Audio gain controls

2 – Obtaining equal gains in the two channels of a stereo pair

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Continuing his survey of gain control problems and solutions, Peter Baxandall discusses tracking volume controls in stereo amplifiers, concluding with a proposal for an unusual design of control.

Stereo gain control tracking

Connected with the problem of obtaining a satisfactory scale-shape for the volume-control law in stereo control units, is that of achieving an accurately equal gain in the two channels at all knob settings. Preferably, the channel gains, if adjusted to be equal at one volume control setting, by means of the balance control or otherwise, should remain within ±1dB of equality at all other settings of operational significance. This is quite likely not to be the case if cheap types of carbon-track, ganged log. pots. are used.

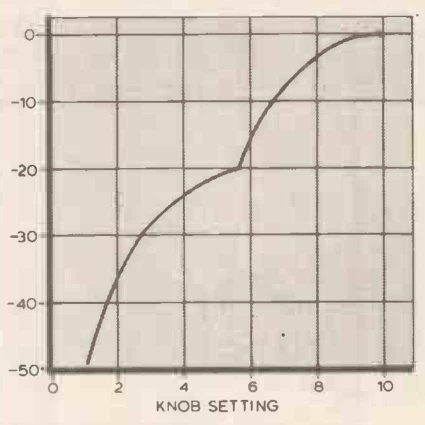


Fig. 20. Approximation to log. law obtained by changing resistivity of halves of carbon-track pot.

Figure 20 shows the measured gain-variation law on one channel of a very high quality, commercial control unit, having a simple, passive volume-control circuit, using the above type of pot. The very rough approximation to a logarithmic (linear-in-dB) law is obtained by making the two parts of the pot. element of different surface resistivities, the resistivity changing suddenly from one value to another at half-rotation of the knob. At the point of change, there is a severalfold change in slope, which is a quite undesirable feature. Though some quite cheap commercial pots. give a better approximation to a logarithmic law than that of Fig. 20, there is clearly much to be said for employing a type of gain control circuit which inherently gives a smooth and nearly logarithmic law without needing pots. with a non-linear resistance law. It ought to be easier to make ganged linear pots. with accurate matching between sections than to make ones with non-linear laws and equally good matching, though unfortunately, limited experience in measuring the departure from linearity of cheap so-called linear carbon-slider pots. has shown that undesirably large errors often occur.

One solution to the problem of obtaining a good scale shape and accurate tracking is, of course, to employ ganged, stud-type volume controls. These should give not more than 2dB per stud, at the most, and should have a click mechanism to make sure they are never left in an unsatisfactory half-way state between one stud and the next. Then, provided their internal resistors are accurate and stable, very accurate tracking will be obtained.

Careful measurements have been made of the resistance versus knob-position relationship for eight specimens of R.S. Components 10kΩ linear "slide tandem" pots, and Fig. 21 shows the results for three of these. It will be seen that:

(a) none of the specimens has a truly linear law;

(b) the departure from linearity, though of somewhat different nature for the three specimens, is nevertheless of fairly accurately the same shape for the two halves of each specimen, and this is the case also for the other five specimens;

(c) there are considerable differences between the absolute total resistance values of the specimens, and, in the case of specimen number 3 particularly, between the two resistance elements in one specimen.

For normal audio control-unit applications, minor departures from the nominal volume-control law are unimportant, provided they are equal for the two channels. Differences in the absolute resistance values for the two elements in a stereo pot. may or may not cause gain mistracking, dependent on the nature of the associated circuit.

Consider first the circuit of Fig. 22(a), which gives a range of gain well suited to most control-unit applications. (The circuits of Figs. 12 and 14 are better suited to microphone-amplifier applications, where the higher maximum gain given is advantageous.) It is necessary in practice to insert a resistor R_1 in series with the input end of the pot. to limit the maximum value of k obtainable to, say, 0.9 or 0.95, otherwise – see Fig. 8(a) – the characteristic becomes too steep at the high-gain end. Note that k is defined as

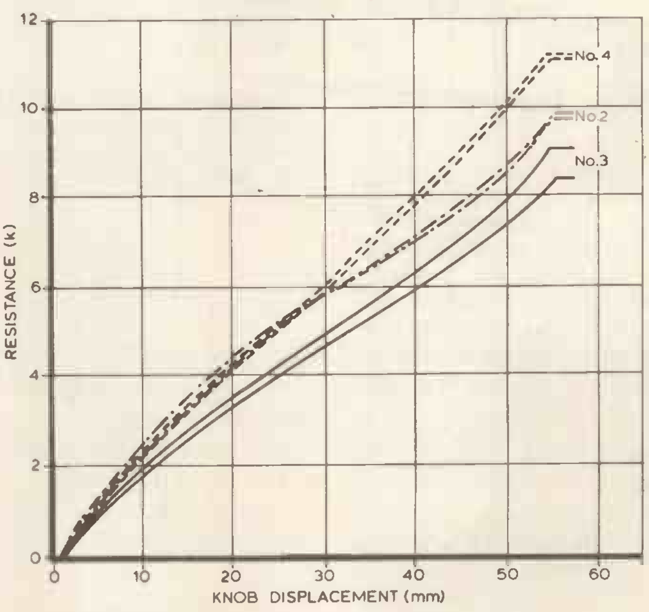
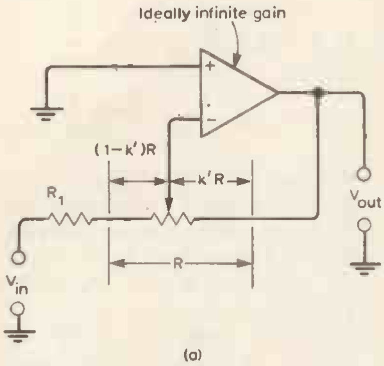


Fig. 21. Samples of characteristics of dual linear pots.

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.



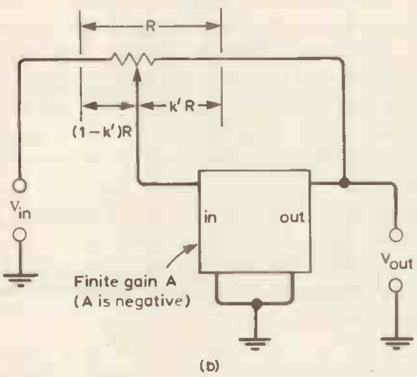


Fig. 22. In circuit (a) the total resistance of R *compared with* R_1 *varies the control curve, whereas the circuit at (b) is independent of track resistance.*

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

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

$$= -\frac{k'}{1-k' + R_1/R} \qquad (5)$$

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

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

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.

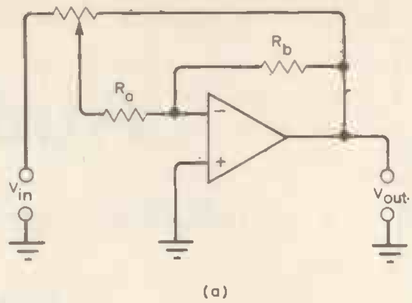
Circuit (b) has an advantage over (a), however, in that the control characteristic is quite independent of variations in the absolute resistance R of the pot. element, whereas in (a) an increase in R requires a proportionate increase in R_1 to return to the same control characteristic. Thus, using a 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 ±1dB. 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 1.09kΩ.

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 ±1dB 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



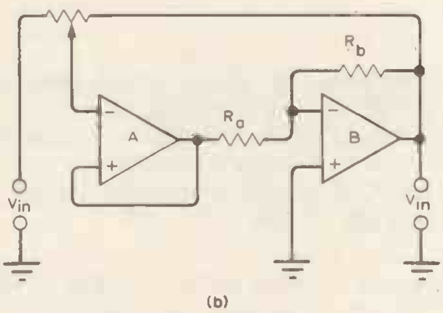
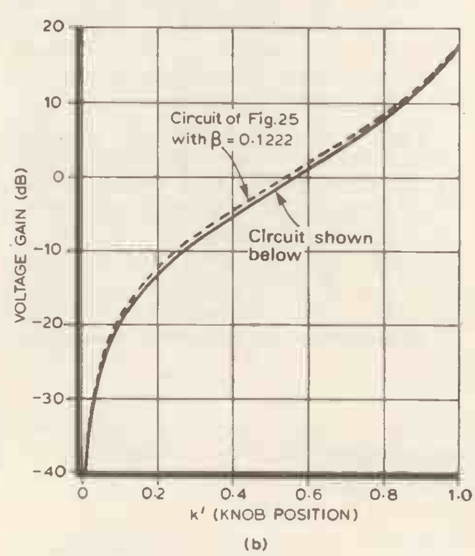
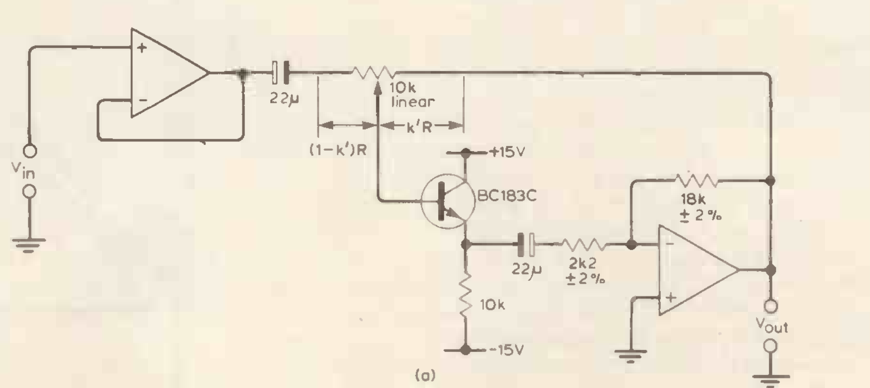


Fig. 23. Two circuits embodying the Fig. 22(b) idea. Circuit (b) uses voltage follower to avoid need for high-value resistors R_a *and* R_b.

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





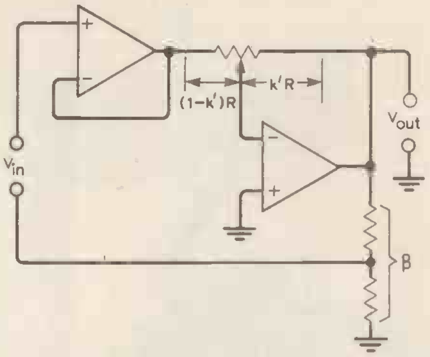


Fig. 25. Feedback amplifier limits maximum gain without use of fixed resistor in series with pot. Characteristic is upper curve in Fig. 24(b).

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

Here a fraction β 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

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

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 β 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:

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

$$= -\frac{1}{1-\beta} \times \frac{(1-\beta)k'}{1-(1-\beta)k'}$$

$$= -\frac{1}{1-\beta} \times \frac{k'}{\dfrac{1}{1-\beta}-k'} \qquad (8)$$

Equation (6) may be written:

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

Comparing (8) and (9), it will be seen that if A and β 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.

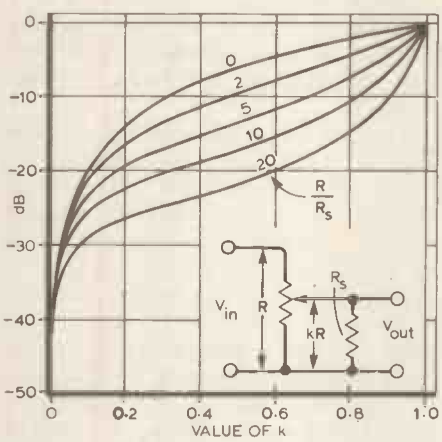


Fig. 26. Family of curves obtained from shunted linear pot. slider.

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 ±1dB. 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

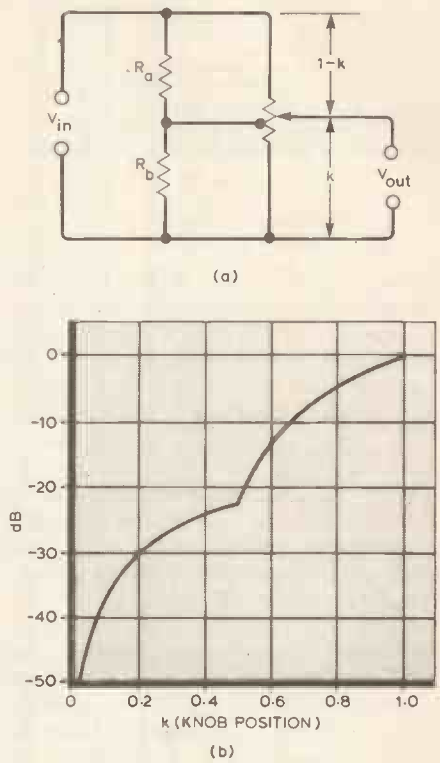


Fig. 27. Tapped linear pot. (a) gives approx. log. characteristic, shown at (b). With R_a and R_b low, gain at mid position is almost independent of track linearity or resistance.

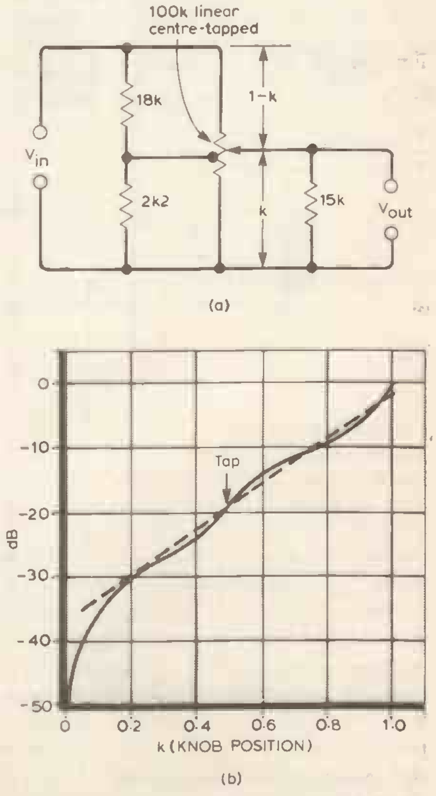


Fig. 28. Practical version of Fig. 27.

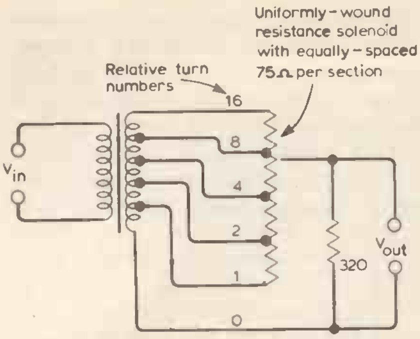


Fig. 29. Multiple-tap linear pot. with transformer-fed taps for precise voltages.

further, providing attenuators of extremely high precision and stability. An interesting example from a different field occurs in the Wayne Kerr B5009 Logarithmic LCR Bridge, in which readings are taken from an approximately 25cm long "slide-rule", which has a logarithmic scale covering a 16 : 1 ratio. The circuit associated with this device is shown in Fig. 29. The use of a tapped transformer winding to energize the tappings on the resistance element ensures extreme precision in the ratios of the voltages at these points, since they are determined almost purely by the turn numbers on the transformer. As the slider is moved down from the top, the attenuation at each tapping position increases by successive factors of 2, or 6.02dB. In the absence of the loading resistor on the slider, V_{out} varies linearly with slider position between tapping points, whereas, for a perfectly logarithmic scale, it is the log of V_{out} that is required to vary linearly. The error amounts to approximately 0.5dB midway between tappings. By adding the right value of loading resistor as shown, this error is reduced to less than ±0.05dB.

By using a transformer, the attenuation characteristic is made almost perfectly independent of production variations or non-uniformity in the resistance element, provided only that the physical positions of the tappings are accurately maintained. With the Fig. 28(a) type of arrangement, variations in pot. resistance do have some effect, but it may be kept small by making the resistance of the resistor-chain connected to the tapping(s) much less than the resistance of the pot. itself.

For high-grade audio control-unit applications, where the use of slider-type controls is considered appropriate, there would seem to be a strong case for using the Fig. 28 arrangement but with two tappings. By using ±2% resistors to feed the tappings, excellent stereo tracking should be obtained with a most desirable shape of control characteristic.

BBC log. attenuator

An interesting and very neat solution to the problem of providing a wide-range gain control having uniformly-spaced decibel scaling was devised in 1946 by C. G. Mayo and R. H. Tanner of the BBC Research Department. It was used in a portable microphone amplifier made by the BBC for acoustic measurements[5], but was unfortunately not taken up commercially.

The principle is given in Fig. 30, and Fig. 31 shows the actual construction. These illustrations are taken from reference 5. A is a block of resistive material, of which the underside is covered by a conductive electrode B. The input is applied between B and another electrode C, the output being taken between B and a slider D. The various series and shunt paths through the resistive material may be regarded as approximately equivalent to the ladder network shown, the output of each successive section of the ladder being a constant fraction of that of the previous section, giving a scaling with uniformly-spaced decibel divisions. The useful range of the model illustrated was about 70dB.

Fig. 31. Attenuator whose principle is shown in Fig. 30. Note screen round output. Photograph by courtesy of Electronic Engineering

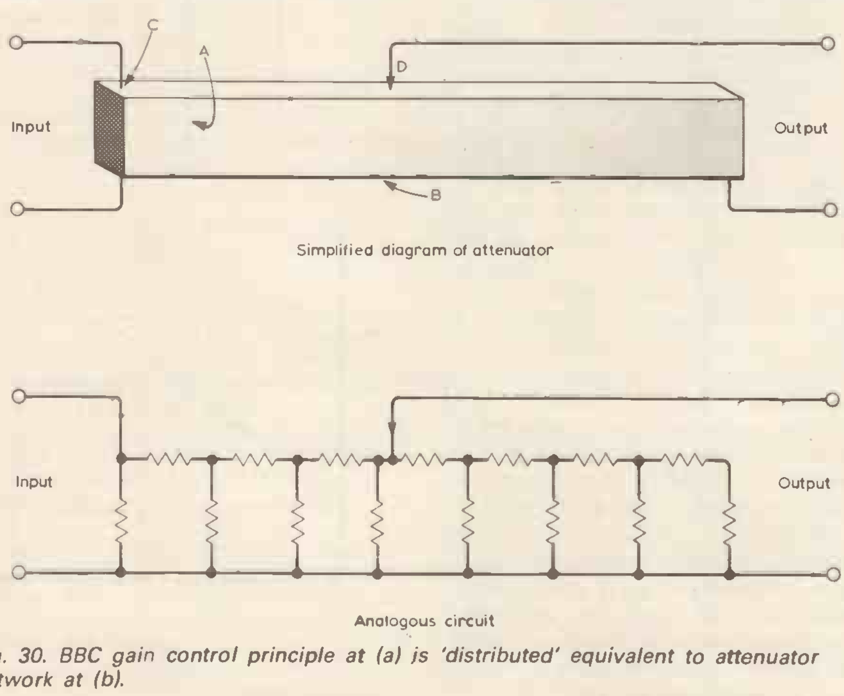


Fig. 30. BBC gain control principle at (a) is 'distributed' equivalent to attenuator network at (b).

It is pointed out that the output impedance of this type of attenuator does not become low when the attenuation is large, so that it is very important to avoid appreciable stray-capacitance coupling between input and output. The output connexion is therefore brought out coaxially, with a screening plate as shown in the photograph.

It has occurred to me that there is no essential need to employ a thick block of resistive material, and that an attenuator based on the same broad principle could be made using carbon-coated s.r.b.p. sheet material of the type commonly used in ordinary carbon pots. To test this idea, a quick experiment was done with the set-up shown in Fig. 32, and yielded the rather impressive result shown in Fig. 33. The very first graph obtained was somewhat inferior, apparently because of unsatisfactory contact between the steel vice jaw and the carbon coating. This was overcome by interposing a strip of polished copper foil between the carbon coating and the vice jaw.

Though an attenuator having a very extended range of operation as in Fig. 33 may fulfil some requirements, it is not ideal for use in control units etc., for the range of control needed in practice covers far less than 100dB, except that an "off" position coming soon after the position giving 40 or 50dB attenuation is really desirable. The Fig. 32 type of construction could readily be modified to provide such a characteristic, by shaping the conductive electrode, or metallic coating, somewhat as shown in Fig. 34. Halving the width of the carbon track, for example, would double the slope of the graph.

It is relevant to consider the suitability of attenuators based on the above principle for stereo purposes, i.e. whether sufficiently accurate tracking would be readily obtainable. Since the slope of the attenuation characteristic depends, to a first order at least, on nothing but the width of the resistive track, it would be important, for stereo use, to adopt a form of construction in which production variations in this width are minimized. The Fig. 34 construction does not appear to be ideal, for it relies on cutting the edge of the carbon material accurately in relation to the position of the metallized coating. The arrangement shown in Fig. 35 would seem much preferable, since accuracy of cutting is no longer involved and the metallized coating could be deposited by some form of printing technique with a very high degree of consistency.

The lower impedances usually used in transistor equipment, compared with earlier valve equipment, ease the problem of keeping the input-to-output stray capacitance sufficiently small, but it is still important to adopt a constructional arrangement which aims to minimize such capacitance. Working at 1kΩ impedance, with a control giving up to 100dB attenuation, the stray capacitance must be kept to less than 0.1pF. The connexion "rail" on which the slider moves must therefore be positioned away from the carbon surface and screened from this and the input connexion by an earthed screening plate.

Another advantage of the Fig. 35 arrangement is that, because of its symmetry, unwanted slight lateral movements of the slider during its traversal would be expected to have less effect on the attenuation than with the Fig. 34 form of construction – though it has been found that even with the latter, movements of about 1mm at right-angles to the direction of traversal produce only a small fraction of 1dB change in output provided the slider contacts the carbon track within 2 or 3mm of its edge.

Other methods of log. control and stereo tracking

● Perfect tracking of stereo channel gains at all settings, without the need for precision gain-control circuits, may be obtained by first producing, from the incoming L and R signals (L + R) and (L − R) signals. If the (L + R) signal is fed to one half of a ganged gain-control circuit, multiplying it by a factor α, and the (L−R) signal is fed to the other half of the gain-control circuit, which multiplies it by a factor β, then the sum of the gain-control circuit outputs is given by:

$$\text{sum} = (\alpha+\beta)L+(\alpha-\beta)R \qquad (10)$$

and the difference of their outputs is given by:–

$$\text{difference} = (\alpha+\beta)R+(\alpha-\beta)L \qquad (11)$$

Thus, though the balance as such is perfect, it is obtained at the price of introducing some cross-talk when α is not

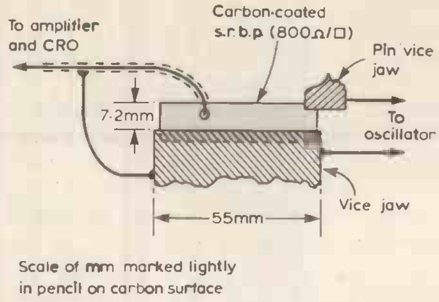


Fig. 32. Experiment using sheet instead of block in Fig. 30.

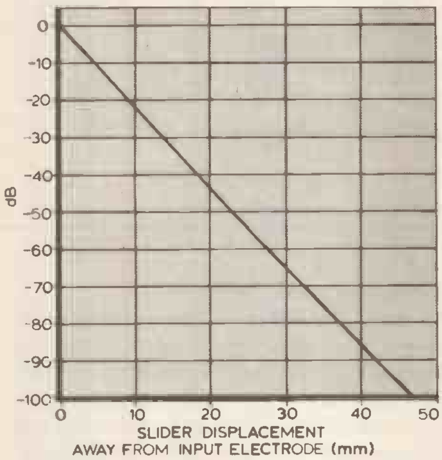


Fig. 33. Measured result obtained with Fig. 32 arrangement.

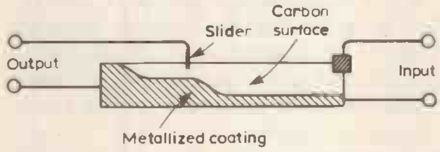


Fig. 34. Suggested form of control using Fig. 32 principle. Characteristic steeper at low-gain settings.

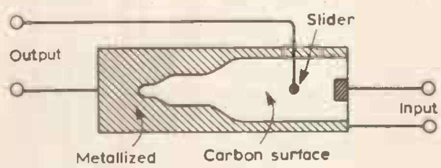


Fig. 35. Symmetrical version of Fig. 34 for improved consistency of performance.

quite equal to β. The effects of stereo cross-talk are discussed in detail in reference 6.

● Perfect tracking without the introduction of crosstalk can be produced if a single gain-control circuit is used to control both channels. This can be done, for example, by first making the L and R audio signals modulate two different r.f. carrier frequencies, the two amplitude-modulated carriers being fed to the same gain-control circuit and being subsequently demodulated in phase-sensitive detector circuits. Though this technique could give virtually perfect results, it would not seem to be very attractive economically.

● Various simple gain-control circuits give a nearly linear relationship between attenuation in decibels and control position over a range of several dB. If a sufficient number of such circuits are put in cascade, and the controls are ganged, an approximately linear relationship may be obtained over any required range. While this technique is not usually very attractive when carried out literally with mechanically-ganged pots., it would appear to be worth bearing in mind as a possible technique for providing electronic gain control with a logarithmic characteristic. The idea is quite old.

● At the present time the most satisfactory technique for wide-range electronic gain control is that which exploits the fact that silicon planar transistors follow with high accuracy the relationship:–

$$I_c = I_o e^{qV_{be}/kT} \qquad (12)$$

where I_c is the collector current and V_{be} is the base-to-emitter voltage. (The other quantities are constants.)

Circuits can be designed in which the gain in decibels is linearly related to the control voltage over a range of about 100dB, and by using the "log-antilog" or predistortion technique, a performance sufficiently good, with respect to distortion and signal-to-noise ratio, to justify the use of such circuits in very high-quality audio systems, can be obtained. A very sound and clear treatment is given in reference 7.

This type of circuit is at the heart of compander systems of the dbx type. It could be used to provide gain control in audio control units, a single pot. varying the control voltage to a pair of such circuits in the two audio channels. The distortion and noise performance, though good, is not quite up to the highest standards sometimes demanded, maybe unnecessarily, in expensive control units, but some further refinement of i.c. versions of these gain-control circuits, including the reduction of residual even-harmonic distortion by the use of more fully balanced arrangements, may take place.

● In a fully digital audio system, gain control with perfect stereo tracking and any desired control law may be carried out on a purely numerical basis.

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