How to perfect the Electro-Acoustic Transfer Function of Electro-Dynamic Loudspeakers

Since the invention of the electrodynamic loudspeaker around 1900 engineers have strived for a more linear transfer function between the electrical input to the chassis and the generated sound pressure output. Many improvements have been realized for the electro-mechanical chassis. However, as for the amplifier technology, further improvements require a closed loop feed back system around the chassis. The article reviews and compares motion feed back technologies proposed or used in order to achieve a nearly perfect electro-acoustic transfer function.

APPROACHES TO IMPROVE THE SOUND GENERATION OF ELECTRO-DYNAMIC LOUDSPEAKERS

There are many ways to improve the generation of sound of a loudspeaker chassis.
Usually a zero output impedance amplifier, a.k.a. Voltage Drive is used - one amplifier for the loudspeaker box, or dedicated amplifiers for each chassis - and this results already in a closed loop control of the sound output. The current through the voice coil is determined by the difference of the voice coil applied voltage and the the voice coil back induced voltage divided by the loop impedance. The movement of the voice coil determines its driving current, which closes the feedback loop.
In order to further improve the quality of the electro-acoustic transfer function of a loudspeaker chassis some manufacturers have modified the amplifiers‘ output impedance. From a negative impedance nearly compensating the positive voice coil resistance and such getting more control through the back induced voltage up to infinite output impedance, a.k.a. Current Drive which completely eliminates the effect of the back induced voltage. As the generation of the membrane acceleration, which is strictly proportional to the SPL in the interesting frequency range, is already a non-linear process and the resulting generation of the back induced voltage is a further non-linear process, these approaches, with exception of Current Drive have limited effect. Current Drive eliminates the effect of the nonlinearly back induced voltage and generates such low harmonic and intermodulation distortions.

The next logical step in improving the electro-acoustic transfer function of a loudspeaker chassis is using a feedback system, usually called Motion Feed Back. The membrane, or voice coil movement is measured and compared with the electrical input signal. Provided highly linear sensors for the measurement and sufficient loop gain of the control loop the non-linearities of a chassis can be reduced to an un-audible level. We will see, that motion can be each of the physical properties: Membrane travel, membrane velocity or membrane acceleration.

MOTION FEED BACK FOR LOUDSPEAKERS

Figure 1 displays as example the frequency responses of the sound pressure level (SPL) and the harmonic distortions k2 and k3 of a woofer in free air under current drive conditions. It is obvious, that for frequencies about 3 times above the resonance frequency the harmonic distortions k2 and k3 are about 65 dB below the fundamental frequency. These excellent values can be achieved also in a closed box with Current Drive [1].

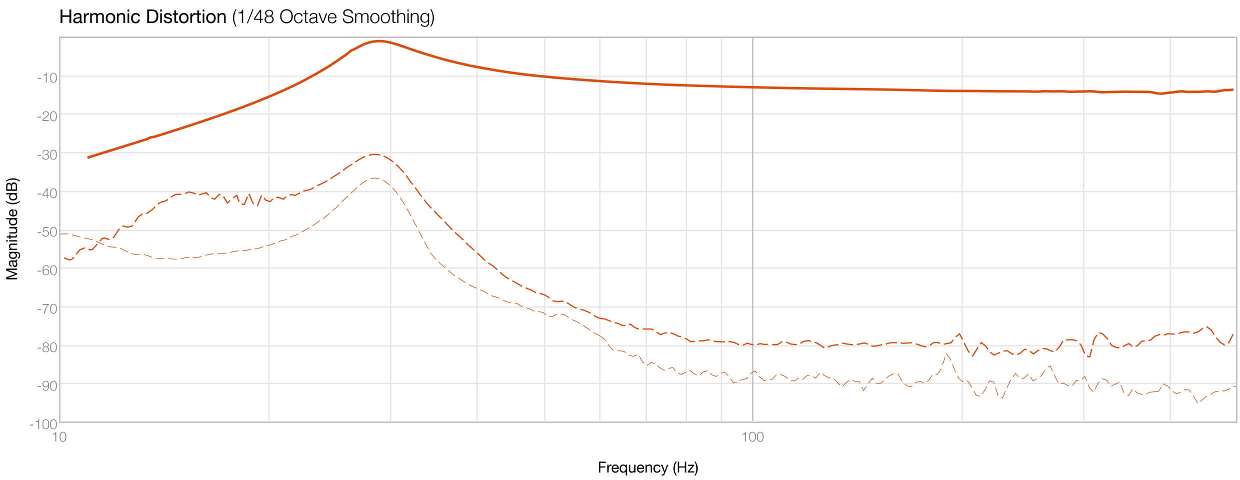


Figure 1: Sound pressure level (SPL) and Harmonic Distortions k2 and k3 frequency response of a SEAS L22 RNX/P in free air under Current Drive conditions.
The prominent resonance of the chassis under Current Drive conditions can easily be equalized by a Pole-Zero Compensation [2].
However, below the resonance frequency the force of the motor of the chassis works less against the constant moving mass, but much more against the highly non-linear suspension, i.e. surround and spider. This is the reason for the growing non-linearity and the increasing harmonic and intermodulation distortions visible in Figure1.

Based on this observation a simple rule of thumb is proposed: When a chassis is operated above 3 times of its resonance frequency a further linearization by motion feed back is not sensible as long as the chassis is of adequate quality. Operation below this limit requires motion feed back in case one wants to keep the linearity and low levels of harmonic and intermodulation distortions. A well engineered motion feed back system eliminates the original resonance of the chassis and extends its frequency response at wish to lower frequencies (e.g. to 16 Hz, the lower limit of the human auditory system [3]). In addition harmonic and intermodulation distortions are reduced at least to below 60 dB wrt. to the fundamental frequency.

MOTION FEED BACK STRATEGIES:

When selecting a motion feedback system there are three fundamental considerations involved:

1. The target of a control concept for loudspeakers is to linearize the transfer function of the electrical input to sound pressure output of the transducer on one hand, and to achieve a linear sound pressure frequency response on the other hand. We will see that these two requirements are not necessarily fulfilled simultaneously.
2. Physics tells us that the membrane acceleration is the time derivative of the membrane velocity, which in turn is the time derivative of the membrane travel (excursion) [4]. Control concepts for loudspeakers can therefore use (measure and control) any of these physical properties.
3. Physics tells us that because of the linearly falling acoustical impedance by 20 dB / frequency decade the velocity of the membrane needs to increase inversely wrt. the frequency for the frequency region of interest in order to achieve a constant sound pressure frequency response [5]. That can be achieved by keeping the membrane acceleration constant over the frequency.

From these considerations a direct control system for the membrane acceleration would be preferable.

As soon as it comes to the realization of any of these control systems the selection of the sensor - if any - plays a decisive role. It is well known from linear control theory [6] that at sufficient loop gain the frequency response of the control loop is the reciprocal one of the sensor frequency response. That has the consequences:
- Using an acceleration sensor results in a constant control loop frequency response.
- Using a velocity sensor results in a single differentiation of the control loop (its frequency response rises with 20 dB/frequency decade).
- Using a excursion sensor results in a double differentiation of the control loop (its frequency response rises with 40 dB/frequency decade).

As a consequence these three sensor types require (in the above sequence) non, a single integration, or a double integration as linear pre-distortion of the audio signal as input to the control loop. Otherwise one would linearize the loudspeaker, but miss a constant frequency response. A single integration of the audio signal costs 20 dB, a double integration costs 40 dB of dynamics per frequency decade. This is a certain disadvantage against an direct acceleration controlled loudspeaker.

DETAILED DESCRIPTION OF THE CONTROL STRATEGIES

A) Membrane excursion control loop

Usually capacitive sensors are suggested. One of the most prominent examples, which was many years in production [7] uses a capacitive sensor for the tweeter. The tweeter acted in fact simultaneously as a condenser microphone whereby the full membrane area of the tweeter was used. Instead of using the voltage of the condenser microphone as output signal, its capacitive current was used.

The described realization of the sensor is well suited for tweeters, but less for woofers because of the large travel distances resulting for low frequencies at high sound pressure levels.

A capacitive sensor for a woofer is proposed in [8]. Here the area and such the capacity of a sensor capacitor is linearly changed with the excursion of the voice coil.

A general disadvantage of all capacitive sensors lies in the high voltages (up to 250V) which are required. Especially humidity can lead to audible corona discharges. Other sensors have been suggested as e.g. Hall sensors, but to the knowledge of the author they have never been commercialized in a product. As the control loop differentiates twice, the linear pre-distortion needs to integrate twice in order to get a constant SPL frequency response.

B) Membrane velocity control loop

The velocity sensor is in principle a dynamic microphone whereby its membrane is substituted by the loudspeaker membrane. One of the most prominent examples, which is in current production [9] uses an additional magnet system in the axis of the loudspeaker magnet system and a dedicated sensor coil fixed at the voice coil former. A patent [10] describes the realization of the necessary pick-up coil als multi layer printed circuit. The sensor is susceptible to magnetic interference coming e.g. from transformers, but also from the voice coil current. There are solutions for the compensation of those stray fields, but a lot of engineering experience is required to realize this control concept successfully. The control loop differentiates once and needs the integration of the audio signal as linear pre-distortion at its input in order to get a constant frequency response.

A sensor-less version of this strategy uses the voice coil induced voltage as velocity signal. This technology was used for many years [11] by using slightly different magnets, i.e. Bl-products for two electrical identical chassis working in the same enclosure. It is such possible to extract an approximate velocity signal.

A further sensor-less version of this strategy measures voltage and current of the chassis. E.g. at constant current the voltage of the chassis is the difference between the komplex voltage generated by the equivalent electrical elements of the chassis and the velocity induced voltage. Again it is possible to extract an approximate velocity proportional signal.

However: Both sensor-less versions suffer from the fact that the transfer function between voice coil current and acceleration is already non-linear and mainly the same non-linearities are present again in the generation process of the velocity induced voltage (varying Bl product, nonlinear compliance …). (1) Footnote

C) Membrane acceleration control loop

The acceleration sensor can nowadays be procured as MEMS (Micro Electro-Mechanical System) sensor with high linearity, low noise and sufficient acceleration range [12]. The advantage of MEMS acceleration sensors is their immunity against electrical and magnetic interference. Those sensor are available with 0.1% linearity which translates in turn to the linearity of the overall control loop provided sufficient high loop gain.

These sensors use tiny spring-mass systems etched in Silizium with an active capacitive read-out. One of the most prominent examples using modern MEMS sensors, which is in current production [13] uses Analog Devices MEMS sensors and achieves better than 0.1% distortions and a perfect constant SPL frequency response from 15 Hz up to the upper limit of the used chassis.

An alternative are Piezo-electric sensors consisting of a thin Piezo material layer on a spring / mass system [14]. Products with this type of sensors have been on the market in the past [15].

A general problem of all acceleration sensors is their principle based on a spring / mass system with usually low damping. As long as the resonance frequency of the spring / mass system is sufficiently above the control loop upper band limit this is a manageable issue. A potential issue, at least for absolute acceleration sensors, is their susceptibility to the gravitational acceleration and physical movements of the loudspeaker box. So don‘t move the loudspeaker around as long as the control loop is active. Otherwise the membrane will try to stay at its original position.

As the acceleration sensor results in a control loop with constant frequency response, no linear pre-distortion is required in front of the control loop. The MEMS sensor may be more costly than other sensors, but it is a high accuracy and simple device not requiring any adjustment.

(1) Footnote: By measuring the voice coil voltage and current one can with a certain update rate adjust a model for the non-linear pre-distortion of the chassis [16]. As this is not a real time control loop and based on a non-linear pre-distortion it is not further discussed in this paper on real time controlled loudspeakers.

Description of the control loop architecture on the example of an Acceleration Feed-Back System with MEMS sensor.

Figure 2 displays the block diagram of a modular integrated solution comprising the power amplifier and the complete control loop electronics [17].

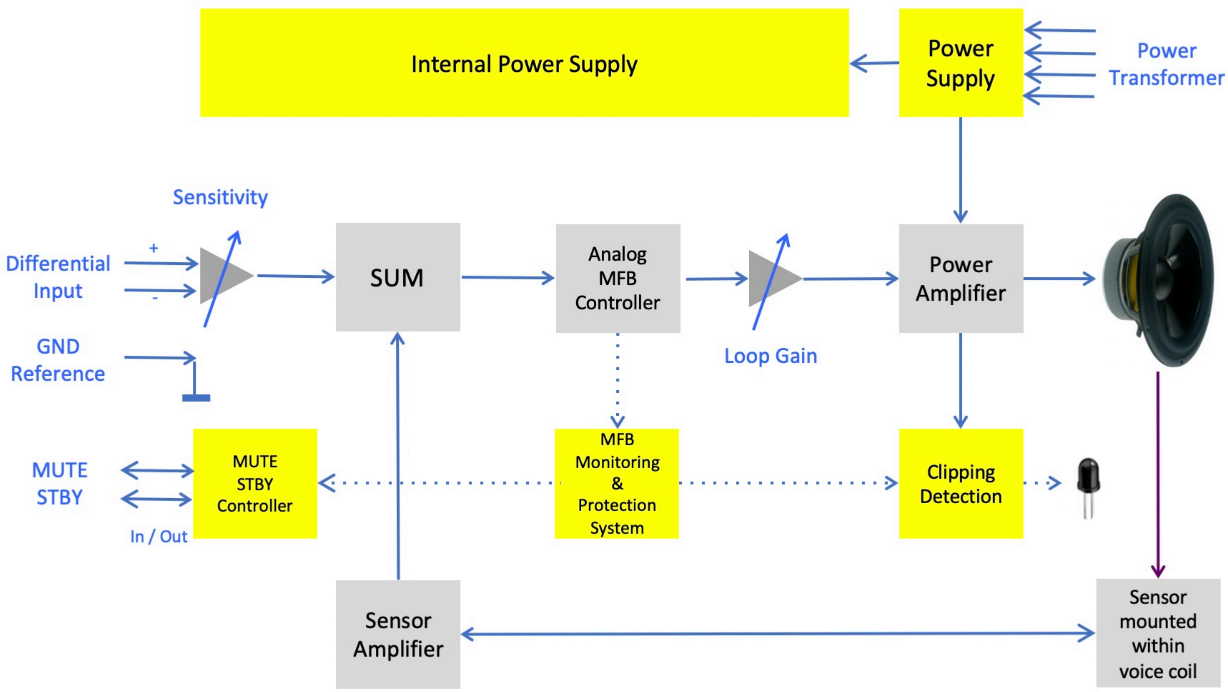


Figure 2: Block diagram of an integrated solution comprising the power amplifier and the complete control loop electronics for an Acceleration Controlled Loudspeaker.

The balanced (differential) audio input is processed by a difference amplifier with at least 60 dB common mode suppression in order to avoid ground loops. The summing amplifier compares the audio signal with the sensor amplifier signal. The sensor is a ratiometric device, i.e. its output voltage is proportional to the acceleration and to the supply voltage. The Sensor Amplifier removes the sensitivity to the supply voltage and compensates the offset voltage of the sensor. An analoge controller ensures with its frequency characteristics a high loop gain, which is centered at the resonance frequency of the chassis. Peak loop gains between 40 dB and 60 dB can be achieved. From the peak the loop gain falls to higher and to lower frequencies with 20 dB /

Frequency Decade, such determining the upper and lower loop gain limits (0 dB) and ensuring the stability of the control loop.
In order to adapt to different chassis, the loop gain can be adjusted by a 10 turn potentiometer. The highly linear DMOS power amplifier completes the forward chain. The feed back sensor is mounted inside the voice coil and its signal closes the control loop. All other blocks ensure the safety of the chassis and of the amplifier and take care of in-audible transition between standby, mute and operational states.
The MFB monitoring and protection system is based on a micro controller, which is also responsible for automatic calibration of the offset of different MEMS sensors and to null the gravitational acceleration in case the chassis is not operated in the vertical orientation.
STBY and MUTE are bidirectional control signals allowing to synchronize all connected amplifiers.

Figure 3 picture the necessary elements of the described acceleration feedback system

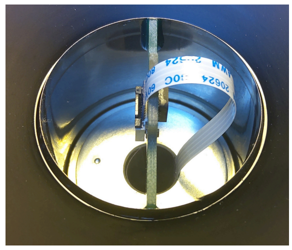


Figure 3 : AC PAR75 Integrated amplifier module comprising the complete acceleration control circuitry.
On the right side: Sensor PCB mounted inside the voice coil with flex lead-out.

Figure 4 shows violett the SPL frequency response and green the acceleration frequency response of an acceleration controlled woofer. Acceleration and SPL are proportional to each other. Both show a constant frequency response up to 200 Hz where the beaming of the chassis becomes visible in the SPL.

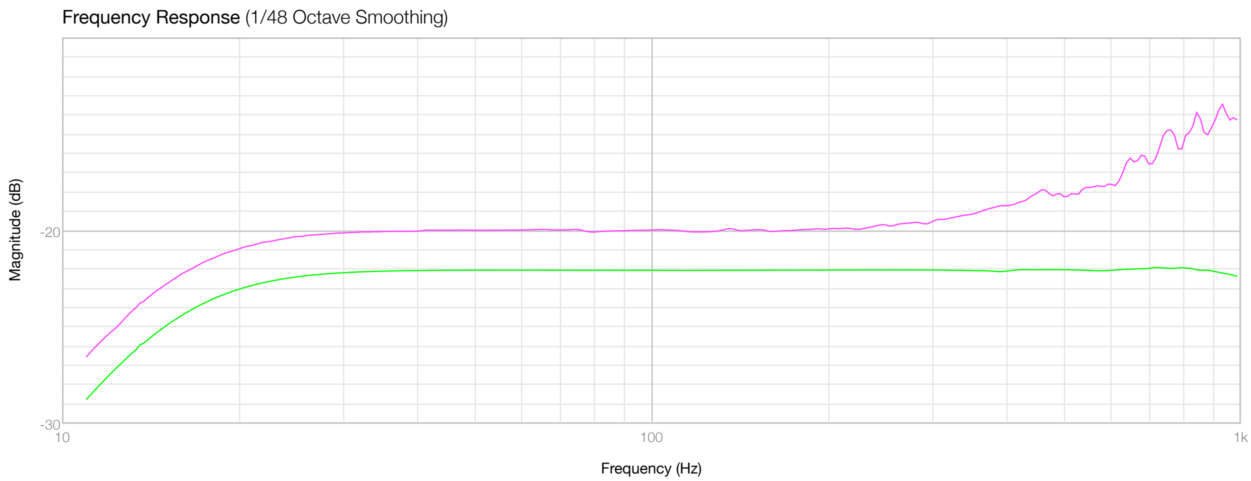


Figure 4: SPL frequency response (violett) and acceleration frequency response (green) of an acceleration controlled SEAS L22 RNX/P woofer. The stimulus signal is 15 Hz (-3dB) high pass filtered in order to avoid too large membrane excursion during the measurement. One has to keep in mind the inverse-square law [18]. Half the frequency leads to the fourfold Membran travel amplitude at constant acceleration. All chassis are in practical terms limited by the maximum (linear) membrane travel at low frequencies, not by the available membrane acceleration. Measurements are performed with the AudioChiemgau ModeCompensator in order to compensate the room modes in the laboratory.

Figure 5 shows the harmonic distortions of the chassis which remain 60 db below the fundamental frequency. The second harmonics shows below 40 Hz a 20 dB per frequency decade increase towards lower frequencies. The reason for this is the Doppler distortion, a.k.a. Phase Modulation of the moving membrane, which generates inter alia a second harmonic. Another article treats this effect in detail.

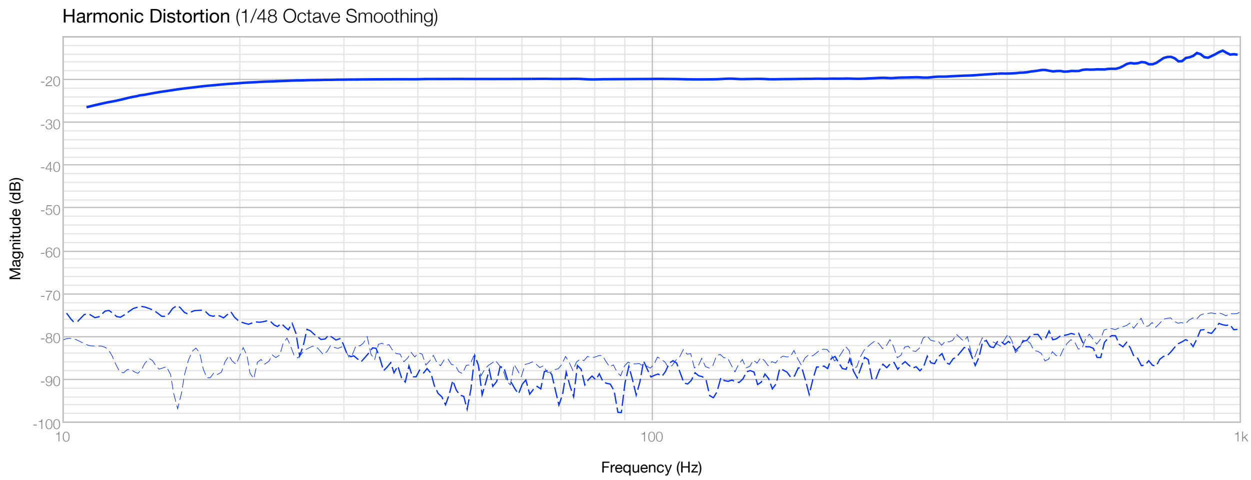
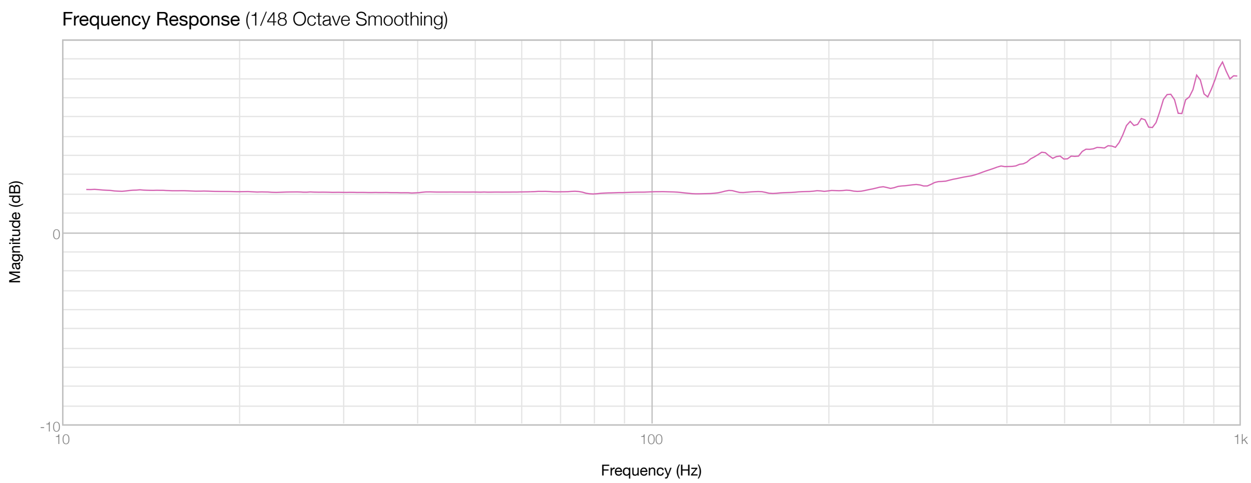


Figure 5: Frequency response of the SPL and the harmonic distortions k2 and k3. The harmonic and intermodulation distortions remain 60 dB below the fundamental frequency. For the level of the second harmonics between 10 Hz and 40 Hz see the text.

Figure 6 shows the SPL frequency response referenced to the acceleration signal. I.e. the mechanic-acoustic transfer function between the membrane acceleration and the sound pressure generation becomes visible. This transfer function is perfectly constant within the measurement accuracy up to 200 Hz, where the beaming of the relative large membrane becomes visible. This fits exactly with theory.



SUMMARY:

Three real time systems for the motion feed back of loudspeakers are discussed with respect to their advantages and disadvantages. Two of the concepts are currently used by High-End manufacturers [19], [20]. Considering the simplicity of the application of the systems in the practical world, the direct acceleration controlled loudspeaker (i.e. using an acceleration control loop) seems to be favorable, even, when the MEMS sensor has its cost. AudioChiemgau offers ready to use modules for High-End acceleration controlled loudspeakers.

REFERENCES:

1 Discussion 'Voltage Drive versus Current Drive', Web Page: https://audiochiemgau.com/voltage-vs-current

2 Pole-Zero Analysis of Multi-Stage Amplifiers: Web Page : https://wordpress.nmsu.edu/pfurth/files/2015/06/Tutorial_Pole_Zero_2011.pdf

3 Horst Kuchling: *Taschenbuch der Physik*. 15. Auflage. Verlag Harri Deutsch (auch VEB Fachbuchverlag Leipzig), Thun u. a. 1991, ISBN 3-8171-1020-0, 23.2.1 Hörfläche, S. 337.

4 R.G. Lerner; George L. Trigg (1991). *Encyclopedia of Physics* (second ed.). New York: VCH Publishers. ISBN 0-89573-752-3. OCLC 20853637.

5 Elektroakustik: Mit 62 durchgerechneten Beisp. (Springer-Lehrbuch) Zollner, Manfred, Zwicker, Eberhard I ISBN: 9783540646655

6 Control Engineering: https://en.wikipedia.org/wiki/Control_engineering#References

7 Capacitive sensor for loudspeakers: Patent DE2419447C3

8 Capacitive Motional Feedback for Loudspeakers: Web Page: pasi.nuutinmaki@servospeaker.com

9 Capacitive Feedback: Patent DE2422232A1

10 Backe&Müller Patentschrift: DE 10 2015 102 643 A1 2016.08.25

11 Backes&Müller BM3: Web Page: https://www.hifi-wiki.de/index.php/Backes_&_Müller_BM_3

12 Analog Devices MEMS Sensor: Web Page: https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL1001-1002.pdf

13 Analog Devices Data sheet: Web Page: https://www.analog.com/en/products/adxl1001.html

14 Piezo Electric Sensors: Web Page: https://mmf.de/iepe_standard.htm

15 Phillips RH 532 MFB Loudspeaker: Web Page: https://www.hifiengine.com/manual_library/philips/rh532.shtml

16 Klippel Controlled Sound: Web Page: https://www.klippel.de/products/klippel-controlled-sound.html

17 AudioChiemgau Web Page: www.audiochiemgau.de

18 Inverse Square Law: Wikipedia: Web PAge: https://en.wikipedia.org/wiki/Inverse-square_law#References

19 Silbersand: Web Page: https://silbersand.de