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Acoustic optimization of curved architecture in practice: the new Straight Cultural Arts Center in Fuzhou

Yann JURKIEWICZ[1] Henrik MOLLER[2] Thomas WULFRANK[1] Jingbo WANG[3] Eckhard KAHLE[1]

[1] Kahle Acoustics Sprl., Belgium

[2] Akukon Ltd., Finland

[3] TongJi Architectural Design Group Co.,Ltd, China

ABSTRACT

October 2018 saw the inauguration of a new cultural center in Fuzhou, China. The complex consists of 5 buildings, including a 800 seat multipurpose hall, a 1700 seat opera hall and a 1000 seat symphony hall. The design of both the symphony and opera halls was entirely based on curved surfaces, both convex and concave, covered with local ceramic tiles. Providing the right amount, distribution and quality of early reflections thus required a precise analysis of the acoustic behavior of curved surfaces. The acoustic design interacted with the architecture in precisely shaping those curves in 3D. In order to explore the acoustic potential and detect problems related to the architectural concept of both rooms, novel geometrical acoustics analysis algorithms were developed within NURBS modeling software. Optimization of the curved surfaces results from a meeting of minds between the output of these algorithms, the interpretation of the acoustic consultant, and the required integration of acoustic solutions within the global architectural concept and building design.

The analysis procedure and geometrical acoustics algorithms used in both rooms will be presented in detail, as well as the related decision-making process, the acoustic predictions and the measurement results of the three built halls.

Keywords: Curve, Reflection, Optimization

1. INTRODUCTION

The Strait Cultural Center in Fuzhou, China was completed in the fall of 2018. The complex consists of 5 buildings; a 800 seat multipurpose hall, a 1700 seat opera hall, a 1000 seat concert hall, an exhibition building and a cinema center.

The complex was designed by PES Architects after winning an architectural competition in 2013. The exterior cladding, as well as the interior cladding of the concert hall and the opera hall, is made of ceramic tiles, which is a traditional handicraft of the area.

For the acoustic design, cooperation was established between the acoustic team of Tongji Architectural Design Group Co.Ltd (TJAD), Kahle Acoustics s.p.r.l and Akukon Ltd. Akukon was responsible for the design contact to the architect and for the design of the Multipurpose Hall, Kahle Acoustic was responsible for the design of the opera hall and the concert hall and TJAD was responsible for sound isolation structures, noise control, Odeon simulation analysis of opera hall and concert hall and site supervision. However it is clear that a proper cooperation means that all participants had inputs to all parts of the design, in order to ensure that the whole team aims for the same goal.

The very innovative architectural concepts proposed for the concert hall and opera hall, entirely based on curved surfaces, required the implementation of a specific acoustic design methodology.

[1] yann@kahle.be
[2] henrik.moller@akukon.com
[3] jbwang827@163.com

While traditional acoustic modeling software keep on being restricted to flat surfaces, such projects exemplify the need for time efficient methods for analyzing, tweaking and sculpting curved surfaces in contemporary architecture. Two complementary methods were developed previously to deal with such cases of complex and/or new geometries: differential raytracing algorithm (1), and early acoustic efficiency (2). Both methods have played a key role in the design of the new concert hall and opera hall in Fuzhou, driving the acoustic design and feeding architectural creativity.

2. Acoustic design of the concert hall

The symphony hall counts a total of 1000 seats, including a few rows of choir or audience seating behind the orchestra. This relatively small seat-count may seem contradictory to the large stage platform, fitting a full symphony orchestra of more than 100 musicians. And a full organ also equips the hall. In order to avoid overly loud acoustics, the acoustic volume was increased much further than the traditionally advised ratio of 10 cubic meters per audience member. The total volume is finally 17'000 m3, similar to that of a medium sized symphony hall, and absorptive acoustic banners are provided so as to tune the reverberation time.

Multiple reflectors suspended under the ceiling (*pendulums*) create a visual and acoustic boundary between a lower main volume and an upper coupled volume. The many smaller pendulums are strongly curved convexly so as to create a homogeneous coverage of low energy early reflections, while 5 larger pendulums of slighter convexity are grouped above the stage to shape a canopy.

But it is the plan shape of concert hall that provides the largest share of early reflections. The hall is entirely shaped out of large portions of spheres. All wall surfaces are convexly curved in the shape of petals, compensating for the general elliptical plan shape of the room.

Figure 1 – Pictures of the vineyard-shape new concert hall in Fuzhou

Like in many vineyard-type concert halls, the separating walls between each terrace of audience are inclined vertically to direct early reflections. The particularity of Fuzhou concert hall is an additional set of inclined walls at the periphery of the room. The large size of those outer "petals" is acoustically advantageous in terms of providing wide band early reflections. But it is also hazardous with regard to late echoes.

The distribution and orientation of the acoustic petals in plan provide lateral reflections to all audience blocks. The appropriate tilt angle for the petals was then validated based on the early acoustic efficiency approach (2). Starting from the architects' first intentions, several different tilt angles of the outer petals have been tested. In all cases, only a small area located on the lower half of each surface effectively generates early reflections, while the upper part of the petals sends acoustic energy across the room, generating late reflections. Increasing or decreasing the tilt angle only moves these areas up or down. But in doing so, the tilt also impact the average angle of incidence of early reflections on audience planes and the efficient solid angle, whose influence on mean early and late acoustic strength has been demonstrated (3). By coincidence, it turned out that the architects' initial proposal provided the best compromise, as can be seen in table 1. Further increasing the tilt angles would have increased the total efficient area and efficient solid angle, but not the early strength as the average angle of incidence of early reflections on audience planes decreases in parallel with an even greater negative impact.

Appropriate echo control then requires that a diffusive treatment be applied to the potentially harmful portions of the petals. In such cases, it is commonly decided to generalize the diffusive treatment to the entirety of the surfaces involved. But recent findings on the potentially negative effects of acoustic diffusion (4, 5) have led the design team to consider another way forward that would allow to preserve specular early reflections.

Table 1. Results of early efficiency calculations in Fuzhou Symphony Hall for several tilt angles of the outer petal-shaped walls (the rest of the hall reaming unchanged). Angle values are given with respect to the architects' initial intentions. Efficiency parameters are defined in (3).

	-15°	-10°	-5°	0°	+5°
Efficient area (m^2)	374,4	389,9	429,6	466,8	493,9
Efficient solid angle (str)	1,68	1,80	1,86	2,07	2,15
Gem (average early strength, dB)	-1,5	-1,1	-1,0	-0,8	-0,9
Glm (average late strength, dB)	3,5	3,5	3,4	3,3	3,3

A specific "wallpaper" algorithm was developed in order to identify which parts of the acoustic petals are efficient in providing early reflections, and which generate late reflections. The algorithm is based on raytracing from 4 different source positions distributed over the stage platform, aiming towards the face centers of the finely facetted reflective surfaces. Acoustic rays are followed until 4th order or until they hit an audience plane. For each source point, each facet (of approximately 0.12m^2) is categorized depending on the delay of the reflection it may generate. 7 times slots were defined ranging from < 20 ms to > 200 ms. A two-stage human decision-making then allows to assigns to each facet the appropriate acoustic attribute.

In the first stage, based on the output of the algorithm it is decided for each source point separately which facet should ideally have a rough surface texture or not. The output of that first stage is illustrated on figure Figure 2 for one example case. In the second stage, the results obtained for each source positions are combined. Whenever contradictory, it is once again a human decision that allows to resolve the issue. The final output is a mapping over each reflective surface in the model of the zones that need to be flat and specular reflecting, zones that need to have a rough and acoustically diffusive surface texture, and those that can be both indifferently. In close collaboration with the architects, a non-homogeneous surface texture pattern of strictly limited scope was finally designed, using ceramic tiles of either flat or bumpy pyramid shape.

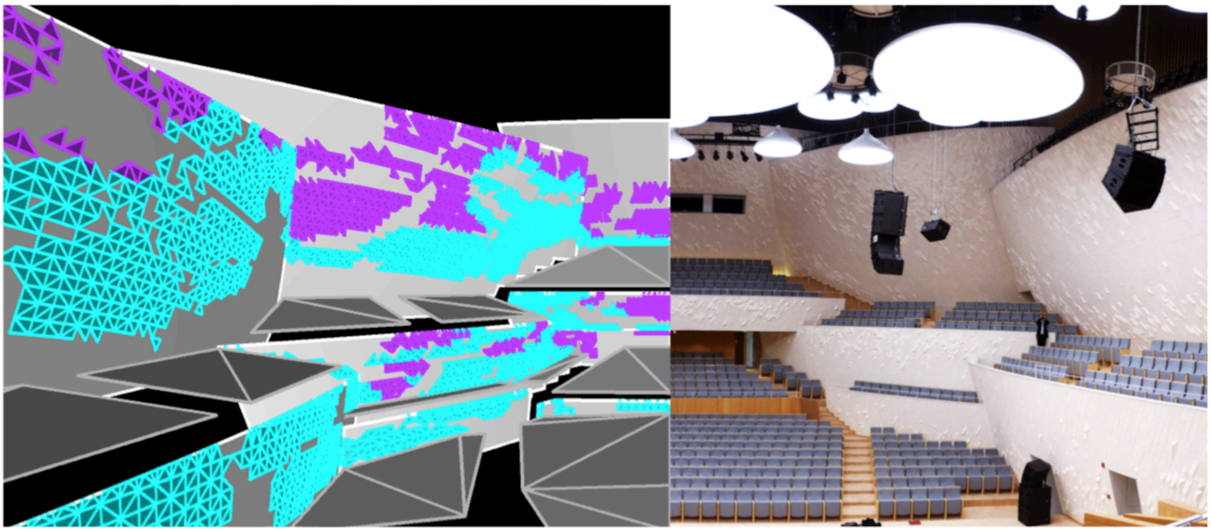

Figure 2 – Split-view of Fuzhou concert hall from the choir balcony, cut along its symmetry axis.

The left-hand half is extracted from the computer model and depicts the output of the wallpaper algorithm for a source position downstage on the room axis. Triangular facets colored in cyan locate areas of the curved wall surfaces creating useful early reflections for this specific source position, which should ideally be flat. Facets colored in purple located areas creating potentially harmful late reflections, which should ideally have a rough surface texture.

The right-hand half is a picture of the built concert hall taken from a similar viewpoint.

3. Acoustic design of the opera hall

The 1600-seat opera hall of the Fuzhou SCAC was designed according to the same acoustic principles as the concert hall (i.e. sufficiently strong reverberation combined with high musical clarity), applied to a “freeform” horseshoe auditorium with two balconies.

The first requirement was to achieve an appropriate acoustic volume for opera performances. The design goal was set to minimum 8.5 m^3/seat. This is in line with contemporary thinking for opera house acoustics, favoring slightly longer reverberation times compared to the historic opera references, as confirmed in recently completed opera buildings, e.g. Oslo Opera House (6). By coupling the volume above the acoustic ceiling reflectors into the main audience chamber, a total acoustic volume of 14’500 m^3 was obtained, corresponding to 9 m^3/seat. The design target for the occupied mid-frequency Reverberation Time was set at 1.5 seconds for unamplified opera.

The second requirement was to obtain a homogeneous coverage of strong early lateral reflections towards the entire audience, both in the parterre and on the two balconies. To this end, the complex walls, balcony fronts, soffits, columns and proscenium zone have been carefully shaped in close collaboration with the architects and blended into a curved 3D wall sculpture. Convex and concave curvatures have been combined together to form a large and efficient acoustic reflector whilst avoiding undesirable focusing effects due to the curved geometry. The iterative design process included many cycles of acoustic analysis of the curved sculpture: identify the portions that create focusing reflections for certain combinations of stage/pit sources and audience zones, quantify the strength of the focusing, optimize the shape by major reorientation, “ironing out” or “inflating” of certain portions until a suitable reflection coverage was obtained. In doing this, a NURBS-based differential raytracing technique (1) was used allowing time efficient calculation of the occurring focusing effect with good approximation. Figure 3 shows an example of this optimization process for a given portion of the reflective 3D wall sculpture. The proscenium walls are also specially designed to combine large lighting/loudspeaker pockets with efficient acoustic wall zones creating early lateral reflections from the stage to the parterre, contributing significantly to the good projection of sound from the singers to the audience.

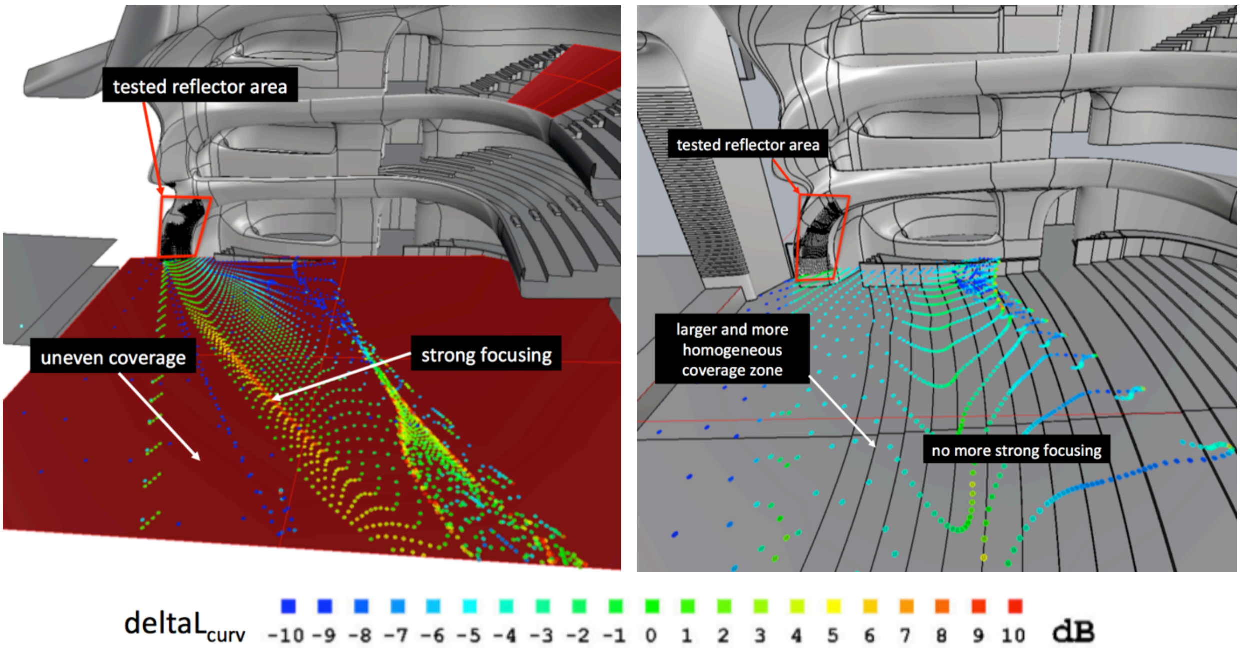

Figure 3 – Example of the 3D optimization process for a given portion (indicated by the red rectangle) of the reflective sculpture, for a downstage source position.
Left: before optimization – although the overall orientation of the studied reflector portion is already suitable, its curvature is not yet acceptable, as the coverage is uneven and shows areas of strong focusing (orange and red dots).
Right: after optimization – after subtle corrections of the surface curvature in 3D, a larger and more homogeneous coverage is obtained without focusing.
The indicated parameter is $deltaL_{curv}$ (3). The reflected rays are not shown for clarity

On top of the large-scale acoustic wall sculpture, a fine-scale texture pattern was applied, in the form of 8 mm thick, flower-shaped ceramic tiles (Figure 4), creating significant diffusion only at high frequencies (≥ 8 kHz) in order to avoid any harshness that could arise from flat ceramic surfaces.

The ceiling was also optimized acoustically: the ceiling reflector above the orchestra pit and the integrated reflectors below the main lighting bridges are shaped to complete the early reflection coverage to the audience and to the musicians in the orchestra pit. In addition, the ceiling was made partially open (around and in-between the acoustically efficient parts of the ceiling reflectors) in order to couple the upper acoustic volume above the reflectors to the main acoustic volume.

Variable acoustic curtains located in the upper part of the room allow adapting the reverberation time to the use of the opera hall. The rear wall of the orchestra pit also has an acoustic curtain in order to allow tuning of the orchestral balance inside the orchestra pit.

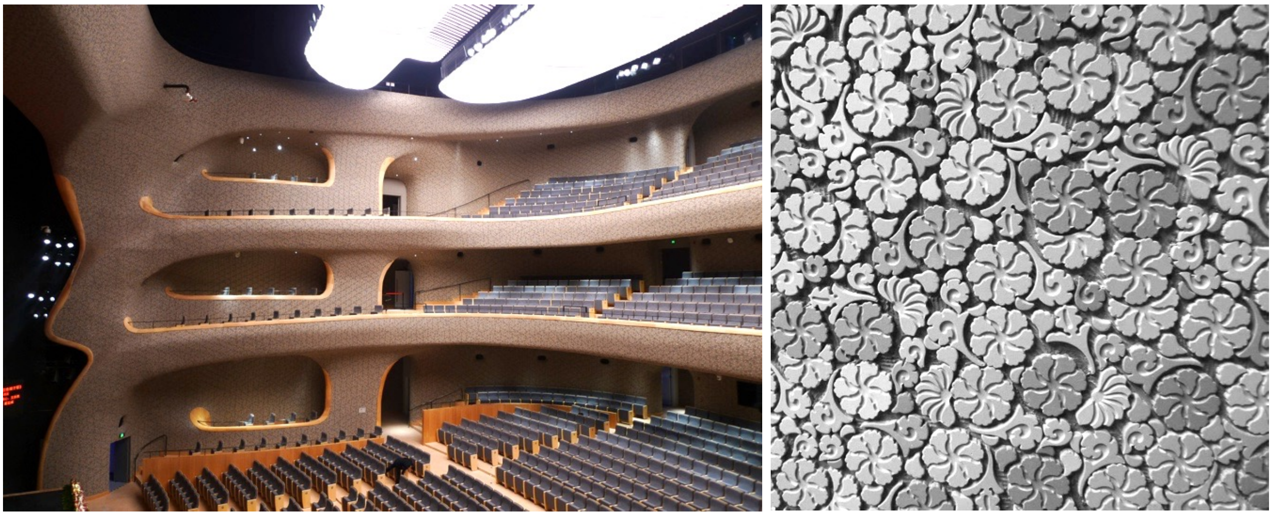

Figure 4 – Left: View of the built complex curved wall "sculpture" that creates a good coverage of early lateral reflections in the entire audience. Right: Close-up of the 8 mm thick flower shaped ceramic tiles that create diffusion at high frequencies only.

4. Acoustic design of the multifunctional hall

The hall has with fixed seating on the side and rear balconies and retractable seats on the main parterre. It is basically shoebox shaped.

Figure 5 – Picture of the built multipurpose hall

The surfaces of the multipurpose hall are mainly compressed Bamboo wood, made as "bands" both in small scale and in large scale. The seats are medium upholstered, with about 30 mm upholster on the backrest and about 50 mm on the seat. The bottom of the seats are perforated.

The Multipurpose hall was designed without the extensive variable acoustics normally associated with these types of halls. As the complex also contains both a concert hall and an opera hall, it was decided in discussions with the architect and the client that the acoustic conditions of the multipurpose hall should be fixed and more like a theater and in general optimized for sound reinforcement.

Absorption surfaces were planned on the lower parts of the sidewalls, which would be exposed when the retractable seating was retracted, on the ceiling surfaces of the balconies and on the upper ceiling surfaces.

5. Measurement results of opera hall and concert hall

With the groundbreaking held on May 2015 marks the start of construction on this prestigious project, the construction of the whole building was finished on August 2018, the multi-purpose hall, opera hall and concert hall were scheduled opening on October 2018. TJAD acoustic consultants undertook the commissioned acoustic measurement including of multi-purpose hall, opera hall and concert hall in unoccupied condition on September 11 to 12, 2018, and the measurement of opera hall, concert hall was carried out again in unoccupied and occupied condition on March 20, 2019.

Impulse responses were measured using Dirac room acoustic measurement software, omni-directional loudspeaker pyrite os12 as source, multi-directional microphone was used for measurement of main parameters with omni-direction, and for measurement of lateral energy fraction with figure-of-eight direction. Part of results of the measurements on the mentioned two phases is shown below.

Table 2. the measurement results of opera hall under unoccupied & occupied condition

index	condition	mid frequency of octave band					
		125	250	500	1k	2k	4k
T30/s	unoccupied	2.07	1.65	1.70	1.60	1.65	1.40
	occupied	1.86	1.62	1.56	1.51	1.47	1.41
EDT/s	unoccupied	1.87	1.64	1.55	1.66	1.64	1.35
	occupied	1.88	1.69	1.55	1.54	1.58	1.25
C80/dB	unoccupied	0.08	0.59	1.40	1.34	1.66	2.62
	occupied	-0.68	0.83	0.56	1.37	1.22	2.70

The results are consistent with the design target, and are in line with the Odeon simulation results by TJAD acoustic consultant. In the opera hall, absorptive curtains were all unfolded in the same state during unoccupied & occupied measurement conditions, which was also beneficial for the amplified performance taking place that test night. The occupancy rate was 60% approximately. It can be deduced that the RT can be a bit longer when the curtains are folded, which is favorable for natural sound music performance, including the philharmonic concerts housed in the opera hall.

In the concert hall, depending on the amount of absorptive curtains deployed, the amplitude of variation of mid-frequency RT on the unoccupied is 0.7s, which is the suitable and satisfied criteria. The relative flat spectrum of RT is not a bad situation. It is rather favorable for giving a very clear and precise acoustics suitable for classical and 20th century repertoire. Clarity, EDT and LF are all within the expected design target, and are corresponding to excellent values, rather homogeneously spread over the entire audience area. During the occupied measurement, the acoustic curtain was lowered in a specific amount for the piano recital, the occupancy rate is 40 percent approximately. In general, flexibility in acoustics is the distinct feature of this middle scale concert hall, from full orchestra to chamber music, natural sound to amplified performance, objective measurement results are in line with the design targets, and the excellent acoustic impression unanimously applauded following the past a series of concert.

Table 3. the measurement results of concert hall under different conditions

test date 20180911							
index	condition	mid frequency of octave band					
		125	250	500	1k	2k	4k
T30/s	curtain raised	2.39	2.30	2.47	2.45	2.43	2.02
	curtain lowered	1.93	1.81	1.77	1.76	1.76	1.53
EDT/s	curtain raised	2.21	1.95	2.01	2.11	2.07	1.72
	curtain lowered	1.85	1.62	1.60	1.59	1.61	1.44
C80/dB	curtain raised	-3.68	-0.16	0.42	0.15	-0.08	0.88
	curtain lowered	-2.36	0.19	1.21	1.28	1.09	1.73
G/dB	curtain raised	4.82	4.31	6.54	4.53	4.97	4.78
	curtain lowered	4.58	4.26	6.30	4.40	4.62	4.44
LF	curtain raised	0.27	0.29	0.32	0.32	0.39	0.39
	curtain lowered	0.24	0.27	0.33	0.29	0.32	0.30
test date 20190320							
T30/s	unoccupied	2.16	1.97	1.97	2.03	2.00	1.68
	occupied	1.85	1.77	1.70	1.85	1.96	1.65
EDT/s	unoccupied	2.21	1.87	1.75	1.72	1.71	1.43
	occupied	1.99	1.83	1.74	1.64	1.69	1.47
C80/dB	unoccupied	-3.04	0.46	0.97	1.69	0.48	1.47
	occupied	-2.41	0.58	1.60	2.30	-0.28	1.18

6. Conclusions

The new performing arts spaces built in Fuzhou were received with much enthusiasm since completion. They are an additional embodiment of the current trend from complex geometries and curved surfaces in the contemporary architecture of concert halls, opera halls and even drama theaters. The amount of research and development effort agreed on this project and several previous ones by the authors (Stavanger concert hall (7), Wuxi Grand Theater (8), Paris Philharmonie (9,10,11) and others (12)) has resulted in building a broader acoustic design methodology.

Each new project is an opportunity to develop new algorithms and imagine new ways of optimizing the acoustic performance through architecture, hand in hand with the architects, in such a way that acoustics and architecture are blended together and can no longer be distinguished from each other. This methodology allows both precise control of the acoustic quality offered, and a lot of creativity in the architectural design of performing arts spaces.

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