



**Acoustics'08
Paris**
June 29-July 4, 2008

www.acoustics08-paris.org

euronoise

The acoustics of the Beijing National Grand Theatre of China

Isabelle Schmich^a, Paul Chervin^a, Zhu Xiangdong^b, Yan Xiang^b and L Guo-Qi^c

^aCSTB, 24, Rue Joseph Fourier, 38400 Saint Martin D'Hères, France

^bSchool of Architecture, Tsinghua University, Room 104, Centre Main Building, 100084 Beijing, China

^cThe National Grand Theatre, 2, Chang an east street, 100031 Beijing, China
isabelle.schmich@cstb.fr

The National Grand Theatre of China opened in December 2007 in Beijing. It is a complex of three performance halls: the Opera (2400 seats), the Concert Hall (2000 seats) and the Theatre (1100 seats). These three halls are covered by a super-ellipsoidal shell made out of titanium and glass.

The history of the acoustic design evolution from when the architect Paul Andreu won the competition in 1999 until the final construction will be retraced including the preliminary design, the acoustic simulations and auralisations. The acoustic design of the Opera House hall will be presented with its specifications and detailed particularities such as the use of acoustically transparent materials.

Final acoustic measurements have been done in the empty hall. The results and acoustic criteria will be discussed. In addition, a subjective evaluation has been done with psychoacoustic questionnaires and the results will be presented and analysed.

1 Introduction

Paul Andreu and AdPi won the international competition to create the National Grand Theatre of China. The complex includes three halls including an Opera House (2400 seats), a Concert Hall (2000 seats) and a Chinese Theatre (1100 seats) which are placed under a glass and titanium dome (see Fig.1).

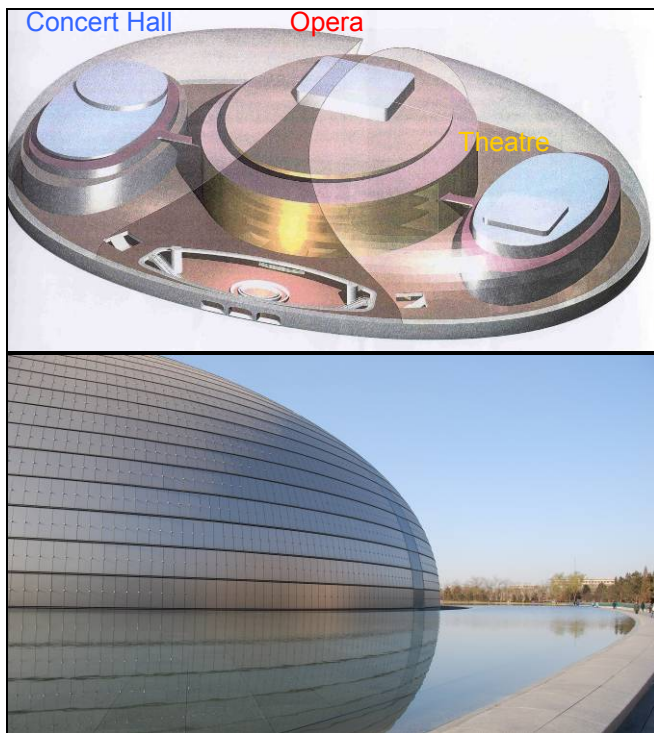


Fig.1 Paul Andreu and AdPi architectural project

Because the Opera House is especially aimed at all international lyric and ballet repertoire the acoustics of the Opera House is fixed and specialised for lyric music accompanied by an orchestra located in the pit.

2 The Opera House acoustic design

The acoustic design of the Opera House has been done in very close association with the architect so as to best satisfy the clients visual and acoustic desires. Amongst other criteria the target mid-frequency reverberation time was 1.5 s (+30% low frequency, -10% high frequency) and the clarity between -1 and 4 at 500 Hz.

2.1 Competition design

During the competition the scheme for the Opera House was rectangular with two balconies and a profiled ceiling designed to adequately spread lateral and ceiling reflections over the audience (see Fig.2). Wall and ceiling reflections were organized to be diffused at the proscenium arch, partly diffused at the walls and almost specular at the ceiling.

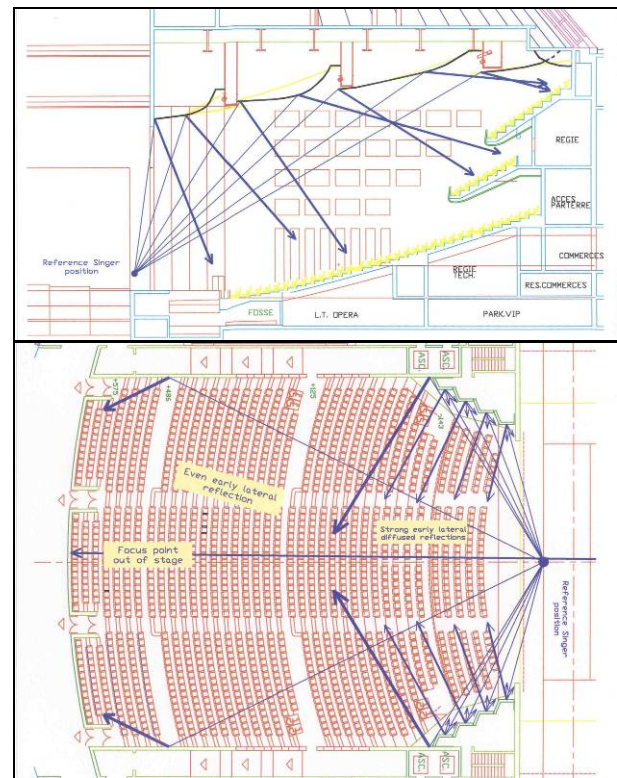


Fig.2 NGTC Competition design

2.2 Final Design

During the development of the preliminary design the architect completely changed his mind for the Opera House design and changed it from a rectangular scheme to a more rounded scheme.

The new acoustic design of the Opera House is based on a classical horseshoe theatre but excludes the viewing and acoustic inconveniences of traditional boxes [1] (see Fig.3). It has two balconies strictly aligned one above the other. The first balcony, with only two rows of seating, is designed for VIPs. The second balcony is much larger and extends up to the ceiling level. The main floor is separated

into two parts: the lower part is similar to classical orchestra stalls surrounded by a highly diffusing curved wall, and the upper part treated as a balcony prolonging the stalls on the rear side.

The horizontal reflecting ceiling includes four narrow light bridges. It is interrupted at the rear to allow the second balcony to have its own ceiling. The acoustic walls are organized to optimize the lateral reflections on the balconies side seats and in the orchestra stalls.

The main characteristics of the Opera House are:

- Volume: 18 900 m³
- Seats number: 2400
- Volume / seat: 7.8 m³/st
- Max width: 36 m - average width 34 m
- Mean ceiling height: 17.5 m
- Distance from the stage to the most distant seats: 43 m

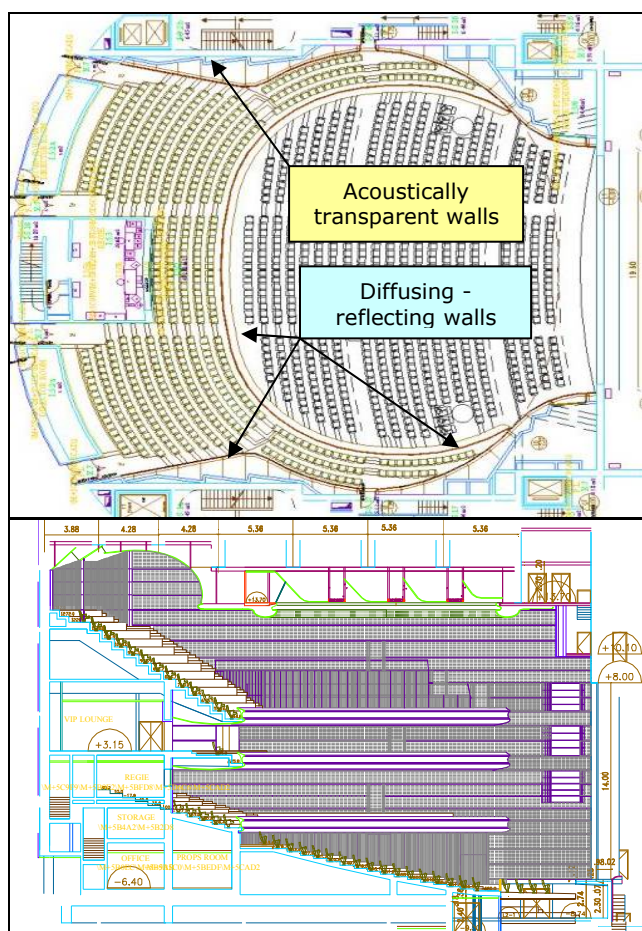


Fig.3 Plane and cross section view of the final design of the NGTC Opera House.

3 Acoustically transparent walls

To allow more freedom in the architectural design, the decision was made to separate the acoustic function from the visual appearance of the walls. To do this, an acoustically transparent wire mesh has been used to create the visually apparent walls of the room while the acoustic walls, made of heavy masonry, are hidden behind.

The acoustically transparent walls should not significantly increase the overall sound absorption of the Opera House for all frequencies. It should be fully transparent for all

frequencies, including at grazing incidence. It should not vibrate for very loud sound pressure levels and should not make special bump noise when shocked.

The architect proposed using a metallic wire mesh stiffly fixed on a frame for making the transparent walls. Depending on the texture, such a metallic wire mesh can obtain perforation rates as high as 50% or more. After analyzing the architectural and acoustic properties of many samples, a 40% perforated wire mesh which suited the architectural expectation was selected for laboratory testing (see Fig.4).

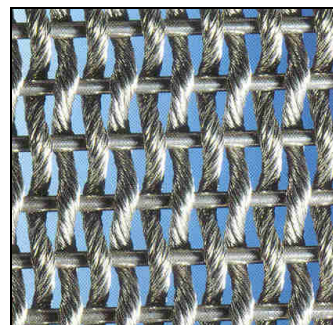


Fig.4 Metallic wire mesh GKD Ocean

3.1 Laboratory tests

A 12 m² sample of this material has been measured hanging in the middle of a CSTB reverberant chamber [2]. The diffused sound absorption coefficients, as shown in the following table, were found to be lower than the maximum acceptable values.

Frequency (Hz)	125	250	500	1000	2000	4000
α_{diff}	0.01	0.00	0.01	0.02	0.05	0.06

Table 1 Diffused sound absorption coefficient

The reflection and transmission coefficients of the same sample have also been measured under free field conditions at grazing incidences. For these tests two microphones have been placed in front of the grid on the same side as the loudspeaker and behind the grid (see Fig.5). The results for 9° incidence are shown in Fig.6. Both coefficients were found absolutely flat up to 4 kHz for all measured incidence.

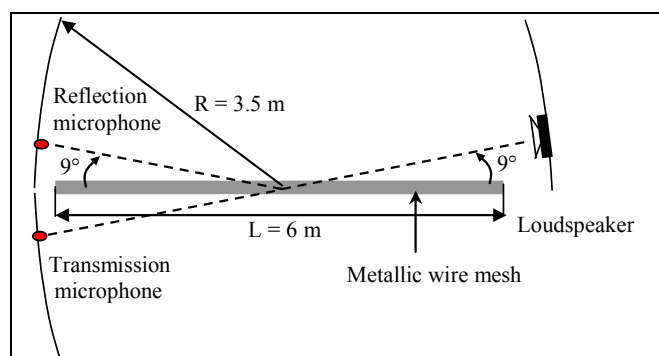


Fig.5 Experimental set-up for the sound transmission and reflection coefficient measurement

In addition to these measurements, listening tests of short clicks produced by a loudspeaker located close to the wire mesh were carried out at grazing incidence in order to detect any time structure alteration of the possible reflected sound. All laboratory tests have been found to be satisfactory.

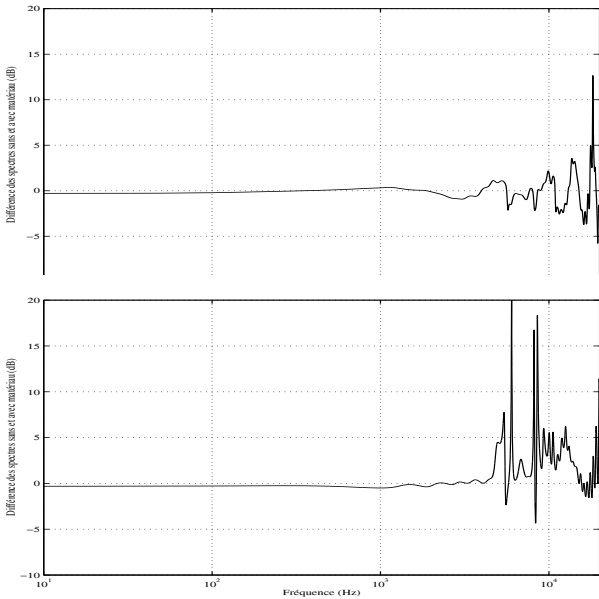


Fig.6 Sound transmission and reflection coefficient measured for 9° incidence on the wire mesh

3.2 On site validation measurements

Other tests have been done on a full scale mockup of the wire mesh wall, through which the mechanical mounting of the mesh has been optimized to control the risk of creating any noise such as permanent stress, damping of the clipping devices, stiffeners, number and size of poles and beams of the bearing frame.

Once the wire mesh was installed in the Opera House (see Fig.7) validation measurements were carried out to insure that the implementation was done correctly.

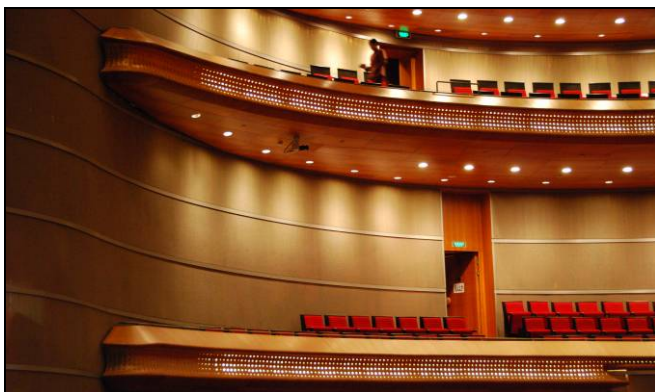


Fig.7 View of the mounted wire mesh

Accelerometers were fixed at different positions on the wire mesh and microphones positioned in front and behind the wire mesh. The wire mesh was exposed to loudspeaker stimulus in grazing incidence and impacted with a hammer. The experimental set-up is shown in Fig.8.

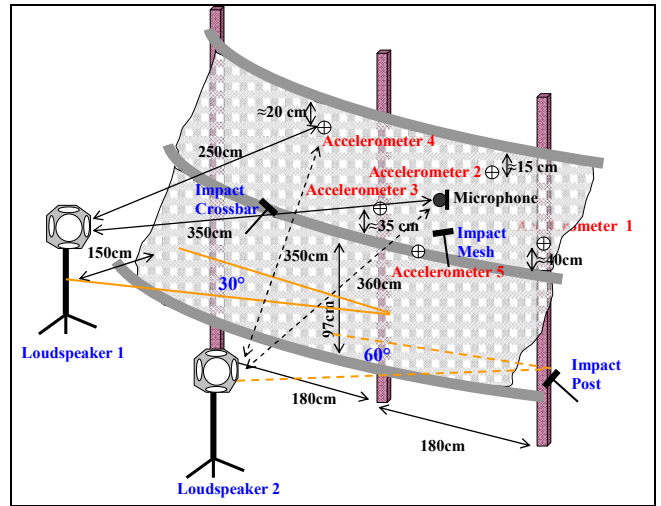


Fig.8 Experimental set-up for the wire mesh measurements on site

The measured vibration levels normalised with the injected force L_{vf} for the wire mesh located at the stall level created by an impact hammer are shown in Fig.9. The levels are highest with an impact on the mesh and lowest with an impact on the posts. This shows that good insulation exists between the wire mesh and its mounting structure.

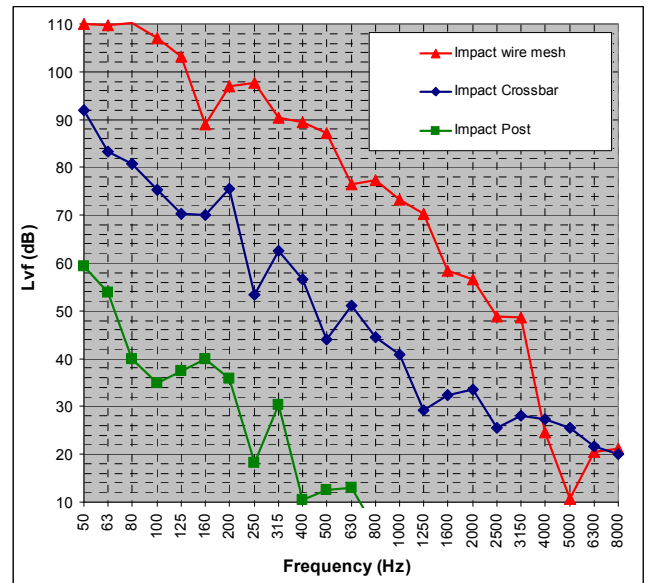


Fig.9 Measured vibration level L_{vf} with different impact stimuli at the stalls level

The measured vibration levels L_v and the sound pressure level SPL for the wire mesh located in the stall level with a loudspeaker stimulus are shown on Fig.10. The measured vibration levels for loudspeaker stimulus are rather low. The sound pressure levels for the microphone placed in front and behind the wire mesh are very similar which shows the transparency of the visual wall.

All tests have been found to be satisfactory and it is extremely improbable that anyone, even the most sensitive person, could perceive any sound effect due to the metallic wire mesh.

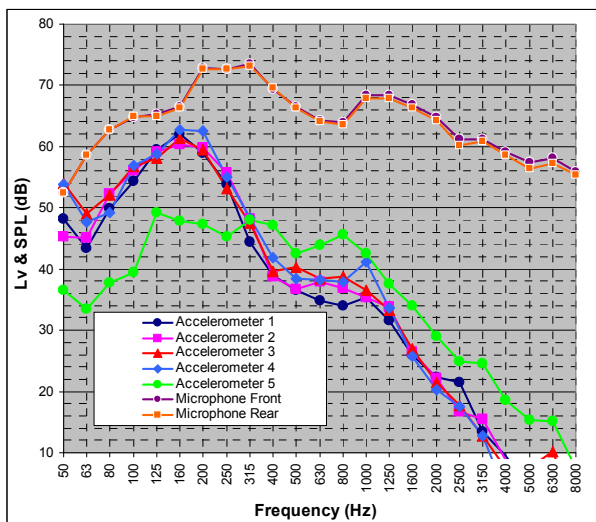


Fig.10 Measured vibration level Lv_v with an loudspeaker stimuli at the stalls level

4 Acoustic quality prediction

Computer simulations of the room have been carried out with the CSTB Epidaure program in order to finalize the room shape and material. The final geometrical model is shown in Fig 11.

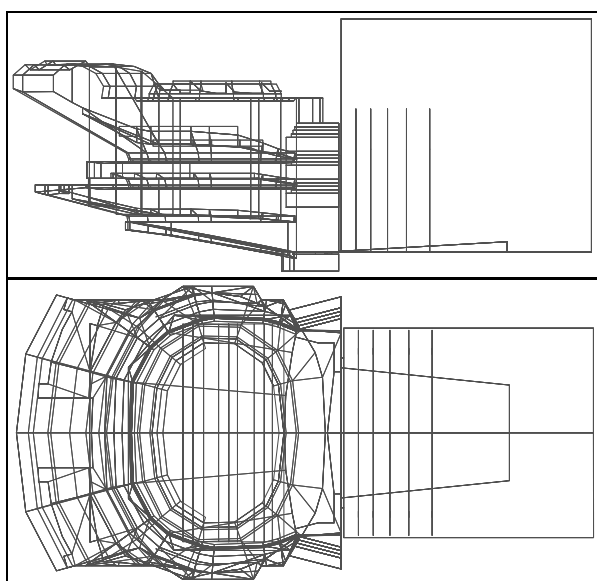


Fig 11: EPIDAURE geometrical model for the opera with stage including a few typical sets

The omni-directional source was set on stage one meter away from the stage opening on the main axis of the room. The sound power level of the source was 100 dB(A). 13 microphones were placed in the room on one half: 5 on the main floor, 3 on the VIP balcony and 5 on the second balcony. Receiving surfaces were defined over half of the audience using a grid of 400 microphones (successively omni-directional and bi-directional). Main criteria mapping were performed on these surfaces. The mean values of the calculated acoustic criteria are shown in Table1 and the mapping of the SPL and C80 are shown in Fig.12 and 13.

Frequency (Hz)	125	250	500	1000	2000	4000
RT 20 (s)	2.07	1.79	1.61	1.55	1.51	1.29
EDT (s)	1.95	1.70	1.51	1.44	1.43	1.26
Definition 50 (%)	42.6	44.6	48.1	49.8	49.9	53.5
Clarity 80 (dB)	1.0	1.5	2.3	2.7	2.7	3.5

Table 1 Mean calculated criteria values of the Opera House

All of the mean predicted values lie in the design criteria targets.

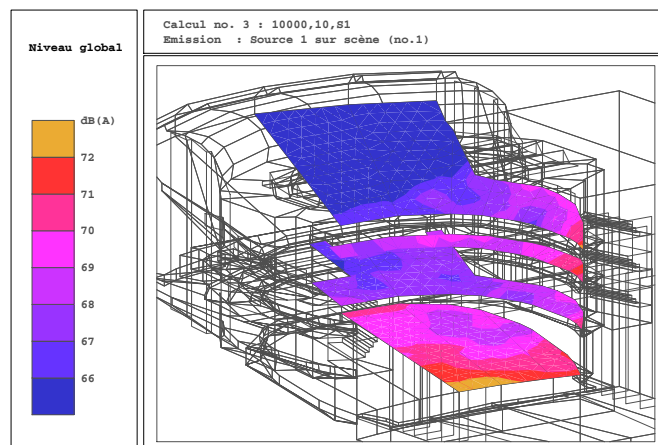


Fig 12: Epidaure SPL calculation mapping

The SPL variation for a singer source position as shown on the map is not more than 6 dBA over all seating. In the stalls and VIP balcony it is only 4 dBA. The clarity index is positive everywhere as is suitable for an Opera House. As it is well known, geometrical prediction models always emphasize the spatial contrast compared to what is usually measured so that an even smoother variation of criteria can be expected.

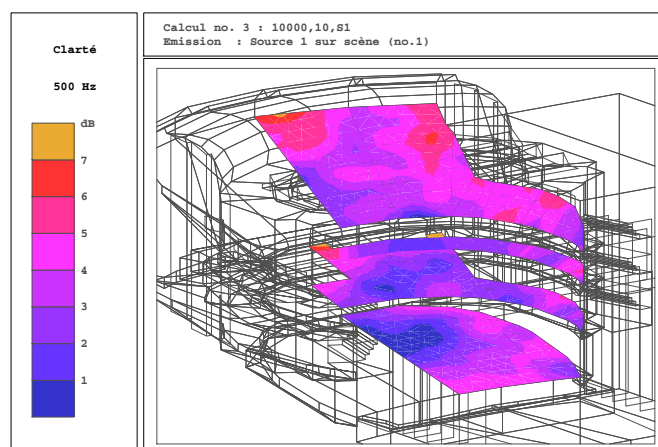


Fig 13: Epidaure Clarity 80ms calculation mapping at 500 Hz

Auralization samples have been carried out with CSTB Ebinaur program for a few key seats. These were appreciated by the client as having a very well balanced and intimate sound despite the rather large dimensions of the Opera House.

5 Final measurement results

Before the opening of the Opera House, final measurements in the empty hall have been carried out (see Fig.14).



Fig.14 Opera House during measurement campaign

The omni-directional source was set on stage at the fire curtain level on the main axis of the room. The sound power level of the source was 103 dB(A). 27 microphones were placed in the room on one half: 15 on the stalls floor, 3 on the VIP balcony and 9 on the second balcony. The measurements have been done with a MLS sequence of order 16 using a white noise filter.

The echograms show a very smooth decay which correspond to a very homogeneous sound [3] (see Fig.15).

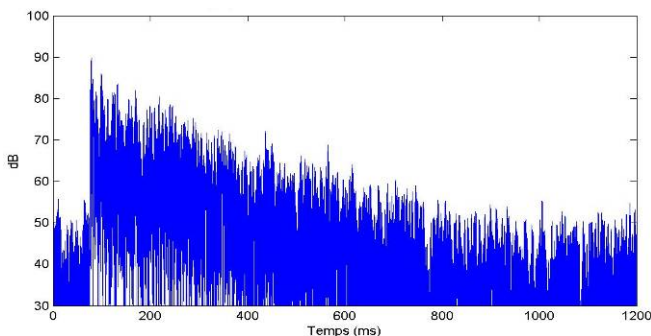


Fig.15 Measured echogram for receiver 9 at 500Hz.

Frequency (Hz)	125	250	500	1000	2000	4000
RT 20 (s)	2.2	1.8	1.6	1.5	1.4	1.3
RT 30 (s)	2.2	1.8	1.7	1.5	1.4	1.3
EDT (s)	1.8	1.5	1.3	1.2	1.1	0.8
Definition 50 (%)	27.8	43.5	52.1	58.0	54.4	62.3
Clarity 80 (dB)	-0.1	1.7	3.0	4.1	4.2	5.7

Table 2 Measured criteria of the NGTC Opera House

The measured criteria shown in Table 2 are very close to the predicted and the target criteria. The clarity is even higher for frequencies above 500 Hz than the predicted criteria based on the computer simulations. This will be very suitable for singers voices.

5.1 Stage – Orchestra pit balance

The sound pressure level at 1kHz measured with the source on stage is equal or higher than the sound pressure level

measured with the source located in the orchestra pit for all receiver positions.

5.2 Background noise

Background noise measurements have been carried out in the empty hall. The HVAC system was not finished tuning at the time of measurement and some chair outlets were very noisy. Despite the noisy HVAC system, the Background Noise is below NR20 for most seats and easily below NR25 for even the noisiest positions. It is supposed that the tuning of the HVAC system will permit the reduction of the noise of the chair outlets and the background noise should be below NR20 for all seats.

5.3 Subjective assessment

In addition to the objective criteria and measurements, a subjective evaluation has been done using psychoacoustic questionnaires.

A listening session with a panel composed of musicians and acousticians has been done and confirmed the very good stage-orchestra pit balance and the homogeneous sound in the Opera House.

6 Conclusion

The evolution of the acoustic design from the competition scheme to the final design has been presented. The innovative use of a wire mesh to separate visual and acoustic walls has been validated through laboratory and on site measurements. Computer simulation results showed that very good acoustic conditions are expected for all of the 2400 spectators in the Opera House which have been verified by the final measurements. The stage-orchestra pit balance has been evaluated. Singing voices should be able to express themselves above the orchestra with ease. The overall quality of the hall has been judged to be very good.

Acknowledgments

The authors are grateful to Paul Andreu, AdPi and the architectural team and to the NGTC officials and employees for their kind collaboration.

References

- [1] L. Beranek "Concert Halls and Opera Houses" 2nd Edition, Springer (2004)
- [2] ISO 354:2003 "Acoustics-Measurement of sound absorption in a reverberation room" *International Organisation for Standardisation, Geneve* (2003)
- [3] L. Cremer, H. A. Müller, "Principles and Applications of Room Acoustics" *Applied Science Publishers* (1982)