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AMPLIFIER TOPOLOGIES FOR CURRENT DRIVEN LOUDSPEAKERS

Dr P. G. L. Mills

Tannoy Ltd., Rosehall Ind. Est., Coatbridge, Strathclyde ML5 4TF

1. INTRODUCTION

At the last conference, Reproduced Sound 9 [1], we considered in detail the theoretical aspects of current driven loudspeaker systems, showing that this approach led to worthwhile improvements in performance over the conventional voltage driven case. Much of the discussion was restricted to subwoofers, where a working arrangement using both velocity and acceleration feedback techniques was described, although little was intentionally said about the power amplifier design requirements for such a system.

Consequently, the aim of this paper is firstly to review the options open to the designer of current driven systems, while discussing the limitations of conventional approaches to achieving a high output impedance, such as current feedback, which although fine for subwoofer applications, does not represent the ideal strategy for wide bandwidth systems. It is demonstrated that for high frequency operation, the use of a cascode grounded base output stage delivers optimum performance. Using these techniques enables us to build up a full range active system, one specific implementation being a recording studio monitor using DSP crossover techniques.

2. BACKGROUND

The moving coil loudspeaker can readily be shown to benefit in terms of linearity when controlled by a current source (having theoretically an infinite output impedance), as opposed to the zero output impedance voltage source amplifier conventionally employed [1,2]. In order to establish the benefits of current drive, it is first necessary to examine behaviour for the voltage driven case. The basic electro-mechanical model is represented in Fig. 1, showing amplifier and interconnect source impedance Z_g, voice coil resistance and inductance R_e and L_e respectively. Analysis of this model gives the transfer function between amplifier output voltage and cone velocity:

$$u = \frac{V_{in}\,Bl}{Z_m\,\{Z_s + (Bl)^2 / Z_m\}} \qquad ...(1)$$

where u = cone velocity (ms^{-1})
V_{in} = amplifier output voltage (V)
B = motor system flux density (T)
l = coil length in field B (m)
Z_m = lumped mechanical impedance (kgs^{-1})
Z_s = lumped electrical impedance (Z_g, R_e and sL_e) (ohm)

Most of the elements within this model provide sources of either linear or non-linear distortion. The Bl product is subjected to changes with displacement, as the coil moves in and out of the magnetic gap. The compliance element of the lumped mechanical impedance is also strongly displacement related, as the suspension stiffens up with travel. The lumped electrical impedance, R_e increases with temperature as discussed, while the value of L_e is displacement related as the voice coil moves from its centre position in the magnetic circuit.

Under current drive, analysis follows the same procedure, although a current source is substituted for the voltage source, with output impedance assumed infinite. As a result of this, the series elements of coil resistance, coil inductance and interconnect impedance no longer influence the driving current. Analysis of the model to derive the velocity transfer function gives:

$$u = \frac{I_0 Bl}{Z_m} \qquad \text{...(2)}$$

where I_0 = amplifier output current (A)

Comparing this result with the voltage driven case, equation 1, reveals that the transfer function is of a simpler form, eliminating the terms Z_s and $(Bl)^2$. It is thus predicted that lower distortion will result from elimination of the term $\{Z_s + (Bl)^2 / Z_m\}$. Performance is thus free of any linear and non-linear contributions from Z_s, the $(Bl)^2$ term and is thus less sensitive to compliance non-linearity within the term Z_m.

However, as the voice coil resistance is no longer providing damping, due to the infinite driving impedance, only the mechanical Q of the drive unit acts to control the response function at the system fundamental resonance, whereas under voltage drive, the combined electrical and mechanical Q is set to give a generally critically or overdamped characteristic. Thus the requirement for target response realignment, preferably achieved through feedback techniques.

So in practical terms, from the preceding discussion, we predict two main areas where benefits would be gained under current drive: the elimination of thermally induced effects (power compression), and improvements in linearity. In terms of linearity, it is difficult to directly compare voltage drive with open loop current drive, because with the latter, cone excursion increases substantially around the area of fundamental resonance. However, once the target transfer function has been realigned to match the voltage driven case, a low frequency distortion reduction in excess of 10dB at 100Hz has been recorded. Towards the upper operating range of a bass/midrange driver, a more dramatic 25dB or more reduction at 3kHz has been achieved [3]. This arises due to the elimination of the voice coil inductance from the system transfer function, where the inductance is modulated by cone position and eddy current effects.

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3. REVIEW OF TRANSCONDUCTANCE AMPLIFIER TECHNIQUES

3.1 The Current Feedback Approach

A conventional voltage driven system requires a power amplifier with adequate bandwidth, low distortion and a low output impedance which is linear and frequency independent. With current drive, this latter requirement translates to a high output impedance, which again should be linear and frequency independent.

Several alternative approaches to the problem of transconductance amplifier design have been published over the years, but tend to suffer from problems of either poor linearity, high power dissipation, complexity and difficulty in controlling the output offset current, or a combination of all four. It is worth however reviewing several of these schemes.

The easiest and most obvious solution is to apply current feedback around a conventional power amplifier [4,5], as shown in the Fig. 2. The transconductance of such an amplifier is simply defined by the reciprocal of the current feedback resistor R_f. However, in reality, things are not quite that simple, and this assumes infinite forward gain from the amplifier. If we look at the system in more detail, analysis reveals that the transconductance, g_m, can be written:

$$g_m = \frac{I_O}{V_{in}} = \frac{A}{(Z_O + Z_L) + R_f(1 + A)} \qquad \ldots(3)$$

where: Io = load current,

Vin = input voltage,

Z_O = open loop output impedance,

Z_L = load impedance,

R_f = current sensing resistance,

and A = forward gain of the amplifier.

So consequently, the output impedance of the amplifier may be written:

$$Z_e = (1 + A)\,R_f + Z_O \qquad \ldots(4)$$

This illustrates that while this configuration is perfectly feasible, it has two major limitations. Firstly, the forward gain of the amplifier is frequency dependent as a result of its dominant pole, so consequently the output impedance falls with increasing frequency. Secondly, the loudspeaker impedance is both frequency dependent and non-linear, leading to variations in the system transconductance (top equation), and being analogous to interface distortion in a conventional amplifier.

To investigate this effect in more detail, consider an error function E_1, which is defined:

$$E_1 = \frac{g_m}{g_t} - 1$$

where g_t is the target transconductance (i.e. $g_t = \frac{1}{R_f}$).

So, using equation 3 for the transconductance, we can define E_1:

$$E_1 = \frac{A\,R_f}{(Z_O + Z_L) + R_f(1 + A)} - 1$$

$$\text{i.e.}\quad E_1 = -\frac{Z_O + R_f + Z_L}{(Z_O + Z_L) + R_f(1 + A)}$$

and assuming $R_f(1 + A) >> (Z_O + Z_L)$

E_1 can be approximated to by: $-\dfrac{(Z_O + R_f + Z_L)}{A\,R_f}$

$$\text{i.e.}\quad -\frac{Z_L}{A\,R_f} \qquad \text{...(5)}$$

Now if we suppose as a numerical example, that we specify that E_1 should be less than 0.1%, then from equation 5 we require that:

$$A > \frac{1000\,Z_L}{R_f}$$

Hence, if R_f is set to 0.5 ohm and Z_L assumes a maximum value of 20 ohms, then an open loop gain of greater than 92dB is required. This is seen to be rather high to maintain over the full audio range, and illustrates well the limitations of the current feedback technique. We can observe also that the loop gain of the amplifier is dependent on frequency as a result of the dominant pole, and this is reflected in the output impedance. Additionally, the loudspeaker impedance, which varies with frequency and is non-linear, modulates the transconductance, as can be seen from the preceding analysis. This approach though is regarded as being satisfactory for subwoofer systems, as at low frequencies, high values of open loop gain are quite feasible.

By way of an example circuit, Fig. 3 shows a practical current feedback amplifier, which was used in a commercial subwoofer for home cinema applications. Operational amplifier IC1 provides voltage gain and drives transistors Q1 and Q2 which themselves provide voltage and current gain in order to drive output MOSFETS Q3 and Q4. Low frequency transconductance is defined by resistor R15. Inductor L1 rolls off high frequency transconductance in order to maintain stability. Further compensation is provided by local feedback R16 and C8 around IC1. Control of output offset current is provided by servo amplifier IC2, which detects the voltage across current sensing resistor R15, and injects a compensation current back to IC1, with LF behaviour determined by time constant C1 R4, together with the associated summing resistors. As high levels of return difference are possible at low frequencies, the circuit exhibits low distortion and high output impedance, at 100Hz the circuit is capable of 0.01% THD @ 1A RMS and output impedance of 100k ohm.

3.2 Enhanced Current Feedback Schemes

A refinement of the basic scheme was shown by Lewis [6], and shown in simplified form in Fig. 4. By being symmetrical in nature using two current sensing resistors, the load may be ground referenced, which is often advantageous. Good linearity was reported at 10W average power output, but due to Class A operation, would be very wasteful of power at the 100W or more required for practical purposes. Care must be taken to minimise output offset current with such a scheme. In terms of performance, the same constraints apply as to the basic scheme.

A further ground referenced scheme was described by Nedungadi [7], and although novel, required the complexity of a differential voltage to current converter combined with a floating sensing resistor, in order to maintain current feedback. The reported current output and linearity (100mA at 1% THD), falls somewhat short of our requirements.

3.3 Error Feedforward

The use of error feedforward with voltage amplifiers is by now a well established (and hopefully well understood) technique for attaining low distortion levels with low power dissipation [8]. This approach would initially appear more amenable to transconductance amplifier applications, as the error and current dumping amplifier outputs, being of high impedance could directly be summed into the load, unlike with voltage amplifiers, where summing elements are required. Fig. 5 shows the arrangement in block diagram form, showing a linear error amplifier E, non-linear Class B current dumper D, and feedback transimpedance . Analysis shows:

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$$I_O = \frac{V_{in} E (D / E + 1)}{(1 + a D)} \qquad \ldots(6)$$

where V_{in} = input voltage
I_O = output current
E = error amplifier transconductance
D = current dumper transconductance
a = feedback transimpedance

Thus to eliminate the influence of the non-linear current dumper D,

set $\quad a E = 1$

So in the balance condition,

$$I_O = E V_{in}$$

Assuming that the error amplifier E is perfectly linear, in theory the amplifier offers zero distortion. However in reality, there are a few complications. Firstly, the balance condition will need to be stable in terms of temperature, and be insensitive to drift. For the balance condition to be frequency independent, any high frequency dominant poles in the error amplifier will need to be tracked by compensation in the feedback transimpedance path. If the current dumper operates purely in Class B (i.e. with zero quiescent), the error amplifier is forced to supply the full load current at the crossover transition. As distortion in the error amplifier will not be cancelled, care must be taken to ensure that it is not taken out of Class A operation by such current demands, which places constraints on the minimum standing current.

One factor not immediately obvious is the difficulty in generating the feedback voltage V_f. This requires an active differential current to voltage converter. As it is in the feedback path, any distortion generated will not be cancelled. Wilson [9] described an operational amplifier implementation, producing around 0.2% THD at 1A peak output. To improve on this would require well designed discrete circuitry for the error amplifier and differential transimpedance converter. The optimisation of such a scheme is possible, but certainly not trivial.

4. ENHANCED TECHNIQUES FOR WIDE BANDWIDTH APPLICATIONS

In the previous section, we saw how the current feedback approach was ideal for subwoofer applications. The limitations discussed mean that an alternative strategy is necessary for higher frequency applications, such as when considering a full range active current driven loudspeaker system.

An alternative approach proposed by the author [10] involves the use of an open loop grounded base isolation stage, to isolate the transconductance amplifier from the load. This is shown in block diagram form in Fig. 6. Amplifier

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stage A_t is used to determine a current in sensing resistor R_f. This same current flows through the floating power supplies V_{S1} into the common base output stage (I_L), and thus into the load. Several advantages result from this enhanced technique:

a. Output impedance is essentially independent of the transconductance amplifier A_t, being a function of the grounded base isolation stage.
b. Performance of the transconductance amplifier is isolated from the non-linear load, Z_L, thus eliminating interface distortion through open loop gain modulation.
c. Amplifier A_t can, if desired, operate in Class A, with its own power supply +/- V_{S1}, which may be of low voltage in order to minimise power dissipation.
d. The grounded base stage can operate in Class AB, with a small standing current to give minimal power dissipation without a distortion penalty. The load current I_O is equal to the input current to the stage, I_L, except for any base current leakage to ground, which can readily be made sufficiently small.
e. Unlike the basic transconductance amplifier described, the load is referenced to ground, which is more convenient and reduces the effects of stray capacitances at high frequencies.
f. If points P and Q in the diagram are coincident, earthing related errors are reduced, due to signal currents forming well defined closed paths.
g. The circuit topology is in effect a complementary cascode, with the common base devices being cascoded with those in the transconductance amplifier. This offers performance advantages in terms of bandwidth and linearity.
h. As the grounded base stage operates open loop, it does not degrade the loop gain and bandwidth characteristics of the transconductance amplifier.
i. Finally, for a high efficiency system, the supply voltages +/- V_{S2} can be made adaptive to the signal level, when used in conjunction with a predictive digital processor.

A variation on the theme of this topology is shown in Fig. 7. Instead of the gain defining resistor R_f being referenced to ground, it is connected to the emitters of the common base isolation stage. All the current in R_f flows through the load, except for base current loss, and that flowing through the input of the amplifier. Hence, it is necessary to operate this amplifier as a current gain stage, driven from a transconductance preamplifier. The advantage here is that the current gain stage A_i can operate from ground referenced power supplies, meaning that several amplifiers can share the same supply in an active speaker system.

This system thus represents the preferred design approach. With highly linear low feedback circuitry used in the input current amplifier A_i, making use of localised error correction techniques, the following measured performance has been recorded:

THD @ 75W average output power/ 8 ohm	1kHz	0.005%
	20kHz	0.015%
Intermodulation distortion @ 75W average	19kHz & 20kHz	0.005%
Hum and noise re. 75W average output		-90dB
Small signal bandwidth, -3dB		0.1Hz to 50kHz

Output impedance	20Hz	4.1M ohm *
	1kHz	106k ohm *
	20kHz	11.4k ohm *

* From computer simulation, due to difficulty in performing these measurements.

On a practical note, when performing measurements, apparent distortion levels are often governed by the linearity of the load resistor chosen. For the above measurements, a large number of high stability metal film resistors in a tank of motor oil gave a far more accurate indication of the amplifier capabilities than a standard wirewound resistor load bank. Similar considerations must apply to the transconductance defining resistor within the amplifier itself.

5. ACTIVE LOUDSPEAKER SYSTEMS USING CURRENT DRIVE

As an example of the application of current drive, Fig. 8 shows in block diagram form a two way system, intended to power a Dual Concentric drive unit for studio monitoring applications. After the differential to single ended input stage, HF and LF signals are extracted by the subtractive Linkwitz Riley active crossover [11]. The HF feed is provided with level adjustment. On the LF side, a sensing coil is used to provide velocity and derived acceleration feedback [1]. As well as compensating for the damping loss experienced under current drive, this allows low frequency equalisation to be easily achieved. On the HF drive unit, no resonance control problems were evident under current drive, with magnetic cooling fluid providing adequate damping.

At Reproduced Sound 9 [12], a digital crossover and equalisation system was described, which was shown to yield a flat target amplitude response, together with phase linearity. Fig. 9 shows the adaptation of this scheme within the current drive architecture. In addition to the primary role of the DSP, a secondary function is to process the LF velocity feedback signal, via an inexpensive A to D converter. By mapping the drive unit force factor and compliance non-linearity into the system EPROM, further distortion reduction is possible. In addition, compensation for displacement related variations in the generating factor of the sensing coil allow even greater linearity to be achieved.

6. CONCLUSIONS

In this paper, we saw that the technique of current drive offered valuable reductions in both linear and non-linear distortion, when applied to the moving coil drive unit, amongst them being the elimination of thermally related errors. However, to exploit the potential benefits to the full, it was demonstrated that considerable care needs to be taken with the design of the transconductance power amplifier. For low frequency applications such as subwoofers, the established current feedback technique was demonstrated to be adequate. However, for full range active systems, non of the conventional design approaches were deemed to offer acceptable performance, which is where the use of a symmetrical open loop cascode output stage was felt to benefit. This effectively isolates the non-linear load from any feedback loops within the amplifier gain stages, and gives a naturally high output impedance without recourse to high loop gain.

In terms of applications, the studio monitoring field was regarded as one where particular benefit could be gained, due to the need for such systems to offer high levels of transparency. In addition to the analog implementation, it was shown that within a DSP based architecture, further enhancements in linearity were possible by including low frequency motional feedback within the processing structure, instead of in the usual analog domain. By significantly reducing drive unit distortion mechanisms, current drive should be viewed as a useful technique for optimising the performance of well designed drive units.

7. REFERENCES

[1] P. G. L. Mills, "Improvements in Subwoofer Performance and Quality using Current Drive Technology", presented at the 9th Institute of Acoustics Conference, Windermere, November 1993.

[2] P. G. L. Mills and M. J. Hawksford, "Transconductance Power Amplifier Systems for Current Driven Loudspeakers", JAES, Vol. 37, No. 10, pp. 809-822, October 1989.

[3] P. G. L. Mills and M. J. Hawksford, "Distortion Reduction in Moving Coil Loudspeaker Systems using Current Drive Technology", JAES, Vol. 37, No. 3, pp. 129-148, March 1989.

[4] J. Catrysse, "On the Design of Some Feedback Circuits for Loudspeakers", presented at the 73rd AES Convention, Eindhoven, March 1983 (preprint 1964).

[5] R. A. Greiner, T. M. Sims, "Loudspeaker Distortion Reduction", JAES, Vol.32, No. 12, pp. 956-963, December 1984.

[6] K. Lewis, "Transconductance Amplifiers", Electronics and Wireless World, Vol. 93, No. 1616, pp. 580-582, June 1987.

[7] A. Nedungadi, "High Current Class AB Converter Technique", Electronics Letters, Vol. 16, No. 11, pp. 418-419, May 1980.

[8] P. J. Walker, "Current Dumping Audio Amplifier", Wireless World, Vol. 81, pp. 560-562, 1975.

[9] B. Wilson, "Low Distortion High Output Class B Current Converter Using Error Feedforward", Electronics Letters, Vol. 17, No. 13, pp. 461-463, June 1981.

[10] P. G. L. Mills, "Active Loudspeaker Systems with Transconductance Amplification", Ph. D. Thesis, University of Essex, 1988.

[11] M. J. Hawksford, "A Family of Circuit Topologies for the Linkwitz Riley (LR-4) Crossover Alignment", presented at the 82nd AES Convention, London, March 1987 (preprint 2468).

[12] K. Rodgerson, "DSP Design for Digital Monitoring Loudspeakers", presented at the 9th Institute of Acoustics Conference, Windermere, November 1993.

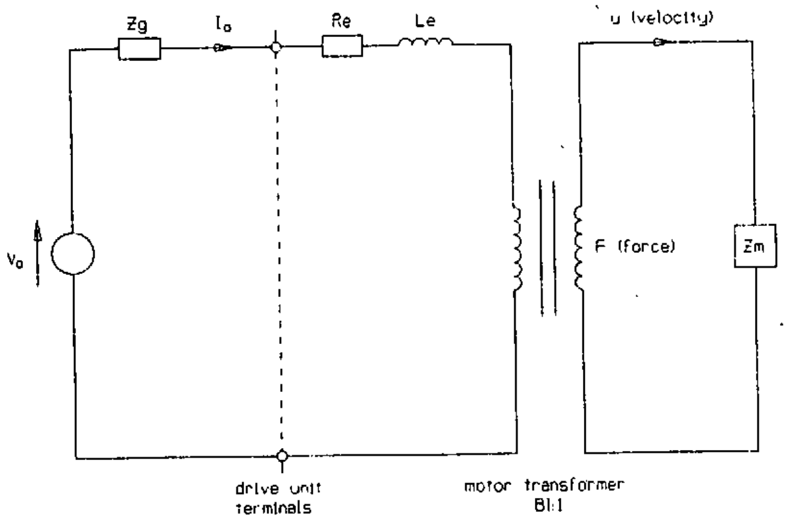

Fig. 1. Basic drive unit electro-mechanical model

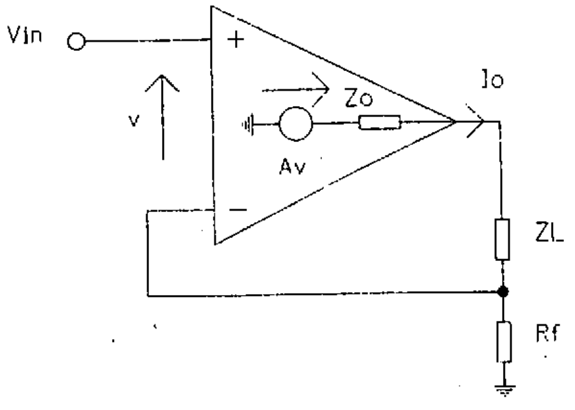

Fig. 2 Current feedback transconductance power amplifier

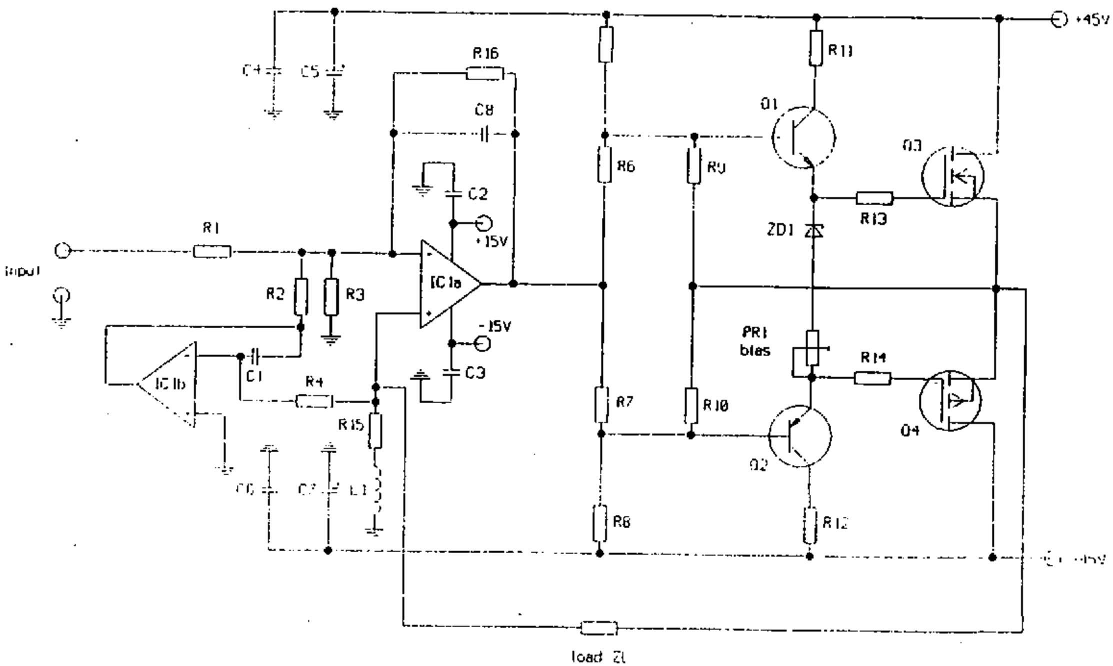

Fig. 3 Current feedback amplifier for subwoofer applications

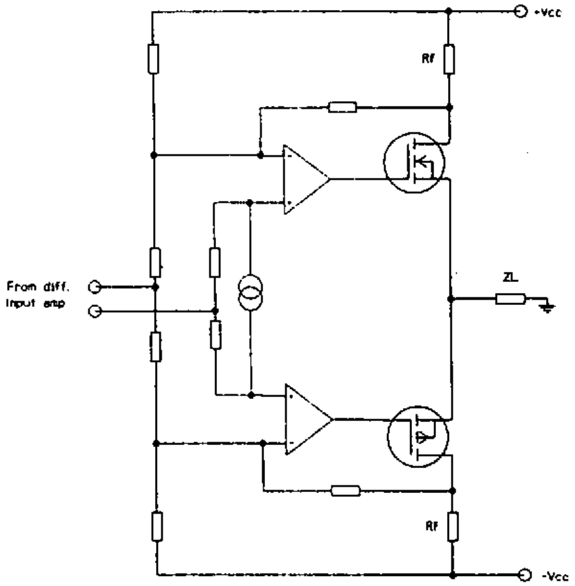

Fig. 4 Symmetrical current feedback scheme (after Lewis)

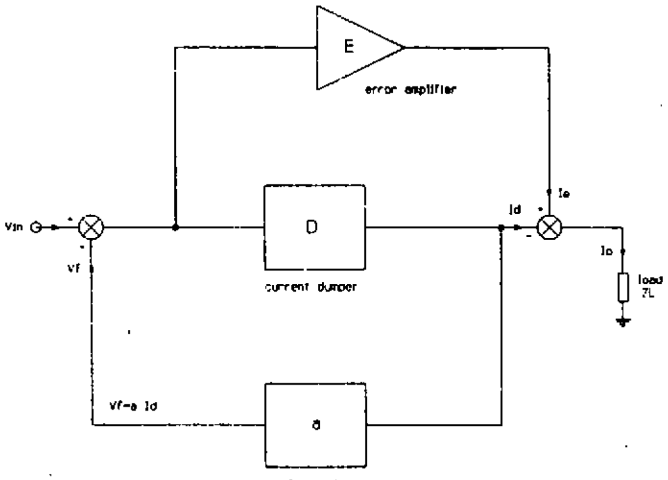

Fig. 5 Block diagram of error feedforward scheme

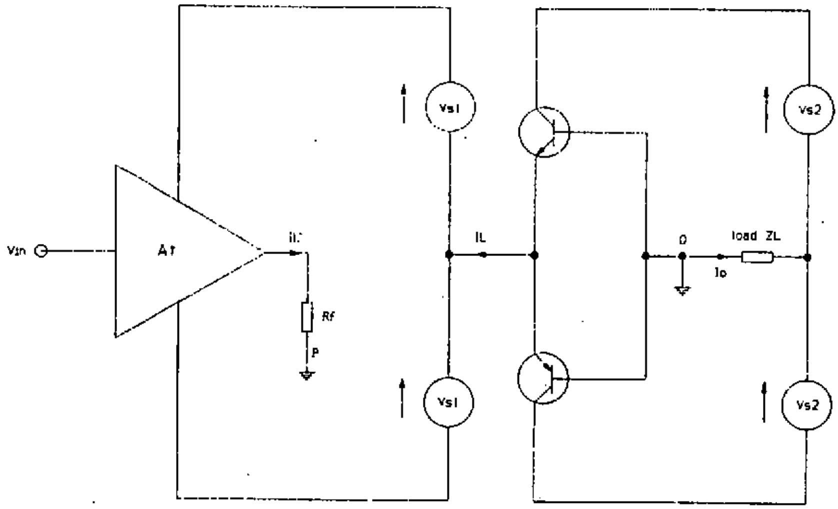

Fig. 6 Proposed grounded base output stage

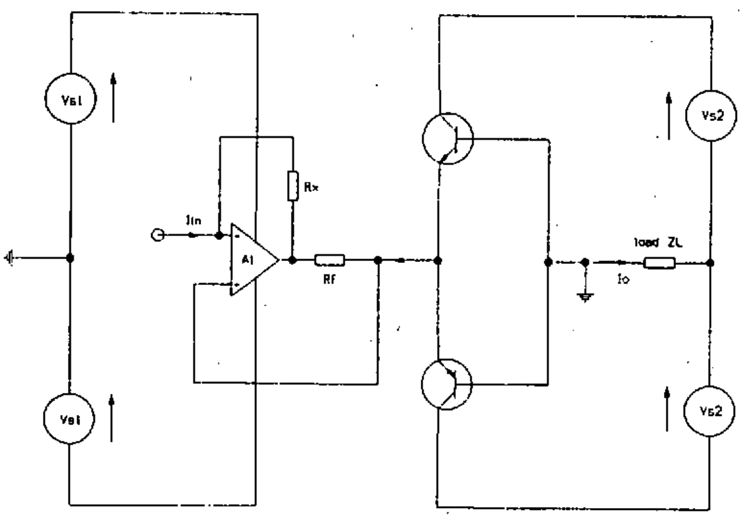

Fig. 7 Variation on Fig. 6, with ground referenced input stage

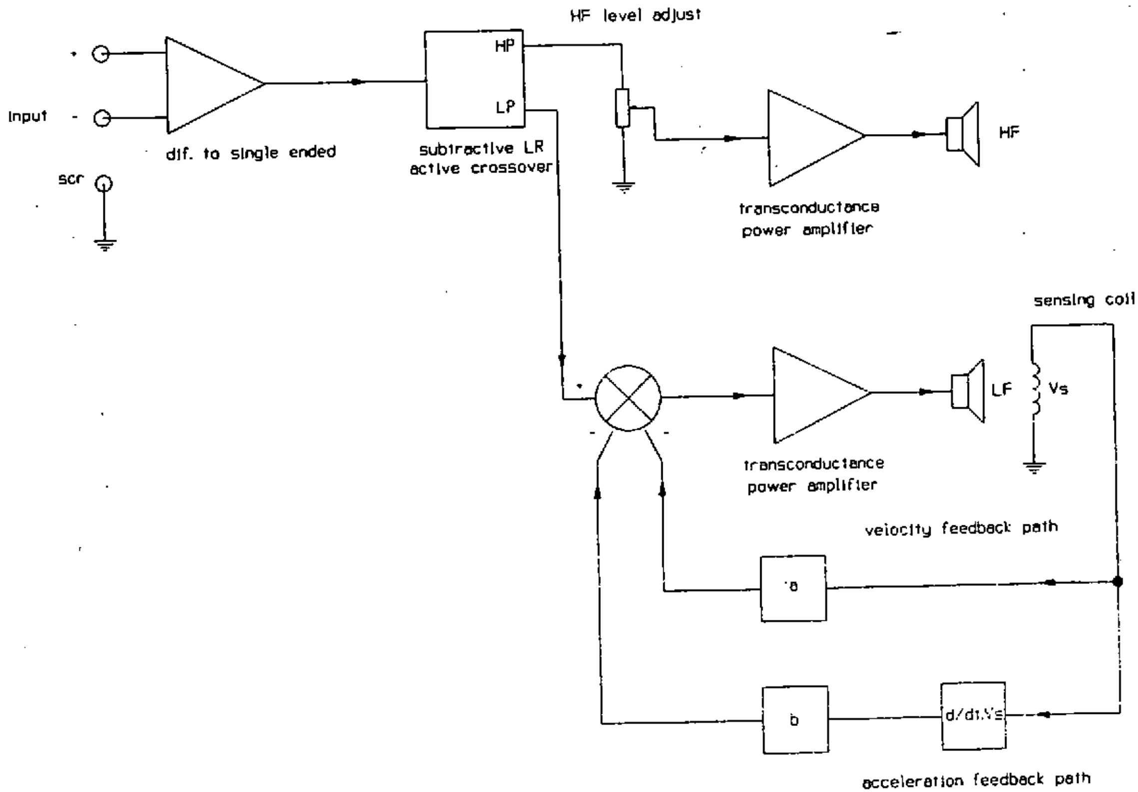

Fig. 8 Anolog active current driven system

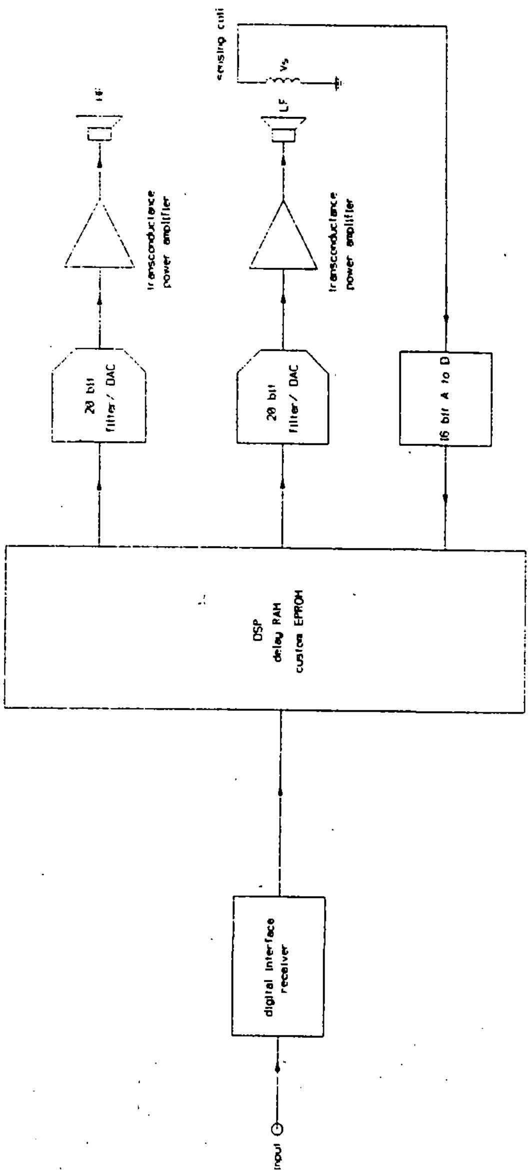

Fig. 9 Digital active current driven system