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How far should the geometry of a concert hall be optimized?

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ABSTRACT

When designing concert halls, acoustic consultants tackle the challenge of providing an appropriate amount of early reflections to each audience member and to the musicians on stage. This critical issue in concert hall design implies the development of an appropriate architectural shape through a collaborative and creative process of geometrical optimization.

But in the case of a large concert hall with a seat count of more than 2'000 seats, how far can the geometry possibly be optimized? Is such an optimization process necessarily positive or can it be detrimental regarding the late diffused sound field? In symphony halls of smaller seat count, is there a limit beyond which early reflections become excessive?

A recently developed approach based on the acoustic solid angle criterion can shed some light on these key questions. In particular, the direction of arrival of early reflections is found to play an important role, which highlights interesting practical implications for acoustic design.

The efficient solid angle can be used both as an architectural criterion and a prediction method relating the shape of a concert hall to its efficiency in providing early reflections. Implications of geometrical optimization for early reflections on the late diffused sound field can also be predicted and studied. This approach based on solid angles will be illustrated in the practical case of some existing or hypothetical concert hall geometries.

1 INTRODUCTION – NEW TRENDS IN GEOMETRICAL OPTIMIZATION FOR EARLY REFLECTIONS

Architectural design methods evolved rapidly in recent years. Concert halls are now very often designed directly in three dimensions, sometimes using specific algorithms to generate complex geometries that could otherwise not have been created. These new developments in computer-aided design allow an increased freedom of shape for the architects and design teams. A new visual relationship between the stage and the audience is wanted, initiating new typologies of concert halls. Double-curved and warped surfaces have also emerged as a standard vocabulary in contemporary concert halls design.

This rapid evolution in architectural design requires from acoustic consultants the development of new geometrical analysis tools, better adapted to the new design process. The freedom of shape recently acquired by architects is not unrestricted and acoustic requirements may appear as a constraint. This apparent freedom needs to be channeled in order to ensure acoustic quality while encouraging rather than preventing creative solutions.

The shape of a concert hall mainly influences acoustic quality through the provision of early reflections to audience members and musicians on stage. Each individual reflective surface in a hall can be optimized to provide acoustic reflections of appropriate delay and level to some part of the listeners. Several acoustic firms specialized in the design of performance spaces have now developed their own computer-aided acoustic analysis tools facilitating this optimization process. These tools allow the reach of higher levels of acoustic optimization. Each detail of a concert hall shape can quickly be modified for a specific acoustic purpose, allowing a collaborative design process with architects. Examples of such geometrical optimization were previously presented by the authors[1, 2].

But these tools do not address some more fundamental issues: How far can the geometry of a concert hall possibly be optimized? The new design methods push the limits of acoustic optimization to the great benefit of the new-built concert halls. Is there an upper limit to these improvements and can it be quantified?

And how far should the geometry actually be optimized? What is the risk of providing excessive amounts of early energy and how can this be avoided? Can the right balance be described in geometrical terms and quantified? In other words, can the shape and architecture of a concert hall be directly related to its acoustic characteristics through a set of geometrical parameters?

2 HOW FAR CAN CONCERT HALL GEOMETRY POSSIBLY BE OPTIMIZED?

2.1 Efficient surfaces and the efficient solid angle

The concept of early acoustic efficiency was introduced and developed in previous papers[2-4]. Early efficiency can be defined as the level of optimization of the geometry of a room in the purpose of creating early reflections. This level of optimization can be quantified, the first and simplest method being to consider the total area of efficient surfaces.

The geometry of a concert hall basically consists of three types of surfaces:

- Absorptive surfaces (including audience areas and the occupied stage).
- “Efficient surfaces”: surfaces reflecting 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).
- The other reflective surfaces that participate to the creation of the late sound field.

Obviously, this approach deliberately ignores what each audience member will experience at his specific location in the room to focus on the global room acoustic behavior. In a given room, optimizing the orientation of a surface to make it efficient will increase the amount of early energy received by some audience members. Early efficiency then relates to the average over the entire audience of the early-reflected energy. It neither describes the homogeneity of the early sound field nor the case of a specific listener location in the room.

The second and more correct method to quantify early acoustic efficiency makes use of solid angles. The total efficient solid angle Ω_{eff} can be defined as the solid angle of all efficient surfaces measured from the point of a sound source. By definition, $\Omega_{eff} / 4\pi$ 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 figure 1, pictures from the 3D computer model of the new concert hall in Stavanger, Norway, are used to illustrate the three possible ways of analyzing early efficiency: the traditional ray-tracing method, the extraction of the efficient surfaces within the considered reflecting surface, and the solid angle approach.

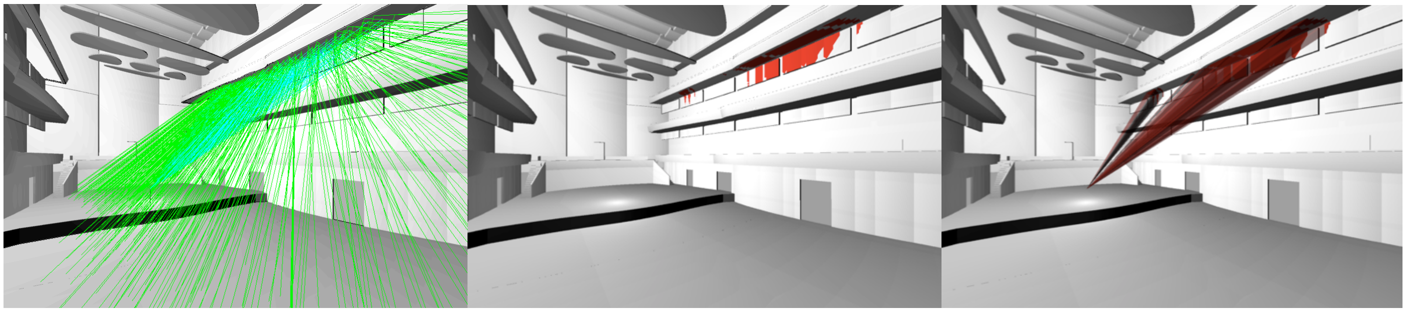

Figure 1: Three approaches to early efficiency analysis. The picture on the left displays the results of a ray-tracing algorithm on the 2nd side balcony soffit (acoustic rays in cyan and green). The middle picture displays the efficient surfaces in red, and the picture on the right the corresponding cones that represent the individual efficient solid angles.

The efficient solid angle is a precise and intuitive indicator of early efficiency, and clarifies the inherent limits to geometrical optimization. For a sound source included in an absorptive plane (for example the location of an instrument within the orchestra, or surrounded by audience), the maximum value of Ω_{eff} will be 2π (50% of the entire space). 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.

2.2 Audience size: the main limit to early efficiency

The most common limit to geometrical optimization is known as the "large concert hall problem"[5]. In concert halls of large seat-counts, the large volume required for obtaining sufficient reverberation tends to move reflecting surfaces further away to the audience. The provision of sufficient early-reflected energy to each audience member and musician is traditionally considered as a challenge in halls of more than 2'000 seats.

Another way to think of this "large concert hall problem" would be to consider that the energy produced by the sound source is spread between each audience member and musician. (As will be discussed later, this idea of spreading is not fully correct). In halls of higher seat-counts, securing the same acceptable level of early energy would require a higher proportion of the produced energy to be used for early reflections. Larger seat-counts would then require a larger efficient solid angle.

This can be illustrated by a simple geometrical example. An hypothetical room of pyramid shape is considered, with a flat square base representing the audience and four sloped reflective planes surrounding the audience and reaching the top point of the pyramid. The sound source is located at the center of the base, in the middle of the audience. As long as the height of the pyramid is sufficiently small (8m in our case), all four reflective surfaces will be totally efficient and the efficient solid angle will equal 2π (50% of the entire space). The rest of the space as seen from the source is entirely occupied by the audience. This geometry can be thus considered as “perfectly optimized” in the sense that the highest possible value of Ω_{eff} is reached. This remains valid for larger dimensions of the pyramid base, corresponding to rooms of larger seat-count.

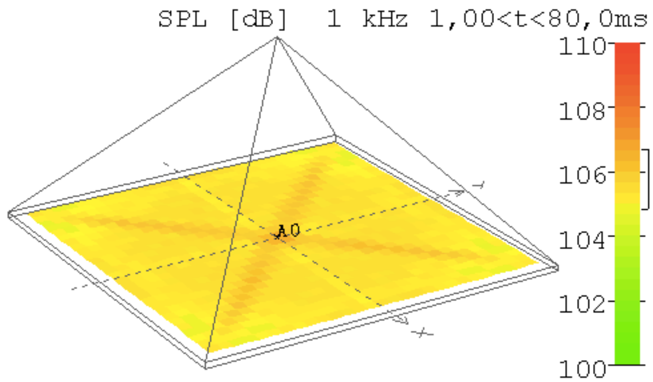

Figure 2: Example of an audience area mapping of early-reflected level for the smallest pyramid shape. The source power level was chosen so that G values simply equal SPL - 100dB

The average amount of early-reflected energy across the audience base plane was predicted for several values of the audience area using CATT-Acoustic software. The results displayed in figure 3 indicate a decreasing level of early energy along with the increase of the pyramid base area.

A level inferior to -3 dB is reached for a receiving area of 1’600 m^2, roughly corresponding to a symphony orchestra plus an audience of about 2’000 members. In that case, total strength values G inferior to 0 dB will inevitably be obtained in a significant part of the audience, which is generally considered as a serious acoustic defect[6].

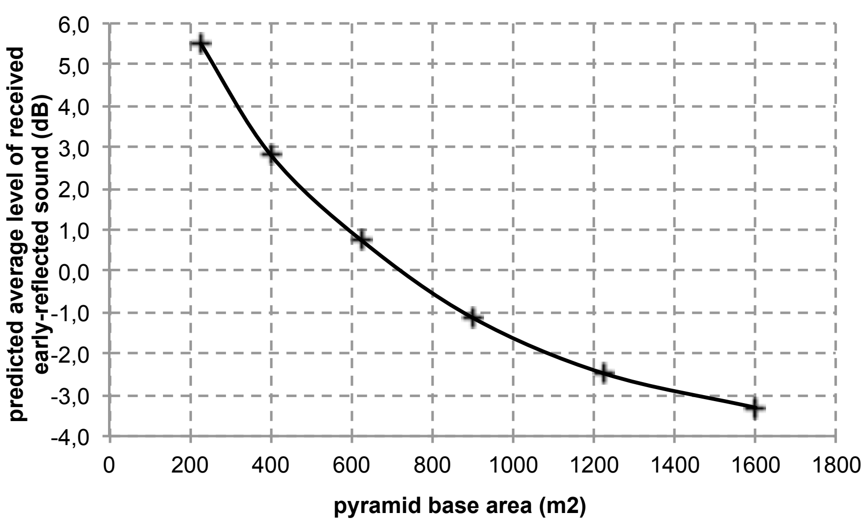

Figure 3: Average level of the early-reflected sound field (between 1 and 80ms) predicted by CATT-Acoustic plotted against the audience area, while the efficient solid angle remains unchanged. The plotted levels are relative to the pressure level produced by the same source in free field at a distance of 10m.

According to this pyramid example, it would not be possible to provide a sufficient amount of early reflections to a receiving area (audience and orchestra) covering more than 1'600 m^2. But some existing concert halls can refute this conclusion, which suggests the existence of yet another geometrical criterion characterizing early efficiency. The solution to the "large concert hall problems" necessarily involves this last criterion.

2.3 Reflections from the lower part of the space are advantageous

The angle of incidence of early reflections on receiving areas has a key influence of early acoustic efficiency. A simple example can illustrate this influence.

Figure 4 is a view in short section of a generic seating layout in a room, with a sound source located at the center of the stage. Two cases of hypothetical acoustic reflectors can be compared: a zenithal reflector providing reflections with an angle of 0° with respect to the audience surface normal, and a lateral reflector whose reflections are oriented with an angle of 60° with respect to the surface normal. Both reflectors receive the same amount of energy from the source (same distance to the source, same size, same orientation with respect to the source) but the lateral one spreads this energy to twice as many audience members. The idea of spreading is in fact improper in that case: both reflectors are flat and bring reflections with virtually the same delay (of approximately 60ms near the source). The acoustic intensity of the sound wave reaching each audience member is virtually identical in both cases.

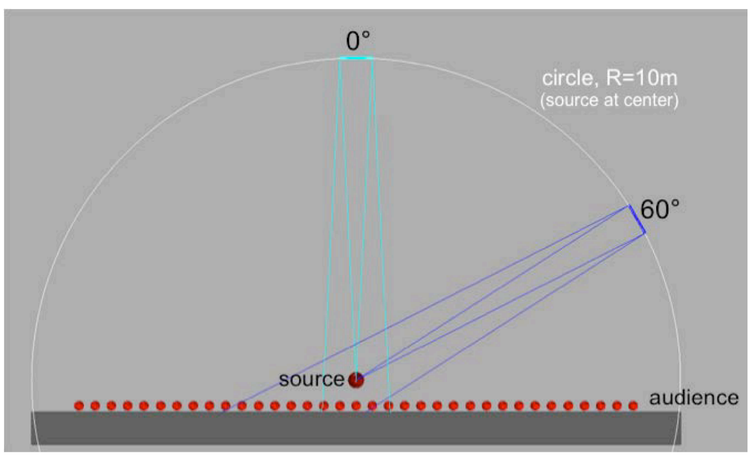

Figure 4: Cross section representation of a generic concert hall seating layout, displaying the effect of two hypothetical acoustic reflectors. The red dots represent audience heads.

This observation demonstrates that when reflectors are located in the lower part of a hall, the same amount of energy emitted by the source can be used and channeled in order to have a stronger impact on average early energy in the audience. Such reflectors obviously do not create stronger reflections, but their reflections are brought to a larger number of audience members.

2.4 Relationship between the geometry of a room and the average amount of early energy provided

Under the assumptions of geometrical acoustics, the author previously demonstrated[4] that the average amount of early reflected energy across the audience area could be predicted through a simple formula. This formula relates the early reflected acoustic strength 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.

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

This formula uses the following definition of early-reflected strength:

$$G_{em} = 10 \times \log\left(\frac{I_{em}}{I_{10}}\right) \tag{2}$$

Where I_{em} is the average over the audience areas of the total reflected acoustic intensity reaching the audience ears before a specific delay D after the arrival of direct sound (and not including the direct sound). And I_{10} is the acoustic intensity created by the same non-directional sound source in free field at a distance of 10m.

And θ_m is defined from the individual angles of incidence θa_i (0° for normal incidence, 90° for grazing incidence) weighted by the individual efficient solid angle $d\Omega_i$ of each reflector:

$$\frac{1}{\cos(\theta_m)} = \sum \frac{d\Omega_i}{\cos(\theta a_i)} \Big/ \sum d\Omega_i \tag{3}$$

Formula (1) is based on the following assumptions: sound source and receivers are omnidirectional, the limits of validity of geometrical acoustics are respected (wave lengths are small compared to the size of the reflecting surfaces), no surface roughness (diffusion) and no surface absorption are applied on reflective surfaces, absorptive surfaces are totally absorptive and air absorption is neglected. The formula remains valid for curved reflective surfaces, and it can also be refined in order to take into account the effect of surfaces diffusive and absorptive properties.

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. It also indicates that very comfortable seating layouts do not only reduce reverberation time but also early energy, and strength in general. Spreading audience over wider areas will require higher values of Ω_{eff} to obtain the same amount of early energy.

Through Ω_{eff}, the existence of a physical limit to early reflection design is formulated. In large concert halls, good acoustic design can only increase Ω_{eff} up to a certain limit in order to obtain appropriate values for early strength.

This inherent limit to the value of Ω_{eff} 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. Acoustic designs favoring such "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.

When favoring shallow incidence reflections, the famous seat-dip effect should not be disregarded. Sound waves propagating above an audience area under grazing incidence are attenuated. This attenuation is mostly effective at low frequencies but also to a lesser extent at mid-frequencies[7-9]. As a consequence, the proposed formulas for G_{em} can only be considered fully valid for reflections with angles of incidence on the audience that are not too large.

3 STRIKING THE RIGHT BALANCE

3.1 Influence of early efficiency on the late reverberant field

As discussed previously, a sufficient level of acoustic optimization in concert halls of large seat-count requires a large value of the efficient solid angle Ω_{eff} and/or a large proportion of early reflections provided from the lower part of the room (large value of θ_m).

The strategy of increasing Ω_{eff} is not only inherently limited, it also involves some side effects. Large values of the efficient solid angle means that a substantial proportion of the energy produced by the sound sources is reoriented by the room towards the audience. The proportion of energy that is left to contribute to the late sound field is then significantly reduced.

The solid angle of the entire space – 4π – can be divided in four acoustic components:

- The solid angle Ω_{dir} that the audience surfaces subtend at the point of the source.
- The solid angle Ω_{abs} containing all acoustic rays emitted by the source that will meet an absorptive treatment in the room before the chosen transition time between early and late response (commonly 80ms).
- The efficient solid angle Ω_{eff}.
- And the solid angle Ω_l containing all the acoustic rays that will contribute to the late part of the room response.

The first three components can also be regrouped in a single early solid angle Ω_e.

$$4\pi = \Omega_{dir} + \Omega_{abs} + \Omega_{eff} + \Omega_l = \Omega_e + \Omega_l \tag{4}$$

With this solid angle approach, the commonly expressed apprehension that optimizing the geometry of a concert hall for early reflections might be detrimental to the late response appears justified. A formula for the average value of late strength across the audience G_{lm} can even be derived from statistical acoustic theory:

$$G_{lm} = 10.\log\left(31200.(1-\beta)\frac{T}{V}\right) \tag{5}$$

In which G_{lm} is defined the same way as G_{em} but with a time frame corresponding to the late acoustic field; β is given by:

$$\beta = \frac{\Omega_e}{4\pi}\alpha_a \tag{6}$$

α_a is the average absorption coefficient of the audience and other absorptive surfaces in the room, and T and V are respectively the reverberation time (in seconds) and volume (in cubic meters) of the room.

Formula (5) is obtained under the assumption that the reflective surfaces are not significantly absorptive ($\alpha_r << 1$) and far less absorptive than absorptive surfaces ($\alpha_r << \alpha_a$). In comparison tests with computer simulations using CATT-Acoustic software, formula (5) gave significantly better prediction results than the traditional Sabine and Barron[10] formulas for reverberated energy.

As anticipated, while formula (1) implied that large seat-counts will require a room geometry characterized by a high value of Ω_{eff} to keep a sufficient amount of early energy, formula (5) states that smaller values of Ω_{eff} will be required to preserve enough energy for the late response.

3.2 Towards a full set of geometrical parameters

The optimization of the geometry of a concert hall is then not a "more is better" process. Beyond the fascination with new 3D acoustic optimization possibilities, the development of suitable concert hall geometries requires an appropriate goal to be set for early efficiency.

Using formulas (1) and (5), the impact of a room geometry on the balance between its early and late acoustic responses can be quantified and a full set of related geometrical parameters be defined. Material properties and reverberation time are other parameters influencing the average level of early and late energy, but that cannot be considered as geometrical parameters. The room shape can of course influence reverberation time, and it is likely that the value of Ω_{eff} will affect reverberation time. However, at this point of the development, the choice has been to consider reverberation time as a purely acoustic parameter, which is set as a separate acoustic goal.

Under this assumption, reverberation time can be determined by the volume V and total absorption A in the room through Sabine formula. In addition, Kosten[11] proposed a proportional relationship between total absorption and audience surface area in concert halls that brings an interesting simplified reformulation of formula (5):

$$G_{lm} = 10.\log\left(\frac{5030}{\alpha_K}\frac{(1-\beta)}{S_{aud}}\right) \approx 10.\log\left(4410\frac{(1-\beta)}{S_{aud}}\right) \qquad (7)$$

In which α_K is the equivalent absorption coefficient defined by Kosten, which was found empirically to be close to 1.14 in symphony halls[12]. It is not intended that formula (7) should provide very reliable predictions after as many simplifications have been applied. However, this formula has the advantage of clearly displaying the influence of the geometrical parameter S_{aud} on the average level of the late response. This simple model brings us to this final set of geometrical parameters:

- Ω_{eff}, S_{aud} and θ_m for early energy
- Ω_{dir}, Ω_{abs}, Ω_{eff} and S_{aud} for late energy

When designing a concert hall for a given audience and orchestra size, the target value of Ω_{eff} can be obtained from the desired value of G_{em} and G_{lm} using the two following formulas:

$$\Omega_{eff} = \frac{S_{aud}}{100}.\cos\theta_m.10^{G_{em}/10} \qquad \text{(8), derived from (1)}$$

$$\Omega_{eff} = \frac{4\pi}{\alpha_a} - \frac{\alpha_K}{\alpha_a} \cdot \frac{S_{aud}}{400} \cdot 10^{G_{lm}/10} - \Omega_{dir} - \Omega_{abs}$$ (9), derived from (7)

In figure 5, these two formulas are represented graphically for an acoustic goal of G = 3 dB and C_{80} = 0 dB (on average on the entire audience and stage), with α_a = 0.85 and α_K = 1.14. This graph illustrates how the levels of early and late energy are influenced by the various predefined geometrical parameters.

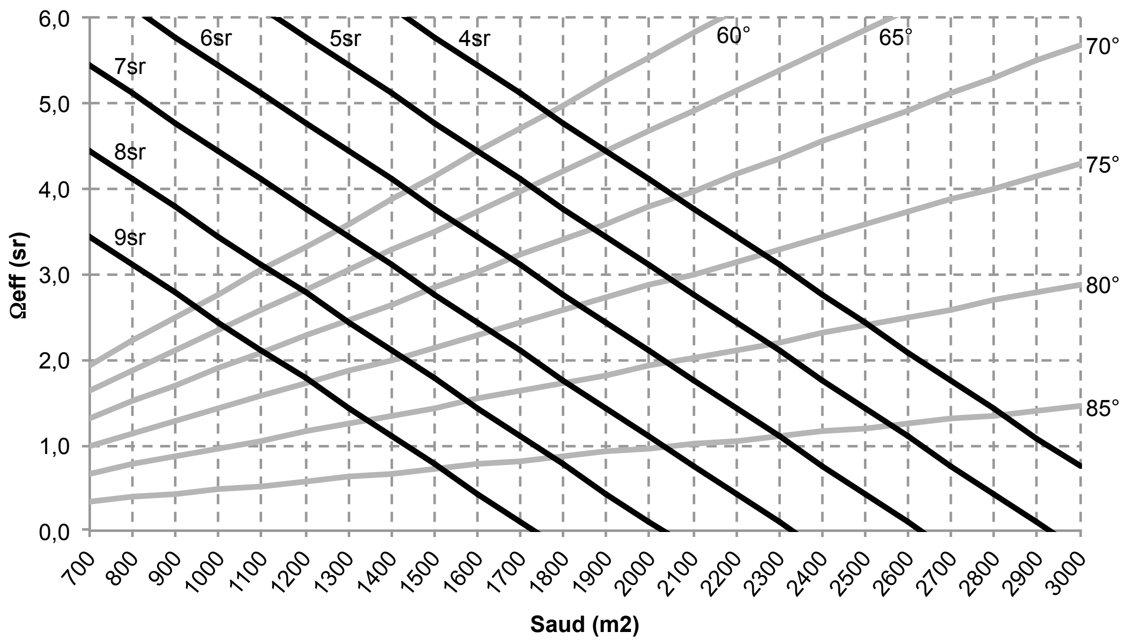

Figure 5: Target value for the efficient solid angle Ω_{eff} as a function of the total audience area S_{aud}. Black lines depict formula (9) results for various values of the direct and early-absorbed solid angle $\Omega_{dir} + \Omega_{abs}$ in steradians (sr). Grey lines depict formula (8) for various values of the average angle of incidence of early reflections on audience planes θ_m in degrees (°).

For a given audience side (S_{aud}), the appropriate target for Ω_{eff}, $\Omega_{dir} + \Omega_{abs}$ and θ_m for a predefined acoustic goal (G_{em} and G_{lm}, obtained from G and C_{80} target values) can be obtained graphically as one of the intersection between a black and a grey line in figure 5.

3.3 The large concert hall problem

The acoustic solid angle criterion was first introduced in a simplified version for the acoustic brief of the Paris Philharmonie project[3]. The challenge for the designers of this project was the client's wish for a novel room typology (neither a shoebox nor a vineyard) and the requirement of providing excellent acoustics for symphonic music with a minimum seat-count of 2'400.

As illustrated in figure 5, with an audience and stage area S_{aud} of 1'900 m^2 (roughly corresponding to a symphony orchestra plus a seat-count of 2'400) achieving sufficient amounts of both early and late energy at all seats is particularly demanding. An average angle of incidence of early reflections θ_m of more nearly 80° is required if the audience and orchestra occupies half of the space as seen from the source ($\Omega_{dir} = 2\pi = 6.3$) and no absorptive treatment is applied (Ω_{abs} = 0). This target is feasible, but to achieve it many early reflections will have to reach the audience under grazing incidence and will therefore be attenuated. Better strategies include:

- Limiting the surface area occupied by audience and the orchestra by reducing seat spacing. For example S_{aud} = 1'800 m^2. Lower values of Ω_{dir} can then also be achieved.
- Reducing the total amount of acoustic absorption by avoiding absorptive treatments (Ω_{abs} = 0), limiting the audience absorption coefficient by proper seat design (for example α_a = 0.8 for occupied seats) and limiting residual absorption (smaller values of α_K).
- Aiming at an average angle of incidence θ_m of about 75° by favoring reflections from the lower part of the room and avoiding zenithal reflections.

Interestingly, the required value of Ω_{eff} is not that high, about 2.5 to 3 sr (20% of the entire space as seen from the stage). This demonstrates that the large concert hall problem is not to be solved through early reflection optimization only. In particular, optimizing the ceiling profile for early reflections will be counterproductive.

The validity of this conclusion can be illustrated by two recent exemplary case of refurbishment of existing halls. The first one is the Queen Elizabeth Theatre in Vancouver, Canada, home of the Vancouver Opera and Ballet. After the renovation by Aercoustics Engineering of this very large hall (more than 30'000 m^3 and a seat-count of 2'750), the designers presented measurement results demonstrating a significant increase of both early and late energy, and suggested that improving the amount of early reflection also improved the late response[13].

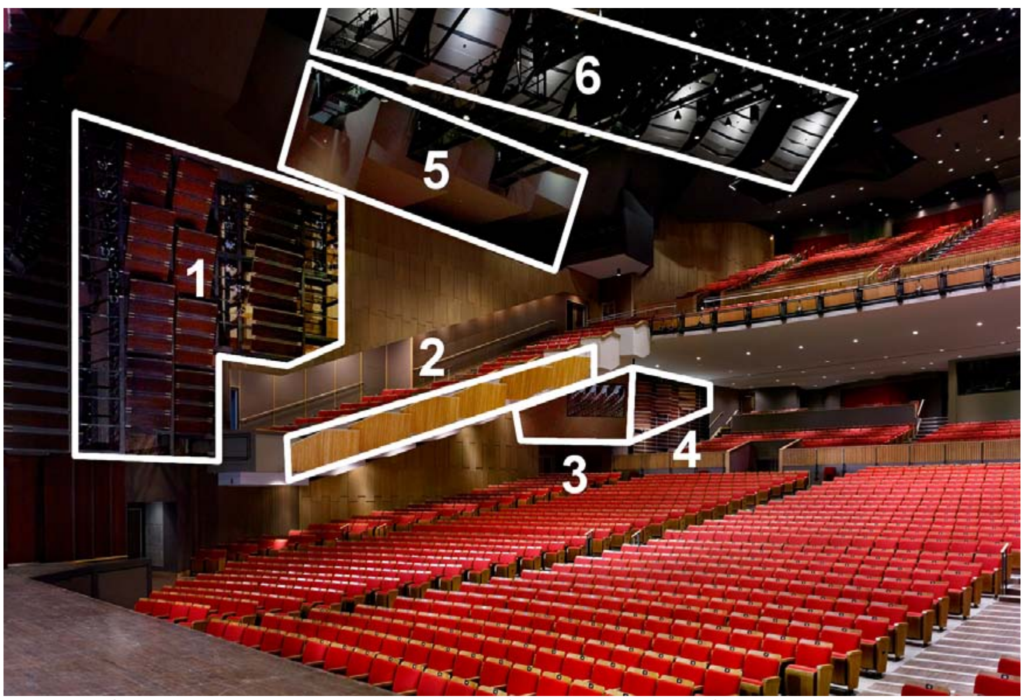

Figure 6: Picture of the Queen Elizabeth Theatre taken from reference[12]. The various sidewall reflectors integrated in the refurbished hall are identified.

Looking at the measurement at mid-frequencies, it appears that total strength was increased by 2.5 dB while early strength G_{80} was increased by 1.8 dB, which implies a 4 dB improvement of

G_{lm}. This cannot be explained by the reverberation time improvement alone: its increase from 1.4 s to 1.7 s can only account for a 0.9 dB improvement of late energy.

During the refurbishment, the old reflective ceiling was removed and replaced by a simple flat ceiling with under-hanged catwalks in cable-tension grid. In addition, many reflectors were added on the sidewalls to provide early lateral energy. In replacing existing ceiling reflection by side reflections, it is obvious that the designers considerably increased the average angle of incidence of early reflections on the audience θ_m. As a consequence, a smaller proportion of the energy produced by the sound sources is used to produce early reflections, leaving more energy for the late sound field. In the meantime, the increase of θ_m allows for an increased value of G_{em} even though Ω_{eff} has been reduced.

The second exemplary case is the Auditorium du Nouveau Siècle in Lille, France, home of the Orchestre National de Lille. The very wide fan-shaped hall originally designed for congresses and seating about 2'000 was transformed into a narrower shoebox-type concert hall dedicated to symphonic music. Two parallel sidewalls – including two levels of side-galleries – were built inside the volume of the old hall, and the seat-count was consequently reduced to 1'800. In addition, the old sound-directing ceiling was removed and a new coffered-ceiling was build more than 2 m higher than the old one. The direction followed is very similar to that of the Queen Elizabeth Theatre in the sense that the amount of reflections from the lower part of the hall was increased, while amount of zenithal reflections from the ceiling was reduced, leading to a higher value of θ_m and a lower value of Ω_{eff}.

Figure 7: Picture of the new Auditorium du Nouveau Siècle in Lille, France

The new concert hall opened in January 2013 and received great critical acclaim. At the time of writing, no acoustic measurement of the new hall has yet been possible, but acoustic predictions from computer simulations and listening tests confirmed that both early and late energy were considerably improved.

3.4 The small symphony hall problem

The issue of designing symphony halls of small seat-count is less documented but can also be acoustically challenging. Extensive provision of early energy can cause excessive loudness and "saturation". If the volume is not sufficiently large, the sound quality becomes overly "dense" and aggressive, for the audience as well as for the orchestra.

One possible approach to this "small symphony hall" problem is to impose a much larger volume than what would be required architecturally. Instead of setting a volume per seat target (traditionally 10 m^3 /seat), it can make more sense to set a minimum volume per musician. However, this approach doesn't solve the issue of the amount of early reflections to be provided by the room geometry. Müller-BBM even recently designed a concert hall in l'Aquilla, Italy, whose geometry was intentionally not optimized for early efficiency in order to control sound strength[14]. This example raises a very important issue: what is the limit to excessive provision of early energy, and should the geometry of small halls be less optimized in terms of early efficiency?

In figure 8, the possible target values of Ω_{eff} are represented graphically for an acoustic goal of G = 5 dB and C_{80} = 0 dB (on average on the entire audience and stage). α_a and α_K are kept with the same values as in figure 8.

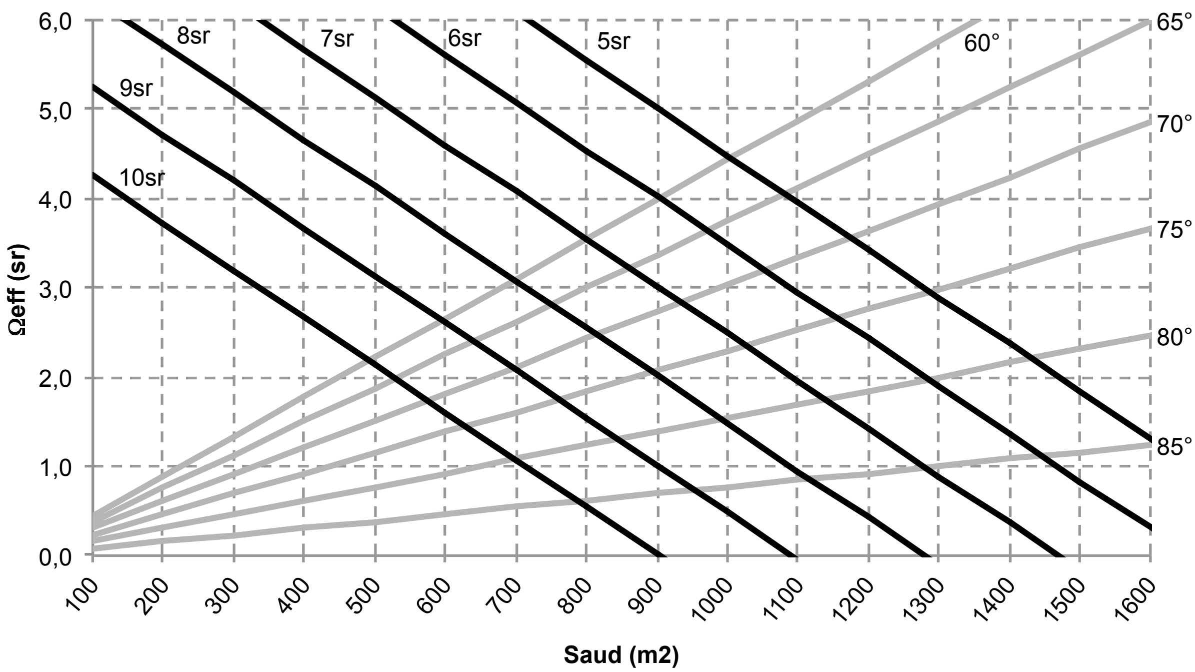

Figure 8: Target value for the efficient solid angle Ω_{eff} as a function of the total audience area S_{aud} for small symphony halls. Black and grey lines as previously defined in figure 5.

In a symphony hall of 1'000 seats (S_{aud} of about 900 m^2), it appears that the designer can choose between two options:

1. Favoring reflections from the lower part of the hall (θ_m of about 75°) with Ω_{eff} = 2 sr and $\Omega_{dir} + \Omega_{abs}$ = 8 sr.

2. Or providing more reflections from the upper part of the hall (θ_m of about 60°) with Ω_{eff} = 4 sr and $\Omega_{dir} + \Omega_{abs}$ = 6 sr.

From an acoustic point of view, option 1 implies the addition of absorptive treatments exposed to direct sound that will simulate the presence of a larger audience. This addition of acoustic treatment will increase the amount of residual absorption in the hall (higher α_K). Which, in turn, will modify the black lines in figure 8. For a θ_m value of 75°, the appropriate value for $\Omega_{dir} + \Omega_{abs}$ can finally be estimated at about 7.3 sr.

Option 2 will not require the addition of absorptive treatments but implies a larger value of Ω_{eff} and a lower value of θ_m, corresponding to a more efficient design of the ceiling. A potential benefit of this second option is that the smaller total amount of acoustic absorption should allow for a relatively smaller volume for a given reverberation time target. A possible disadvantage is that providing more reflections from the ceiling will create less enveloping acoustics.

In the case of a symphony hall of only 700 seats (S_{aud} of about 700 m^2), the addition of absorptive treatments is no longer optional. A θ_m value of about 40° would be required to reach the early and late energy targets with a value of $\Omega_{dir} + \Omega_{abs}$ close to 2π. This would involve a large amount of zenithal reflections and would clearly be detrimental in terms of source broadening and envelopment. A more suitable strategy would be to aim at a θ_m value of 65°, and to provide absorptive treatment with a target of Ω_{abs} = 1.3 sr and α_K = 1.4. In that case, the required value of Ω_{eff} will be of 2.7 sr.

From these two examples, it can be observed that the required value for Ω_{eff} in small symphony halls is not smaller than in the larger ones. The required Ω_{eff} can even be larger when it is decided that the addition of absorptive treatments should be avoided. This may appear to contradict the idea that smaller symphony halls require less geometrical optimisation for early efficiency. However, a Ω_{eff} value of 2.5 is much easier to obtain in a small hall in which reflective surfaces are naturally closer to the sound sources and second or third order reflections can easily reach the audience with a delay inferior to 80ms. Simply scaling down the geometry of a large concert hall is not a suitable strategy. The required effort of geometrical optimization for early efficiency is actually reduced in symphony halls of smaller seat-counts.

4 CONCLUSION

A new approach based on solid angles and other geometrical parameters has been proposed for the design of concert halls. This solid angle approach can be considered as a proposal for new architectural parameters intended to serve as guidance for the design, in a similar way to acoustic volume being a a criterion for reverberation.

It is also an approach to early reflection design, clearly displaying what aspects of architectural shape are the most important and how architectural shape influences acoustics. And finally it is a prediction method for early and late energy in concert halls and other performing arts spaces. At this stage, predicted values obtained with the proposed formulas have to be considered with due care as the required refinements to account for material absorptive and diffusive properties are not yet integrated.

This new tool for acoustic designers allows for a fast analysis and comparison of several room shapes and the definition of appropriate geometrical targets. It also proved to allow for very good collaboration with the architects in developing acoustic designs that blend with the architecture. Especially during the competition phase, their use by acoustic consultants could help to forge a better integration of acoustic requirements in the architectural design and thus contribute to a significant improvement of the finally obtained acoustic quality.

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