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IMPROVEMENTS IN SUBWOOFER PERFORMANCE AND QUALITY USING CURRENT DRIVE TECHNOLOGY

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1. INTRODUCTION

The performance of a moving coil drive unit is compromised by a number of distortion mechanisms, many of which are a function of motor system behaviour [1-8]. The effect of self heating on the voice coil resistance is of particular concern, where the positive temperature coefficient (0.4%/°C for copper) results in sensitivity loss, often known as power compression, loss of fundamental resonance damping and passive crossover misalignment. Such problems are frequently exasperated in subwoofer systems, where the already high operating powers are often increased by electronic equalisation, used to extend the low frequency bandwidth to below the natural driver/cabinet roll-off point.

With a conventional amplifier and loudspeaker system, the power amplifier has effectively a zero output impedance and the output voltage of the amplifier is regarded as the information-representing quantity. We shall term this type of system *voltage drive*. In such a system, the current flow in response to a particular voltage demand, is governed by the series elements of voice coil resistance and inductance, together with the interconnect and amplifier output impedance. A force related to the *current* in the system then acts on the drive unit moving elements as a result of the motor principle. Once motion occurs, an emf is induced in the coil to oppose the applied signal voltage, thus limiting the magnitude of current flow. Thus the accuracy with which the drive unit responds to the applied signal is dependent on the series elements in the circuit. Any signal related change in their values will result in distortion.

2. ANALYSIS UNDER VOLTAGE AND CURRENT DRIVE

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 Figure 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. The error resulting from the interconnect component of Z_g is typically 15-20dB below the main signal, and while mainly linear, contains non-linear elements due to the nature of the load.

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:

$$u = \frac{I_o Bl}{Z_m} \qquad \ldots(2)$$

where I_o = 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.

From this analysis, as well as eliminating thermally related problems, we would expect enhanced linearity under current drive. 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 gives a generally critically or overdamped characteristic. This is illustrated by the normalised frequency response curves in Figure 2, which for illustration purposes are for a 12 inch bass unit in a 40 litre sealed box enclosure.

In order to realign the system transfer function under current drive, velocity feedback from the drive unit is proposed as the most effective method [9]. This is detailed in Section 4 of the paper.

3. COMPARISON BETWEEN VOLTAGE AND CURRENT DRIVE

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.

To investigate thermal effects, Figure 3 shows a computer simulation of the normalised frequency response of the example 12 inch bass unit in a 40 litre closed box. At 20°C, the response is as intended, with an overdamped roll off characteristic. However, at 200°C, the response can be seen to exhibit less damping, together with a sensitivity loss of up to 3dB.

In terms of linearity improvements, 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. With this proviso, Figure 4 indicates a useful reduction in levels of second and third harmonic distortion under current drive. For a fairer comparison, distortion levels under closed loop conditions are also shown where velocity feedback is applied to match the response function of the voltage driven case.

It is worth noting that under closed loop conditions, the drive unit is driven less hard around the area of fundamental resonance, thus giving rise to an improvement in efficiency, as well as the reduction in distortion. This is because we are no longer wasting power in directly applying electro-mechanical damping to the drive unit.

4. TRANSFER FUNCTION ALIGNMENT UNDER CURRENT DRIVE

Although many methods have been proposed to sense drive unit motion [10, 11, 12], the most cost effective method is to make use of a sensing coil wound over the primary drive coil, resulting in little additional complexity over a conventional drive unit [9]. It should be noted that to avoid reintroducing thermal errors, the sensing coil must be interfaced to a high input impedance buffer amplifier.

Such a coil generates an output voltage V_s, given by the expression:

$$V_s = (Bl)_s u \qquad \ldots(3)$$

where u = cone velocity, and $(Bl)_s$ is the generating factor for the sensing coil.

Analysis shows that the application of velocity feedback results in a system transfer function of the classic high pass filter form:

$$G(s) = \frac{s^2 T_s^2}{s^2 T_s^2 + s T_s / Q + 1} \qquad ...(4)$$

where T_s is the time constant of the system fundamental resonance, with associated Q factor. By variation of the velocity feedback factor, it is possible to set the system Q to the desired value.

Differentiating the velocity output from the sensing coil gives an acceleration signal. By the use of acceleration feedback, it is possible to effectively lower the driver/ box fundamental resonance, thus gaining low frequency extension. This is a particularly valuable tool in subwoofer design, enabling very extended bass to be reproduced from a cabinet of acceptable dimensions. It must be considered however, that the drive unit must have adequate excursion capabilities for the sound pressure levels required from the system. The overall system transfer function will now take the normalised form:

$$G(s) = \frac{s^3}{s^3 + 2s^2 + 2s + 1} \qquad ...(5)$$

with coefficients set here for a Butterworth alignment. Note that the system transfer function is now third order, giving a greater rejection of out of band information, but without the disadvantages of higher order bandpass (coupled cavity) systems.

A block diagram of the feedback arrangement is shown in Figure 5, which shows the two distinct velocity and acceleration feedback paths. By adjusting the two feedback coefficients a and b, it is possible to vary the system roll off point and Q independently, thus enabling any practical system response to be attained. Figure 6 shows a family of typical curves, generated by computer modelling of the closed loop system. In Figure 6a, the effect of increasing velocity feedback can be seen to reduce the system Q as predicted, with the top curve representing the open loop case. No acceleration feedback was applied here. Figure 6b shows, for a fixed level of velocity feedback, the result of increasing values of acceleration feedback, resulting in lowering of the system cut-off frequency.

One practical application of the ease of response function realignment is with domestic home theatre systems, where the subwoofer may also be called upon to accurately reproduce music. As the measurements of Figure 7 show, in the *home theatre* setting, energy is concentrated in the 35-70Hz region, to attain the best subjective impact from movie special effects. However in the *hi-fi* mode, a flatter more extended response is required. The alignment chosen here was -6dB at 18Hz. Note that the response has been 4th order low pass filtered -6dB at 90Hz, in order to match in with the main speakers in the system.

5. OVERVIEW OF PROTOTYPE SYSTEM

Figure 8 outlines the prototype home theatre system in more detail. A 4th order Linkwitz-Riley input filter was found to be necessary, as lower order filters resulted in too much output in the upper bass region, giving unacceptable levels of colouration, a problem with many existing commercial systems. The feedback arrangement from the sensing coil is as previously outlined. The transconductance power amplifier stage benefits from the stable thermal behaviour of power MOSFETS, while a DC current sensing servo loop is used to minimise the output offset current in the load. Unlike a conventional voltage amplifier, switch-on transient protection is achieved with a start-up delay by shorting the output to ground. The exact topology of the power amplifier is not covered in this discussion, but follows from previously presented work [13].

In order to provide automatic operation, an input signal sensing circuit is employed, which under no signal conditions mutes the output and reduces the output stage quiescent current to zero, in order to minimise power dissipation. 'Wake-up' time is under 250ms, while a delay of approximately 10 minutes is set before re-entering standby mode.

6. CONCLUSIONS

This paper has presented an alternative approach to active subwoofer design, where the application of current drive has been seen to either avoid or minimise many of the problems inherent in the amplifier/ loudspeaker interface under conventional voltage drive. The most significant benefit is the elimination of thermal power compression effects, though benefits in terms of linearity are also significant.

In order to restore damping to the drive unit, which is lost under current drive, velocity feedback from a sensing coil was demonstrated as being an effective method, while also enabling derived acceleration feedback to be applied in order to extend low frequency bandwidth.

The techniques presented may be applied equally to domestic subwoofer systems or at a higher power level, to professional sound reinforcement systems, where the ability to safely parallel power amplifiers leads to increased levels of reliability, due to redundancy within the system.

7. ACKNOWLEDGEMENTS

Thanks are due to Simon Rae of Tannoy Ltd., for his assistance in performing measurements on the prototype system.

8. REFERENCES

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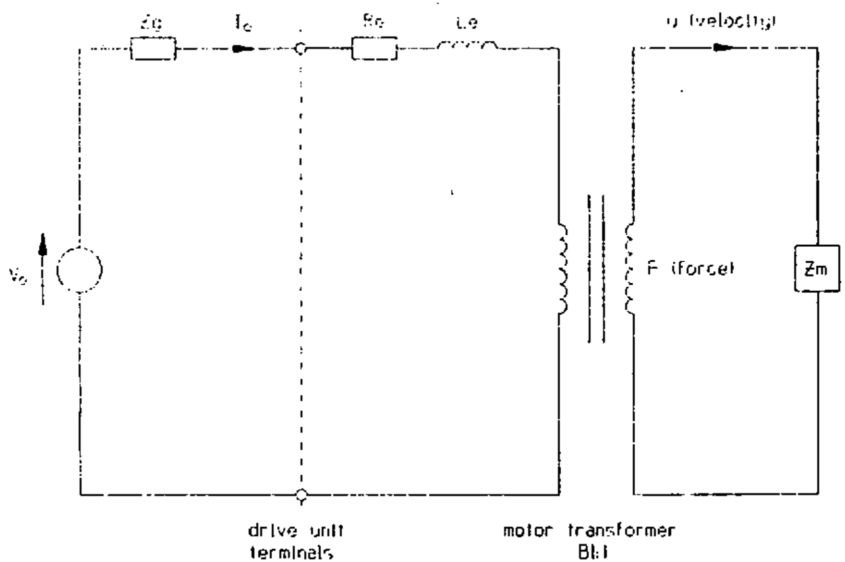

Fig. 1. Basic drive unit electro-mechanical model

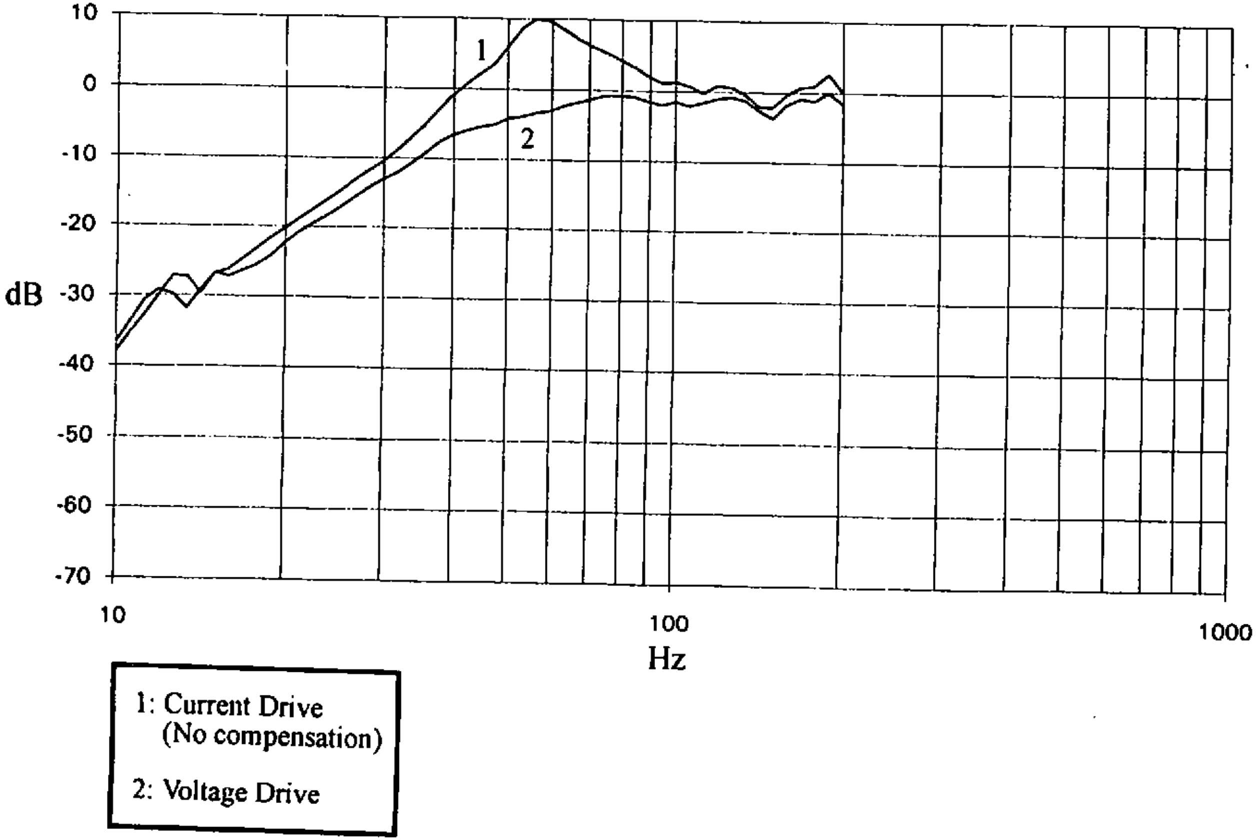

Fig. 2. Comparison of normalised frequency response curves under voltage and current drive.

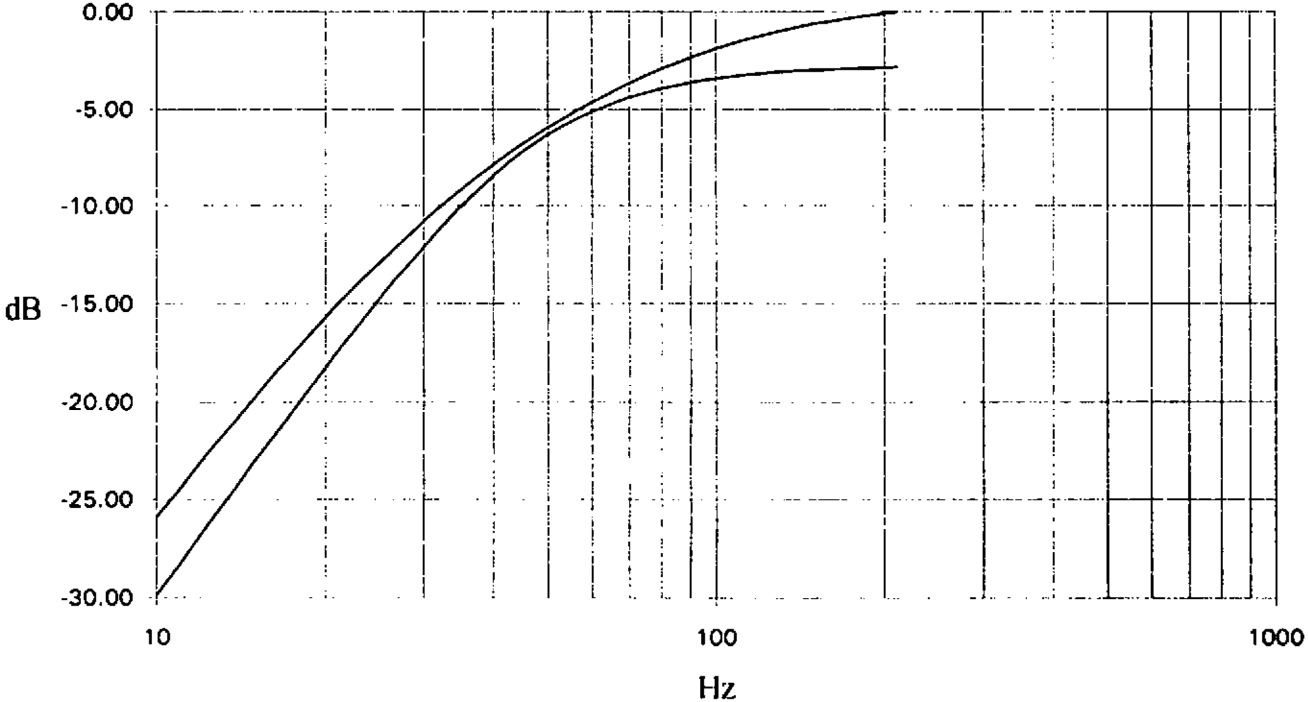

Fig. 3. Comparison of Normalised frequency response under voltage drive at 20 deg. C. and 200 deg. C.

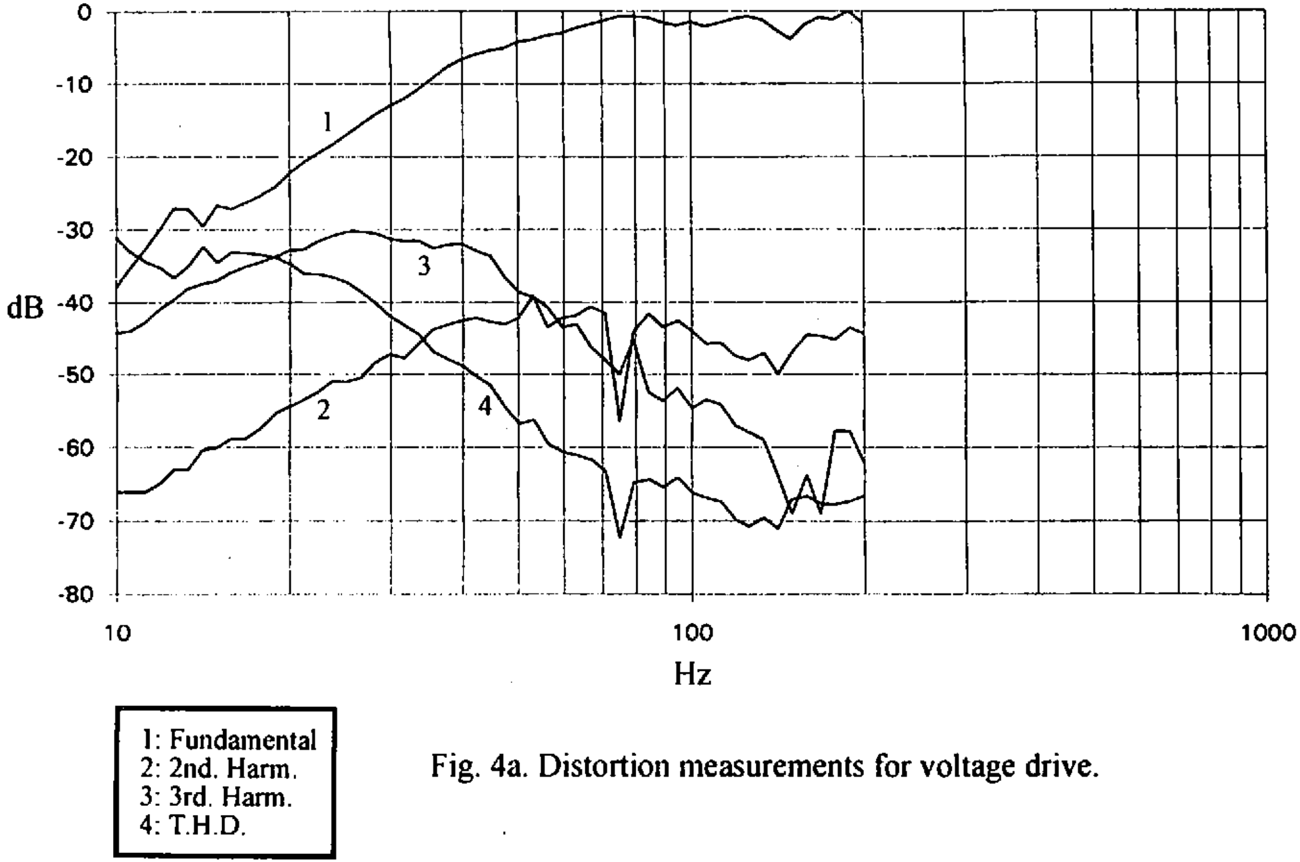

Fig. 4a. Distortion measurements for voltage drive.

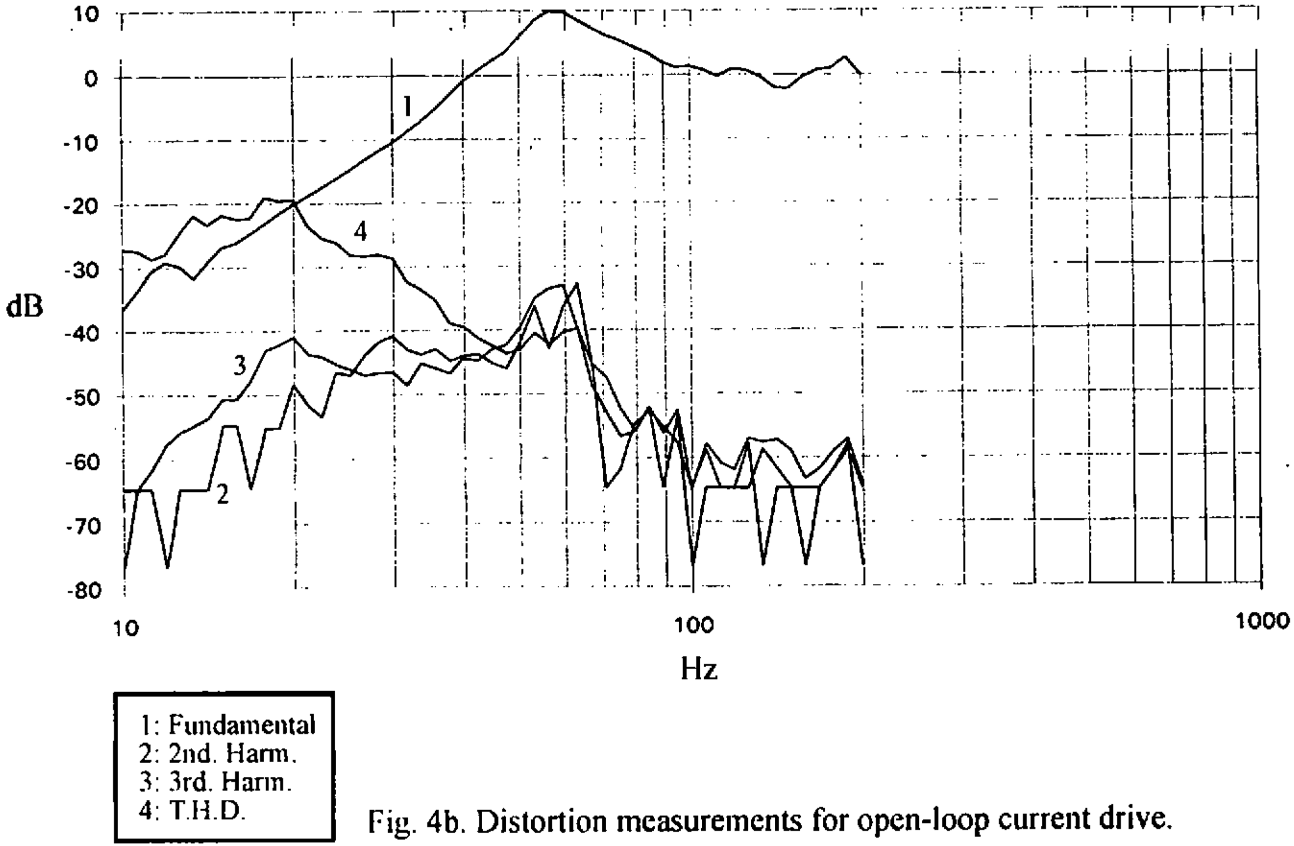

Fig. 4b. Distortion measurements for open-loop current drive.

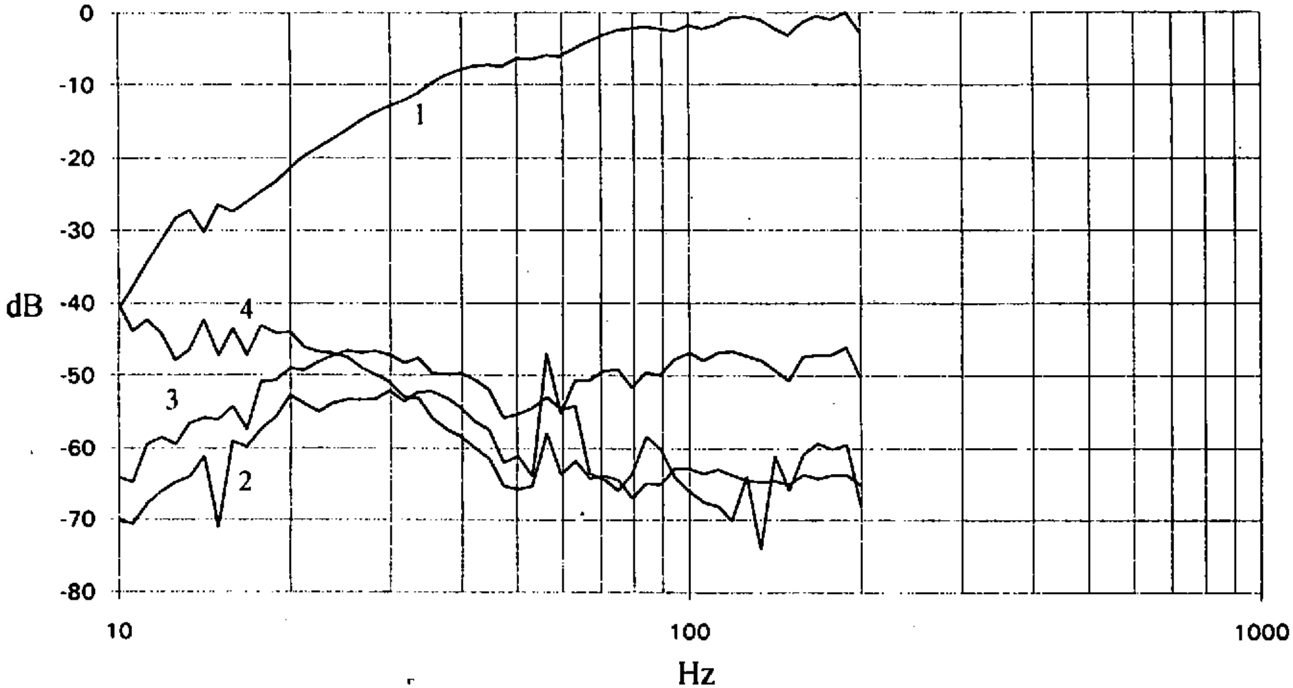

Fig. 4c. Distortion measurements for closed-loop current drive.

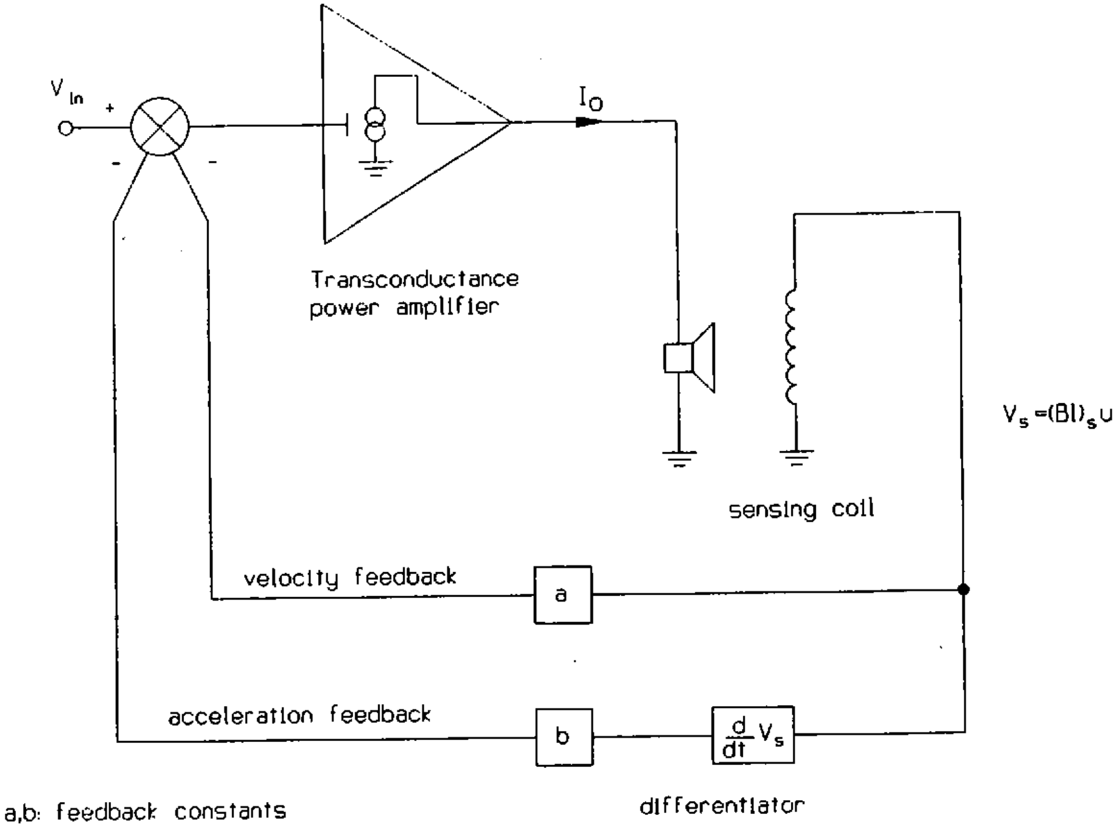

Fig. 5. Block diagram of closed loop control system

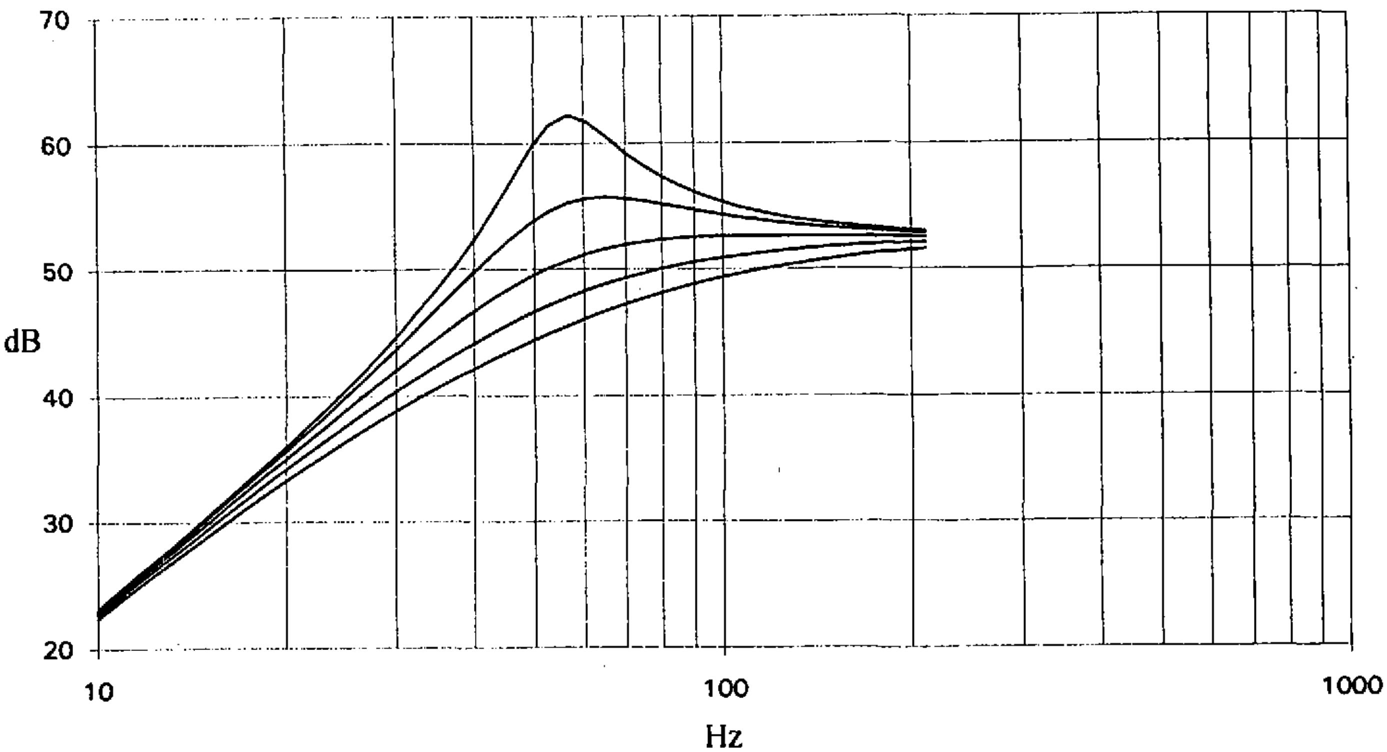

Fig. 6a. Closed-loop response curves, with velocity feedback

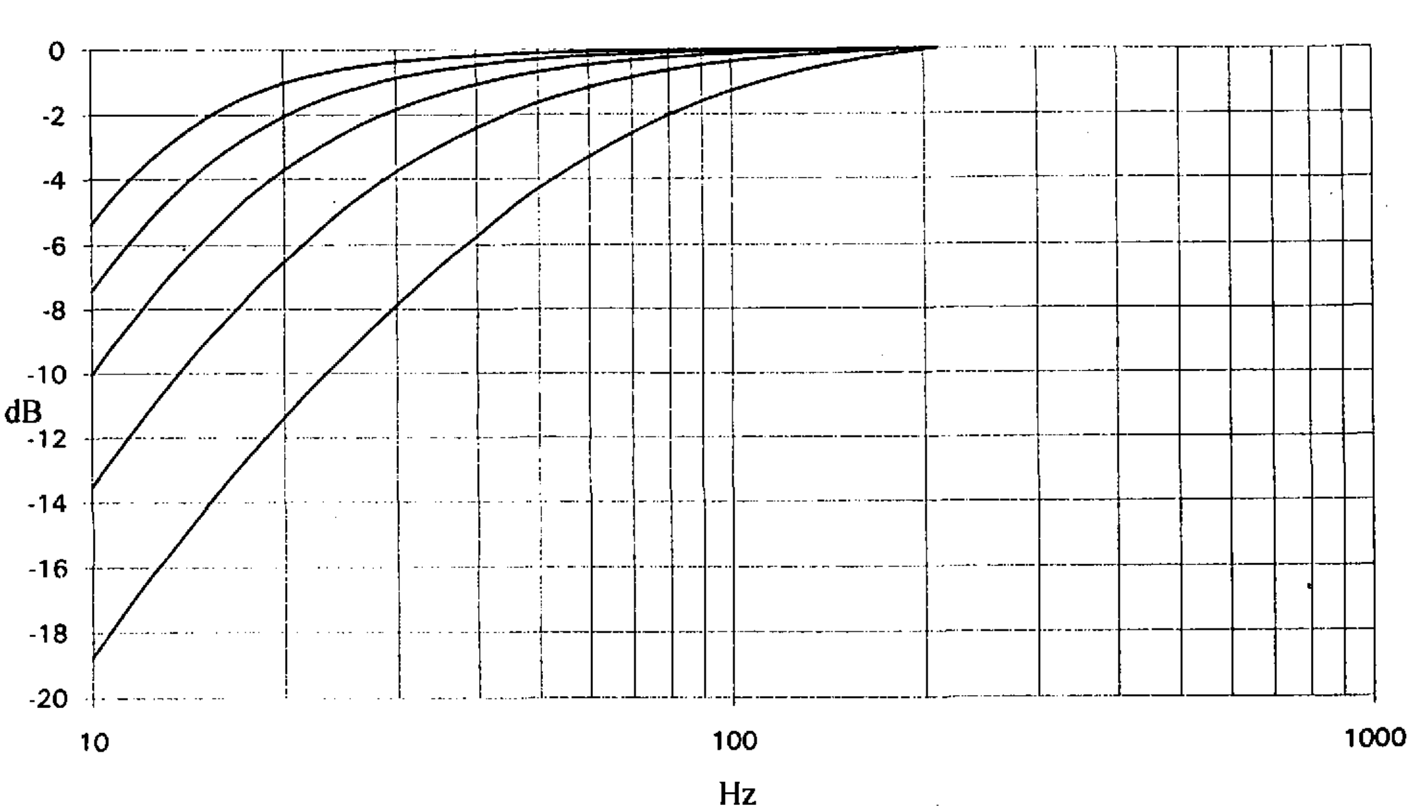

Fig. 6b. Closed-loop response, with velocity and acceleration feedback

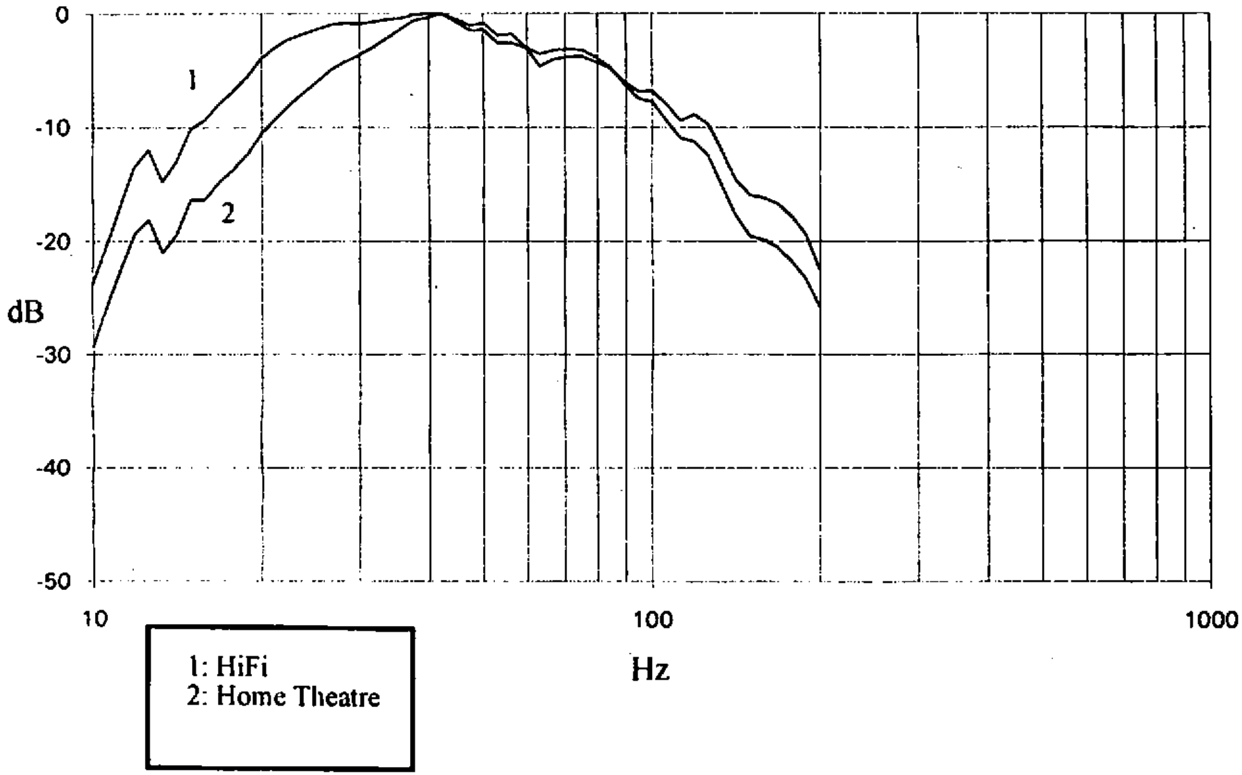

Fig. 7. Measurements on prototype system, for both HiFi and Home Theatre settings.

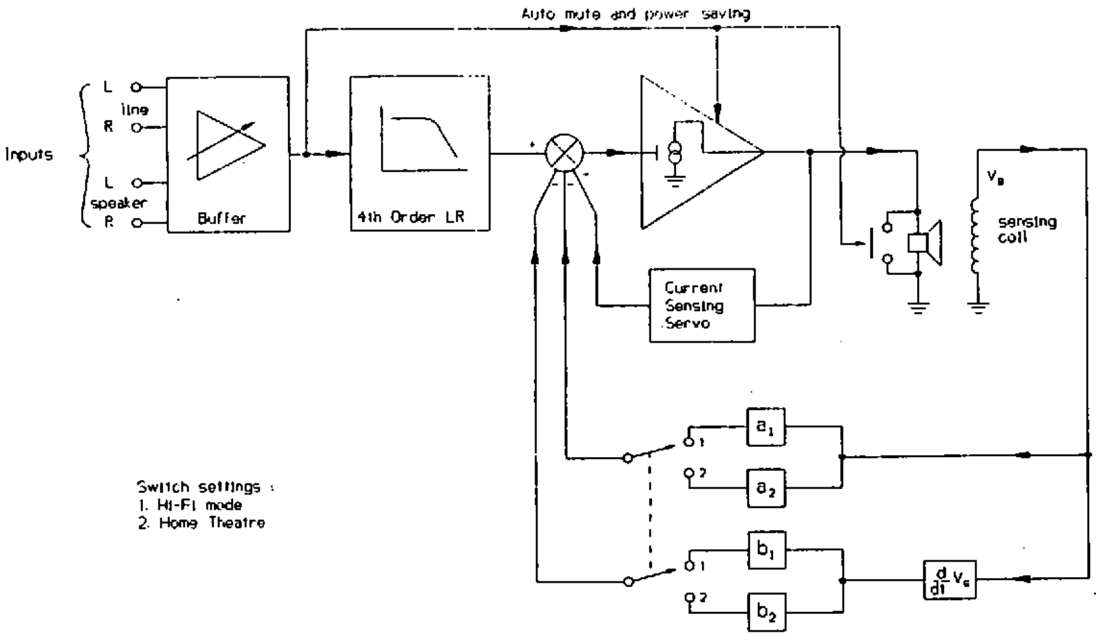

Fig. 8. Block diagram of prototype system