The acoustics of the Concert Hall and the Chinese Theatre in the Beijing National Grand Theatre of China

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ABSTRACT

The National Grand Theatre of China designed by the architect Paul Andreu opened in December 2007 in Beijing. It is a complex of three performance halls: the Opera House (2400 seats), the Concert Hall (2000 seats) and the Chinese Theatre (1100 seats). These three halls are covered by a super-ellipsoidal shell made out of titanium and glass. This presentation will focus on the acoustics of the Concert Hall and the Chinese Theatre. The history of the acoustic design evolution will be retraced from when the competition was won in 1999 until the final construction. It includes the preliminary design and the acoustic simulations. The specifications and detailed particularities of each hall such as the reflector position in the Concert Hall will be discussed. Final acoustic measurements have been done in the empty halls and in the occupied Concert 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 (NGTC). The complex includes three halls including an Opera House (2400 seats), a Concert Hall (2000 seats) and a Chinese Theatre (1100 seats) which are situated under a glass and titanium dome (see Figure 1). The acoustic design and the final results of the Opera House have already been presented [1]. This paper will focus on the Chinese Theatre and Concert Hall.

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2 CHINESE THEATRE

The NGTC Chinese Theatre is especially aimed at Chinese opera performances and speech drama repertoire and is the smallest of the three halls with 1100 seats.

It has a movable forestage and corresponding stage tower which can be replaced by audience seats. When performances take place on the main stage the forestage soffit doors are closed and seating is installed in the forestage area (see Figure 2). When performances take place on the forestage, the forestage soffit doors are opened and stage sets or decor can be placed on the main stage. For Chinese opera performances the orchestra is located on a side platform close to the forestage partially hidden behind the proscenium lateral walls.

2.1 Acoustic Design

The main acoustical challenge of the Chinese Theatre comes from the two possible performance areas where singers or actors can perform. The critical first order reflections are therefore not easy to handle.

The Chinese Theatre is a horseshoe-type theatre with two balconies and an upper circle. Volume and distances have been kept as compact as possible in order to give adequate acoustics for the Chinese Theatre. To achieve high clarity and even sound level distribution over the audience the ceiling has been carefully designed as well as the lateral walls, particularly at the proscenium.

The acoustic design targets were as follows:

- Reverberation time: 1.2s at mid frequency, [+30% Low Freq, -10% High Freq]
- Strength Index: -30 dB(A) Variation allowed: [+3,-2] dB(A)
- Clarity: ≥ 1dB (500Hz)
- Intelligibility: > 0.7 without Public Address
The main characteristics of the theatre are (see Figure 3):

- Number of seats: ~1100 (classical stage); ~950 (fore stage)
- Volume: ~7200 m$^3$ ⇒ V/N ~ 6.5 m$^3$
- Maximum width: 30 m
- Maximum depth in the stalls: 23 m
- Maximum distance of the farthest seat: 26 m
- Minimum ceiling height: 12 m

Figure 3: Plane and cross section view of the final design of the NGTC Chinese Theatre.

2.2 Acoustic quality Prediction

Computer simulations of the theatre have been carried out with CSTB’s Epidaure program in order to finalize the room shape and materials. Two models of the theatre have been built: one with the source on the main stage and audience on the forestage and a second with the source on the forestage (see Figure 4).
Figure 4: Epidaure geometrical model for the Chinese Theatre with stage including a few typical stage sets

The main source (omni-directional) was set onstage one meter away from the stage opening on the main axis of the hall for the classical stage and 4 m away from the forestage border in the forestage case. The sound power level of the source was 100 dB(A). 8 microphones were placed in the room on one side: 3 on the main floor, 2 on the VIP balcony and 3 in the upper balconies. Receiving surfaces were defined over half of the audience using a grid of 400 microphones. Main criteria mapping were performed on these surfaces. The mean values of the calculated acoustic criteria are shown in Table 1 and 2 and the mapping of the SPL and RASTI are shown in Figure 5 and 6.

Figure 5: Epidaure SPL and RASTI calculation mapping at 500 Hz for the forestage configuration

Figure 6: Epidaure SPL and RASTI calculation mapping at 500 Hz for the classical stage configuration
Table 1: The average expected values of the criteria for the forestage theatre.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT 20</td>
<td>1.66</td>
<td>1.39</td>
<td>1.29</td>
<td>1.25</td>
<td>1.22</td>
<td>1.12</td>
</tr>
<tr>
<td>RT 30</td>
<td>1.61</td>
<td>1.46</td>
<td>1.39</td>
<td>1.36</td>
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<td>1.14</td>
</tr>
<tr>
<td>EDT</td>
<td>1.45</td>
<td>1.19</td>
<td>1.02</td>
<td>0.92</td>
<td>0.89</td>
<td>0.81</td>
</tr>
<tr>
<td>Definition 50</td>
<td>52.9</td>
<td>58.2</td>
<td>63.6</td>
<td>67.2</td>
<td>66.9</td>
<td>68.7</td>
</tr>
<tr>
<td>Clarity 80</td>
<td>3.1</td>
<td>4.3</td>
<td>5.4</td>
<td>6.2</td>
<td>6.2</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 2: The average expected values of the criteria for the classical stage theatre.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
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</thead>
<tbody>
<tr>
<td>RT 20</td>
<td>1.69</td>
<td>1.37</td>
<td>1.24</td>
<td>1.20</td>
<td>1.15</td>
<td>1.04</td>
</tr>
<tr>
<td>RT 30</td>
<td>1.60</td>
<td>1.43</td>
<td>1.33</td>
<td>1.29</td>
<td>1.23</td>
<td>1.09</td>
</tr>
<tr>
<td>EDT</td>
<td>1.45</td>
<td>1.20</td>
<td>1.04</td>
<td>0.93</td>
<td>0.92</td>
<td>0.84</td>
</tr>
<tr>
<td>Definition 50</td>
<td>50.2</td>
<td>54.5</td>
<td>59.7</td>
<td>63.2</td>
<td>63.2</td>
<td>65.1</td>
</tr>
<tr>
<td>Clarity 80</td>
<td>3.1</td>
<td>4.4</td>
<td>6.1</td>
<td>7.4</td>
<td>7.4</td>
<td>7.9</td>
</tr>
</tbody>
</table>

The results of the Epidaure simulation of the theatre are satisfactory with respect to the design targets. The acoustic criteria are a little higher than the expected values for pure speech drama theatre but appear to be well adapted to musical theatre such as Chinese opera.

The reverberation time, almost unchanged between the classical stage and the forestage configurations, are again strongly dependant on the absorption of the overall stage settings. They are marginally higher than the expected value of 1.2 s. This means that the forestage tower opening compensates for the lack of audience absorption when seats are removed to set the forestage.

Criteria maps show substantial differences between the two stage positions for the sound pressure level distribution. In the forestage configuration the source is much closer to the audience giving higher levels. In both cases, sound pressure levels are relatively evenly distributed with no more than 3 dB(A) variation on the main floor (2 dB(A) for the classical stage). Speech intelligibility is very high and never goes below 50% at the centre of the main floor (classical stage). Average values are higher than 60%. The clarity and definition are also very high which is adapted to the main uses foreseen for the theatre.

2.3 Final measurements results

Before the opening of the Chinese Theatre, final measurements in the empty theatre for the forestage configuration have been made (see Figure 2). The Chinese Theatre was measured in an empty configuration with the stage free of any stage set or decor. Very light curtains were mounted on the sides of the stage.

The omni-directional source was set in the middle of the forestage on the main axis of the theatre. The sound power level of the source was 103 dB(A). 9 microphones were placed in the theatre on one side: 5 on the floor of the stalls, 2 on the VIP balcony and 2 on the second balcony. The measurements have been done with an MLS sequence of order 15 using a white noise filter.

The echograms show a very smooth decay which corresponds to a very homogeneous sound [2] (see Figure 7).
Figure 7: Measured echogram for receiver position 6 at 500Hz.

Table 3: The average measured criteria of the Chinese Theatre for the forestage theatre.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT 30 (s)</td>
<td>1.8</td>
<td>1.5</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>EDT (s)</td>
<td>1.5</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Definition 50 (%)</td>
<td>17.7</td>
<td>37.8</td>
<td>50.7</td>
<td>58.3</td>
<td>57.5</td>
<td>64.4</td>
</tr>
<tr>
<td>Clarity 80 (dB)</td>
<td>-0.8</td>
<td>0.9</td>
<td>3.3</td>
<td>4.1</td>
<td>4.7</td>
<td>6.8</td>
</tr>
</tbody>
</table>

The averaged measured criteria shown in Table 3 are very close to the predicted and target criteria.

The measured RT in the empty hall was 1.25 s. It is probable that the occupied RT will be around 1.1 s due to audience sound absorption. The early decay time is slightly shorter at 1.2 s which ensures a good listening reverberance impression of the sound. The RT spectrum is slightly inclined as expected with longer reverberation time at low frequencies and shorter ones at higher frequency which gives some warmth to the theatre keeping a high sound intelligibility for voice.

The RT depends strongly on the overall stage setting absorption. Since there was very light stage absorption, the final RT and EDT will probably be a little bit shorter than measured.

C80 and D50 results are more difficult to interpret in such a small theatre because they depend highly on direct sound which is never lower than the reverberated sound. Nevertheless, the measurements were above the design targets even if they are lower than the simulation results. They both correspond to high clarity and definition, typical for drama theatre acoustics. This will be very suitable for singing voices.

The average values for speech intelligibility are higher than 0.60 for both source positions which correspond to the simulation results. The target was not reached because of the measurement conditions: the stage being very open with almost no stage set had a bad influence on this parameter. With a more absorbent stage set, the speech intelligibility should be above 0.70.

The mean strength index value G has been measured to be -30.3 dB(A). As already shown in the simulations, the Strength Index of the source S1 is higher than that of source S2, which is normal because S1 is located on the forestage which is further in the actual volume of the theatre. The Strength Index spectrum is slightly influenced by that of the RT in the lower frequencies. This spectrum confirms the good bass support of the hall.

The maximum difference between the most and the least favored seats in the audience area has been measured to 2.7 dB(A). This is better than the expectation and very satisfactory.

2.4 Subjective assessment

In addition to the objective criteria measurements, a subjective evaluation has been done using psychoacoustic questionnaires. A listening session with a panel composed of students,
musicians and acousticians confirmed the very good acoustic conditions for the Chinese Theatre.

3 CONCERT HALL

The NGTC Concert Hall with its 2000 seats is especially aimed at an international symphonic repertoire. The slightly curved shoe-box shape has been designed to give rich and warm acoustics [3]. Acoustic simulations predicted very broad and high quality acoustics [4].

3.1 Reflector position

A large movable stage reflector placed above the orchestra platform has been added for better musician support and to increase the diffusive reflections (see Figure 8).

Figure 8: NGTC Concert hall movable reflector above the stage

Three main acoustic uses have been foreseen for the Concert Hall: Organ concert, symphonic performance and chamber music performances. A different reflector position in the Concert Hall is required for each use.

During organ performances the reflector should be positioned as high as possible so that its position does not disturb the sound propagation from the stops which are placed at a very high level and to use of the complete volume of the concert hall for the organ. Additionally, the visibility of the organ from almost all seats is assured.

Different height positions have been tested using laser beam methods for symphonic performances which will host large symphonic orchestras and/or large choirs onstage. Impulse response measurements at three receiver positions have been tested for two different heights (see Figure 9).

Figure 9: Receiver positions for the reflector adjustment measurements.
The measurement results show that the lower position at a height of 11.50 m above the stage gives better early reflections and avoids some undesired echoes (see Figures 10 to 12). In addition to the reflector height, an angle of 5° towards the audience has been chosen as shown in Figure 13. This will ensure a higher sound level and better sound clarity in the stall seating.
Similar to the symphonic performance usage, the reflector position for Chamber music performances has been optimised. Chamber music performances generally host a smaller number of musicians onstage. During these performances the sound clarity is of the highest importance. For this use, the best reflector position in the Concert Hall is at a height of 9.5 m above the stage with an angle of 5° towards the audience.

3.2 Final measurements

Before the opening of the Concert Hall, final measurements in the empty hall and in the occupied hall have been carried out (see Figure 14).

The omni-directional source was set in 4 positions on the stage of the Concert Hall: at centre stage close to the conductor, at centre stage at the woodwinds location, at left stage at the cello double bass location and at right stage at the 1st violin location. The sound power level of the source was 103 dB(A). 31 microphones were placed on one side of the hall for the empty hall measurements and 10 microphones were placed in the hall for the occupied measurements. The measurements have been done with a MLS sequence of order 16 using a white noise filter.

3.2.1 Unoccupied hall measurements results

The Concert Hall was measured in an empty configuration with the stage free from any stands or seats. Once again, the echograms of the unoccupied measurements in the Concert Hall show a very smooth decay corresponding to a very homogeneous sound [2] (see Figure 15).
The averaged measured criteria shown in Table 4 are very close to the predicted and target criteria.

Table 4: The average measured criteria of the unoccupied Concert Hall.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>4000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT 30 (s)</td>
<td>2.5</td>
<td>2.3</td>
<td>2.2</td>
<td>2.3</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>EDT (s)</td>
<td>2.4</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Definition 50 (%)</td>
<td>21.5</td>
<td>27.2</td>
<td>38.9</td>
<td>40.1</td>
<td>41.6</td>
<td>48.3</td>
</tr>
<tr>
<td>Clarity 80 (dB)</td>
<td>-2.5</td>
<td>-1.7</td>
<td>0.5</td>
<td>0.4</td>
<td>0.8</td>
<td>2.2</td>
</tr>
</tbody>
</table>

The RT design target was 2.2 s at mid frequency with a maximum increase of 50% at low frequencies and a maximum decrease of 10% at high frequencies. This target has been achieved with slightly higher values at mid frequencies. The rather flat RT spectrum is remarkable. It corresponds to favorable musical aesthetics offering clear and precise listening conditions, as is suitable for classical and 20th century repertoire.

The clarity C80 values are even higher than the target values (-3 to 0 dB at 500Hz). This will probably be greatly appreciated, especially by the musicians on stage.

The averaged main acoustic criteria such as EDT and the Strength Index, fall within the expected design targets.

### 3.2.2 Occupied hall measurements results

The occupied hall measurements have been carried out in the Concert Hall during the intermission of a test concert. Seat occupancy has been estimated to be 75%. The averaged measured criteria are shown in Table 5.

Table 5: The average measured criteria of the occupied Concert Hall.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>4000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT 30 (s)</td>
<td>2.6</td>
<td>2.2</td>
<td>2.3</td>
<td>2.2</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>EDT (s)</td>
<td>2.2</td>
<td>1.9</td>
<td>1.7</td>
<td>1.8</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Definition 50 (%)</td>
<td>21.4</td>
<td>36.6</td>
<td>45.5</td>
<td>48.0</td>
<td>46.6</td>
<td>48.4</td>
</tr>
<tr>
<td>Clarity 80 (dB)</td>
<td>-3.0</td>
<td>0.2</td>
<td>1.7</td>
<td>1.8</td>
<td>1.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The occupied hall measurement results are very similar to the unoccupied measurement results. This shows that the seat absorption has been well designed and assures similar acoustic conditions for the musicians with or without a full audience. The EDT values are about 0.2 s below the unoccupied measurements and the clarity is slightly higher which should be appreciated during rehearsal sessions.

### 3.3 Subjective evaluation

In addition to the objective criteria measurements, a subjective evaluation has been done using psychoacoustic questionnaires. The subjective assessment of the Concert Hall was
done during a test concert. The audience was composed of approximately 2000 people. 507 questionnaires were returned. Because of the large number of people assessed it is assumed that most of them did not have any acoustic background.

A specific psychoacoustic questionnaire was distributed to the audience. General questions were asked to qualify the overall acoustics of the Concert Hall. More precisely, five acoustic parameters were assessed by the audience: reverberance, clarity, liveness, warmth and intimacy. These were described in the questionnaires as following:

- Reverberance: persistence of the sound, superimposition of the different sounds
- Clarity: perception of musical details
- Liveness (brilliance): richness and persistence of high sounds
- Warmth: low sounds distinguished rich and clearly
- Intimacy: the music gives the impression of being in a small enclosure

The psychoacoustic evaluation results for these five acoustic quality parameters are shown in Table 6.

<table>
<thead>
<tr>
<th>Subjective criterion</th>
<th>Linear scale</th>
<th>Scale from 0 to 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberance</td>
<td>Restrained</td>
<td>Spacious</td>
</tr>
<tr>
<td>Clarity</td>
<td>Blurred</td>
<td>Very clear</td>
</tr>
<tr>
<td>Liveness, brilliance</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Warmth</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Intimacy</td>
<td>Close</td>
<td>Remote</td>
</tr>
</tbody>
</table>

In addition to these results, the sounds of the different instruments are distinguished clearly or very clearly for 89.5% of the audience, and the soloists are distinguished clearly or very clearly for 90.1%. This confirms the very high clarity in the Concert Hall which is well related with the high measured value of the clarity criterion in the occupied Concert Hall at mid frequencies.

A general question was asked to assess the overall acoustics of Opera House: “How do you classify overall the acoustics of the NGTC concert Hall?”. 88.3% of the people felt satisfied with this acoustics – 42.6% good and 45.7% very good. This subjective impression is very important and permits the assumption that listeners will be very satisfied with the NGTC Concert Hall acoustics.

4 CONCLUSIONS

The acoustic designs of the NGTC Chinese Theatre and Concert Hall have been presented. Computer simulation results showed that very good acoustic conditions are expected in the Chinese Theatre as well as in the Concert Hall. For both halls final measurements and subjective assessments have been carried out which validate the proposed acoustic design. Actors and singers should enjoy performing in the homogeneous and intimate Chinese Theatre. The acoustics of the Concert Hall correspond quite well with the expectations and can be ranked among the best concert halls in the world.

5 ACKNOWLEDGEMENTS

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