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Rethinking Flat Panel Loudspeakers – an Objective Acoustic Comparison of Different Speaker Categories

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ABSTRACT

The home entertainment market is growing, but connected devices like multi-room and streaming loudspeakers are increasingly replacing traditional audio systems. Compromises in the acoustic quality are made to satisfy additional requirements such as smaller, lighter and cheaper products. The number of smart speakers sold suggests that the customers accept speakers with lower acoustical quality for their daily use. Concepts like soundbars aim to achieve better spatial reproduction, but try to stay visually unobtrusive. Thanks to the low visual profile flat panel loudspeakers give opportunities for invisible integration. This paper presents an objective acoustic comparison of four speaker categories: smart speaker, flat panel, soundbar and studio monitor. The comparison reveals that recent technological advances could make flat panel loudspeakers an alternative.

1 Introduction

The home entertainment market is growing [1], but connected devices like multi-room and streaming loudspeakers are increasingly replacing traditional audio systems [2]. The main benefit of smart devices lies in the seamless integration into all household processes and the customers can play music from a variety of sources on their speakers. The number of smart and multi-room devices is growing and companies like Sonos hitting probably the right note with this direction. Sonos customers had registered more than 19 million speakers in 6.9 million households worldwide [3]. The sales are rising from 1.5 million products in 2013 to 4.6 million sold products in 2018 and the forecast shows continuing growth [1].

One of the upcoming practical problems is the simple integration of several devices in the living area. To guarantee an acceptance by the customer the size of the speakers is limited. Even if the speakers are small, the customers of audio devices expect that the audio signal can be reproduced with sufficient amplitude and quality [4]. A lot of research was done to improve the quality and the maximum SPL of small speakers. Klippel [4] presented an approach to control speakers more efficiently to generate more output with smaller loudspeakers. Furthermore, Klippel [5] recommends new speaker design criteria for higher SPL_{max}.
But it is known that compromises are made to satisfy additional requirements such as smaller, lighter, and cheaper products. The acoustic performance of a smart speaker is not comparable to the performance of a stu-

dio monitor. They can generate less SPL_{max}, have a higher lower cut-off frequency and a more uneven response. But the increasing number of smart speakers sold suggests that the customers accept speakers with lower acoustical quality for their daily use.

Thanks to their low visual profile, flat panel loudspeakers were originally thought as a way to facilitate the integration of several loudspeakers in an existing environment [6]. Flat panels have the chance for seamless integration, e.g as a picture on the wall, the front of your furniture or completely hidden in the wall. The usable radiating surface is for flat panel loudspeakers more important than the volume of the chamber. The properties of the panel offer possibilities for a wide field of applications. The loudspeaker could be constructed as a water-resistant and antibacterial loudspeaker, e.g. for hospital usage. Furthermore, it could be used as a whiteboard, projection wall or advertisement wall.

Several comparisons of flat panel loudspeakers and piston motion driven speakers show that flat panel loudspeakers have a potential for many applications [8, 9]. Flanagan and Moore [7] mention an improved sound radiation which is less affected by the room acoustics. The sound variation is less affected by the flat panel loudspeaker compared to the cone loudspeaker. This is the result of the diffuse nature and the smoother spectral propagation in a room.

It is known that flat panel speakers cannot reach the same acoustic performance as a piston motion driver. This is the result of the complex physics, e.g. the mode driven radiation system with phase and anti-phase components and a strong frequency dependent directivity. This makes this system more inefficient and more difficult to optimize. But the low visual profile gives opportunities to integrate larger and more powerful devices for higher acoustical quality in the living areas compared to speakers of the smart speaker category. This paper continues the discussion about flat panel loudspeakers and why we should rethink and reconsider this technology. An objective acoustical comparison of four different speaker categories is presented and a range of acoustic parameters is analysed.

2 Definition of speaker categories

This paper compares loudspeakers of different speaker categories with multiple cases of usage. A definition of each speaker category is presented below. The properties of the selected speakers like dimensions, channel logic and number of drivers are given in Table 1.

Category 1: Smart speaker
The category smart speaker represents small speakers with one or two small drivers in a compact enclosure. They are wireless and they are smart audio playback devices that use several types of connectivity for additional functions. Smart speakers can be located throughout the living space. That includes the kitchen, the bedroom and the living room [10].

Category 2: Flat panel
The flat panel category represents speakers, which are mode driven and radiating sound by bending the surface. A large surface is necessary for this type of speaker, which results in large dimensions. Flat panel speakers can be integrated in places with lower space restrictions of the customers, e.g. as a front of the furniture, as a picture on the wall or inside the wall.

Category 3: Soundbar
The category soundbar represents a type of loudspeaker that radiates sound from a wide enclosure mostly combined with an external subwoofer. The soundbar is a wide, typically thin and short (vertically) speaker with multiple drivers. It needs to be placed below the television. Because of space limitation small drivers are used, which are not capable of reproducing deep, low, bass sounds. They are used to supplement television sound and to play back multimedia content.

Category 4: Studio monitor
Studio monitors are specifically designed for professional audio production applications in which accurate audio reproduction is crucial. The category studio monitor implies that the speaker is designed to produce relatively flat frequency responses. They are used for professional audio production in recording studios, filmmaking, television studios, radio studios and project or home studios.

3 Measurement setup

All measurements were performed at the anechoic chamber at the Technical University Dresden. The following equipment was used for the measurement:

- Microphone: Gras 40HL (Low-noise)
- Power Module: Gras 12AK
- Measurement system: Klippel DA2
- Turntable: LinearX LT360
- Software operations: Robotics, TRF and MTON.

Table 1: Specifications of chosen speakers for each speaker category.

Properties	Smart speaker	Flat panel	Soundbar	Studio monitor
Selected speaker	Bose Revolve+	Hommbru Areal 1.5	Samsung K850	Genelec 8250A
Dimension in mm (W x H x D)	184 x 105 x 105	950 x 400 x 110	1210 x 82 x 131 204 x 399 x 414	452 x 286 x 278
Drivers	1x 2.5"Fullrange	6x 1" Exciter 2x 7" Woofer	3x 1" Tweeter 6x 2.5" Midwoofer 1x 8" Woofer	1x 1" Tweeter 1x 8" Woofer
Basssystem	Passivradiator	Bassreflex	Bassreflex	Bassreflex
Channel logic	1.0⋆	2.1⋆	2.1⋆	1.1

⋆ Speaker logic with applied mono signal to left and right channel

The measured distance is 2 m to guarantee that all speakers are perform in the far field. All levels are referenced to 1 m distance. The applied smoothing for all measurement is 1/6 per octave. The microphone was placed for all cone speakers on the tweeter level and for the flat panel speaker to the center. The input signal is a mono signal, which is applied with a y-connection to both channels of the smart speaker, the flat panel speaker and the soundbar. The studio monitor is connected with one channel. The soundbar is evaluated in the standard mode, which results in a better performance compared to the surround mode for the chosen criteria. The speaker works in the standard mode as a 2.1 speaker, if the input is a stereo signal.

4 Results

In this section the investigated acoustic parameters will be introduced and the measured results will be presented. The acoustic parameters are as followed: frequency limits, frequency response on-axis, frequency response in horizontal plane, SPL_{max} with sinus sweep, SPL_{MUCO} with multitone signal and the directivity pattern.

4.1 Frequency limits

The effective frequency range is the range of frequencies, bounded by stated upper and lower limits f_{up} and f_{low} for which the transfer function of a speaker does not drop more than 10 dB below the mean value of the sound pressure level SPL_{mean} (according to IEC standard [11]). The SPL_{mean} to [11] is the Root Mean Square of equal logarithmical frequency bands and will be calculated with Equation 2 from $\tilde{p}_m$, the mean of the squares of the sound pressure. The sound pressure $\tilde{p}_k$ is the sound pressure of each band k within the chosen frequency range from 100 Hz to 1 kHz:

$$\tilde{p}_m = \sqrt{\frac{1}{K}\sum_{k=1}^{K}(\tilde{p}_k)^2} \tag{1}$$

or in dB

$$SPL_{mean} = 20 \cdot log_{10}\left(\frac{\tilde{p}_m}{p_0}\right). \tag{2}$$

The following Table 2 shows the individual frequency ranges of all speaker categories. All speakers have a wide frequency range. The biggest differences are in the lower frequency limit. The studio monitor has the lowest limit with 33.3 Hz followed by the soundbar. The smart speaker has the highest lowest frequency with a value of 52.4 Hz. This frequency is low, compared to other speakers in this category. The flat panel has nearly the same lowest frequency compared to the studio monitor and the soundbar. All speakers transfer energy up to the highest frequencies.

4.2 Frequency response on-axis

Figure 1 shows the frequency response on-axis. All responses are normalized to their mean SPL shifted by 20 dB in order to maintain clarity.

To compare the frequency response in terms of linearity the quality of the transfer function can be described

Table 2: Effective frequency range with lower limit f_{low} and uppper limit f_{up}.

Speaker category	f low	f up
Smart speaker	52.4 Hz	21.8 kHz
Flat panel	36.6 Hz	19.2 kHz
Soundbar	34.1 Hz	18.9 kHz
Studio monitor	33.3 Hz	>22 kHz

mathematically using the logarithmic standard deviation σ_{log} calculated with Equation 3:

$$\sigma_{log} = \sqrt{\frac{1}{K-1}\sum_{k=1}^{K}\left[SPL_k - SPL_{mean}\right]^2}. \qquad (3)$$

The logarithmic standard deviation is a basis to compare multiple responses with different amplitudes since scale factors in the data are cancelled out. σ_{log} is an index for the flatness of a frequency response. This calculation is also used by van Dorp Schuitman and de Vries [12] for assessing the quality of flat panel speakers. For a perfectly flat frequency response, the logarithmic standard deviation will be 0 dB, which is the lower limit. A higher value corresponds to a more irregularly frequency response.
The results for the σ_{log} for on-axis response are presented in Table 3 and averaged in horizontal plane in Table 4. Furthermore the maximum and minimum difference from the SPL_{mean} are plotted. The criteria Max decribes the maximum difference from SPL_{mean} to the highest and Min to the lowest level in the frequency band. The chosen frequency range is limited from

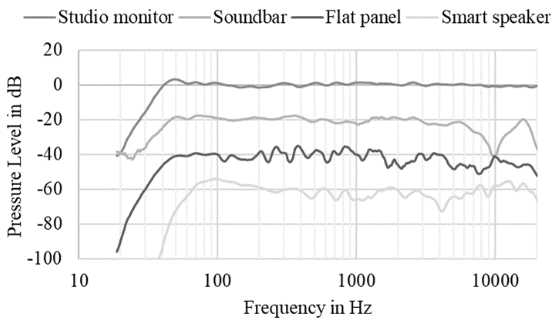

Fig. 1: Frequency response on 0 deg axis of all speakers referenced to their SPL_{mean} and shifted by 20 dB in order to maintain clarity.

Table 3: Plot of the logarithmic standard deviation σ_{log} of the frequency response on-axis and the Max and the Min value in a frequency range of 100 Hz to 5 kHz.

Speaker category	SPL_{dev}	Max	Min
Smart speaker	4.09 dB	+5.6 dB	-12.9 dB
Flat panel	3.32 dB	+4.7 dB	-8.6 dB
Soundbar	1.46 dB	+2.2 dB	-3.5 dB
Studio monitor	0.82 dB	+1.4 dB	-1.5 dB

100 Hz to 5 kHz. This gives a more realistic result from the σ_{log} if we consider the frequency response of the soundbar. The large dip at 10 kHz shown in Figure 1 can be a result of a stereo widening and anti-phase components of the tweeters. The frequency response of SPL_{AVG} presented in Figure 2 shows that this dip is not present any more and therefore this should not be considered when it comes to on-axis evaluation.
The results of Table 3 show the on-axis response of all speakers. The smart speaker performs with the higher deviation of σ_{log} of 4.09 dB and a maximum deviation of +5.6 dB and -12.9 dB. This is much higher compared to the studio monitor which is in the range of +1.4 dB to -1.5 dB. The transfer function has less deviation with is a σ_{log} of 0.82 dB. The flat panel performs in a slightly more linear way than the smart speaker, but has also higher deviation compared to the soundbar and the studio monitor.

4.3 Frequency response averaged in horizontal plane

It is known that the directivity pattern of a flat panel is strongly dependent on position. Azima et al. [13] advise to use a power measurement as a representative acoustic measurement for flat panel speakers, which correlates well to the subjective performance. In this study a measurement in horizontal plane is used by averaging the pressure response of individual angles. It is known that there are some slight differences to the acoustic power. But the average SPL gives a more realistic overview compared to a single point measurement. The SPL_{AVG} will be calculated with Equation 4, where T is the number of angles θ measured:

$$\tilde{p}_{AVG} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(\tilde{p}_\theta)^2} \qquad (4)$$

Table 4: Plot of the logarithmic standard deviation σ_{log} of the frequency response averaged over θ and the Max and the Min value in a frequency range of 100 Hz to 5 kHz.

Speaker category	SPL_{dev}	Max	Min
Smart speaker	2.78 dB	+6.8 dB	-6.1 dB
Flat panel	2.19 dB	+4.8 dB	-5.4 dB
Soundbar	1.72 dB	+3.7 dB	-3.1 dB
Studio monitor	1.20 dB	+2.2 dB	-2.2 dB

or in dB

$$SPL_{AVG} = 20 \cdot log_{10}\left(\frac{\tilde{p}_{AVG}}{p_0}\right). \quad (5)$$

The measurements were performed from -90° to +90° with 2° resolution. The resulting transfer functions are plotted in Figure 2. The resulting deviation changes by averaging the pressure in the horizontal plane. The results are less distributed and the differences of the studio monitor and the smart speaker are smaller. The studio monitor performs in a more uneven way, which is the result of a certain directivity at higher frequencies. By comparison, the smart speaker and the flat panel radiate their power more equally. This is also confirmed by the results that can be seen in the plots of the radiation pattern in section 4.6. The flat panel performance is closer to the soundbar in the horizontal plane.

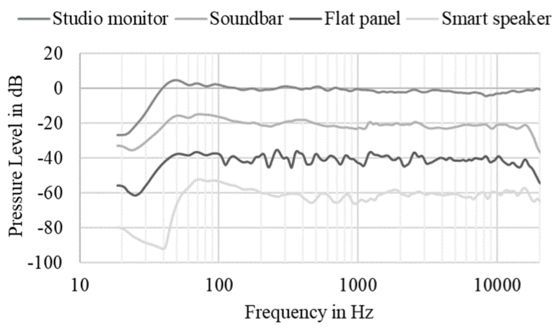

Fig. 2: Averaged frequency responses in horizontal plane of all speakers referenced to their mean SPL and shifted 20 dB.

4.4 Maximum SPL for 10 % THD

This section describes the measurement of the SPL_{max} for a given value of total harmonic distortion (THD). The measurements were performed with the Klippel DA2 and the TRF module. The relative harmonic distortion will be calculated with Equation 6. The level of the input voltage was increased until a single frequency band of 1/40 octave reaches a relative total harmonic distortion of -20 dB or 10 %. The analysed frequency range is not limited by a fixed frequency range to avoid comparing speakers outside of their field of application. The individual frequency range is defined by the frequency limits of section 4.1. The THD will be calculated using Equation 6:

$$THD(f) = \frac{\sqrt{\sum_{n=2}^{N} \tilde{p}_{nf}^2(f)}}{\tilde{p}_{ref}(f)}. \quad (6)$$

The SPL_{max} is a result of the fundamental of the highest input signal, where the fundamental reaches 10% THD. The SPL_{max} is the Root Mean Square of equal logarithmical frequency bands from 100 Hz to 5 kHz from $\tilde{p}_m$, the mean of the squares of the sound pressure calculated using Equation 1 and 2.

The results of Table 5 show the biggest difference of all speaker categories. The smart speaker reaches a SPL_{max} of 76.6 dB, which is 22 dB lower compared to the studio monitor. The flat panel speaker is more than 13 dB louder than a smart speaker, which is nearly 2.5 of the loudness. The soundbar is again 4 dB louder and the difference to the studio monitor reaches 8.7 dB. The SPL_{max} of the flat panel loudspeaker is limited, but enough for many cases of usage. The soundbar has nearly the same results in the standard mode as in the surround mode. The SPL_{max} is limited by the distortion of the subwoofer.

Table 5: SPL_{max} for 10% THD with sinus sweep

Speaker category	SPL_{max}	SPL_{diff}
Smart speaker	76.6 dB	-22.0 dB
Flat panel	89.9 dB	-8.7 dB
Soundbar	94.3 dB	-4.3 dB
Studio monitor	98.6 dB	

4.5 SPL muco with multitone signal

The multitone measurements were performed with the Klippel DA2 and the MTON module. A preheating time of 60 s and a pause of 60 s are applied. The stimulus is shaped with CEA2034 standard. The frequency range is from 50 Hz to 18 kHz. The SPL_{MUCO} is the measured Maximum Usable Continuous Output SPL and is calculated as the sum level of the fundamentals in the microphone signal in the frequency domain with the following Equation 7:

$$SPL_{MUCO} = 10log_{10} \sum_{n=1}^{N} \left[\frac{p(n)}{p_0} \right]^2 . \qquad (7)$$

The SPL_{MUCO} is limited by a 3 dB compression or -20 dB relative multitone distortion. All measurements were started in the low level range with no compression. The multitone distortion references the mean SPL to calculate the distortion level. The values of SPL_{MUCO} in Table 6 show nearly similar results with the same order compared to Table 5. The SPL values are a bit higher, which is the result of the method of calculation. The SPL_{mean} is a mean SPL value, the SPL_{MUCO} is a sum of the level of the recorded microphone signal lines.
The difference between the soundbar and the studio monitor is reduced to 1.9 dB difference. The smart speaker does also perform a bit better, with just 19.4 dB difference, but is also driven close to the compression limit of -3 dB at low frequencies. The flat panels distortion increases at lower SPL_{MUCO} values with -10.6 dB to the studio monitor and 8.8 dB to the smart speaker. This is a result of the frequency dependent efficiency, which correlates to the efficiency of single modes. Through the indirect excitation of more efficient modes the non-linear behaviour of the electromechanical system will be additionally amplified through the panel.

4.6 Radiation pattern

The following section describes the results of the polar radiation pattern of the chosen speakers. These loudspeakers are placed on a rotating table and the radiation pattern is measured using a fixed microphone. Angus [14] points out that the polar pattern of a distributed mode radiator depends on the mode of radiation. Therefore, Azima and Harris [15] consider that off-axis measurements of flat panel loudspeakers are generally more representative of the sonic behaviour of these loudspeakers. More generally Klippel and Schlechter [16] advise to measure directivity, which determines the diffuse sound in enclosed spaces (rooms). Figure 3 - 6 show the individual radiation pattern. All responses are shifted to 80 dB mean SPL. The smart speaker radiates omnidirectionally with some small dips and peaks at higher frequencies above 5 kHz. The contour plot of the studio monitor is homogenous with a certain controlled directivity starting above 500 Hz. The long dimensions of the soundbar result in an interfering contour plot and an angle dependent frequency response. Whether this dependency is audible cannot be answered. The contour plot of the flat panel speaker looks closer to the plot of the soundbar. It is symmetric and angle dependent. There is a minor difference between 3 kHz to 8 kHz between both. Close to the 0 deg axis in a range of ± 30 deg the flat panel loudspeaker transfers less energy compared to other angles, which are supposed to sound more diffuse and not direct compared to the soundbar or the studio monitor.
In terms of directivity it is not meaningful to define the best performance. The best directivity performance is strongly dependent on the case of usage. The smart speaker performs performs best in transferring energy homogeneously in all directions. The studio monitor focuses energy more to a listening area. The soundbar and the flat panel loudspeaker have a bit more deviation in the frequency response at different angles, which results in an angle dependent energy distribution. Whereby the soundbar focuses more on a listening area and the flat panel speaker radiates in a more distributed way.

Table 6: SPL_{MUCO} for 10% relative multitone distortion.

Speaker category	SPL_{MUCO}	SPL_{diff}
Smart speaker	83.8 dB	-19.4 dB
Flat panel	92.6 dB	-10.6 dB
Soundbar	101.3 dB	-1.9 dB
Studio monitor	103.2 dB	

5 Summary

Four different speaker categories are compared with standard acoustic parameters. The evaluation of frequency limits, maximum SPL output with two different

Table 7: Results of the acoustic parameters for different speaker categories. The evaluation is relative to the best performing speaker of each acoustic parameter.

Parameter	Smart speaker	Flat panel	Soundbar	Studio monitor
Frequency limits	o	+	+	++
Deviation on 0° axis	– –	–	+	++
Deviation averaged	–	o	+	++
SPL_{max} Sinus	– –	o	+	++
SPL_{max} Multitone	– –	o	++	++

signal types and the radiation pattern gives an objective overview of the performance of different speakers for various cases uf usage. On global terms, the result is not surprising. In terms of acoustic parameters the studio monitor performs best, followed by the soundbar and the flat panel. The smart speakers achieved the lowest scores. An overview of the results are presented in Table 7.

With another perspective the accepted acoustic performance of smart speakers is presented. This opens a discussion to reconsider other technologies, which cannot reach optimum performances, but far better than the accepted ones. The flat panel loudspeaker cannot reach the values of the soundbar and the studio monitor in terms of SPL_{max} and SPL_{MUCO}. The differences are large with 4 dB to 8 dB compared to the soundbar and 9 dB to 10 dB compared to the studio monitor, depending on the applied signal type. The SPL_{max} of the flat panel loudspeaker is limited, but compared to the smart speaker enough for many cases of usage. In terms of frequency limits the flat panel loudspeaker is close to the soundbar and studio monitor.

The overall acoustic performance of the chosen flat panel loudspeaker is between the smart speaker and the soundbar, but predominantly in the direction of the soundbar. The main benefit of the total invisible integration offers opprtunities: The flat panel speakers are an alternative for customers who prefer quality higher acoustical quality and more power in relation to speakers of the smart speaker category and who do not have space for larger devices.

This paper is an advisory to reconsider flat panel loudspeakers. Even if they cannot reach the optimum acoustic performances, they have an average acoustic quality which may be sufficient for many use cases in daily life.

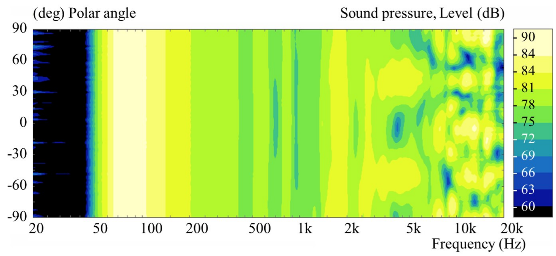

Fig. 3: Contour plot of the radiation behavior over frequency and the polar angle theta of a smart speaker.

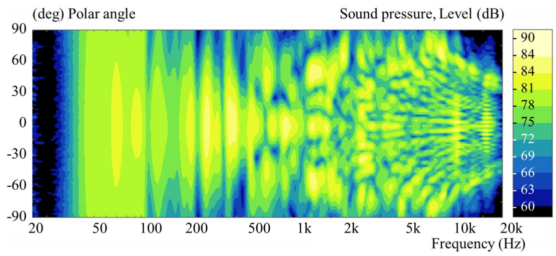

Fig. 4: Contour plot of the radiation behavior over frequency and the polar angle theta of a flat panel loudspeaker.

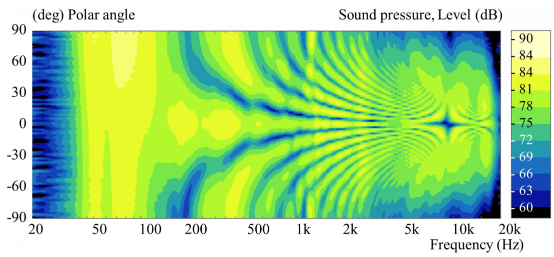

Fig. 5: Contour plot of the radiation behavior over frequency and the polar angle theta of a soundbar.

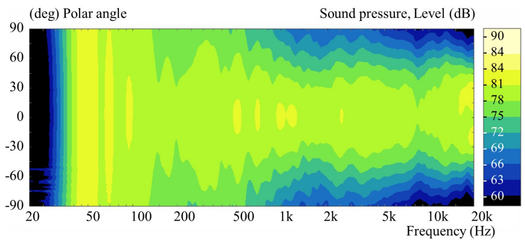

Fig. 6: Contour plot of the radiation behavior over frequency and the polar angle theta of a studio monitor.

References

[1] "Smart Home Report 2019 – Home Entertainment," in *Statista Digital Market Outlook – Segment Report*, "Statista - The Statistics Portal", 2019.

[2] "Absatz von Unterhaltungselektronik im Bereich Home Audio auf dem Konsumentenmarkt in Deutschland von 2005 - 2018 (in 1.000 Stück)," in *https://de.statista.com/statistik/daten/studie/20221/umfrage/umsatz-im-bereich-home-audio-seit-2005/*, "Statista - Das Statistik Portal", Accessed 12th of May 2019.

[3] "Sonos Hits the Right Note With Customers," in *https://www.statista.com/chart/14610/sonos-unit-sales-and-household-penetration/*, "Statista - The Statistics Portal", Accessed 12th of May 2019.

[4] Klippel, W., "Green Speaker Design (Part 1: Optimal Use of System Resources)," in *Audio Engineering Society Convention 146*, 2019.

[5] Klippel, W., "Green Speaker Design (Part 2: Optimal Use of Transducer Resources)," in *Audio Engineering Society Convention 146*, 2019.

[6] Caulkins, T., Corteel, E., van NGuyen, K., Pellegrini, R., and Warusfel, O., "Objective and Subjective Comparison of Electrodynamic and MAP Loudspeakers for Wave Field Synthesis," Audio Engineering Society, 2007.

[7] Flanagan, S. and Moore, B. C. J., "The Influence of Loudspeaker Type on Timbre Perception," in *Audio Engineering Society Convention 109*, 2000.

[8] Horbach, U., de Vries, D., and Corteel, E., "Spatial Audio Reproduction using Distributed Mode Loudspeaker Arrays," in *Audio Engineering Society Conference: 21st International Conference: Architectural Acoustics and Sound Reinforcement*, 2002.

[9] Beer, D., Brix, S., de Vries, D., and Kuster, M., "Structural and Acoustic Analysis of Multi-Actuator Panels," in *Audio Engineering Society Convention 118*, 2005.

[10] "The Smart Audio Report from NPR and Edison Research, Fall-Winter 2017," National Public Media LLC, 2017.

[11] "IEC standard 60268-5 Sound System Equipment – Part 5 Loudspeakers," 2003.

[12] van Dorp Schuitman, J. and de Vries, D., "Wave Field Synthesis using Multi-Actuator Panel: Further Steps to Optimal Performance," in *Audio Engineering Society Conference: 28th International Conference: The Future of Audio Technology–Surround and Beyond*, 2006.

[13] Azima, H., Panzer, J., and Reynaga, D., "Distributed-Mode Loudspeakers (DML) in Small Enclosures: 8193," in *Audio Engineering Society Convention 106*, 1999.

[14] Angus, J. A. S., "Distributed Mode Loudspeaker Polar Patterns," in *Audio Engineering Society Convention 107*, 1999.

[15] Azima, H. and Harris, N., "Boundary Interaction of Diffuse Field Distributed-Mode Radiators," in *Audio Engineering Society Convention 103*, 1997.

[16] Klippel, W. and Schlechter, J., "Distributed Mechanical Parameters of Loudspeakers, Part 2: Diagnostics," *Journal of the Audio Engineering Society*, 57(9), pp. 696–708, 2009.