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Design and Evaluation of Accelerometer based Motional Feedback

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ABSTRACT

The electro dynamic loudspeaker is often referred to as the weakest link in the audio chain due to low efficiency and high distortion levels at low frequencies and high diaphragm excursion. Compensating for loudspeaker non-linearities using feedback or feedforward methods can improve the distortion and enable radical design changes in the loudspeaker which can lead to efficiency improvements. In combination this has motivated a revisit of the accelerometer based motional feedback technique. Experimental results on a 8 inch subwoofer show that the total harmonic distortion can be significantly reduced at low frequencies and large displacements.

1. INTRODUCTION

In 1973 Edward R. Hanson from Phillips [1] stated the most important loudspeaker conditions to comply with being

- Size as small as possible
- Frequency response as wide as possible
- Frequency response as flat as possible
- Distortion as little as possible
- Efficiency and power handling capability must be considered

Back then the size condition was stressed by the advent of 4 channel sound and today this condition is still actual with the advent of 3D sound which require 12 loudspeakers in a 7.1.4 set up. A small transducer will have to move the diaphragm further to provide the same sound pressure level compared to a larger transduceer and this tends to increase the distortion due to displacement dependent non-linearities of the compliance, the force factor and the self inductance [2]. Further more a small loudspeaker enclosure will have a high impedance which will limit the low frequency range resulting in a narrow and non flat frequency response if no action is taken. It was noted that the efficiency and power-handling capability must be considered in any attempt to correct these problems. Today, efficient and powerful class-D amplifiers and switch mode power supplies are up for this task.

The distortion and frequency response can be corrected by equalization combined with motional feedback (MFB) or model based feedforward methods. Feedforward methods have received a lot of focus in recent years due to advances in digital processors, loudspeaker characterization methods and loudspeaker modelling [3–5]. Feedforward compensation avoids a motional sensor but requires an accurate model of the loudspeaker that is able to adapt to time drifting loudspeaker parameters, and non-linearities [6]. Even though feedforward compensation has come a long way and seems very promising the alternative MFB technique is revisited in this work. The output or motion of the loudspeaker can either be captured as acceleration [1, 7, 8], velocity [9–14], pressure [15] or position [16–18]. MFB is normally implemented on closed box systems because only a single sensor is necessary to sense the output. Attempts with higher order systems including passive radiators has also been successfully implemented [19]. In [20–22] MFB was alternatively used to control the undamped mechanical resonance of a current driven loudspeakers. Loudspeaker protection using feedforward or feedback has also been proposed [23, 24].

2. CONTROL THEORY

A block diagram of the control scheme used in this work is shown in figure 1. The design of the controller is based on the transfer function of the Plant which consist of an amplifier, a loudspeaker and an accelerometer. The Feedback applies a gain to control the level of feedback compared to the input level.

2.1. Class-d amplifier

The class-D amplifier can be modeled as a 2nd order butterworth filter given by

$$G_{amp} = \frac{G_0 \omega_c^2}{s^2 + \sqrt{2}\omega_c s + \omega_c^2} \tag{1}$$

where

$$\omega_c = 2\pi f_c = \frac{1}{\sqrt{L_f C_f}} \tag{2}$$

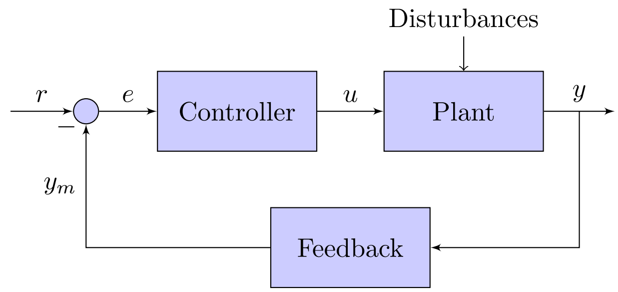


Figure 1: Block diagram of negative feedback

2.2. Loudspeaker

The transfer function from voltage to acceleration given in equation (3) is derived from the well known equations (4) of the lumped loudspeaker model [5].

$$G_{(a/v)} = \frac{Bls^2}{Bl^2 s + (sL_e + R_e)(s^2 M_{ms} + sR_{ms} + \frac{1}{C_{ms}})} \tag{3}$$

$$\begin{aligned} u(s) &= R_e i(s) + sL_e i(s) + sBlx(s) \\ F(s) &= Bl \cdot i(s) \\ F(s) &= M_{ms} s^2 x(s) + R_{ms} sx(s) + \frac{1}{C_{ms}} x(s) \end{aligned} \tag{4}$$

R_e and L_e are electrical resistance and inductance, Bl is the force factor, M_{ms}, Rms and C_{ms} are respectively the mechanical mass, resistance and compliance.

2.3. Sensor

The accelerometer has a bandwidth of 10 kHz and a sensitivity of 6.7 mV/G with a supply voltage of 5 V. The accelerometer can be modelled as a 2nd order peaking low-pass filter with a peak located around 21 kHz, and a peaking magnitude of 7 dB.

2.4. Control

A bode plot of the Plant which consist of $G_{amp} \cdot G_{v/a} \cdot G_{sens}$ is shown in figure 3. As seen the magnitude of the Plant needs to be raised at low frequencies in order to obtain a higher loop gain at lower frequencies. The controller consists of two

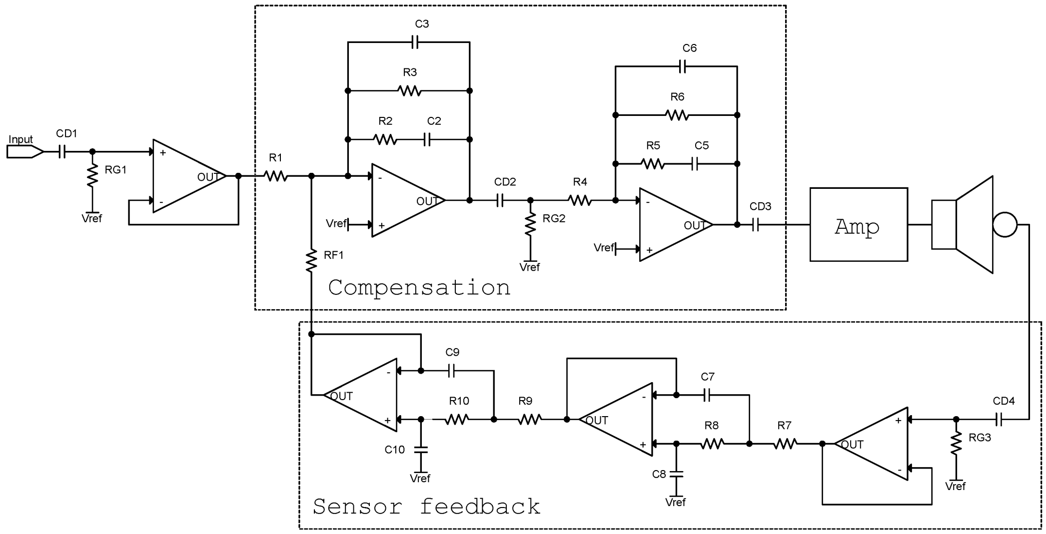


Figure 2: Simplified schematic.

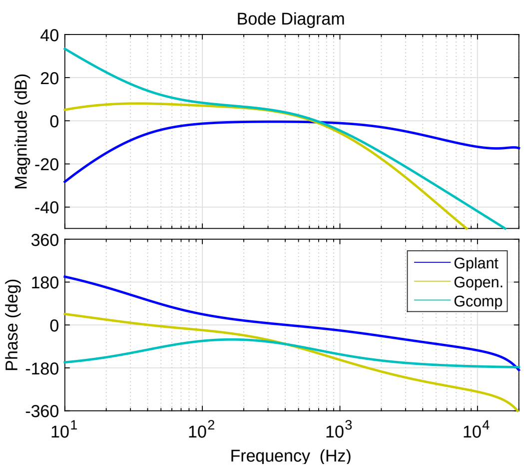


Figure 3: System transfer functions

poles at DC, 2 zeroes at the lower cut-off frequency of the Plant and 2 poles at 600 Hz. This is done to attenuate noise and high frequency break up modes of the cone as seen in the sound pressure level measurement in figure 5a.

The compensation transfer function is given by

$$G_{comp} = K_c \frac{(\tau_{z1}s+1)(\tau_{z2}s+1)}{(\tau_{p1}s)(\tau_{p2}s)}, \tau_{z,p} = \frac{1}{2\pi f_{z,p}} \tag{5}$$

The resulting open loop transfer function G_{open} is plotted in figure 3. It resembles a low-pass characteristic with an open loop phase margin of around 70 degrees at 630 Hz.

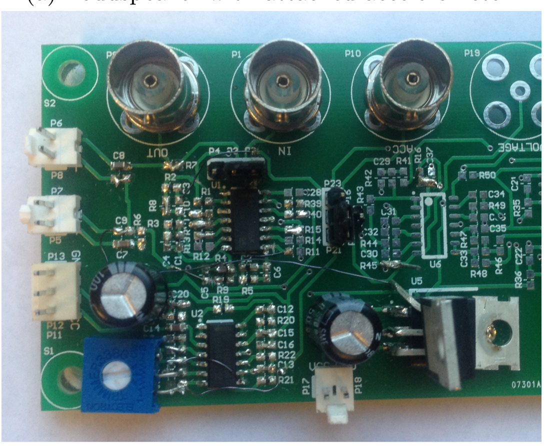
3. EXPERIMENTAL WORK

The transducer used during this work is an 8" woofer, HiVi-M8N. The cone of the transducer is an aluminium/magnesium blend, which gives a light weight and stiff cone. Severe breakup modes appear from 1 kHz and up as seen in figure 5a. The sensor is implemented with an of the shelf one-axis accelerometer from Analog Devices (ADXL001-250BEZ) that can handle up to 250 G and provides a 10 kHz bandwidth. The accelerometer is glued to the center of the transducer, figure 4a. Small wires run from the accelerometer to the printed circuit board (PCB) connecting supply voltage, ground, and the output signal of the accelerometer. The wires goes in a soft arc from the accelerometer to the loudspeaker frame to avoid bending stress on the wires.

3.1. Implementation

It is out of scope to fully describe the analogue design and implementation of the MFB scheme. However figure 2 can be used to get a rough idea of the implementation. V_{ref} is a bias voltage, equal

(a) Loudspeaker with attached accelerometer.



(b) Control PCB prototype.

Figure 4: Hardware

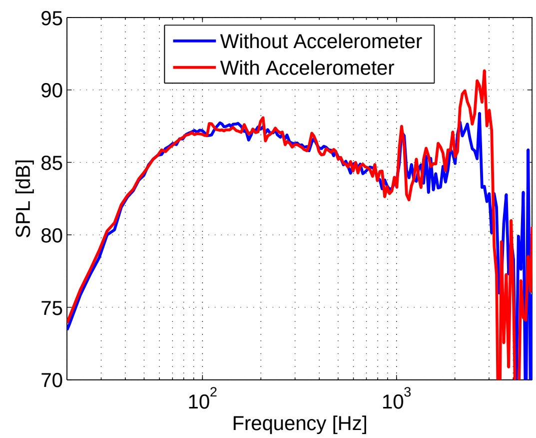
to half of the supply voltage of the operational amplifiers. The operational amplifiers use a single supply voltage of +12 V. Figure 4b shows a picture of the prototype. Three BNC connecters are mounted on the PCB to be able to measure the input signal, the output signal (signal to amplifier) and the output of the accelerometer. A set of jumpers makes it possible to enable/disable the controller and the MFB.

The gain G_0, as described in equation 1, of the used amplifier is 20 and the cut-off frequency is $61kHz$. It is noted that the accelerometer has a relatively high noise floor at low accelerations. Two series connected 2nd order butterworth low-pass filters are therefore utilized and they are modelled with (1). The gain is set to 1.5 and the cut-off frequency is set to 600 Hz.

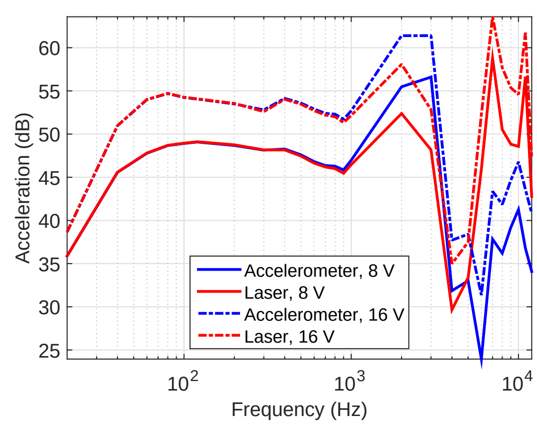
3.2. Sensor verification

A Polytec Doppler laser is used to investigate the influence of the accelerometer mounted to the cone. The sound pressure response is measured with and without the accelerometer mounted on the speaker cone, figure 5a. It is found that the response is not affected particularly until around 1 kHz. Since the design is intended for a subwoofer, this is beyond the required frequency range.

Laser measurements were also used to verify the



(a) Loudspeaker SPL response.



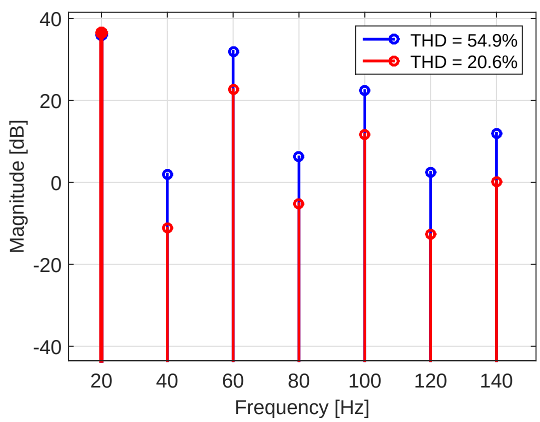
(b) Comparison of accelerometer and laser measurements.

Figure 5: Validation of accelerometer

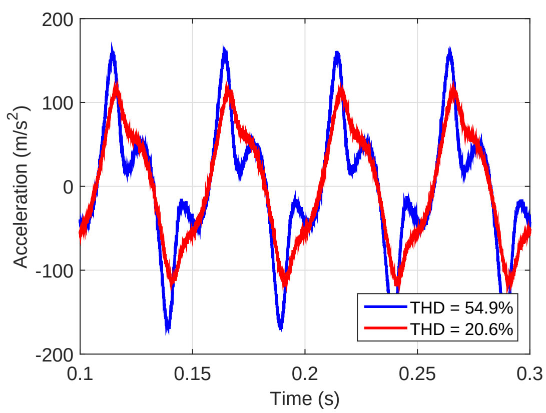
output of the accelerometer. A comparison of laser and accelerometer measurements at different voltage levels is shown in figure 5b. The measurements show a very good coherence up to around 900 Hz. The bandwidth of the controller was chosen to be lower than 900 Hz based on this observation.

3.3. Results

A comparison of a 20 Hz measurement with and without MFB can be seen in figure 6a and 6b. As seen in figure 6a the harmonics are lowered and the THD is improved by more than 2 times from 54.9 % to 20.6 %. Figure 6b illustrates the time domain signals where it is clearly seen that the distortion has been improved greatly with MFB.



(a) Spectrum comparison of acceleration with (RED) and without (BLUE) MFB measured with laser.



(b) Time comparison of acceleration with (RED) and without (BLUE) MFB measured with laser.

Figure 6: 20 Hz and 8 V_{RMS} comparison

Frequency (Hz)	THD w/o. / w. (%)		
	$2\,V_{rms}$	$4\,V_{rms}$	$8\,V_{rms}$
20	5.3 / 1.2	15.0 / 3.7	54.9 / 20.6
30	2.4 / 0.8	5.6 / 1.8	22.0 / 6.7
40	1.3 / 0.7	2.5 / 1.2	7.0 / 2.8
50	0.9 / 0.7	1.5 / 1	3.2 / 1.7

Table 1: Laser THD Measurements Without and With Compensation

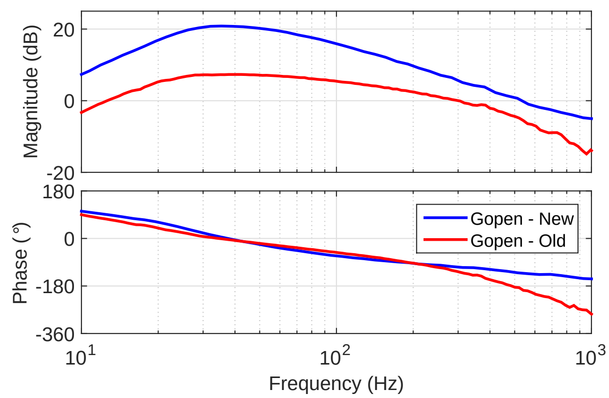


Figure 7: Measured original (RED) and improved (BLUE) open loop response

Frequency (Hz)	THD w/o. / w. (%)		
	$2\,V_{rms}$	$4\,V_{rms}$	$8\,V_{rms}$
20	5.3 / 1.1	15.0 / 1.3	54.9 / 9.1
30	2.4 / 0.4	5.6 / 0.5	22.0 / 2.1
40	1.3 / 0.3	2.5 / 0.5	7.0 / 1.6
50	0.9 / 0.5	1.5 / 0.8	3.2 / 0.5

Table 2: Improved Laser THD Measurements Without and With Compensation

In table 1 the THD at low frequencies with and without MFB are shown at different voltage levels. The magnitude of the open loop response will drop at low frequencies and high excursions due to the non-linear behaviour of the loudspeaker which was not accounted for in the small signal analysis. In order to improve the open loop gain at lower frequencies an integrator was added to the control circuit. A comparison of the old and new open loop response is shown in figure 7. New laser measurements where performed and the improved results are listed in table 2. The THD is improved over the whole measuring range and at 20 Hz and 8 V_{RMS} the THD is lowered by more than 5 times.

4. FUTURE WORK

In future work the MFB could be limited as a function of displacement in order to improve the signal to noise ratio. Listening tests and transient response should also be performed in order to reveal the full acoustical potential of MFB. As mentioned previously the power requirement will increase when the transducer is forced to deliver a certain frequency response which is the case with MFB. The power requirement and protection must thus also be investigated. The sound quality and power requirements vs. enclosure size is another interesting topic to explore. A digital implementation would probably be advantageous in terms of added functionality. The added cost of the MFB implementation may be compensated for by cost savings on the transducer, since the linear requirements of the transducer is lowered.

5. CONCLUSION

Accelerometer based MFB of an 8 inch woofer is designed and validated. Experimental results show that the accelerometer is useful as a sensor and the feedback loop was successfully implemented. The worst case THD was substantially reduced by more than 5 times. The full potential of motional feedback in terms of transient response, perceived sound quality, cost and power requirements is still to be revealed.

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