Capacitive motional feedback for loudspeakers

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1 Disclaimer

This document is presented as is. Care have been taken to ensure correctness of the text, but it is not guaranteed.

If you use this technology, you do it on your own risk. As all electronic appliances, this can also be dangerous or fatal if used incorrectly.

2 Introduction

The basic working methods of dynamic loudspeaker drivers have remained almost unchanged from the first models. Traditional speaker driver consists of a cone, moved by a voice coil that is placed in magnetic field. When current is driven through this coil, it causes a force that moves both the coil and cone attached to it. This produces a sound that can be heard. In the picture 1 (page 3), normal loudspeaker components are displayed along with the components special to the measurement method described in this document. Due to the non-ideal characteristics of motor system, suspension and like, sound generated by loudspeaker driver consists of unwanted characteristics like harmonic distortion and compression.

Motional feedback means a technique where the movements of the loudspeaker cone are measured and this measurement is used for creating a driving signal correcting the unideal characteristics as well as possible. Motional feedback can be most successfully used in frequency range where the cone can be handled as a piston (low frequency).

This paper further describes the method presented in patent publication WO 2004/082330 and construction and measurements of loudspeakers utilizing this method. For more information you may read the patent publication itself.

3 Short description of the method

The current implementation of the method is based on the cylindrical capacitor placed in the space inside the voice coil former and above the pole piece of magnet system. The inner surface (cylinder) of the capacitor is attached to the top of the pole piece and outer surface inside the voice coil former. Capacitance of this capacitor changes linearly according to the deflection of the cone. Principle of the measurement method and it's utilization in motional feedback is presented at the following figure:

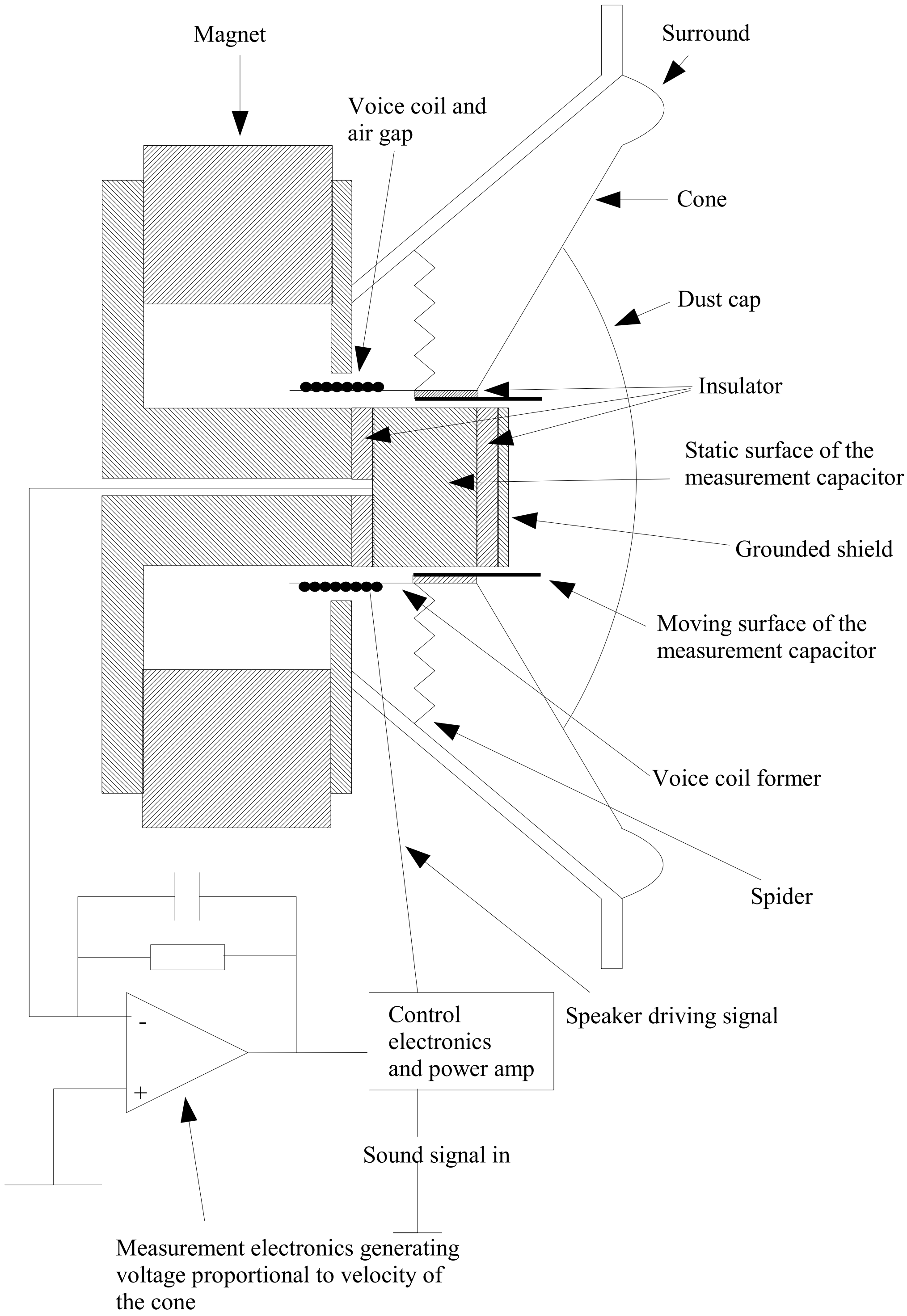


Figure 1: Principle of the measurement method

Capacitance of the measurement capacitor can be calculated using the following formula:

$$C = 2*\pi*\varepsilon_r*\varepsilon_o \frac{l}{\ln(\frac{r2}{r1})}$$

Formula 1

ε_o =	permittivity of vacuum (8,8542 * 10^{-12} C^2 * N^{-1} m^{-2}),
ε_r =	relative permittivity (for air approximately 1),
l =	length of the capacitor (m),
r1 =	inner radius of the capacitor (m),
r2 =	outer radius of the capacitor (m).

In this formula, the length l is changed according to the movement of the loudspeaker cone.

For calculating capacitance per unit of length, following formula can be used (l set to 1):

$$C_m = \frac{2*\pi*\varepsilon_r*\varepsilon_o}{\ln(\frac{r2}{r1})}$$

Formula 2

Measurement circuit is implemented with simple current to voltage-converter. Voltage generated from the circuit is proportional to the change of the capacitance of the measurement capacitor according to following formulas:

$$U_{out} = R*\frac{dQ}{dt}$$

Formula 3

$$U_{out} = R*U_{cap}*\frac{dC}{dt}$$

Formula 4

$$U_{out} = R*U_{cap}*C_m*\frac{dl}{dt}$$

Formula 5

U_{out} =	output voltage of the current to voltage converter (V),
R =	value of the feedback resistor of the current to voltage converter (Ω),
Ucap =	voltage applied to the measurement capacitor (V),
dQ/dt =	derivative of the charge of the measurement capacitor (As/s (=A)),
dC/dt=	derivative of the capacitance of the measurement capacitor (F/s (=A/V)),
dl/dt =	derivative of the length of the measurement capacitor (m/s).

With sine signal the deflection of the cone and length of the measurement capacitor follow the following formula:

$$l = x_{max} \sin(f * t)$$

Formula 6

x_{max} = peak value of the deflection (one way),
l = length of the capacitor,
f = frequency of the sound.

The output voltage of the current to voltage converter can be derived from the formulas 5 and 6 (for sine signal):

$$U_{out} = R * U_{cap} * C_m * \frac{dl}{dt}$$
$$= R * U_{cap} * C_m * 2 * \pi * f * x_{max} * \cos(f * t)$$

Formula 7

Because maximum value of the cosine-function is 1, the cos(f*t)-term can be set to one and the maximum value of the voltage can be calculated with frequency and deflection in question.

For forthcoming examinations, it is necessary to make these deflection values into physical SPL-levels. Following formula can be used for that purpose:

$$SPL = 94{,}3 + 20 * \log(x * 2) + 40 * \log(f) + 40 * \log(d) - 20 * \log(r)$$

Formula 8 (source http://www.linkwitzlab.com)

x = maximum value of deflection (one way) (m),
f = frequency of sound (Hz),
d = diameter of the cone (m),
r = distance from the cone (m).

4 Prototype 1 (Peerless XLS)

This prototype is based on Peerless 10-inch XLS-driver. This driver was chosen for following reasons:

- High linear excursion value (±12,5 mm).
- Large diameter voice coil (51 mm). Gives plenty of room for adding the measurement capacitor.
- Heavy cone (135,3 g). Little added mass doesn't change other properties considerably.
- Powerful motor (force factor 17,5 N/A).
- Voice coil and cone are attached to the magnet with screws (easy to modify without a danger of causing damage to the driver).
- Well-known and popular driver.

Volume of the loudspeaker cabinet is about 28 litres. It is made of 25 mm chipboard. Shape of the cabinet is cube of about 35,5 cm sides. Electronics are placed completely outside the box.

This driver has aluminium voice coil former. This former is used as a shield against external noise sources and thus it is grounded. The outer surface of the measurement capacitor is made of 0.1 mm aluminium sheet that was insulated from the former using 0.13mm nomex-insulator sheet. Diameter of the outer surface is about 51mm. Inner surface of the measurement capacitor is made of aluminium rod with diameter of 46 mm and about 20mm hole inside. Outer surface is connected to a voltage source of 1200V.

4.1 Electronics

The electronics of the prototype is made with standard operational amplifiers (TL074 and NE5532). Following figure shows the main part of the circuit:

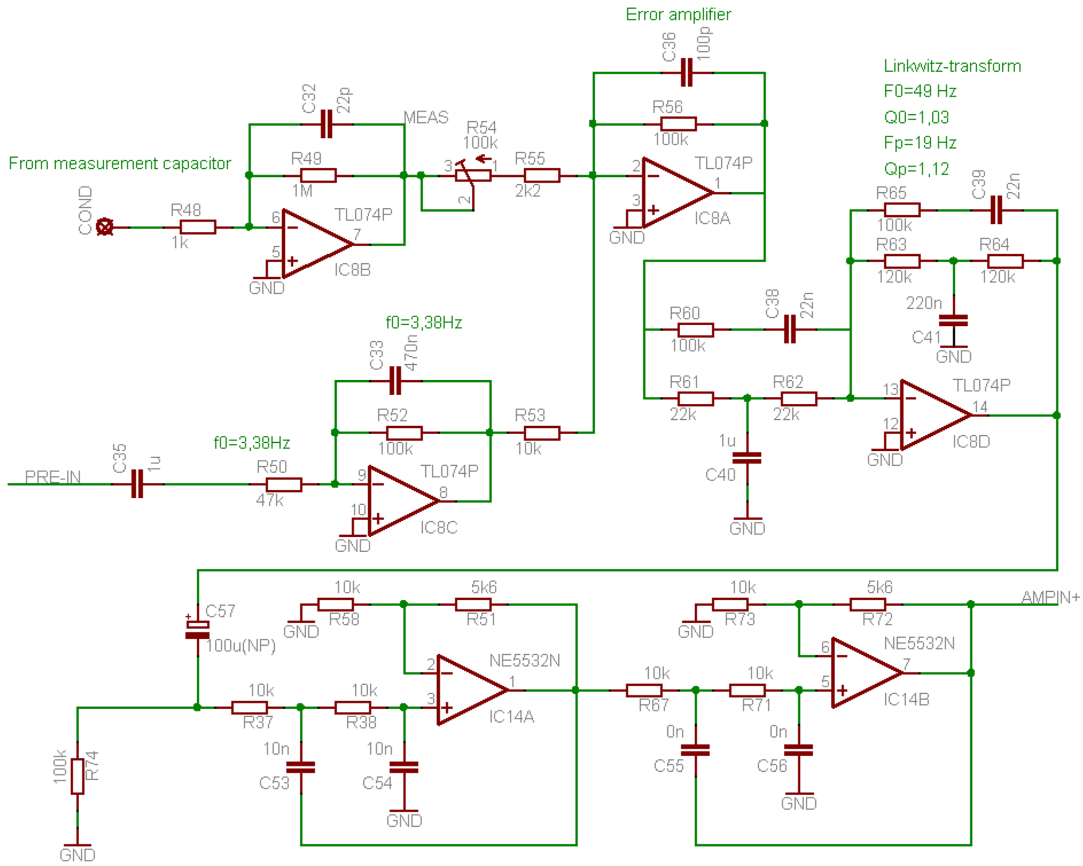


Figure 2: Prototype 1 circuit

In addition to the circuit shown, there are power supply, power amplifier and high-voltage (1200V) generator implemented using simple cockroft-walton voltage multiplier (this circuit does not consume any current apart some leakage).

4.1.1 Functional description of the circuit

The signal from the inner surface of the measurement capacitor is connected to the “COND”-signal of the circuit (with about 0.5 m coaxial cable). The current to voltage-converter made around IC8B generates an output signal that is proportional to cone velocity. Audio signal is brought to the combined integrator/high-pass filter made around the operational amplifier IC8C. Output of this amplifier is the wanted instantaneous velocity value of the loudspeaker cone.

These previous signals are fed into the summing (or differential as it is used at this case) amplifier IC8A. Amount of motional feedback can be adjusted by trimmer R54. Output of this amplifier is fed into linkwitz transform-circuit made around IC8D that extends the low frequency response of the system and so allows for more feedback at low frequencies. Two-stage (fourth order) lowpass-filtering using IC14A&B can be done to the signal fed to the power amplifier to lower the level of high-frequency noise. In this case only the first stage was used at cutoff frequency of about 1600 Hz and Q of about 0,7.

The signal from “AMPIN+” is fed to the power amplifier stage consisting of two bridged TDA7294-amplifier-IC's and total amplification of about 7 (17dB).

4.2 Calculations

Capacitance of the measurement capacitor per 1m of length (formula 2):

$$C_m = \frac{2 * \pi * \varepsilon_r * \varepsilon_o}{\ln\left(\frac{r2}{r1}\right)}$$
$$\approx \frac{2 * \pi * 1 * 8{,}8542 * 10^{-12} A^2 s^2}{N * m^2 * \ln\left(\frac{51\text{mm}}{46\text{mm}}\right)}$$
$$\approx 539\ pF/m$$

Output voltage of the measurement circuit (IC8B) (formula 7 at page 5), when frequency is 20 Hz and deflection +-12.5mm:

$$U_{out} = R * U_{cond} * C_m * 2 * \pi * f * x_{max} * \cos(f * t)$$
$$= 1 * 10^6 * 1200\text{V} * 539 * 10^{-12} * 2 * \pi * 20 * 0{,}0125\, m * 1$$
$$\approx 1{,}02\, V$$

As SPL level (1m, full space) this means (formula 8 at page 5):

$$SPL = 94{,}3 + 20 * \log(x * 2) + 40 * \log(f) + 40 * \log(d) - 20 * \log(r)$$
$$= 94{,}3 + 20 * \log(0{,}0125 * 2) + 40 * \log(20) + 40 * \log(0{,}212) - 20 * \log(1)$$
$$\approx 87{,}3\, dB$$

Since it is known that the voltage is directly proportional to the absolute sound pressure level and inversely proportional to the frequency, we can derive one formula that takes sound pressure level and frequency into account:

$$U_{out}=c*\frac{10^{\frac{SPL}{20}}}{f}$$
$$\rightarrow c=\frac{U_{out}*f}{10^{(\frac{SPL}{20})}}$$
$$\approx\frac{1,02*20}{10^{(\frac{87,3}{20})}}$$
$$\approx 880*10^{-6}$$
$$\rightarrow U_{out}=880*10^{-6}*\frac{10^{\frac{SPL}{20}}}{f}$$

Formula 9

Below is a table, where some values (in volts) using formula 9 are calculated using different frequencies and sound pressure levels:

Frequency (Hz)	20	28,28	40	56,57	80	113,14	160	226,27	320
SPL (dB)									
0	4,35E-5	3,08E-5	2,18E-5	1,54E-5	1,09E-5	7,69E-6	5,44E-6	3,84E-6	2,72E-6
5	7,74E-5	5,47E-5	3,87E-5	2,73E-5	1,93E-5	1,37E-5	9,67E-6	6,84E-6	4,83E-6
10	1,38E-4	9,73E-5	6,88E-5	4,86E-5	3,44E-5	2,43E-5	1,72E-5	1,22E-5	8,60E-6
15	2,45E-4	1,73E-4	1,22E-4	8,65E-5	6,12E-5	4,32E-5	3,06E-5	2,16E-5	1,53E-5
20	4,35E-4	3,08E-4	2,18E-4	1,54E-4	1,09E-4	7,69E-5	5,44E-5	3,84E-5	2,72E-5
25	7,74E-4	5,47E-4	3,87E-4	2,73E-4	1,93E-4	1,37E-4	9,67E-5	6,84E-5	4,83E-5
30	1,38E-3	9,73E-4	6,88E-4	4,86E-4	3,44E-4	2,43E-4	1,72E-4	1,22E-4	8,60E-5
35	2,45E-3	1,73E-3	1,22E-3	8,65E-4	6,12E-4	4,32E-4	3,06E-4	2,16E-4	1,53E-4
40	4,35E-3	3,08E-3	2,18E-3	1,54E-3	1,09E-3	7,69E-4	5,44E-4	3,84E-4	2,72E-4
45	7,74E-3	5,47E-3	3,87E-3	2,73E-3	1,93E-3	1,37E-3	9,67E-4	6,84E-4	4,83E-4
50	1,38E-2	9,73E-3	6,88E-3	4,86E-3	3,44E-3	2,43E-3	1,72E-3	1,22E-3	8,60E-4
55	2,45E-2	1,73E-2	1,22E-2	8,65E-3	6,12E-3	4,32E-3	3,06E-3	2,16E-3	1,53E-3
60	4,35E-2	3,08E-2	2,18E-2	1,54E-2	1,09E-2	7,69E-3	5,44E-3	3,84E-3	2,72E-3
65	7,74E-2	5,47E-2	3,87E-2	2,73E-2	1,93E-2	1,37E-2	9,67E-3	6,84E-3	4,83E-3
70	1,38E-1	9,73E-2	6,88E-2	4,86E-2	3,44E-2	2,43E-2	1,72E-2	1,22E-2	8,60E-3
75	2,45E-1	1,73E-1	1,22E-1	8,65E-2	6,12E-2	4,32E-2	3,06E-2	2,16E-2	1,53E-2
80	4,35E-1	3,08E-1	2,18E-1	1,54E-1	1,09E-1	7,69E-2	5,44E-2	3,84E-2	2,72E-2
85	7,74E-1	5,47E-1	3,87E-1	2,73E-1	1,93E-1	1,37E-1	9,67E-2	6,84E-2	4,83E-2
90	1,38E+0	9,73E-1	6,88E-1	4,86E-1	3,44E-1	2,43E-1	1,72E-1	1,22E-1	8,60E-2
95	2,45E+0	1,73E+0	1,22E+0	8,65E-1	6,12E-1	4,32E-1	3,06E-1	2,16E-1	1,53E-1
100	4,35E+0	3,08E+0	2,18E+0	1,54E+0	1,09E+0	7,69E-1	5,44E-1	3,84E-1	2,72E-1
105	7,74E+0	5,47E+0	3,87E+0	2,73E+0	1,93E+0	1,37E+0	9,67E-1	6,84E-1	4,83E-1
110	1,38E+1	9,73E+0	6,88E+0	4,86E+0	3,44E+0	2,43E+0	1,72E+0	1,22E+0	8,60E-1

Table 1

4.3 Measurements

Measurements were made from device where motion feedback is active (abbreviation MFB) and one where it is not used (abbreviation NoMFB, signal “pre-in” is connected straight to the input of linkwitz-transform-circuit (IC8D) at the schematic). Some measurements are also performed without feedback-signal (open loop). In this case the connection from measurement capacitor was cut (“COND” in schematic).

Measurement microphone used was Behringer ECM-8000, sound card was M-audio MobilePre USB. Program used for measurements was Speaker Workshop V1.06. Harmonic distortion measurements were made using FFT-analysis and signal generator, both running on PC.

Measurement were done at normal living room with near field-method. Below is a figure of the measurement arrangement:

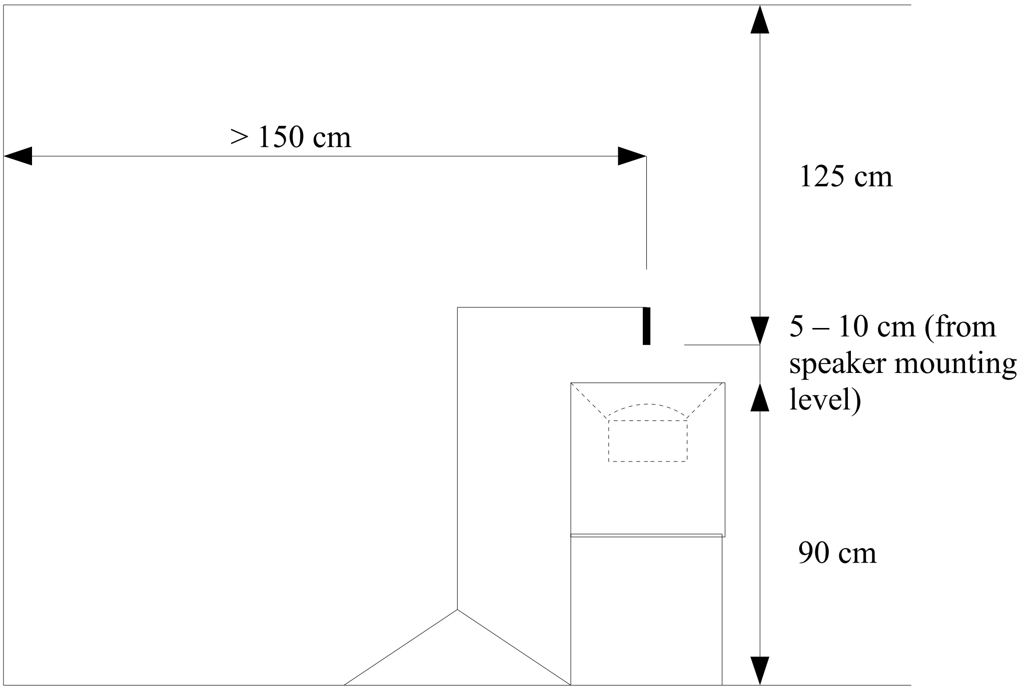
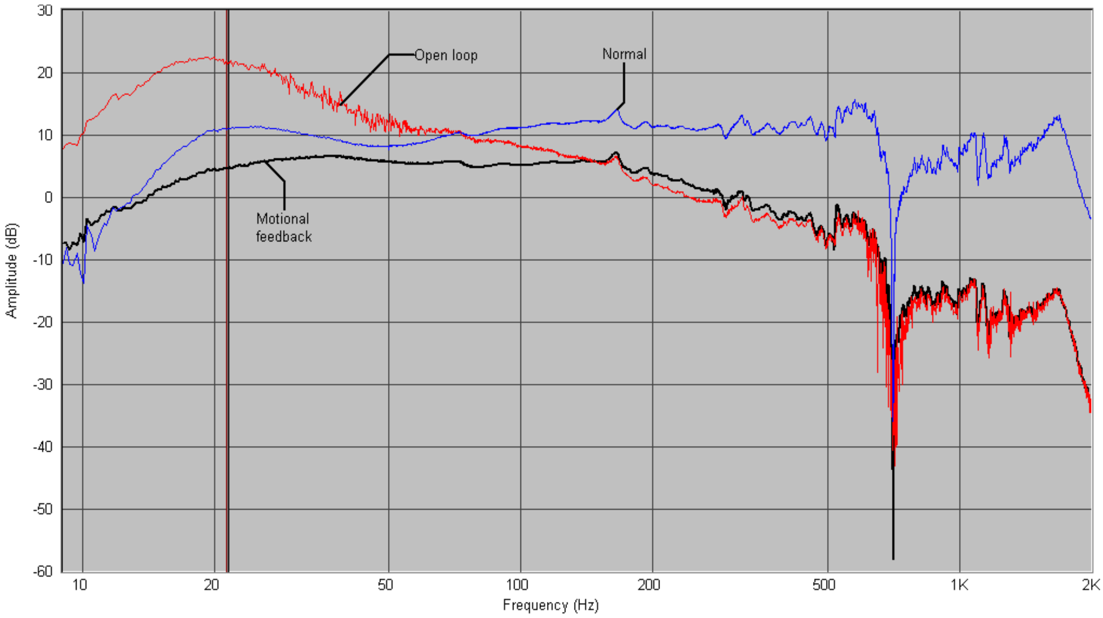


Figure 3: Measurement arrangement

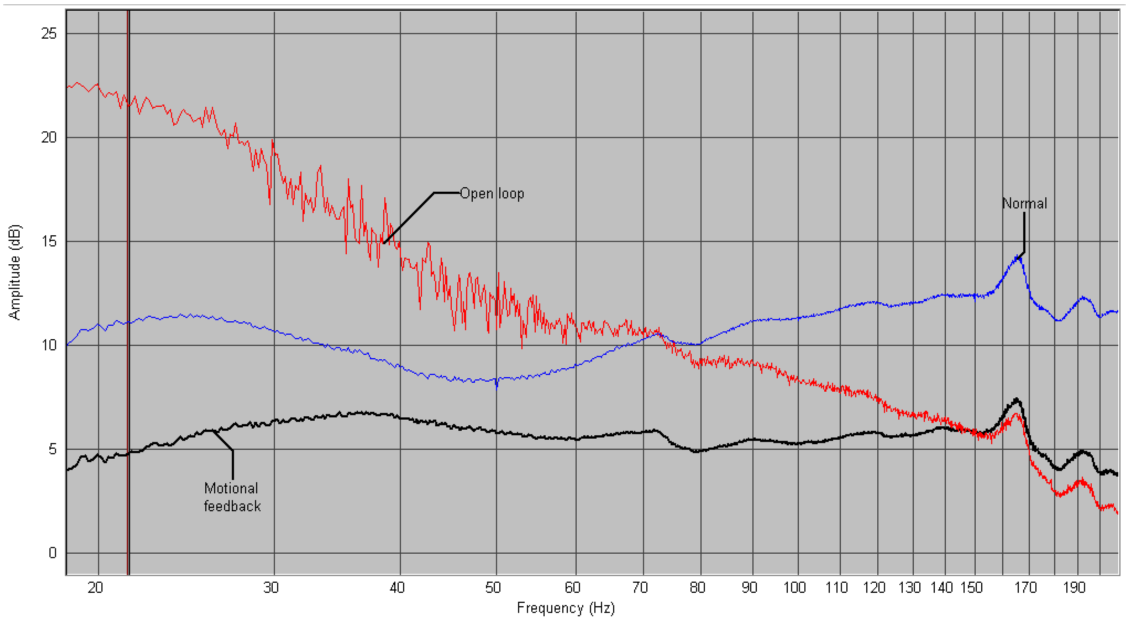
4.4 Frequency responses

Black is response with motional feedback on, Blue without motional feedback, red with motional feedback loop cut (open loop).



Graph 1: Frequency response 10Hz...2kHz

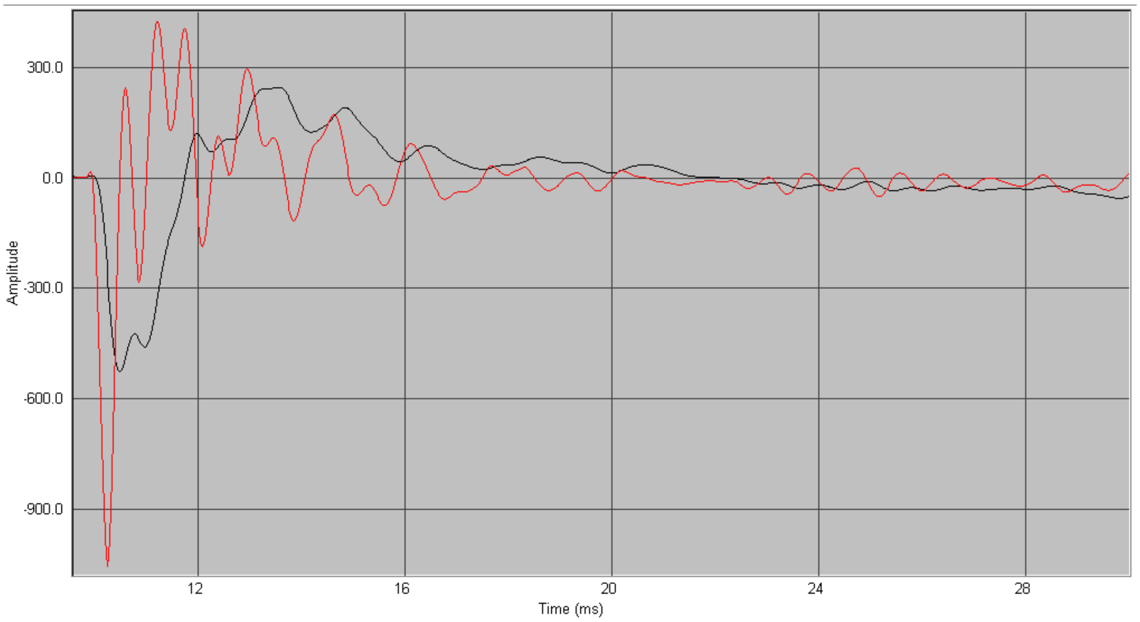
Next is a zoomed view from 20 to 200 Hz:



Graph 2: Frequency response 20Hz...200Hz

4.5 Impulse responses

Black trace is measured with motional feedback, red without.



Graph 3: Impulse responses

Cone resonances can clearly be seen in this graph.

4.6 Harmonic distortion and distribution

Harmonic distortion (THD) was measured using microphone distance of 10 cm from the speaker mounting level using various signal levels. Level indicated means level (measured) of fundamental frequency. Harmonic distribution shows level relative to the fundamental in decibels. Distortion is measured between half-octaves from 20 to 320 Hz (where possible). Slight “rounding errors” on frequency values are caused by the measurement method (frequencies are adjusted so that they fall into FFT bin).

4.6.1 -6 dBFS (93 dB SPL)

Measurement at 20 Hz not possible, because excursion is too high.

Frequency	THD+N MFB	THD+N NoMFB
27,83	6,02	13,28
39,55	0,99	2,55
57,13	0,69	0,72
80,57	0,91	2,96
112,79	0,57	0,31
159,67	0,41	0,56
225,59	0,46	0,46
319,34	0,51	0,6

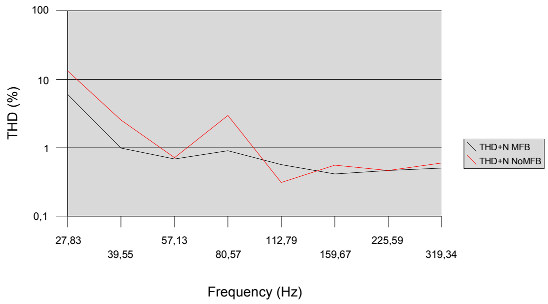


Table 2 & Graph 4

Harmonic distribution at 28 Hz:

Frequency	MFB	NoMFB
55,66	-32,01	-19,16
83,5	-25,78	-22,81
111,33	-37,74	-37,57
139,16	-39,65	-42,2
166,99	-46,43	-46,25
194,82	-51,45	-59,99
222,66	-57,01	-68,03
250,49	-50,14	-60,13
278,32	-66,74	-59,65
306,15	-49,4	-55,04
333,98	-51,32	-54,21
361,82	-60,25	-64,44
389,65	-55,72	-58,19
417,48	-54,25	-57,61
445,31	-60,73	-59,29
473,15	-68,49	-63,2
500,98	-69,37	-69,82
528,81	-58,8	-63,89
556,64	-57,93	-73,21
584,47	-58,83	-73,02

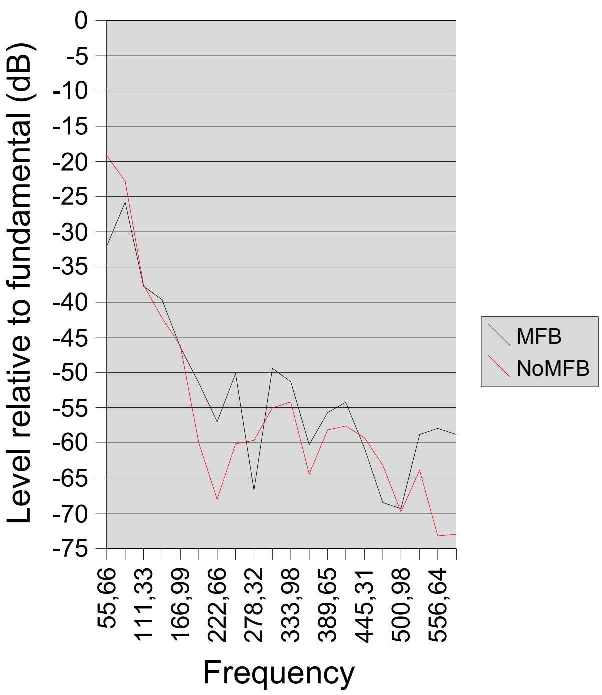


Table 3 & Graph 5

Harmonic distribution at 80 Hz:

Frequency	MFB	NoMFB
161,13	-40,93	-41,96
241,7	-66,43	-64,21
322,27	-62,1	-63,66
402,83	-77,52	-68,69
483,4	-88,16	-72,95
563,97	-87,89	-74,63
644,53	-83,44	-76,26
725,1	-95,58	-77,56
805,66	-103,78	-82,02
886,23	-99,12	-85,96
966,8	-93,6	-86,77
1047,36	-94,2	-84,81
1127,93	-99,43	-83,59
1208,5	-96,59	-82,42
1289,06	-92,92	-80,01
1369,63	-98,02	-82,28
1450,2	-95,66	-81,02
1530,76	-93,89	-80,89
1611,33	-94,57	-85,05
1691,9	-97,74	-85,84

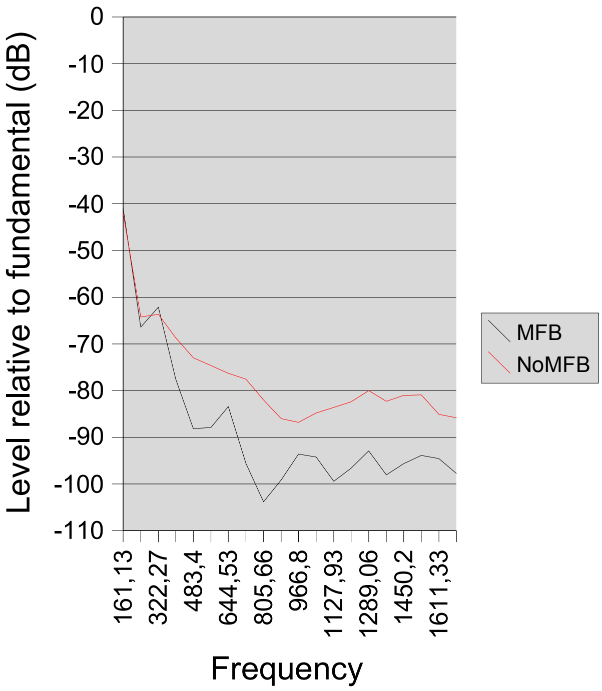


Table 4 & Graph 6

4.6.2 -12 dBFS (87 dB SPL)

At this level excursion is at maximum (12.5 mm one way) at 20 Hz.

Frequency	THD+N MFB	THD+N NoMFB
20,51	15,28	33,35
27,83	2,42	6,32
39,55	0,67	1,55
57,13	0,36	0,35
80,57	0,44	0,4
112,79	0,33	0,17
159,67	0,26	0,31
225,59	0,32	0,29
319,34	0,63	0,53

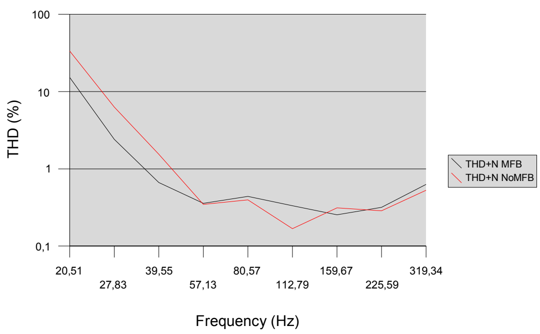


Table 5 & Graph 7

Harmonic distribution at 20 Hz:

Frequency	MFB	NoMFB
41,02	-25,01	-12,97
61,52	-17,4	-12,6
82,03	-33,04	-25,99
102,54	-30,73	-25,56
123,05	-38,97	-34,63
143,56	-35,77	-38,2
164,06	-38,1	-44,41
184,57	-44,12	-53,55
205,08	-49,92	-58,83
225,59	-60	-67,88
246,09	-53,26	-60,33
266,6	-59,11	-61,37
287,11	-49,48	-53,73
307,62	-57,59	-67,9
328,13	-47,68	-51,98
348,63	-60,95	-54,63
369,14	-54,7	-59
389,65	-54,37	-56,59
410,16	-62,72	-57,26
430,66	-53,93	-55,7

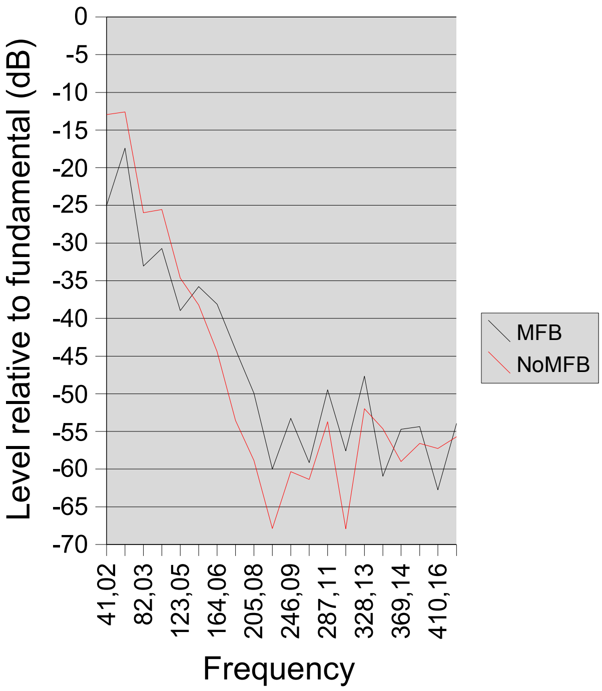


Table 6 & Graph 8

Harmonic distribution at 80 Hz:

Frequency	MFB	NoMFB
161,13	-47,7	-48,57
241,7	-64,83	-66,95
322,27	-96,35	-83,68
402,83	-78,4	-78,46
483,4	-101,89	-101,77
563,97	-84,6	-83,01
644,53	-91,42	-92,27
725,1	-105,4	-99,57
805,66	-102,42	-109,97
886,23	-105,72	-100,32
966,8	-95,63	-95,84
1047,36	-106,43	-105,55
1127,93	-108,03	-108,78
1208,5	-110,68	-107,73
1289,06	-102,39	-104,45
1369,63	-106,78	-106,22
1450,2	-99,72	-100,73
1530,76	-99,22	-98,23
1611,33	-93,54	-103,94
1691,9	-98,37	-98,35

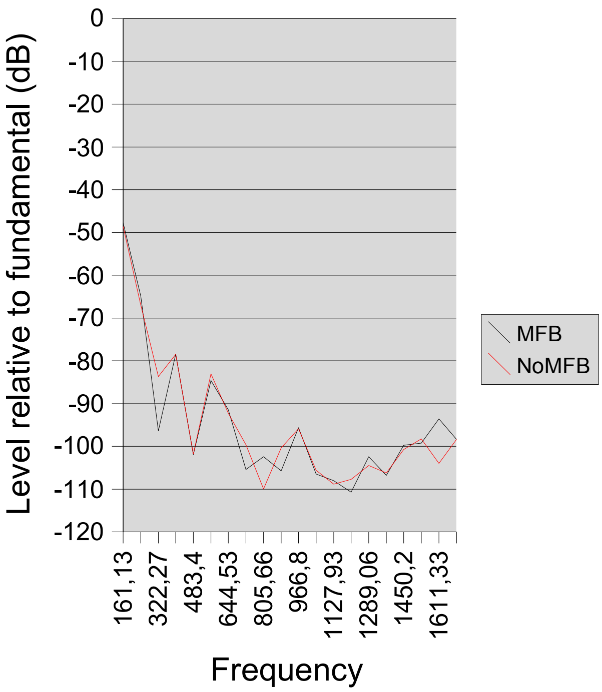


Table 7 & Graph 9

4.6.3 -18 dBFS (81 dB SPL)

Frequency	THD+N MFB	THD+N NoMFB
20,51	4,08	11,35
27,83	1,68	4,39
39,55	0,25	0,65
57,13	0,32	0,32
80,57	0,28	0,32
112,79	0,26	0,26
159,67	0,24	0,3
225,59	0,24	0,3
319,34	0,28	0,23

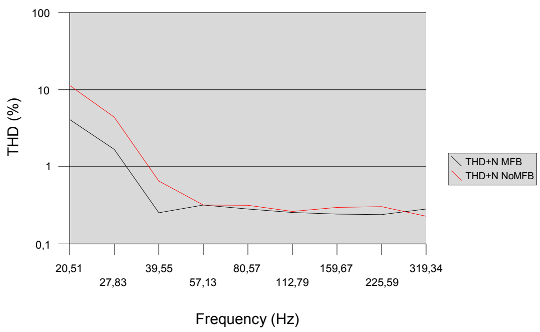


Table 8 & Graph 10

Harmonic distribution at 20 Hz:

Frequency	MFB	NoMFB
41,02	-29,39	-19,38
61,52	-33,13	-29,02
82,03	-50,3	-52,02
102,54	-54,73	-52,3
123,05	-64,07	-57,25
143,56	-78,03	-75,19
164,06	-60,32	-64,58
184,57	-72,77	-73,25
205,08	-63,59	-83,85
225,59	-62,3	-68,85
246,09	-66,89	-68,67
266,6	-59,05	-62,23
287,11	-63,15	-78,63
307,62	-57,63	-64,45
328,13	-60,49	-62,75
348,63	-64,17	-66,79
369,14	-71,62	-72,04
389,65	-86,06	-79,75
410,16	-73,12	-77,58
430,66	-80,38	-81,74

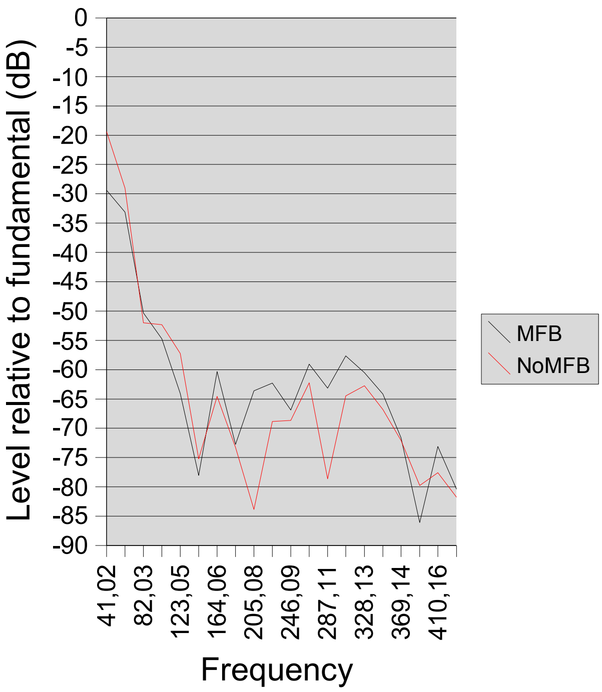


Table 9 & Graph 11

Harmonic distribution at 80 Hz:

Frequency	MFB	NoMFB
161,13	-53,74	-55,43
241,7	-68,22	-71,51
322,27	-89,78	-96,42
402,83	-79,61	-78,96
483,4	-93,97	-97,6
563,97	-90,46	-89,62
644,53	-95,68	-101,18
725,1	-105,46	-102,47
805,66	-108,27	-102,65
886,23	-104,24	-106,29
966,8	-106,52	-102,96
1047,36	-104,5	-102,67
1127,93	-105,51	-105,27
1208,5	-102,87	-103,58
1289,06	-101,69	-100,5
1369,63	-100,37	-106,52
1450,2	-103,22	-98,95
1530,76	-97,98	-96,98
1611,33	-100,26	-96,11
1691,9	-103,57	-91,37

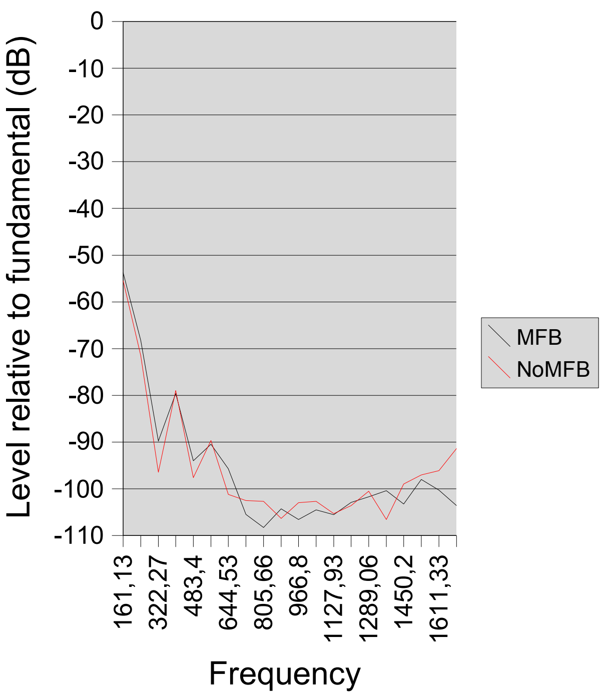


Table 10 & Graph 12

4.7 Interpretation of the measurements

It can be seen that frequency response of the speaker straightens compared to (linkwitz-transformed) normal speaker. THD for lowest frequencies (20 Hz) approximately halves. There can be seen slight increase in harmonic components above 100 Hz (20 Hz fundamental), but since even after that increase components still stay below about -50 dB, they can be considered negligible.

It is actually possible to lower the THD-values at lowest frequencies for about one fifth of those of the speaker not using motion feedback by increasing the amount of feedback. This unfortunately causes ringing and rise of THD at higher frequencies. Also harmonic distribution measured at lower (fundamental) frequencies will show increase in higher harmonic products. These are probably caused by phase lag in the feedback loop at higher frequencies.

5 Prototype 2 (Seas L17REX)

This prototype is constructed using Seas L17REX/P aluminium cone driver. Speaker is 2-way implementation using Seas 25TAC/GW as a tweeter. Crossover is 4th order linkwitz-riley.

Volume of the loudspeaker cabinet is about 8 litres with outer dimensions of 20 * 20 * 33 cm and inner dimension of 16.4 * 16.4 * 29.4 cm. Electronics are made into base of the speaker making total height of 90 cm. Otherwise the construction is almost same as the subwoofer-prototype. Measurement capacitor is about 40 mm in diameter (same as voice coil of the driver) with about 2.5 mm air gap between capacitor surfaces.

5.1 Electronics

Motional feedback circuit of this speaker closely resembles circuit of the subwoofer prototype. Only some component values have been changed and power amplifier is implemented as transconductance amplifier. Transconductance amplifier was chosen because the driver seemed to have better phase behaviour with it. Below is the part of the schematic concerning the motional feedback:

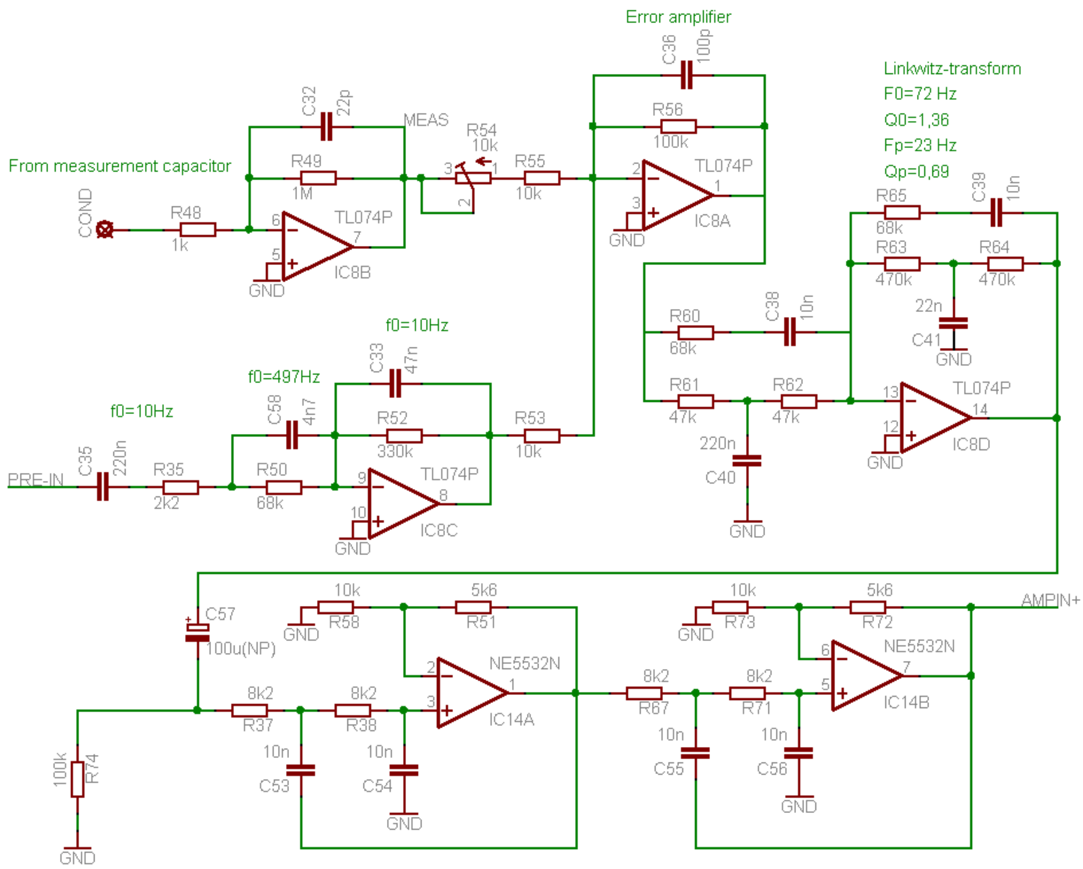


Figure 4: Prototype 2 circuit

Again, power supply and amplifier (transconductance type) is not shown.

5.1.1 Functional description of the circuit

The signal from the inner surface of the measurement capacitor is connected to the “COND”-signal of the circuit (with about 0.5 m coaxial cable). The current to voltage-converter made around IC8B generates an output signal that is proportional to cone velocity. Audio signal is brought to the combined integrator/high-pass filter made around the operational amplifier IC8C. Output of this amplifier is the wanted instantaneous velocity value of the loudspeaker cone. In contrast to subwoofer prototype, this circuit passes frequencies above 500 Hz. This frequency is the (approximate) “crossover frequency” where motional feedback is not used any more.

These previous signals are fed into the summing (or differential as it is used at this case) amplifier IC8A. Amount of motional feedback can be adjusted by trimmer R54. Output of this amplifier is fed into linkwitz transform-circuit around IC8D that extends the low frequency response of the system and so allows for more feedback at low frequencies. Two-stage (fourth order) lowpass-filtering using IC14A&B is done to reduce noise and to act as linkwitz-riley crossover low pass-section.

The signal from “AMPIN+” is fed to the transconductance power amplifier stage made around TDA7294.

5.2 Calculations

Capacitance of the measurement capacitor per 1m of length (formula 2):

$$C_m = \frac{2*\pi*\varepsilon_r*\varepsilon_o}{\ln(\frac{r2}{r1})}$$
$$\approx \frac{2*\pi*1*8{,}8542*10^{-12} A^2 s^2}{N*m^2*\ln(\frac{39\text{mm}}{34\text{mm}})}$$
$$\approx 400\ pF/m$$

Output voltage of the measurement circuit (IC8B) (formula 7 at page 5), when frequency is 20 Hz and deflection +- 4 mm:

$$U_{out} = R*U_{cond}*C_m*2*\pi*f*x_{max}*\cos(f*t)$$
$$= 1*10^6*1200\text{V}*400*10^{-12}*2*\pi*20*0{,}004\,m*1$$
$$\approx 0{,}24\,V$$

As SPL level (1m, full space) this means (formula 8 at page 5):

$$SPL = 94{,}3+20*\log(x*2)+40*\log(f)+40*\log(d)-20*\log(r)$$
$$= 94{,}3+20*\log(0{,}004*2)+40*\log(20)+40*\log(0{,}124)-20*\log(1)$$
$$\approx 68\,dB$$

Since it is known that the voltage is directly proportional to the absolute sound pressure level and inversely proportional to the frequency, we can derive one formula that takes sound pressure level and frequency into account:

$$U_{out} = c * \frac{10^{\frac{SPL}{20}}}{f}$$
$$\rightarrow c = \frac{U_{out} * f}{10^{(\frac{SPL}{20})}}$$
$$\approx \frac{0{,}24 * 20}{10^{(\frac{68}{20})}}$$
$$\approx 2 * 10^{-3}$$
$$\rightarrow U_{out} = 2 * 10^{-3} * \frac{10^{\frac{SPL}{20}}}{f}$$

Formula 10

U_{out} of this prototype is over two times bigger than that of the subwoofer (at same frequency / SPL).

5.3 Measurements

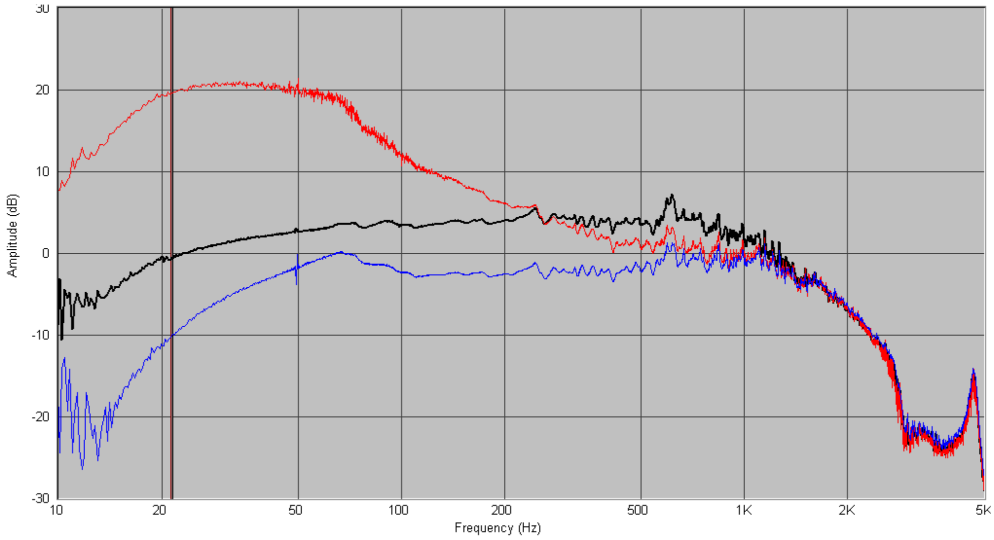
Measurements were made from device where motion feedback is active (abbreviation MFB) and one where it is not used (abbreviation NoMFB, signal "pre-in" is connected straight to the input of linkwitz-transform-circuit (IC8D) at the schematic). Some measurements were also performed without feedback-signal (open loop). In this case the connection from measurement capacitor was cut ("COND" in schematic).

Measurement microphone used was Behringer ECM-8000, sound card was M-audio MobilePre USB. Program used for measurements was Speaker Workshop V1.06. Harmonic distortion measurements were made using FFT-analysis and signal generator, both running on PC.

Measurement were done at normal living room with near field-method with 5 cm microphone distance (frequency response-measurements) and 10 cm microphone distance (distortion measurements).

5.4 Frequency responses

Black is response with motional feedback, blue without motional feedback and red with motional feedback loop cut (open loop). No tweeter was connected.



Graph 13: Frequency response 10Hz...5kHz

Peak below 5 kHz is caused by cone break up.

5.5 Harmonic distortion and distribution

Harmonic distortion (THD) was measured using microphone distance of 10 cm from the speaker mounting level using various signal levels. Level indicated means level (measured) of fundamental frequency. Harmonic distribution shows level relative to the fundamental in decibels. Distortion is measured between half-octaves from 20 to 1280 Hz (where possible). Slight "rounding errors" on frequency values are caused by the measurement method (frequencies are adjusted so that they fall into FFT bin).

5.5.1 86 dB SPL

No measurements below 57 Hz were possible because of excursion limit.

Frequency	THD+N MFB	THD+N NoMFB
20,51		
27,83		
39,55		
57,13	1,98	2,42
80,57	0,87	0,85
112,79	1,6	1,29
159,67	1,49	1,37
225,59	3,01	2,02
319,34	1,92	1,79
452,64	1,87	1,82
640,14	1,71	1,71
905,27	1,76	1,73
1280,27	1,84	1,73

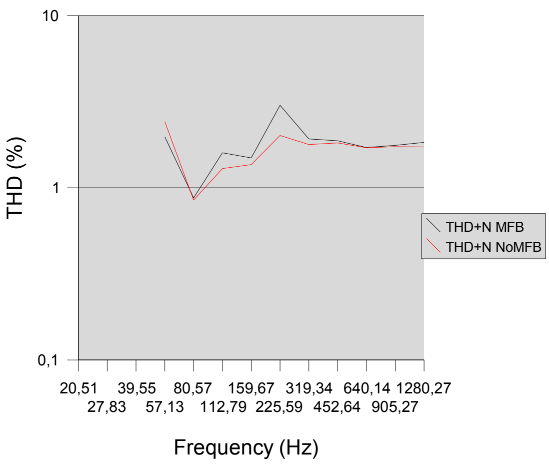


Table 11 & Graph 14

Harmonic distribution at 57 Hz:

Frequency	MFB	NoMFB
114,26	-51,68	-51,08
171,39	-34,6	-32,51
228,52	-52,34	-57,65
285,65	-45,31	-48,44
342,77	-68,03	-65,28
399,9	-63,53	-70,72
457,03	-61,2	-68,31
514,16	-60,56	-69,97
571,29	-68,81	-78,96
628,42	-70,31	-73,81

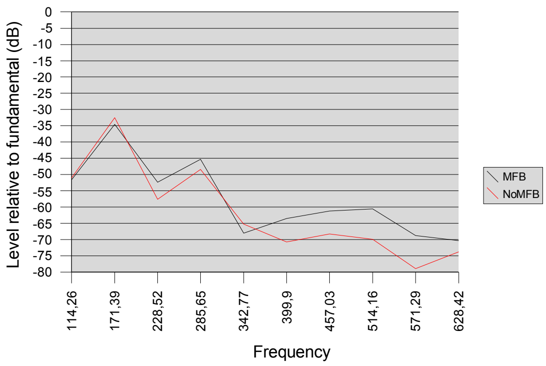


Table 12 & Graph 15

Harmonic distribution at 160 Hz:

Frequency	MFB	NoMFB
319,34	-36,83	-37,56
479	-48,25	-49,82
638,67	-68,56	-68,2
798,34	-78,85	-74,22
958,01	-78,28	-80,41
1117,68	-83,33	-83,1
1277,34	-81,65	-81,3
1437,01	-90,22	-86,59
1596,68	-92,31	-97,63
1756,35	-90,5	-90,07

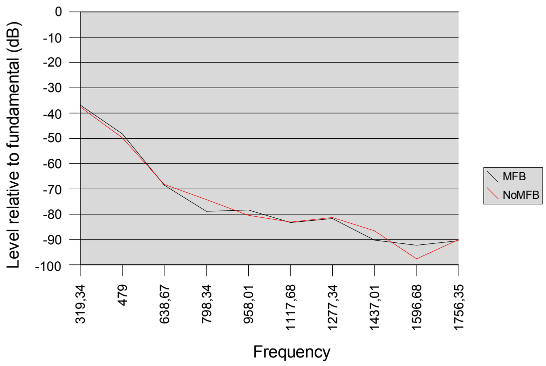


Table 13 & Graph 16

5.5.2 74 dB SPL

No measurements below 28 Hz were possible because of excursion limit.

Frequency	THD+N MFB	THD+N NoMFB
20,51		
27,83	14,78	45,48
39,55	1,22	2,92
57,13	0,44	0,67
80,57	0,47	0,53
112,79	0,45	0,49
159,67	0,61	0,44
225,59	0,57	0,43
319,34	0,52	0,45
452,64	0,5	0,52
640,14	0,54	0,47
905,27	0,56	0,45
1280,27	0,46	0,38

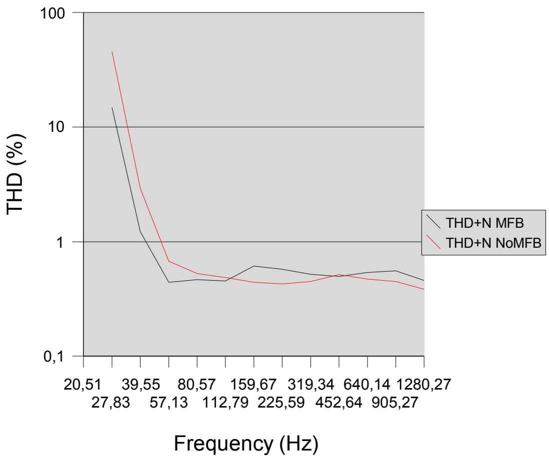


Table 14 & Graph 17

Harmonic distribution at 28 Hz:

Frequency	MFB	NoMFB
55,66	-35,22	-37,13
83,5	-16,89	-7,01
111,33	-36,84	-32,06
139,16	-30,6	-21,72
166,99	-57,3	-60,12
194,82	-55,62	-39,37
222,66	-55,73	-50,89
250,49	-63,68	-71,8
278,32	-69,53	-58,21
306,15	-70,58	-64,61

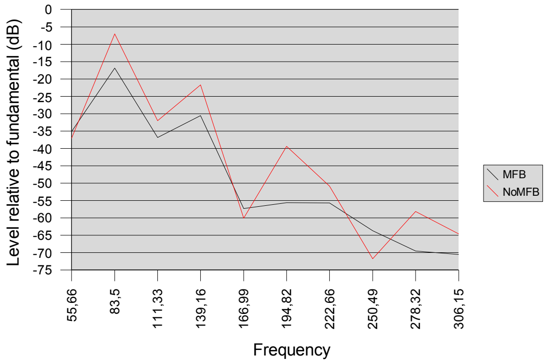


Table 15 & Graph 18

Harmonic distribution at 160 Hz:

Frequency	MFB	NoMFB
319,34	-50,09	-50,8
479	-57,14	-61,04
638,67	-84,2	-88,67
798,34	-75,35	-74,4
958,01	-97,15	-100,77
1117,68	-75,5	-75,91
1277,34	-95,8	-94,88
1437,01	-86,5	-88,36
1596,68	-94,04	-94,52
1756,35	-92,08	-96,43

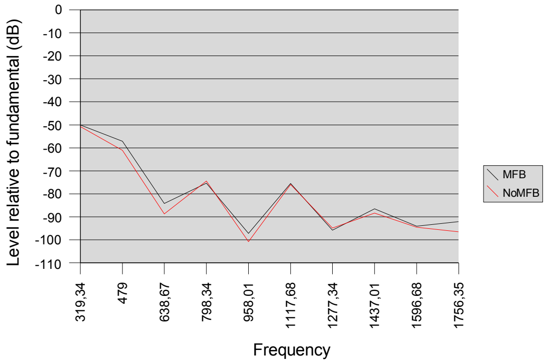


Table 16 & Graph 19

5.5.3 68 dB SPL

Frequency	THD+N MFB	THD+N NoMFB
20,51	15,56	86,23
27,83	2,89	8,45
39,55	0,86	1,88
57,13	0,69	0,79
80,57	0,8	0,79
112,79	0,95	0,79
159,67	0,6	0,67
225,59	0,58	0,89
319,34	0,62	0,88
452,64	0,58	0,79
640,14	0,59	0,75
905,27	0,57	0,64
1280,27	0,46	0,65

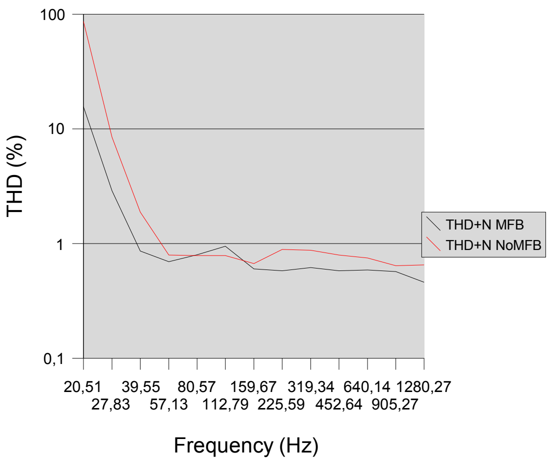


Table 17 & Graph 20

Harmonic distribution at 20 Hz:

Frequency	MFB	NoMFB
41,02	-34,67	-36,62
61,52	-16,64	-1,49
82,03	-31,73	-22,04
102,54	-28,38	-15,75
123,05	-51,63	-38,61
143,56	-61,02	-28,79
164,06	-50,68	-52,26
184,57	-58,77	-45,65
205,08	-63,78	-56,07
225,59	-65,42	-67,58

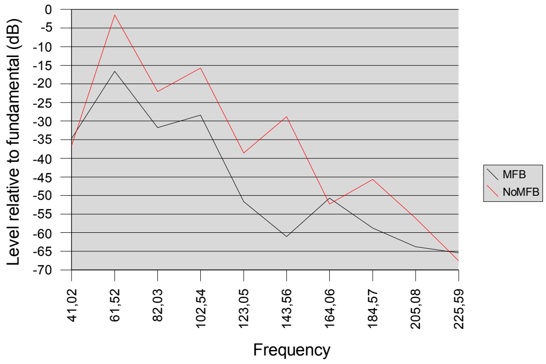


Table 18 & Graph 21

Harmonic distribution at 160 Hz:

Frequency	MFB	NoMFB
319,34	-56,73	-57,01
479	-58,13	-63,15
638,67	-89,63	-85,56
798,34	-81,41	-89,18
958,01	-94,41	-96,64
1117,68	-85,6	-94,02
1277,34	-93,04	-92,2
1437,01	-91,11	-93,51
1596,68	-94,18	-95,51
1756,35	-94,78	-96,38

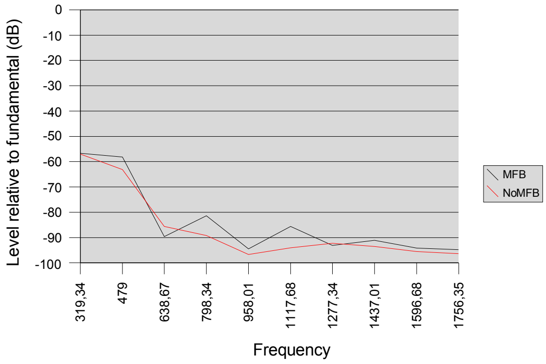


Table 19 & Graph 22

5.5.4 62 dB SPL

Frequency	THD+N MFB	THD+N NoMFB
20,51	3,13	16,33
27,83	2,19	4,15
39,55	1,12	1,59
57,13	1,04	1,21
80,57	1,21	1,21
112,79	1,14	1,34
159,67	1,22	1,2
225,59	1,2	1,97
319,34	1,25	1,77
452,64	1,28	1,38
640,14	1,95	1,2
905,27	1,31	1,03
1280,27	1,56	1,25

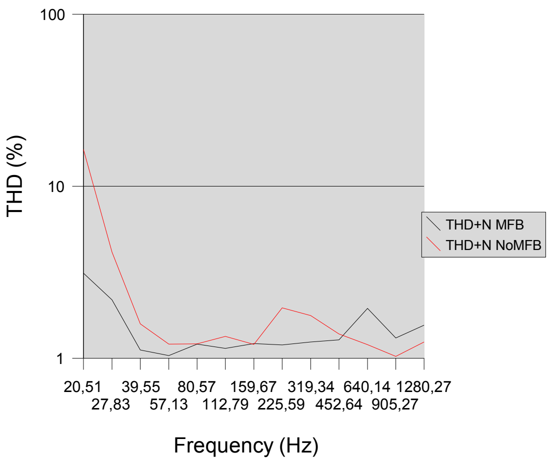


Table 20 & Graph 23

Bad THD+N performance at higher frequencies is caused by background noise.

Harmonic distribution at 20 Hz:

Frequency	MFB	NoMFB
41,02	-46,96	-31,53
61,52	-31,08	-15,96
82,03	-49,96	-38,77
102,54	-46,4	-39,01
123,05	-76,75	-67,89
143,56	-63,02	-58,68
164,06	-77,28	-72,82
184,57	-69,84	-65,18
205,08	-72,8	-80,84
225,59	-69,88	-75,86

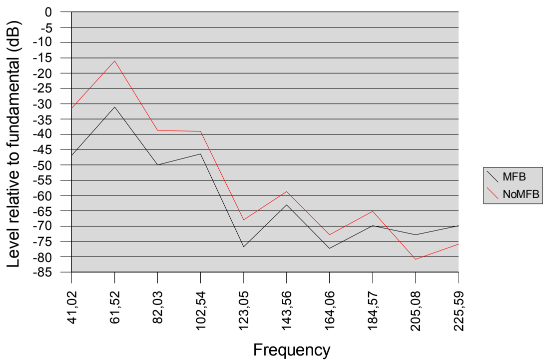


Table 21 & Graph 24

Harmonic distribution at 160 Hz:

Frequency	MFB	NoMFB
319,34	-62,26	-62,41
479	-76,76	-78,71
638,67	-87,18	-90,38
798,34	-84,04	-89,68
958,01	-84,61	-92,6
1117,68	-89,17	-91,15
1277,34	-88,23	-92,06
1437,01	-87,46	-95,18
1596,68	-91,61	-93,5
1756,35	-89,74	-93,55

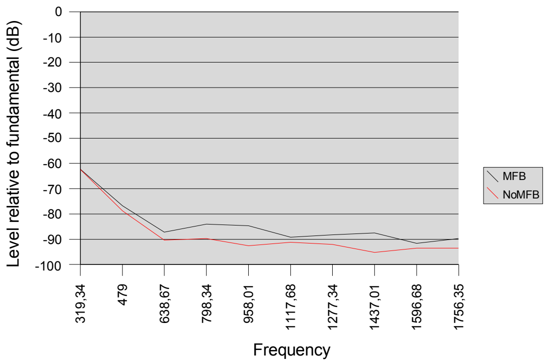


Table 22 & Graph 25

5.6 Interpretation of the measurements

It can be seen that frequency response of the speaker straightens compared to (linkwitz-transformed) normal speaker. THD for lowest frequencies (20 Hz) is below fourth of the speaker without motional feedback.

6 Patents and licensing

This technology is patented (patent granted in Finland, pending in EU). Permission is granted for any individual person to use this technology for his/her personal use. If you want to use this technology as a part of commercial product, take contact for licencing.

7 Contact information

More information about the method presented here can be found from the internet: www.servospeaker.com or directly from the author: pasi.nuutinmaki@servospeaker.com