Acoustic solid angle criteria in practice: transforming the Chapelle Corneille in Rouen into a concert hall

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A new concert hall for early music, chamber music and small ensembles is to be outfitted in a 17th century church in the city Rouen. The *Chapelle Corneille* is a large and beautifully renovated landmarked monument, with highly reverberant acoustics. The addition of a large amount of early energy is a major requirement for the acoustic transformation of the church into an Auditorium. But the imperatives of historical preservation are strong, and a previous project was cancelled due to an addition of acoustic reflectors that was judged visually offensive. During the architectural competition that followed the first project cancellation, the use of the solid angle criteria made it possible for our design team to consider many options and quickly estimate their acoustic efficiency. This approach led to innovative solutions, both acoustically effective and architecturally integrated.

1 Introduction

The purpose of this publication is twofold. Firstly, the context of the project and the proposed solutions are worth discussing. Secondly, an innovative prediction and design method was used during the design competition. This method is based on geometrical acoustics and the estimation of the efficient solid angle: the total solid angle of all reflectors bringing early reflections to audience members or musicians as seen from a given source point. Prediction of the average level of early reflected energy is made possible without the use of ray-tracing or image source algorithms and the early reflection design becomes parametric. Of particular interest is the influence of the angle of incidence of reflections onto the audience that will be discussed here.

2 An existing space with many qualities

The starting point of our work on the project is an existing and very promising space. The 17’000 cubic meters of the *Chapelle Corneille* offer a beautiful reverberation, significantly longer and stronger than those of modern concert halls. Its interior architecture has been wonderfully renovated and one can already feel its very high potential for housing classical music concerts.

Figure 1: *Chapelle Corneille* in its current state. This is the picture that was provided to every competitor with the instruction of using it to display the visual impact of planned acoustic installations.

The brief for the design team competition precisely defined the concerts that will be housed in the future 600 seat auditorium. It took into account the qualities and limitations of the space and announced a program including sacred and secular baroque works as well as choral music. The *Chapelle Corneille* and its natural acoustics suits the sacred and vocal repertoire with very few adjustments. Acoustic modifications and improvements are primarily needed for the chamber music concerts that will require higher clarity and a stronger impact and presence of the sources than what a church of approximately 17’000 m3 can offer.

The acoustic brief was established by *Altia Acoustique* and set out quantified acoustic goals for the transformation of the church into an auditorium. It stated that the preservation of a landmarked monument is not only about the building but also its ambiances. The very long reverberation of the *Chapelle Corneille* is an important characteristic of this monument and should not be lost during its transformation. However, better clarity has to be obtained by adding a sufficient amount of early energy.

Table 1: Acoustic characteristics of the *Chapelle Corneille*: comparison of the acoustic brief requirements with measurements of the existing state (with no audience and no seats, except when the contrary is indicated)

Measurments of the church in its existing state	Acoustic brief requirements
Reverberation time : T30 = 5,6 s at mid-frequencies	Reverberation time T30 > 5 s at mid-frequencies
Clarity : C80 = -7,5 dB at mid-frequencies	Clarity : -3 dB < C80 < 3 dB at mid-frequencies, with empty seats
Very few surfaces creating early reflections	100 to 120 m2 of acoustic reflectors
No aborptive materials	100 m2 of acoustic curtains
No sound reinforcement system	Subtle reinforcement can be studied for the zones of audience seating far from the stage

As can be seen in Table 1, the required increase for the C80 parameter involves a considerable addition of reflecting surfaces. This is in direct conflict with another part of the brief, namely historical preservation that requires the vaulted ceilings as well as several altarpieces to remain fully visible. Before the organisation of this competition, a previous project that included the addition of many transparent ceiling reflectors was judged visually offensive by the historical preservation services of the French ministry of culture. This previous project was cancelled and a new design team competition was organised, with stronger preservation requirements.

The context of the acoustic intervention was very sensitive. Architects and acoustic consultants had to propose very efficient solutions, but invisible ones were preferred!

3 Designing efficient solutions for early energy

The acoustic success of the *Chapelle Corneille* transformation project will of course not exclusively rely on the amount of early energy provided to the audience. It is deliberate that this publication concentrates on this important and interesting aspect of the design work.

The amount of early energy that has to be added to the acoustic response of the existing *Chapelle Corneille* can be quantified. The goal being to reach an average parameter C80 > -3dB, the average early energy of direct sound and early reflections (reaching the audience less than 80ms after the direct sound) has to be larger than twice the average late energy (reaching the audience more than 80ms after direct sound):

$G_{[0,\ 80ms]} > G_{[80ms,\ \infty]} - 3dB$

It is disappointing that the acoustic measurements provided in the brief did not include values for acoustic strength G. However, Barron's revised theory [1] can be used to estimate $G_{[0,\ 80ms]}$ and $G_{[80ms,\ \infty]}$ from the acoustic volume and the measurements of reverberation time and C80 that were provided.

Using Sabine's Formula, it can also be predicted that installing 600 medium to lightly upholstered seats in the church will reduce the reverberation time to approximately 3,9s unoccupied. This decrease of reverberation time implies a slight decrease of early energy (-0.2dB according to the revised theory) and a more significant decrease of late energy (-1.9dB according to the revised theory).

In the existing state of the church, with seats but no audience, the following values can therefore be predicted:

$G_{[0,\ 80ms]} = 1.5$ dB

$G_{[80ms,\ \infty]} = 7.3$ dB

If no other changes impacting the level of late energy are made, obtaining a C80 superior to -3dB will require a 2.8 dB increase of average early energy in the audience. At each seat, the total acoustic strength of the early reflections to be added is about 1.1 dB ($1.5 \oplus 1.1 = 4.3$ dB $= 7.3 - 3$, with $\oplus$ representing the addition of energy in decibels). Clearly, this is a very demanding goal in terms of acoustic reflectors.

3.1 Audience proximity to the stage

Favoring audience proximity to the stage is a first element of a solution that increases early energy in the audience with no alteration to the architecture. Our design team consequently proposed a layout consisting in a central stage surrounded by audience on all sides. All 600 seats can be accommodated in the central part of the church, at a distance of less than 10 meters to the stage. The farthest end of the nave – where direct sound is very weak – is transformed into a lobby. The proposed organization is fully flexible and it will still be possible to use the space of the lobby to extend the auditorium on special occasions.

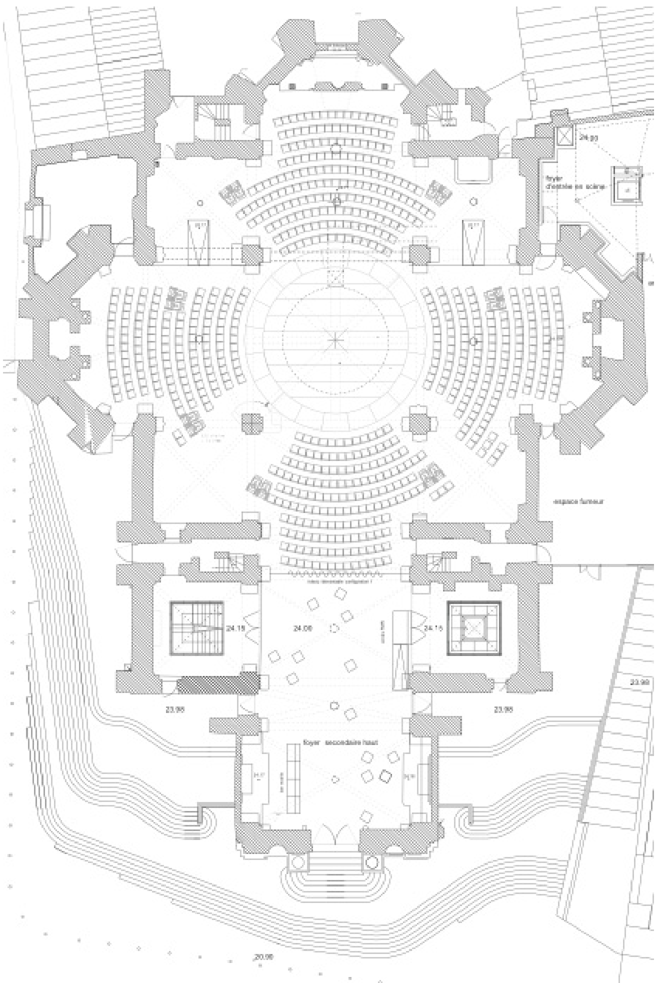

Figure 2: Seating layout proposal, with a central stage favouring audience proximity.

3.2 A spherical reflecting canopy

Transforming a church into an auditorium also requires the addition of stage lighting. These technical installations can be visually obtrusive and had to be properly integrated.

The proposed solution takes the form of a spherical chandelier, acting both as a technical element allowing proper integration of stage lighting and ambiance lighting, as well as an acoustic canopy providing early reflections to the stage and all audience members.

The sphere has a diameter of about 7m. Assuming an average distance of 11m to the sound sources Rindel's theory [2] for reflection on curved surfaces can be used to predict the strength of the created reflections. This evaluation results in an attenuation due to the convex curvature that is always superior to 12dB, and an acoustic strength of the corresponding reflection always inferior to -19dB. All audience members will receive one reflection from this surface, but its energy will be very low and almost insignificant compared to what is required.

It was consequently decided to divide the sphere into an upper and a lower half and to make it rotating. One side of the chandelier is a half spherical mirror and will be oriented towards the stage floor for other uses than concerts and rehearsals. The visual effect of this spherical mirror reflecting the whole church will be impressive and emblematically important. The other side is a convex disk with a much larger radius of curvature of 25m, located behind a half spherical open grid incorporating the ambiance and stage lighting equipment. The radius of 25m was chosen to maximize the strength of acoustic reflections while still providing one reflection to all seats around the stage. Attenuation due to curvature is reduced to approximately 3 to 4 dB, corresponding to an acoustic strength of approximately -10 dB.

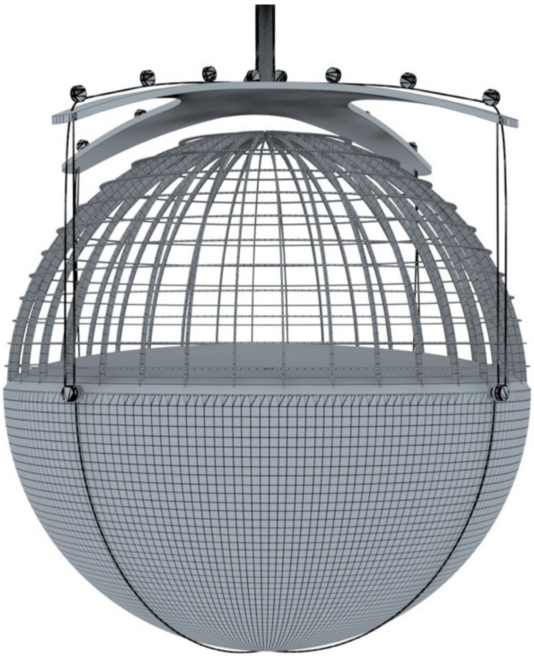

Figure 3: Initial 3D sketch of the rotating spherical canopy, in its

This reflection alone is obviously still not sufficient to provide a significant increase of early energy and clarity. The aim for a 2.8 dB increase of early energy could only be obtained if 13 such reflections where brought to all seats. As installing 13 such spherical chandeliers in the *Chapelle Corneille* is clearly not realistic, additional and more efficient acoustic solutions had to be developed.

3.3 Reflections from the lower part of the space are advantageous

In a previous study [3] related to the Philharmonie de Paris project, a good correlation between the total surface area of efficient reflectors in a hall and the mean value of measured clarity C80 was demonstrated. The correlation was further improved with another method based on a simplified definition of the solid angle of these efficient reflectors as seen from a given source point.

Following this study, a new method was developed in order to predict the average amount of early reflected energy onto areas occupied by receivers (audience members or musicians). Under the assumptions of geometrical acoustics it can be demonstrated that the average amount of early reflected energy is proportional to the solid angle of efficient reflectors as seen from a given source point and inversely proportional to the total area of receiving surfaces in square meters. These proportionalities are rather intuitive: if the sound source is considered omnidirectional and diffusion effects are neglected, the total solid angle of efficient reflectors Ω_{eff} divided by the solid angle of the entire space (4π) represents the proportion of energy emitted by the sound source that is oriented towards the receivers by reflecting surfaces and that reaches those receivers less than 80ms after the direct sound.

A third and less intuitive geometrical parameter was found to have a key influence on acoustic efficiency: the angle of incidence of early reflections on receiving areas. A simple example can illustrate the influence of the angle of incidence of the reflections. Figure 4 is a view in short section of a generic seating layout in a room, with a sound source located at the centre of the stage. Two cases of hypothetical acoustic reflectors can be compared: a zenithal reflector providing reflections with an angle of 90° with respect to the horizontal, and a lateral reflector whose reflections are oriented with an angle of 30° with respect to the horizontal. 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.

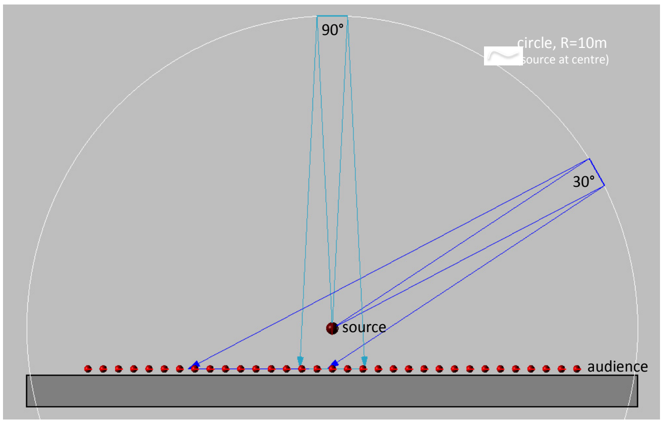

Figure 4: Cross section representation of a generic concert hall seating layout, displaying the effect of two hypothetical acoustic reflectors. The red dots represent audience heads.

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 channelled 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.

This finding is of great interest to the particular case of the *Chapelle Corneille* project. It implies that in order to respect the historical preservation requirements by minimizing the total area of acoustic reflectors, those should preferably be located in the lower part of the church. It also explains what was observed in the previous chapter concerning the spherical canopy: the exclusive use of reflectors suspended in the upper part of the church is inadequate to provide the required amount of early energy and cannot fulfil simultaneously the acoustic and historical preservation requirements for this project.

3.4 Acoustic reflectors integrated into the seats

The predicting method that was developed allowed a quantification of the exact required amount of properly oriented reflecting surfaces, depending on their location.

The basic idea was then to incorporate those reflecting surfaces in the design of the seats. The seats located in the last row will be equipped with very high reflecting seat backs. The addition of a horizontal surface at the top of the seat back further improves the acoustic efficiency of this reflector.

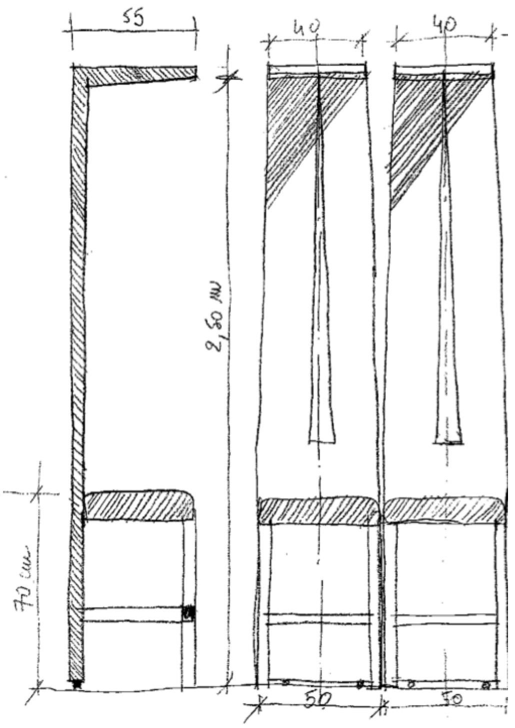

Figure 5: Hand sketch of seats equipped with high reflecting seat backs, by *Atelier d'Architecture King Kong*.

Depending on the seating layout and the amount of early energy that is desired for a specific concert, up to 90 seats can be equipped with such seat backs, each of them offering about 1m^2 of efficient reflecting surface area.

The circular seating layout may seem problematic, as the seat backs will form a concave and potentially highly focusing shape. However, this issue can be easily solved by properly shaping these reflectors, which will be developed during the next design phases of this project.

4 Acoustic prediction results for the developed design

Together with the spherical canopy, the reflecting seat backs will provide a very significant amount of early energy to all audience members as well as musicians on stage. Under the assumptions of geometrical acoustics, it can be predicted that the average value of added early reflected energy corresponds to an acoustic strength of up to 1.3 dB, which is slightly more than what was estimated as a minimal requirement. Interestingly, the prediction method did not require the construction of a 3D computer model, which would have been especially difficult and time consuming in this particular case.

In addition, a need for variable acoustic absorption was anticipated as not all concerts would benefit from the very long reverberation of the church. Chamber music from the secular baroque or classical repertoire will require a more subtle late response of the room. Variable absorption devices consist of a set of boxes containing acoustic curtains that can be deployed upward using an integrated mechanical system. Approximately half of these boxes are located in the upper galleries of the church, the other half being equipped with wheels and can be disposed either near the orchestra or in more discreet parts of the church.

A summary of the prediction results for the proposed design is displayed in Table 2.

Table 2: Acoustic characteristics of the *Chapelle Corneille*: comparison of the acoustic brief requirements with the prediction results for the proposed design.

Acoustic brief requirements	**Prediction results for the proposed design**
Reverberation time T30 > 5 s at mid-frequencies, with no seats and no audience	T30 > 5 s in the empty church, and = 4,5 s with no seats but with all other removable devices 2.7 s < T30 < 3.5 s with empty seats 2.5 s < T30 < 3.2 s with occupied seats and an orchestra on stage
Clarity : -3 dB < C80 < 3 dB at mid-frequencies, with empty seats	Tunable clarity: -3,4 dB < C80 < -2,4 dB at mid-frequencies, with empty seats
100 to 120 m2 of acoustic reflectors	Up to 130 m2 of efficient acoustic reflectors
100 m2 of acoustic curtains	250 m2 of retractable acoustic curtains
Subtile reinforcement can be studied for the zones of audience seating far from the stage	Reinforcement will be studied only if a frequent use of the nave as an extenstion of the auditorium is desired

5 Conclusion

The opening of the auditorium is currently planned for 2015. It will house several regional orchestras for rehearsals and concerts and is intended to become the main auditorium in the region for repertoires before the 19^{th} century, choral and small instrumental ensembles.

The architectural project also involves the construction of a new building (public entrance) and the refurbishment of an adjacent building (offices and dressing rooms).

Acoustic predictions will of course be pursued during the subsequent design and construction phases. Acoustic testing with several musical ensembles will also be planned before the beginning of the construction works in order to precisely refine the acoustic solutions also from subjective impressions and criterions.

Figure 6: Rendering of the *Chapelle Corneille* in its future state, with the rotating canopy in its spherical mirror mode.

The very sensitive architectural context of this competition was a perfect illustration of the interest of solid angle based methods for the prediction of early reflected energy in concert halls. These methods allow a very dynamic collaboration with the architects in developing acoustic designs that blend well 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.

References

[1] M. Barron, L-J. Lee, “Energy relations in concert Auditorium.I”, *J. Acoust. Soc. Am.* 84(2), 618-628 (1988)

[2] J. H. Rindel, "Attenuation of sound reflections from curved surfaces", Proceedings of 24th Conference on Acoustics, Strbské Pleso, 194-197 (1985)

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