ACOUSTIC ANALYSIS OF WIGMORE HALL, LONDON, IN THE CONTEXT OF THE 2004 REFURBISHMENT

T. Wulfrank(*) Arup Acoustics, St Giles Hall, Pound Hill, Cambridge, UK
R.J. Orlowski Arup Acoustics, St Giles Hall, Pound Hill, Cambridge, UK
(*) current address: Kahle Acoustics, Avenue Molière 188, 1050 Brussels, Belgium

During the course of the Twentieth Century, the Wigmore Hall in London has acquired an outstanding reputation as one of the leading venues in Europe for chamber music. This reputation is founded both on the high standing canon of musicians and music on the programme, and on the acclaimed acoustic of the Hall, which has been favoured by generations of audiences and performers alike.
The Wigmore Hall has recently undergone a thorough refurbishment to bring the state of the main auditorium, the front of house facilities, the restaurant and the multi-purpose Bechstein room in line with current standards of comfort. In the auditorium the refurbishment included the installation of sufficiently silent mechanical ventilation and stage lighting, the improvement of the roof construction with respect to sound insulation from outside noise, and the replacement of the entire seating. Arup Acoustics was commissioned as acoustic consultant to the design team for the refurbishment works (2003-2004), with the principal task to preserve the existing acoustic. This presented the authors with an opportunity to investigate in depth some aspects of the Wigmore Hall's room acoustic qualities, of which to date no extensive publications are known in the literature.
This paper aims at describing some of these aspects, especially in connection with the Hall's concave surfaces, including the analysis and subsequent findings carried out during the refurbishment of the Hall.

1 INTRODUCTION

The Wigmore Hall in London, formerly known as Bechstein Hall, dates from 1901. It was designed by Thomas Collcutt and is a typical example of late Victorian architecture. Until the First World War it was owned and used as a performance space by the German piano manufacturer Bechstein. From 1917 onwards it has been open to the public as a recital hall for chamber music, attracting artists the likes of Arthur Rubinstein, Alfred Cortot, Benjamin Britten, The Lindsay Quartet etc. There were a number of refurbishments, the last of which in 2003-2004 was lead by the architects Arts Team (RHWL).

Plan and sections of the Wigmore Hall are given in Figure 1, along with a 3D wireframe.

The Hall's basic plan shape is rectangular, 12.3 m wide and 22.9 m long, with the audience seated on a flat (i.e. not raked) carpeted floor. There are many concave surface boundaries. The ceiling is an elliptic vault, with a height between 6.7 m and 10.7 m above the floor, incorporating a series of glazed laylights. The stage platform incorporates a cylindrically shaped apse, topped by a spherical cupola. A shallow balcony is located on the rear wall, 3.35 m above the floor and with an overhang of only 3.5 m. The side walls are hard plaster with mahogany panels on the lower walls, and the only diffusion seems to be provided by shallow marble pilasters (0.1 m deep and 1 m wide) which run all along the side walls and the ceiling.

There are 542 fully upholstered seats, and the volume per seat is 5.3 m^3, which is rather low for a typical recital hall. Combined with the presence of carpet one might assume a dry, non-reverberant acoustic. However, quite the opposite is true - the mid-frequency reverberation time of approximately 1.5 s (occupied) is an indication of ample reverberance for chamber music.

The typical 'Wigmore sound' could be described as loud, spacious, reverberant yet clear. The former two characteristics are especially true in the balcony. The acoustic is most suited to small chamber ensembles such as a string quartet and solo instrumental recitals. For ensembles of more than, say, 8 musicians the stage is too small and the acoustic is said to be less suitable.

The existing literature on the Wigmore Hall is sparse[1,2] and to date no in-depth accounts of its acoustic are known to the authors.

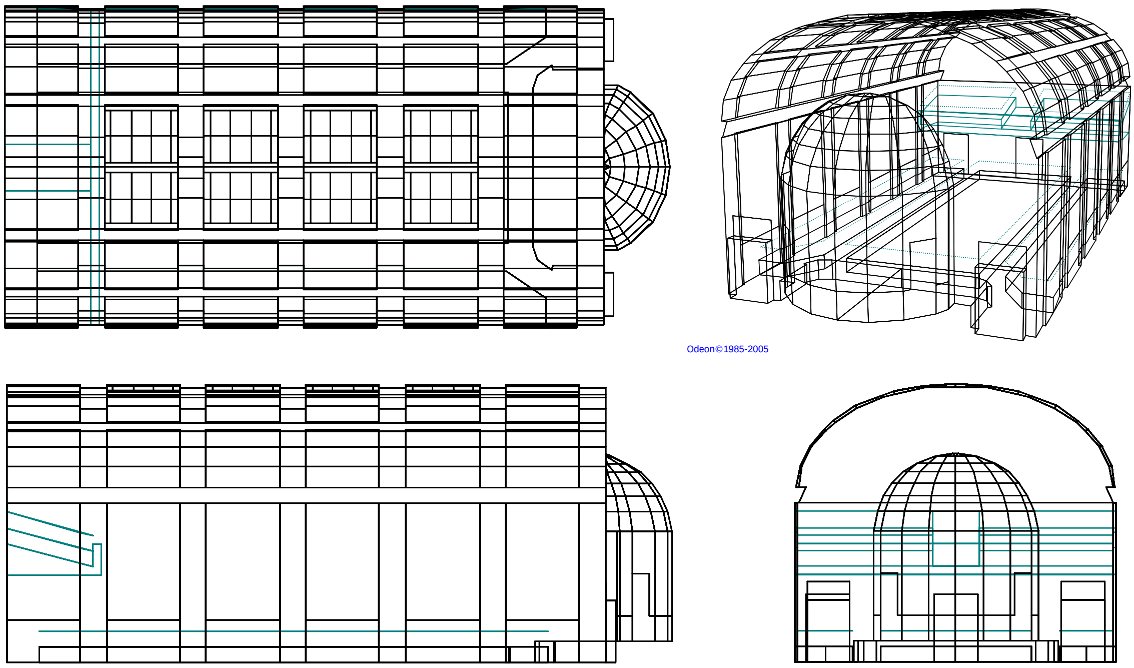


Figure 1: Plan, sections and 3D wireframe model of the Wigmore Hall. (In reality, the concave surfaces are continuous and not facetted as shown here.)

2 CONCAVE SURFACES: FOCUSING OR DIFFUSING?

One of the most striking features of the geometry of Wigmore Hall is the presence of large areas of concave surface boundaries: the elliptic ceiling, the cylindrical apse and the spherical cupola. It is well known by acousticians that concave surfaces present a risk in terms of acoustic faults such as focusing, uneven sound distribution and flutter echoes. However, what is sometimes forgotten is that the actual reflective behaviour of curved surfaces – and concave surfaces in particular – depends on the geometrical relationship between the sound source, the receiver and the reflective surface.

It is considered that concave surfaces play a key role in the Wigmore acoustic. In this context, it is useful to revisit some elementary properties of concave surfaces, as it is felt that there is often misunderstanding regarding curved surfaces in present day acoustics.

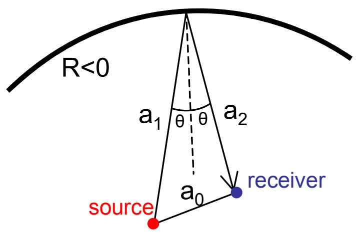
2.1 Reminder on the Theory of Concave Surfaces

Cremer[3] has given an in-depth overview of the reflective behaviour of concave surfaces, analogous to the concave mirror laws in the field of geometrical optics. Any one-dimensionally curved concave surface can - in the neighbourhood of a reflection point - be approximated by a circle with radius R. The location of the source relative to the centre of this approximating circle determines the reflective behaviour of the concave surface. Four different types of reflection can be identified: hyperbolic, parabolic, elliptic and circular. The source is always located at a focal point of one of these conic section types. The actual reflection type depends on the distance from the source to the reflection point on the concave surface, the source-to-reflector distance a1, as follows:

- <u>Elliptic</u> reflection occurs when the source-to-reflector distance is greater than R/2. The source is located at one focus of an ellipse, and the reflected rays will converge in the other focus, where a high concentration of sound will be found. Once past the focus the rays are divergent to a higher degree than reflections off a plane surface. Circular reflection occurs when the source-to-reflector distance equals R and is a special case of elliptic reflection in which the two foci coincide.

- Parabolic reflection occurs when the source-to-reflector distance equals R/2. In this case, the concave surface can be approximated by a parabola with the source at its focus, and the reflections form a beam of parallel rays (being neither divergent nor convergent).
- Hyperbolic reflection occurs when the source-to-reflector distance is less than R/2. In this case all reflections seem to emanate from a point located behind the surface. The bundle of rays is divergent, but less divergent than reflections off a plane surface.

Based on geometric considerations, Rindel[4] describes how reflections from curved surfaces can be quantified by calculating the approximate amplification ΔL_{curv} in dB of reflections from a cylindrical reflector with radius of curvature R at a given receiver location (see Figure 3). In this equation, θ is the angle of incidence and a* is a characteristic distance which depends on the source-to-reflector distance a_1 and the reflector-to-receiver distance a_2 (all in meters). The radius of curvature R (in meters) is positive for convex surfaces and negative for concave surfaces. For flat surfaces ΔL_{curv} = 0 dB. Negative values of ΔL_{curv} obviously denote attenuation of sound.



$$\Delta L_{curv} = -10\log\left|1+\frac{a^*}{R\cos\theta}\right|$$

$$a^* = \frac{2a_1a_2}{a_1+a_2}$$

Figure 2: Sound reflection from a curved surface, for given source/receiver locations. Adapted from Rindel[4].

2.2 Concave Surfaces in the Wigmore Hall

Application of the above theory to the three concave surfaces of the Wigmore Hall yields a basic understanding of their first order reflective behaviour.

2.2.1 Elliptic Ceiling

The ceiling of the Wigmore Hall is hemi-elliptical in cross section, with its elliptic foci at approximately 4.6 m either side of the centre line, at 6.7 m above floor level. This is well above the musicians and the audience (apart from the rear balcony where tall people might just be able to reach up to focal height). Therefore the elliptic foci do not pose any acoustic problems.

It is useful to apply the above theory and to consider the ellipse as a curve with continuously varying radius of curvature R, between the extremes of 9.4 m at the top and 2.6 m at the sides. This is illustrated in Figure 3, where the numbers indicated along the ceiling line represent the local radius of curvature. The theoretical amplification of first order reflections by the ceiling from a centred stage source is plotted in Figure 4 as a function of the radius of curvature of the ceiling, on the assumption of normal incidence. The red line gives the amplification for a receiver in the stalls, the blue line for a receiver in the balcony, both assumed to be on the centre line of the Hall. The peaks in the curves indicate that strong amplification (i.e. focusing) occurs from different parts of the ceiling.

In the stalls, the theoretical amplification is strongest – more than 10 dB – for a radius of curvature between approximately 8 m and 9.4 m. This corresponds to a broad zone at the top of the ceiling, including the laylights. Moving down along the ellipse, the amplification gradually weakens, and when the radius of curvature becomes less than 4.5 m – at the sides of the ceiling – the amplification becomes negative (i.e. diffusion occurs).

In the balcony, there is also amplification due to the top part of the ceiling, but to a lesser extent than in the stalls. The strongest amplification in the balcony occurs from the zone with radius of curvature between 6 m and 7 m. This corresponds to approximately midway between the top and sides of the elliptic ceiling, meaning that these strong reflections are more lateral than in the stalls and possibly increase – other than loudness - the sense of spaciousness (apparent source width) in the balcony. Finally, when the radius of curvature becomes less than approximately 3 m, i.e. at the sides of the elliptic ceiling, diffusion occurs again. It is true that the exact location and shape of the peaks in Figure 4 are very sensitive to the actual geometric relationship between source, receiver and ceiling, but the general trends hold for reasonable changes of source and receiver height, deviation from the centre line etc. In addition, there is diffusion from surface irregularities on the ceiling (e.g. edges of the laylights, pilaster coffering etc.) which will make any focusing effect in reality less pronounced than the theoretical predictions, in particular at high frequencies.

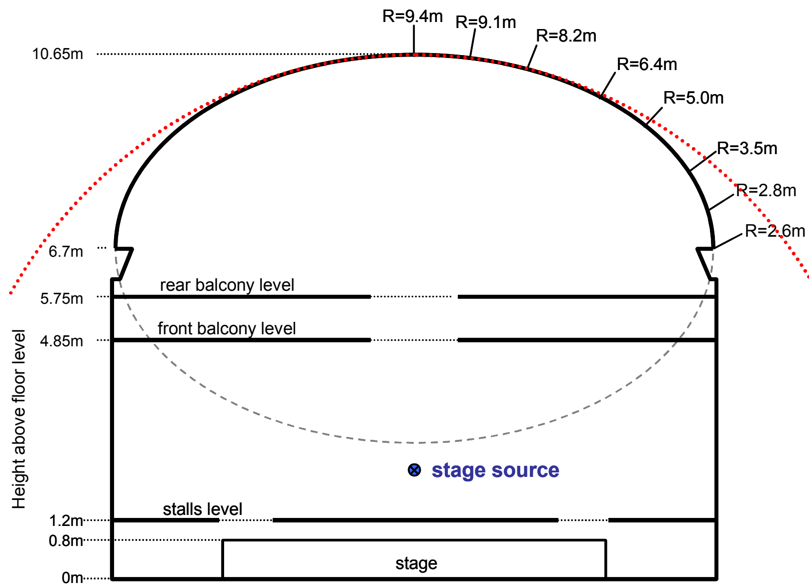


Figure 3: Cross section showing the elliptic ceiling. The numbers indicated along the ceiling represent the local radius of curvature (R). The red dotted line is a circular approximation of the top part, with radius 9.4 m.

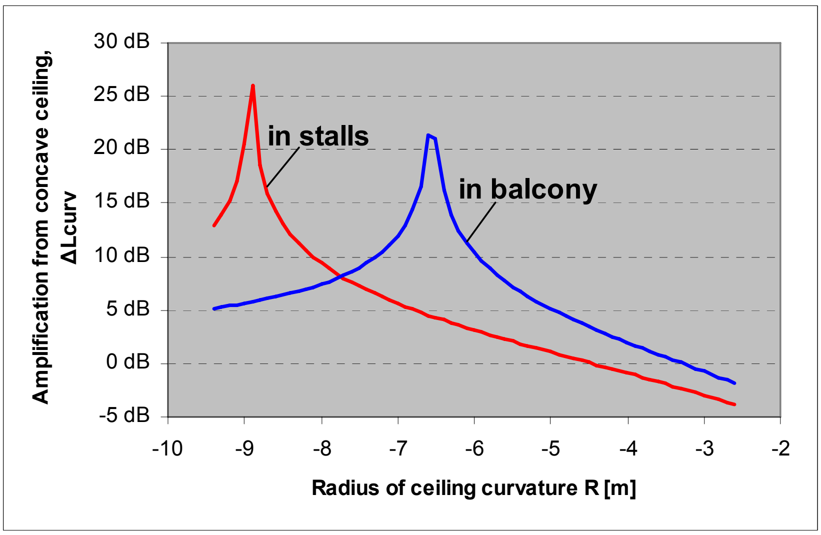


Figure 4: Theoretical amplification (in dB) from the concave ceiling as a function of the varying radius of curvature, for a source at 1.4m above the stage floor.

2.2.2 Cylindrical Apse

The stage platform of the Wigmore Hall is dominated at its rear by an apse, which in plan is a section of a circle with a radius of approximately 3.5 m. A plan of the stage is shown in Figure 5, together with typical locations of a string quartet and a grand piano. Application of the concave surfaces theory to the apse identifies three main zones or types of reflective behaviour. Moving along the centre line of the stage these zones are the following:

- Between the stage edge and the circular focus (0 m – 1.8 m from stage edge): **backward elliptic projection**. Reflections from sources in this zone are focused back behind the source, to a point in-between the circular and parabolic foci.
- Between the circular and parabolic foci (1.8 m – 3.55 m from stage edge): **forward elliptic projection**. Sound emanating from this zone focuses forward to a point located somewhere between the circular focus and infinity, i.e. to the front of the stage or somewhere in the audience.
- Between the parabolic focus and the apse wall (3.55 m – 5.3 m from stage edge): **hyperbolic projection**. Reflections from sources in this zone appear to be originating from a virtual focal point behind the apse wall. The rays diverge, but to a lesser degree than had the wall been a flat surface, which means that seen from a receiver in the audience (on the centre line) the apse amplifies the reflected sound.

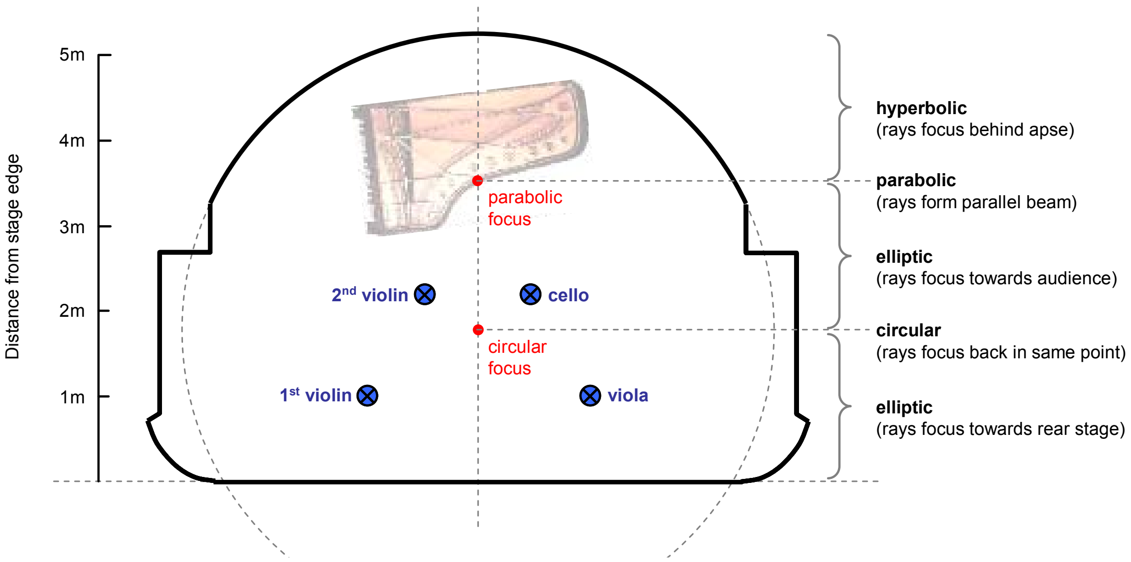


Figure 5: Plan of the stage platform at Wigmore Hall, showing typical locations of a string quartet and a grand piano. The different zones and points of hyperbolic, parabolic, elliptic and circular reflective behaviour from the apse are also identified.

The calculated amplification ΔL_{curv} from the concave apse is given in Table 1 for three stage locations (First violin, cello and piano) and four audience receivers (at 5 m, 10 m, 15 m and 20 m from the stage edge). The analysis is restricted to the centre line (angle of incidence θ = 0).

	1st Violin	**Cello**	**Piano**
Distance from stage edge	1.0 m	2.3 m	4.0 m
Reflection type	backward elliptic	forward elliptic	hyperbolic
Receiver-to-stage distance	**Reflection amplification due to cilindrical apse, ΔL_{curv} [dB]**		
5m	1.3 dB	4.8 dB	4.6 dB
10m	0.4 dB	3.6 dB	4.9 dB
15m	-0.1 dB	3.1 dB	5.1 dB
20m	-0.4 dB	2.7 dB	5.2 dB

Table 1: Theoretical amplification (in dB) due to the concave apse, for 3 different source locations, as seen from the audience at different distances from the stage edge.

The above table shows that for a first violin the apse reflects with an amplification of about 0 dB (except near the stage, where the amplification is more, e.g. 1.3 dB at 5 m distance). This means that the apse reflections have nearly the same strength as the reflections of a flat surface. Further away from the stage, i.e. at a distance of more than 15 m, ΔL_{curv} becomes negative, indicating that the apse amplifies less than a flat surface. In other words, in the rear seats, the apse effectively behaves as a diffuser of sound for soloist locations on stage, rather than as a focusing projector.
For sources a little more upstage, such as a cello in a string quartet, the apse amplifies the reflections in the order of 3 - 5 dB, depending on the listener's distance to the stage. The amplification is higher near the stage than towards the rear of the auditorium, because the second elliptic focus is near the front of the stage.
Towards the rear of the stage, for locations inside the apse, the amplification is more. The instrument that is most likely to be in these locations is the grand piano accompanying chamber ensembles. (For solo performance or accompaniment of singers, the situation is different as the staff tends to move the grand piano towards the front of the stage, out of the apse.) The sounding board of the piano typically covers the distance range of 3 - 4.5 m away from the stage edge, theoretically leading to apse amplifications of up to 20 dB for distinct source-receiver combinations. However, in practice the piano lid will either be open - in which case the sound from the strings and the sounding board will not reach the apse - or the lid will be closed, in which case the piano will behave as a 'diffuse' distributed source, smoothing out the highly localised foci with high amplification. Averaged over 160 source and receiver points, the theoretical amplification for upstage locations is about 7 dB.

Combination of the apse amplification with the inverse-square-law for spherical propagation allows the comparison of direct sound levels with apse reflection levels in a certain seat. This straightforward analysis reveals that for a first violin source, the apse reflections are between 8 dB (near the stage) and 4 dB (near the rear of the Hall) weaker than the direct sound. For a cello location, the direct sound and the apse reflected sound are similar in strength. Further than 8m away from the stage, the reflected sound is up to 1 dB stronger than the direct sound. Hence the apse works as an amplifier for sources located behind the circular focus. This would appear to be good as it is likely to increase the apparent loudness to those who are benefiting from the reflections. However, a side effect of focusing is that it seems to slightly 'colour' the perception of music. In any case, the fact that the cello and the first violin, even though they are closely spaced together on stage, are reflected differently by the apse, might be one element in explaining the typical Wigmore 'sound'. It could be that the different reflective behaviour of the apse for the different instruments in an ensemble contribute to a different perception of each of these instruments, which may enhance the musical experience. For example, the combination of a clear violin sound with a slightly coloured but strong cello sound could be beneficial.

As a consequence of the cylindrical shape, the apse also produces some acoustic peculiarities. For example, if one sits towards the rear of the stalls, the cello and the second violin in a string quartet can be perceived as mirrored along the centre line. Thus, the sound of the cello appears to be coming from the left whereas the second violin can be heard as coming from the right. This will happen if one is seated behind the focal points of these sources, beyond which the rays diverge in a mirrored way.

Another peculiarity is the existence on stage of reasonably strong and late echoes (delayed by 160 ms) near the parabolic focus. This happens because the apse reflects sound from this point as a bundle of parallel rays, which remain parallel when travelling back after reflection off the rear wall, and which re-converge in the parabolic focus. However, this does not seem to disturb the performers, but rather gives them useful musical support. (See also section 3.2.)

It should be noted that the grand piano is often moved into the apse when not used. This is typically the case in mixed recitals, e.g. a string quartet before the interval, followed by a piano quintet. In this case the piano will obstruct the sound rays in reaching the cylindrical apse. Hence, the focusing effects described above will be less pronounced in reality.

Also, so far we have only considered the sources (and receivers) to be located on the centre line, to simplify the analysis. For sources away from the centre line, the amplification will be less as the angle of incidence θ increases. In addition, any focal point or zone in which reflected rays tend to converge will move across to the other side of the centre line. This means that the focusing will only be noticed by audience members located accordingly off-axis. However, even with these limitations, the above analysis still stands qualitatively and has been useful to gain an understanding of the acoustic behaviour of the apse.

2.2.3 Spherical Cupola

The cupola on top of the stage apse is a portion of a sphere with radius of curvature 3.5 m. Its geometrical coverage for first order reflections from typical stage sources extends over most of the audience area, including the balcony. Taking the correct distances and angles into account, Rindel's theory applied to a surface curved in two dimensions leads to the theoretical amplification values for a 1st Violin source given in Table 2. As all values are negative, it is clear that no focusing occurs from the cupola. The cupola acts as a diffuser, and the amount of diffusion increases as the listener is seated more towards the rear of the Hall. This is contrary to the commonly held belief as if the cupola would 'beam' sound to the audience, as is the case with the apse. This diffusive property is believed to be beneficial, as it reduces the risk of false localisation.

	Reflection amplification due to cupola, ΔL_{curv} [dB] source: 1st Violin
Front stalls	-0.1 dB
Mid stalls	-4.0 dB
Rear stalls	-5.1 dB

Table 2: Theoretical amplification (in dB) of cupola reflections for a 1st Violin source location.

3 REFURBISHMENT STUDIES

The following studies partially describe the investigations carried out during the refurbishment of the Hall, which bear some relationship to the theoretical descriptions above.

3.1 Influence of the Laylights on the Room Acoustics

The Wigmore Hall possesses a series of glazed laylights incorporated in the elliptic ceiling in-between the pilasters, allowing the penetration of daylight (Figure 6). Each laylight consists of 6 concavely glass panels measuring approximately 0.7 m by 2 m in plan each. However, prior to the 2004 refurbishment the laylight nearest the stage lacked 4 of the 6 glass panels, such that there are 4 openings in the elliptic ceiling into the pitched roof void above. This had been the case for many decades. During the design phase of the refurbishment, the Architect had the intention of reinstating these 4 missing panels for esthetical reasons and an investigation into the associated acoustic effects was requested.

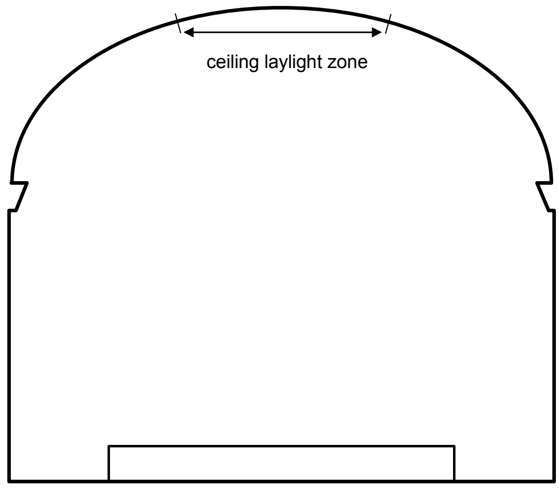


Figure 6: Location of the glazed ceiling laylights.

The total surface area of all the openings is approximately 6 m^2, which would appear to be too small to consider the volume of the roof void above as being acoustically coupled into the main auditorium volume. Rather, it was assumed that – at least above approximately 1 kHz where little or no diffraction happens - the openings act as being fully absorptive. In the occupied Hall, 6 m^2 constitutes less than 2% of the total absorption area. Therefore, it was not thought that closing off the openings would have a significant measurable or perceivable acoustic effect in terms of sound absorption and reverberation. However, in cross section the missing panels follow the shape of the focusing ceiling – albeit in facets - and are furthermore located such that specular first order reflections for stage sources focus into a significantly large central area of the stalls seating. (For any given source location on stage, the total specular coverage area is approximately 6 rows deep by 7 seats wide, i.e. about a sixth of the central stalls area.) As shown in section 2.2.1, the top zone of the ceiling, in which the laylights are located, contributes most towards focusing in the stalls. Consequently, there was a risk that reinstating the glass panels would significantly alter the spatial pattern of early reflections in the centre stalls, potentially affecting the acoustic quality. For that reason it was decided to carry out testing in the Hall to objectively and subjectively assess the impact of covering up the ceiling openings.

To simulate the acoustic effect of the glazing, curved plywood panels were mocked up which could cover the laylight openings or be removed again in a matter of seconds. A test audience of about 15 listeners from the Wigmore Hall, Arup Acoustics and other members of the Design Team were asked to listen to brief musical excerpts (piano solo, piano and alto, piano and cello, clarinet solo) played twice over, once with and once without the panels in place. The listeners were seated in or near the specular coverage zone of the panels. Any perceived acoustic differences were marked up in questionnaires. In addition to these subjective tests, accurate 3D impulse responses were measured to quantify the influence of reinstating the laylight.

The subjective results indicated that the majority of the subjects (including the musicians) heard a subtle difference between the two cases. Of those that perceived a difference, the majority did not have a strong preference for either case. A typical response was that the sound was perhaps slightly clearer with the panels in place. However, a minority of people expressed a strong preference for the panels not being in place (i.e. with the openings exposed), claiming that the sound was clearly less spacious with the panels in place.

In addition, a sold out evening performance of Schubert's Winterreise song cycle was attended twice in the same central stalls seat, on the first evening without the panels, and on the second evening with the panels in place. Whilst the performers - Ian Bostridge and Leif Ove Andsnes - did not perceive any noticeable difference between the two performances, there were some minor instances of focusing from the tenor voice in the central stalls when the panels were in place; as the tenor - located near the centre line - made head movements during certain musical phrases, it was possible to sometimes 'hear the ceiling focus shoot past' in the centre stalls. This was not found to be unacceptably disturbing. However, it was taken into account to inform the final decision.

3D room impulse responses with and without the panels were obtained in the unoccupied Hall using the logarithmic sine sweep deconvolution method[5], in conjunction with an omnidirectional dodecahedron loudspeaker on stage and an ambisonic[6,7] (SoundField) microphone in a couple of locations in the specular coverage zone. The sine sweep method is capable of delivering very repeatable impulse responses, allowing the detection of minor differences between different responses. Figure 7 shows the omnidirectional impulse response (pressure squared) measured at seat H11 for a typical violin source location, with and without the laylight panels. A small difference can be seen at 37 ms where the reflection peak is subtly stronger when the panels are in place.

On the assumption of plane wave incidence, the sound intensity vector **I** = p**u** can be derived from the four B-format signals of the SoundField microphone. Figure 8 shows elevation plots of the instantaneous sound intensity measured at seat H11. In these polar plots, the individual dots give the amplitude and the direction of the instantaneous sound intensity vector at successive points in discrete time. In this way, individual reflections can be singled out and the instantaneous direction of incoming sound energy found. The 'loops' visible in these plots, correspond to strong reflections (including the direct sound). The colours correspond to different arrival times of reflections. The black loop at 60 degrees corresponds to the ceiling reflection (at 37 ms). It is clear that the sound intensity arriving from the ceiling is slightly higher when the laylight panels are in place.

Based on the available results it was concluded that the reinstatement of the laylights reinforces the ceiling reflection in the central area of the stalls. Whether this is perceived as being worse or not depends on individual preference. However, overly strong frontal overhead reflections are generally not considered to be desired for music performance as they reduce the impression of spaciousness and are likely to cause false localisation (lifting up) of the sound source. In addition, it was thought that the impedance changes associated with the alternation of acoustically hard materials and openings in the ceiling increase diffusion in a broad frequency range (low and mid frequencies), which is beneficial.

On this basis it was decided to preserve the openings in the ceiling and to not reinstate the glass panels.

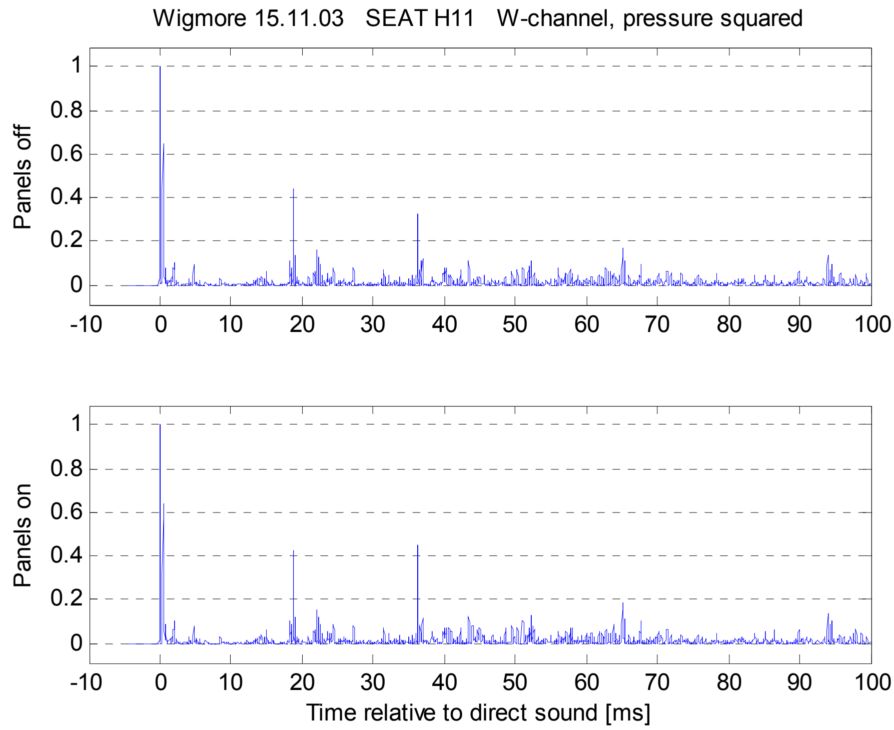


Figure 7: Pressure squared time response with and without the laylight panel, measured in a specularly covered seat. The reflection at 37 ms corresponds to the ceiling reflection and is mildly stronger in the case with the panels in place.

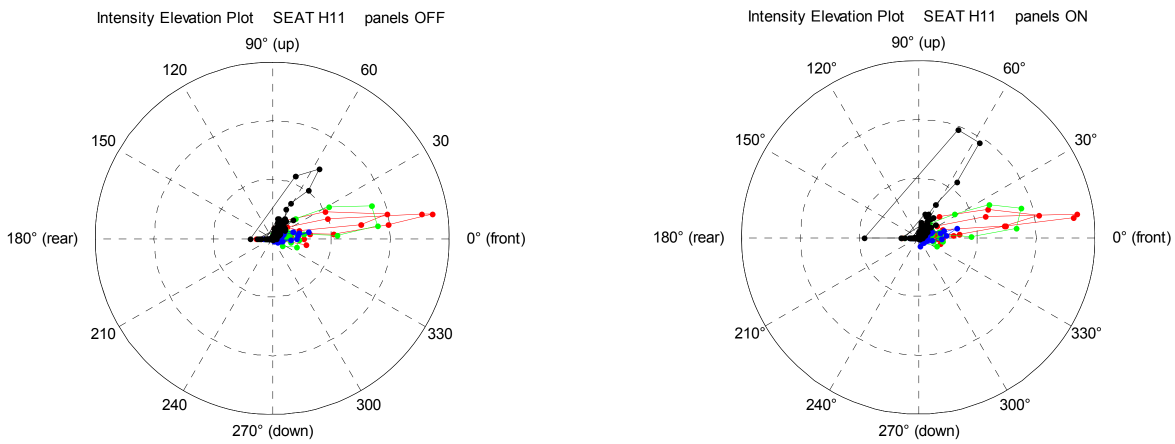


Figure 8: Elevation of the instantaneous sound intensity (on a linear scale to only show the strongest reflections), with and without the panels. The colours correspond to the reflection arrival time (red = 0-10 ms, green = 10-20 ms, blue = 20-30 ms, black = 30-40ms). The red loop corresponds to the direct sound, the green loop to a strong side wall reflection and the black loop to the ceiling reflection. The ceiling reflection is clearly stronger when the laylight panels are in place.

3.2 Influence of the Seating Rake on the Room Acoustics

The Wigmore's entirely flat (i.e. horizontal) stalls floor had always caused limited sightlines towards the rear of the Hall. Therefore, it was proposed during the design stage of the refurbishment to subtly raise the rear 9 rows of the stalls, to improve the sightlines. The proposal was to start raising the seats increasingly from row P onwards with the final row X being raised by a maximum of 225 mm. The remaining 15 rows would remain flat as before. At first it was not thought that this subtle change would have much noticeable impact on the room acoustics.

Nevertheless, it was decided to carry out testing to allow assessment of the risk that the proposed change would degrade the acoustic. As it is very difficult to use computer modelling or physical scale modelling to study acoustic changes of this level of detail, real scale testing was carried out by laying cushions of different thicknesses and planks on the existing flat seating, and by thus creating a mock up of the proposed seating rake. The Friends of Wigmore Hall attended a test concert where five pieces of music (string quartet, piano trio, baritone, clarinet, piano) were played twice over, once on the flat floor, and once with the 9 rear rows raked. No fixed order of the two seating modes was adhered to. The audience – including those in the front seating block that remained flat throughout - filled in and returned over 400 questionnaires. The musicians were asked the same questions. In addition, objective impulse responses were obtained in a number of seating positions in the stalls.

The audience were instructed to listen for changes in the room acoustics and to ignore any differences in the musical performance. The following questions were asked:

1. Did you hear a difference between the two presentations?
2. If yes, did you prefer the first, the second or neither?
3. Do any of these adjectives match your preference? (Louder/clearer/more reverberant/more intimate/more spacious)

It was also possible to make other comments for every presentation.

Analysis of the questionnaires showed that over 65% of the audience noticed a difference between the flat and raised seating modes. For people in the last 9 rows this figure increased to over 70%. Thus better sightlines for people at the back had an influence on the acoustics of the entire stalls area, including the front. This was unexpected as it had been anticipated that a majority would have heard no difference between the small changes being made to the seating.

Secondly, the preference for flat seating or raked seating (or neither) depended on the type of instrument(s) played. For the string quartet, the baritone and the piano, the majority preferred the flat floor. For the piano trio and the clarinet, the preference was for the raked seating. Whenever there was a preference for low seating, this was stronger than for elevated seating. Remarkably, the preference of the musicians was always correlated with that of the majority of the audience.

Thirdly, the distribution of chosen adjectives for flat and raked seating preferences indicated the following (small) differences. The adjective “clearer” was chosen mostly in connection with raked seating (52% vs. 47% for the flat seating). For the flat seating the adjectives “more reverberant” (19% vs. 15% for the raked seating) and “more spacious” (12% vs. 8% for the raked seating) were more often chosen. These changes are small, but being the results of a large statistical population they are meaningful.

It was also useful to study individual comments on the questionnaires. Many different kinds of responses were found, but the more recurring extremes were “because I could see better I felt I could hear better” (for people sitting in the last 9 rows) and “raising the seats at the back restricts the sound at the front” (for people sitting in the front 15 rows). The latter response was also supported by some of the musicians, including Sir Thomas Allen.

Analysis of the objective impulse responses, obtained using an in-house sine sweep deconvolution routine, showed that no significant changes to ISO 3382 room acoustic parameters such as RT and C80 could be detected. However, inspection of the impulse responses revealed that in general a significant number of early reflections was reduced by raising the seats. An example is given in Figure 9, where the strong reflections at 45 ms, 54 ms and 62 ms diminish when raking the seats. The reflection at 45 ms corresponds to the back wall. (However, the other two reflections do not correspond exactly to the 2nd order reflections from the rear corners, as one could expect.)

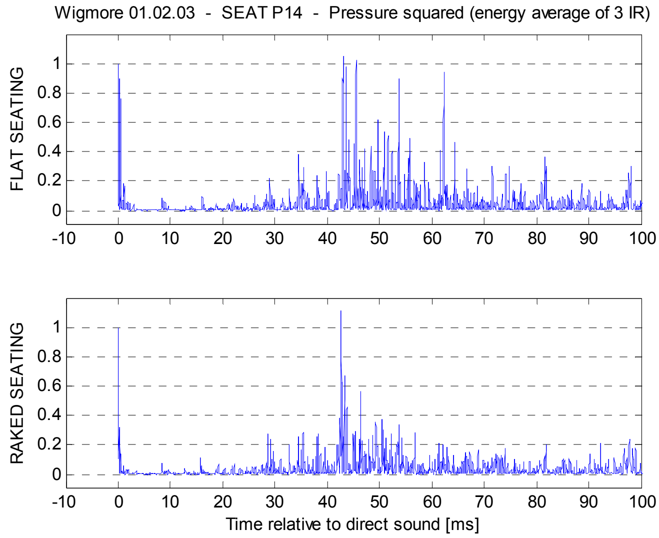


Figure 9: Influence on a room impulse response from putting the 9 rear seating rows on a subtle rake. The strong reflections at 45 ms, 54 ms and 62 ms diminish by raising the rear seats.

Closer study of the Wigmore Hall's geometry using plans and sections and an Odeon room acoustic computer model[8] shows that a narrow strip of the back wall just above audience head height is very important in reflecting sound back to the performers on stage (with a delay of minimum 120 ms) and to most seating locations in the stalls. In addition, for stage locations in-between the circular and parabolic focus of the apse (see Figure 5), the apse "beams" a focused reflection across the stalls onto the back wall, which then bounces back to the performers (with a delay of more than 150 ms), providing the latter with useful room support. As the rear rows are raised, even by a maximum of only 225 mm, the heads of the audience start to eclipse the useful narrow reflection strip of the back wall, and the backward propagating sound waves are diffracted. It is thought that this mechanism plays an important role in explaining the sensitivity of the Hall's acoustic to raising the seats.

Based on the studies described above, it was decided to not rake the seating, but to maintain the flat floor arrangement. However, to improve the sightlines marginally, the new seating was installed in a staggered arrangement.

3.3 Replacing the Seating

All soft finishes, i.e. the carpet and the seating, were replaced during the refurbishment. The sound absorption of the existing and the proposed carpet was checked in an impedance tube. Samples of the existing and the new seats were tested in a reverberation chamber according to ISO 354, both in the occupied and unoccupied conditions. The new seats were very carefully specified. A number of modifications were made on the prototype seats to get a closer absorption match to the existing seating, and the results were suitably good.

Room acoustic measurements were carried out before and after the refurbishment. The sine sweep deconvolution method was used in combination with an omnidirectional source on stage, for multiple receiver locations. Figure 10 shows the average reverberation time spectra before and after the refurbishment in the occupied condition. According to these measurements, there has been a marginal increase in reverberation time towards the low frequencies, which has been perceived by some regular concert goers as being an enhancement.

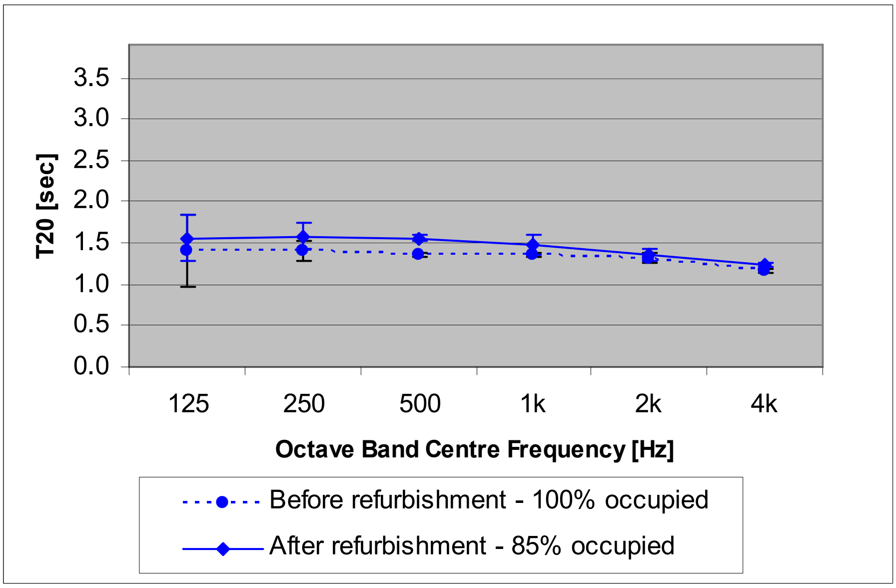


Figure 10: Reverberation time before and after the 2003-2004 refurbishment, in the occupied condition.

4 CONCLUSION

The geometry of the Wigmore Hall would not be favoured in current day acoustic design because of all the focusing surfaces and yet it is revered by international musicians and audiences alike. This paper has explored and explained some of the acoustic properties and idiosyncrasies of the Hall, in light of the recent refurbishment. Full understanding of acoustic behaviour with respect to concave surfaces would permit acoustic designers to be more innovative with the use of such geometries.

5 REFERENCES

1. M. Barron, 'Auditorium Acoustics and Architectural Design', E&FN Spon (1993)
2. D. Sugden, 'The Wigmore Hall and its Acoustic'. Chapter from 'Wigmore Hall 1901-2001 a Celibration', The Wigmore Hall Trust (2001)
3. L. Cremer & H. Müller, 'Principles and Applications of Room Acoustics, Volume 1', Applied Science Publishers Ltd (English edition 1982)
4. J.H. Rindel, 'Attenuation of Sound Reflections from Curved Surfaces', Proceedings of 24th Conference on Acoustics, Strbské Pleso, pp. 194-197 (1985)
5. A. Farina, 'Simultaneous measurement of impulse response and distortion with a swept-sine technique, Proceedings of 108th AES Convention, Paris (2000)
6. T. Wulfrank, 'Auditory Virtual Reality using Ambisonics/B-Format', MSc thesis, Technical University of Denmark, Department of Acoustic Technology / Ghent University, INTEC, Faculty of Engineering (2000)
7. http://www.ambisonic.net
8. Odeon Room Acoustics Software, http://www.odeon.dk