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DISTORTION CORRECTION IN AUDIO POWER AMPLIFIERS

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Distortion Correction in Audio Power Amplifiers

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Abstract

An audio power amplifier design technique is presented that has the property of minimising the non-linear distortion that is generated in Class A and Class AB output stages.

A modified feedback technique has been identified that is particularly suited to the design of near unity gain stages. The technique can linearise the transfer characteristic and minimise the output resistance of the output stage. Consequently it is possible to design a power amplifier that uses fairly modest overall negative feedback yet attains minimal crossover distortion together with an adequate damping factor.

The paper presents initially a generalised feedforward/feedback structure from which a system model is derived that can compensate for both non-linear voltage and non-linear current transfer characteristics.

From this theoretical model, several circuit examples are presented which illustrate that only circuits of modest complexity are needed to implement the distortion correction technique.

The paper concludes by describing a design philosophy for an audio power amplifier which is appropriate for both bipolar and FET devices, whereby only modest overall negative feedback is necessary.

1. Introduction

This paper is addressed to the problems of minimising crossover distortion in class A and class AB audio power amplifiers. Traditionally, the use of output voltage derived negative feedback and appropriate biassing of the output transistors has been applied with varying degrees of success in an attempt to achieve acceptable linearity. However, since all transistors exhibit non-linearity and that in particular, the output transistors are generally operated into cut-off, then successful suppression of the distortion using these techniques is limited.

There are several fundamental problems that can be encountered when using negative feedback to minimise distortion in power amplifiers:

(i) Bipolar power transistors are usually of limited bandwidth (typical $f_T = 1 \rightarrow 5$MHz), thus if non-dynamic behaviour is required within the audio band, then loop gains of only 30dB are possible.

(ii) Since crossover distortion is transient in nature and of wide bandwidth, then the inevitable falling high frequency loop gain, together with the resulting loop delay, severely limits the degree of distortion suppression possible.

(iii) In output voltage derived negative feedback amplifiers, the distortion that is generated by the output transistors is fed back to the input circuitry. Consequently, the pre-output stages process both the desired input signal plus the output stage distortion; thus intermodulation is impaired especially as the distortion bandwidth can significantly exceed that of the audio signal.

(iv) If the output resistance of the output stage is non-zero (independent of any overall feedback), then the loudspeaker load is an integral component in the feedback loop. Hence, if the load exhibits non-linearity, then distortion components are again fed back to the amplifier's input stage.

A technique is described in this paper that can dramatically linearise the output device characteristics both with respect to voltage transfer and current transfer. Hence an amplifier philosophy evolves that helps to reduce the problems outlined ((i) → (iv)).

2. *The Theoretical Model*

The principle of the distortion cancellation technique can be described by considering the generalised error feedback structure shown in Figure 1. In this network, there is both error sensing feedforward and feedback applied around the non-linear element, N, where in the most general case, the input N is unspecified. The error signal used in the system, is defined as the difference between the input and the output of N, thus if N is ideal (i.e. N = 1), then the error signal is zero and no correction is applied. However, in all practical amplifiers, N will deviate from unity, thus the error signal represents the exact distortion due to N.

Analysis

Let V_n and $N(V_n)$ be the input and output of the N network, thus examination of the signals in Figure 1 reveals:

$$V_{out} = N(V_n) + b\{V_n - N(V_n)\}$$

$$V_n = V_{in} + a\{V_n - N(V_n)\}$$

eliminating V_n,

$$V_{out} = N(V_n)\ \{(1 - b) - \frac{ab}{(1-a)}\} + \frac{b}{(1-a)}\ V_{in} \ldots\ldots\ldots 1$$

If $(1-a) = b$ 2

then $V_{out} = V_{in}$ 3

Thus providing stability is maintained and V_n remains finite, then distortion cancellation results when equation 2 is enforced.

The result (equations 2 and 3) indicates that there is a continuum of solutions extending from an error feedback system through to an error feedforward system.

It is interesting to note that the input of N is unspecified, it may therefore be derived directly from V_n or indeed any other point within the structure providing stability is maintained. For example by putting $a = 0$, $b = 1$, then the classic feedforward system results, where if the input of N is derived from the output of the error difference amplifier, then the Quad[1,2] feedback structure results (see dotted connection in Figure 1).

In this paper we consider the opposite extreme where a = 1, b = 0 and the input of N is equal to V_n. This system is of the type first discussed by Llewellyn in 1941[3] in relation to valve amplifiers and later by Cherry[4] in 1978. It will now be shown that this feedback technique is particularly relevant to the design of unity gain, follower type output stages, where with modest circuitry, dramatic improvement in performance is possible. The theory is extended to show that linearisation of devices with non-linear current gain is also feasible.

3. Circuit Topologies for Output Stage Linearisation

Power amplifiers generally use bipolar output transistors that exhibit low, non-linear current gain. Consequently when such devices are used in a complementary emitter follower configuration, the transformed loudspeaker load as seen by the base terminals is rendered non-linear and therefore contributes to the amplifier distortion.

If distortion correction feedback is configured to include input current sensing, then it is possible to compensate for changes in current gain. Thus when combined with voltage error sensing feedback, a unity gain stage results that can be driven from a stage with a finite output resistance.

In Figure 2, the schematic of a system with both voltage and current sensing circuitry is shown, where the system is configured to illustrate how a practical circuit (Figure 3) may be realised.

Analysis shows when;

$$k_1 = 1 + \frac{2R_1}{R_2} \qquad \text{..........5}$$

$$R_1R_3 = R_2R_4 \qquad \text{..........6}$$

that the voltage gain is unity even when the base currents of T_1 and T_2 are finite and V_{Be}/I_e introduce non-linearity.

As a point of design interest, the resistor R_1 includes the output resistance of the driving stage, consequently the driving amplifier is not required to have zero output resistance.

Corollary

Since the voltage gain is unity, then it follows that the output resistance of the stage is zero, even when the output resistance of the driving stage is finite. As a result, an amplifier that uses this error correction feedback system, does not in principle have to rely upon an overall output voltage derived negative feedback loop to achieve adequate loudspeaker damping. Also, the loudspeaker load is then effectively decoupled from the overall feedback loop, and it is this factor that prevents loudspeaker generated distortion products from reaching the input circuitry of the power amplifier.

Three practical output stage circuits are shown in Figures 3, 4 and 5. The circuit of Figure 3 has both voltage and current sensing and is derived from Figure 2. However, if the output devices have adequate current gain (e.g. MOSFET or Darlington transistors), then current sensing is unnecessary. As a result, the much simplified circuits of Figures 4 and 5 are illustrated to show the modest circuit requirements that are needed to realise only error voltage sensing. The circuit of Figure 5 is particularly attractive as the transistors T_3, T_4 form both a complementary error difference amplifier as well as 'amplified diodes' for biassing the output transistors.

4. Conclusions

This paper has described an approach to power amplifier design where the non-linear distortion generated by the output transistors is compensated by simple, fast acting, local circuitry that can result in a high degree of linearity that is appropriate to class A and AB follower type output stages.

The technique should find favour amongst designers who adhere to the low feedback school of design, as corrective feedback is only applied when distortion in the output stage is generated. If, therefore, the output stage (N) is designed to be as linear as possible, a fact that can be aided by parallel connection of output transistors, then only minimal error signals result.

Since output stage and loudspeaker generated distortions are in principle isolated from the input stages, then these stages are required only to produce modest voltage gains, as large loop gains are not required in an attempt to produce a linear amplifier. Consequently the loop gain is low and the loop bandwidth can be high, enabling a non-dynamic loop behaviour well in excess of the audio bandwidth.

In practical amplifier design, the sensitivity of adjustment of the balance conditions is dependent largely on the quiescent bias current of the output transistors, where critical adjustment results only under extremely low biassing. It has been found that for normal bias levels, adjustment is non-critical, also that sensitivity is aided by modest overall feedback.

Several prototype circuits have been investigated where the technique has proved effective. In these amplifiers, no stability problems have been encountered other than with the susceptibility to oscillation of power Darlington transistors which appear critical on layout. In fact, due to the low loop gain load dependent instability is minimal, though standard series Zobel circuitry was employed. In practice, the bandwidth of the correction circuitry is high which enables fast correction of output stage non-linearities. In fact, it is partly the speed of the correction loop that enables a greater suppression of distortion compared with an overall feedback system.

5. *References*

1. P J Walker, M P Albinson, 'Current dumping amplifier', Proceedings of 50th Convention of the AES, 1975.

2. P J Walker, 'Current dumping audio power amplifier', Wireless World, Vol 81, No 1480, pp 560-562, December 1975.

3. F B Llewellyn, 'Wave translation systems', US Patent 2, 245, 598, 17 June 1941.

4. E M Cherry, 'A new result in negative feedback theory, and its applications to audio power amplifiers', Circuit Theory and Applications, Vol 6, pp 265-288, 1978.

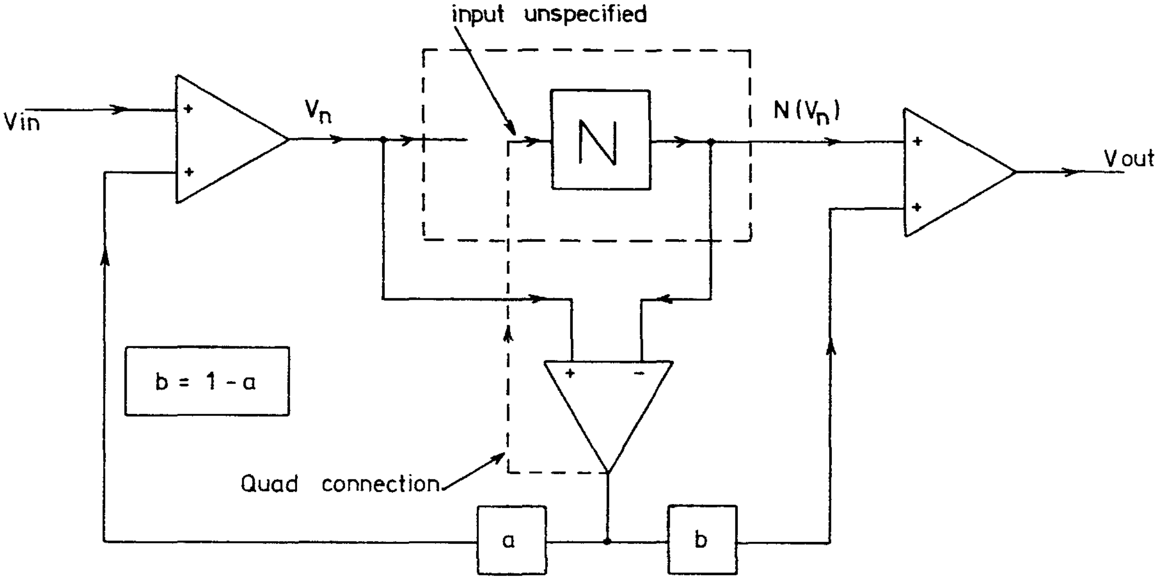


Fig. 1 Generalised feedback / feedforward structure

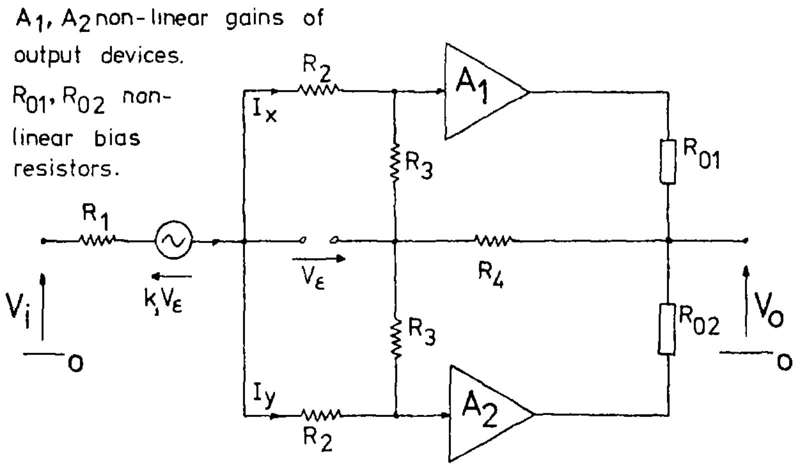


Fig 2 Current and voltage error sensing feedback

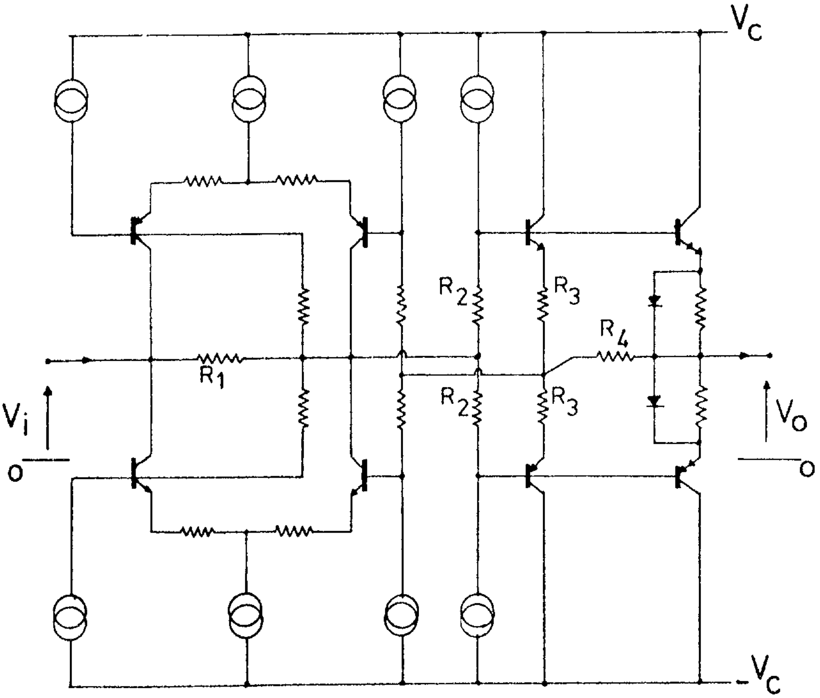


Fig 3 Circuit schematic of current and voltage error sensing output stage

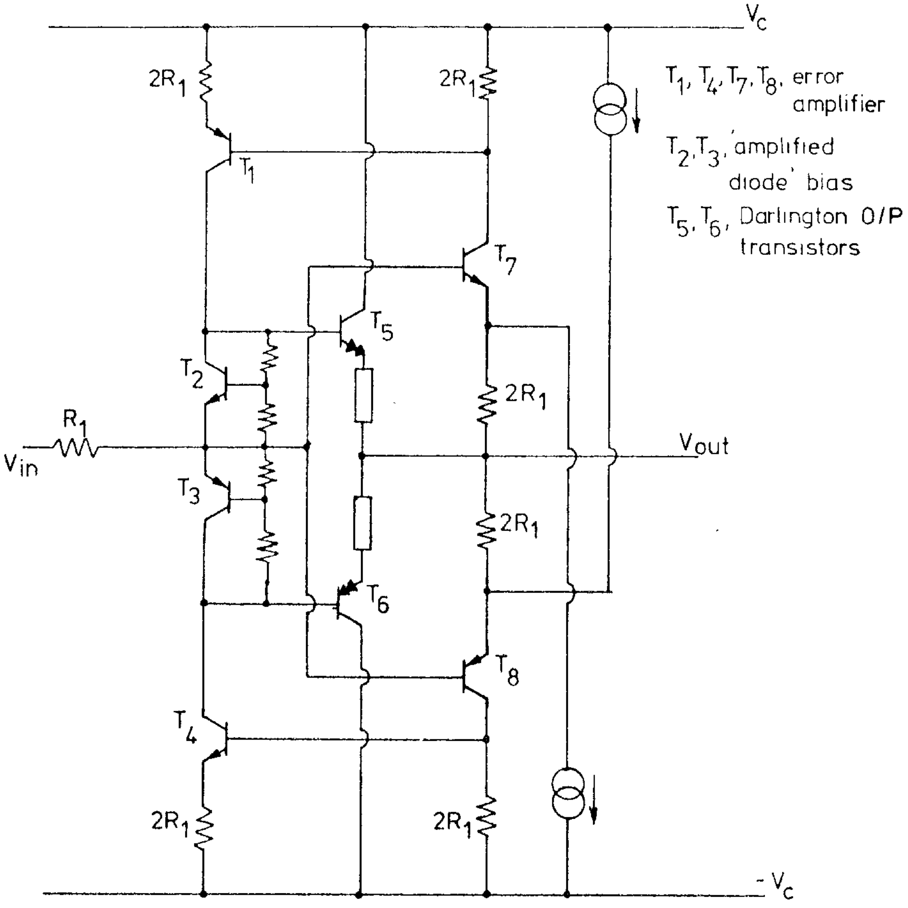
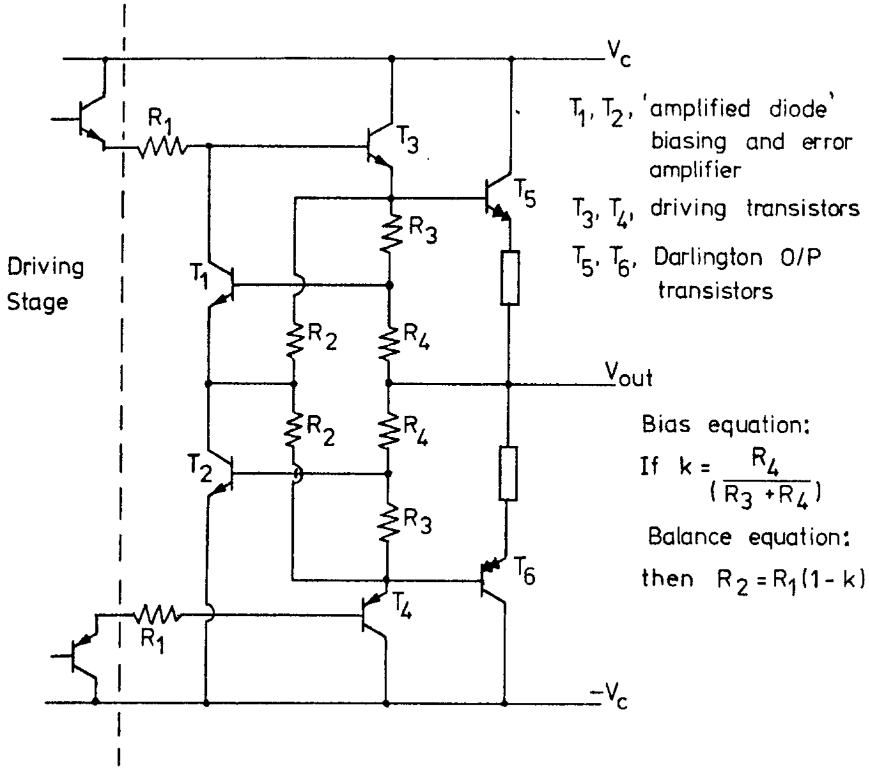


Fig. 4 Example of voltage error sensing circuit



T_1, T_2, 'amplified diode' biasing and error amplifier

T_3, T_4, driving transistors

T_5, T_6, Darlington O/P transistors

Bias equation:

If $k = \frac{R_4}{(R_3 + R_4)}$

Balance equation:

then $R_2 = R_1(1-k)$

Fig. 5 Voltage error sensing circuit using 'amplified diodes' as error amplifier.