ACOUSTIC DESIGN OF THE TOWER THEATRE AT THE IRISH WORLD ACADEMY OF MUSIC & DANCE

S Di Rosario	Buro Happold Ltd, London, UK
A Meachin	Buro Happold Ltd, Bath, UK

1 INTRODUCTION

The Irish World Academy of Music and Dance is a new departmental building for the University of Limerick in Ireland and was completed in 2010. A central feature of the building is the Tower Theatre, a cylindrical recital room of approximately 20m height and 13m diameter.

This paper describes challenges and solutions in acoustic design of the Tower Theatre.

2 ARCHITECTURAL BACKGROUND

The building's architect Daniel Cordier recognised that the cylindrical shape of the Tower Theatre would create difficulties, and in an interview[1] said "architecturally and acoustically it is the worst possible plan and volume to select for a performance space." However, also recognising the aesthetic significance of the form (to create a heart to the building and a visually meaningful destination when coming over the "Living Bridge"), the acoustician and architect collaborated to develop a room design that supported its intended use. Photographs of the completed development are shown in Figure 1.

Irish World Academy of Music & Dance – Copyright Ros Kavanagh

Figure 1 - Left: exterior view of the Irish World Academy of Music and Dance, with the Tower Theatre visible in the centre of the roofline. Right: interior view of the Tower Theatre

Some architectural constraints on the acoustic design were:

- The room had to retain its round plan. An architectural study of the Tower Theatre[1] concluded "curved plan spaces retain a sense of informality as they focus the musicians and the audience towards each other within the space". Great emphasis was placed on this desired informality and it could not be compromised

- The room had to retain its impression of being a tall tower. An intention was to "echo the monastic towers of Clonmacnoise"[1] and to establish an urban landmark

The Tower Theatre is mainly used for unamplified traditional Irish music. A section can be seen in Figure 8.

3 ACOUSTIC DESIGN CHALLENGES

The shape and size of the Tower Theatre presented these initial room acoustics challenges:

- Focusing effects due to concave wall surfaces. These would risk creating uneven sound level distributions and unnatural image location impressions

- Late reflection from the ceiling. This would be around 100ms after direct sound arrival, so would risk creating a disturbing and easily perceptible echo

Problems that could be created by solutions to the above include lack of reflections and reverberation could result from excessive absorptive treatment. These would render the room unsatisfying to play in and unflattering to music.

The acoustic design sought to balance treatment of the inherent room shape defects with maintaining an adequate level of reflections and long reverberation time.

4 ACOUSTIC DESIGN SOLUTIONS

The adopted room acoustic design had the following features:

- Upward inclined section of the wall at head level to shift focused reflections upwards to where they could not be heard

- Low-frequency absorbers around the bottoms of the walls. The purpose of these was to control focusing at frequencies below which the inclined walls could effectively redirect reflections

- Treating the walls with absorbers and modifying their shape to prevent second order reflections back to source locations

- Absorptive ceiling to prevent echo from the ceiling

- Multiple suspended reflectors with diffusive surface to re-enforce early reflections and to mask residual echo from ceiling

4.1 Low wall

4.1.1 Design description

The structural design of the Tower Theatre included two concrete ‘ring beams’, separated by concrete columns at 4m spacing. The spaces between the ring beams and between the columns offered a suitable location for acoustic treatment without reducing the room’s floor area. A sketch of the adopted solution for this region at the bottom 4m of the round wall is shown in
Figure 2.

The wall has these parts, ordered from floor level upwards:

- **PART 1** Below the lower ring beam the cavity is concealed by slatted timber backed with 50mm mineral wool. Where this construction would restrict airflow from the vents in the cavity behind the mineral wool is locally omitted. The slats were configured to pick up an architectural theme used in many areas of the building and illustrated in Figure 5

- **PART 2** The front of the lower ring beam is covered by slatted timber backed with mineral wool, which is a continuation of the covering to the wall part below

- **PART 3** Above the lower ring beam is an area of wall inclined upwards at 20 degrees from vertical. This wall is formed from 18mm thick MDF panel perforated with 70mm x 70mm square holes on a square 300mm grid. 50mm mineral wool with black tissue facing backing is fixed to the rear of the perforated panel. These panels form faceted curves (using flat panel sections)

- **PART 4** Wooden slats as used on the lower wall sections are continued over this part of wall mainly for appearance, but also having the acoustic benefit of increasing high frequency diffusion

- **PART 5** The underside of the upper ring beam is inclined at 30 degrees from horizontal as illustrated. The lower surface of the ring beam is covered by slatted timber backed with black tissue-faced mineral wool

- **PART 6** The front surface of the upper ring beam and the concrete block wall above are untreated

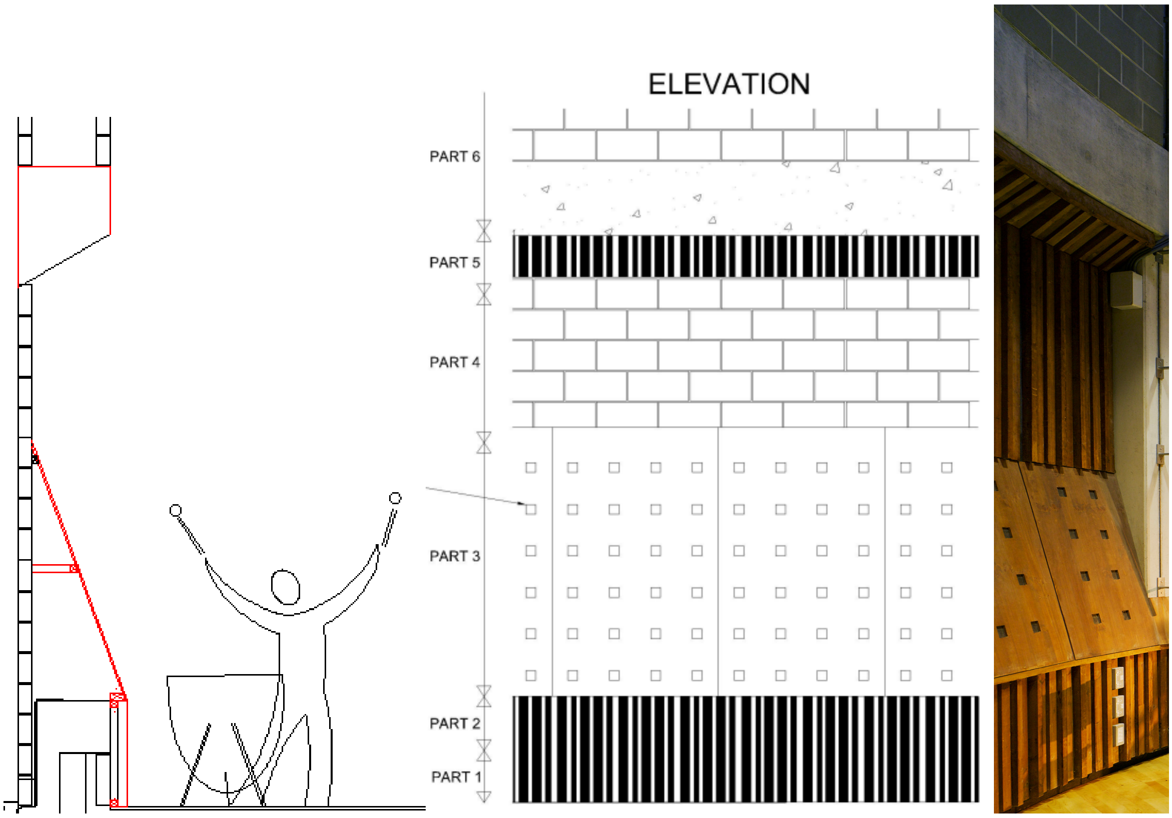


Figure 2 - Low wall acoustic design sketches and photograph (Irish World Academy of Music & Dance – Copyright Ros Kavanagh)

4.1.2 Inclined wall effective frequency range

A simple boundary element model was used to calculate the relative level of reflections at various frequencies as a function of receiver height; the results are illustrated in Figure 3. Note that the graph shows only the reflection due to the inclined wall section (part 3) – the result is more complicated when taking into account the other wall sections, but with the same fundamental features. The model was two-dimensional and based on summation with phase of reflections from 20mm elements of the wall surface. The calculations were implemented using a Microsoft Excel spreadsheet. Frequency-dependent surface absorption is taken into account. It can be seen that high frequencies are effectively deflected to well above normal audience height, but at 63Hz and 125Hz there is little variation in reflection level with height.

The strategy adopted was:

- High frequencies are deflected above listener heads to mitigate focusing effects
- The inclined wall includes a Helmholtz resonator tuned to the 125Hz octave band. This reduced the level of reflections in the frequency range to make focusing less noticeable
- At low frequencies (63Hz and below) sound is not effectively deflected or absorbed by the low wall arrangement. However, there is little energy content at such low frequencies in traditional Irish music, so this was expected to be acceptable

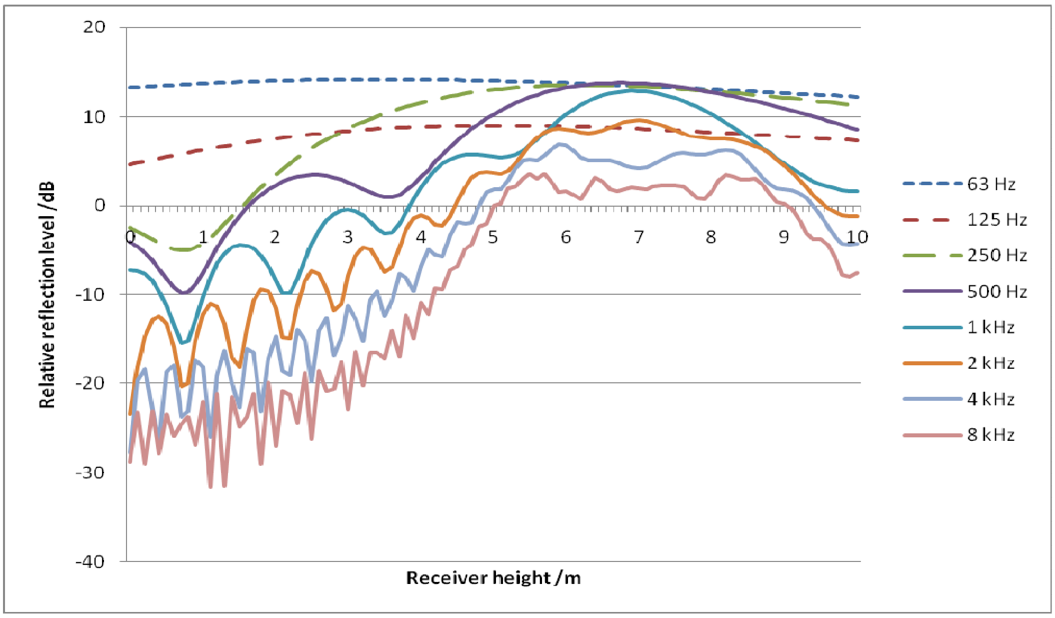


Figure 3 - calculated reflection level from inclined wall (part 3) as a function of receiver height; source at 1.5m height; source and receiver on room central axis

4.1.3 Control of double reflections

Wall parts 1 and 2 (below the inclined section) are absorptive to prevent double reflections causing focusing problems. Wall part 5 (underside of top ring beam) is inclined for the same reason. The strategy is illustrated in Figure 4.

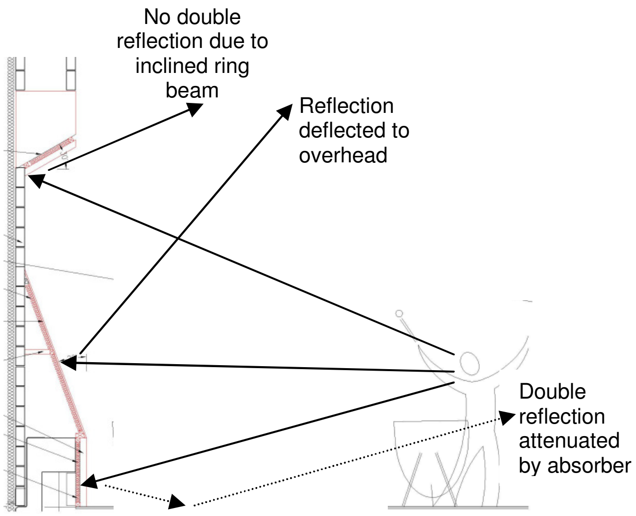


Figure 4 - Low wall high-frequency reflection control strategy

4.2 Ceiling

The ceiling was treated with a mineral wool absorber concealed behind timber slats as shown in Figure 5.

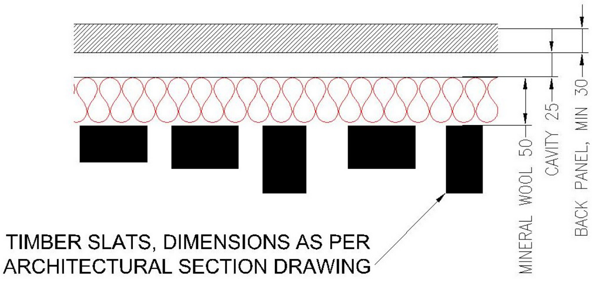


Figure 5 – Section through ceiling acoustic treatment

The aim of this was to prevent reflections from the ceiling being perceived as a discrete echo. This aim was also assisted by the suspended reflectors – see section 4.3. It was known that the depth of the cavity behind the mineral wool would determine low-frequency absorption, and in turn influence the subjective ‘warmth’ of the room. A room acoustic model using CATT-Acoustic auralisation was used to assist in making a judgment of appropriate depth – see section 4.3 for more details.

At design stage it was stated by the acoustician that the optimum cavity depth (and hence low frequency absorption) could not easily be accurately predicted, and that therefore an ideal solution would be to make the depth adjustable at commissioning stage. However, due to access difficulties this was deemed impractical and not implemented.

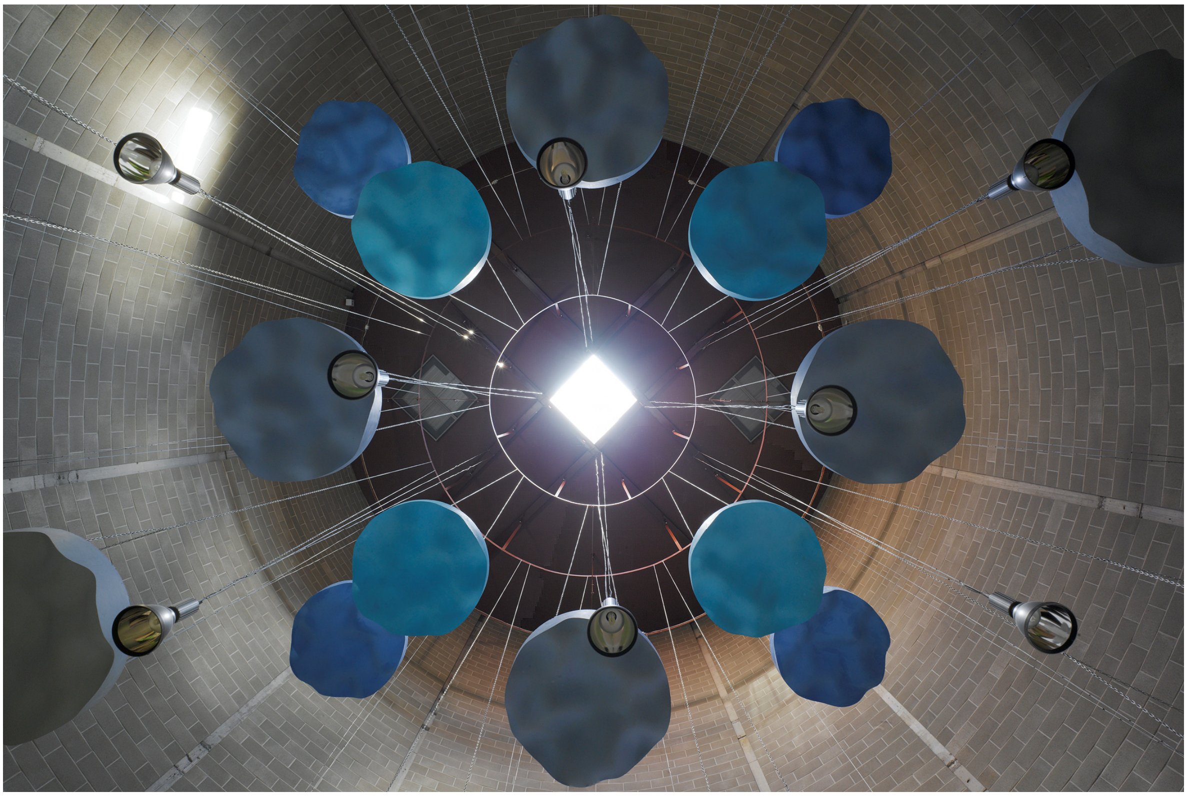
4.3 Suspended reflectors

A sparse array of overhead suspended reflectors was included. The purpose of these was:

- To increase early reflections to improve strength, stage support and room diffusivity at high frequencies
- To provide multiple early reflections to prevent the late ceiling reflection being perceived as an echo

The RPG Waveform Bicubic product was chosen for the reflectors, as it was acceptable to the architect in appearance as well as offering useful high-frequency scattering. A special round 1.2m diameter version was commissioned to fit in with the visual theme of the room. Nineteen units were suspended at a range of heights from 4m to 9m above floor from a steel grid at ceiling level. A photograph of the installation is shown in Figure 6.

It was desirable to use the minimum possible number of suspended reflectors, both to control cost and to maintain a visual connection with the high overhead volume. It was also desirable to restrict their size for the same reasons.



Irish World Academy of Music & Dance – Copyright Ros Kavanagh

Figure 6 - View of the ceiling showing suspended reflectors

The frequency range over which the suspended reflectors were effective as reflectors was considered. Based on the work of Rindel[2,3], we know the approximate response of the reflector for normal incidence and reflection will be:

- Below a cut-off frequency f the reflection level will drop at 6dB/octave
- Above f the reflector will act as a geometric reflector

$$f = \frac{c}{\left(\frac{1}{r}+\frac{1}{s}\right)A^2} \tag{1}$$

where r=receiver distance, s=source distance and A=reflector diameter

For the range of reflector heights used (4m to 9m) and assuming source / listener height of 1.2, the calculated cut-off frequency will be f = 330Hz to 920Hz.

Figure 7 shows the reflection strength averaged over the range of reflector heights; a typical reflection at 400Hz will be 6dB below high-frequency level. We can conclude that these reflectors are not very effective below 400Hz. Acoustically it would be desirable to have a lower cut-off frequency, but the visual implications of having larger or lower reflectors were not compatible with the architectural constraints.

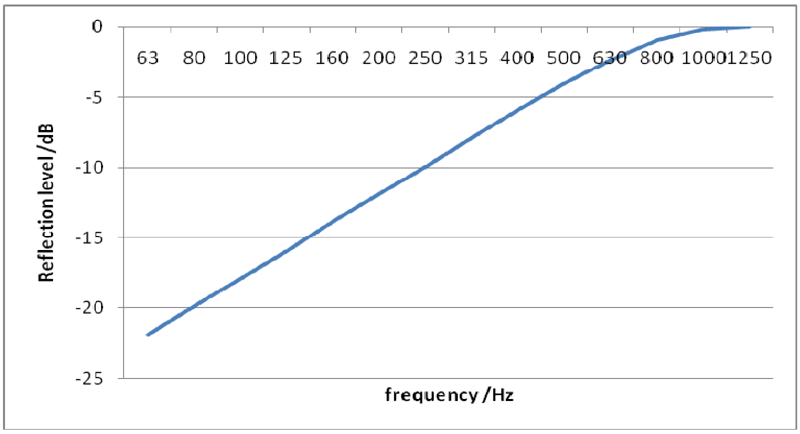


Figure 7 - Relative level of reflection (compared to simple geometric reflection) from suspended reflectors as energy average over range of suspension heights

The effect of the limited effective frequency range of the reflectors is illustrated in Figure 8. The reflectors create a diffuse field at high frequencies (>>400Hz), but the room acts as transmission line terminated at the ceiling for low frequencies (<<400Hz). The low-frequency absorption of the ceiling is seen to be critical in balancing the two risks of late low-frequency ceiling echo and inadequate low-frequency reverberation.

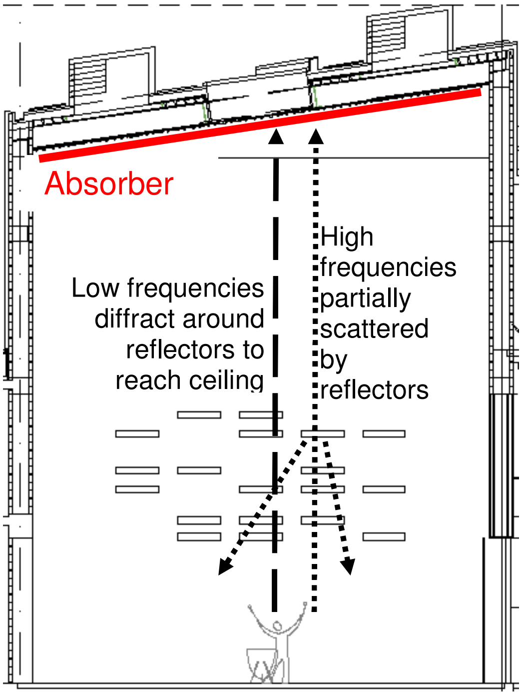


Figure 8 – Suspended reflector action at low and high frequencies

To determine an appropriate quantity of suspended reflectors a CATT-Acoustic auralisation was used. Increasing the quantity of reflectors had these effects:

- Early reflections were added, which masked the echo from the ceiling (although treated with absorber, the residual reflection was expected to be audible, and this was confirmed subjectively on site prior to the installation of suspended reflectors)

- The ceiling reflection was reduced due to the introduction of obstacles

The quantity of reflectors in the model was gradually increased until the discrete late reflection was no longer audible in auralisation, and this informed the decision to specify a quantity of 19 reflectors. The quantity of reflectors needed to create a pleasing visual pattern was also taken into account.

5 RESULTS

5.1 Subjective impressions

Buro Happold made these notes on our subjective evaluation of the room acoustics during a commissioning site visit:

- No significant room defects (as might be expected in a tall cylindrical room) observed. In particular, no focusing effects or late echoes were heard
- Some minor local variations to reflection timbre. These were noted to depend on whether the lobbied doors were open or shut. This effect was very subtle and careful listening was needed to identify it
- Moderately ‘bright’ sound
- ‘Overhead’ sound to reverberation due to a clap or shout created by the listener, but more ‘enveloping’ when listening to sounds from other sources or performers
- Fairly short reverberation time for the perceived room volume
- Intimate, loud and clear sound

5.2 Objective measurements

All room acoustics parameters were measured by a laptop-based system using Easera V1.0.60 software. This method compares computer-generated stimulus signals reproduced using a loudspeaker to the sound recorded by a microphone. The software calculates the corresponding impulse response, and the various room acoustics parameters are derived by post-processing the impulse response.

An Edirol UA-101 sound card was used to interface all analogue audio signals to the computer.

A 5.5s swept sine wave was used for all measurements, with each sweep repeated four times. The stimulus signal was generated by the Easera software.

The stimulus signal was reproduced by a Genelec 8030A active loudspeaker at a tweeter height of approximately 1.2m. This has directivity properties similar to a human head and was therefore useful to give an approximate indication of the sound strength of a person speaking. Earthworks M30 omni-directional and Core Sound Tetramic Ambisonic microphones were used for measurements.

For strength calculations, the impulse response at 1m from the Genelec loudspeaker on axis was measured, then reduced by 20dB to simulate 10m measurement distance and trimmed to remove room reflections. Note that the use of a directional loudspeaker does not correspond to the method defined in ISO 3382, but gives a good indication of strength and other aspects of performance with real directional sources.

Some of the main results of the measurements are below. These values are all averaged over a representative sample of source and receiver positions.

- Average reverberation time T_{20} over 500Hz and 1kHz octave bands: 1.1s. See Figure 9 for more details
- Average clarity C_{80} over 500Hz and 1kHz octave bands: 9.0dB
- Average strength G over 500Hz and 1kHz octave bands: 9.3dB

These results could be interpreted to say that the room is moderately reverberant with high levels of clarity and strength.

Figure 10 shows a typical measured Schroeder reverse integration curve. It can be seen that there is not a linear decay (in dB), but the slope of the curve becomes less steep after a more rapid early decay.

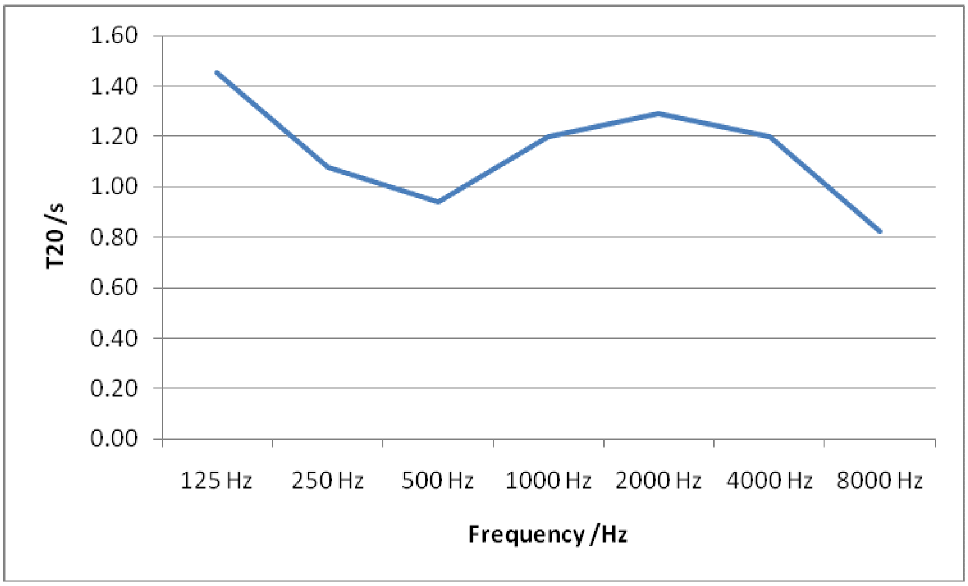


Figure 9 - Measured reverberation time

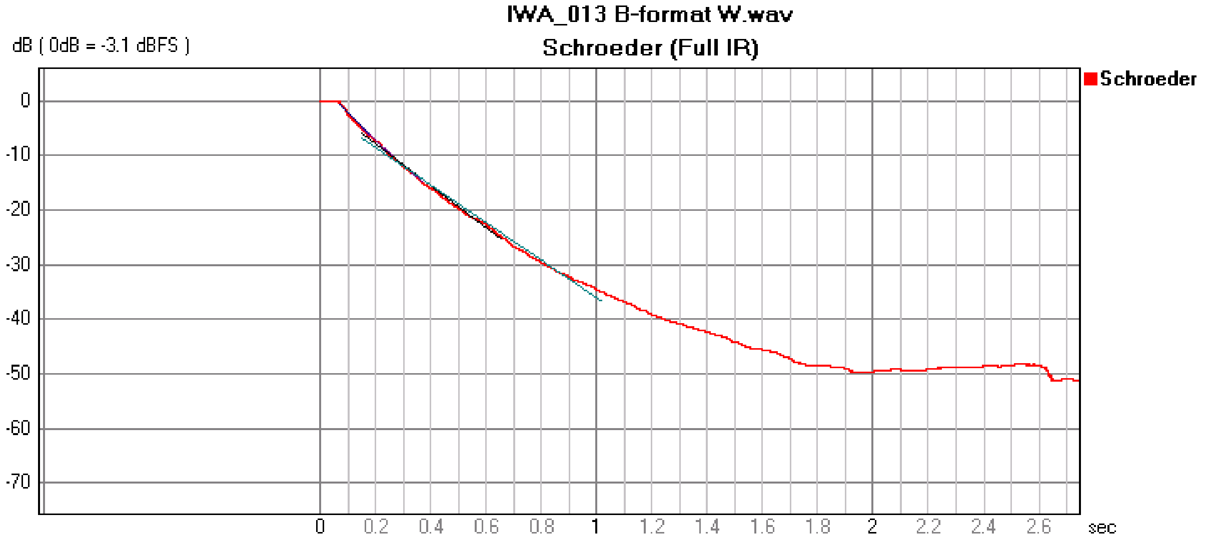


Figure 10 - Schroeder reverse integration curve

6 CONCLUSIONS

The reverberation properties of the Tower Theatre can be considered in three frequency regions:

- >>400Hz – the sound field had a high level of diffusivity and acted largely as a Sabine space
- 250Hz to 400Hz - the tower acts as a transmission line and the ceiling had significant absorption. Hence the transmission line was largely absorber-terminated, leading to fairly short reverberation time
- <250Hz - the ceiling has little absorption and the transmission line mechanism has little effect on reverberation. There will be a late ceiling reflection at these frequencies, but it was not observed to be problematic

These observations align with the measured reverberation time shown in Figure 9.

The acoustic design effectively controls the acoustic defects inherent in the tall cylindrical shape of the Tower Theatre. Neither focusing effects nor ceiling echo were observed by listeners. Overall, the acoustic design has struck a reasonable balance between curing these inherent defects and providing a supportive space for musicians and listeners.

7 REFERENCES

1 P Shore, Shaping informal interaction for the transmission of Irish traditional music, BArch thesis, Waterford Institute of Technology (2010)
2 M Barron, Auditorium Acoustics and Architectural Design, E & FN Spon, Appendix A (1992)
3 JH Rindel, Attenuation of sound reflectors due to diffraction, Proceedings of the Nordic Acoustical Meeting (1986)