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ACOUSTICS OF THE SYDNEY OPERA HOUSE CONCERT HALL

Part Two: The Acoustician's Perspective

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ABSTRACT

The challenges for an acoustician working in the Concert Hall at the Sydney Opera House are complex and profound. Kirkegaard Associates' work in the hall began with identification of the acoustics shortcomings of the hall, but finding the means to correct them proved to be a challenge because of the myriad constraints of the building. Beginning in November 2008 and continuing through September 2009, a series of temporary mock-ups were constructed in the hall to demonstrate acoustics improvements that could be achieved with architectural modifications. The mock-ups included reorganization of the reflectors suspended above the platform, changes to the stalls level "sawtooth" walls, suppression of long-delayed reflections from sidewall soffits, and demonstration of an electronic architecture system. The entire set of full-scale mock-ups was in place for a series of acoustic trials in September 2009 for listening evaluation during both rehearsals and concerts. The acoustics changes were positively audible by both musicians and audiences. In this paper we discuss the process of identifying the hall's shortcomings, the acoustic design concepts behind the mock-ups, and results of objective measurements made during the mock-up evaluation process.

INTRODUCTION

The Sydney Opera House is an architectural marvel and source of inspiration for the many who visit every year. The acoustics of the Concert Hall, however, have never matched the venue's reputation as a world class destination for classical music. We began our investigations into improving the hall's acoustics in 1996, building on observations made by other professional colleagues between 1996 and 2003.

During September 6-12 2009, Kirkegaard Associates participated in a series of acoustic trials in which several physical changes to the hall were temporarily implemented for evaluation by both performers and audiences. The acoustic trials demonstrated remarkable improvements in the hall's acoustics for both musicians and patrons. This paper summarizes the objective and subjective findings of these acoustic trials within the context of previous acoustic studies, while a companion paper [1] gives further background on the history and operation of Sydney Opera House and the process of managing the acoustic trials.

The Concert Hall is a 2,679 seat venue used for a wide range of concerts including symphony orchestra, choirs, chamber music, and amplified events. Beranek has published detailed information about the hall, including dimensions, materials, and measurements of standard acoustical pararmeters [2].

Previous Work

Several acousticians have studied the Concert Hall since its inauguration and have made recommendations for improving the hall's acoustics [3], including:

- Kirkegaard Associates (1996, 2007)
- Karlheinz Müller (1996)
- Peter Knowland and Associates (1997)
- Arup Acoustics (1998)
- Nagata Acoustics (2003)

These studies indicate a general consensus about the concert hall's most serious acoustic flaws:

- The surface area of the overhead reflectors is too small to be effective.
- The mass of the hall's wall and ceiling surfaces needs to be increased to improve bass response.
- The shaping of the 'saw-tooth' paneling flanking the stage and lower stalls audience creates seriously disturbing high frequency distortion.
- The height and shape of the stage platform needs to be altered to enable the best orchestral configuration and ensemble sound.
- Background noise is excessive.

In 2001 a solid overhead reflector was mocked-up to evaluate its impact on musicians' onstage hearing conditions. While this mock-up did improve hearing conditions, and was further supported in the 2003 follow-up report by Nagata Acoustics [3], this approach was ultimately abandoned because of structural, heritage, and coordination difficulties.

The 2003 Nagata report also recommended a set of semi-circular risers to improve musician communication and audience views of the orchestra. In March of 2006, the risers were mocked up with noticeable improvements for both musicians and audience members. However, the improvements were perceived as incremental and additional improvements would be necessary to achieve acceptable acoustics onstage.

In 2007 Kirkegaard Associates was commissioned to continue investigations into the Concert Hall's acoustical deficiencies. Our recommendations emphasized that acoustic conditions should be improved not only for performers, but for audience members as well, requiring a holistic approach to overall acoustics improvements.

During our 2007 visit, fabric panels were placed in front of the lower saw-tooth walls in order to demonstrate the improvement in sound with the distortion of the saw-tooth shaping removed. Due to the success of this trial, the fabric panels were subsequently left in place. It was acknowledged, however, that a sound-reflective covering would be a more acoustically appropriate long-term solution to this problem, since the lower sidewalls are important sound reflecting surfaces for both audience and performers.

Finally, in June 2009 the existing "ring" reflectors above the stage were temporarily in-filled with Perspex panels in an attempt to increase sound reflections to the platform. While this trial made an incremental improvement in onstage hearing, the reflector array was still too sparse to provide a satisfactory level of sound reflection on the platform.

ACOUSTIC TRIALS

In order to further explore and demonstrate the potential benefits of more extensive improvements to the Concert Hall, a series of acoustic trials was conducted during the week of September 6-12, 2009. For the acoustic trials, a series of temporary mock-ups was installed in the concert hall to coincide with rehearsals and performances by the Sydney Symphony Orchestra and the Sydney Philharmonia Choirs. Surveys were distributed to both performers and audience members to gauge subjective responses to the acoustic trials. Acoustic measurements were also performed in order to document the objective improvements to the room's acoustics.

The acoustic trials included 4 primary elements: modifications to the stage canopy, modifications to the lower sidewall geometry around the platform and the stalls level, strategic placement of lightweight fabric at the sidewalls behind the boxes, and installation of an electronic architecture system.

Source: Author

Figure 1. Photograph of the Concert Hall interior with acoustic trial elements in place

Stage Canopy

As a part of the acoustic trials the existing acoustic reflectors were redistributed to a more densely packed cluster over the center of the stage. They were supplemented by two rows of curved plywood panels at the downstage edge of the canopy and one row at the upstage edge. Figure 2 compares the existing and acoustic trial reflector layouts.

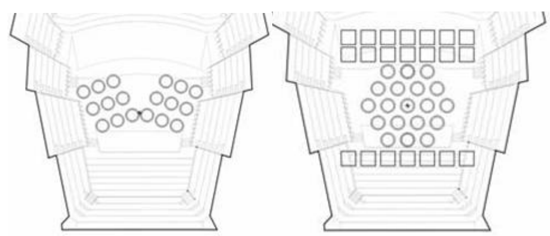


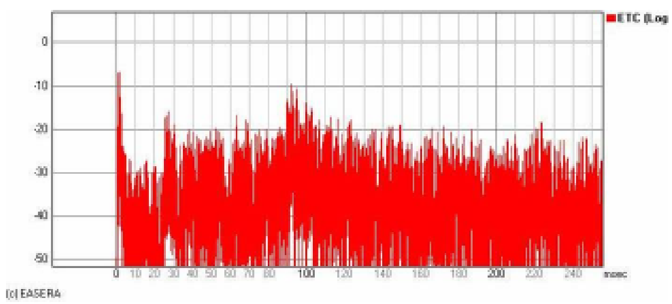
Figure 2. Diagrams of existing reflector layout (left) and acoustic trial reflector layout (right).

Musicians immediately reported improvements in hearing conditions with the redistributed reflector array. The improved layout provides two key benefits to onstage hearing conditions. First, by bringing the rings more closely together, the array begins to act like a continuous reflecting surface which enhances the strength and consequent audibility of overhead reflections. Secondly, the denser gathering of reflectors prevents excess amounts of energy from escaping to the upper volume above the stage and being reflected back down to the ensemble with a confusing delay.

Figure 3 shows impulse responses measured before and after the canopy was reconfigured, with the source at a percussion position on the stage and the receiver at the conductor's position. The sound source used was a small directional loudspeaker (Meyer Sound MM-4XP) to simulate the directivity of musical instruments better than a standard dodecahedral loudspeaker. The loudspeaker was aimed slightly upward to study the overhead reflection structure. Measurements were made using an Earthworks QTC30 omnidirectional microphone and EASERA acoustic measurement software.

In Figure 3 note several strong reflections at approximately 90ms after the initial arrival of sound, corresponding to late reflections from the crown and the ceiling immediately in front of the crown. These particular reflections are responsible for timing difficulties for percussion instruments heard downstage, especially at the Conductor's position. After the canopy was reconfigured the magnitude of this reflection was substantially lowered, as seen in Figure 4. This energy is visibly shifted closer to 25ms after the initial arrival of sound where it blends more smoothly with the rest of the room's reflections. This change represents a strong improvement in rhythmic clarity that can be directly attributed to the reconfiguration of the overhead canopy. This audible improvement was noted in conversations with the conductor between rehearsals. Members of the choir also cited an increased ability to hear other ensemble members. Members of the choir seated in the center terrace reported particularly significant improvements in the clarity of musical instruments which aided in their tuning and timing of vocals passages.

Existing reflector array



Modified reflector array

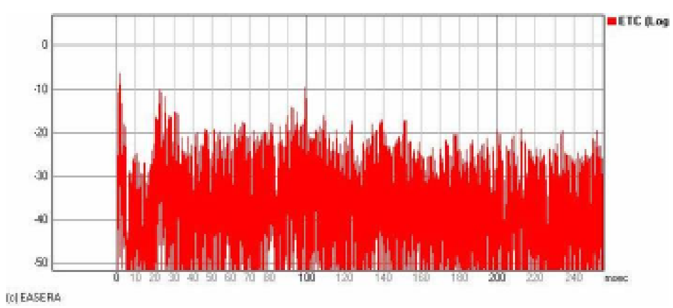


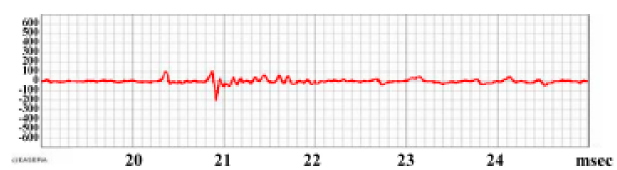
Figure 3. Impulse response showing overhead reflections at the conductor's position before and during the acoustic trials.

While the reconfigured stage canopy offered improvements to onstage hearing, we also found challenges with the underlying geometry of the reflectors themselves. The existing reflectors have evolved from their original configuration as empty rings. In June 2009 the rings were in-filled with a convex acrylic lens that greatly improved their effectiveness. However, these modified reflectors still fall far short of being optimal. The reflectors are strongly curved and are not smooth continuous surfaces where the lens intersects the outer ring. Both of these factors contribute to the sound being scattered too widely. In moderation, this spreading can be beneficial, but the geometry of these reflectors is too diffusive to provide adequate overhead coverage for musicians. The arrival of multiple weak reflections within a short time window leads to an aural "smearing" of the sound which is also highly undesirable for musicians attempting to play in unison.

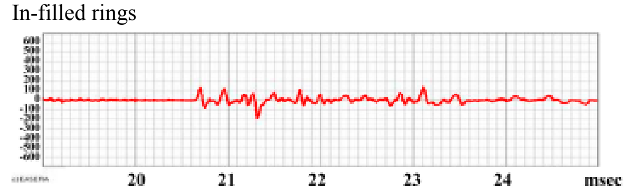
In order to evaluate potential improved reflector geometries, four types of reflectors were mocked up over the Concert Hall stage: the original rings, the rings in-filled with acrylic lenses, the rings covered at the underside by a flat circular wooden panel, and slightly bowed square plywood reflectors. Using the semi-directional loudspeaker described above together with an Audio Technica 835b shotgun microphone to discriminate against reflections from other room surfaces, we measured impulse responses for each type of reflector. The loudspeaker and microphone were aimed along the expected specular reflection path for the source-receiver configuration, and gain settings held constant to properly compare each reflector sample.

Figure 4 compares the reflection patterns for each reflector type. The comparison between the original and in-filled rings shows a modest increase in acoustic energy reflected to the platform when the rings were in-filled. Both the plywood coverings and the square plywood reflectors, however, provide substantially stronger reflections. The flatter plywood geometries also eliminate the "smeared" sequence of small reflections exhibited by the rings, resulting in a much more coherent and useful reflection for hearing other members of an ensemble across the stage. Not only is the level louder, but the acoustic integrity of sound coming from the overhead reflectors is preserved. Although the square plywood reflectors have a larger surface area, the magnitude of the reflection is slightly less than that from the circular plywood reflectors because the square panels are slightly bowed. This slight degree of reflection spreading is controlled and helps to blend the sound from adjacent reflectors to compensate for the gap between them, while avoiding excessive overlap. This bowing also helps to project appropriate amounts of sound into the house while retaining enough for onstage communication.

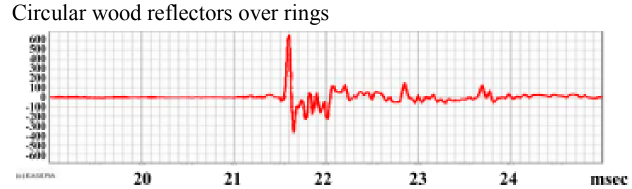
Original rings



In-filled rings



Circular wood reflectors over rings



Curved square plywood reflectors

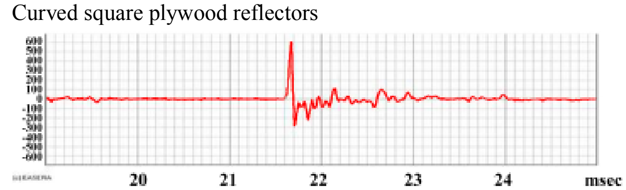


Figure 4. Comparison of reflection patterns from stage canopy reflectors. The vertical scale is linear pressure and the horizontal scale is time from 19 to 25 ms.

Lower Sidewalls

In 2007 the sawtooth-shaped walls were covered with a black sound-absorbing fabric to mitigate distortion artifacts that were detected from these surfaces. In a final implementation, however, these walls should be sound reflective surfaces to provide useful reflections to performers and audience members.

For the acoustic trials, sealed medium density fibreboard (MDF) panels were placed in front of the sawtooth walls. The MDF panels were designed to be adjustable to allow experimentation and optimization of wall angles. Over the course of the week, the orientation of the panels was optimized in plan and section. While noticeable to musicians onstage, the improvements from this modification were most significant in the stalls seating.

Initially, the panels were placed parallel to the existing wall surfaces in plan and vertical in section. However, it became apparent that this orientation sent excessive amounts of sound back to the stage and front of the stalls at the expense of listeners in the rear of the stalls and boxes. Loudness at the front stalls also built up to uncomfortable levels during *fortissimo* musical passages.

The second configuration rotated the panels in plan to distribute sound more evenly throughout the hall. This change improved sound distribution through the audience area, but loudness in the stalls was sometimes still excessive.

In the third configuration, the panel orientations were preserved in plan, but were tilted back to direct sound slightly upward into the space. This last configuration provided the best balance of useful undistorted reflections in the stalls and upper circle while controlling loudness. The tilted panels also improved listening conditions for the boxes by providing these locations with beneficial cross-room reflections.

Source: Jack Atley

Figure 5. Photograph of adjustable sidewall panels erected for acoustic trials. Threaded rod supports at the tops of the panels allowed tilt adjustments in plan and section.

Sound Absorbing Finishes

The intersection of the soffit with the outer walls behind the boxes forms a near 90-degree angle that returns reflections at nearly the same angle as the arriving sound. This geometry results in long delayed reflections that are distracting to performers and audience.

During the September 2009 acoustic trials, a 1m strip of lightweight felt was hung at the top of the walls that meet soffits behind the boxes, visible in the photograph across.

At one point in the acoustic trials the fabric came loose from its mounting during a rehearsal. The unexpected change was apparent to those listening in the stalls and musicians onstage, and demonstrated how critically this treatment is needed.

Electronic Architecture

For the acoustic trials we collaborated with the Dutch firm Acoustic Control Systems B.V. (ACS) to install a trial electronic architecture system within the Concert Hall. The system uses sound captured onstage with arrays of directional microphones. This sound is processed to create a field of early reflections and reverberation that is reproduced by a set of strategically placed loudspeakers distributed throughout the hall [3]. Because weak bass response has been a predominant criticism of the hall's acoustics, the reproduced sound was adjusted primarily to compensate for low frequencies.

In general, musicians and listeners described the resulting sound being fuller and warmer, with some explicitly commenting that the bass sound was clearer and easier to identify. There were no negative comments from musicians complaining about artificiality, over-emphasis of bass, or even noticeable amounts of sound coming from the loudspeakers on stage.

However, loudspeakers placed immediately behind the boxes were sometimes noticeable due to their close proximity to listeners in the boxes. This loudspeaker placement was a compromise for the temporary system installation during the acoustic trials, and would not be used in a permanent ACS system installation.

The ACS system provided much needed low frequency support without masking the natural acoustic sound or calling attention to itself. Figure 6 shows reverberation time measurements made in the fully occupied hall with the ACS system both off and on.

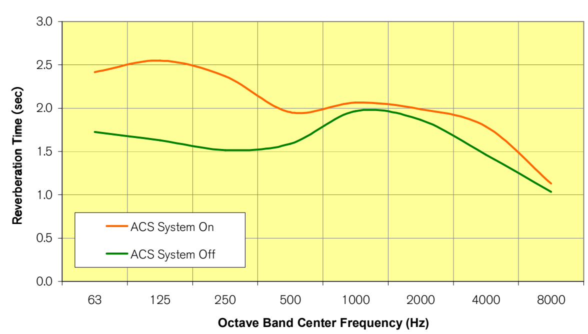


Figure 6. Reverberation time measurements made in the occupied hall with the ACS system on and off.

The reverberation time measurements were made with a Meyer Sound MM-4XP loudspeaker supplemented with a UMS-1P subwoofer to extend the low frequency response to the 63Hz octave band. This loudspeaker system has been found to give equivalent mid-frequency reverberation time results to the standard dodecahedral loudspeaker typically used for room acoustics measurements [5].

Measurements were made in the occupied hall following the procedure outlined in [5], in which a series of logarithmic sine sweeps was played and captured with EASERA to measure room impulse responses. The system enabled simultaneous measurement of 12 channels, allowing data at several audience and stage positions to be gathered with one set of sweeps, which is an important consideration for occupied measurements that require cooperation of the audience.

Figure 6 shows that the system substantially enhances low frequency energy in the room. For the acoustic trials the ACS system was tuned to create a natural RT curve for the Concert Hall, providing early reflection and reverberation support below approximately 500Hz. The slight dip visible in the orange curve at 500Hz was addressed by subsequent system tuning during the course of the week.

It is worth noting that the system will always reproduce the same acoustic response within the room as if it were part of the permanent architecture. Figure 7 shows the reverberation time curves for the system on during 4 different concerts. The small differences in the reverberation curves can be directly attributed to the differences in occupancy and crowd distribution for the various concerts, as opposed to the ACS system.

What began as a healthy skepticism about any electronic intervention in the natural acoustics, gradually transformed into an enthusiastic acceptance of the "acoustic" improvement it created, complementing the natural acoustics improvements achieved by the other trial elements.

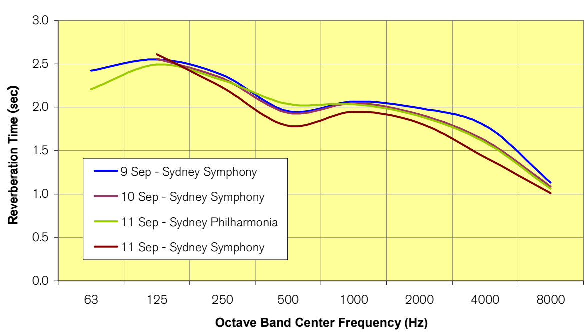


Figure 7. Reverberation time measurements made in the occupied hall with the ACS system in operation during 4 different concerts.

AMPLIFIED SOUND

The use of the Concert Hall for events using amplified sound is an increasing reality, so much that the number of amplified events now exceeds the number of purely acoustic events [1]. Because of this shifting pattern of use, it is important for the Concert Hall's acoustics be able to adapt to controlling reverberant sound rather than promoting it. Our visit to Sydney Opera House for the acoustic trials also allowed an opportunity to attend an amplified performance and measure room acoustic conditions during this mode of use. See also Figure 8 in [1].

During the concert (Ben Folds, 6Sep09) we used EASERA SysTune software to measure reverberation times in the hall, using program material from the PA system as a sound source. This approach allowed measurements to be made continually through the concert without any disruption. A direct feed from the mixing desk served as a reference signal, and measurements were limited to one microphone position located at the front of house mix position. Average results for reverberation times measured during the course of the concert, and also in the unoccupied hall during a sound check prior to the concert, are shown in Figure 8.

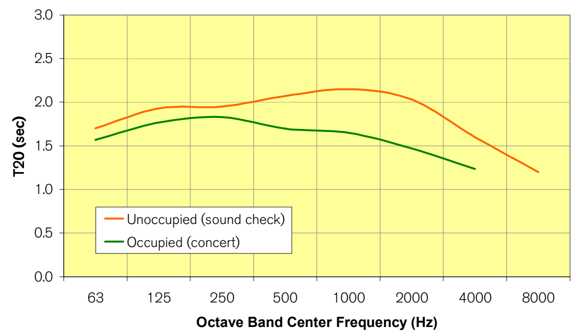


Figure 8. Reverberation time measurements made in the hall during an amplified event.

SUMMARY

The acoustic trials successfully demonstrated the potential for dramatic acoustics improvements to the Sydney Opera House Concert Hall. A denser, more efficient stage canopy significantly improved onstage hearing for musicians. Adjustable panels placed in front of the lower sawtooth-shaped walls provided useful sound reflections to both musicians and audience members. Carefully placed frequency-limited sound-absorbing materials attenuated disturbing reflections. Finally, an ACS electronic architecture system provided much-needed support for low frequency sound energy in the hall. Efforts are currently underway to develop detailed design solutions and make the modifications permanent.

ACKNOWLEDGEMENTS

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