Optimized Radiation Pattern and Time Response of Flat Panel Loudspeakers due to the Specific Damping of the Boundary Conditions

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Introduction

Nowadays flat panel loudspeakers are a promising alternative to conventional loudspeakers. Especially the invisible integration, e.g. as a cabinet front or as a module inside the wall, offers new design options. This gives opportunities to integrate very large radiating surfaces and volumes into rooms without disturbing the architectural room design. However, besides the design aspects, flat panel loudspeakers have to reach comparable acoustic performance to conventional speakers systems.

As described in previous papers, flat panel loudspeakers have a higher deviation in the frequency and power response compared to pistonic speakers [1]. This is a result of their resonance-based behavior, which additionally affects the temporal and frequency depending radiation of the speaker [2]. The audibility of resonances is a major factor in subjective assessments of loudspeakers or headphones [3]. Furthermore, Olive [4] has shown, that a speaker with an unusually constant directivity is not prefered, cause of it's colorations and unusual spatial artifacts, compared to speakers with a flat and smooth on-axis as well as off-axis response.

If one assumes an ideal infinite or highly damped panel the reflections of the edge are negligible and an ideal impulse can follow. Once the plate has finite dimensions the impulse will be reflected from the edges and dissipates in the panel. Using a layer of highly damped material increases the damping loss factor of the panel. Next to this option, additional damping can be applied using flexible damped boundary conditions.

The goal of this paper is to address the influence of the edge boundary conditions to the quality of the emitted wave field, by comparing free and clamped boundary conditions. Furthermore, the influence of flexible boundary conditions are shown, which reduce edge reflections and improve the impulse reponse. The first section compares the radiation characteristics of a flat panel loudspeaker with that of a conventional studio monitor. In the following section, the problem of an in-homogeneous directivity pattern is discussed and an example of the compromise of an ideal DSP-filtering is given. The next section compares the directivity of the following four different boundary conditions: free, clamped, clamped with bitumen and clamped with rubber. Finally, the temporal behavior of all types of boundaries conditions are compared to the decay of a conventional studio monitor and a commercial flat panel loudspeaker.

Preliminary analysis

As shown in previous studies, flat panel loudspeakers have a very different radiation pattern compared to conventional speakers [1]. The on-axis and the reduced sound power behavior of the studio monitor Genelec 8250A and the commercial flat panel loudspeaker Hommbru Areal 1.5 are shown in Figure 1. In addition, the Sound Power Directivity Index (SPDI) according to ANSI/CEA-2034 [5] is calculated to compare the directivity of both speakers. In this paper, the SPDI is defined as the difference between the on-axis curve and the reduced sound power curve, as a pressure average from - 90 deg to + 90 deg with 10 deg resolution. A value of 0 dB corresponds to an ideal monopole source.

The studio monitor shows a beam with an increasing frequency, which is very constant with 3 - 4 dB starting at 1 kHz. The flat panel loudspeaker shows a highly frequency-dependent directivity. The SPDI increases up to 900 Hz, with a higher SPDI-level compared to the studio monitor. This is due to its larger dimensions. From approximately 1 kHz, however, the SPDI-level decreases and reaches negative values in the range of 7 kHz. This indicates that more power is radiated off-axis than on-axis. Negative SPDI-levels are a reason for the diffuse sounding and missing directness of flat panel loudspeakers, which needs to be improved to make them more comparable to speakers with pistonic behavior.

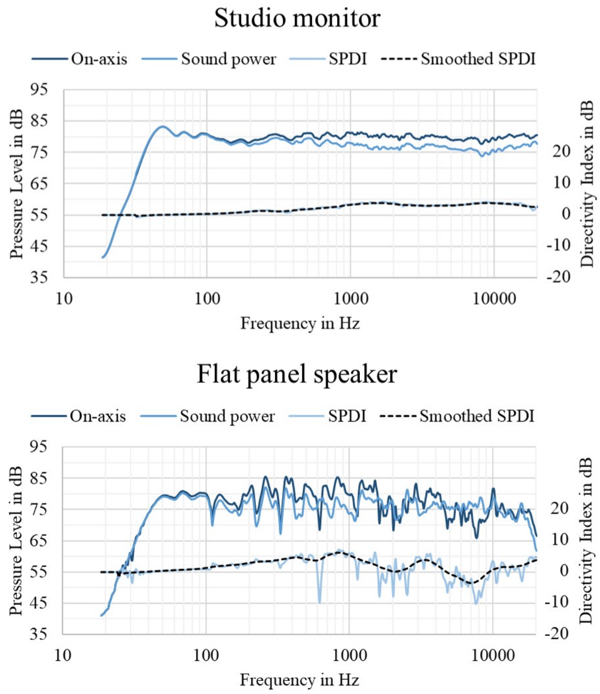

Figure 1: On-axis, sound power and sound power directivity index (SPDI) response of a studio monitor compared to a flat panel loudspeaker according to [1].

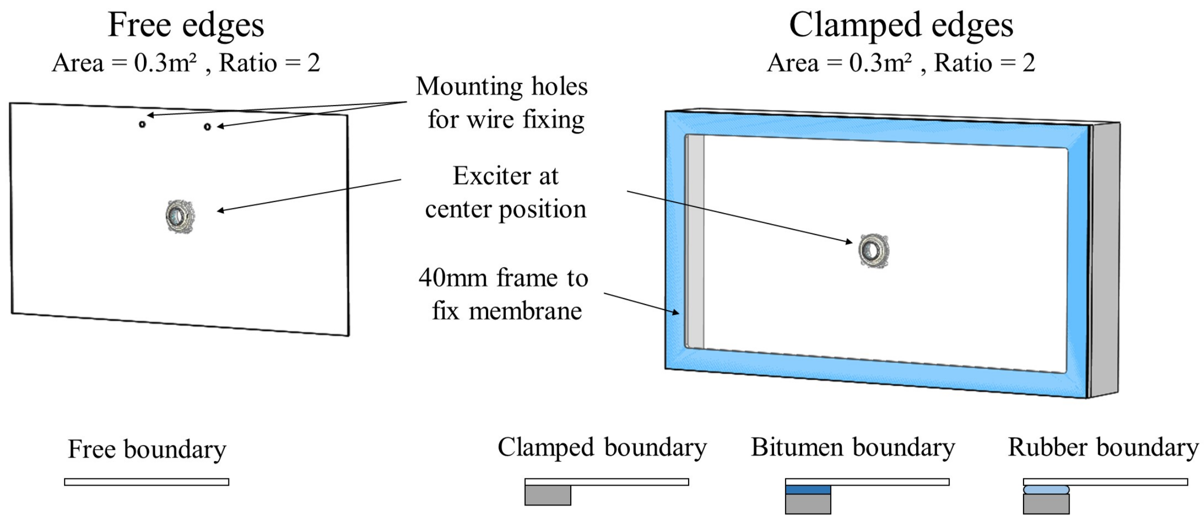

Figure 2: Overview of the modular test frame, the exciter position and the four different panel boundary conditions applied in this study: free, clamped, clamped bitumen and clamped rubber.

Importance of a homogenous directivity

The perceived sound quality of a loudspeaker is a combination of the direct sound, the slightly delayed and attenuated early reflections, as well as the progressively delayed reverberant sound field [2]. If the energy of a loudspeaker is not radiated uniformly, a strong change of the program material occurs and speakers have colorations and unusual spatial artifacts [4]. Toole [2] and Olive [4] have shown that loudspeakers with such irregular radiation characteristics are rated worse than loudspeakers with homogeneous directional characteristics.

Nowadays it is easy to filter the response of a speaker to create a smooth response. For a flat panel loudspeaker, as shown in Figure 1, the filtering can be used to optimize either the on-axis or the sound power response to a flat response. In Figure 3 the on-axis and sound power response of the flat panel loudspeaker of Figure 1 are ideally compensated to a flat response. It becomes obvious that no satisfactory result can be achieved even with strong filtering. With a negative SPDI, a flat on-axis response can cause too much excitation of early reflections, which will result in a colored timbre perception. The optional filtering to a flat sound power response results in a higher SPL on-axis in the mid frequency range, which will causes a missing directness of speech and voice

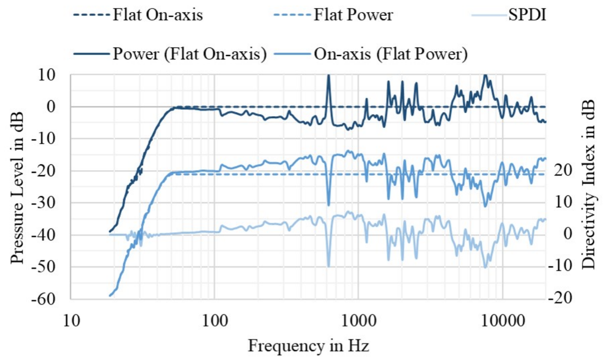

Figure 3: Filtered on-axis and sound power response to visualize the importance of a homogenous directivity.

reproduction. The preferred tuning for irregular sound radiation is always a compromise.

In both cases, the SPDI is not affected by the DSP compensation, since both transfer functions are modified by the identical magnitude. Hence, this is a constructive problem that can not be solved by applying filters to the loudspeaker. Therefore, an in-homogeneous radiation characteristic needs to be constructively improved to be comparable with conventional speakers.

Test set-up

All measurements are based on a modular test frame, in which different panels can be replaced and tested under equal mounting conditions. The basis of this study is a 3 mm HPL (High pressure laminate) panel, which has the following material parameters: $E = 16.4\,\text{GPa}$, $\rho = 1480\,\text{Kg/m}^3$ and $\nu = 0.32$. This material was chosen because of its low damping loss factor, which clarifies the effect of the boundary conditions. In this paper, four variants are compared as shown in Figure 2. One of them has free boundary conditions and three others have clamped boundary conditions. Two of these three clamped variants are built with an additional damping medium in the frame to absorb the energy of the incident wave and to reduce its reflection. For the version with clamped boundaries, the panel is directly glued to the frame. In the case of the damped version, bitumen and rubber are glued between the frame and the panel. All four variants have the same radiating surface, which implicate that the total panel dimensions for the variants with clamped edges are 80 mm larger in both longitudinal dimensions, which corresponds to the frame width. In addition, the three variants with clamped edges have an 11 cm deep frame, which is used to stabilize the edges. All variants have an open backside to avoid stiffening by the enclosed volume and allow an objective comparison to the variant with free edges.

All measurements were performed in the anechoic chamber at the Technical University Dresden, under equal conditions and with the same equipment as described in [1].

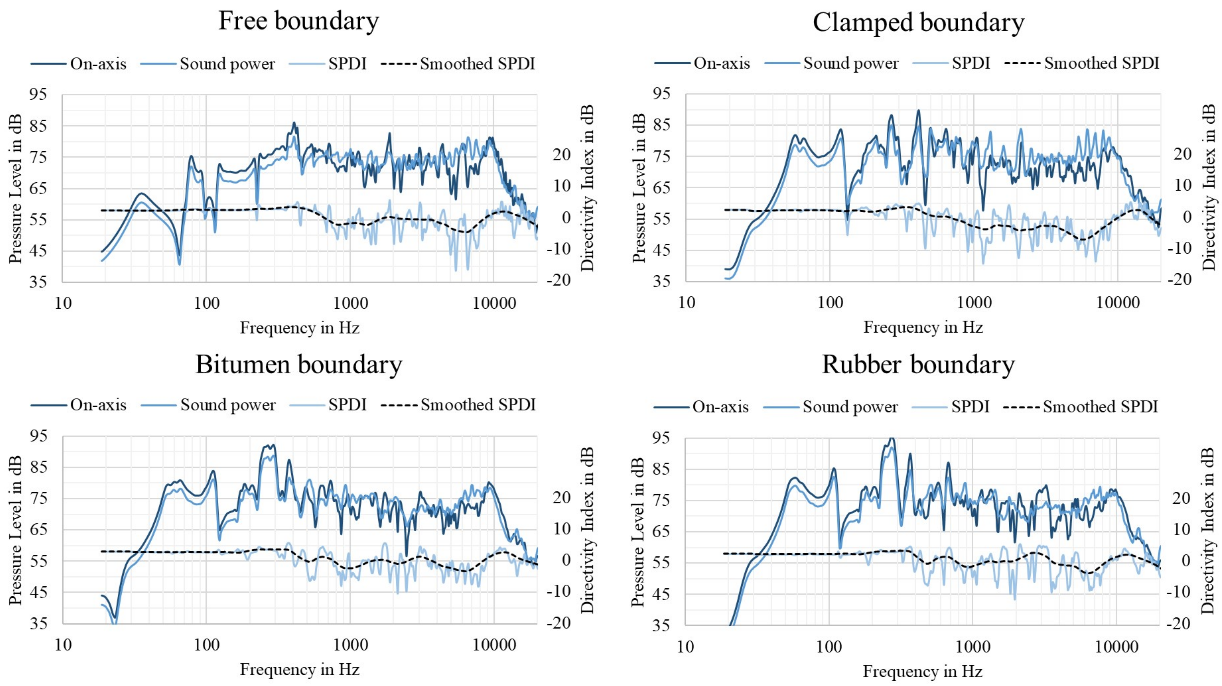

Figure 4: On-axis, sound power and sound power directivity index (SPDI) response of four different boundary conditions.

Radiation characteristics

At first a short summary of all variants: The loudspeakers are measured with an open backside, which results in a +3 dB SPDI for low frequencies. Furthermore, all speakers have a dip at 6.5 kHz, which is due to the coincidence frequency of the panel. This is material-specific and independent of the boundary conditions [6]. At this frequency, the radiating angle is 90 deg, which results in strong off-axis radiation, while the angle decreases to higher frequencies. The used exciter is the DAEX30HESF-4, which has a cut-off frequency of 10 kHz, which increases the SPL on-axis [6].
First of all, the radiation characteristics of the clamped and free boundary conditions are compared. Because of the increased stiffness due to clamped boundaries, the natural frequencies of the panel are shifted to higher frequencies. For that reason, the lowest cut-off frequency of the free boundary conditions is lower and the speaker can radiate from 35 Hz. However, a notch follows, which can be explained by the strong anti-phase component of the free edges. From 50 Hz up to 1000 Hz the loudspeaker with clamped boundary conditions transmits much more sound and has a higher sensitivity. Above 1000 Hz the level difference of both types becomes smaller. From this frequency upwards, a further effect occurs. In the configuration with clamped boundary conditions, the sound pressure level off-axis is significantly increased, which can be seen by the higher sound power value compared to the on-axis response. This leads to negative SPDI above 700 Hz. In the variant with free boundary conditions, the difference between the on-axis and the sound power radiation is smaller. Only low negative SPDI values are achieved from 700 Hz.

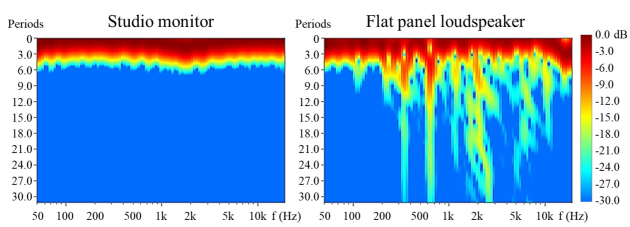

Figure 5: Periodic cumulative spectral decay of the studio monitor in comparison to the flat panel loudspeaker.

Periodical decay behavior

The system response of a loudspeaker has two characteristic time regions: rise time and decay time. The following study concentrates on the decay behavior, which is more critical to the timbre perception. The periodic cumulative spectral decay (PCSD) measures the frequency content of a loudspeaker's decay response following an impulsive input. It gives a detailed analysis of loudspeaker resonances. The PCSD is based on a period-based scale in accordance with the results of the psychoacoustical researches of Toole and Olive [3]. They have shown that the human perceptual system gives similar weights to resonances with the same Q factor on all frequencies. The following is a simple illustration: A resonant response with resonance frequency ω_n can be represented by a time decaying sine wave with Equation 1 in accordance with [7]. For the same Q, higher frequency resonances decay more rapidly than low-frequency ones.

$$envelope(h(t)) = e^{-\frac{\omega_n t}{2Q}} \tag{1}$$

$$ln[envelope(h(t))] = -\frac{\omega_n t}{2Q} \tag{2}$$

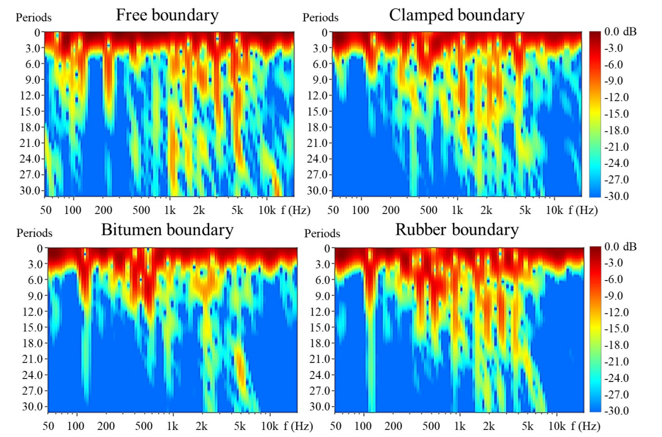

Figure 6: Periodic cumulative spectral decay of flat panel loudspeakers with four different boundary conditions.

The logarithm of a single resonance shown in Equation 2 is proportional to the number of periods with proportionality factor equal to the resonance damping. That means, resonances with the same Q are presented similarly in PCSD. Furthermore, to refer all results to a flat response the deviations in the frequency response are compensated by dividing the transfer function H(f) by itself.

Preferably, the impulse response of a loudspeaker should decay immediately. Figure 5 visualizes the large difference of a flat panel loudspeaker compared to a conventional speaker. Flat-panel loudspeakers are resonance-based and have inertia as well as stored energy, so that they take much more time to dissipate compared to the studio monitor. Obviously, the studio monitor, which is not based on resonance, decays very quickly.

In the following Figure 6 the PCSD of the filtered responses of the four different boundary conditions are compared. The decay is mainly determined by the total effective damping loss factor. There are only minor differences between the free edges and clamped edges variants. Clamped edges slightly improve the decay behavior because of the damping of the boundaries. The free edge panel has only the material damping, therefore the temporal behavior is slightly worse. The further comparison of the flexible boundary conditions shows clearly the difference between the bitumen and rubber boundary. By using a highly damped boundary conditions, like bitumen, the temporal behavior can be improved and the impulse decays much faster. This is closer to an ideal response. When using rubber boundary conditions, a little additional damping occurs and the temporal behavior is similar to the clamped boundary condition.

Conclusions

This paper address, the influence of the edge boundary conditions to the quality of the emitted wave field. It describes the impact of the boundary conditions of a flat panel loudspeaker to the radiation characteristics and to the temporal behavior. Four types of edge boundary conditions: free, clamped and two types of flexible clamped boundary conditions are explored.

For manufacturing reasons, the panel is usually glued firmly to a frame. Reflections occur at this edge, causing interference on the panel. It could be shown that the reflections of clamped edges significantly increase the sensitivity in the low-frequency range. Furthermore, the temporal behavior is not affected. However, the boundary reflections have a significant influence on the directivity of the loudspeaker for higher frequencies above 1 kHz. This can actually result in a negative SPDI. By using flexible boundary conditions the directivity can be improved. Both variants suppress strong boundary reflections and avoid interferences on the panel. This results in a more homogenous directivity response that is close to the one with free boundaries. In addition, a highly damped material such as bitumen significantly improves the temporal behavior of the flat panel loudspeaker.

By assuming a speaker with a diffuse sounding, the clamped boundary conditions can be helpful. To manufacture a flat panel speaker which sounds closer to a conventional speaker, damped boundary conditions should be used. This reduces causes of colorations and unusual spatial artifacts and a better perceptual speaker quality can be achieved [4].

In summary, by increasing the damping loss factor of the boundary conditions, an improvement of the directness as well as a strong reduction of the decay behavior can be determined.

References

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