

shown in Fig. 9, and is not the same as  $k'$  in Fig. 22. The reason for introducing  $k'$  is that it enables a more straightforward comparison to be made between the behaviour of the (a) and (b) circuits in Fig. 22 —  $k'$  is a measure purely of the knob position, whereas, as shown in Fig. 9,  $k$  involves also the value of the fixed series resistor.

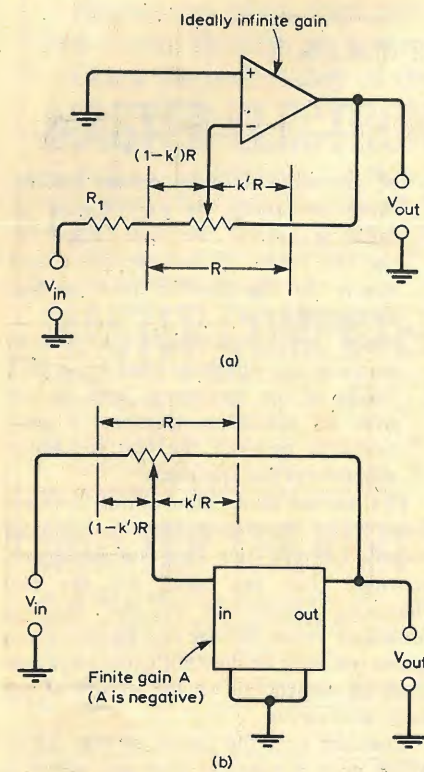


Fig. 22. In circuit (a) the total resistance of  $R$  compared with  $R_1$  varies the control curve, whereas the circuit at (b) is independent of track resistance.

The gain of the Fig. 22(a) circuit is given by:-

$$\frac{V_{out}}{V_{in}} = -\frac{k'R}{(1-k')R + R_1} = -\frac{k'}{1-k' + R_1/R} \quad (5)$$

The gain of the Fig. 22(b) circuit is given by:-

$$\frac{V_{out}}{V_{in}} = -\frac{k'}{1-k' - 1/A} \quad (6)$$

It will be seen that equations (5) and (6) are of exactly the same form,  $A$  being a negative number to represent the fact that the amplifier is a phase inverting one. Thus if  $A$  is made equal to  $R/R_1$ , the two circuits will have identical graphs relating overall gain to knob position.

Circuit (b) has an advantage over (a), however, in that the control characteristic is quite independent of variations in the absolute resistance  $R$  of the pot. element, whereas in (a) an increase in  $R$  requires a proportionate increase in  $R_1$  to return to the same control characteristic. Thus, using a pair of circuits of the (b) type in a

stereo system, differences in the element resistances in the two halves of the ganged pot., which, as already mentioned, are found to occur in practice, will not affect the accuracy of tracking between the channels, whereas in (a) an increasing discrepancy will occur as the gain setting is increased. It has been assumed that the amplifier input impedance in circuit (b) is very high, so that there is no significant loading on the pot. slider.

To carry out the Fig. 22(b) scheme in practice, an economical recipe is required for a phase-inverting amplifier of high input impedance and feedback-stabilized gain. The simple arrangement shown in Fig. 23(a) is not very good, for to avoid significant loading of the slider, the resistors  $R_a$  and  $R_b$  must be made very high in value, which then seriously degrades the noise performance. This problem may be satisfactorily solved by inserting a unity-gain follower between the slider and  $R_a$ ,  $R_a$  and  $R_b$  now being made of very much lower values. This arrangement is shown in Fig. 23(b).

Amplifier A in Fig. 23(b) has to handle only quite small voltage excursions, even though  $V_{in}$  and/or  $V_{out}$  may sometimes reach levels of several volts. There is no need to use an op. amp. for A, better economy, with little degradation in performance, resulting if a simple emitter-follower is used. A satisfactory practical design is given in Fig. 24. Over a range of gain adjustment of approximately 30dB, the departure from the ideal straight-line graph is no more than  $\pm 1$ dB. The unity-gain op. amp. follower at the left has been included so that the complete circuit presents a high input impedance to the source of  $V_{in}$  at all gain settings — this source may be the tape and radio inputs to a control unit, for example. Without this follower, the input impedance at maximum gain setting falls to  $1.09k\Omega$ .

Because the gain of the Fig. 24 circuit is independent of the total resistance of the pot. element, being dependent only on the slider tapping ratio, the tracking error between stereo channels can probably be held within  $\pm 1$ dB limits in production, over a 30dB range of gain, using low-cost carbon pots.

**Alternative technique.** An alternative technique, which, like the previous one, avoids the necessity to put fixed resistance in series with the pot. to limit the

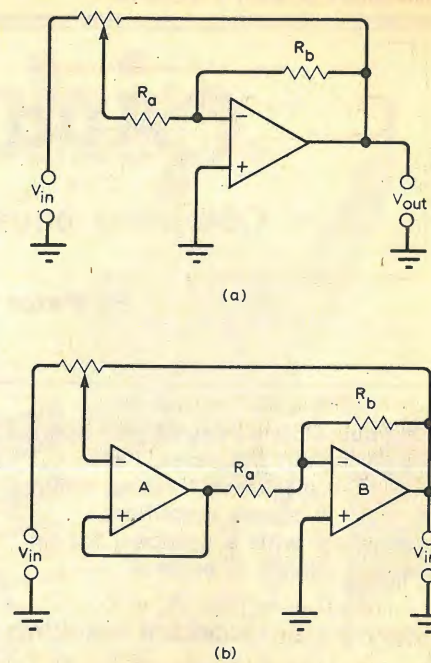


Fig. 23. Two circuits embodying the Fig. 22(b) idea. Circuit (b) uses voltage follower to avoid need for high-value resistors  $R_a$  and  $R_b$ .

Fig. 24. Practical version of Fig. 23(b) is shown at (a), with its control characteristic at (b) (lower curve).

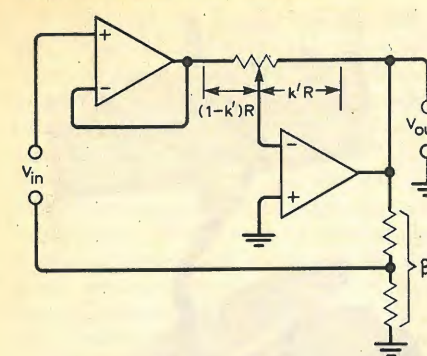
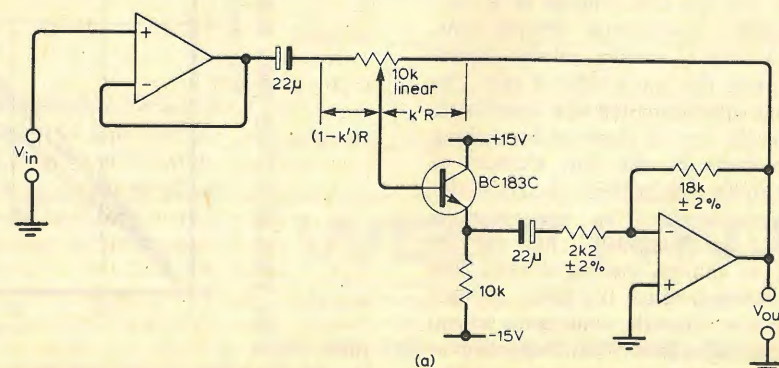
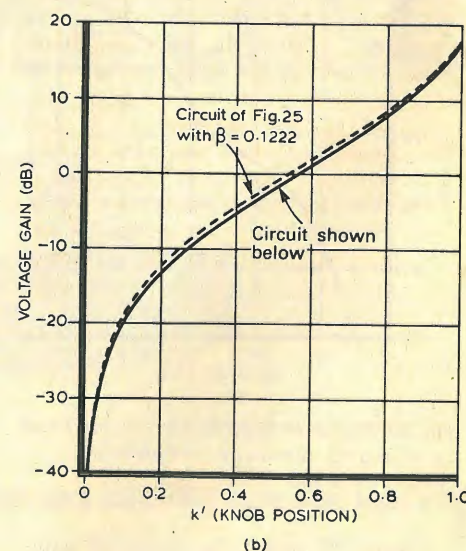


Fig. 25. Feedback amplifier limits maximum gain without use of fixed resistor in series with pot. Characteristic is upper curve in Fig. 24(b).

maximum gain, is shown in Fig. 25 in its simplest form.

Here a fraction  $\beta$  of  $V_{out}$  is fed back as overall negative feedback in series with  $V_{in}$ . The forward gain,  $A$ , of this feedback system is  $-k'/(1-k')$ , so that applying the usual feedback formula gives:

$$\frac{V_{out}}{V_{in}} = \frac{A}{1-A\beta} = \frac{-k'/(1-k')}{1-[-k'/(1-k')]\beta}$$

From which

$$\frac{V_{out}}{V_{in}} = -\frac{k'}{1-k'+k'\beta} \quad (7)$$

Comparing equation (7) with (5) and (6), it will be seen to be not quite of the same form, for the third term in the denominator of (7) involves  $k'$ , whereas this is not the case in (5) and (6). Suppose we choose  $\beta$  in the Fig. 25 circuit so that equation (7) gives the same maximum gain, i.e. gain at  $k' = 1$ , as that given by the Fig. 24(a) circuit in accordance with equation (6). This requires  $\beta = 0.1222$ , and equation (7) then yields the broken-line curve shown in Fig. 24(b). Looking at these two curves, it is very tempting to conclude that the circuits of Figs. 24 and 25 inherently give slightly different shapes of characteristic, but more careful thought shows that this is actually not the case.

Referring to equation (7), this may be written:

$$\begin{aligned} \frac{V_{out}}{V_{in}} &= -\frac{k'}{1-(1-\beta)k'} \\ &= -\frac{1}{1-\beta} \times \frac{(1-\beta)k'}{1-(1-\beta)k'} \\ &= -\frac{1}{1-\beta} \times \frac{k'}{1-\beta-k'} \end{aligned} \quad (8)$$

Equation (6) may be written:

$$\frac{V_{out}}{V_{in}} = -\frac{k'}{1-1/A-k'} \quad (9)$$

Comparing (8) and (9), it will be seen that if  $A$  and  $\beta$  are so chosen that  $(1-1/A) = 1/(1-\beta)$ , then the only difference between the equations is that the right-hand side of (8) is multiplied by the constant factor  $1/(1-\beta)$ . This

means that the curves for the two circuits are exactly the same in size and shape, but that represented by equation (8) is displaced upwards relative to the equation (9) curve by  $20 \log 1/(1-\beta)$  decibels.

Thus, the real difference in behaviour between the circuits of Figs. 24 and 25 is that when designed to give identical shapes of control characteristic, the Fig. 25 circuit, at all knob settings, gives a slightly higher gain than does that of Fig. 24.

## Passive control using linear pots.

A single linear pot. used as shown in Fig. 1 or Fig. 2 gives a control law which is quite intolerable for normal audio purposes. It is well known that by shunting a load resistor from the slider to earth, a characteristic approximating more closely to the ideal uniform decibel spacing may be obtained, though unfortunately only over a range of some 20dB or thereabouts. Fig. 26, based on calculations I did while a student in 1942, shows what happens as the loading is varied.

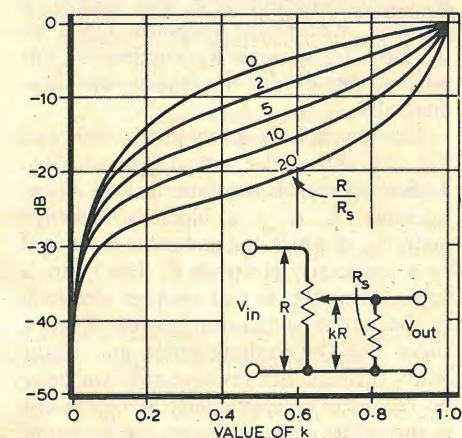


Fig. 26. Family of curves obtained from shunted linear pot. slider.

Very much better results than the above can be obtained with passive circuits using linear pots. if one or more fixed tapping points are provided, and the simplest such scheme is that shown in Fig. 27(a). If the resistors  $R_a$  and  $R_b$  are made of very much lower value than the pot. resistance, the attenuation with the slider at the tapping position is determined almost entirely by the values of  $R_a$  and  $R_b$ , and is virtually unaffected by any non-linearity in the law of the pot. element itself. There is, however, a sudden change in slope as the slider passes the tapping point, and a typical characteristic is shown in Fig. 27(b).

By adding a loading resistor between the slider and earth, a much better characteristic can be obtained, and it is possible to choose the value of this resistor so that there is no discontinuity in slope as the tapping point is passed. Fig. 28 shows a practical design employing a centre-tapped linear pot. with the slider output suitably loaded, together with the characteristic obtained. Over a control range of about 35dB, the departure from the ideal straight line is not much more

than  $\pm 1$ dB. By having two tapping points on the pot. element — and low-cost slider pots. can be obtained with this feature — the nearly-linear control range can be extended to about 50dB if required, satisfying the most exacting needs.

For instrumentation purposes, the above technique can be extended much

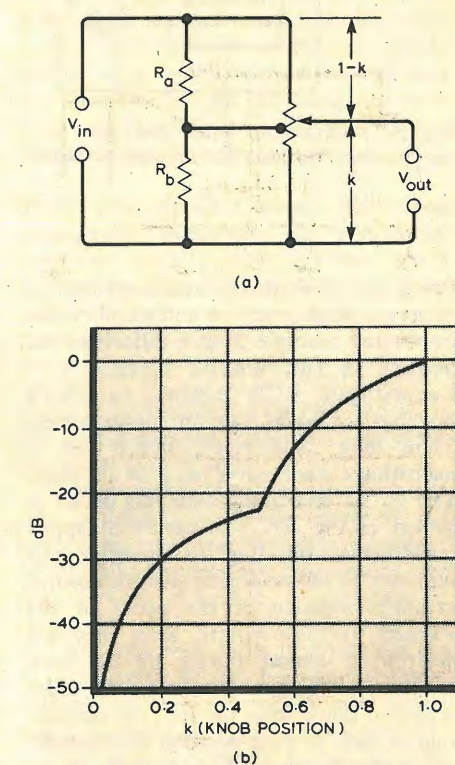


Fig. 27. Tapped linear pot. (a) gives approx. log. characteristic, shown at (b). With  $R_a$  and  $R_b$  low, gain at mid position is almost independent of track linearity or resistance.

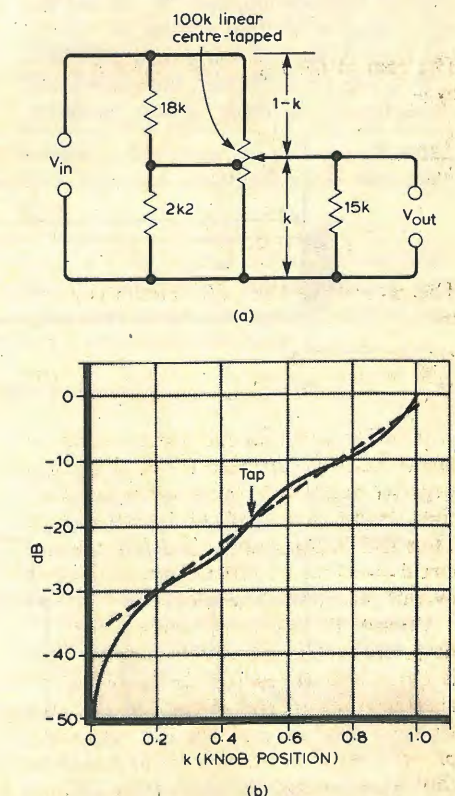


Fig. 28. Practical version of Fig. 27.