R_{g2} and R_{g2}' and a cathode follower B_3, which, via capacitor C_1, transmits the voltage variations on the screen grids almost entirely to point b. As a result the differential resistance between the screen grids and the anode-voltage source is much greater than $R_{g2} + R_{g2}'$, which can mean a considerable increase in the rejection and discrimination factors.

In this circuit too (fig. 11) the cathode follower B_3 can be changed for an amplifier whose gain is closer to unity. Use can also be made of circuits combining the principles of figs 10 and 11. Details of these circuits, however, are beyond the scope of this article.

The methods illustrated in figs 10 and 11 for increasing the differential resistance in the common cathode lead can also be adopted, of course, when cascodes are used in the differential amplifier instead of pentodes. As mentioned above, when cascodes are used these methods will generally be needed only when the differential amplifier is required to amplify DC potentials, in which case voltage-stabilizing valves must be used instead of capacitors, and the grids of the "upper" valves (see fig. 6) are therefore connected via a relatively small resistance to the anode-voltage source.

Some results of measurements

It will be clear from the foregoing that we can choose from a wide variety of circuit arrangements in order to design a difference amplifier whose rejection and discrimination factors can be guaranteed to have very high values. From the numerous possibilities, we have chosen three examples with a view to comparing the measured rejection factors with the minimum values calculated for these circuits.

Fig. 12 shows the circuit of a difference amplifier equipped with two E 80 F pentodes. The high

differential resistance required in the common cathode lead is obtained with the triode B_2 and the resistor R_{k2}. By means of the cathode follower B_3 the voltage variations on the cathodes of B_1 and B_1' are transmitted to point b. The influence of the screen-grid resistance on the rejection factor is thus reduced here by a circuit which combines the principles illustrated in the figures 10 and 11. The two halves of a double triode ECC 81 are used for B_2 and B_3.

The minimum value of the rejection factor, assuming $\delta = 0.1$, is calculated to be 20 000 for this circuit. In *fig. 13* the calculated minimum is represented on a logarithmic
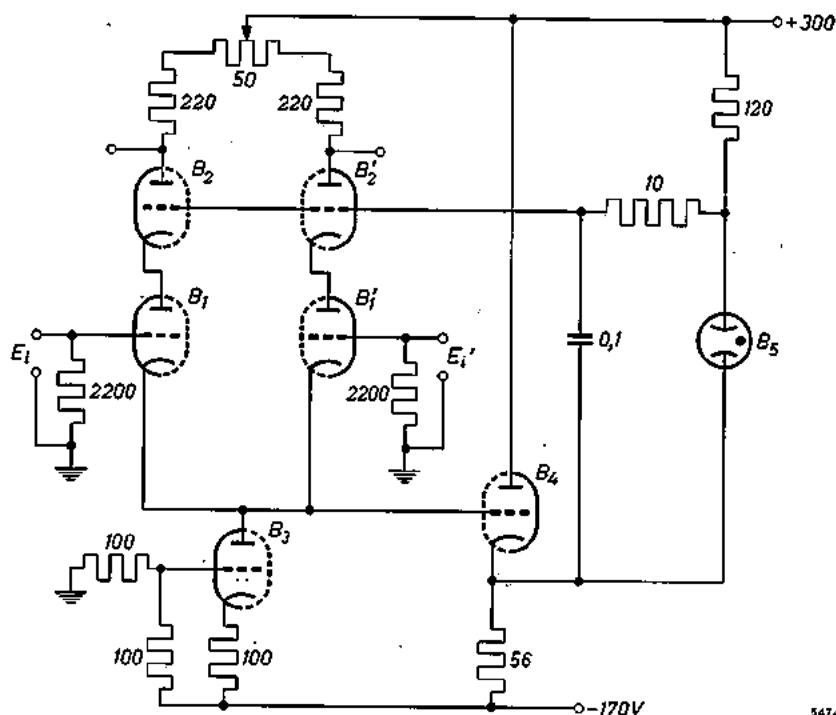

Fig. 14. Difference amplifier for DC signals, with two cascodes composed of two double triodes type E 80 CC. Triodes B_3 and B_4 are formed from the two halves of a double triode type ECC 81. B_5 is a voltage-stabilizing valve type 85 A 2. Resistances in kΩ, capacitances in μF.
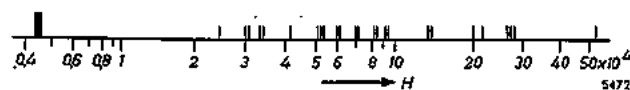

Fig. 15. Measured values of rejection factor H (thin marks) and calculated minimum value H_{min} (thick mark) for the circuit of fig. 14.

scale together with the rejection factors measured on 25 arbitrary combinations of valves. The measurements were done at a frequency of 1 kc/s. The lowest value measured was 24 000.

Fig. 14 gives the circuit diagram of a difference amplifier with two cascodes consisting of two double triodes, type E 80 CC. One half of a double triode ECC 81 is used for B_3 and the other half as a cathode follower, B_4, for transmitting the voltage variations on the cathodes of B_1 and B_1' to the grids of B_2 and B_2'. The transmission is effected by a voltage-stabilizing valve B_5 of type 85 A 2. Since the differential resistance of such a valve increases with increasing frequency, a capacitor of 0.1 μF is connected in parallel with B_5. The resistance of 10 kΩ between this capacitor and B_5 serves to correct instability effects likely to occur in a circuit of this kind.

Assuming that all quantities involved may show mutual deviations of 10%, we calculate a minimum value of 4500 for the rejection factor of this circuit. The values measured on 25 arbitrary combinations of valves are again shown on a logarithmic scale in *fig. 15*. The lowest value measured, 24 000, is much higher than the calculated minimum value.
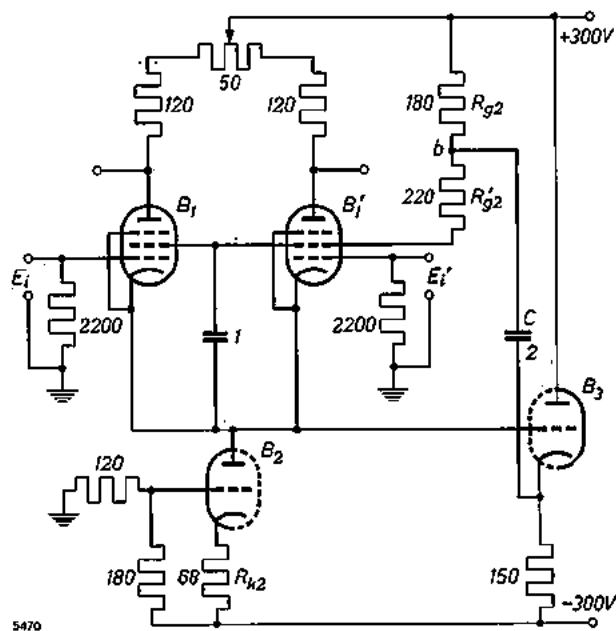

Fig. 12. Difference amplifier with two pentodes, type E 80 F. Triodes B_2 and B_3 are formed from the two halves of a double triode ECC 81. Resistances are given in kΩ, capacitances in μF. The 50-kΩ potentiometer is adjusted in such a way that in the steady state the anode voltages of the pentodes do not differ too much, giving both tubes roughly the desired operating point.
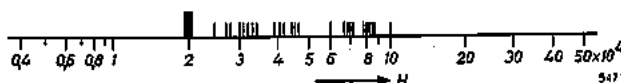

Fig. 13. Measured values of rejection factor H (thin marks) and calculated minimum value H_{min} (thick mark) for the circuit of fig. 12.

The reason is that in fact the mutual disparity in the transconductance and amplification factor of a type E 80 CC double triode very seldom approaches 10%. Consequently there is a good chance that higher values of H will be found with circuits using this valve rather than other types whose S and μ are higher but show a greater mutual disparity.

The measurements whose results are represented in fig. 15 were carried out with direct voltage. If the difference amplifier is intended to handle alternating voltages only, the circuit can be considerably simplified. As already shown in fig. 6, the voltage for the grids of B_2 and B_2' can then be obtained from a voltage divider between the anode-voltage source and the cathodes of B_1 and B_1'. The voltage variations on the cathodes of the latter valves can be transmitted to the grids of B_2 and B_2' by means of a capacitor. *Fig. 16* represents the diagram of a circuit on which, with various combinations of valves, measurements were carried out at a frequency of 100 c/s. Two E 80 CC double triodes were used for B_1, B_1', B_2 and B_2', and half of a double triode ECC 81 was used for B_3. Again assuming 10% deviations in the values of all quantities involved, the minimum value calculated for the rejection factor was 6500. In *fig. 17* the measured values are again set out together with the calculated minimum value of H. The lowest value measured on 25 arbitrary combinations of valves was 24 000. Here, too, owing to the constancy of the E 80 CC double triode, this measured minimum is appreciably higher than the calculated value.

Part II of this article will deal with various problems that arise in the design of multi-stage difference amplifiers. Indications will also be given of the proper method of connecting the amplifier to
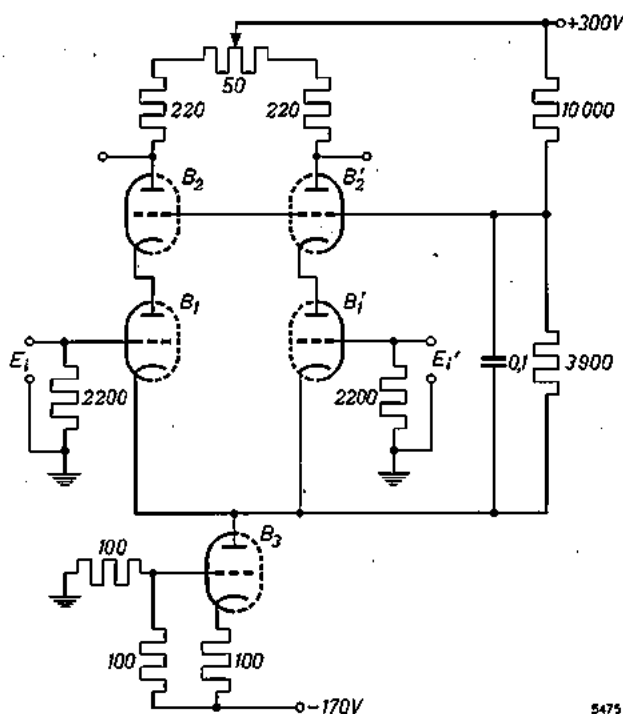

Fig. 16. Difference amplifier for AC signals, with two cascodes composed of two E 80 CC double triodes. B_3 is one half of an ECC 81 double triode. Resistances in kΩ, capacitances in μF.
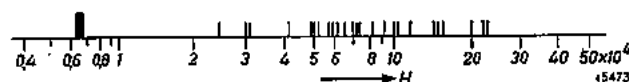

Fig. 17. Measured values of rejection factor H (thin marks) and calculated minimum value H_{min} (thick mark) for the circuit of fig. 16.

points between which the potential difference is to be measured. Finally, some cases will be mentioned where difference amplifiers can also be used with advantage where the object is not to amplify the potential between two points.

Summary. An efficient single-stage difference amplifier can be produced by incorporating in the common cathode lead of the two valves of a balanced amplifier an element which has a very high differential resistance. The latter is necessary to obtain a high discrimination factor. In order to be able to guarantee a high rejection factor, even though the parameters of valves and other components show the maximum (adverse) deviation from their rated value, not only must the differential resistance in the cathode lead be high but the valves must also have a high amplification factor. The valves used may be either pentodes, or triodes in a cascode arrangement. The voltage on the screen grids of the pentodes or on the grids of the "upper" triodes in the cascodes must follow the voltage variations on the cathodes closely. Some circuits which achieve this result are described. The high differential resistance in the common cathode lead can be obtained with circuits using pentodes, triodes or cascodes. Measurements on three circuits are discussed, and the calculated minimum rejection factor is compared with the values measured on 25 arbitrary combinations of valves.