Scale Model Study of Audience Related Transfer Functions (ARTF) for Direct Sound and Early Reflections

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Introduction

A 1:20 scale model has been constructed to investigate grazing attenuation by seats and audience at various angles of sound incidence, for both direct sound and early reflections. Transfer functions for a range of azimuth and elevation angles have been measured both for unupholstered seats and with modeled audience: these are referred to as the Audience Related Transfer Functions (ARTF). The measurements reveal not only the low frequency seat dip effect and its dependency on the incidence angle but also show a significant broadband attenuation. This broadband attenuation is strongly inversely dependent on the source elevation and can reach up to 16 dB between 400 Hz and 3 kHz. This has consequences equally for the direct sound and early reflections in auditoria. In order to overcome this effect, a possible solution using early reflections are discussed. A greater efficiency of audience coverage can be achieved with low-elevation early reflections (the so-called solid angle principle). Analyzing the measured ARTF, the reflection level also suffers from grazing attenuation inversely dependent on the elevation angle. Balancing the solid angle principle with the grazing attenuation, an optimum elevation of 10° - 15° for the reflection surface is proposed.

Scale Model

A 1:20 scale-model has been constructed and shall be described in this paragraph using the corresponding real world dimensions. It consists of laser cut wooden slats approximating unupholstered seats of 100 cm height, a row distance of 95 cm and a seat spacing of 55 cm (see Figure 1). The audience members are modeled by a 110 cm high and 20 cm thick prism shaped body and 60 cm x 20 cm cuboid legs. The supplier of the PU-foam states an absorption coefficient of 85% at 1600 Hz (model scale). The authors expect the material to react completely absorbing for higher frequencies. The heads are wooden balls of 20 cm diameter pinned on top of the body. In total, 15 rows consisting of 25 seats have been manufactured. A Visation FRS 5 X loudspeaker is paired with an inverse horn of 35 mm height developed by Kahle Acoustics [1] and excited using logarithmic sweeps. The speaker is mounted on a stand and is placed along a quarter circle of 20 m radius around row 12, seat 6. The seating area is shaped like a quarter circle in order to keep the audience area passed by the direct sound constant for all source positions (see Figure 2). In a subsequent step, to measure azimuth angles $> 90°$, the detachable rows are mounted facing the opposite direction. The source is located in the free field without a stage floor reflection and keeps a constant distance of 10 m to the nearest seat. This distance ensures far field conditions and smaller elevation deviations between rows. Two DPA 4060 omni directional microphones have been fitted instead of a head at 1.2 m height above the floor in various seats (Figure 1). The measured frequency range corresponds to 45 Hz - 3 kHz in real scale. All measurements are corrected regarding the distance loss and frequency response with a free field impulse response of the source and receiver combination. The derived impulse responses are cropped in time domain after 160 ms (real scale) to exclude reflections from the laboratory itself. The indicated azimuth and elevation angles always refer to a receiver based coordinate system with origin in row 12, seat 6, 1.2 m above the floor. All results are presented as power levels per frequency band.

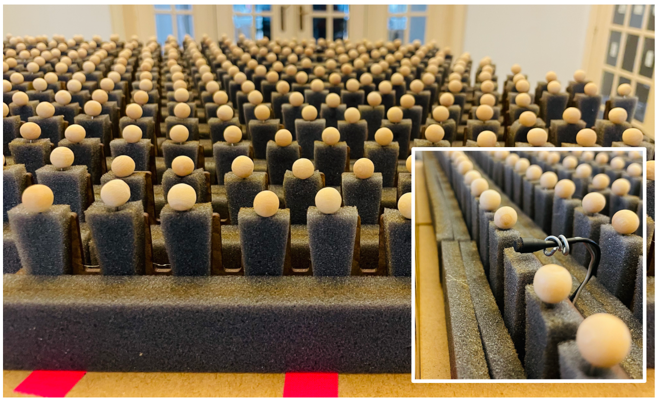


Figure 1: Scale model with close up of microphone placement.

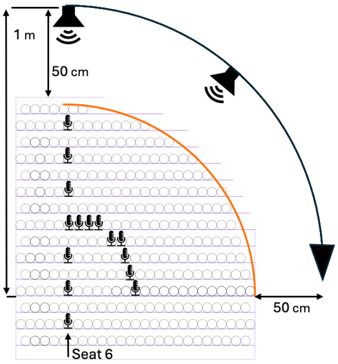


Figure 2: Sketch illustrating the floor plan of the model, measurement positions and dimensions in model scale.

Audience Related Transfer Functions

In this section, the measurement results will be presented. After focusing on sound from frontal incidence, audience centered directivity plots are introduced. All

Figures are based on the measurements in the 12th row, seat 6 if not otherwise specified.

Frontal Sound Incidence

In a first step, impulse responses have been measured for frontal sound incidence at seat 6 in every second row (Figure 3). Two main notch frequencies can be distinguished. The first notch between 85-107 Hz corresponds to the seat dip frequency with $\frac{\lambda}{4} = 1\,\mathrm{m}$ [2]. The second notch at 315 Hz might correspond to the patch of floor not covered by dampening material with $\frac{\lambda}{4} = 0.27\,\mathrm{m}$. Because of the interleaved seating arrangement, a head dip cannot be identified [3]. In addition, the known low frequency boost below the first seat dip is evident at 50 Hz for all measurement positions. Since Figure 3 is already corrected for the free field distance loss, the broadband offset of the lines corresponds to an attenuation in excess of the spherical spreading. It quantifies to approximately $0.7\,\frac{\mathrm{dB}}{\mathrm{m}}$ and is in line with earlier findings [3, 4, 5]. This broad band attenuation accumulates with distance to a very severe magnitude and is expected to continue for further rows of seats. In the PHD of Mommertz 1996 [6] these effects are explained with good alignment to the presented measurements using the guided boundary wave to explain the low frequency gain and a complex reflection factor for the audience plane.

Further measurements displayed in Figure 4 investigate the influence of the source elevation angle based on the receiver position in the 12th row. Two primary effects can be distinguished: First, the inversely proportional relationship between grazing attenuation and source elevation angle [7]. Second, the shift of the seat dip frequency towards lower frequencies with increasing elevation [8]. The magnitude of attenuation is more sensitive towards grazing incidence, as the increase in level from 0° to 5° elevation measures $\approx 7.5\,\mathrm{dB}$. This equals a halving of the attenuation.

For the sake of completeness measurements with empty unupholstered seats reveal only a 5 dB lower broad band attenuation despite a direct line of sight. Measurements above 30° source elevation do not show a significantly different behavior to the illustrated measurement at 30° source elevation for frequencies above 200 Hz and are not discussed further.

Summarizing, the broad band attenuation for frequencies of 400 Hz and above increases with the number of rows passed and with approaching grazing sound incidence. It is the most sensitive for sound incidence angles $< 10°$.

Arbitrary Sound Incidence

After focusing on the intuitive frontal sound incident behavior, free field ARTF measurements of 10° azimuth resolution shall be presented in Figure 5. The influence of the sound source elevation angle on broad band attenuation can be studied at the example of the 1 kHz octave band in Figure 5a. For 0° and 5° elevation angles, the amplification of sound at 100° azimuth might result from the reflective seat backrests. While Increasing the source elevation the ARTF approaches an omni directivity. In Figure 5b the ARTF frequency bands affected by the broad band attenuation are given.

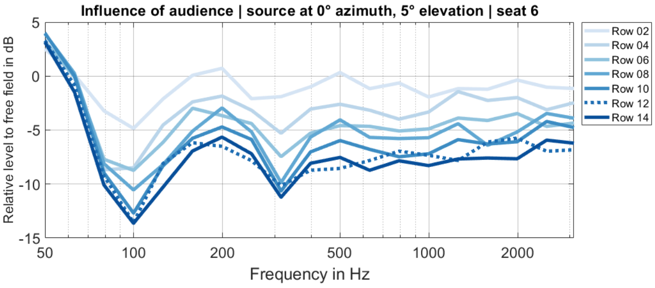


Figure 3: Free field compensated ARTF for frontal sound incidence along the rows. The source elevation corresponds to 5° in row 12. A general attenuation of $0.7\,\frac{\mathrm{dB}}{\mathrm{m}}$ and the seat-dip effect can be recognized.

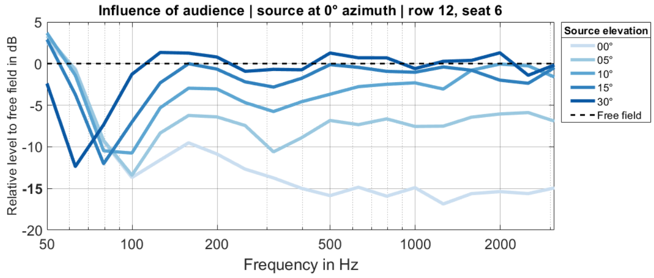
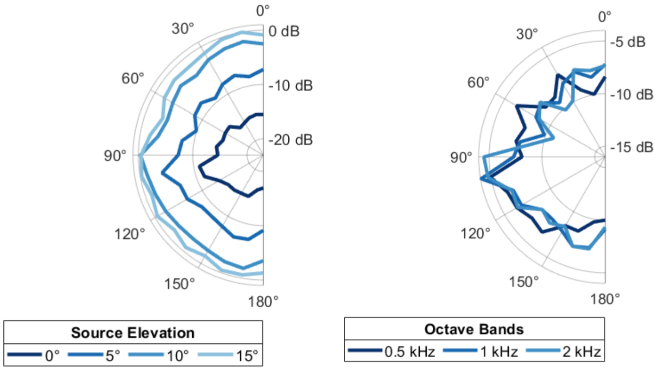


Figure 4: Free field compensated ARTF. The broad band grazing attenuation pronounces strongest for a low source elevation angle. The seat dip frequency is elevation dependent.



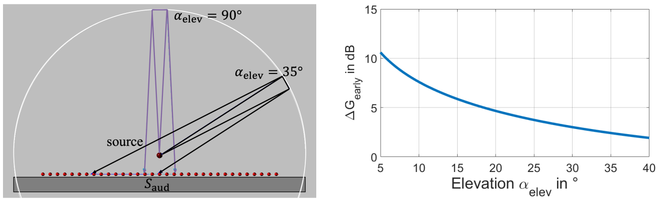
(a) Influence of the source elevation, 1 kHz octave band

(b) 5° source elevation, various center frequencies

Figure 5: Free field ARTF given as directivity plot. The measurements are expected to be axially symmetrical to the median plane. Measured in row 12, seat 6.

Compensation with early Reflections

Even with respect to 5° source elevation in the 12th row, which relates to 2.5 m source height in 15 m distance, the broad band grazing attenuation accumulates to 7 dB. In order to overcome this effect possible solutions have been considered recently by Meyer *et al* [9]. Adjusting the stage height is architecturally limited and seem not to raise the average level of direct sound and early reflections but only reduce the variability across the seats in their study. Meyer *et al* identify a raked audience plane as best solution to significantly raise the level. This comes together with a severe increase on the apparent absorption coefficient of the audience as shown recently by Changhyok *et al* [10] reducing not only the reflection



(a) Illustration of the geometric principle used.

(b) Visualization of the term $10 \cdot \log(\sin(\alpha_{\mathrm{elev}}))$

Figure 6: Lowering the average elevation angle of reflectors will raise G_{early}. After [12]

from the back wall but also the general level of the late reverberant field G_{late}. In addition, it is often not possible to rake the seating area retrospectively in auditoria with a flat seating arrangement for architectural reasons. An alternative approach is to compensate the mid and high frequency loss by introducing early reflections within the perceptual 50 ms integration interval. In the design of reflective surfaces the shape, dimension and distance to the sound source needs to be considered, as well as their orientation in respect to the audience [11]. The latter question is investigated using the solid angle design principle by Jurkiewicz [12]. It will be shortly summarized in the following paragraph before combing it with the ARTF measurements.

Solid Angle Principle

The solid angle approach to early reflections considers the solid angle Ω_{eff} covered by surfaces used for early reflections, measured from the point of a sound source [12]. It is a tool used in the early design phase of concert halls in order to elaborate the acoustic efficiency of a room. In this study, only the geometric relationship described between a reflective surface and the audience plane is of particular interest. A reflective surface mounted with a lower elevation angle α_{elev} with respect to the receiver can cover a larger area of audience S_{aud} with reflected energy (Figure 6a). The same proportion of the energy emitted by the sound source is used, but supplied to a larger proportion of the audience. If the average elevation angle of all surfaces is small, the average strength G_{early} for all seats will be higher, since the same energy is redirected to more audience members. Equation 1 formulates the relationship of all parameters introduced in this paragraph.

$$G_{\mathrm{early}} = 20+10 \cdot \log(\Omega_{\mathrm{eff}}) - 10 \cdot \log(\sin \alpha_{\mathrm{elev}}) - 10 \cdot \log(S_{\mathrm{aud}}) \tag{1}$$

Assuming a fixed audience size S_{aud}, a target value of G_{early} can be achieved either using a high efficient solid angle Ω_{eff} and a high average elevation angle α_{elev} or with a low Ω_{eff} and a low α_{elev}. The second approach uses a smaller proportion of the total energy emitted by the sound source for early reflections, leaving a higher proportion for the late reverberant field which is desirable. The conclusion to use smaller α_{elev} originating from the purely geometric approach seem to contradict with the grazing attenuation presented in the ARTF measurements and is already pointed out by Jurkiewicz in [13].

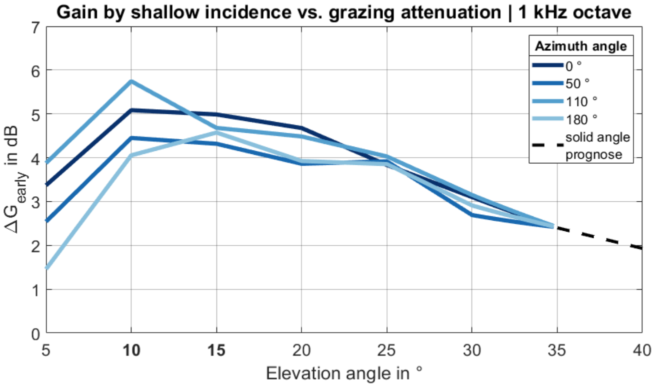
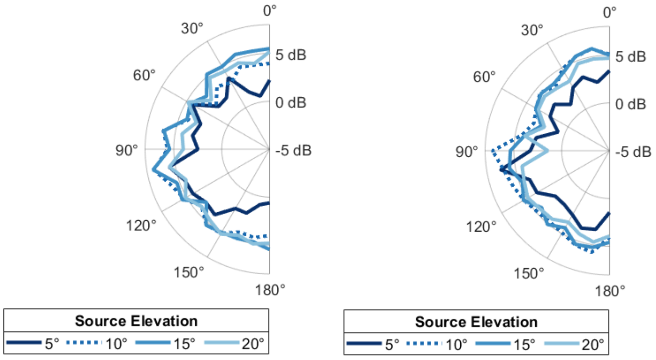


Figure 7: Optimization results $\Delta G_{\mathrm{early}}$ for individual azimuth angles.



(a) 500 Hz octave band

(b) 1 kHz octave band

Figure 8: Optimization results $\Delta G_{\mathrm{early}}$ as polar plots.

Optimization

This chapter will suggest a way to balance the grazing attenuation measured by the free field compensated ARTF with the purely geometric approach of the solid angle design strategy. Within the context of this study, only the elevation dependent term of Equation 1 shall be manipulated. It is decreasing with increasing elevation angle as shown in Figure 6b.

The optimization approach is given in Equation 2:

$$\Delta G_{\mathrm{early}} = 10 \cdot \log(\mathrm{ARTF}) - 10 \cdot \log(\sin \alpha_{\mathrm{elev}}) \tag{2}$$

Depending on incident angle and frequency band, the highest $\Delta G_{\mathrm{early}}$ is obtained for elevation angles of 10°-15°. The ARTF grazing attenuation cannot be overruled by the high gain applied in Equation 2 for incident angles $< 10°$. In Figure 7 individual azimuth incident angles are analyzed for continuous elevation angles. The dashed line indicates the influence of the solid angle term for further elevation angles (compare to Figure 6b). For the same 1 kHz octave band a polar plot of the optimization is given in Figure 8b. Figure 8 emphasizes the vicinity of the optimization results for 10° and 15° elevation angles.

Conclusion

The free field compensated Audience Related Transfer Functions have been measured using a 1:20 scale model fully occupied with audience. The measured broad band grazing attenuation of up to 16 dB for frontal incidence is in line with earlier findings by Meyer and Mommertz [3, 5]. The broad band grazing attenuation is inversely proportional to the source elevation angle and the most sensitive for elevation angles $< 10°$. It vanishes only for elevation angles $\geq 30°$. Different approaches are considered in order to compensate for this effect. The authors propose to focus on early reflections to achieve a raise in level. An optimal elevation angle of 10° - 15° for these reflections is proposed under the consideration of the solid angle principle.

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