CIRCUITS FOR DIFFERENCE AMPLIFIERS, II

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*Part II of this article deals with some of the problems that arise in the application of the circuits discussed in part I **). Some other uses for difference amplifiers are described, in particular as an "electronic voltage microscope" and as a logarithmic voltmeter.*

Effect of the input network on the rejection factor

Where a potential difference between two points is to be measured, and a difference amplifier having a high rejection factor is used for this purpose because both points have a high voltage with respect to earth, careful attention should also be paid to the network by which the amplifier is coupled to the points in question. Any asymmetry in that network can ruin the results obtained with a good difference amplifier.

If the measurement is concerned solely with alternating voltages, the amplifier is usually coupled to the points by two capacitors, C and C' (*fig. 18*). Voltage division then occurs across these capacitors and across the input resistances R_i and R_i' of the amplifier. If the products R_iC and $R_i'C'$ are not equal, an in-phase component of E_i and E_i' gives rise to an anti-phase component in the voltage on the input terminals. This coupling network may then be said to have its own finite rejection factor. Provided the discrepancy is not too great, this factor is given by:

$$H = \frac{4\pi f R_i C}{\delta}, \qquad (17)$$

where f is the signal frequency and δ the relative difference between the products R_iC and $R_i'C'$. Using components for R_i, R_i', C and C' that may show a maximum deviation of 5% from the nominal value, the products R_iC and $R_i'C'$ may show a maximum discrepancy of 20% ($\delta_{max} = 0.2$). In this case the minimum value of the rejection factor is:

$$H_{min} = 20\pi f R_i C. \qquad (18)$$

Given the requirement $H_{min} = 50\,000$ at $f = 50$ c/s, for example, then the product R_iC must be at least equal to 16 seconds. If R_i and R_i' are rated at 1 MΩ, the capacitors used for C and C' must therefore have a rating of at least 16 μF.

This is a much higher value than would be needed for simply keeping the voltage drop in such a network reasonably low. Simple calculation shows that, for the input signals of the amplifier to differ by no more than 1% from E_i and E_i', the capacitance of C and C' under the conditions mentioned need be only 0.022 μF.

Another important quantity to be considered when using a difference amplifier is the internal resistance of the voltage sources that supply E_i and E_i'. Here too even a slight difference may reduce the rejection factor considerably. In *fig. 19* the internal resistances of the signal sources are denoted by R_b and R_b'. The network sketched can again be said to have a rejection factor, which, if R_i and R_i' are identical and R_b and $R_b' \ll R_i$, is given by:

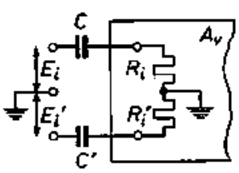

Fig. 18.

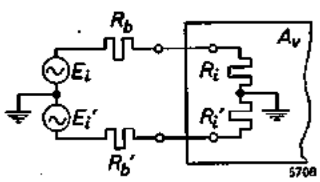

Fig. 19.

Fig. 18. Network for coupling a difference amplifier A_v to the points between which the potential difference is to be measured. Mutual disparities between C and C' and between R_i and R_i' can have a marked effect on the rejection factor.

Fig. 19. Connection of a difference amplifier A_v to two points regarded electrically as voltage sources having internal resistance R_b and R_b'. Any difference in these resistances may considerably reduce the rejection factor.

$$H = 2\frac{R_i}{\Delta R_b}. \qquad (19)$$

Here ΔR_b is the absolute value of the difference between R_b and R_b'. Where the amplifier is to be used for a variety of purposes, it must be taken into account that in some cases the internal resistance of one of the voltage sources, e.g. R_b', is zero. In that case ΔR_b is equal to the internal resistance of the other voltage source, and therefore:

$$H = \frac{2R_i}{R_b}. \qquad (20)$$

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When R_b has a specified value, then in order to allow for this unfavourable situation the input resistances of the difference amplifier must be equal, according to (20), to at least:

$$R_i = \tfrac{1}{2} H R_b . \quad \quad (21)$$

If R_b is 1 kΩ and the minimum acceptable rejection factor of the input circuit is 50 000, then according to (21) the input resistances R_i and R_i' must be at least 25 MΩ. A value of this order is nearly always to be found in DC amplifiers, where the grids of the first valves are directly coupled to the input terminals and where no grid leaks are necessary for these valves. In AC amplifiers, where capacitors are connected between the grids and the input terminals and therefore grid leaks must be used, special measures are sometimes needed in order to obtain the high input impedance required.

In practice, cases are frequently encountered where the rejection factor of the input network is governed both by coupling capacitors and by the internal resistance of the voltage sources. Here again, it is a fairly simple matter to calculate the values which the various resistances and capacitances must have in order to be able to guarantee a specific minimum rejection factor.

Multi-stage difference amplifiers

Hitherto we have been concerned solely with single-stage difference amplifiers. We shall now briefly consider various problems that arise in the design of multi-stage amplifiers. In a previous article [5]) it was shown that as a rule the rejection factor of a difference amplifier is primarily governed by that of the first stage. It should be noted that the rejection factor of a multi-stage amplifier can also be influenced by the coupling elements between the stages: asymmetry in these elements may reduce the rejection factor that can be guaranteed for a given circuit. The considerations applicable to the coupling elements between the stages are similar to those mentioned in regard to the circuit elements used for connecting the difference amplifier to the measuring points. Since lower demands are made on the part of the circuit following the first stage, however, the requirements are not so rigorous.

In AC amplifiers the stages are nearly always coupled in the conventional way by means of capacitors and resistors. In this case, then, the above remarks also apply to these circuit elements. In DC amplifiers, where coupling capacitors obviously cannot be used, the grids of the valves in the second stage can be directly connected to the anodes of the valves of the first stage (see *fig. 20*). In order for the second-stage valves to be biased to their normal operating point, their anodes and cathodes must have a higher potential than the corresponding electrodes in the previous stage. The higher supply voltages then needed may be felt as a drawback. To get around this difficulty, voltage dividers can be used for the coupling between the various stages (*fig. 21*), thereby lowering the "voltage level" of the second and successive stages. Of course, this has the effect of reducing the sensitivity of the amplifier. An even greater objection to the use of voltage dividers is that they increase the output resistances of the first stage and lower the input

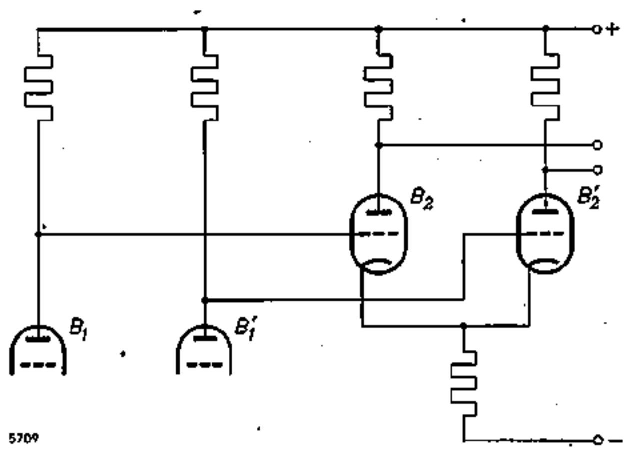

Fig. 20. Difference amplifier for DC voltages with direct interstage coupling.

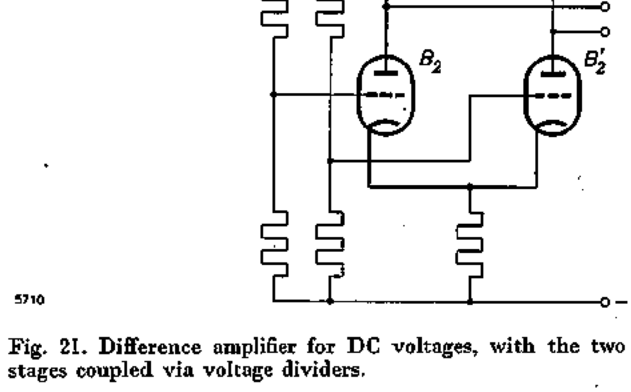

Fig. 21. Difference amplifier for DC voltages, with the two stages coupled via voltage dividers.

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

resistances of the second stage; in connection with the mutual disparity between these resistances, the result is that the guaranteed rejection factor for the coupling network is lower (see eq. (20)). For this reason, in DC difference amplifiers where very high demands are made on $H_{\min}$ the grids of the valves in the second stage are frequently connected directly to the anodes of the valves in the first stage. In the further stages the coupling can be as shown in fig. 21 (see also fig. 26).

Reducing the DC voltage level without any appreciable loss in sensitivity can be achieved with a circuit using elements whose differential resistance is much higher than their DC resistance. A circuit of this type is shown in *fig. 22*. The elements having a very high differential resistance are formed

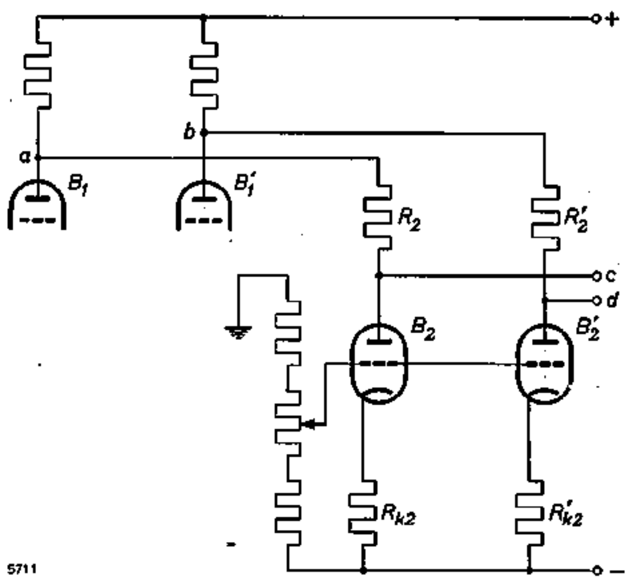

Fig. 22. Circuit in which the DC voltage level of points c and d is lower than that of points a and b, although there is scarcely any attenuation of the signal voltage.

by triodes B_2 and B_2' with resistances R_{k2} and R_{k2}' incorporated in the cathode leads. If the resistances R_2 and R_2' are small compared with these differential resistances, the voltage level of points c and d can be much lower than that of points a and b, although the signal voltages are passed with virtually no attenuation. An arrangement as sketched in fig. 22 can be used with particular advantage where the difference amplifier is required to deliver strong output signals, e.g. for deflecting the beam in a cathode ray tube. In this way it is possible to avoid the difficulties that may arise from the use of a voltage divider built up from normal resistors, owing to the fact that the last stage then has to supply a signal voltage several times higher than the voltage taken from the divider.

Gain control

When a difference amplifier is built up from several stages, gain control will generally be wanted. When choosing the appropriate circuit it should be borne in mind that the gain control too may reduce the rejection factor. For this reason it is usually inadvisable to apply the gain control to the first stage, the rejection factor of which has to meet the highest demands.

A widely used method of gain control — varying the transconductance of the valves by changing the negative grid bias — is not effective here in view of the high differential resistances in the cathode leads.

A severe drawback also attaches to the method represented in *fig. 23*. If it is used in a DC amplifier, its effect is also to alter the operating point of the valves in the next stage. Here too, the guaranteed rejection factor is lowered, owing to the mutual disparity in the voltage-division ratios of the potentiometers.

Fig. 24 indicates an arrangement with which the gain of the difference amplifier can be varied without altering the operating points of the valves. The gain for anti-phase signals is controlled by the variable resistance between the two anodes. This resistance does not, however, affect the gain for in-phase signals, and therefore the discrimination factor F varies in the stage whose gain is controlled. Consequently the rejection factor H of the next stage has to meet higher demands.

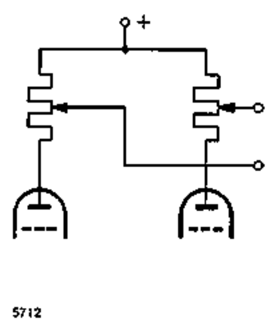

Fig. 23.

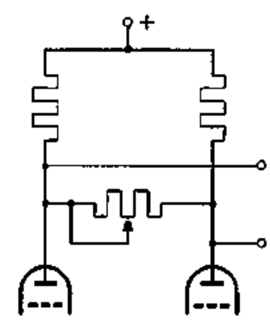

Fig. 24.

Fig. 23. Method of gain control. A discrepancy in the voltage-division ratios of the two potentiometers may result in a lower rejection factor. If this circuit is used in a DC amplifier, the setting of the gain control affects the operating point of the valves in the following stage.

Fig. 24. Method of gain control where the discrimination factor is dependent on the value of the variable resistance.

The same can be said of the circuit sketched in *fig. 25a*, where a variable resistance is inserted between the two cathodes. Here again, the magnitude of this resistance determines the gain for anti-phase signals, but has no influence on the gain for in-phase signals. Increasing the gain therefore again

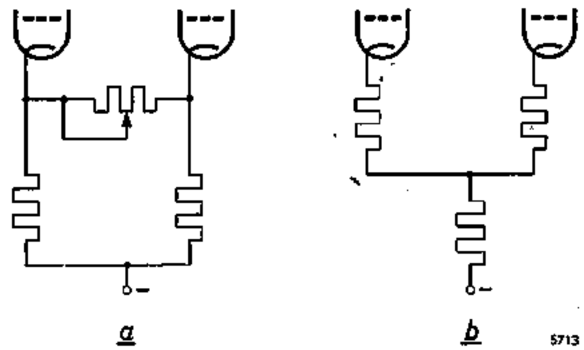

Fig. 25. *a*) Method of gain control, where both the discrimination factor and the rejection factor are dependent on the value of the variable resistance.
b) Equivalent circuit, with the delta resistance network replaced by a star network.

reduces the discrimination factor. Moreover, the variable resistance in this circuit can also influence the rejection factor. This can be seen most readily if we replace the delta network of resistances by an equivalent star network, as in fig. 25*b*. In this arrangement there is negative feedback as a result of the resistances in the cathode leads of the valves. These resistances are roughly equal to half the resistance between the cathodes in fig. 25*a*. The result of this negative feedback is to reduce the effective transconductance of the valves, which again reduces the guaranteed rejection factor. This network too should therefore preferably be applied to one of the last stages of a difference amplifier, where the rejection factor is not so critical.

As a further illustration of the methods of controlling the gain, *fig. 26* shows the circuit diagram of a 3-stage difference amplifier. The second stage contains a 3-step volume control as shown in fig. 24, and the gain of the third stage is controlled on the principle represented in fig. 25. Further particulars of this circuit will be found in the caption to the figure.

Influence of supply voltages; stability

In a sensitive, unbalanced amplifier designed for signals of very low frequency the constancy of the supply voltages, particularly for the first stage, is always an important consideration. A fluctuation in the anode supply voltage, for example, can produce a change in the output voltage from the valves in the first stage which is amplified by the following stages and thus occurs as an interference component in the amplified signal. It is important to note that, for a given sensitivity, the demands made on the constancy of the supply voltages for a difference amplifier need not be as high as in the case of a normal amplifier. This can be understood by considering a difference amplifier in its simplest form, with triodes whose control grids in the quiescent state are at earth potential (see fig. 1). A change in the positive and negative supply voltages by the same amount in the same direction, corresponds to an in-phase signal at the input terminals. This in-phase signal appears at the output terminals attenuated by the rejection factor with respect to the anti-phase signal to be amplified.

If only one of the two supply voltages changes, the effect on the output signal is not so simple to analyse. It can be shown that a change in the *positive* supply voltage of the first stage appears in the output signal as an anti-phase signal which is attenuated with respect to the input signal by a factor

$$\frac{2\mu^2}{\Delta\mu},$$

and that the corresponding factor for a change in the *negative* supply voltage is:

$$\frac{4SR_\mathrm{k}}{\dfrac{\Delta S}{S}+\dfrac{\Delta R_\mathrm{a}}{R_\mathrm{a}}+\dfrac{1}{4}\dfrac{R_\mathrm{a}}{R_\mathrm{k}}\dfrac{\Delta\mu}{\mu^2}}.$$

From equation (5) we see that the sum of the reciprocals of these two factors is equal to $1/H$, which confirms the effect deduced above of a simultaneous change of both supply voltages in the same direction. Since the rejection factor is at least equal to $H_{\min}$, both the above attenuation factors are always greater than the minimum value of the rejection factor.

More complicated circuits also involve auxiliary voltages, which are often derived for simplicity from the positive and negative supply voltages and are therefore affected by changes in the latter (see e.g. figs 10 and 11). It can be shown that the disturbances thus introduced are always a few orders of magnitude smaller than those occurring in an unbalanced amplifier.

As the thermionic emission of a valve depends on the *heater voltage*, and this dependency differs from one valve to another, changes in heater voltage will also appear at the output terminals as an anti-phase signal, obviously of very low frequency. The magnitude of this anti-phase signal depends on the construction of the valves, and its maximum value is therefore dependent on the type of valve used. Experiments with numerous valves have shown that in this respect the type E 80 CC triode gives the best results. It was found that in a difference amplifier fitted with this type of valve a change of

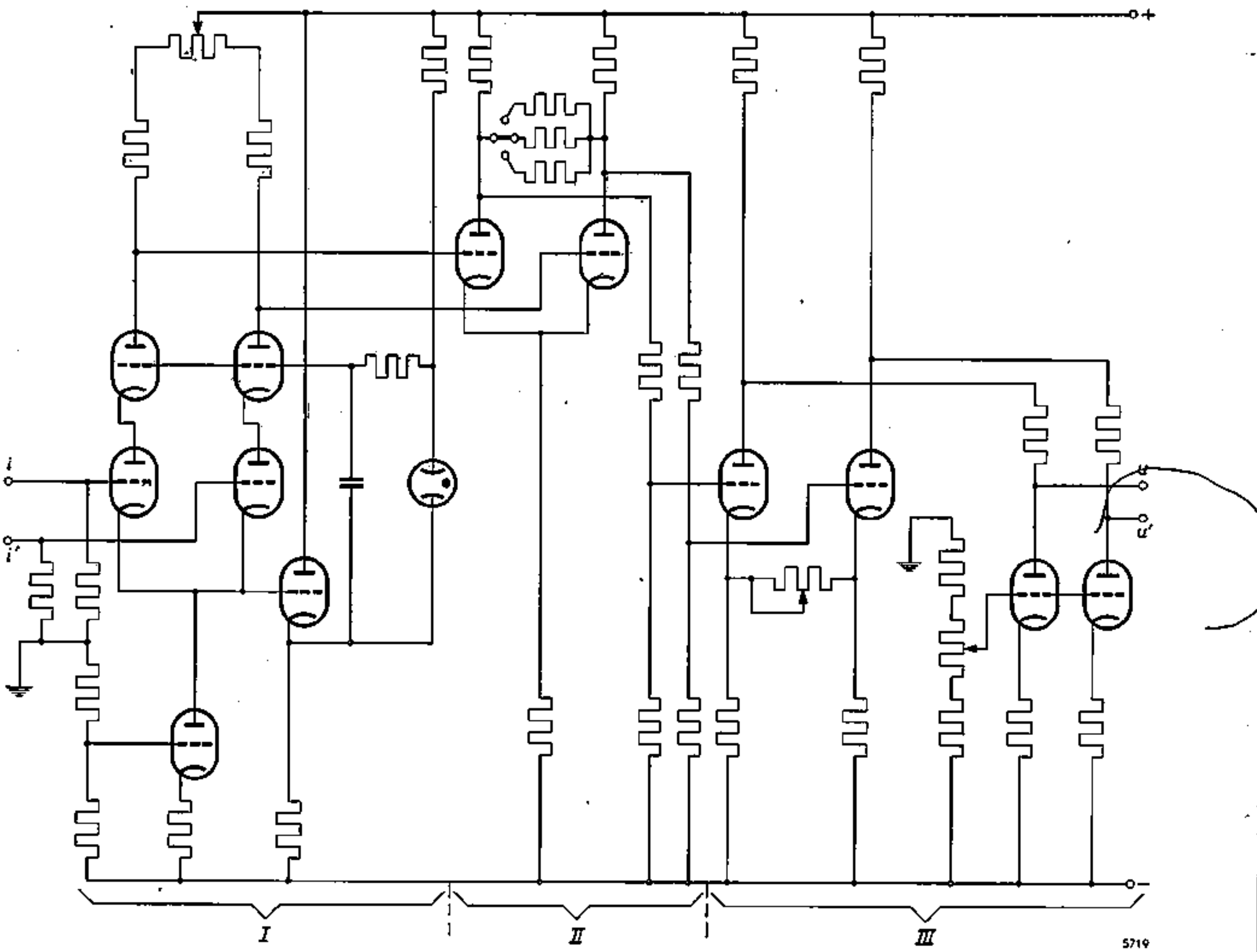

Fig. 26. Circuit diagram of a three-stage difference amplifier. The stages are denoted by *I*, *II* and *III*. Stage *I* is designed as in fig. 14; stages *II* and *III* are simple circuits, each with two amplifying triodes. Stages *I* and *II* are directly coupled (cf. fig. 20); stages *II* and *III* are coupled via voltage dividers to reduce the DC voltage level (fig. 21). Stage *II* uses three-step gain control as in fig. 24; the gain control in *III* is as in fig. 25. The output terminals are given earth potential in the quiescent state by the circuit shown in fig. 22. The different heights at which the valves are drawn correspond to the differences in their DC voltage levels.

10% in the heater voltage caused an interfering anti-phase signal the maximum value of which corresponded to an anti-phase signal of 10 mV at the input. Although this disturbance is small compared with the corresponding disturbance in an unbalanced amplifier (100 to 200 mV), it is still excessive in many cases. For difference amplifiers too, therefore, it may be necessary to ensure that the heater voltage remains reasonably constant, with variations considerably less than 10%.

Another complication frequently encountered with sensitive amplifiers is the occurrence of feedback via the supply circuit, which may even give rise to oscillation. In a *balanced amplifier* there is generally much less feedback of this kind than in an unbalanced amplifier, owing to the fact that the current variations in the output valves are in anti-phase and the supply circuit need therefore deliver hardly any current varying with the signals. A *difference amplifier* is even more favourable in this respect, because, as shown above, a signal voltage returned from the output via the supply circuit to one of the previous stages undergoes very little amplification.

To a considerable extent the advantages mentioned can often be obtained by designing only the *first stage* as a difference amplifier and the remainder as normal amplifying stages. The effect of supply-voltage fluctuations and any tendency to instability can frequently be substantially suppressed in this way. Usually, however, the full advantages of a difference amplifier are only obtained by designing the amplifier with *all* its stages as difference amplifiers. Since the stages following the first stage can usually be fairly simple in circuitry, an entirely balanced amplifier may even in fact be simpler than an amplifier which is partly unbalanced.

The above-mentioned advantages of a difference amplifier enable such an amplifier to be used in cases where it is not a question of amplifying the voltage difference between two arbitrary points, but the potential of one point to earth. One of the two input terminals is then earthed (*fig. 27*) and the difference amplifier is used as a "normal" amplifier. The output voltage may be taken either in push-pull from the output terminals or between one of these terminals and earth, as desired.

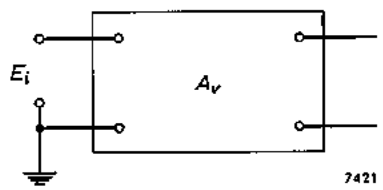

Fig. 27. Difference amplifier used as an unbalanced amplifier.

Negative feedback

It is easily seen that the discrimination factor of a difference amplifier is lowered if a simple form of negative feedback is introduced, the in-phase and anti-phase signals being returned in the same ratio from the output terminals to the input. Since the in-phase signals undergo much less amplification, the feedback also reduces the gain for these signals much less than for the anti-phase signals. In a difference-amplifier with negative feedback, then, the feedback ratio for in-phase signals should be much larger than for antiphase signals. Because of the interaction of in-phase and anti-phase signals, it is not so easy to see what effect the feedback has on the rejection factor. For this reason we shall not be concerned in this article with the problems arising from the use of feedback in a difference amplifier.

Quite another matter is the fact that a difference amplifier can be used as a means of producing highly effective negative feedback in an unbalanced amplifier. In this procedure a signal voltage derived from the output is returned in the usual way to the input stage of the amplifier, the aim being to amplify the difference between the input signal and the feedback signal. In a commonly used circuit the latter signal is applied to the cathode of the first valve, which then in fact functions as a difference amplifier. After what has been said it will be clear that the rejection factor of such a "difference amplifier" will as a rule be very small. Although the object of the feedback, i.e. to reduce distortion and minimize the extent to which the parameters of valves and other components influence the gain, may be satisfactorily achieved, better results are possible if a good difference amplifier is used as the first stage (see *fig. 28*). The feedback is then more effective, because the input signal and the feedback

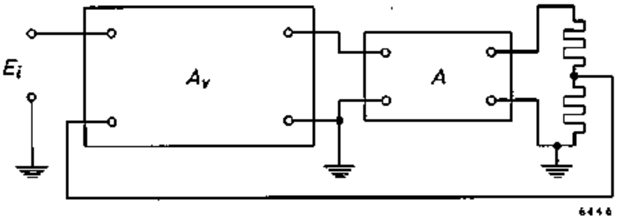

Fig. 28. Difference amplifier used as the first stage in a feedback amplifier.

signal contribute almost equally to the output signal. This also offers advantages in circuitry, since there is hardly any load on the feedback network and because the feedback signal can be applied to the first stage at earth potential.

The use of difference amplifiers with large anti-phase signals

Where high voltages are to be measured or otherwise investigated, the use of a high-gain amplifier is seldom considered. Nevertheless a sensitive difference amplifier offers advantages here that are not so easily obtained by other means. To make this clear, we should first of all point out that in the above theory on the operation of a difference amplifier we assumed that the anti-phase signal on the grids is small enough to allow a reasonable current to flow in both valves, this signal then being amplified as in a conventional balanced amplifier. There is no amplification, however, if the anti-phase signal exceeds the above-mentioned limit, for in that case the anode current in one of the valves is cut off, with the result that the other valve functions as an unbalanced amplifier with a very high cathode impedance. The gain of this valve is then extremely low. It may further be said that a difference amplifier gives amplification only when the difference in potential between the two input terminals does not exceed a specific value. As soon as this potential difference exceeds that value the difference amplifier is "overdriven". This does not mean, however, that the valves are overloaded. If the input signal of a multi-stage amplifier is progressively increased, it will generally be the valves in the last stage that are "overdriven" first, since it is here that the signals are strongest. If the gain for anti-phase signals is high, only a small potential difference between the input terminals is sufficient to overdrive the last stage. The amplifier may be so designed, for example, that amplification occurs only if the potential difference between the input terminals amounts to no more than a few millivolts, and if necessary even less.

This property of a difference amplifier can occasionally be turned to good use, particularly for the purpose of very accurately comparing two differently time-dependent signals at the moments when they are almost identical. Suppose, for example, that the one input voltage, E_i, is a DC signal and the other, E_i', a large AC signal (see *fig. 29*),

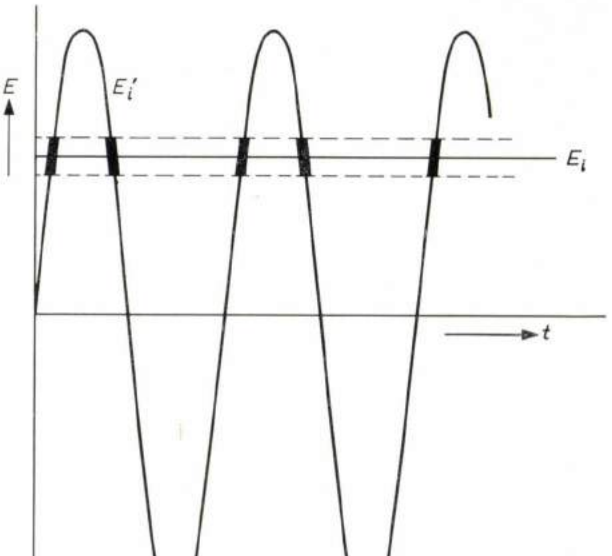

Fig. 29. Amplitude-versus-time plot of the voltages E_i and E_i' on the input terminals of a difference amplifier when the latter is used in combination with an oscilloscope as an "electronic voltage microscope". Only the thickly outlined portions of E_i' are displayed on the oscilloscope.

then the latter signal will only be amplified at the moments at which its instantaneous value differs only very slightly from the magnitude of the DC signal. By connecting the output of the difference amplifier to an oscilloscope, very small portions of the waveform of the alternating voltage can then be displayed distinct from the remainder of the wave form. The portions concerned are drawn thick in fig. 29. The combination of a difference amplifier and oscilloscope in this way may be described as an "electronic voltage microscope". Using a high-gain difference amplifier, it is thus possible to display a detail of a few millivolts of a waveform whose amplitude is ten or more volts. If E_i is made roughly equal to the peak value of E_i', the "voltage microscope" displays only the peaks of the AC signal (*fig. 30*). This constitutes a highly accurate method of checking the constancy of the signal amplitude. *Fig. 31* shows an example of such an

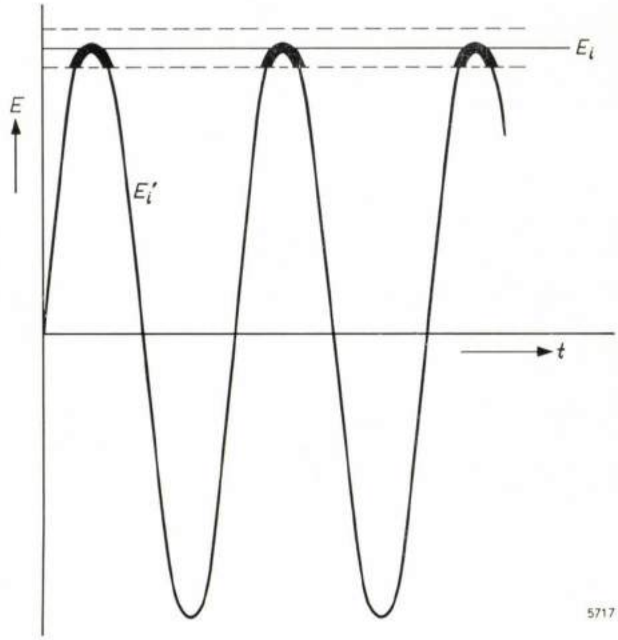

Fig. 30. When the DC voltage E_i is made roughly equal to the amplitude of E_i', only the peaks of E_i' appear on the oscilloscope.

oscillogram, obtained by applying to one input terminal of the difference amplifier an alternating voltage of 10 V amplitude and 80 c/s frequency, and to the other a DC voltage of 10 V. The height of a square in the figure corresponds to 2 mV. It can be seen that amplitude variations of roughly 4 mV occur, i.e. 0.04%. *Fig. 32* shows the top portion of a 10 V square-wave voltage. We see here that the tops are not perfectly flat but show variations in amplitude of about 2 mV, i.e. 0.02%.

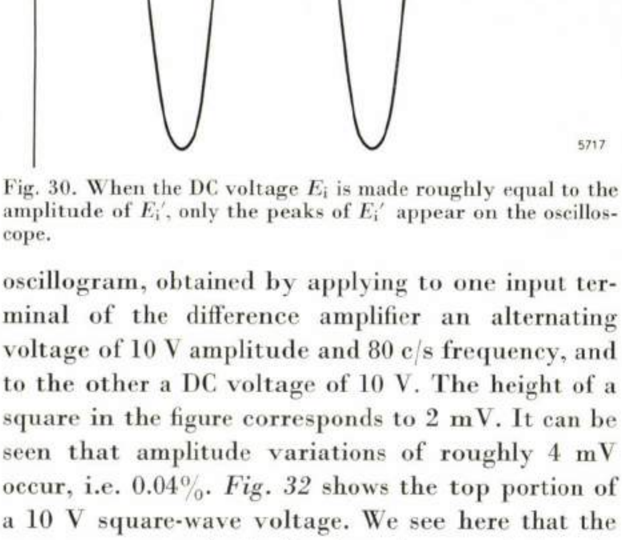

Fig. 31. Oscillogram obtained with a "voltage microscope" used to investigate an AC signal of amplitude 10 V. Only the peaks are displayed. The height of each square on the screen corresponds to 2 mV, so that in order to display the whole waveform the paper would have to be 35 m in height! Very small variations in amplitude can be demonstrated in this manner.

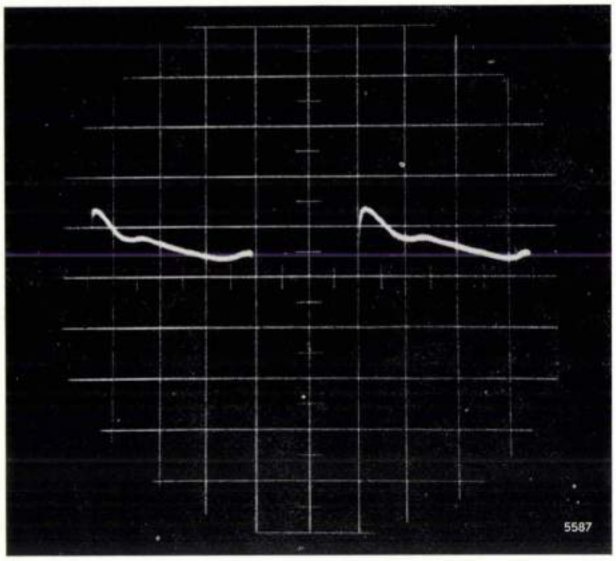

Fig. 32. Top of a 10-V square-wave voltage. One square corresponds in height to 2 mV. The tops are not flat but show variations in amplitude of roughly 2 mV.

Since a DC voltage can as a rule be measured directly with greater precision than an AC voltage (e.g. using a compensator), a difference amplifier also makes it possible to determine the amplitude of an AC signal in a very accurate but simple manner. The procedure is simply to make E_i equal to the amplitude of the AC signal to be measured, E_i', as illustrated in figs 30 and 31, and to measure E_i.

To conclude, we shall describe another application of a difference amplifier where a high DC voltage E_i is applied to one input terminal and a periodically varying voltage E_i' is applied to the other. In fig. 29 the waveform of E_i' is sinusoidal, but we shall now assume that E_i' is a different periodic function of time. As an example, it is assumed in *fig. 33* that E_i' decays exponentially in each cycle:

$$E_i' = E_{i0}' \, e^{-\frac{t}{T_0}}, \quad \ldots \ldots \quad (22)$$

where T_0 is a constant.

Anode current now flows in both valves of the last stage only as long as the signal voltage on the grid of the relevant valve is greater than that on the grid of the other valve. During these times the anode currents are practically constant; the output signal E_o of the difference amplifier thus has a square-wave form, as shown in fig. 33 below. A simple calculation shows that the mean value E_{om} of E_o is a logarithmic function of E_i:

$$E_{om} = \frac{E_1}{T}(2T_0 \ln E_{i0}' - 2T_0 \ln E_i - T) \quad \ldots \quad (23)$$

(E_1 and T are explained in fig. 33). The value E_{om}, measured with an integrating circuit, is a measure of E_i on a logarithmic scale, and the whole arrangement thus constitutes a *logarithmic voltmeter*.

If E_i' is a periodic exponentional function of time, we thus obtain an output signal whose mean value is the *inverse* (logarithmic) function of E_i. It is not difficult to see that, even if E_i' is some other periodic function of time, this method still produces an output signal which is the inverse function of E_i. This can be turned to use in various ways [6]).

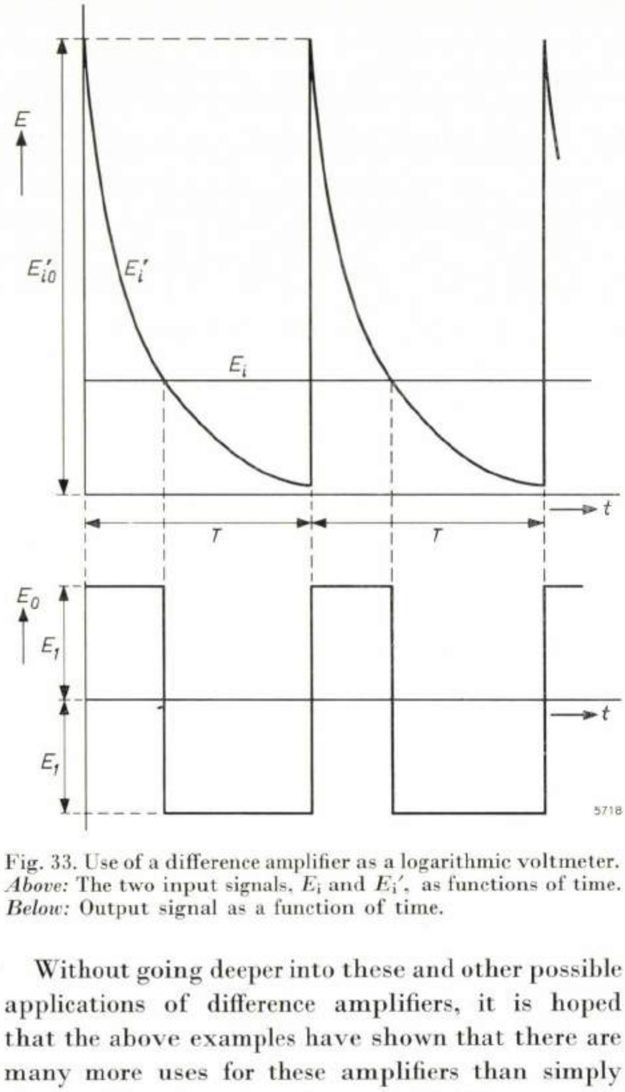

Fig. 33. Use of a difference amplifier as a logarithmic voltmeter. *Above:* The two input signals, E_i and E_i', as functions of time. *Below:* Output signal as a function of time.

Without going deeper into these and other possible applications of difference amplifiers, it is hoped that the above examples have shown that there are many more uses for these amplifiers than simply the amplification of small potential differences.

[6]) See G. Klein and J. M. den Hertog, A sine-wave generator with periods of hours, Electronic Engng. **31**, 320-325, 1959.

Summary. The minimum value of the rejection factor of a difference amplifier is affected by the elements coupling the amplifier to the points between which the potential is to be measured. In a multi-stage amplifier, the coupling elements between the stages also have an important influence. An incidental advantage of a difference amplifier compared with normal types is that less rigorous demands are made on the constancy of the supply voltage; a difference amplifier also shows much less tendency to oscillate. Further applications for difference amplifiers are discussed, in particular as a means of introducing highly effective feedback in an unbalanced amplifier, as an "electronic voltage microscope" and as a logarithmic voltmeter.

INSPECTION OF NEGATIVES FOR PRINTED CIRCUITS

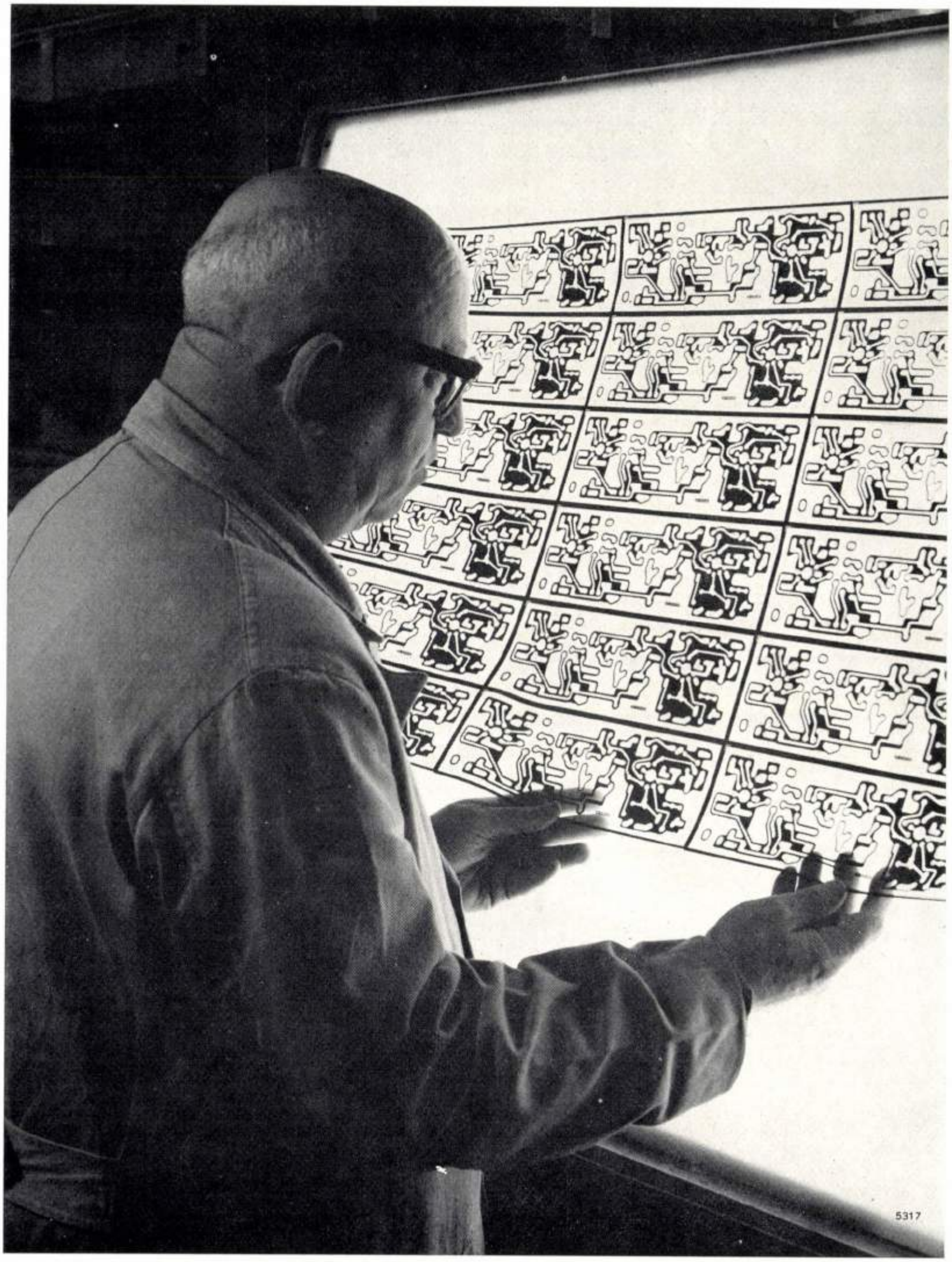

Photo Maurice Broomfield

Inspection of a master negative used in the manufacture of printed circuits by the photographic etched-foil process. Prints of this negative are made on a copper-plated panel of laminated board coated with photographic emulsion. The unexposed parts of the copper foil are removed by etching. This method lends itself particularly well to the reproduction of fine detail. Since the slightest fault is reproduced in the finished product, the negatives are subjected to careful scrutiny all the time they are in use.