D.C. Amplifiers

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A CERTAIN ambiguity must be cleared up at the start: this concerns the initials d.c. as used in the title and elsewhere throughout this article. These letters can mean one of two things: *direct current* amplifiers, or *directly-coupled* amplifiers. The former meaning refers to circuits which are intended primarily for amplifying steady voltages, that is devices with input and output terminals where a steady voltage of 1 volt across the input produces, say, 10 volts across the output, 2 volts in gives 20 volts out, 3 volts in gives 30 volts out, and so on. Such a device has a value of gain (10 in this case) which is entirely analogous to the gain of any a.c. amplifier.

The second meaning, directly-coupled amplifiers, refers to the electronic configuration of the circuit instead of its purpose. A directly-coupled amplifier has no coupling capacitors or transformers between the stages, but instead, the anode of one valve is connected to the grid of the next either directly, or via a network containing only resistance and/or inductance.

These two names are not inter-changeable. Many direct current amplifiers *are* directly coupled, but there are other types that are not. Directly-coupled amplifiers certainly will amplify direct current but they can also be used for a.c. signals. This article is concerned with direct current amplifiers of the directly-coupled type, but a few brief comments on other forms of direct current amplification will be given at the end.

A SIMPLE DIRECT CURRENT AMPLIFIER

The simplest possible direct current amplifier (hereafter called d.c. amplifier) is shown in Fig. 1a. When no signal is applied to the input a certain amount of anode current flows in the valve thus developing a fixed voltage across the anode load R_a. If a fixed negative voltage is applied to the valve grid the anode current decreases and the voltage across R_a falls. By connecting a voltmeter across R_a this system could be calibrated by applying known input voltages to the grid and drawing a graph of these input voltages against the rise in anode voltage. The circuit could then be used as a voltmeter, unknown input signals being found by noting the rise in anode voltage and reading off from the graph the input voltage required for such a rise.

A circuit such as this would certainly work, and by using high resistances in the grid circuit (R_g in Fig. 1a) an electronic voltmeter of extremely high input resistance is produced. However there are several undesirable features about such a simple arrangement. For example in one way it "works backwards" in the sense that increasing the input actually decreases the output voltage: although this is of no consequence electrically, it is aesthetically displeasing.

More important from the electrical point of view is the mere presence of the no-input voltage in the output. A more satisfactory arrangement is one where no input signal gives no output, a voltage appearing across the output only when something is applied to the input. This may be accomplished by using a bridge network as in Fig. 1b. In this case the steady d.c. across the anode load is balanced by an equal voltage taken from the appropriate point on a bleeder circuit across the h.t. supply. In the absence of any input on the grid, a voltmeter is connected across the output terminals and adjusted to read zero by the Set-Zero control. Any voltage now applied to the grid will cause a reading on the meter by changing the anode voltage and unbalancing the bridge. Many valve voltmeters work on this or a similar principle.

This example of a valve voltmeter was discussed in some detail as it illustrates the whole point of a d.c. amplifier. A small voltage applied to the input produces a larger voltage across the output, altering the input causes the output to change in direct proportion.

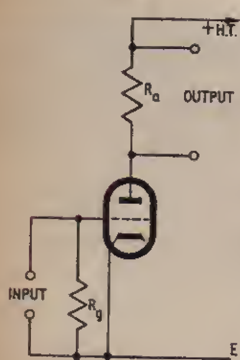


Fig. 1a. The simplest form of direct current amplifier. The output is negative "going"

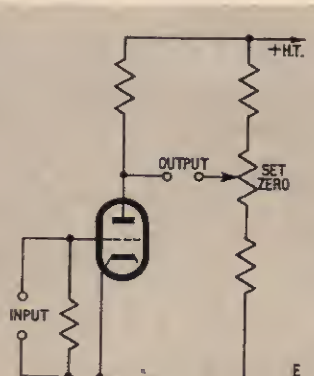


Fig. 1b. Bridge circuit. An input signal produces a "positive" output

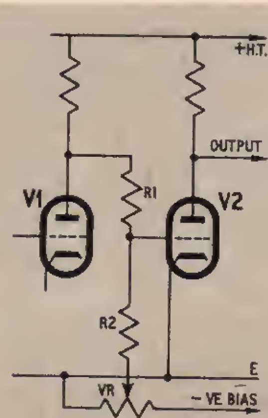


Fig. 2. Large negative bias voltage on V2 grid

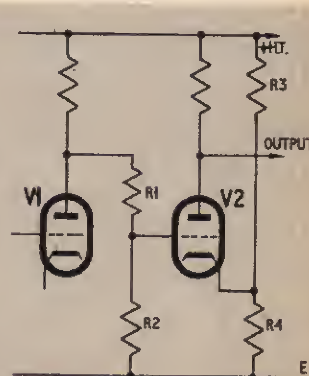


Fig. 3. An alternative arrangement (to Fig. 2) is to return the cathode of V2 to a point above earth

In Fig. 1 only negative input signals can be satisfactorily amplified, a positive input would cause grid current to flow and although amplification would still occur, the input/output characteristic would be unlinear. To make possible amplification and measurement of positive or negative inputs the grid must be biased negative with respect to the cathode. The various ways of doing this will be discussed in some detail shortly.

MULTI-STAGE AMPLIFIERS

So far we have considered only one-valve circuits used as voltmeters. There are many applications where the voltage gain provided by one valve is insufficient, this being partly due to the comparatively low gain of each stage. It is then necessary to build multi-stage amplifiers and a number of new problems arises. In conventional amplifiers of a.c., especially those dealing with audio frequencies, multi-stage amplifiers are fairly simple, the coupling between consecutive valves being accomplished by resistance and capacitance. The capacitor connected between the anode of one valve and the following grid will pass the a.c. signals with little attenuation, but prevents the high d.c. potential on the anode from being transferred to the grid of the next valve.

When amplifying d.c. it is impossible to use coupling capacitors between stages since obviously these would not pass a d.c. signal. It is here that directly-coupled amplifiers are useful since they do not use capacitors to transfer the signal from one stage to the next. The anode of one valve is connected to the grid of the next and the great difficulty arising as a result of this is preventing the high voltage on the anode from reaching the grid of the following valve, which must be negative.

One way of doing this is given in Fig. 2. Here a negative bias is used of approximately the same voltage, but opposite polarity, as the h.t. supply. In the absence of any input to the amplifier the potentiometer VR is adjusted so that the grid of V2 is a few volts negative with respect to the cathode. As the anode of V1 rises and falls in potential so the grid of V2 also rises and falls in sympathy; however, while the anode swings, say, 200 $\pm$ 10 volts, the grid of V2 swings $\pm$ 5 volts around a steady negative voltage of, for example, 10 volts.

This is then one way of directly coupling the stages in an amplifier which overcomes the problem of the potential difference between the anode and grid. However it does so at a price, and this price is the attenuation of the signal. In the example given the negative bias is about equal to the h.t. voltage and for V2 grid to be 10 volts negative the slider of VR must be slightly more negative than the anode of V1 is positive.

Under these conditions the coupling resistors R1 and R2 will be equal and the signal appearing at V2 grid will be half that at V1 anode. If the bias is made twice as negative as the h.t. is positive, then for the same bias on V2 grid $R2 = 2R1$; so only a third of the signal is lost in transfer. This idea can be taken further of course but is limited by the practical difficulties in obtaining a very high negative bias, and by the fact that the setting of VR becomes more critical as the bias is increased.

If making the grid negative is impractical then the converse can be tried, that is making the cathode positive. This is done simply by returning the cathode to h.t. as well as to earth as in Fig. 3. The value of R3 will be several times that of R4 and it is usually only practical to run the cathode at up to one-eighth of the h.t. voltage. Beyond this point the effective h.t. supply to the valve becomes so reduced that distortion, in the form of non-linear input/output response, begins to appear. Since the anode of V1 will almost certainly be at least half the h.t. voltage or higher, it is necessary to make R1 several times the value of R2 in order to drop V2 grid to below the potential of the cathode. This attenuates the signal to such an extent that the voltage gain between V1 anode and V2 anode is a mere 2–4 times.

A modification of Fig. 3 uses a double triode with one half acting as signal amplifier while the other half passes a heavy current to keep the common cathode potential high. This circuit is given in Fig. 4 and there is little to say about it as the general characteristics are those of Fig. 3.

Although the "positive cathode" stage as in Fig. 3 is of little use in the later stages of an amplifier, it can be very useful in the input stage. Here the input on the grid must be kept down to plus or minus a few volts, and returning the cathode to h.t. so as to maintain it a few volts positive provides an efficient high impedance input stage. Fig. 5 is the circuit of a working d.c. amplifier with a voltage gain of about 75. Used to drive a 6in cathode ray tube, this gave a spot deflection sensitivity of $\frac{1}{2}$ volt/cm, or about $\pm$ 4 volts to move the spot from top to bottom of the screen.

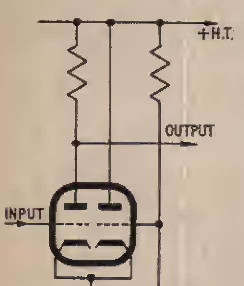
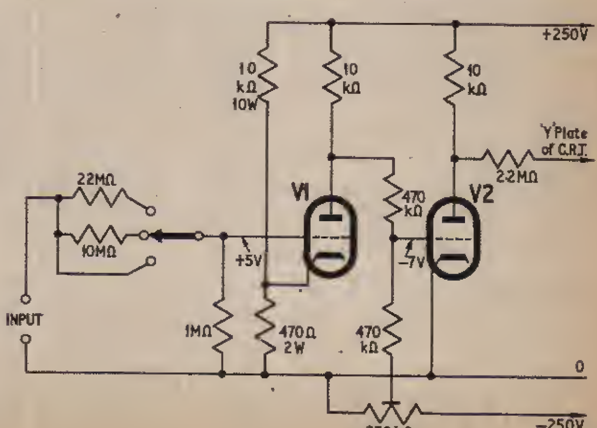


Fig. 4 (left). This is a development from Fig. 3. A double triode is used, one half as a signal amplifier, while the other passes heavy current to maintain the common cathode at a high potential

Fig. 5 (right). A practical two stage d.c. amplifier. The voltage gain is about 75



SEPARATE POWER SUPPLIES

If cost is no problem in building a d.c. amplifier, then several simple stages may be put in series using an independent power supply for each stage. Such an amplifier is shown in Fig. 6. With careful design this arrangement can be made very effective and efficient as there are no coupling resistors to attenuate the signal, also each grid except the first automatically receives the required negative bias due to the standing current in each anode load. The most obvious difficulty with this "stepped" system is the necessity of providing separate power supplies for each stage. Each individual supply is small but the cost of building one for each stage tends to mount up over a multi-stage system.

It is possible to use a single power supply and incorporate a series of potential dividers to give several series-connected supplies, each being of a much lower potential than the original. This is a wasteful method as a lot of power is dissipated as heat in the potential dividers and also interaction between stages with effectively a common power supply can produce unwanted feedback with resultant complications.

GAIN CONTROL PROBLEMS

Unless the amplifier is required for one specific purpose only, it is customary to incorporate a gain control somewhere in the circuit. In conventional a.c. amplifiers a gain control can be incorporated almost anywhere in the circuit but unfortunately this is not the case with d.c. amplification. Suppose that the resistors R1 and R2 in Fig. 2 and Fig. 3 were replaced by a potentiometer track and the slider connected to V2 grid; altering the setting of this potentiometer would vary the amplification by, in effect, varying the ratio of R1 and R2. However, it would also alter the bias point of V2 which must be kept constant in order to prevent the grid from either going positive (R1 too small) or going too negative and cutting off the valve (R1 too large).

An alternative method of gain control in a.c. amplifiers is to have one stage as a cathode follower, using the track of the potentiometer as the cathode resistor, and tapping off the required amount of signal on the slider. This method too is of no direct use in d.c. amplifiers for the same reason as before, i.e. altering the setting of the control would still alter the bias point of the next stage.

Up to a point these problems can be solved by using a ganged potentiometer, one half acting as in an a.c. circuit while the other half somehow cancels out the changing bias. Fig. 7 is a simple way of using a cathode follower as part of the gain control in a d.c. circuit: VR1b selects a negative bias which cancels out the effect of voltage across VR1a. The output is at a constant potential unless some input is applied to the valve grid.

A better solution is to have all the required gain controls connected between the amplifier input terminals and the first valve grid. As explained before, and shown in Fig. 5, the input stage of a d.c. amplifier usually uses a "positive cathode" arrangement rather than biasing the grid negative.

LIMITATIONS DUE TO "DRIFT"

Any audio amplifier has a certain minimum signal which it can amplify; below this level the noise inherent in the circuit makes amplification useless. The lower limit of input for a d.c. amplifier is set by the stability of the circuit, and this in turn is dependent on temperature changes in components, slow changes in component values with age, and variations in the supply voltages. The slow variations in these factors produce a slow change in the supposedly fixed amplification of the circuit, this manifests itself in, for example, frequent re-adjustment of the Set Zero control.

Such slow changes are known as drift and are usually more marked in d.c. than a.c. amplifiers. Drift is clearly undesirable and can be minimised by such methods as using high wattage, close tolerance resistors, using a stabilised power supply, and having a well ventilated chassis to keep down temperature changes. A small drift in any d.c. potential in the input stages will be amplified by later stages as a signal, so every effort is needed to ensure a very stable input stage.

Despite all precautions there is always drift to a certain extent and this places a definite upper limit to the complexity of a d.c. amplifier. Using directly-coupled stages of the types described so far, it is very difficult to use more than three stages of amplification; beyond this limit even a few millivolts of drift in the first stage are amplified to the extent of overloading the final stage. Even with three directly-coupled stages the bias and/or h.t. may need to be stabilised to ensure drift-free operation.

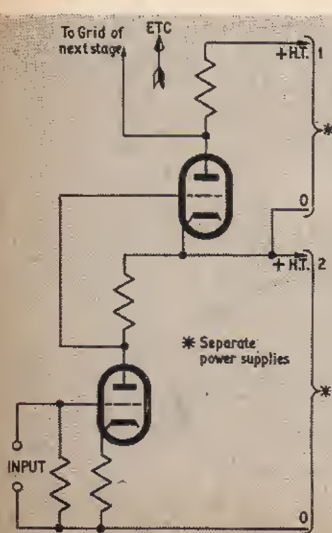


Fig. 6 (left). A "stepped" amplifier system using several stages in series

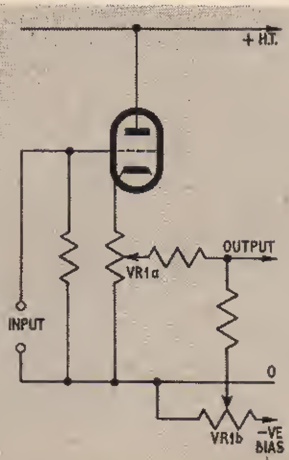


Fig. 7. Cathode follower as part of gain control

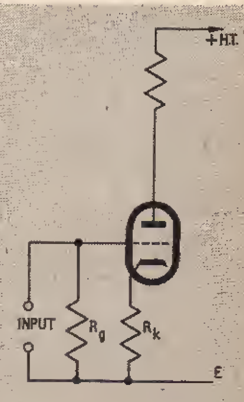


Fig. 8. Absence of decoupling capacitor across R_k causes negative feedback

OUTPUT ARRANGEMENTS

The type of output stage employed depends on the purpose for which the d.c. amplifier is intended to fulfil. The output signal appears as a variation in the anode voltage of the output stage valve. If this is to run a cathode ray tube in an oscilloscope the anode can usually be coupled direct to one of the Y plates; if the amplifier is acting as a voltmeter then the output is better taken from between the anode and a backing-off network as in Fig. 1b.

Sometimes the circuit has to be arranged so that the output terminal is at earth potential when no signal is applied and varies above and below earth with positive and negative inputs to the amplifier. In this case it is necessary to use an output similar to the coupling method of Fig. 2, the output coming from the junction of R1 and R2 and being set to zero in the absence of any input by VR. The chief snag about this kind of output is its extremely high output resistance, this being several megohms in some cases.

NEGATIVE FEEDBACK

We have already said that the voltage gain of d.c. amplifiers of the types discussed here is not very high, a net gain of 5–10 times being fairly average. This is due partly to the loss across the coupling resistors, but it is aggravated by the inevitable addition of negative current feedback. This problem can now be considered in some detail.

One of the unusual features of d.c. amplifiers is the virtual absence of capacitors anywhere in the circuit. In most audio equipment cathode resistors are by-passed by capacitors of various values, but this is not so in the amplifiers mentioned here so far. Suppose we consider just what happens to a signal when amplified by a valve not having a cathode by-pass capacitor. This will show just where the signal is lost.

In Fig. 8, suppose that the grid is made more negative with respect to the chassis, then the valve passes less current so the voltage across R_k falls. This drop in voltage across R_k means that the grid-to-cathode voltage change is less than the input voltage change between grid and earth because some of the input has been cancelled out by the change in potential of the cathode. In the case of an a.c. amplifier the cathode capacitor keeps the voltage across R_k almost constant, so the grid-to-cathode swing is almost the same as the input grid-to-chassis swing. It is these two drawbacks, the loss across coupling resistors and the inevitable negative feedback which reduce the gain of this type of d.c. amplifier to low values. Obviously capacitors across the cathode resistors will have no effect on d.c. signals.[1]

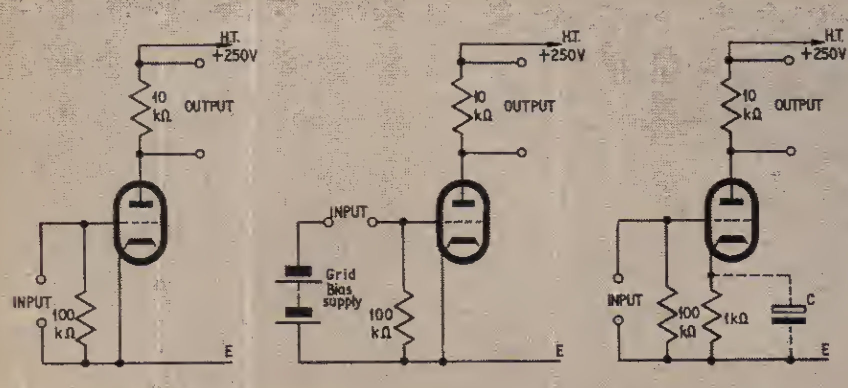
DETERMINING THE LOSS OF GAIN

It would be interesting to discover how much each of these factors affects the gain. The loss due to the coupling resistors can be found from simple potential divider theory; to find the effect of negative feedback the following set of experiments was performed.

First, using the circuit of Fig. 9a the voltage gain was measured for d.c. signals driving the grid negative, this gain was measured as the change in voltage across the anode load divided by the change in grid voltage which caused this. In this circuit, where there is no cathode resistor and hence no feedback, the voltage gain was almost exactly 10. Next, a battery was inserted in the grid circuit biasing the grid 6 volts negative (the effective internal resistance of the battery was only a few ohms). The voltage gain of this arrangement, shown in Fig. 9b, was measured by the same technique using positive and negative inputs but taking care not to run the grid positive. There was still no feedback due to a cathode resistor, but some feedback did occur as a result of the internal resistance of the battery. The voltage gain now dropped slightly, to 9·7.

At this stage a 1 kilohm resistor was inserted in the cathode circuit as in Fig. 9c. Initially this was unbypassed and the voltage gain for d.c. was measured and found to be 4·8. Using a 50c/s a.c. signal from the valve heater circuit the a.c. gain at this frequency was also measured; it turned out to be 5·0. Then a 16μF electrolytic capacitor was connected across the cathode resistor and both a.c. and d.c. gain re-measured. The a.c. gain was now 10, but the d.c. gain was unaffected though there was now a noticeable time needed for the circuit to settle down after the d.c. was applied; that is, when the d.c. was applied to the grid the anode rose slowly to its new value instead of rising sharply as it did when C was absent.

The results of these experiments can be summarised as follows: In the absence of negative current feedback



(a) No feedback, voltage gain 10 *(b) Some feedback due to internal R of battery* *(c) With cathode resistor. Add C to increase gain*

Fig. 9. Circuits used to determine the effect of negative feedback

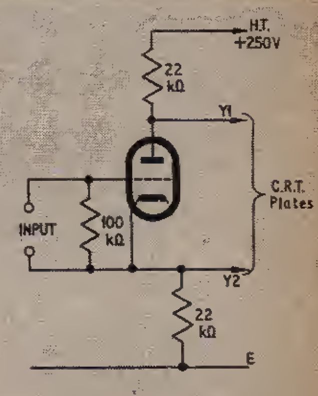


Fig. 10. Simple phase splitter for d.c. operation

the (negative-going) d.c. gain was 10, this value representing the maximum gain attainable using this particular set of component values. The addition of an un-bypassed cathode resistor introduced a degree of negative current feedback which reduced both a.c. and d.c. gain to about half their original values. By-passing the cathode resistor with a large-value capacitor restored the a.c. gain to its former value but had no effect on the absolute d.c. gain, though it introduced a delaying factor in the amplifier.

All this gives a somewhat paradoxical result as far as the design of d.c. amplifiers is concerned. If a cathode resistor is inserted in the amplifier stage this provides some bias for the grid but reduces the gain of the stage by negative feedback. The cathode resistor can be omitted by returning the grid to a negative bias supply but this automatically causes attenuation of the signal across the coupling resistor. Directly-coupled amplifiers of this type of circuit are therefore of necessity something of a compromise between several evils.

A note at this point on the measuring of the 50c/s gain of the amplifier as in Fig. 9c. As in the d.c. experiments, the gain is measured as output signal voltage across anode load divided by input signal voltage between grid and chassis. The input voltage can be found easily with an ordinary a.c. voltmeter but measurement of the output a.c. is complicated by the standing d.c. across the anode load. To measure the output an a.c. voltmeter in series with a large-value capacitor is connected across the anode load—the capacitor blocks the d.c. allowing only the wanted a.c. to reach the meter. To be strictly accurate the a.c. voltage drop across the capacitor should be taken into account, and this can easily be found from the equation giving the impedance of a capacitor at a given frequency.

A.C. PERFORMANCE

The question might well be asked—to what extent do the d.c. amplifiers described here amplify a.c.? The quick answer to this is—not very much. In designing simple apparatus to deal with d.c. only, no attempt is made to eliminate or neutralise stray inductance and capacitance, so for frequencies from a few hundred cycles per second upwards there is a steady falling off of the a.c. response. This does not mean that it is impossible to build a circuit which will amplify a.c. as well as d.c. Modern oscilloscopes sometimes incorporate amplifiers which have a response from d.c. to 50Mc/s or more, but these work on principles rather more complex than those described here. It is of course very useful to extend the response as far as possible up the frequency scale in order to avoid rounding off sharp pulses which include very rapid potential changes.

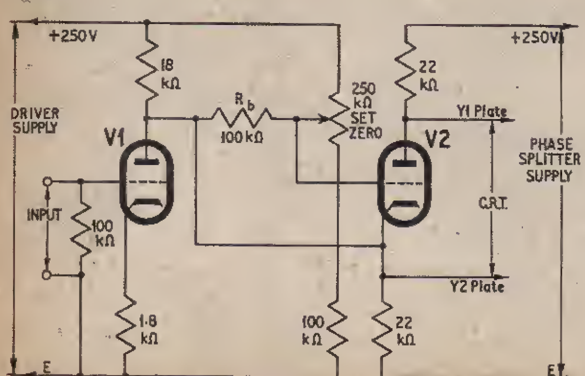
D.C. PHASE SPLITTER

Before concluding this article it would be interesting to consider a few variations on the ideas so far given.

In order to drive a cathode ray tube to give optimum results it is usual to employ push-pull deflection of the plates and to do this some form of phase splitter is required, analogous to that used in an audio amplifier to drive a push-pull output stage. A simple d.c. phase splitter is shown in Fig. 10 and is similar to the a.c. circuit called the split-load phase splitter. With the grid connected to the cathode, about 100 volts is present across each 22 kilohm resistor, and when the grid is 10 volts negative with respect to the cathode this falls from 100 to 25 volts per resistor. The difference, from 200 volts down to 50 volts, is enough to drive most oscilloscope tubes.

The real problem with this type of circuit is finding a suitable driver stage to work it. The most obvious solution is to connect the anode of the driver direct to the grid of the phase splitter, via a potential divider to adjust the voltages if necessary. Such a circuit in practice loses so much signal due to negative feedback in the very large cathode resistor that the gain is barely above unity. Whatever the voltage swing between earth and anode of driver, the swing between grid and cathode of the phase splitter is only a fraction of this and the output voltage changes across both 22 kilohm resistors is quite inadequate for driving anything but the most sensitive cathode ray tubes. After a great deal of trouble the only satisfactory way of driving the phase splitter was found to be the use of a bridge network in the anode of the driver which was run from an independent power supply.

Fig. 11. A bridge network is used here to drive the phase splitter



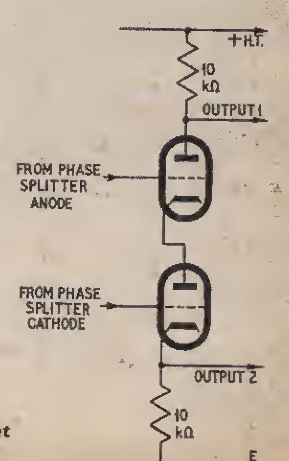


Fig 12. Cascode arrangement following the phase splitter

The bridge circuit action, as described at the beginning of this article and shown in Fig. 1b, gives no voltage across the output unless there is an input applied to the valve. When using the bridge network to drive the phase splitter as in Fig. 11, the Set Zero control is adjusted so that there is no voltage across the 100 kilohm bridge load resistor (R_b in Fig. 11) when V1 grid is a few volts negative of its cathode, and signals of either polarity can then be accepted. V1 in Fig. 11 can be preceeded by any type of d.c. amplifier, but this must be run from the same power supply as V1 itself. V2 must have its own separate supply.

Of course we are really doing things in a somewhat absurd fashion here, using a form of phase-splitter as the output section; in conventional audio equipment the phase splitter only has the job of supplying power to, usually, a symmetrical push-pull output stage. The reply to this is that there is nothing simple in d.c. circuitry which is analogous to an a.c. push-pull output stage. The following arrangements have been attempted, all based on a form of cascode arrangement.

CASCODE ARRANGEMENTS

Fig. 12 applies the outputs from the phase splitter to the two halves of a twin triode in cascode, again taking the outputs from one cathode and one anode.

Another idea was to use two such cascodes and strap both grids together. The output from the cathode of the phase splitter went to the grids of one such cascode pair which had no cathode resistor but retained the anode load and took the output from the "top" anode. The anode output from the phase splitter went to both grids of the other cascode pair, this had no anode load but retained the cathode load at the bottom and took the output from this.

Both these ideas worked in the sense that they provided some output when a signal was applied to the phase splitter. Unfortunately both were non-linear and one acted as an attenuator instead of an amplifier!

CHOPPER-TYPE D.C. AMPLIFIER

There are, of course, other types of d.c. amplifier than those discussed here. Other forms of coupling between stages can be used, there are several forms of coupling found in transistorised circuits, including the so-called long-tailed pair, which are very useful in this respect. Alternatively the d.c. input can be made to modulate an a.c. signal which is then amplified and measured in the usual a.c. way. This modulation is carried out in a chopping device which may be either mechanical or purely electronic, and the complete circuit is called a chopper-type d.c. amplifier.

This article should have outlined the simpler design features of d.c. amplifiers of one type. It is a field of study with considerable scope for experimental work since the uses of d.c. amplifiers are numerous. They can be used to amplify the output of photo-electric tubes and other units which produce small, fairly steady, d.c. voltages. They are used in computers of some kinds and in various forms of research, often as parts of oscilloscopes. Bearing in mind the considerable difficulties involved, the study and construction of this type of circuit presents something of a challenge which is very interesting to attempt to meet.

Reference

1. For a much fuller discussion of this type of feedback see the article "Impedance and Negative Feedback" by the same author, published in Practical Electronics, May 1966.

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