

Reducing amplifier distortion

Avoiding conventional negative feedback by "error take-off"

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Error take-off is a method of overcoming the basic limitation of negative feedback which is increasingly limited loop gain with increasing frequency. Two practical configurations are discussed, a new bridge circuit with low output impedance offering a finite and worth-while improvement and an iterative circuit with higher output impedance having the ability to reduce distortion in principle, by any arbitrary amount. The bridge circuit uses basically four resistors and two amplifiers, and the iterative circuit uses three resistors and two amplifiers per distortion-reducing stage.

Negative feedback incorporates two essential features into one system. These are the measurement of error voltage at the output of an amplifier to produce a voltage proportional to this error voltage, and the amplification of this proportional error voltage in such a way as to reduce the distortion. Usually this is done with one amplifier, but this has the serious disadvantage of limiting the amount of error reduction, which typically falls with increasing frequency. The error in an amplifier cannot be reduced to an arbitrary amount by using negative feedback alone because the gain at a given frequency is inherently limited if oscillation is not to occur.

Error take-off, which avoids Nyquist

instability, can be used in principle to reduce error by any arbitrary amount. Basically the measurement of the voltage proportional to the error is very easy; it can be done with just two resistors when an inverting amplifier's output is compared with the system input (Fig. 1).

In audio and line transmission we are interested in non-linear distortion reduction rather than error, so I now refer to distortion rather than error as it is more evocative. Distortion is defined as the notional voltage (V_D) which adds algebraically to the notionally undistorted signal $V_{in} R_2/R_1$ at the output to produce the output of $V_{in} R_2/R_1 + V_D$.

It cannot be too strongly stressed that distortion in this sense includes any

fundamental components of the signal due to low gain as well as any noise and hum which the amplifier may have picked up. Once the simplicity of this concept of distortion is grasped the next step is to use a separate amplifier to take off the distortion from the distorted output.

Basic circuitry

It may be done in at least two ways: with a kind of bridge circuit shown in Fig. 2 (ref. 1) or by the iterative circuit of Fig. 3. In Fig. 1 the undistorted part of the output $V_{in} R_2/R_1$ balances off at the junction of R_2 and R_1 to produce zero voltage, the only voltage to appear at this point being proportional to the distortion.

Applying this to Fig. 2 and making

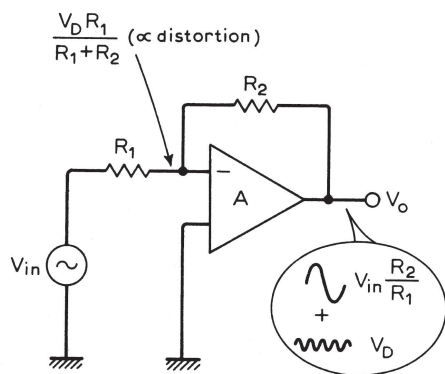


Fig. 1. Undistorted part of the output of this circuit balances out at the junction of R_1 and R_2 leaving a voltage $V_D R_1 / (R_1 + R_2)$, which is proportional to the amount of distortion.

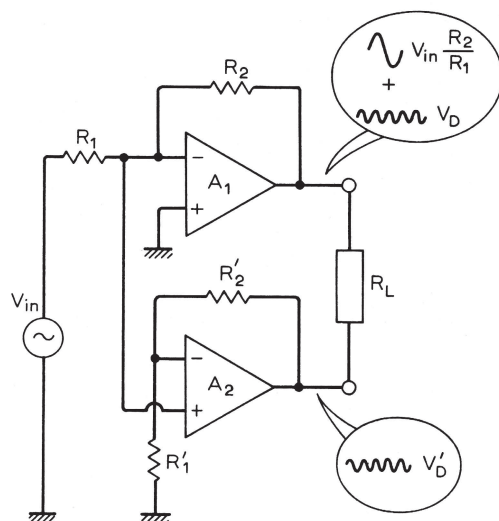


Fig. 2. The distorted part of the signal is taken off from the R_1, R_2 junction of Fig. 1 and returned through A_2 to the load to largely eliminate the distortion V_D .

$R'_1=R_1$ and $R'_2=R_2$ produces an output V_D at A_2 which in both amplitude and phase matches V_D . By taking R_1 to the output of A_2 instead of to the usual earth the error is taken off the original distorted output.

Examination of Fig. 2 shows the basic way in which error take-off differs from negative feedback and also why it is less prone to oscillation. It is because the output of the second amplifier A_2 in principle does not affect the output of A_1 . This I call "non-interaction".

The iterative circuit of Fig. 3 is also based on a voltage proportional to the distortion appearing at the junction of R_1 and R_2 . But this time, although for $R_A = R_B = R_C$ the voltage amplitude is the same, V_D , is applied to R_A it is cancelled out by the voltage applied to R_B . The error in doing this, due to A_2 being finite, is corrected by A_3 and its associated resistors—a process which may be iterated indefinitely.

Examination of the circuit shows up an important design principle, that of "rigidity of interconnection". For $R_A = R_B = R_C$, V_1 , V_2 and V_3 would have the same rigidly fixed effect on the output. In addition, R_1 to R_6 are rigid components, as distinct from the operational amplifiers which are not because their gain varies with frequency among other causes.

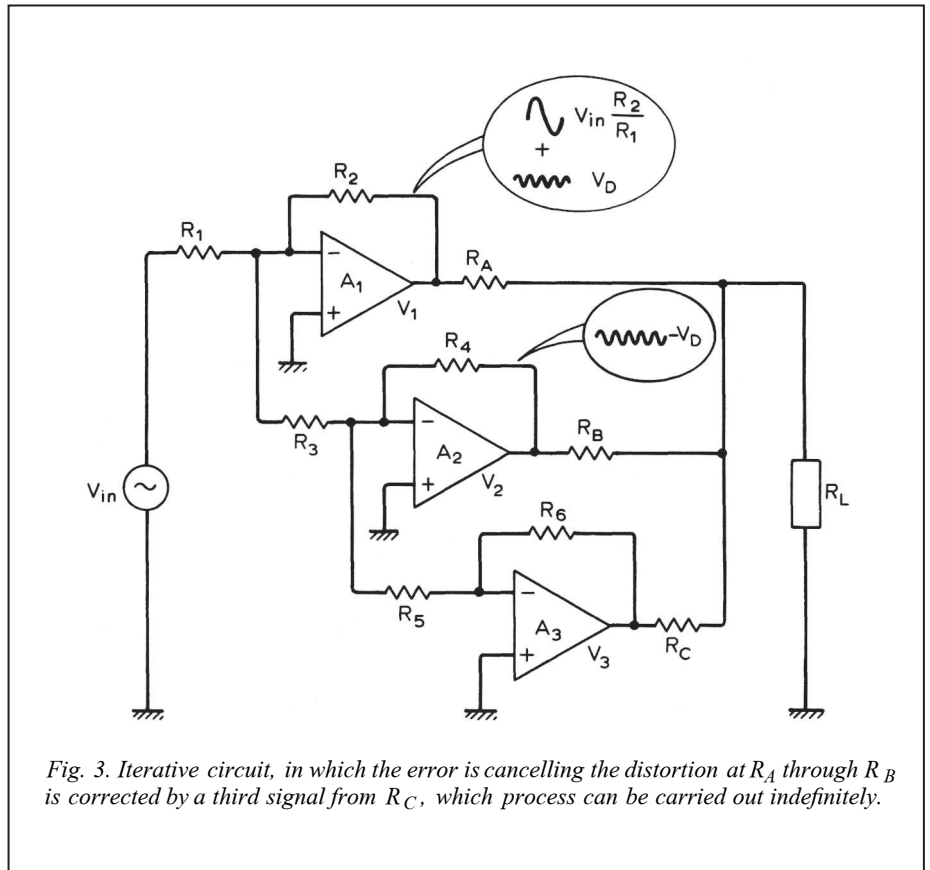


Fig. 3. Iterative circuit, in which the error is cancelling the distortion at R_A through R_B is corrected by a third signal from R_C , which process can be carried out indefinitely.

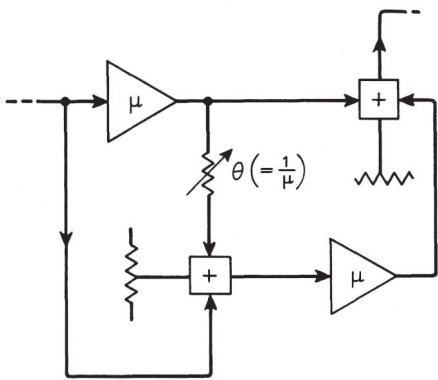


Fig. 4

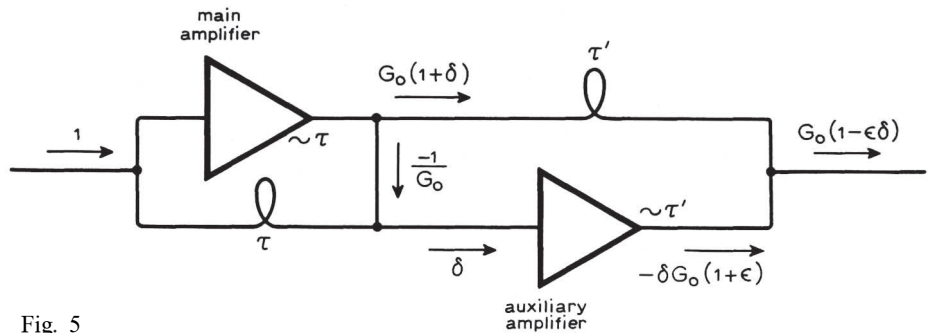


Fig. 5

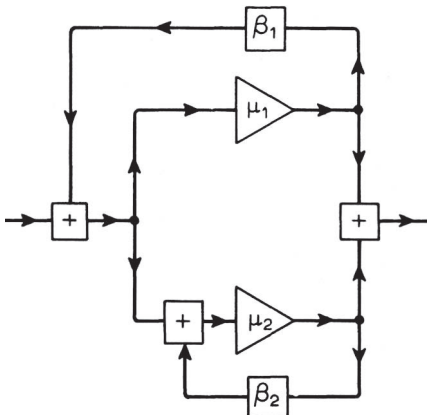


Fig. 6

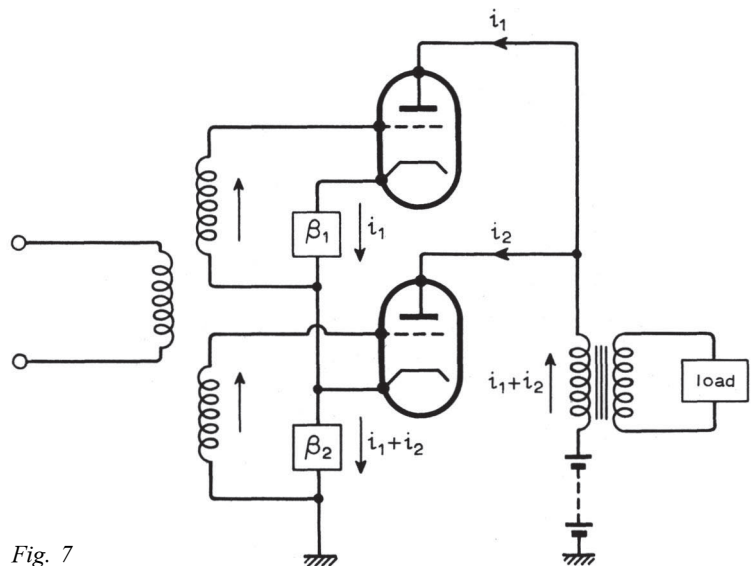


Fig. 7

Related techniques that pre-date error take-off are H. S. Black's feedforward, Figs. 4&5, and McMillan's multiple feedback, Figs. 6&7.

Historical note

There are two important schemes which predate error take-off. The first is Black's feedforward² (Fig. 4) which falls down because of the unstabilized amplifiers. For this reason Black used negative feedback; in Black's own view he did not invent it: "... applicator uses negative feedback for a purpose quite different from that of the prior art ... " in the process forgetting feedforward (ref. 3).

Feedforward surfaces again in another form in which a delay line and transformer play essential parts⁴; Fig. 5 is an example.

Just as I was telling myself that error take-off was novel, by pursuing references I found McMillan's multiple-feedback system⁵.

This is well-developed in theory but is incapable of achieving any worth-while practical results as in all the engineered circuits the distortion of the output transformer is not dealt with! Figs. 6 & 7 are separate examples of theory and practice. To the best of my knowledge, however, the circuit of Fig. 2 is quite novel.

Although resistors are shown in Fig. 2, they could be impedances. If R_1 and R'_1 were retained but R_2 and R'_2 were replaced by capacitors then a very much more accurate integrator could be constructed than is possible using conventional circuitry.

Conditions for minimizing distortion (which are similar to those for balance in a bridge) are $R_2/R_1 = R'_2/R'_1$ for Fig. 2 and for Fig. 3 $1 + (R_2/R_1) = R_4/R_3$ (assuming $R_3 \gg R'_1, R_3 \gg R_3$ and $R_A = R_B = R_C$)

Limitation of negative feedback

Could a negative feedback system do what error take-off does? Consider the circuit of Fig. 8 and its amplitude-frequency plot, Fig. 9. For $R_2 \gg R_1$ the feedback is as shown and the maximum amount that it is possible to apply without bursting into oscillation is depicted. This is a basic limit and cannot be overcome by additional amplification within the loop in the region P to Q which will usually cover the audio range. Additional amplification in the loop would help at frequencies below P but it would be essential for it to have a flat frequency response and a gain of one between P and Q.

Performance comparison

If the performance of the conventional virtual earth amplifier of Fig. 8 is compared with that of the error take-off circuit of Fig. 2 it can be shown by conventional theory that, in Fig. 8, the output voltage is

$$V_A = V_{in} \frac{R_2}{R_1} \left(\frac{1}{1 + \frac{R_2}{A_1 R_1}} \right) \approx V_{in} \frac{R_2}{R_1} \left(1 - \frac{R_2}{A_1 R_1} \right)$$

$$\approx V_{in} \frac{R_2}{R_1} - V_{in} \left(\frac{R_2}{R_1} \right)^2 \cdot \frac{1}{A_1} \text{ and the gain is}$$

$$G = V_A/V_{in} \text{ or } \frac{R_2}{R_1} \left(1 - \frac{R_2}{A_1 R_1} \right)$$

Now the voltage component due to $V_{in} R_2/R_1$ (Fig. 2) is balanced to zero at the junction of R_1 and R_2 and so may be ignored when working out V'_D , i.e. only the contribution of V_D need be considered, which has the value

$$\frac{V_D R_1}{R_1 + R_2} = V_{in} \frac{R_2^2}{A_1 + R_1^2} \cdot \frac{R_1}{R_1 + R_2}$$

$$= V_{in} \frac{R_2^2}{A_1 + R_1^2} \cdot \beta$$

$$V'_D = -V_{in} \left(\frac{R_2}{R_1} \right)^2 \frac{1}{A_1} \left(\frac{\beta A_2}{1 + \beta A_2} \right)$$

where $\beta = R_1/(R_1 + R_2)$, $R_1 = R'_1$, $R_2 = R'_2$ and $A_2/(1 + \beta A_2)$ is the gain for a conventional non-inverting amplifier (β in the numerator, which is the conventional feedback factor, allows for the attenuation of R_1 and R_2).

$$\therefore V'_D \approx -V_{in} \left(\frac{R_2}{R_1} \right)^2 \cdot \frac{1}{A_1} + V_{in} \left(\frac{R_2}{R_1} \right)^2 \frac{1}{\beta A_1 A_2}$$

To find the voltage across R_L subtract V_D from V_A

$$V_A - V'_D = V_{in} \left(\frac{R_2}{R_1} \right) - \left(\frac{R_2}{R_1} \right)^2 \frac{1}{\beta A_1 A_2}$$

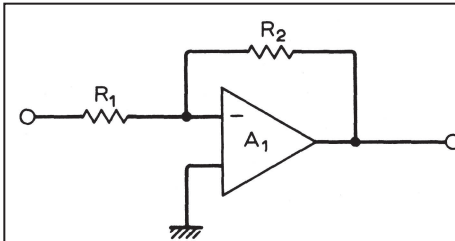


Fig. 8. Distortion of the balanced error take-off circuit is reduced by βA_2 compared with the virtual earth circuit above.

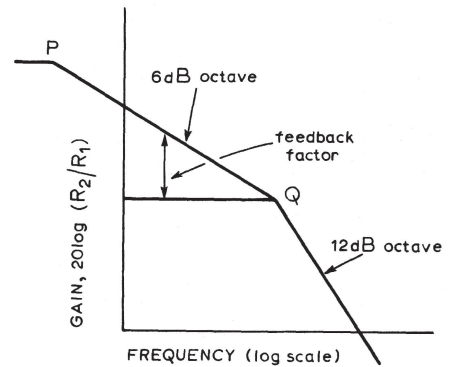


Fig. 9. Error take-off permits distortion to be reduced while avoiding the stability limit of negative feedback amplifiers which cannot be overcome by additional amplification within the loop in the region P to Q.

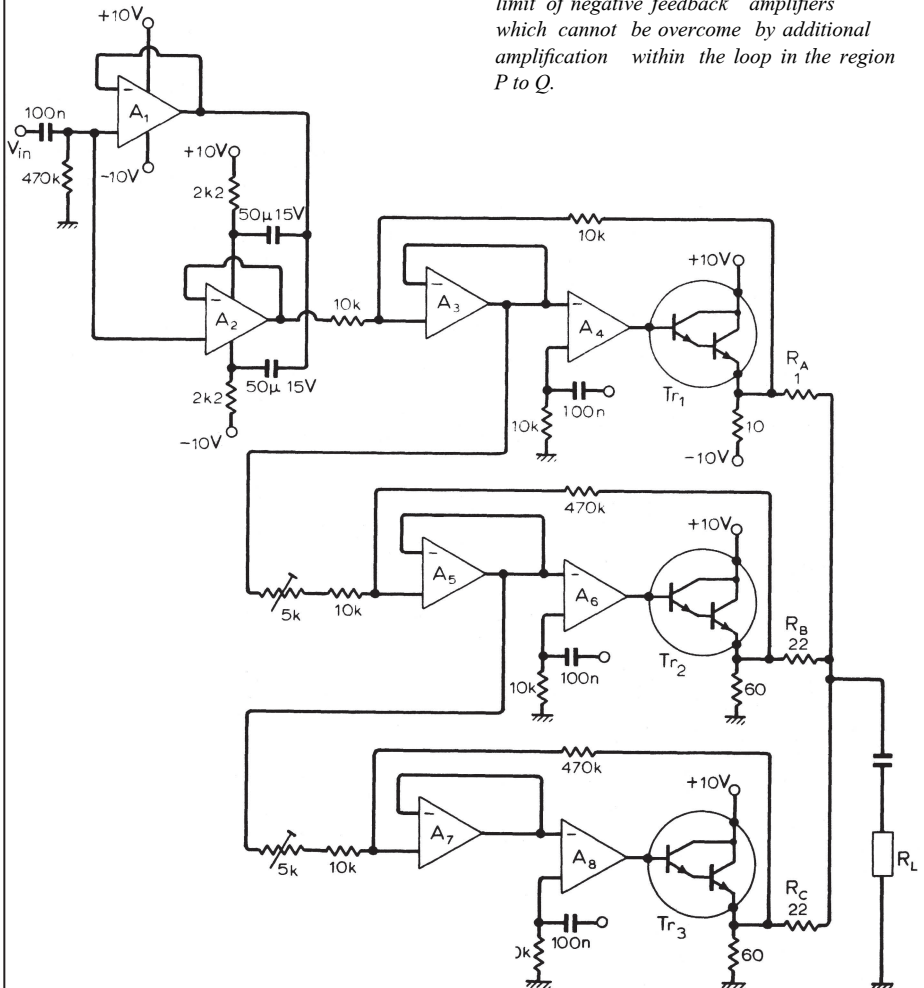


Fig. 10. Practical circuit of single-ended amplifier based on Fig. 3 circuit. Op-amps are 741 types, and power Darlington transistors type MJ4000.

Therefore the gain for the error take-off configuration, G_{ET} , is

$$\frac{V_A - V_D}{V_{in}} = \frac{R_2}{R_1} \left(1 - \frac{R_2}{R_1 \beta A_1 A_2} \right)$$

Comparing the conventional circuits gain, V_A/V_{in} , with G_{ET} , the distortion has fallen by an improvement factor βA_2 , a considerable improvement.

The above analysis assumes accurately-known resistors. By setting the resistors R'_1 and R'_2 associated with A_2 to $R_1 (1 + \Delta)$ and $R_2 (1 - \Delta)$ it can be shown that the distortion V_D is reduced to ΔV_D for $\beta \Delta \gg 1$,

i.e. 1% resistors would reduce it to one-hundredth of its former value. This demonstrates that the circuit is not abnormally sensitive to lack of stability in the circuit resistors.

Iterative circuit

By assuming that $R_2 \gg R_1$ the attenuation from the output (Fig. 3) of A_1 to the junction of R_1 and R_2 , $R_1/(R_1 + R_2)$ may be approximated by R_1/R_2 . In addition, for A_1, A_2, A_3 etc., if we choose the lowest value of A for $A_1 A_2$ we may write A_2 and get a pessimistic answer, which is acceptable.

With these approximations and assuming $R_A = R_B = R_C$ the uncancelled error (Fig.3) for two stages is $R_2^3/A^2 R_1^3$ and for n stages $R_2^{n+1}/A^n R_1^{n+1}$.

But the summing resistors attenuate the gain by a half for two stages and $1/n$ for n stages, so that the gain for two stages is

$$\frac{R_2}{2R_1} - \frac{R_2^3}{2A^2 R_1^3}$$

and for n stages

$$\frac{R_2}{nr_1} - \frac{R_2^{(n+1)}}{na^n R_1^{(n+1)}}$$

Experimental circuits

Two separate circuits have been built, the first based on Fig. 2, the second on Fig. 3. The circuit around Fig. 2 has already been published¹, so the single-ended version based on Fig. 3 will be described

It is desirable for a circuit for general use to have a high input impedance and to be capable of working from a high impedance source. If R_1 is connected directly to the voltage source (Fig. 3) then, if parasitic capacitances and the input current of A_1 are to have negligible effect, R_1 will be about 10kΩ, and the resistance of the signal source would enter directly into the take-off effect.

A normal voltage follower would solve this but at the cost of introducing some distortion. In the practical circuit, by bootstrapping the supply rails to A_2 (Fig. 10), the distortion is much reduced because all A_2 is called on to do, in effect, is maintain a low source impedance relative to a 10-kΩ load since its conditions are kept constant apart from what it sees as a current supplied to it by the 10-kΩ load. Amplifier A_1 provides the bootstrap voltage. (Even a germanium transistor could have a wide bandwidth if used under no load conditions with a broad-band A_1 .)

Amplifier A_3 transmits the voltage at the junction of the two 10-kΩ resistors with negligible distortion since by the nature of things it is very small. Its function is to enable the 10-kΩ resistor plus 5-kΩ potentiometer associated with A_5 to function without loading the two 10-kΩ feedback resistors. Amplifier A_5 functions similarly while A_7 is included to enable the effect of a further stage to be studied. This stage was found to have negligible effect and so was unsoldered.

The output of A_3 is connected to A_4 , which drives the output Darlington pair. The chain A_3, A_4, Tr_1 forms a conventional operational amplifier. Devices A_5, A_6, Tr_2 and A_7, A_8, Tr_3 form two further operational amplifiers with different feedback resistors to provide different gains to compensate for the higher resistors R_B, R_C with which they are connected to the load point. Resistors R_B and R_C are, as far as the main amplifier A_3, A_4, Tr_1 is concerned, part of the load and so it is necessary to have them as high in value as possible to avoid wasting output power.

Bridge circuit

An improved version of Fig. 2 will now be described. It is principally of interest as an

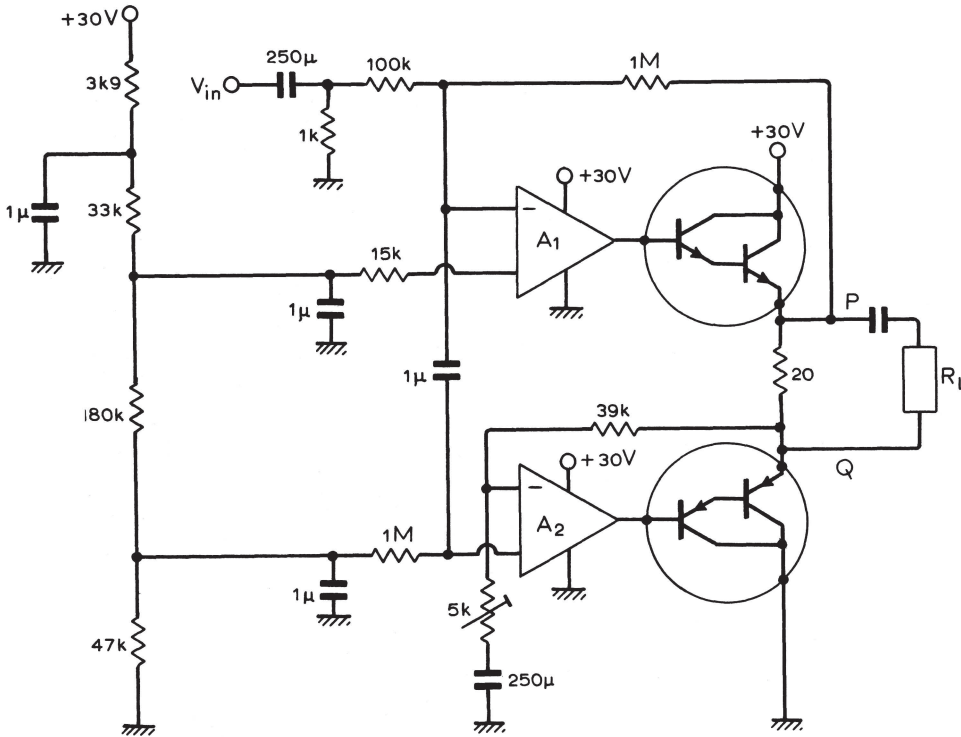


Fig. 11. Improved version of circuit based on Fig. 2 first published in Circuit Ideas, W.W., January 1973. Op-amps are 741 types and power Darlington MJ4000 and MJ4010.

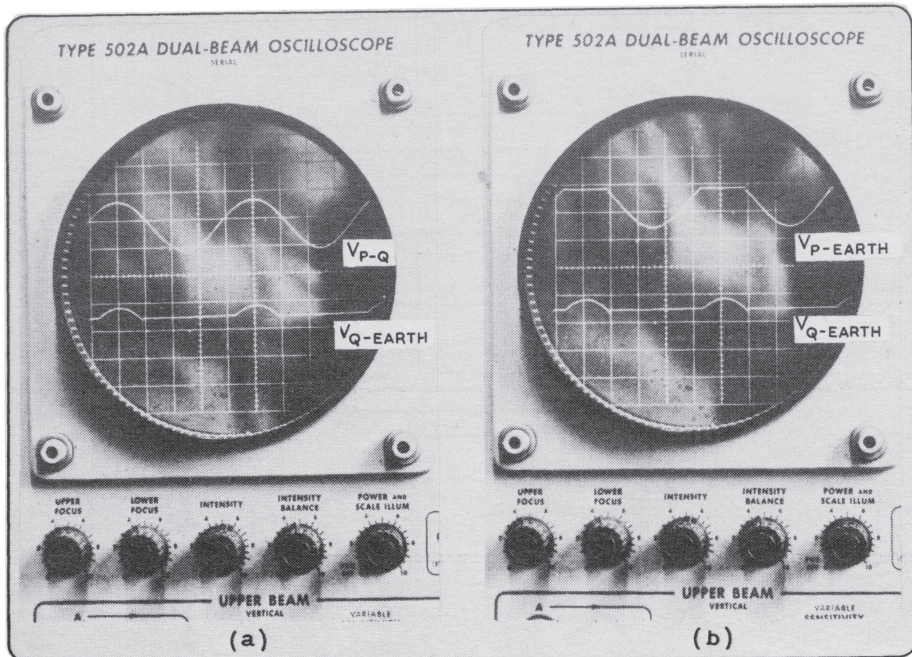


Fig. 12. Output voltage, V_{P-Q} , at (a) compared with voltage V_P (b), with the add-on signal (lower traces).

introductory circuit to the system; apart from its low output impedance its performance is not as good as the second circuit from the point of view of a power amplifier.

The input voltage is applied to the 1-k Ω resistor (Fig. 11) which is 1% of the 100k Ω equivalent to R_i of Fig. 2 so that if the source impedance varies from zero to infinity in resistance the error take-off signal at Q will vary by only 1%. The junction of the 1M Ω and 100k Ω resistors is coupled to the input of A_2 by the 1- μ F capacitor, allowing d.c. conditions at P and Q to be adjusted independently to enable the standing current through the 20 Ω resistor

to be designed. The 5-k Ω pre-set resistor enables the distortion to be adjusted to a minimum; a voltage is introduced on the 15k Ω resistor for this purpose from the bias potential divider.

The waveforms (Fig. 12) of P to earth, the inverse of Q to earth, and the voltage between P and Q (Fig. 12) show clearly the effect of error take-off on distortion. The inverse of Q to earth is used as a reference on the waveforms.

I believe that the applications of error take-off are numerous and that this article has just scratched the surface. It should have application in those many problems where the negative feedback-zero mechan-

ism approach falls down because the speed of response is insufficient and more feedback is impossible to achieve on grounds of stability.

References

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