ACOUSTIC CONSIDERATIONS IN THE REFURBISHMENT OF A 1960’S BRUTALIST CONCERT HALL

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1 INTRODUCTION

Southbank Centre is a complex of artistic venues in London, England, on the South bank of the River Thames. Originally built in the 1950s and 1960s, it comprises three main performance venues, Royal Festival Hall, Queen Elizabeth Hall (QEH) and Purcell Room. Southbank Centre has recently undergone a substantial refurbishment programme consisting of works in Queen Elizabeth Hall, Purcell Room and Hayward Galleries. This paper presents the acoustic considerations in the refurbishment of Queen Elizabeth Hall, a brutalist 1000 seat concert hall originally designed to accommodate classical chamber music but substantially modified to accommodate amplified music, and dance performances.

Overall, the room acoustics of Queen Elizabeth Hall prior the refurbishment was confirmed good, but there were certain areas that needed improvement. Hence, the brief was to retain the overall acoustics of the auditorium and improve certain areas, such as stage acoustics, diffusion of the rear wall and variability of the acoustics to allow better amplified music use. In addition, a major exercise was carried out on the absorption of the Helmholtz resonators which line the walls and how best to refurbish them.

Alongside room acoustic enhancements, one of the key items within the refurbishment was reversing the ventilation system to improve the energy efficiency of the hall whilst maintaining a low background noise level of NR15. This involved detailed measurements of the existing concrete builders work duct network which had been acoustically lined 50 years previously. It was also important to carry out laboratory measurements of a mock-up of the underseat vents to develop a low noise solution based around the existing concrete slots.

This paper starts by presenting the background and the acoustic brief for the refurbishment in Section 2. Next, in Section 3, key areas of the design development are discussed. Section 4 presents and discusses the commissioning testing results and compares the room acoustic parameters before and after the refurbishment. Finally, in Section 5 and Section 6, subjective feedback and conclusions are presented.

Figure 1 shows the frontal view of the QEH auditorium before and after the refurbishment. The main visual changes in frontal area are added stage linings, decluttered stage area and omission of the second lighting bridge.

Figure 1: QEH prior the refurbishment in 2015 (left) and after the refurbishment in 2018 (right).
2 BACKGROUND & THE BRIEF

Overall, the room acoustics of Queen Elizabeth Hall prior to the refurbishment was confirmed good, but there were certain areas that needed improvement.

Acoustic measurements have been made in the Hall on a number of occasions since it opened. The results of these, which are broadly in agreement, indicated that the key acoustic parameters fell within the preferred ranges for a concert hall.

A number of subjective observations were made by careful listening at a number of concerts which were pooled together with published impressions by other listeners such as (Gilford, Humphries, Barron et al).

A recurring observation was that the clarity of sound varied significantly with position. In particular, there appeared to be a difference between the front half of the auditorium and the rear; dividing line being the cross-aisle. The reason for this was likely to be that there was not enough scattering or diffusion of sound around the auditorium leading to specular reflections and uneven distribution of sound.

Another observation was that reverberant sound appeared to be coming from behind. The cause of this was likely to be reflections from the rear wall which presented a large reflecting surface to incident sound. These rear reflections increased the amount of late energy in the hall which could be detrimental to clarity.

In addition, the bass sound in the hall was not always considered properly balanced, especially during amplified music concerts. A common feedback from the front of house mixing engineers was that there is a coloration around 160Hz.

Regarding the stage, the feedback from the musicians often was that the reflections from the stage walls were very strong and overpowering and the musicians could not always hear each other properly.

Based on the above feedback and observations, the acoustics brief for the refurbishment was summarized as follows:

1. Retain the overall room acoustics of the hall
2. Improve the balance of stage acoustics
3. Improve the clarity and evenness of sound within the (rear) auditorium
4. Declutter the stage area to increase the reverberation time slightly towards the 1967 situation
5. Add variability to the room acoustics to allow better acoustics for amplified music concerts
6. Retain the background noise level of NR15, whilst reversing the ventilation system

3 DESIGN DEVELOPMENT

3.1 Room acoustics

The architectural vision for the refurbishment of the QEH was to make very minimal changes to the interior, treating the surfaces almost as if they were listed. The main visual changes were the removal of the second lighting bridge (as shown in Figure 1), an addition of diffusive timber linings to the stage, and an addition of a diffuser and variable absorption curtains to the rear wall of the auditorium.

Otherwise, the changes were limited to refurbishing the old upholstered leather seats to their original spec, cleaning the old concrete surfaces, and cleaning and polishing the old timber surfaces.
The room acoustic enhancements within the stage and the auditorium are discussed in the following.

### 3.1.1 Stage

The stage is effectively in two parts namely, the rear part which has a ceiling at around 7m and the front part where the ceiling is full height at 15m. This difference in height gave rise to two different acoustic characteristics.

When musicians were located in the rear part, such as for a large orchestral performance, they received very strong reflections from overhead and surrounding walls which were somewhat overpowering.

Also, the upstage wall which was lined with flat plywood sheets above a certain height did not direct sound into the auditorium in a uniform way.

Ideally, the height of the rear stage should have been increased to allow the stage to better couple acoustically with the main volume of the hall. However, this operation was too costly for the budget and hence was not implemented.

Instead, diffusing timber linings were designed to cover most of the rear stage walls and stage ceiling. The aim of these linings was to scatter the reflections from the stage walls and ceiling to create more even and balanced response for the musicians. Later in the design process, the ceiling diffuser was omitted for cost reasons and the final design was to have the diffusers only on the stage walls.

The diffuser pattern follows the principle of Quadratic residue diffuser (QRD) and was designed to be effective at mid-frequencies. The entire diffuser is constructed from three slightly varying patterns as shown in Figure 2 below. The aim was to scatter mid-frequencies whilst avoiding scattering (and hence attenuating) high frequencies too much. The installed diffusers can be seen in Figure 3.

![Figure 2. Three stage diffuser patterns. Figure © RPG inc.](image-url)
In addition to the stage linings, movable stage reflector was designed to give supportive early reflections with smaller ensembles and solo musicians. The stage reflector, however, was omitted from the final design for cost savings.

### 3.1.2 Auditorium rear wall diffuser

To address the problem of uneven distribution of sound within the rear auditorium, a diffusive structure was designed to cover the flat rear wall at a low level. The architectural requirement was that the wall should look white and flat when observed from the auditorium. This limited the acoustic design considerably, but the outcome was still considered to contribute positively to the room acoustics.

### 3.1.3 Helmholtz resonators

When the QEH was first designed in the 1960’s, it was necessary to introduce a significant amount of low-frequency absorption into the hall due to its massive concrete enclosure. The low-frequency absorption was implemented using Helmholtz resonators which line most of the side walls of the auditorium.

Originally, the Helmholtz resonators were tuned to function at 4 different resonant frequencies (115 Hz, 80 Hz, 63 Hz and 40 Hz). The tuning was implemented with timber plugs with different sized slots as shown in Figure 4.
The original 1960’s resonator design included a 25mm polyurethane foam inserted into the resonators cells just behind the neck. The purpose of this foam was to increase the airflow resistance in the mouth of the resonator and hence add extra absorption.

It was noticed early during the refurbishment project, that the polyurethane foam had disintegrated over time and was just dust in the resonators cells.

An extensive study was undertaken by Christina Higgins on the QEH resonators and how to refurbish them. Replica resonators were built, and their absorption characteristics studied with measurements in the reverberation chamber. Tests were carried out with and without 25mm foam inserted into the cells and with absorptive fabric hung in front of the resonators at different distances from the resonator bank.

Key findings from the resonator study were:

1. Polyurethane foam boosts and broadens the absorption of the resonators.
2. Acoustic curtain 0 cm from the resonator bank boosts and widens the resonance (and absorption coefficient) (Figure 6.).
Based on the resonator study, earlier room acoustic measurements and room acoustic modeling, it was decided that it is not necessary to re-fit new polyurethane foam into the resonators for classical music use. Instead, it was proposed to clean the old polyurethane foam dust from the resonator cells and design a variable acoustic system based on acoustic fabric on top of the resonators. The variable absorption system is discussed next.

### 3.1.4 Variable absorption system

Based on the resonator study and acoustic (Odeon) modeling, a variable absorption system was designed to lower the reverberation time for amplified music concerts. The proposal was to build 530 m² of motorised banners deployable from the perimeter of the ceiling. These banners would be hung on top of each resonator bank to gain not only mid and high frequency absorption, but also low-frequency absorption. Figure 7 illustrates the banners hung on top of the resonators.
The variable absorption system was later omitted from the final design for two reasons. Firstly, there was strong pressure to lower project costs, and secondly, the front of house mixing engineers did not support the idea of fabric banners due to their negative experiences of such systems in the past.

The final compromise was to clean the resonators and have acoustic curtains covering only part of the rear wall.

### 3.2 Ventilation system

One of the key parts of the QEH refurbishment was to refurbish and replace the mechanical services to the auditorium. The works included reversing the ventilation system to improve the environmental comfort. The new ventilation system was designed to supply from under seat plena and extract from a high level, whereas the old system used to function the opposite way. Figure 8 shows the old (left) and new (right) air supply and extract routes in section.

![QEH air supply and extract routes](image)

The plan was to replace the air handling units and to use new air supply routes for both supply and extract. This meant that it was necessary to measure the attenuation of all the existing builders work ducts. After the measurements, it was possible to specify the maximum sound power level requirements for new air handling units, so that the noise rating NR15 would be met in the auditorium and on the stage.
As the new air supply would be from the under-seat plena, the termination would be very close to the audience. The main design objective was to limit the air velocity at the grille to a minimum (0.5 m/s). However, it was still necessary to investigate whether the regenerated noise from the supply diffusers would be an issue or not.

A mock-up of an under-seat plenum with air supply grilles was constructed for regenerated noise tests. The regenerated noise of several different diffuser types was tested in a reverberation chamber using several different air speeds. The test results showed that the regenerated noise was just low enough not to be an issue.

4 COMMISSIONING TESTING RESULTS

Room acoustic measurements were carried out after the refurbishment according to ISO 3382-1:2009. The measurements were taken in an unoccupied hall using omnidirectional loudspeaker and subwoofer as sound sources. Swept sine technique was used to derive the impulse responses and key acoustic parameters were calculated from the impulse responses. The key results and discussion are presented below.

Figure 11 shows the spatially averaged unoccupied reverberation time in octave bands, compared with similar measured values in 1967, 2013 and 2015.
4.1 Reverberation time

Figure 10. QEH Reverberation time comparison.

Figure 10 shows that the reverberation time measured in 2018 is very close to the values measured in 1967. This was the nominal target which is in line with the overall objective of decluttering the auditorium and bringing it back to its original 1967 state. The marginal difference at mid and high frequencies is likely to be due to the stage drapes and half deployed rear wall drapes that were present in the most recent measurements. The difference at 63 Hz is likely to be at least partly due to the absence of the resonators’ 25mm polyurethane foam in 2018 measurements. As discussed in Section 3.1.3, the 25mm polyurethane foam was found to boost the resonance and hence improve the absorption of the resonators at low frequencies.

4.2 QEH Predicted occupied Reverberation Time in 2018

Figure 11 shows predicted occupied Reverberation Time in Queen Elizabeth Hall when the hall is full and 2/3 full. The prediction has been calculated based on the occupied/unoccupied reverberation time measurements in 2013 (Ramboll) and 2004 (Arup). The graph includes the recommended ranges for orchestral music and classical music recitals. The graph also gives measured unoccupied values for reference.

It can be seen from Figure 11 that the predicted occupied Reverberation Time after the refurbishment is around 1.8 seconds and well controlled across the entire frequency spectrum. This is suitable for the performance of orchestral music and for classical music recitals.
4.3 Summary of room acoustic parameters based on the impulse response

Table 1 includes a summary of room acoustic parameters, namely Reverberation Time (T30), Early Decay Time (EDT), Clarity (C80), Sound Strength (G) and Stage Support (ST1).

Table 1. A summary of measured room acoustic parameters in the QEH after the refurbishment.

<table>
<thead>
<tr>
<th>Acoustic Parameter</th>
<th>Subjective listener aspect</th>
<th>Measured 2018</th>
<th>Optimal range</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unoccupied T30&lt;sub&gt;(500Hz-1kHz)&lt;/sub&gt; (seconds)</td>
<td>Reverberance</td>
<td>2.3 s</td>
<td>2.0 - 2.5 s</td>
<td>Close to 1967 value</td>
</tr>
<tr>
<td>Occupied T30&lt;sub&gt;(500Hz-1kHz)&lt;/sub&gt; (seconds)</td>
<td>Reverberance</td>
<td>1.8 s (predicted)</td>
<td>1.8 – 2.2 s</td>
<td>In design range for orchestral/recital music</td>
</tr>
<tr>
<td>Unoccupied EDT&lt;sub&gt;(500Hz-1kHz)&lt;/sub&gt; (seconds)</td>
<td>Perceived reverberance</td>
<td>100% of RT value</td>
<td>80-100% of RT value</td>
<td>Within optimal range</td>
</tr>
<tr>
<td>Unoccupied C80&lt;sub&gt;(500Hz-1kHz)&lt;/sub&gt; (dB)</td>
<td>Perceived clarity</td>
<td>-1.5 dB</td>
<td>-2dB ≤ C80 ≤ 2dB</td>
<td>Beneficial increase in 2018</td>
</tr>
<tr>
<td>Unoccupied G&lt;sub&gt;(500Hz-1kHz)&lt;/sub&gt; (dB)</td>
<td>Subjective level of sound</td>
<td>6.3 dB</td>
<td>0dB ≤ G ≤ 10dB</td>
<td>Within optimal range</td>
</tr>
<tr>
<td>Unoccupied ST1&lt;sub&gt;(500Hz-1kHz)&lt;/sub&gt; (dB)</td>
<td>Perceived stage support (for musicians)</td>
<td>-11.0 dB</td>
<td>-13dB ≤ ST1 ≤ -11dB</td>
<td>Within optimal range</td>
</tr>
</tbody>
</table>
4.4 Internal ambient noise level

Internal ambient noise from the mechanical services was tested during and after the final ventilation system commissioning and airflow adjustments. The target value of NR15 was reached with the two air handling units running at design duties.

5 SUBJECTIVE FEEDBACK

The Queen Elizabeth Hall re-opened on 9th April 2018 with a sell-out concert by the resident Chineke! Orchestra. Reviews for both the orchestra and the venue were equally positive, with the Guardian’s Tim Ashley saying “… the acoustic, always fine, strikes me as fractionally warmer than before. Chineke!... sounded wonderful in it”.

Regarding amplified music use, the feedback from the house mixing engineers and the sound system tuning staff has been very positive. The problematic 160 Hz coloration was noticed almost missing after the refurbishment. The reason for this is likely to be partly the new (Meyer Elephant) sound system with cardioid subwoofer, and partly the low-frequency absorption provided by the stage linings.

6 CONCLUSIONS

The acoustic refurbishment of the Queen Elizabeth hall resulted in a successful outcome. Limitations on costs did not permit all the acoustic installations proposed but the main acoustic brief was attained. The feedback from the audience and the musicians has been purely positive.

The reverberation in the Queen Elizabeth Hall has not changed substantially from its original 1967 value and the good reputation that the hall has enjoyed will be maintained.

Ambient noise from the ventilation system has been adequately controlled to meet specified levels.

7 REFERENCES

5. Hewett, I. Chineke! at Queen Elizabeth Hall, review – a joyous, eloquent way to mark the building’s new opening, Telegraph, 10th April 2018 (https://www.telegraph.co.uk/music/classical-music/chineke-queen-elizabeth-hall-review-joyous-eloquent-way-mark/)

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