IMPACT OF GRAZING INCIDENCE ATTENUATION ON EARLY REFLECTION DESIGN

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1 INTRODUCTION

When designing concert halls, the interplay between architectural design and the optimisation of early reflections is particularly complex. In particular in large concert halls, an appropriate and sufficient level of early-reflected energy is a prerequisite for optimal clarity and acoustic presence.

Previous studies into the geometrical optimisation of early reflections have led to the concept of “early efficiency” and the definition of a solid angle criterion (the effective early reflection surface quantified as a fraction of the source solid angle). The outcome is that early reflections from low elevations are particularly efficient, since a given quantity of acoustic energy covers a greater proportion of the audience with very similar intensity. However, the grazing incidence attenuation of low-elevation reflections must also be considered.

Recent scale model measurements of the broadband grazing attenuation of both direct sound and early (specular) reflections have made it possible to factor this aspect into the geometrical optimization process. The most strategic elevation and azimuth angles for optimised early reflections can now be established. In addition to a clarification of the importance of generating reflections from the lower part of the space, valuable conclusions can be drawn on the ideal methods to shape a concert hall.

2 PREVIOUS RESULTS

2.1 The efficient solid angle approach and the importance of providing reflections from a shallow incidence

The efficient solid angle approach[1] was proposed as a geometric analysis method to quantitively relate the shape of a concert hall and its ability to generate early reflections. In this approach, the geometry is divided into three categories of surfaces: absorptive ones (including audience areas) ; efficient ones which reflect the direct sound they receive from a sound source to some parts of the audience before a specific delay (generally 80ms), thus providing early reflections (of 1st, 2nd or higher order) ; and other reflective surfaces that contribute to the development of the late sound field.

Each efficient surface receives a proportion of the total acoustic energy emitted by the sound source, depending on its size, orientation and distance to the source point. This can be quantified with solid angles. The total efficient solid angle Ω_{eff} is defined as the solid angle of all efficient surfaces measured from the point of a sound source. In the context of geometrical acoustics, $\Omega_{eff} / 4\pi$ equals the fraction of energy emitted by the non-directional source which is oriented by the room surfaces towards the audience to create early reflections. In practice, the author observed that in medium sized symphony halls (seat-counts of about 1’500 to 1’800), only 8 to 16% of the entire space is occupied by efficient surfaces with simple shoebox shapes (Ω_{eff} between 1.0 and 2.0 steradians), while this ratio can reach 25-30% (Ω_{eff} around 3.5 steradians) in highly optimized shapes. These considerations clarify the inherent limits to geometrical optimization: in large concert halls, generating sufficient early energy for all seats will require a high value of Ω_{eff}, leaving a smaller proportion of the emitted energy available to feed the late reverberant field[2].

But the angle of incidence of early reflections on receiving areas also has a key influence on early acoustic efficiency. Under the assumptions of geometrical acoustics, the author previously demonstrated[1] that the average amount of early reflected energy across the audience area G_{em} could be predicted through a simple formula, relating G_{em} to three parameters characterizing the geometry of the hall: the efficient solid angle Ω_{eff}, the total surface area occupied by audience or musicians S_{aud}, and a specific average value of the angle of incidence of early reflections on audience planes θ_m (θ = 0° at normal incidence and 90° at grazing incidence).

$$G_{em} = 20 + 10 * \log(\Omega_{eff}) - 10 * \log(\cos(\theta_m)) - 10 * \log(S_{aud}) \quad (1)$$

Through S_{aud}, the proposed solid angle formulation confirms that a very large seat-count can be conflicting with the wish of providing sufficient early energy to all audience members. The inherent limit to the value of Ω_{eff} then implies that obtaining sufficient early strength in a very large room requires low values of $\cos(\theta_m)$. This factor depending on the direction of origin of early reflections indicates that those arriving at the listeners' ears from surfaces low in the room have a stronger impact on average early energy. Another formulation of equation (1) is obtained when the angle of incidence θ is replaced by the elevation angle relative to the audience plane $\varphi = 90° - \theta$:

$$G_{em} = 20 + 10 * \log(\Omega_{eff}) - 10 * \log(\sin(\varphi_m)) - 10 * \log(S_{aud}) \quad (1')$$

Acoustic designs favouring "shallow incidence" reflections can channel the same proportion of acoustic energy generated by a sound source to generate stronger loudness and a better source presence. Alternatively, such reflections can spend a smaller proportion of the emitted energy to generate an equivalent early energy level, leaving a larger proportion of this emitted energy to fuel the late reverberant field.

When favouring shallow incidence reflections, the famous seat-dip effect should not be disregarded. Sound waves propagating above an audience area under grazing incidence are attenuated. A better quantification of this attenuation is therefore required to precisely inform the geometrical optimisation process.

2.2 Audience related transfer functions (ARTF), systematic measurements of grazing incidence attenuation

More recently[3,4], measurements on a 1:20 scale model of seated audience were completed to quantify the attenuation of incident sound waves depending on their direction of origin. This attenuation was found to not be limited to the famous seat-dip effect at low frequencies. Very significant attenuation was measured at mid-frequencies for grazing sound incidence, impacting both direct sound and specular reflections from low elevation and all azimuth angles. Measurement results can then be used to predict this attenuation effect for all possible elevation and azimuth angles, through what is referred to as the Audience Related Transfer Functions (ARTF).

Key findings from these measurements are:

- Attenuation at mid-frequencies inversely relates to source elevation, reaching up to 16dB at 0° elevation, and almost 0dB at 15° elevation.
- Azimuthal variations in attenuation are modest, except when sound waves travel parallel to the seat rows (azimuth near 90°) at low elevation. It is expected that this dependency on azimuth would be further reduced in the case of curved seat rows. Still, it is expected that attenuation will remain slightly smaller for lateral sound. This is particularly relevant when considering the increased sensitivity of the ear to lateral sounds[5].
- Attenuation remains relatively stable across all 9 third octave bands contributing to the mid-frequency range (500Hz, 1kHz and 2kHz octaves).

- In line with earlier findings[6,7], mid-frequency attenuation is found to increase proportionally to the distance travelled above the audience. An attenuation of 0.7 dB/m is measured for an elevation of 5° and an azimuth of 0°.

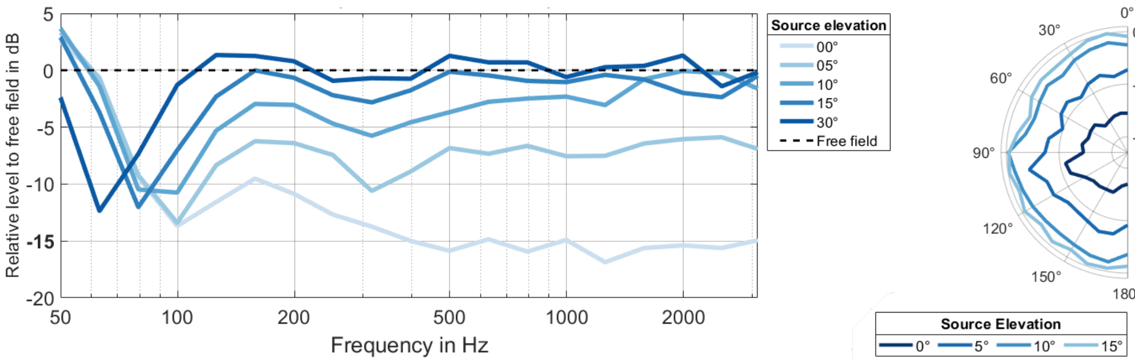

Figure 1: Measured ARTF from a seat on row 12. Left: attenuation as a function of frequency for several elevation angles and an azimuth of 0° (frontal incidence). Right: attenuation in the 1kHz octave band as a function of azimuth for several elevation angles φ.

As both the direct sound and a significant part of early specular reflections suffer from grazing incidence attenuation, providing sufficient early energy in large concert halls appears even more challenging. Regarding the direct sound, an increased audience rake and/or stage height can result in an increased elevation, thus reducing grazing incidence attenuation. However, extreme measures must be considered to reach an elevation angle φ = 7° for the direct sound, which would still imply an attenuation of about 5dB at the 12th row. Regarding specular reflections, increasing the audience rake would only reduce attenuation for those coming from a frontal direction, while reflections coming from the rear would suffer from even stronger attenuation. In addition, an increased audience rake is associated with an increase in effective audience absorption (both because of an increased absorption coefficient, and an increased solid angle for direct sound directed into absorption), which can negatively impact the overall strength and late strength in a hall.

Early reflection design should therefore consider – and accept – that some important reflection paths will experience grazing attenuation and then compensate for this by also providing reflections from non-grazing incident angles. This appears to contradict the conclusions of the efficient solid angle approach and calls for a more detailed study of how the two effects combine.

3 COMBINING THE GEOMETRIC AND WAVE EFFECTS OF GRAZING INCIDENCE

Geometrical considerations originating from the solid angle approach have shown that, when considering an audience plane as a whole, specular reflections from low elevation angles use a smaller proportion of the total energy emitted by the sound source to achieve the necessary strength in the early part of the room response (G_{em}, averaged over all receivers). However, due to the wave nature of sound, low elevation reflections will undergo grazing attenuation and consequently contribute less to early strength at each receiver. Using the ARTF measurement results, these two effects can be combined in a revised estimation of the mean early reflected strength G_{em}.

3.1 A first simplified model for ARTF

The first step is to establish a simplified model of grazing attenuation at mid-frequencies. Variations in this attenuation as a function of frequency and azimuth angle will deliberately be ignored to retain only a dependence on the elevation angle and on the distance travelled above the audience. Measured ARTF results at the 12^{th} row are first averaged across all azimuth angles and all frequencies in the mid-frequency region (500Hz, 1kHz and 2kHz octave bands), and the dependence on elevation angled is modelled with 2^{nd} order polynomial regression on the elevation φ, in the range [0°, 90°]. The following formula is obtained for attenuation in decibels.

$$\mathrm{grazing\_att\_dB_{row12}}(\varphi) \sim \min(0,\ 10 * \log(3.40 * \sin^2(\varphi) + 2.17 * \sin(\varphi) + 0.02)\ ) \qquad (2)$$

The obtained regression function reaches an attenuation of 0dB at an elevation just under 18° and is no longer valid for higher elevation angles, for which no attenuation occurs, hence the added *min* function.

ARTF measurements for frontal direct sound performed every 2 rows from row 2 to row 12 exhibit a linear attenuation of constant decibels/row. The previous model for attenuation at row 12 can therefore be generalized for any distance travelled above the audience. The proposed model assumes a 12^{th} row receiver located 11m from the edge of the audience plane to transpose the row numbers into meters. Also, no attenuation occurs at the 1^{st} row receiver, which is assumed to be located 1m from the edge of the audience plane. The following formula is then obtained for attenuation in decibels.

$$\mathrm{grazing\_att\_dB}(\varphi, \mathrm{d}) \sim \min(0,\ (d-1) * \log(3.40 * \sin^2(\varphi) + 2.17 * \sin(\varphi) + 0.02)\ ) \qquad (3)$$

Or expressed as an attenuation factor applying to the intensity of the sound wave:

$$\mathrm{grazing\_att}(\varphi, \mathrm{d}) \sim \min\left(1,\ (3.40 * \sin^2(\varphi) + 2.17 * \sin(\varphi) + 0.02)^{(d-1)/10}\ \right) \qquad (4)$$

Three limitations of the measurement set need to be mentioned, as they lead to corresponding limitations in the proposed simplified model. First, all measurements were for a flat audience floor. Sloped or stepped audience were not measured. As an approximation, which is thought to be sufficiently correct for small rake angles, the case of a raked floor can be considered equivalent to a flat floor with a higher source position, leading to identical elevation angle with respect to the audience plane. Second, the measured attenuations are representative of the reflected path from an image source to an audience member. This properly accounts for the grazing incidence attenuation occurring between a reflector and a receiver but not for any attenuation potentially occurring from the sound source to the reflector. Third, the linearity of the dB attenuation as a function of the distance travelled above the audience was only established for a frontal sound at 5° elevation and would still need to be confirmed for other azimuths and elevations. The last two aspects are currently being studied in the same scale model environment to fully quantify grazing incidence attenuation all the way from the source to the receiver and with a more robust estimation of the influence of distance travelled above the audience. At the time of writing, in the absence of complete data, only the attenuation from the reflector to the receiver can be considered, which implies an underestimation of the attenuation that should be borne in mind. As such, the general model for ARTF that was proposed in this chapter can only be considered as a first attempt.

3.2 Optimum elevation for early reflections

The simplified model for grazing incidence attenuation can now be combined with the geometric formulas of the efficient solid angle approach. Equation (5) from reference[1] can be adjusted to incorporate the ARTF effects, leading to this expression for mean early reflected intensity received by the audience:

$$\mathrm{I_{em}} = \frac{\mathrm{E_0}}{4\pi \mathrm{S_{aud}}} \sum \left(\mathrm{d}\Omega_\mathrm{i} \,.\, \frac{\mathrm{grazing\_att}(\varphi_\mathrm{i}, \mathrm{d_i})}{\cos(\theta_\mathrm{ai})} \right) = \frac{\mathrm{E_0}}{4\pi \mathrm{S_{aud}}} \sum \left(\mathrm{d}\Omega_\mathrm{i} \,.\, \frac{\mathrm{grazing\_att}(\varphi_\mathrm{i}, \mathrm{d_i})}{\sin(\varphi_\mathrm{i})} \right) \qquad (5)$$

With $d\Omega_i$ the infinitesimal solid angle of each small portion of efficient surface generating early reflections, θ_{ai} the corresponding angle of incidence of the produced reflection on the audience plane ($\theta_{ai} = \pi/2 - \varphi_i$), and E_0 a constant related to the sound power of the source.
This leads to a revised version of equation (1):

$$G_{em} = 20 + 10 * \log(\Omega_{eff}) + 10 * \log(W_m) - 10 * \log(S_{aud}) \quad (6)$$

In which W_m is a weighted average of a w function that is defined as follows:

$$W_m = \frac{\sum d\Omega_i .w(\varphi_i, d_i)}{\sum d\Omega_i} \quad (7)$$

$$w(\varphi_i, d_i) = \frac{\text{grazing\_att}(\varphi_i, d_i)}{\sin(\varphi_i)} \sim \frac{\min\left(1, \left(3.40 * \sin^2(\varphi_i) + 2.17 * \sin(\varphi_i) + 0.02\right)^{(d_i - 1)/10}\right)}{\sin(\varphi_i)} \quad (8)$$

In terms of acoustic design, it can be observed from equation (6) that a general optimum in elevation angle of all early specular reflections is reached when the factor 10.log(Wm) is maximised. In a hypothetical case for which all reflections would be perfectly zenithal (90° elevation), this factor would equal 0dB. The value for 10.log(W_m) can therefore be understood as the effective gain in early reflected energy obtained by providing early reflections from lower elevation.
The w function exhibits the combined influence of grazing incidence attenuation and geometrical spreading. It applies to each infinitesimal portion of efficient surfaces. For a large efficient surface such as a canopy, d_i and φ_i should be estimated separately for smaller portions of the surface on which these two parameters can be considered relatively constant, to get separate estimations of w. On each small portions of efficient surfaces, the potential compensation of grazing incidence attenuation by geometrical spreading can be analysed.

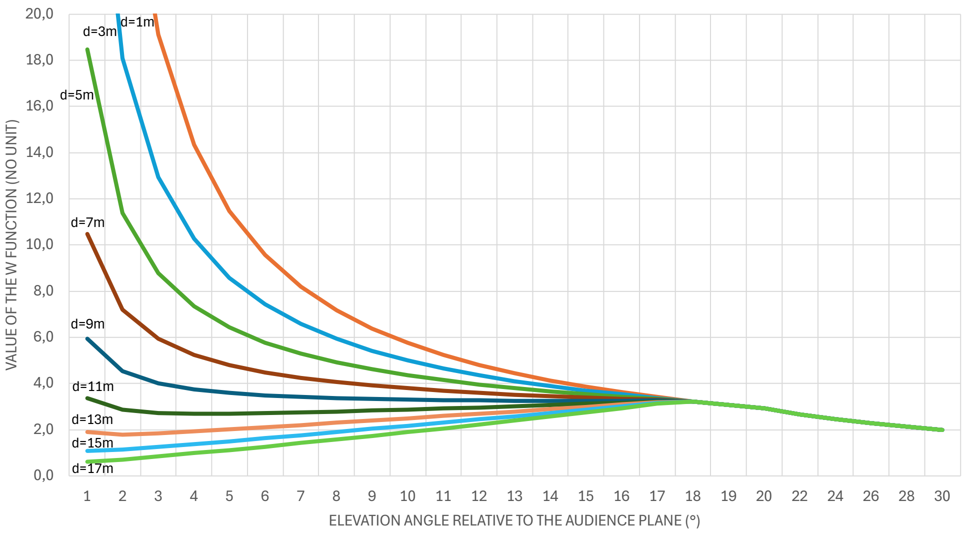

Figure 2: Angle-dependant function w for various distances travelled above the audience, as a function of the elevation angle φ_i relative to the audience plane.

For all elevation angles ≥ 18°, no grazing attenuation occurs, and the w function decreases with increasing reflection elevation. At 30° elevation the w function generates a 3dB gain in mean strength compared to a perfectly zenithal reflection. This gain reaches 5.1dB at 18° elevation. Then for elevation angles < 18°, the combined geometric and wave effects of grazing incidence results in different outcomes depending on the propagation distance above the audience. At d = 1m, no attenuation occurs, and the advantages of low elevation reflections fully remains. Up to d = 8m, w remains a continuously decreasing function of φ_i, and grazing incidence attenuation does not eliminate the geometric advantage of low-elevation reflections. For distances between 8 and 10m, w exhibits a plateau of almost constant value between 5° and 18° elevation where the two effects cancel each other out (but a gain of about 5dB compared to zenithal reflection is still obtained). Finally, for distances d ≥ 10m, ARTF become predominant, and w is a mostly increasing function of φ_i.

From these observations, it is possible to conclude that the optimal elevation angle of a specular reflection depends on the exact situation: the optimum is near 0° in the case of reflectors aiming at close by audience members; and near 18° for reflectors aiming at audience members relatively far away involving sound propagation above the audience of 10m or more. It is also interesting to observe that in the intermediate distance region where the two effects appear to cancel each other out, any elevation angle between 0 and 18° can be considered optimal, but will generate different situations: a reflection of low elevation will spread out more evenly on the audience plane, while a reflection near 18° elevation will generate a less homogeneous coverage but stronger reflections in the coverage zone. The plateau observed for the w function implies that these two scenarios ultimately result in an equivalent average value of early reflected strength.

4 CONSEQUENCES FOR EARLY REFLECTION OPTIMISATION

4.1 Lessons from a set of real concert hall geometries

At this point, some typical grazing incidence attenuation values can be estimated from the geometry of various existing concert halls, using equation (3). In a selection of 5 modern concert halls (4 built ones and 1 under construction), the geometric paths for direct sound and all main early reflections were computed between a sound source and a receiver in the main floor. Geometrical considerations from the solid angle approach (and the w function) are not taken into consideration at this point, in order to focus solely on the impact of grazing incidence attenuation. The sound source was always located on the room axis, 3m upstage. The receiver was also located on the room axis, at a horizontal distance of 12m from the source (which corresponds approximately to row 9). Obtained attenuations for the main early sound paths are gathered in Table 1.

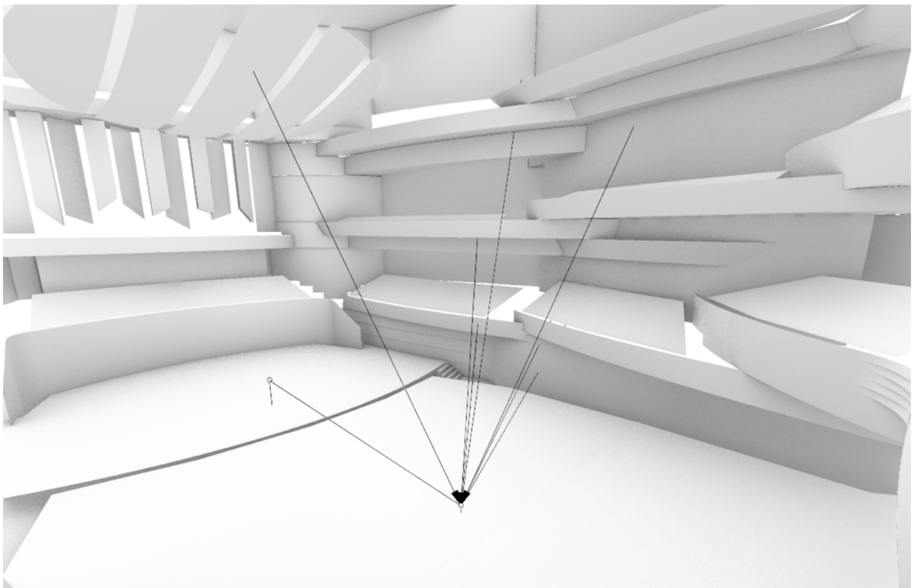

Figure 3: Main direct and reflected paths from the chosen source point to the chosen receiver point, in Turku Fuuga concert hall 3D model, used to estimate grazing incidence attenuation values.

At this specific seat relatively close to the stage, estimations of the mid-frequency grazing incidence attenuation of direct sound ranges from -3 to -5dB. The strongest attenuation values are reached in concert halls with an almost flat main floor, while significantly raked main floors allow for a significant

reduction in attenuation, especially when combined with a relatively high stage platform (86cm in Lille Nouveau Siècle).
Reflections off vertical sidewalls suffer more severe attenuation, with typical values around -9 / -10dB. The -6dB value obtained in Lille Nouveau Siècle can only be explained by the presence of a wide corridor near the receiver, along which most of the reflected sound travels. Attenuation is reduced by about 1dB in halls with a narrow main floor (Stavanger and Turku) compared to wider halls (Bordeaux and Beijing).
Reflections off 1st side balcony soffits and their tilted balustrade get less attenuated, with typical values around -2dB, while reflections originating from higher areas of the halls are no longer attenuated. Overall, when cumulating the energy of direct sound and all main early specular reflections, grazing incidence attenuation results in an estimated reduction of about 3dB in most cases.

grazing incidence attenuations values (dB)	direct sound	sidewall reflections	1st balc. soffit and/or balustrade reflections	2nd and higher balc. soffit reflections	canopy reflection	overall attenuation of cumulated early energy
Stavanger Fartein Valen concert hall	-4,8	-9,0	-2,2	0,0	0,0	-3,2
Bordeaux Auditorium	-3,1	-10,4	-2,3	0,0	0,0	-2,8
Lille Nouveau Siècle concert hall	-3,0	-6,0	0,0	0,0	0,0	-1,8
Beijing PAC Tongzhou concert hall	-3,6	-9,8	-1,8	0,0	0,0	-3,4
Turku Fuuga concert hall	-5,0	-8,7	-2,8	0,0	0,0	-3,6

Table 1: Grazing incidence attenuation (in dB, as negative gain values) for main contributors to the early acoustic response at a receiver in 5 reference concert halls, estimated using equation (3).

Another related aspect is the effective audibility of lateral reflections. Previous research[8, 9] suggested that improved 'spatial responsiveness' is obtained when lateral reflections arrive before overhead reflections and can then be considered unmasked. In narrow shoebox concert halls such as Stavanger Fartein Valen, the lateral reflections from both the sidewalls and the lower side balcony soffits arrive before the canopy reflection. The strong grazing incidence attenuation applying to 1st order sidewall reflections may reduce their audibility. But 1st and 2nd balcony soffit reflections are much less (or not at all) attenuated and still arrive before the 1st overhead reflection. In a wider concert hall such as Lille Nouveau Siècle, 1st order sidewall reflections arrive slightly after the canopy reflection. The attenuation due to grazing incidence applies strongly to these sidewall reflections and not to the 1st overhead reflection, as a result the former will most likely not be audible. However,1st and 2nd balcony soffit reflections are no longer attenuated. Their arrival time is grouped around 30ms after the canopy reflection and the cumulated energy of the four individual reflections is more than 3dB larger than that of the canopy reflection. Their effective audibility is therefore entirely plausible, especially when considering the increased sensitivity of the ear to lateral sound. Using the perception thresholds measured by M. Barron[10] for a single side reflection with a ceiling reflection present, each of these four lateral reflections would in fact be perceivable, even without the support of the other three.
Overall, regardless of the room width, it appears that 1st order sidewall reflections are very likely to be masked by the overhead reflection. Providing lateral reflections from slightly higher elevation therefore seams crucial for 'spatial responsiveness', and a narrow room width does not appear to be sufficient on its own.

4.2 Parametric shoebox study

Several geometrical parameters such as the main floor slope angle, the room width and the side balconies height were found in the previous chapter to have a significant impact on grazing incidence attenuation and early strength in the main floor seats of concert halls. A parametric 3D model of a shoebox concert hall was built within the Rhino3D/Grasshopper environment to study these aspects in more detail over all seats on the main floor.

The basic shoebox geometry has a width of 24m, a length of 40m and a ceiling height of 20m above stage floor (volume of approx. 19'000m^3). A sound source is placed on the room axis, 3m upstage. Stage platform height is fixed to 0.9m. The early acoustic response generated by the room geometry is computed at each receiver point on a grid covering the main floor. A total of 2499 receivers covers the 24x25m audience plane (one receiver every 50cm). The intensity of each contributor (direct sound, 1st order or 2nd order reflection with less than 80ms delay) is estimated using an image source model on which grazing incidence attenuation is applied using equation (3). Considered contributors are direct sound, ceiling reflection, canopy reflection, sidewall reflections and side balcony soffits reflections. Three different internal arrangements of the shoebox hall were defined (A, B and C), each of them providing the same predicted early acoustic strength averaged over the audience grid: $\overline{G_{[0,80ms]}} = -2\ \text{dB}$ (arithmetic averaging on energy values and not on dB values, following the same definition as for G_{em}). Varied geometric parameters and obtained acoustic results are summarized in Table 2 and Figure 4.

Geometry A has a strongly sloped main floor allowing for reduced grazing incidence attenuation of direct sound and sidewall reflections. The absence of side balconies requires a lower canopy setting to reach the targeted $\overline{G_{[0,80ms]}}$. In contrast, geometry B reaches the same target with a moderately raked main floor and a much higher canopy setting thanks to the side balcony soffit reflections. With geometry C, the addition of a second level of balcony soffits allows for the same average early strength on a perfectly flat main floor. It can also be observed from the colormaps in Figure 4 that geometries B and C allow for a much-improved homogeneity in the acoustic coverage.

Parametric shoebox comparison	Geometry A	Geometry B	Geometry C
Main floor rake	7.5°	4.5°	0°
Canopy height above stage edge (always 10° tilted / horizontal)	11m	14m	14m
1st level of side balconies above stage floor (if existing)	-	4m	3m
2nd level of side balconies above stage floor (if existing)	-	-	7m
Average early strength $\overline{G_{[0,80ms]}}$	-2.0 dB	-2.0 dB	-2.0 dB
Average early reflected strength $\overline{G_{]0,80ms]}} = G_{em}$	-6.1 dB	-5.9 dB	-5.5 dB
Direct solid angle Ω_{dir}	0.644 str	0.563 str	0.440 str
Efficient solid angle Ω_{eff}	0.840 str	0.764 str	0.831 str
Impact of reflection elevation on average early reflected strength: 10.log(W_m)	2.5 dB	3.1 dB	3.1 dB

Table 2: Geometric parameters and acoustic results for 3 different shoebox geometries.

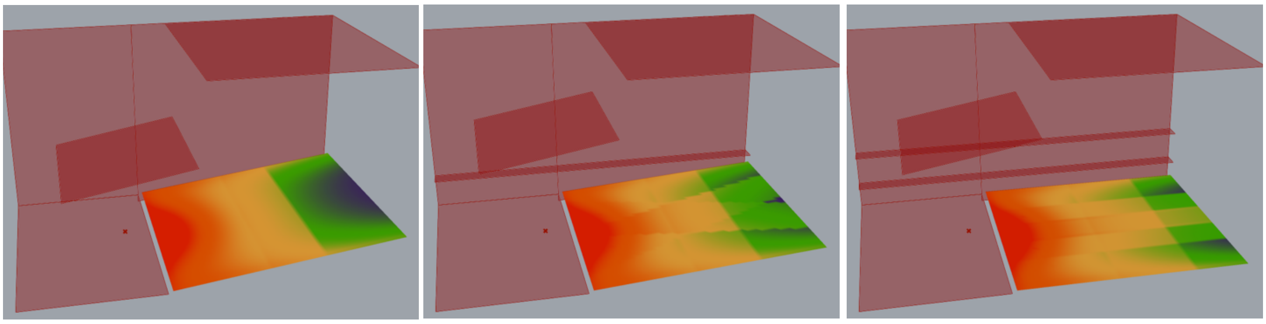

Figure 4: Geometries and colormaps of the 3 studied shoebox geometries: Left = A, centre = B, right = C. Colours mapped on the receivers' grid indicate predicted value for early strength $G_{[0,\ 80ms]}$: red = 5dB and more, orange = 0dB, yellow = -5dB, green = -10dB, blue = -15dB and less. Average value over the main floor is the same in each case, but reflection coverage differs.

Ω_{dir} (solid angle subtended by the audience plane at the source point) logically decreases from A to C as the audience rake decreases, while the efficient solid angle Ω_{eff} is significantly smaller with geometry B than in the other two cases. With geometry A, a significantly larger proportion of the energy emitted by the source is therefore spent to reach the early strength target, which is expected to negatively impact average late acoustic strength[2].

The results obtained for 10.log(W_m) illustrate the level of optimization in early reflection elevation angles when both geometric and wave effects of grazing incidence are combined. It can be observed that the addition of side balconies in geometries B and C allow for a significantly improved gain compared to geometry A (+0.6dB).

Geometry A mainly relies on strong direct sound and canopy reflections. Geometry B relies both on non-overly attenuated direct sound and on soffit reflections of adequate elevation. Geometry C relies both on soffit reflections of adequate elevation and an increased efficient solid angle through the addition of a 2nd side balcony level. It is then clear that the perceived acoustic quality corresponding to these 3 shoebox geometries will differ greatly, even though reverberation time and early strength may remain identical. Early lateral energy is weakest with geometry A and strongest with geometry C, while the opposite is true for the energy of direct sound and overhead reflections. Improved spatial impression can therefore be expected in concert hall designs featuring relatively severe direct sound attenuation compensated by additional early lateral reflections from adequate elevation angles.

In another investigation based on geometry B, the side balcony level was varied in the search of an optimum height, characterised by a peak in the value of 10.log(W_m). This maximum was found at a balcony height of 5.3m above stage floor. All other aspects remaining constant, balcony soffits significantly lower than 5.3m generate a reduced average reflected strength G_{em}, due to both low reflection elevation (decreased value of 10.log(W_m) due to grazing incidence attenuation effects overruling the geometrical spread) and a reduced efficient solid angle (decreased value of 10.log(Ω_{eff})). Balcony soffits higher than 5.3m generate a stable G_{em} as the decreased value of 10.log(W_m) due to high reflection elevation is compensated by an increased efficient solid angle. Interestingly enough, the optimum 5.3m balcony height was also found to be the configuration allowing an equal spread of reflection elevation angle around an average value of 18°.

Geometry B with adjusted side balcony height above stage floor (in meters)	3.6	4.0	4.4	4.8	**5.3**	5.8	6.4	7.0
10.log(W_m)	2.9 dB	3.0 dB	3.0 dB	3.1 dB	3.1 dB	3.0 dB	3.0 dB	2.9 dB
10.log(Ω_{eff})	-0,9 dB	-0,9 dB	-0,8 dB	-0,8 dB	-0,7 dB	-0,6 dB	-0,6 dB	-0,5 dB
Average early reflected strength G_{em}	-5,8 dB	-5,7 dB	-5,6 dB	-5,5 dB	-5,4 dB	-5,4 dB	-5,4 dB	-5,4 dB

Table 3: Impact of side balcony height above stage floor on early reflected strength and its main contributing factors according to equation (6).

As a conclusion, increasing the balcony height above stage floor appears advantageous up to the identified optimum height, as grazing incidence attenuation is reduced. But increasing it further will not provide any further gain in early energy, while slightly reducing the energy available for the late reverberant field as the efficient solid angle continuously increases.

5 CONCLUSION

In performance venues, direct sound and early specular reflections can undergo significant broadband attenuation when travelling above the audience under grazing incidence. A simple empirical model quantifying grazing incidence attenuation, based on scale model measurements, was proposed. This model is certainly limited and is intended to be refined in further research. It is currently expected to underestimate the total attenuation. Nevertheless, it already allows for the introduction of a quantitative approach to grazing attenuation effects in concert halls, and the identification of valuable implications for acoustic design.

In five reference concert halls of varying geometries, a typical attenuation of early energy of around 3dB was found to apply at a main floor seat 12m from the source on the room axis. Such significant attenuation surely requires consideration. This overall grazing incidence attenuation of early energy can be minimised through appropriate design features such as a high stage platform and a strongly raked main floor. But these design choices also have some drawbacks. Based on the ARTF measurements, early reflections from an elevation ≥ 18° no longer appear to be attenuated. Integrating such reflections into the acoustic design is therefore advantageous, especially when considering lateral reflections and their impact on 'spatial responsiveness'. Non-attenuated lateral reflections could be unmasked even when preceded by a ceiling reflection.

However, reflections from high elevation spend a larger proportion of the energy produced by the sound source to generate an equivalent early energy coverage, which can negatively impact the late reverberant energy, especially in large concert halls. Geometrically, low-elevation reflections spread more evenly on the audience plane, still producing similar acoustic intensity. This geometric effect appears to contradict the grazing incidence attenuation effect. A previously proposed formula predicting the average early reflected sound strength G_{em} as a function of the efficient solid angle was then updated to incorporate grazing incidence attenuation. The updated formula (6) combines the influence of reflection elevation on both grazing incidence attenuation and geometrical spreading. This has allowed for further investigation regarding the existence of an optimal elevation angle for early specular reflections. The optimum angle was found to depend on the distance the reflected sound wave has to travel above the audience: near 0° in the case of reflectors aiming at close by audience members; and near 18° when the propagation distance above the audience is 10m or more.

Several internal arrangements of a simplified shoebox concert hall were investigated using a parametric 3D model, illustrating different design strategies leading to equivalent results in terms of average early energy in the main floor. Design options featuring strong direct sound and overhead reflections minimize grazing incidence attenuation but will lead to reduced late reverberant energy and reduced 'spatial responsiveness'. In contrast, design options involving severe direct sound attenuation should not be overlooked as long as this can be balanced by fairly strong early lateral reflections. Finally, varying the side balcony level in a given shoebox geometry illustrated the existence of an optimal height (5.3m above stage floor in that case). At that specific height, the effects of grazing incidence attenuation are optimally balanced by the geometric spread, while a higher balcony level will spend a larger proportion of the energy emitted by the source to generate similar early energy coverage.

In conclusion, the geometrical optimisation of concert halls should not only aim at maximizing early reflected energy but also consider the impact on the late reverberant field as well as the audible effects related to the spatial distribution of early reflections. Richer, more enveloping and spatially responsive acoustics will be achieved when direct sound is significantly attenuated due to grazing incidence, but generous early lateral reflections from adequate elevation angles are provided as a compensation.

6 REFERENCES

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