FORUM ACUSTICUM EURONOISE 2025

FORGET ABOUT THE SEAT DIP EFFECT – YOU HAVE OTHER PROBLEMS! EARLY REFLECTIONS TO COMPENSATE FOR BROADBAND GRAZING INCIDENCE ATTENUATION.

N. Rummler[1*] **E. Green**[1] **Y. Jurkiewicz**[1] **E. Kahle**[1]

[1] Kahle Acoustics srl., Brussels, Belgium

ABSTRACT

The seat dip effect is a prominent acoustic phenomenon describing the attenuation of low frequencies due to sound passing at grazing incidence over seating. An often-overlooked aspect is that this attenuation is not limited to a narrow dip around 80 – 300 Hz but extends to much higher frequencies. Measurements on a 1:20 scale model of seated audience have established Audience Related Transfer Functions (ARTF) for a range of azimuth and elevation angles. This dataset shows that the broadband attenuation is inversely related to the source elevation and can reach up to 16 dB between 400 Hz and 3 kHz for grazing sound incidence. This has consequences both for the direct sound and early reflections in auditoria since grazing incident attenuation is equally affecting reflections in the horizontal plane. These findings support the need for early reflections from non-grazing incident angles, to compensate for the attenuated spectral content of both the direct sound and grazing incidence reflection paths. By coupling considerations of reflection coverage efficiency (solid angle criteria), head-related transfer functions and the ARTF, acoustically optimised reflection surface positions can be derived.

Keywords: *Grazing Attenuation, Solid Angle Principle, Room Acoustics, Early Reflections, Seat Dip*

**Corresponding author*: *nrummler@kahle.be.*

1. INTRODUCTION

The seat dip effect is a prominent acoustic phenomenon describing the attenuation of low frequencies due to sound passing at grazing incidence over seating. It is dependent on a multitude of factors, for example the seat shape, upholstering and arrangement, the audience rake as well as the source and receiver heights in relation to the seating plane. The phenomenon has drawn substantial attention in recent decades. Unfortunately, an often overlooked aspect is that the attenuation is not limited to a narrow dip around 80 – 300 Hz but can extend to much higher frequencies. This article collects findings from previous studies, summarizes recent scale model measurements to verify the attenuation effect and discusses possible compensation approaches for attenuated early reflections.

2. LITERATURE REVIEW

The first widely acknowledged papers about the seat dip effect were published by Schultz & Watters in 1964 [1], directly followed within a year by Sessler & West [2]. These two contributions did not identify an attenuation effect by theater seating for frequencies above 800 Hz and the scale model investigations described were restricted to an upper real-scale frequency of 1 kHz. In contrast, Meyer *et al.* conducted measurements around the same time, showing that the grazing incidence attenuation caused by unupholstered seats leads to a broadband dampening in excess of the spherical spreading by $\approx 0.7 - 1.5\,\frac{\mathrm{dB}}{\mathrm{m}}$ [3]. Those findings agreed with even older measurements by v. Békésy from 1933 [4]. More recent measurements of sound attenuation over seated audience by Mommertz in 1993 employing the full acoustic bandwidth confirmed the

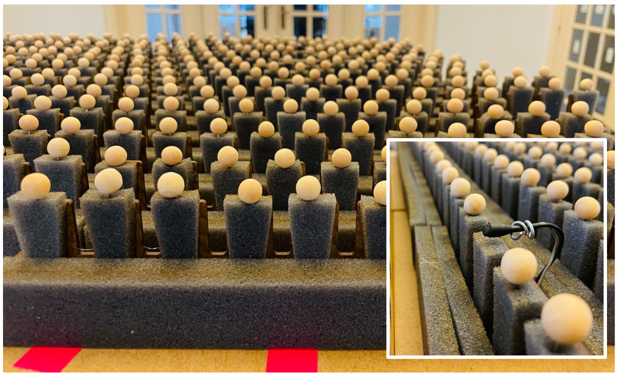


Figure 1: Scale model with close-up of microphone.

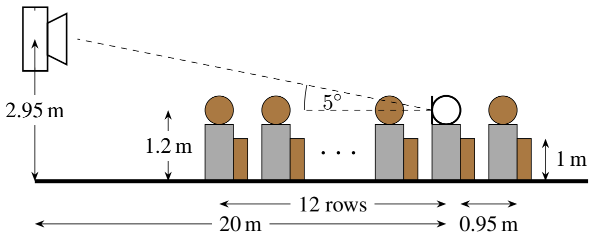


Figure 2: Long section of model with corresponding real scale measures for frontal sound incidence (azimuth 0°, elevation 5°).

previous results by Békésy and Meyer while noting the so called *head dip* around 2 kHz - 10 kHz [5]. Bradley retrieved similar attenuation magnitudes up to 10 kHz for grazing sound incidence when investigating similar backrest height to seat spacing dimensions [6].

By the date of Bradley's contribution, the mechanism leading to the low frequency dip had been widely analyzed using real scale and scale model measurements, theoretical derivations as well as FDTD and BEM simulations. However, although the broadband nature of grazing attenuation over a seated audience has been known for nearly a century, there seems to be limited awareness (perhaps due to earlier publications being exclusively in German [3–5]).

3. SCALE MODEL

The present study discusses the measurements of 1:20 scale model audience previously described in more detail in [7]. The model consists of laser cut wooden slats approximating unupholstered seats and audience members modeled by a porous PU-foam (see Figure 1). The seating area is shaped in a half circle in order to keep the audience

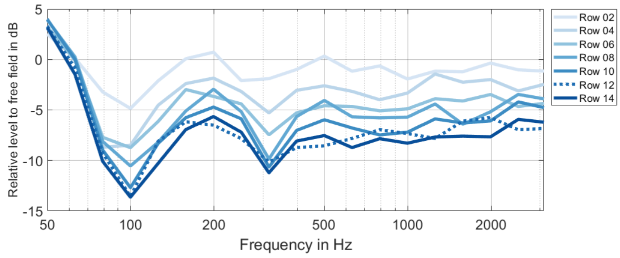


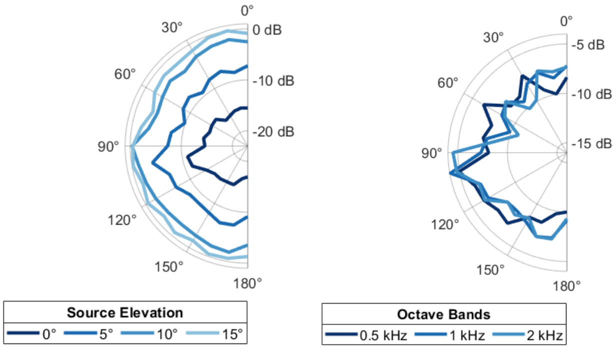
Figure 3: Free field compensated ARTF for frontal sound incidence. The source elevation corresponds to 5° in row 12. A general attenuation of $0.7\,\frac{\text{dB}}{\text{m}}$ and the seat-dip effect around 100 Hz can be identified.

area passed by the direct sound constant for all sound incident angles. A DPA 4060 omni directional microphone replaces a model head at 1.2 m height above the floor in various seating locations (see Figure 2). The measured frequency range corresponds to 45 Hz - 3 kHz in real scale. All measurements are corrected regarding the distance loss (spherical spreading) and for source and receiver frequency response using a free field impulse response. The indicated azimuth and elevation angles always refer to a receiver based coordinate system with origin in row 12, as shown in Figure 2.

In Figure 3, the 3$^{\text{rd}}$ octave bandwidth magnitude response for an increasing number of audience rows is shown for frontal sound incidence and 5° source elevation. While the distinct low frequency seat dip at around 100 Hz can be clearly seen, the broadband attenuation of up to around 8 - 10 dB should also be noted. The level offset between rows corresponds to an attenuation in excess of the spherical spreading. It quantifies to $\approx 0.7\,\frac{\text{dB}}{\text{m}}$ and is in line with earlier findings [3, 5].

4. AUDIENCE RELATED TRANSFER FUNCTIONS

In the previously introduced scale model, transfer functions for a range of azimuth and elevation angles have been measured. The resulting data are called Audience Related Transfer Functions (ARTF), as illustrated in Figure 4. The influence of the sound source elevation angle on broadband attenuation can be seen for the 1 kHz octave band in Figure 4a. As the source elevation elevation increases, the ARTF attenuation due to grazing sound incidence decreases, reaching almost 0 dB at 15° source elevation. Figure 4b shows that the directivity of the attenu-



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

(b) Attenuation for 5° source elevation.

Figure 4: Free field ARTF given as directivity plot. The measurements are expected to be axially symmetrical to the median plane. Row 12, 10° grid.

ation effect in azimuth direction remains relatively stable across all mid-frequency octave bands.

The magnitude responses in Figure 5 illustrates the influence of the source elevation angle for frontal sound incidence exclusively. The attenuation is inversely correlated from 200 Hz upwards and inversely proportional to source elevation angle [6, 8]. The attenuation reaches 16 dB for 0° elevation and only approaches 0 dB for elevation angles of greater than 15°.

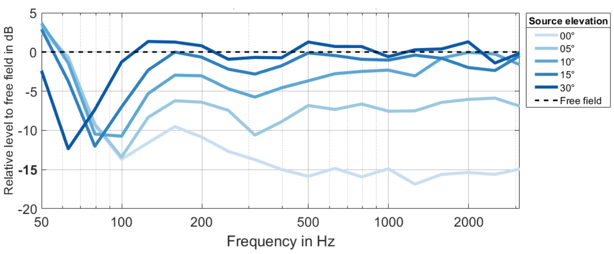


Figure 5: Free field compensated ARTF from row 12. The broadband grazing attenuation pronounces strongest for a low source elevation angle. The seat dip frequency is source elevation dependent.

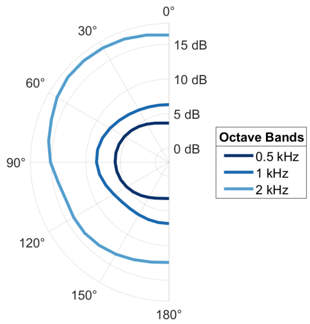


Figure 6: Binaural loudness derived after Sivonen & Ellermeier for 5° source elevation angle [11].

5. IMPLICATIONS FOR AUDITORIUM DESIGN

In order to match loudness expectations in the audience, large concert hall design requires strength values exceeding $G \geq 0\,\mathrm{dB}$ for *all* seats [9]. In halls with seat counts of 1,800 or above, the average distance between the conductor and the receivers can span 20 m or more. This leads to the necessity of average G values around 2 dB - 3 dB as discussed recently by Kahle *et al.* [10]. When it is already difficult generating sufficient strength and in particular sufficient early energy, concert hall or opera house design becomes even more challenging if the direct sound and near-horizontal reflections are strongly attenuated by grazing.

Earlier perceptive studies have identified a preference of lateral reflections due to the increased binaural loudness for lateral sound incident angles [11]. In the context of this study, the gain in binaural loudness due to the HRTF in isolation would not be sufficient to compensate for the grazing attenuation (see Figure 6). Energetic compensation should therefore be integrated into the design of the auditorium.

The magnitude of attenuation is most sensitive towards full grazing incidence (0°). In flat or slightly inclined audience planes, as found in many concert halls, the range of frontal source elevation angles is typically around 2° to 5°, relating to 1.7 m - 2.5 m source height at 15 m distance. An increase in source elevation angle by 1° in that range equals a gain in direct sound level of $\approx$ 1.25 dB for frequencies above 200 Hz. A high stage and large elevation angle would therefore seem to be acoustically desirable. In contrast to historic halls however, modern concert hall designs usually feature lower stage heights to improve spatial intimacy between performers and audience. In addition, Meyer *et al* [12] derived that an increase in stage height does not appear to raise the average level of the early sound field in concert hall simulations but instead reduces variability across seats. While increasing the audience rake does narrow the seat dip [6] it is more importantly associated with an increase in the apparent absorption coefficient of the audience [13]. The latter can negatively impact the overall strength and late strength in a hall. While the audience rake should be carefully considered, adjustments to the rake are generally not sufficient to compensate for grazing attenuation.

The early reflection design should therefore provide compensation for grazing attenuation, while also taking into account the fact that some important reflection paths will also experience grazing attenuation.

6. SOLID ANGLE OPTIMIZATION

Clearly, it is not desirable to accumulate a large proportion of acoustic energy in the early impulse response, since this reduces the available energy for reverberation and late sound [14]. In large halls, this raises the need for efficient early reflection design strategies such as the solid angle approach of Jurkiewicz *et al.* to provide a maximum early energy coverage with a minimum reflection surface area [15]. The summary conclusion emerging from the solid angle approach is that the average G_{early} can be most effectively increased by providing reflections from low elevation angles. In this way, a smaller proportion of the total energy emitted by the sound source must be used to achieve the necessary strength, leaving a higher proportion for the late reverberant field.

Since the efficient low-elevation reflections will also undergo grazing attenuation, the results of the scale model ARTF measurements have been combined with the solid angle theory to determine the optimum elevation angle resulting in the greatest energetic gains. The optimization discussed in [7], identified a average sound incident angles of $10° - 15°$ as the most efficient, balancing ARTF attenuation and the solid angle efficiency gains. This elevation range implies a reflector height of 3 m - 4 m above the floor at 10 m source-receiver distance. The first balcony fronts are typically in this height range and therefore ideal to optimize for early reflections and to provide sufficient level in the parterre.

7. CONCLUSION

Forget about the seat dip effect at low frequencies- we already know a lot about this phenomenon. Now, the room acoustics community should discuss the associated broadband attenuation in more detail. The presented study emphasizes the connection with existing research of the last century. In particular non- or only slightly inclined parterres can suffer from the strong broadband attenuation of up to 16 dB. The Audience Related Transfer Functions (ARTF) helped to quantify model quantify the effect systematically for both direct sound and early specular reflections, as a function of source elevation and azimuth angles [7]. In addition, the measured attenuation in excess of the spherical spreading for sound radiating over an 1:20 scale audience has been shown to be in agreement with the literature [3–5]. The present study highlights the importance of the direct sound attenuation and attenuation of critical early reflection paths in the context of the necessary strength values in large concert halls and other auditoria. Due to the high source receiver distances, it is challenging to direct a sufficient number of early reflections to all seats to provide the necessary early energy [10]. When grazing attenuation is also considered, the need for further compensation and optimization arises. By combining the described grazing incidence insights with research into efficiently generating early reflections using low-elevation reflections [15], reflection elevation angles of $10° - 15°$ have been found to be most effective in providing early energy at all seats.

8. REFERENCES

[1] T. J. Schultz and B. G. Watters, "Propagation of Sound across Audience Seating," *JASA*, vol. 36, pp. 885–896, May 1964.

[2] G. M. Sessler and J. E. West, "Sound Transmission over Theatre Seats," *JASA*, vol. 36, pp. 1725–1732, Sept. 1964.

[3] E. Meyer, H. Kuttruff, and F. Schulte, "Versuche zur Schallausbreitung über Publikum," *acta acustica*, vol. 15, pp. 175–182, 1965.

[4] G. v. Békésy, "Über die Schallfeldverzerrungen in der Nahe von absorbierenden Flachen und ihre Bedeutung fur die Raumakustik," *Z. tech. Phys*, vol. 14, p. 6, 1933.

[5] E. Mommertz, "Some Measurements of the Propagation of Acoustic Waves Skimming over the Public and Seats," *acta acustica*, vol. 79, pp. 42–79, 1993.

[6] J. S. Bradley, "Some further investigations of the seat dip effect," *JASA*, vol. 90, pp. 324–333, July 1991.

[7] N. Rummler, E. Green, T. Wulfrank, Y. Jurkiewicz, and E. Kahle, "Scale Model Study of Audience Related Transfer Functions (ARTF) for Direct Sound and Early Reflections," in *Fortschritte Der Akustik - DAGA 2024*, vol. 50, (Hannover), pp. 275–278, Deutsche Gesellschaft für Akustik e.V., 2024.

[8] Y. Ando, M. Takaishi, and K. Tada, "Calculations of the sound transmission over theater seats and methods for its improvement in the low-frequency range," *JASA*, vol. 72, pp. 443–448, Aug. 1982.

[9] M. Barron, "When is a concert hall too quiet?," in *19th International Congress on Acoustics*, (Madrid, Spain), Sept. 2007.

[10] E. Kahle, Y. Jurkiewicz, E. Green, and V. Berrier, "Why do large Concert Halls need to be optimized or early Reflection Coverage?," in *Proceedings of the Institute of Acoustics*, vol. 45 of *2*, (Athens), 2023.

[11] T. Lokki and J. Pätynen, "Lateral reflections are favorable in concert halls due to binaural loudness," *JASA*, vol. 130, pp. EL345–EL351, Nov. 2011.

[12] J. Meyer, H. Tahvanainen, J. Saarelma, and T. Lokki, "Investigation of the seat-dip effect using finite-difference time-domain simulations," *JASA*, vol. 154, pp. 1628–1639, Sept. 2023.

[13] C. Changhyok, L. Hyojin, and J. Daeup, "Measurements of sound absorption coefficients of raked audience seating in a rectangular scale model room," *Applied Acoustics*, vol. 217, p. 109872, Feb. 2024.

[14] Y. Jurkiewicz, T. Wulfrank, and E. Kahle, "How far should the geometry of a concert hall be optimized ?," in *International Symposium on Room Acoustics*, (Toronto), June 2013.

[15] Y. Jurkiewicz, T. Wulfrank, and E. Kahle, "Architectural shape and early acoustic efficiency in concert halls (L)," *JASA*, vol. 132, pp. 1253–1256, Sept. 2012.