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CREATIVE POSSIBILITIES AND LIMITATIONS OF CURVED SURFACES IN THE ACOUSTIC DESIGN OF CONTEMPORARY AUDITORIA

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Contemporary "freeform" architectural spaces often exhibit large areas of concavely and convexly curved surfaces (walls, ceilings). Interestingly, many historic halls - some of them acoustically highly successful - also feature concave surfaces such as domes, barrel vaults and apses. Considering room acoustics quality, curved surfaces strongly influence how incoming sound waves are reflected: convex surfaces weaken the strength of the reflections due to divergence, while concave surfaces create local sound amplification due to focusing, often in combination with unwanted flutter echoes. Due to the complexity of predicting the acoustic behaviour of concave surfaces, their full creative potential for architectural design is often not fully explored. However, when using appropriate 2D or 3D geometrical acoustic approximations, it is possible to predict the acoustic behaviour of curved architectural designs with sufficient confidence to use them in an acoustically creative way. A summary of design concepts and analysis techniques for curved surfaces is presented, illustrated by case studies of both historic halls with curved surfaces (including Wigmore Hall, London; Kulturcasino, Bern; La Monnaie / De Munt Opera, Brussels) and new build halls where the creative use of curved surfaces has been successfully applied, including the new Musikforum concert hall in Bochum; the new Comédie theatre in Clermont-Ferrand and the new Opera House in Fuzhou.
Keywords: acoustic focusing, concert hall acoustics, auditoria design

1. Introduction

A major element of room acoustics design, particularly for auditoria, is the control and optimisation of reflections to the audience and performers. While the reflection from flat surfaces is well researched and very predictable, curved surfaces present additional complexity. Convex surfaces always create divergence and therefore attenuation of the reflected sound energy density in comparison with a flat surface. Concave surfaces are more complex: they always create convergence of sound energy and therefore amplification of the reflected energy density (compared to a flat surface) near the focal point or zone, but also attenuation in other areas (further away from the focal point). Due to their complexity and the hitherto lack of straightforward analysis techniques for concave surfaces, along with the associated acoustical risks (uneven sound distribution, strong hot spots, flutter echoes, colouration of tone), they are often excluded from room acoustic design, despite many historic precedents where focusing leads to positive acoustical effects. It is shown in this paper that sufficient knowledge is available to study and control the behaviour of curved surfaces and to exploit their potential in contemporary room acoustics design.

Cremer (Ref. 1) has given an in-depth overview of the qualitative behaviour of curved surfaces, while Rindel (Ref. 2) has defined the term ΔL_{curv} which allows quantification in dB of focusing or attenuation resulting from a given curved surface for a given source and receiver location. Positive values denote amplification of sound compared to a flat surface at the same distance, while negative values indicate a local attenuation of sound (Ref. 3). In an earlier paper (Ref. 4), a differential ray-tracing method to calculate ΔL_{curv} using NURBS based 3D modelling software was proposed. Despite the obvious limits associated with this purely geometrical method (absence of wave phenomena and frequency dependency, discussed in more detail by Vercammen in (Ref. 5)), it is possible to explore curved geometries and to gain valuable insight into their acoustical behaviour, sufficient to inform creative acoustics design.

2. Historic precedents of auditoria with curved surfaces

There are many examples of successful historic halls with concave surfaces. In the following sections two representative typologies are discussed: horseshoe shaped opera houses and rectangular halls with concave ceilings.

2.1 Horseshoe shaped opera houses

The majority of historic opera houses in Europe and elsewhere in the (western) world are based on the Italian style "horseshoe" paradigm with concave balconies wrapping all around the auditorium. Typically, both the balcony fronts and the enclosing walls of the auditorium are concavely curved, providing many opportunities for focusing of sources both on stage and in the orchestra pit. Nevertheless, most of these opera houses are praised for their good acoustics, and only rarely is focusing mentioned as being problematic. Halmrast (Ref. 6) has reported on image shifts (phantom images) and undesirable delays/echoes for certain instruments in specific seats due to concave surfaces (e.g. Munich Opera House), but also acknowledges that their overall effect is beneficial in most opera houses by for instance broadening the apparent source width of the orchestra in large parts of the audience. This effect can be clearly heard in the Copenhagen Opera House in the rear part of the parterre.

One of the main reasons why concave balcony fronts are less problematic in 3D reality than a 2D raytrace of their plan shape might suggest, is the fact that for most natural opera sources the focal points arising from first order reflections off the balcony fronts lie well above audience head height; as long as the audience is located far enough from these focal points, no problems due to focusing are expected and the focusing may in fact contribute to a better spreading of sound across the audience plane. It is typically after "downkicking" by ceilings and soffits that focusing can occur in the audience plane (e.g. 2nd order reflections from a concave wall and balcony soffit above; or 2nd order reflections off orchestra pit reflector in combination with balcony front).

In addition, some well-regarded horseshoe opera houses feature a large concave dome (e.g. La Monnaie / De Munt in Brussels and Opéra Garnier in Paris, both dating from the 2nd half of the 19th Century), further multiplying the possible paths for focusing. If similar designs were pursued nowadays, today's acoustics community would clearly consider them to be very risky. However, mainly positive evaluations have been reported (e.g. Beranek (Ref. 7) for Opéra Garnier), without mention of negative effects.

In this context it is instructive to carry out a 2D raytrace and ΔL_{curv} calculation of the long section of La Monnaie (see Figure 1). For a typical string source in the orchestra pit, a well-defined area of the dome creates significant focusing (5 to 6dB amplification relative to a flat ceiling) in the middle of the parterre and in the first balcony. In these locations the focusing produces a pleasant amplification of the string treble sound, which would otherwise be blocked by the pit rail, but indeed the "price to pay" are orchestra balance problems for seats off centre. For a singer on stage, the effect is even stronger (up to 10dB amplification) with the focusing beams shifted further back, towards the 1st and 3rd balcony respectively. In the front row of the 1st balcony focusing effects can indeed be heard that can be considered to be over the limit of acceptability. Via 2nd order reflections from the balcony fronts, the beams reach the rear of the parterre. Perhaps due to diffusion by the heavily decorated balcony fronts, this focusing – whilst occasionally audible as an image shift or a "moment of unbalance" - is not considered to be problematic in the overall acoustic assessment of

La Monnaie, but is on the limit of acceptibility. It should rather be noted that the rear curved "corner" of the dome creates a broad spreading of the first order reflection over the entire parterre and to the orchestra pit. With ΔL_{curv} in the range -9 to -7dB, this reflection is sufficiently weakened by the strong curvature (once beyond the focal point) to not be perceived by the audience as a disturbing late reflection.

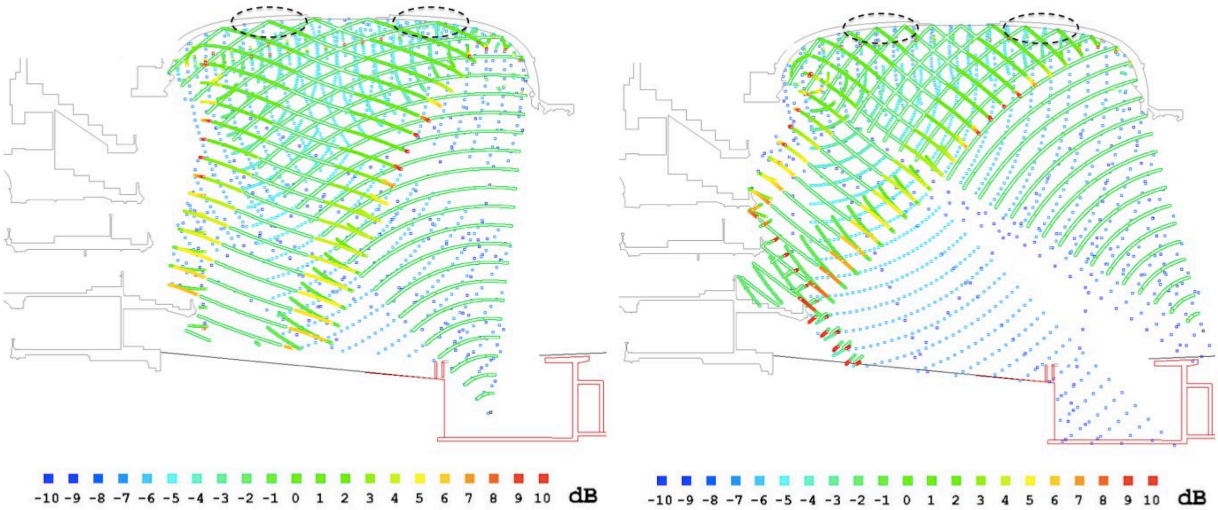

Figure 1: Long-section showing the focusing effect of the dome of La Monnaie opera house, for a source in the orchestra pit (left image) and on stage (right image). The parameter plotted is ΔL_{curv}. The parts of the dome creating the strongest focusing in the audience are indicated by dashed ovals.

2.2 Rectangular concert halls with a concave ceiling

Although "shoebox" halls are generally considered to have a flat ceiling, a significant number of rectangular concert or recital halls featuring some form of concave ceiling (full or partial) were built in the 19th and early 20th Centuries. The 550-seat Wigmore Hall (Ref. 3) in London (1901) has an excellent reputation for chamber music despite its multiple concave surfaces (the ceiling has an elliptical cross-section and the cylindrical stage apse is topped by a quarter dome). The 1300-seat Kulturcasino in Bern (1908) is similar in form to the Tonhalle in Zürich and other halls throughout Europe in having a flat parterre and a narrow raised stage at one end, surrounded by gallery seating on four sides. Bearing similarities to Wigmore Hall, the ceiling of the Kulturcasino is concave in cross-section (with a varying radius of curvature), and above and behind the choir the ceiling is double-curved with different and varying radii of curvature in plan, long-section and cross-section. The ceiling curvature leads to a number of effects – both subjectively positive and negative – that are typical acoustical traits of such halls.

Acoustical analysis of the concave ceilings of Wigmore Hall and Kulturcasino illustrates that the concave ceiling produces mild focusing for stage sources towards the parterre (i.e. a positive effect), combined with a few "focal lines" of strong focusing (negative effect). Figure 2 shows a 3D ray-trace of the ceiling at the Kulturcasino: calculation of ΔL_{curv} indicates values typically between 1 and 3dB at Kulturcasino and 3 to 6dB at Wigmore Hall. These are considered beneficial amplifications, although at Wigmore Hall the amplification is on the limit of being too strong near the centreline, as witnessed by the historic removal of the frontmost "laylights" (Ref. 3). At Wigmore Hall, the focusing zone is also significantly less wide compared to Kulturcasino, and only covers the central 1/3rd of the stalls width. For this reason, it could be said that the focusing is globally more favourable in Kulturcasino than in Wigmore Hall. In both halls, due to the gradually changing local radius of curvature of the ceiling, for any source on stage there will be certain areas of the ceiling that have a focal point in the audience and result in maximum amplification. This so-called "residual strong focusing" is sometimes audible and could be considered as a negative artefact of such concave ceilings – in other cases the area of the strong focussing is so small that no audible effect is encountered.

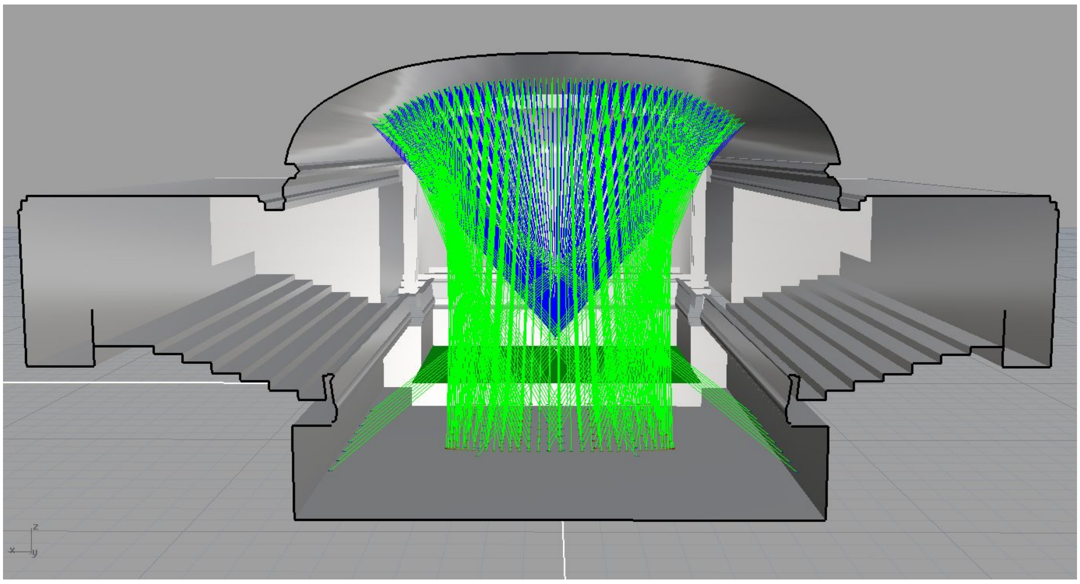

Figure 2: 3D raytrace of the concave ceiling of Kulturcasino, Bern (cross-section view), showing that a large portion of the parterre width is covered by mild focusing from the ceiling.

Another noteworthy finding in Wigmore Hall is that strong focusing occurs from the side portions of the concave ceiling to the rear balcony and results in amplification of these lateral reflections. This contributes towards the strong loudness and source broadening perceived in the balcony, but it is often accompanied by image shifts, where the source image is pulled up from stage, along with a distinct tone colouration.

Finally, an important feature of both Wigmore Hall and Kulturcasino that is loved by musicians on stage (but often ill-regarded by acousticians) is the strong and delayed return of reflections to the stage. In Kulturcasino this happens through a late and focused 2nd order reflection from the audience rear wall and the concave ceiling. It is one of the few reflection paths back to stage that provides the musicians with a sense of "hall response". In halls where such reflections are absent or weak, musicians often complain that they feel detached from the hall. So, although this reflection is strengthened (typically ΔL_{curv} is 1-3dB, in some cases higher) and late (delay 150-170ms), only with strongly transient sounds is it experienced as an echo. The sense of hall response provided by the reflection can be considered a positive acoustical feature of the room. A similar effect occurs in Wigmore Hall: due its flat audience parterre, the rear audience wall is relatively exposed – slightly focused reflections from the circular apse wall behind the stage are reflected from the rear wall back to the stage (Ref. 3). Live testing with a full audience and musicians in 2003 of a mock up of the then planned gentle rake to improve sightlines caused certain musicians to express a significant degradation of the hall support, after which the idea of raking the audience was abandoned.

It is unknown to what extent these historic vaulted halls were designed with acoustics in mind. However, the authors believe that historic selection has played a major role in the survival of only the "fittest" of these concert halls, the biggest acoustic failures having been demolished over time.

In any case, during the course of the 20th Century, curved surfaces mostly disappeared from new built (concert) halls due to changes in architectural style, and evolution of economic and functional needs. Many of these 20th Century "straight" halls are considered acoustically mediocre, and their architectural merit is often questionable.

3. Contemporary auditoria with curved surfaces

With the advent of freeform 3D architecture at the turn of the 21st Century, curved surfaces have been gradually finding their way again into contemporary auditoria design, pushing the boundaries for appropriate acoustic analysis and design techniques. With both the useful and negative acoustic effects of concave surfaces in historic precedents in mind, due thought needs to be given to using concave (as well as convex) geometries in the design of new concert, opera and theatre halls. The aim is to utilise the positive effects (i.e. gentle amplification of reflections) whilst minimising the negative side effects (strong residual focusing, flutter echoes and colouration). The following examples illustrate this design approach.

3.1 Musikforum Bochum

The Annelise Brost Musik Forum opened in 2016 and is the new home for the Bochumer Symphoniker. At the competition stage (2012) the design had initially started off as an “ordinary” 950-seat shoebox concert hall, based only on straight lines (with the exception of the concave upstage wall). When chief conductor Steven Sloane expressed his wish for a more intimate room, with more character and a stronger connection between audience and orchestra, architects Bez + Kock responded with a more rounded room shape in plan (see Figure 3). The curves in plan were all based on two centre points: one at the conductor’s position governing the curves in front of the stage, the other in the middle of the parterre for the curves behind the stage. Needless to say that such a geometric arrangement is a challenging starting point acoustically – at least when considered purely in 2D plan, with strongly focused first order reflections from the walls and balcony fronts back to stage .

Rather than fighting the architectural concept, the focusing on stage was solved in 3D by breaking up in plan some of the curves into a number of segments, by optimising the radius of curvature of each segment, and by angling the segments in section in order to send the focal points safely above the heads of the musicians. All optimisations were carried out by means of parametric modelling in Rhino/Grasshopper (Ref. 8, 9) with real-time monitoring of the focusing behaviour and amplitude up to 3rd reflection order. Some balcony fronts were also given a convex shape in section in order to distribute the sound energy to alleviate focussing hot spots and eliminate flutter echoes.

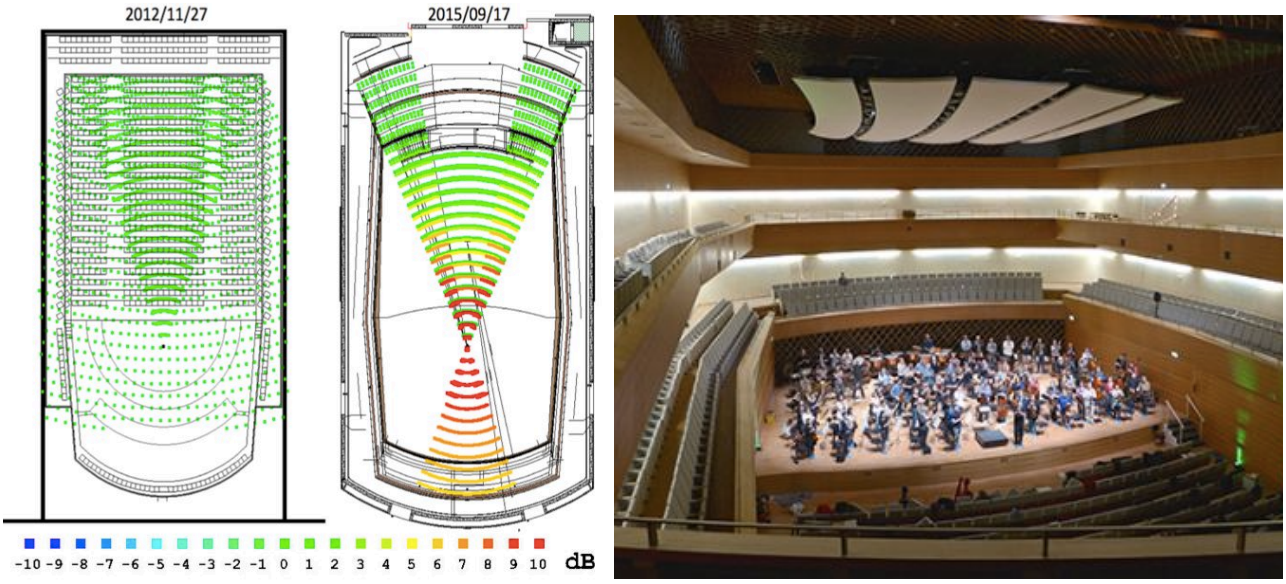

Figure 3: From left to right, evolution of the plan shape of Musikforum Bochum between competition phase (2012) and executed design (2015) with indication of the theoretical 2D focusing amplitude; the first test concert (2016) confirmed that any issues of focusing had been solved in 3D reality.

In addition, careful attention was given to the design of the double curved *convex* canopy above the orchestra, using parametric modelling and real-time acoustic analysis of all curvatures, in order to obtain good coverage patterns for the entire orchestra.

3.2 Comédie, Clermont-Ferrand

For the 900-seat theatre of the future Comédie in Clermont-Ferrand (planned to open in 2019), architect Souto De Moura envisioned a contemporary interpretation of the Italian theatre paradigm: a room consisting of curved bands topped by a dome. Full freedom was given to the acousticians to shape the inner dome on acoustic grounds. Multiple dome designs were explored through parametric modelling; the finally adopted geometry consists of a surface of revolution based on two circular arcs with different radii of curvature: the radius of curvature of the central part of the such obtained dome is approximately 49m, with a focal point well below the audience plane and creating only a mild degree of focusing (ΔL_{curv} approximately 3dB) in the rear half of the parterre; the "rim" of the dome has a radius of curvature of less than 8m, which ensures that the focal points are sufficiently high above the audience. By utilising a geometry with only two radii of curvature, where the two arcs join at a tangent,, the range of dangerously focusing radii of curvature is avoided. Figure 4 shows the concept of the dome and the corresponding raytracing and focusing amplitude.

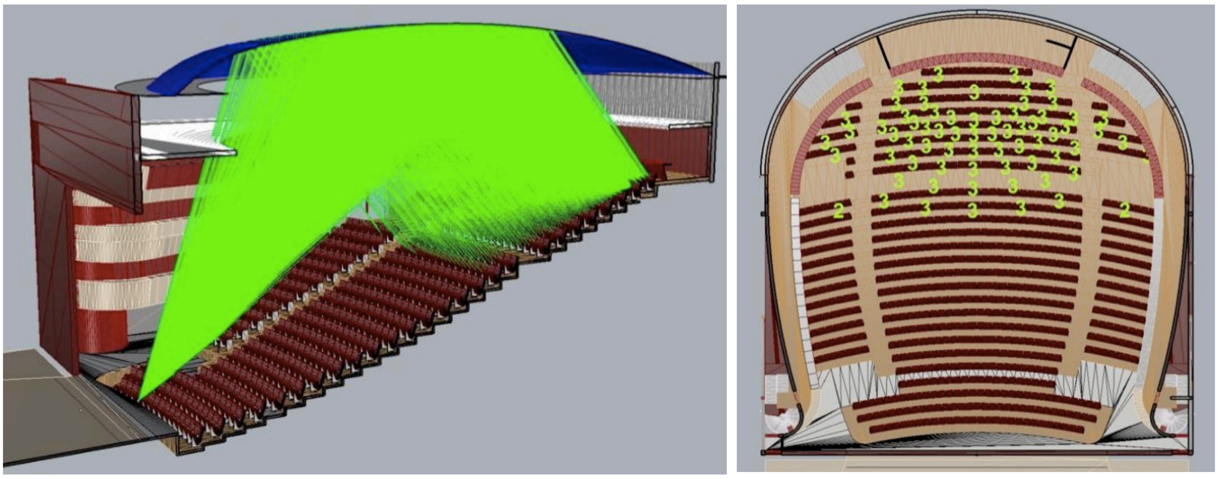

Figure 4: 3D raytrace of the proposed dome of the new Comédie of Clermont-Ferrand for a source near the stage edge, with indication of the focusing amplitude (in dB) in the rear half of the parterre.

The architectural bands wrapping around the entire auditorium have been shaped in plan and inclination through parametric modelling,. The acoustic design aim was to go beyond avoiding problems that may arise from the concave parts of the bands and, where possible, to take advantage of them in optimising the early reflection coverage across the audience. Figure 5 shows the reflection coverage resulting from the bands in combination with the dome up to 3rd reflection order. It can be seen that no strong focusing exists, other than the intended controlled focusing towards the rear of the parterre.

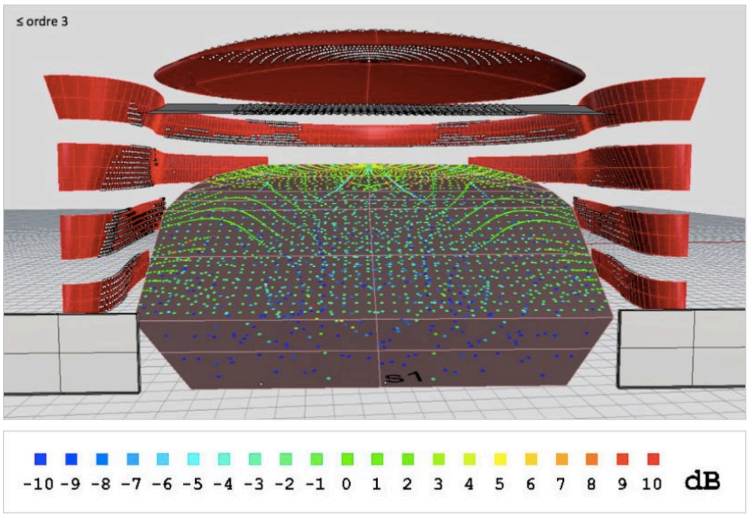

Figure 5: combined focusing study of the proposed bands and dome of the Comédie, showing the reflection coverage for reflections up to 3rd order, for a source 3m behind the stage edge.

3.3 Opera Hall of Fuzhou SCAC

The 1660-seat Opera Hall of the Fuzhou SCAC (Ref. 9), currently under construction, is designed according to the acoustic principle of combining sufficient reverberation with high musical clarity, applied to a freeform architectural shape. The complex 3D side walls of the auditorium have been carefully shaped in close collaboration with PESark architects to optimise the coverage of early lateral reflections towards the audience in the parterre and on the balconies. Convex and concave curvatures have been combined into a unique wall sculpture that behaves like a large acoustic reflector, with a particular attention paid to eliminating too strong focusing. See Figure 6 for a typical 3D raytrace analysis.

The proscenium walls combine large lighting/loudspeaker pockets with efficient acoustic wall zones to create early lateral reflections from the stage to the parterre. In combination with the orchestra pit reflector, this ensures excellent projection of sound from the singers to the audience.

Certain parts of the wall geometry that create too strong late reflections will receive a pseudorandom diffusion pattern (microshaping), softening those reflections to make sure that distinct echoes are inaudible.

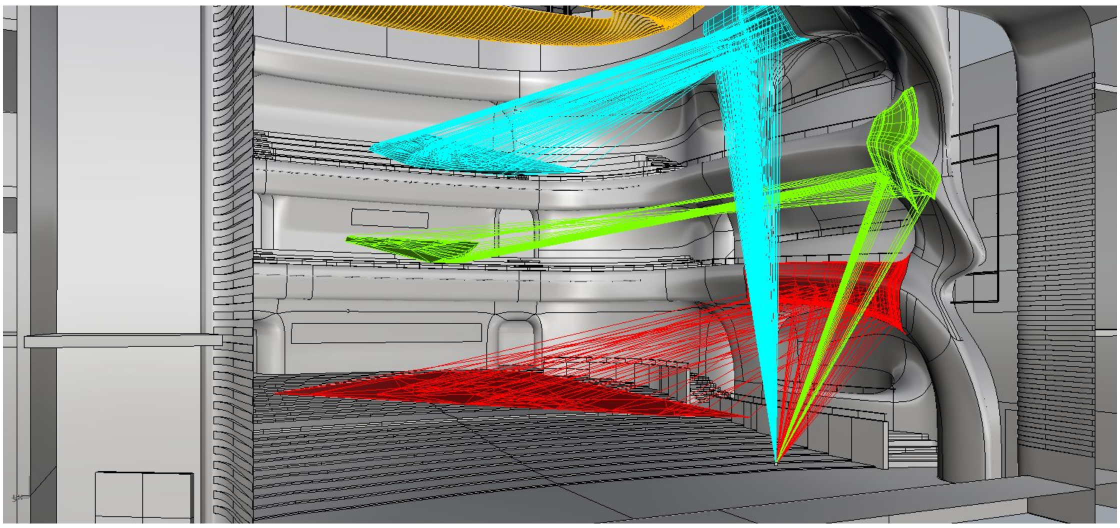

Figure 6: excerpt of 3D raytracing study in Rhino/Grasshopper of the acoustic shaping of the freeform walls of the Fuzhou Opera House.

3.4 Kraakhuis at De Bijloke, Ghent

Another interesting use of focusing is to locate (variable) acoustic absorption in an area of focusing, maximising the efficiency of the absorption. This was done in 2011 in the 16th Century Kraakhuis chamber music hall, where motorised vertical absorption banners were installed below the centre line of the vault, allowing an efficient adaptation of the RT between 1.3 and 1.8s.

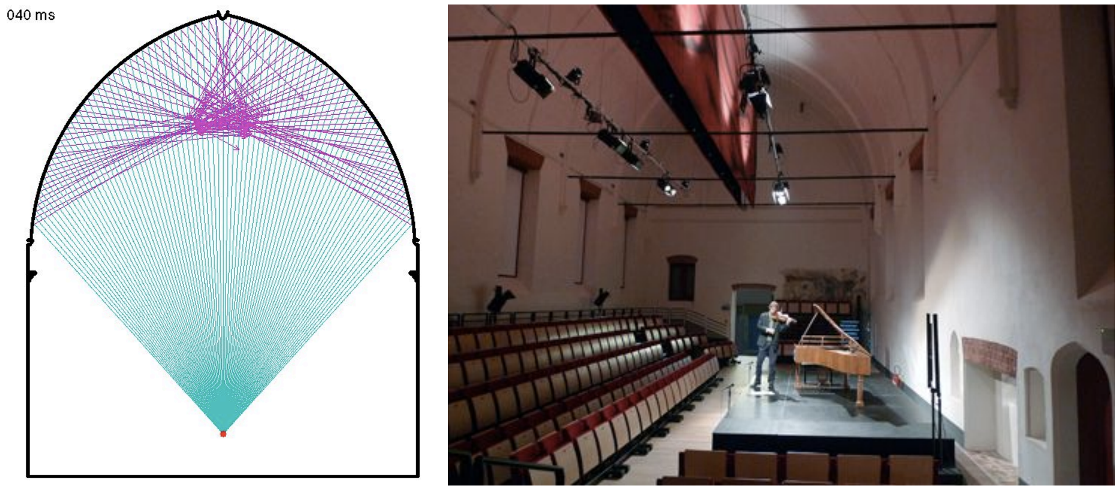

Figure 7: variable absorption located in the focal point of the vault of Kraakhuis, Ghent.

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