Designing for speech in a circular room

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ABSTRACT

Concave surfaces are often avoided by acousticians for fear of focusing and in particular circular room designs are generally avoided for meeting room applications. In 2016 I was approached by Macquarie University to carry out the acoustic design for the refit of their existing circular Council Room. The project was to involve a significant financial investment in a single, high profile chancellery space.

This paper provides a summary of the acoustic effects of surfaces curved in a single dimension and the acoustic requirements for support of speech and the application to circular rooms. The paper then describes the application of these principles to the design of the MQU Council Room project and an examination of the outcomes.

The architectural intent was to highlight the existing circular nature of the space. The acoustic brief noted that speech intelligibility in the existing space was not acceptable requiring that the acoustics in the new fitout space required a significant improvement. The new design needed to provide speech intelligibility between people around the Council Table, the people seated around the periphery of the room. The acoustic design was also required to provide the necessary speech intelligibility for the use of the proposed new video conferencing system to be installed.

The solution was developed using a range of acoustic modelling tools and included 3D impulse response measurements to benchmark the acoustic performance and reflection sequence in the existing space and to perform certification on completion. The most critical element for the rooms acoustic success was the design of the circular ceiling reflectors. These were designed using an iterative process involving collaboration with the Architect, starting with paper cut-outs, before progressing to proprietary 3D modelling and ray tracing.

1 INTRODUCTION

Circular room designs are normally avoided by acousticians when designing rooms for speech. Macquarie University (MQU) in Sydney have recently undertaken a full refit of their Chancellery Council Room, with one of the key drivers behind the project the sub-standard acoustic performance of the previous space. The room is circular and there was no scope or desire from the client to fundamentally change the shape of the space. In particular the architectural vision for the space was to highlight the circular nature of the room.

The acoustic brief was that speech intelligibility in the existing space was not acceptable and the acoustics in the new space had to be significantly improved. The design needed to provide intelligibility for a variety of uses and locations between the people around the Council Table, people seated around the periphery of the room and for the use of the proposed video conferencing system

The particulars for the acoustic requirements for the audio visual and video conferencing systems in the space are however beyond the scope of this paper.

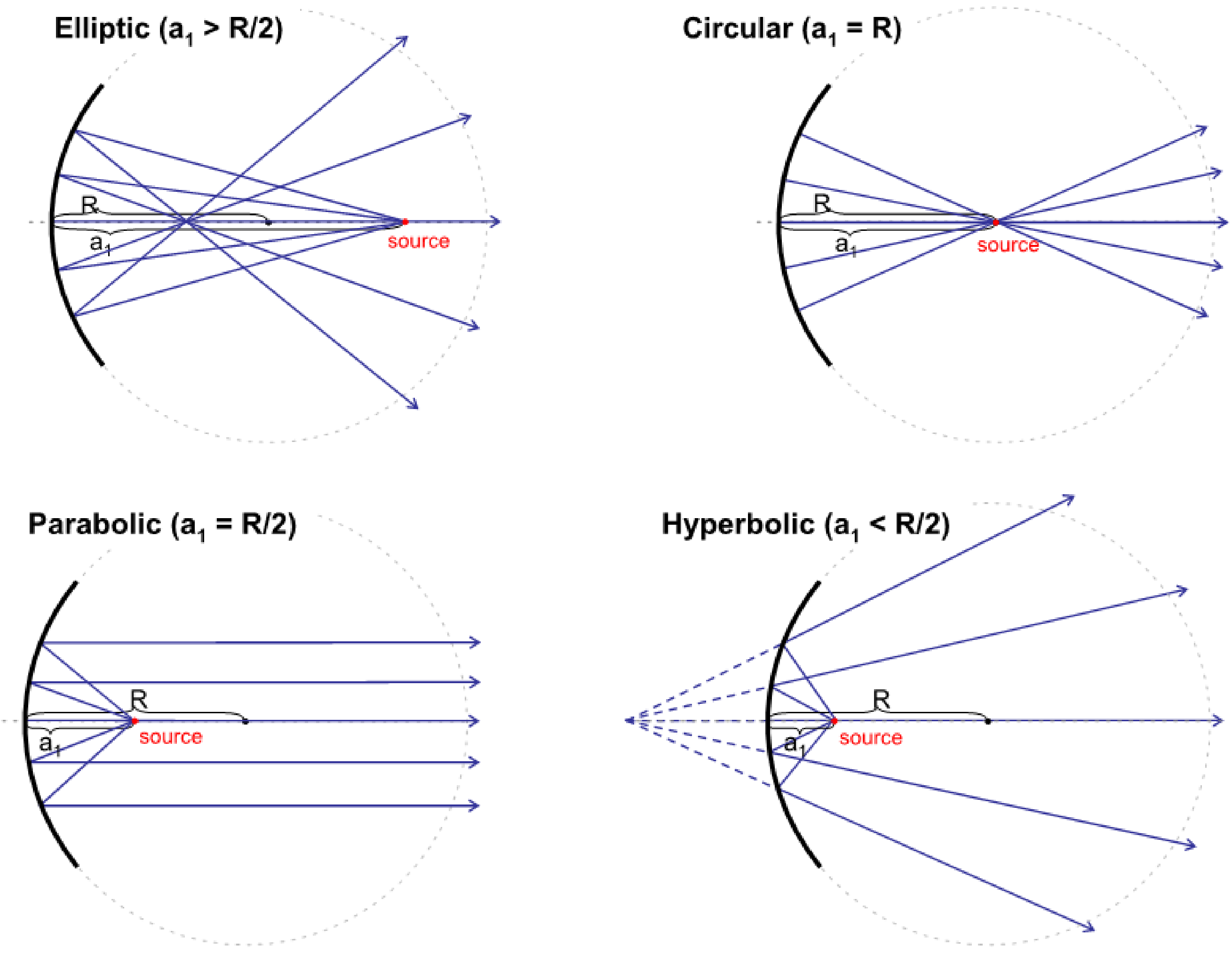
The paper concentrates on the acoustic design of circular spaces with the complexities associated with multiple possible sources locations around the room, i.e. rooms for dialogue, rather than presentation spaces with a single fixed presenter location.

This paper provides a summary of the acoustic effects of surfaces curved in a single dimension and the acoustic requirements for support of speech and the application to circular rooms. The paper follows with a description of the application of these principles to the design of the MQU Council Room project and an examination of the outcomes.

2 ACOUSTICS OF CURVED SURFACES

The acoustics of one-dimensionally curved surfaces is well documented and this paper does not provide methods for calculating the effects of such surfaces. Further reading in this area can be found in Cremer & Muller (1982), Wulfrank and Orlowski (2006), with guidance on quantification of reflections in Rindel (1985). A high-level summary of the qualitative effects of one-dimensionally curved concave surfaces can be adapted from Cremer & Muller (1982).

Such a surface can be approximated by considering a circular segment with a radius R, with the location of the source relative to the centre of the circular segment determining the reflective behaviour of the surface. The type of reflection that occurs can be either elliptic, circular, parabolic or hyperbolic, as shown diagrammatically below (where a1 is the source to reflector distance).



Source (Wulfrank, 2010)
Figure 1: Conic section reflection types

Elliptic reflection occurs where the source to reflector distance is greater than half the radius. The reflected rays will converge at a point (with high sound intensity) before diverging beyond that point.

Circular reflection is a special case of elliptic reflection, where the convergent point of the rays is at the same location as the source.

Parabolic reflection occurs where the source to reflector distance is at the midpoint between the centre of the circle and the reflector. In this case the reflections form parallel rays, which neither converge or diverge.

Hyperbolic reflection occurs when the source to receiver distance is less than half the radius of the circle. In this case the rays diverge, although less so than if they were reflected off a plane surface.

It is important to note that in the elliptic (and circular) case, that beyond a certain point from the reflector the reflections from the concave surface are divergent. A circular surface can therefore act to diffuse sound, rather than focus it. It is worth highlighting that in this instance the reflected rays cross over the centre line and therefore invert or mirror the acoustic image of the source.

3 DESIGN QUALITIES FOR SPEECH CLARITY

The fundamental requirement for achieving clarity of speech communication is that the acoustic content of the speech required for understanding of its content is maximised at the listener, whilst any noise not required for understanding is minimised. This is typically known as the *signal* to *noise* ratio, with higher values being favourable for good Speech Intelligibility conditions.

The *signal* component for speech is the direct sound from the speaker as well as any reflections arriving within the first 50ms of the direct, which serve to reinforce the message (Kutruff 2009). The *noise* component is generally comprised of late reflections, arriving after 50ms of the direct, the background noise from mechanical noise and distracting noise from other sources inside or outside the room.

The balance between early and late arriving energy can be represented as an index of energy before and after 50ms of the direct sound, C_{50} in dB. The higher the value of C_{50} the more sound energy within 50ms of the direct is arriving at the listener, relative to the late energy. Increasing the C_{50} will have the effect of increasing intelligibility.

4 APPLICATION TO CIRCULAR ROOMS

The following guidance is provided as one possible approach for the design of circular spaces to achieve the high signal to noise ratios outlined above.

As outlined in Section 2 the focusing effects of the circular walls are likely to cause uneven response throughout the space. Where speech is to be conveyed across the whole, or significant part, of the floor space and the speaker location can vary (e.g. with multiple speakers in a room, rather than a single speaker at a fixed location) the room can provide elliptic, parabolic and hyperbolic responses. For this reason, the focusing aspects of the curved surface are to be minimised, by the inclusion of absorption and/or diffusion. The lower frequency cut-off of articulated diffusing elements will broadly increase with the depth of the physical element (Cox & D'Antonio 2009). Because the circle will support focusing across a wide range of frequencies the physical depth of diffusion required to effectively break up low frequencies may be prohibitive. For this reason, as well as to control overall reverberation times (as discussed later), the treatment to a curved wall surface is commonly absorptive to some extent and may also have diffusive properties.

The critical zone for installation of absorbent wall materials will vary depending on a range of factors including the dimensions of the space, ceiling height, the layout of the room together with the ceiling and floor finishes. Typically absorptive treatment in a zone from 0.5m to 1.8m above floor level will reduce much of the focusing. Reflections from the wall above or below this zone will normally include at least a second reflection off the wall or floor and be considered as diffuse.

It is worth noting that a receiver location at or very near to the centre of a circular room like that covered in this paper should ideally be avoided, regardless of acoustic treatment. Even with absorptive treatment in the focusing zone of the walls there will still be a level of energy reflected and concentrated at the centre of the room (which is likely to be uneven in frequency) for a source/receiver in this area. The centre of the room is therefore likely to receive noticeably more energy than other locations due to the sheer quantity of reflections focused at this point.

With the walls treated to reduce undesirable reflections, early reflection from the ceiling and floor surfaces must be harnessed to support the useful speech content. The floor plane is often not able to be relied upon for such reflections due to the presence of objects, such as chairs, table and people, between the source and receiver. The ceiling, or reflective elements below the ceiling, therefore becomes the primary means by which early reflections are delivered.

A large table, typically part of a meeting room fitout, can be used to preserve early sound energy transmissions. If the ceiling and tabletop are to be used for reflections it is important to consider the potential path length difference to the receiver experienced by multiple reflections between the two surfaces. In that instance the receptor will receive the signal from reflection paths via both the ceiling and the table, with the path difference between the two having an influence on Speech Intelligibility.

If the ceiling is to be employed for the provision of early reflections to the receiver then its height is important, as the higher the ceiling is the longer the path length difference and time delay to receivers.

If the ceiling (or suspended reflector) is too high above the table there may be significant energy arriving at the receiver more than 50ms after the direct sound, reducing clarity.

The ideal height acoustically for this reflecting surface may be lower than the ceiling height required for other reasons such as for visual connection to screens, aesthetics, Building Code requirements or overall reverberation time in the space. In such instances a reflector surface suspended or constructed below the ceiling may be considered.

The shape of the ceiling must also consider where the sound energy from reflections is to be directed. Ideally the shape should support the transfer of early energy between source-receiver locations and minimise any energy transfer to areas where there are no receivers. Not only does energy that is directed outside the receiver zones not reinforce the early reflections, but it becomes part of the 'noise' in the room which masks the required signal. Similarly, any sound reinforcement or audio equipment should be designed to direct signal only to areas with receivers.

Any additional absorptive treatment (other than deployed on the curved surface) required to reduce late reflections and achieve the desired reverberation time in the room should be placed on surfaces that do not support early reflections between source-receiver zones.

Minimising noise in the space is obviously critical in achieving a good signal to noise ratio and thus intelligibility. This paper does not go into detail of how to reduce such noise but broadly the approach is to reduce noise from sources inside the room and intrusion from external noise sources.

Noise sources inside a room usually include mechanical services as well as audio visual equipment. For a large room it is usually a requirement that HVAC machinery is located outside the space, with ducted supply and return air. Noise from audio visual equipment can often be overlooked as it does not form part of the building works. However, such sources must be considered as even with low source levels they can be problematic due to their close proximity to the receivers, the potential to have many of them and the difficulty in applying noise controls retrospectively.

Noise from external sources may include noise from adjacent occupancies within the building (including above or below), noise breaking from external sources such as transportation, noise generated by rain on the roof or via the building structure, for example from lift shafts. The acoustic envelope of the room is obviously important in minimising noise intrusion but is not covered further in this paper.

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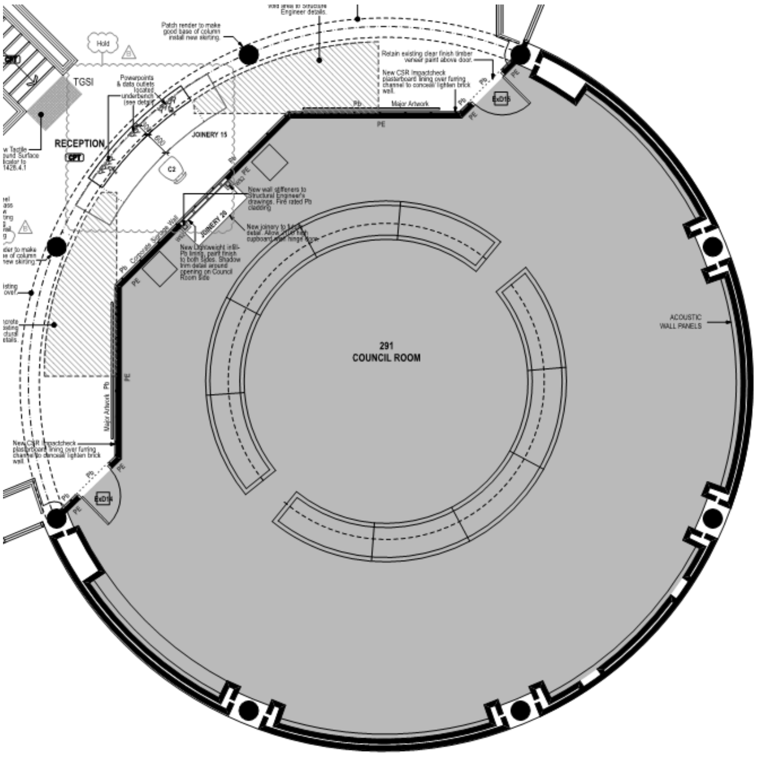
5 MQU COUNCIL ROOM – EXISTING ISSUES

The existing space was a circular room, approximately 16.5m in diameter, with part of one end sectioned off for an external reception point, as shown in Figure 2. The slab to slab height was 4.6m with 3.5m clear height to the underside of structural beams.



Source (BNMH Architects, 2017)
Figure 2: MQU Council Room – plan view prior to acoustic upgrade

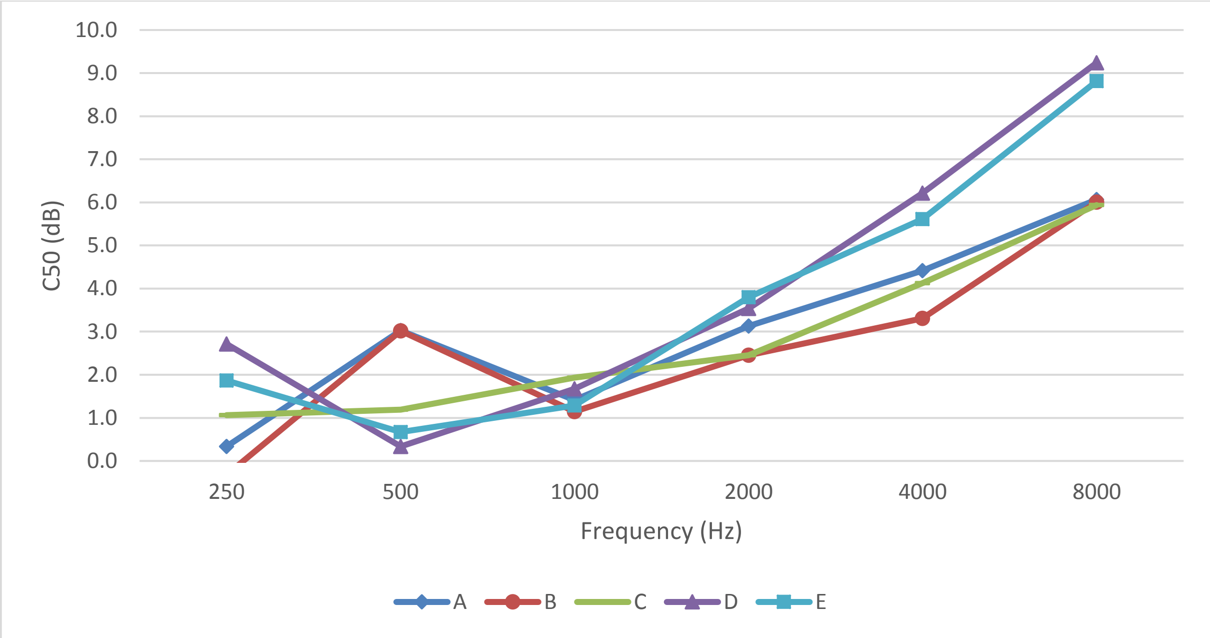
A ring of tables approximately 900mm deep formed a circle in the centre of the room, with the Council seated on the outside of this circle. Further meeting attendees were seated on loose chairs around the periphery of the room.

A narrow circular reflector (approx. 900mm wide) and having a diameter slightly smaller than the ring of tables was installed. The circular reflector included vertical undulations at regular intervals. Square reflectors were installed inside the line of the circular reflector, at a higher level. Slotted timber acoustic panels were installed around the circular wall section. The existing reflectors and wall panels are shown (in part) in Figure 3.

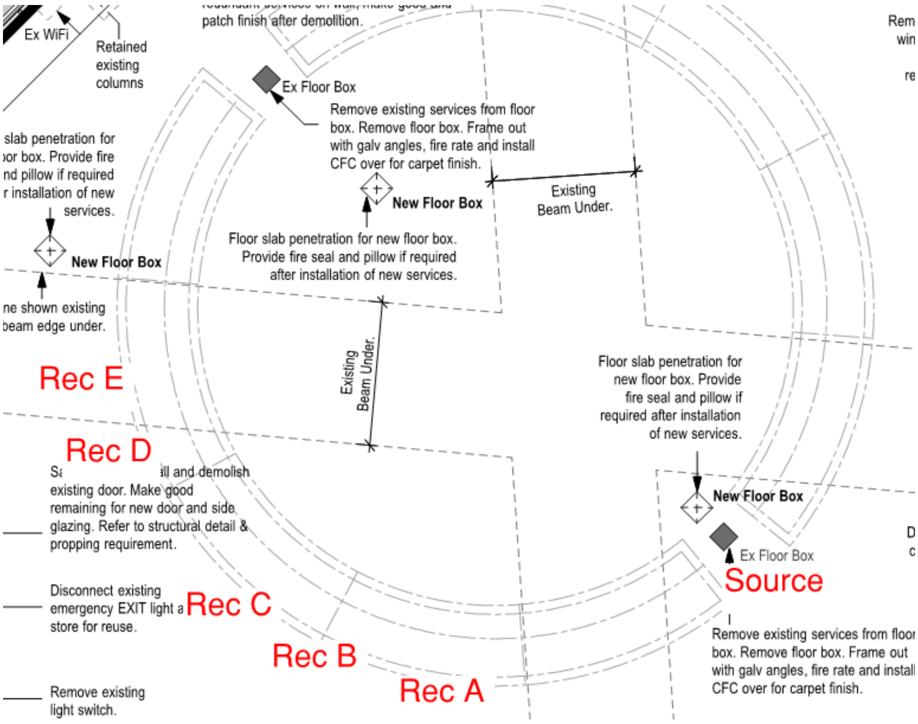
Source (Author, 2017)
Figure 3: MQU Council Room – existing reflectors and wall panels prior to works

The acoustic conditions within the previous fitout were poor. Ambient noise levels from the mechanical services were high, at around NR36, 40dB L_{A90}. The overall reverberation time was moderate at around 1.0seconds but early reflections to between source-receiver locations were insufficient. Speech clarity was low and varied due to anomalies existing around the table due to the undulation of the circular overhead reflector.

For a fixed source at the table the undulations in the overhead reflecting surface resulted in diffusion of overhead reflections to some seats, particularly at high frequencies. The effect was that as the listening position moved around the table away from the source or speech position speech was initially clear (in seats very close to the speaker). Speech then became muffled (noted loss of sibilance) for a number of seats (under the circular reflector) before the clarity returned at seats further away (where the circular reflector did not influence the reflection path). The effect is shown in the measured clarity (C_{50}) spectrums in Figure 4 where high frequency results are improved at locations D and E compared with the closer locations A, B and C.



Source (Author, 2018)
Figure 4: Clarity at receivers under existing reflectors prior to acoustic upgrade



Source (Author, 2018)
Figure 5: Measurement locations referenced in Figure 4

6 MQU COUNCIL ROOM – DESIGN PROCESS

Directions from the client and architect confirmed that the basic circular room shape was to be retained and that any treatment to the ceiling must also reinforce the circular aesthetic of the room. The ceiling design also needed to pass below two structural beams traversing the length of the room while providing sufficient height for the required video conferencing screen dimensions.

During the design process a second usage mode for the room was also identified, being as a function space catering for larger groups.

The design concept would have a ceiling height of between 3.1 and 3.5m, with a completed room volume of 600-700m^3. An overall reverberation time target of 0.6-0.9 seconds was nominated based on the room volume and proposed use, based on Cremer & Muller (1982). Targets for ambient noise from plant was set at NR25 when used for meetings and NR40 when used as a function space.

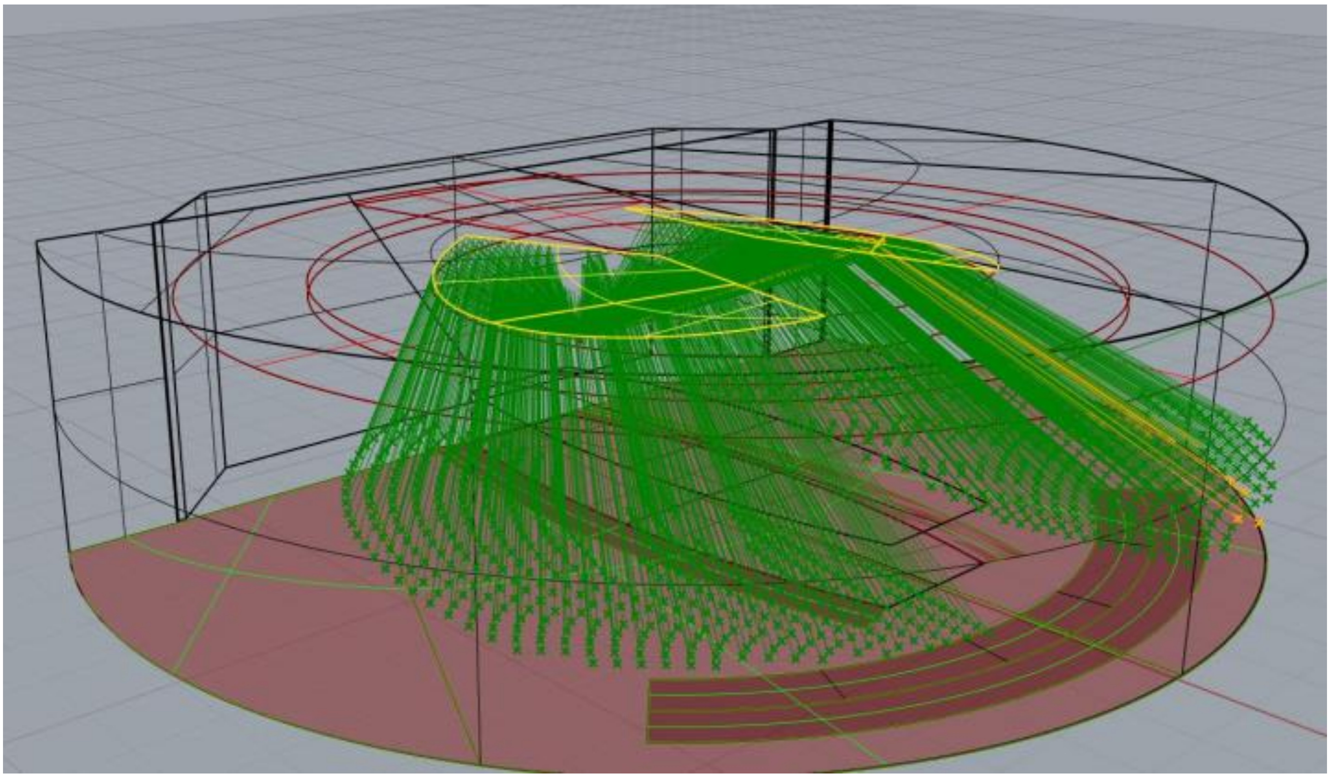
A reflective ceiling system was conceived to foster early overhead reflections. The design aim was to

(1) concentrate vocal effort from speech at the table seating positions to as much of the table area (and therefore seated receptors) as possible

(2) direct vocal effort from speech at the table to listeners seating around the arc of the room and

(3) direct vocal effort concentration away from the front of the Council Room (i.e. that part of the room near the doors and screen) where there are no fixed listening positions and where provision of vocal concentration would be wasted.

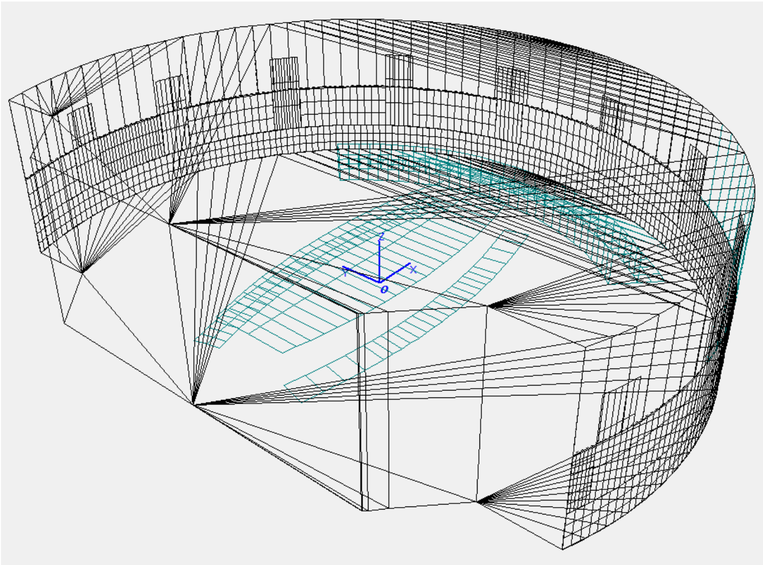
A reflective circular ceiling concept was developed to match the proportions of the room. Initial design ideas were evolved using paper cut-outs of the ceiling reflector in order to visualise the complex shapes. Development then moved to a 3D model in Rhino3D, using a ray tracing plugin developed in Grasshopper (a graphical algorithm editor). An example of this ray tracing is shown in Figure 6, with a preliminary reflector design. The green rays show first order reflections to from a source position at the far end of the table.



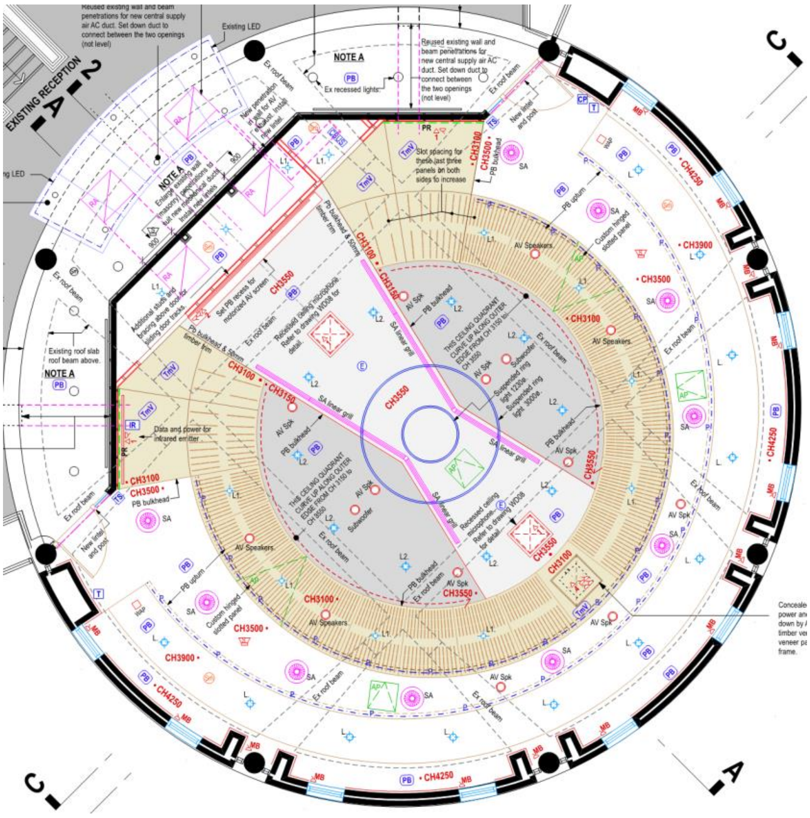
Source (Author, 2017)
Figure 6: Rhino 3D ray trace of first order reflections from proposed ceiling reflector

While a circular arrangement was maintained, the modelling showed clear advantages in profiling parts of the outer disc edges. The modelling also showed favourable results with an 8 degree turn down on each side of the ceiling disc, directing sound towards the rear of the room (further from the screen). This locally reduced the height in areas away from the video conferencing screen and assisted with vocal concentration in areas over the table together with the rear seating arc. This aspect was important as there were limitations as to the degree to which the ceiling could be lowered, due to the sight lines required for the video conferencing screen.

Following the early stage of modelling the 3D model was imported to ODEON room acoustic software for final calculations and assessment. The primary purpose of the ODEON modelling was to determine the ideal placement of absorption treatment to achieve reverberation time goals. The final design included absorptive treatment around the circular wall sections, the flat wall sections above and below the screen area at the front of the room and the ceiling plane outside of the reflector zone (towards to doors). An image of the one iteration of the Odeon model is shown in Figure 7 whilst Figure 8 shows the final reflected ceiling plan.



Source (Author, 2017)
Figure 7: ODEON model image



Source (BNMH Architects, 2017)
Figure 8: Final Design Reflected Ceiling Plan

Although outside the scope of this paper noise controls were also designed for the mechanical systems. Plant was located in a remote plantroom and ducted to the space. The air-conditioning system was configured with two operating modes, one for Council meetings and a second mode with higher airflow for functions (with significantly more people in the room). Audio visual equipment was housed in joinery cupboard area at the front of the room, with a dedicated ventilation supply so that the cupboard could be acoustically separated from the room.

7 MQU COUNCIL ROOM – RESULTS

A series of measurements were carried out at completion of the project, for comparison both to the project criteria and to similar measurements carried out prior to the refit. The IRIS 3D impulse response measurement system was used to quantify overall reverberation times as well as clarity.

The overall reverberation time and mechanical plant noise levels are presented in Table 1.

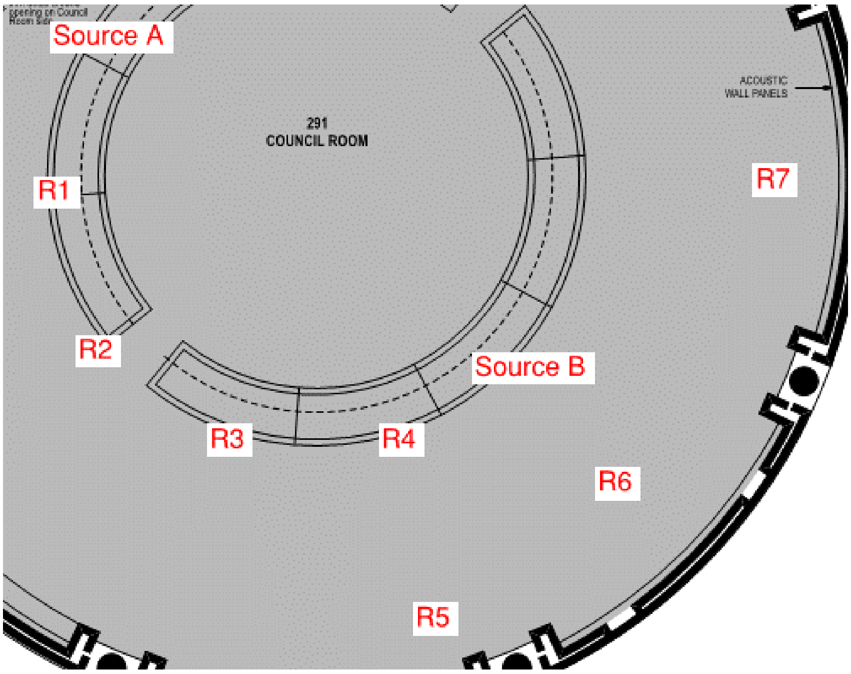
Table 1: Measured reverberation time (s) and mechanical plant noise levels (NR)

Parameter	Pre-refit	Post-refit
Reverberation time, *T30 (S)*	1.0	0.8
Plant noise (meeting mode), (NR)	36	23
Plant noise (function mode), (NR)	NA	25

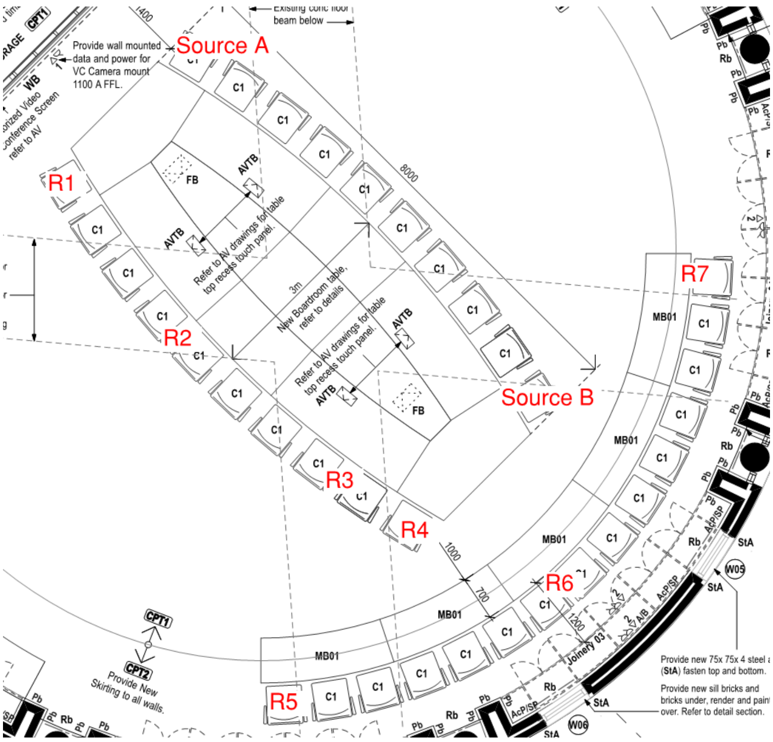
Comparison of clarity (C_{50} 500-1000Hz) results before and after the refit is shown in Table 2. An omni directional source was used for measurements. Different table shapes meant that the measurement locations are not identical for before and after the refit. In both cases the measurement source was located at the end of the table, the first 4 receivers are located on one side of the main table and the last 3 receivers are at the observer positions at the periphery of the room. The measurement locations are shown in Figures 9 (pre-refit) and 10 (post-refit).

Table 2: C_{50} (500-100Hz) comparison

Source	Receiver	C_{50} before	C_{50} after
A	1	4.6	3.8
A	2	2.7	2.3
A	3	0.4	2.8
A	4	3.0	3.2
A	5	-0.1	2.6
A	6	0.3	3.8
A	7	1.0	3.1
B	1	2.2	3.7
B	2	1.4	2.1
B	3	2.0	3.2
B	4	2.0	4.4
B	5	6.2	1.9
B	6	3.3	5.1
B	7	0.3	4.3
Average	-	2.1	3.3
Std Deviation	-	1.7	0.9
Maximum	-	6.2	5.1
Minimum	-	-0.1	1.9



Source (Author, 2018)
Figure 9: Measurement locations before refit



Source (Author, 2018)
Figure 10: Measurement locations after refit

The Just Noticeable Difference (JND) for clarity is 1dB (ISO 3382-1 2009). The average C_{50} increased by 1.2dB, but more importantly the clarity around the room became more consistent, with lowest C_{50} recorded increasing by 2dB.

8 FINAL REMARKS

The Speech Transmission Index of the space was not measured directly in the space however the increase in clarity (C_{50}) measures and significant decrease in ambient noise levels suggests the improvements in intelligibility are significant. Subjective impressions of the space also suggest a significant improvement in speech clarity between the seated areas.

This design philosophy outlined in this paper is not intended to describe the only way to design suitable acoustics for speech in circular spaces but rather to describe one approach which has led to a successful outcome.

ACKNOWLEDGEMENTS

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