Distortion Correction in Audio Power Amplifiers

Conference Paper · February 1980

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Distortion Correction in Audio Power Amplifiers*

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An audio power amplifier design technique is presented which has the property of minimizing the nonlinear 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 linearize the transfer characteristic and minimize 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.

A generalized feedforward–feedback structure is presented from which a system model is derived that can compensate for both nonlinear voltage and nonlinear 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.

In conclusion a design philosophy is described for an audio power amplifier which is appropriate for both bipolar and FET devices, whereby only modest overall negative feedback is necessary.

0 INTRODUCTION

This paper discusses the problems of minimizing crossover distortion in class A and class AB audio power amplifiers. Traditionally output-voltage-derived negative feedback and appropriate biasing of the output transistors have been applied with varying degrees of success in an attempt to achieve acceptable linearity. However, since all transistors exhibit nonlinearity and as, in particular, the output transistors are generally operated into cutoff, successful suppression of the distortion using these techniques is limited.

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

1) Bipolar power transistors are usually of limited bandwidth (typical f_T = 1–5 MHz); thus if nondynamic behavior is required within the audio band, loop gains of only 30 dB are possible.

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

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

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

A technique is described in this paper which can dramatically linearize the output device characteristics with respect to both voltage transfer and current transfer. Hence an amplifier philosophy evolves that helps to reduce the problems outlined in 1)–4).

* Presented at the 65th Convention of the Audio Engineering Society, London, 1980 February 25–28.

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1 THEORETICAL MODEL

The principle of the distortion cancellation technique can be described by considering the generalized error feedback structure shown in Fig. 1. In this network there is error sensing feedforward as well as feedback applied around the nonlinear 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 (that is, $N = 1$), 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.

1.1 Analysis

Let V_n and $N(V_n)$ be the input and output of the N network. Thus examination of the signals in Fig. 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,

$$V_{out} = N(V_n)\left\{(1 - b) - \frac{ab}{(1 - a)}\right\} + \frac{b}{(1 - a)} V_{in}. \quad (1)$$

If

$$(1 - a) = b \quad (2)$$

then

$$V_{out} = V_{in}. \quad (3)$$

Thus providing that stability is maintained and V_n remains finite, distortion cancellation results when Eq. (2) is enforced.

The result [Eqs. (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 that stability is maintained. For example, by putting $a = 0$, $b = 1$, 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 dashed connection in Fig. 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 a dramatic improvement in performance is possible. The theory is extended to show that linearization of devices with nonlinear current gain is also feasible.

2 CIRCUIT TOPOLOGIES FOR OUTPUT-STAGE LINEARIZATION

Power amplifiers generally use bipolar output transistors which exhibit low nonlinear 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 nonlinear and therefore contributes to the amplifier distortion.

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

In Fig. 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 (Fig. 3) may be realized.

Analysis shows that when

$$k_1 = 1 + \frac{2R_1}{R_2} \quad (4)$$

$$R_1 R_3 = R_2 R_4 \quad (5)$$

the voltage gain is unity even when the base currents of T_1 and T_2 are finite and V_{BE}/I_E introduces nonlinearity.

As a point of design interest, the resistor R_1 includes

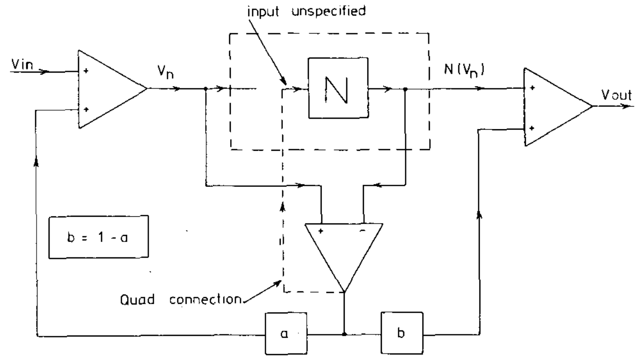


Fig. 1. Generalized feedback-feedforward structure.

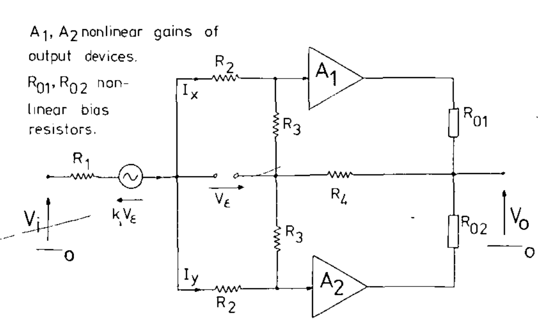


Fig. 2. Current- and voltage-error-sensing feedback.

the output resistance of the driving stage. Consequently the driving amplifier is not required to have zero output resistance.

2.1 Corollary

Since the voltage gain is unity, 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 Figs. 3–5. The circuit of Fig. 3 has both voltage and current sensing and is derived from Fig. 2. However, if the output devices have adequate current gain (such as MOSFET or Darlington transistors), then current sensing is unnecessary. As a result, the much simplified circuits of Figs. 4 and 5 are illustrated to show the modest circuit requirements that are needed to realize only error-voltage sensing. The circuit of Fig. 5 is particularly attractive as the transistors T_3, T_4 form both a complementary error difference amplifier as well as "amplified diodes" for biasing the output transistors.

3 CONCLUSIONS

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

The technique should find favor among 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, 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 nondynamic loop behavior well in excess of the audio bandwidth.

In practical amplifier design, the sensitivity of adjustment of the balance conditions depends largely on the quiescent bias current of the output transistors, where critical adjustment results only under extremely low biasing. It has been found that for normal bias levels, adjustment is noncritical, 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,

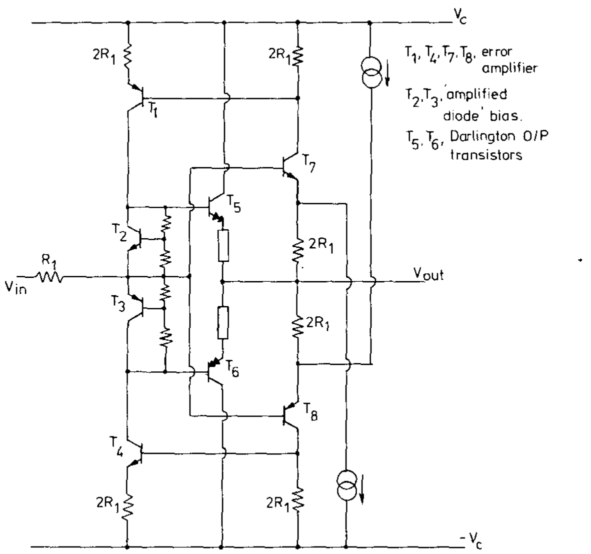


Fig. 4. Example of voltage-error-sensing circuit.

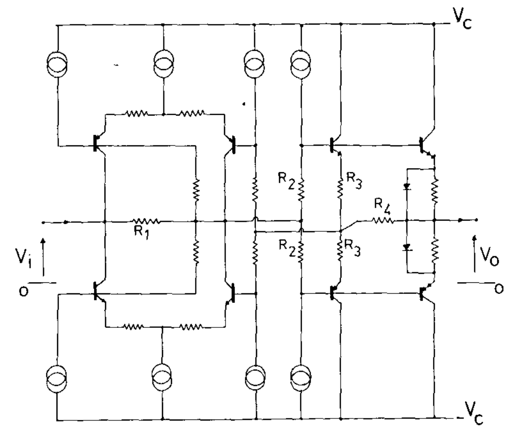


Fig. 3. Circuit schematic of current- and voltage-error-sensing output stage.

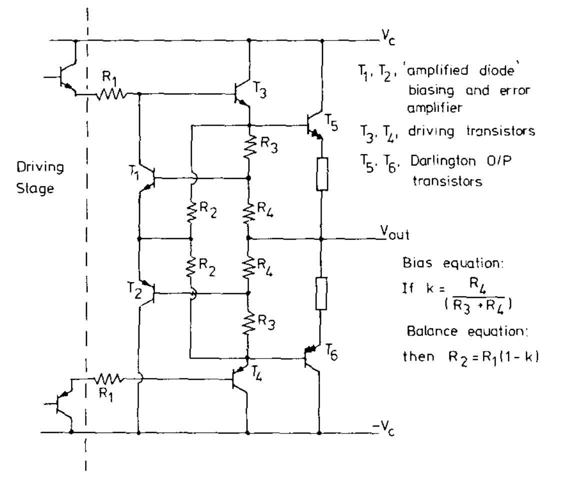


Fig. 5. Voltage error sensing circuit using amplified diodes as error amplifier.

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 nonlinearities. In fact, it is partly the speed of the correction loop that enables a greater suppression of distortion compared with an overall feedback system.

4 REFERENCES

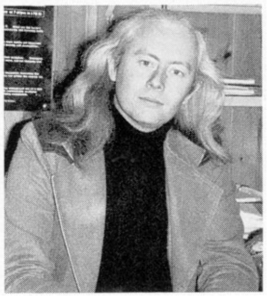
[1] P. J. Walker and M. P. Albinson, "Current Dumping Audio Amplifier," presented at the 50th Convention of the Audio Engineering Society, London, 1975 March 4–7.

[2] P. J. Walker, "Current Dumping Audio Power Amplifier," *Wireless World*, vol. 81, pp. 560–562 (1975 Dec.).

[3] F. B. Llewellyn, "Wave Translation Systems," U.S. Patent 2,245,598, 1941 June 17.

[4] E. M. Cherry, "A New Result in Negative-Feedback Theory and Its Application to Audio Power Amplifiers," *Int. J. Circuit Theory Appl.*, vol. 6, pp. 265–288 (1978 July).

THE AUTHOR



Malcolm J. Hawksford was born in Shrewsbury, England, in 1947. His professional education was at the University of Aston in Birmingham where he studied electrical engineering from 1965–68 and was subsequently awarded a first class B.Sc. degree. In 1968 he obtained a BBC Research Scholarship for three years of postgraduate study at Aston University. His research subject was the application of Delta modulation to color television systems. This work resulted in the award of a Ph.D. degree in 1972.

In 1971 he obtained a lectureship at the University of Essex in the electrical engineering science department where he has taught subjects including electromagnetic theory, audio engineering, digital communications, circuit design and television engineering. At Essex he developed an Audio Research Group where projects on amplifier design, loudspeaker crossover design, analogue-to-digital conversion and music synthesis have been undertaken.

Dr. Hawksford is a member of the Audio Engineering Society, the IEE, the Royal Television Society, and is a chartered engineer.

His hobbies include listening to music, designing audio equipment, home computing and motorcycling.