CONCAVE SURFACES AND ACOUSTICS OF PERFORMANCE SPACES PART I – HYBRID RAY-IMAGE ANALYSIS

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Résumé

Les pratiques acoustiques actuelles considèrent que les surfaces concaves ne fournissent pas de bonnes performances acoustiques. Cependant, les anciennes cathédrales, églises et lieux de spectacle aux intérieurs concaves semblent d'avoir une bonne performance acoustique. La partie I de cette recherche analyse les performances acoustiques des espaces à surfaces courbés. L'objectif principal est de rechercher l'uniformité du champ acoustique produit par les surfaces courbes en analysant la distribution des niveaux de pression acoustique dans l'espace du public. Cela à permit d'étudier l'impact du plan focal sur la distribution générale du son dans un espace clos. Pour analyser l'effet des surfaces courbes à différentes fréquences, trois lieux fermées aux surfaces courbes ont été utilisées pour mesurer les niveaux de pression acoustique dans l'espace du public : la galerie Paul Cocker à l'Université Ryerson à Toronto; l'église Anglicane St. Martin-in-the-Field à Toronto; et le Wigmore Hall au Royaume-Uni. Les évaluations ont été réalisées avec des méthodes expérimentales et des simulations informatiques utilisant des méthodes d'image hybride-rayon. Les simulations sur ordinateur ont été validées par les mesures initiales aux sites à Toronto. Après que ces analyses étaient effectués, les résultats ont montrés que dans ces conditions, les surfaces incurvées avaient un impact négatif minimal tel que perçu par le public. Les résultats de cette étude seront présentés dans cet article.

Mots clefs: Surfaces concaves; focalization; théorie de lancer de rayons; répartition des niveaux de pression sonore; simulation acoustique

Abstract

Current acoustic practices deem that concave surfaces do not provide good acoustical performance. However, old cathedrals, churches, and enclosed performance spaces with concave interiors seem to perform well. Part I of the current investigation analyzes the acoustical performance of spaces with curved surfaces. The main focus of the current investigation was to research the uniformity of the sound field produced by curved surfaces by analyzing sound pressure level distribution throughout the audience space. It studied the impact of the focal plane on the overall sound distribution within an enclosed space. To analyze the effect of curved surfaces at different frequencies, three enclosed rooms with curved surfaces were used to measure the sound pressure levels throughout an audience space: the Paul Cocker Gallery in the Ryerson Architecture Building, Toronto; St. Martin-in-the-fields Anglican Church, Toronto; and Wigmore Hall, United Kingdom. The evaluations were achieved with both experimental methods, and computer simulations using hybrid-ray-image methods. Computer simulations were validated by the initial on-site measurements in the Toronto locations. After these evaluations were performed, results showed that in these conditions, the curved surfaces had minimal negative impact as perceived by the audience. The results of the investigation will be presented in this paper.

Keywords: Concave surfaces; focussing; ray-image theory; sound pressure level distribution; acoustic simulation

1 Introduction

Conventional wisdom states that having concave surfaces as the envelope of any occupied space does not produce good sound [1]. It is well known that the focussing effect produced by concave surfaces can be problematic. Focussing can cause high sound pressure levels, coloration, and echoes [2]. However, throughout history there have been many enclosed rooms with large curved surfaces as envelopes that seem to produce good acoustics. Many churches, opera theatres, auditoriums, and concert halls alike were designed with curved features.

The main aspect investigated in the two papers is to find out if curved surfaces in performance spaces generate unsatisfactory acoustic results. In Part I, analysis was conducted applying hybrid image-ray acoustics. The results are highlighted below. Full details of the investigations can be gleaned from the research report by Johnston-Iafelice [3].

2 Background

The rationale for the current investigation was initiated by the anecdotal observation by O'Keefe during a performance in Toronto's Runnymede United Church, shown in Figure 1. He noted a strong and positive subjective response to a bass note of the 'G String (37 Hz)' even though he was sitting far away from the focal plane of the barrel vault ceiling. He

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wondered about the reasons for his clear perception of the note played by the bass. What happens to the sound beyond the focal plane, he mused. Some of his thoughts resulted in a conference paper [4]. The current investigation was undertaken to answer the truisms accorded to curved surfaces in performance spaces and are highlighted in the following sections.

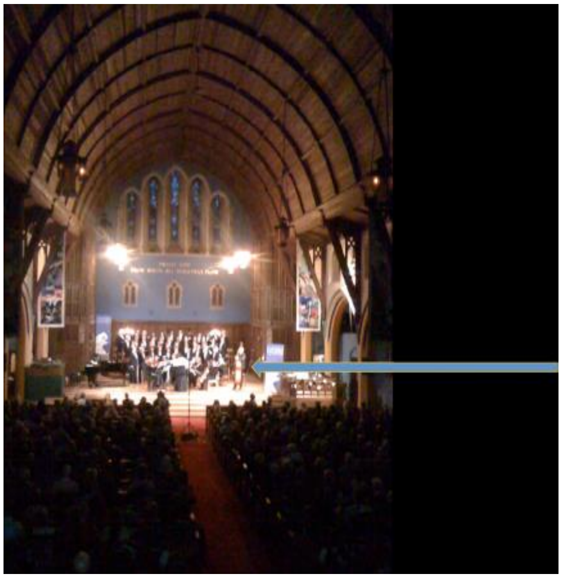


Figure 1: Runnymeade United Church with Curved Ceiling (Photo Credit: John O'Keefe).

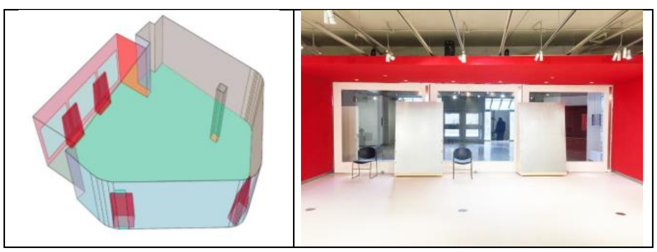


Figure 2: Paul Cocker Gallery, Ryerson University, Toronto

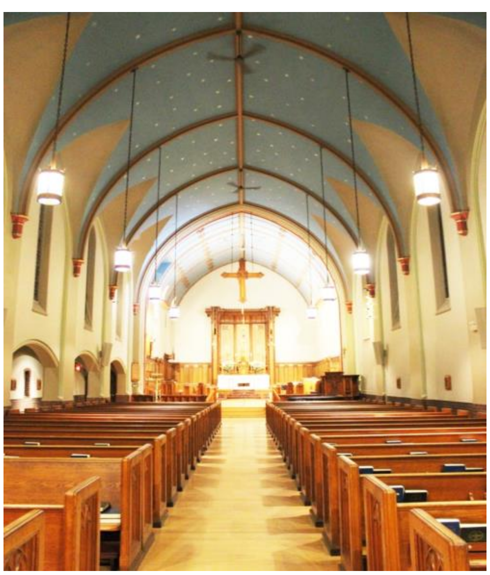


Figure 3: St. Martin in the Fields Anglican Church, Toronto.

3 Case study spaces

Three spaces were chosen for the investigation. They, as shown in Figures 2, 3, and 4, are: a) Paul Cocker Gallery (the Gallery) situated within the Architectural Science Bulding, Ryerson University, Toronto; 2) St. Martin-in-the-Fields Anglican Church (the Church), Toronto; and 3) Wigmore Hall in London England.

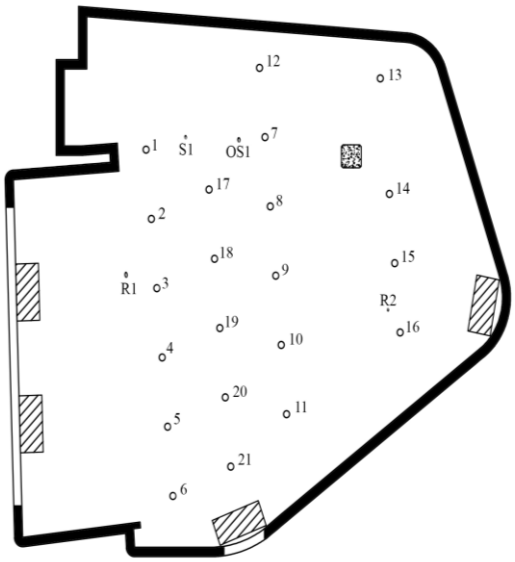
Paul Cocker Gallery was used as a test case to conduct both simulations as well as site measurements. It had no strong curved surfaces. However, three different concave surfaces were created and placed within the gallery to investigate the effects of curved surfaces. On the other hand, Wigmore Hall and the Anglican Church had strong concave surfaces as seen in Figures 3 and 4.

Figure 4: Wigmore Hall, Lonmdon, England.

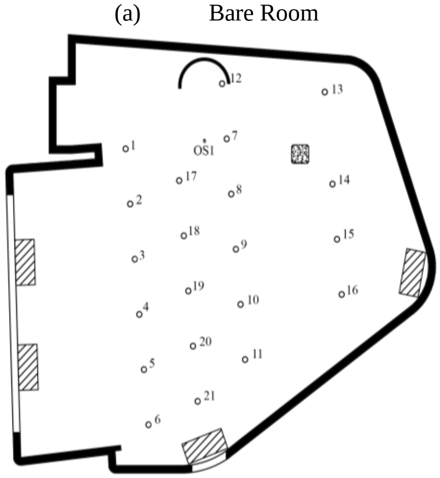
4 Measurements and analysis

Measurements were conducted in the Gallery and the Church by using a sine-sweep signal to calculate the impulse response. Some of the basic acoustic metrics such as reverberation time, clarity, centre time etc were evaluated. In addition, sound pressure level measurements were conducted at a number of locations in the Gallery by generating a pink noise signal through a dodecahedron speaker system. Measurement locations for the sound pressure level distribution, in the Gallery, with and without the curved surface are shown in Figure 5 below.

In addition, field measurements, and simulation of the three performance spaces were conducted. The site measurements of reverberation time, evaluated in the Gallery and the Church, were used to calibrate the simulations. Measurements of Barron were used to calibrate the Wigmore Hall simulations [5]. The commercially available software, ODEON, was used for the simulations, by applying a hybrid method using image-ray theory [6]. Vorlander [7] and Vercammen [8, 9] have discussed the uncertainties associated with the application of commercial software's simulating curved surfaces. However, Vercammne clearly indicates that geometric acoustics can be successfully applied in determining the sound levels beyond the focal plane of the concave surfaces. In addition, Wulfrank and Orlowski have successfully used ODEON in determining the properties of Wigmore Hall with concave surfaces [10]. The application of geometrical acoustics to determine the sound levels in the three spaces, under investigation, is, therefore, valid.



(a) Bare Room



(b) Horizontal Plane at 50 Hz

Figure 5: SPL Measurement Locations in the Gallery.

5 Results and discussion

Measurement results of the Sound Pressure Level (SPL) distribution around the Gallery are shown in Figures 6 and 7 with the source, OS1 located as shown in Figure 5. A pink noise was generated through a dodecahedron speaker system at OS1. The results are shown for four frequency bands at 63 Hz, 125 Hz, 200 Hz and 500 Hz. The SPL variation is also shown with and without the curve surface placed at location shown in Figure 5b.

The results at 63 Hz and 125 Hz do not show much difference with and without the curved surface placed in the Gallery. The SPL, for the two low frequencies, at Location 12 was not modified becasue the source wavelength was larger than the size of the curved surface. The only major change with the curved surface was seen at Location 12 for the 200 Hz and 500 Hz bands. Location 12 is within the curved surface and hence additional reflection at higher frequency of 200 Hz and 500 Hz was evident (Refer to Figure 7).

Finally, the SPL variation at Location 8 is shown in Figure 8 for the two conditions of bare room and the room with the curved surface. Once again, the curved surface is seen to have minimal impact on the SPL distribution.

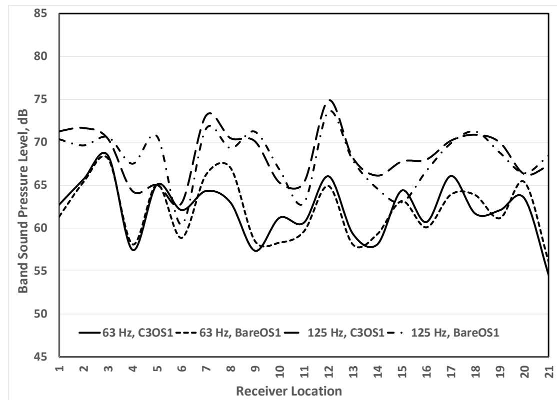


Figure 6: SPL distribution in the Gallery at 63 Hz and 125 Hz third-octave band frequencies.

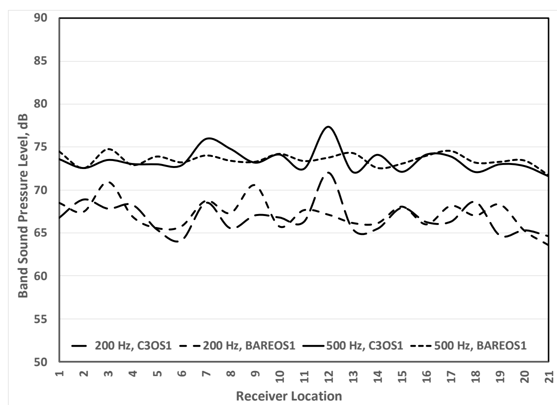


Figure 7: SPL distribution in the Gallery at 200 Hz and 500 Hz third-octave band frequencies.

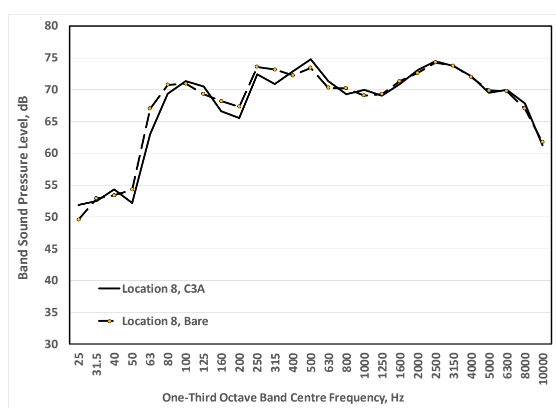


Figure 8: SPL distribution in the Gallery at Location 8.

Next, the simulations results for the three performance spaces are presented below. Simulations were first calibrated with site measurements. Simulations were then undertaken for different source locations within the three spaces. Results for the Gallery are discussed first. The results for the Gallery are presented in Table 1 below.

Table 1: SPL variation across the Gallery space, dB

Band Frequency, Hz	125	500	2 K
Source Location OS1	4.7	3.9	4.5
Source Location LA	4.8	4.4	5
Source Location LB	4.8	3.8	5
Source Location LC	4.8	3.8	5

The four source locations are highlighted in Figure 9 below. The table shows the difference between the minimum and maximum SPL in the gallery with the source placed in four different locations within the room. The maximum deviation is 5 dB and the minimum deviation is 3.9 dB.

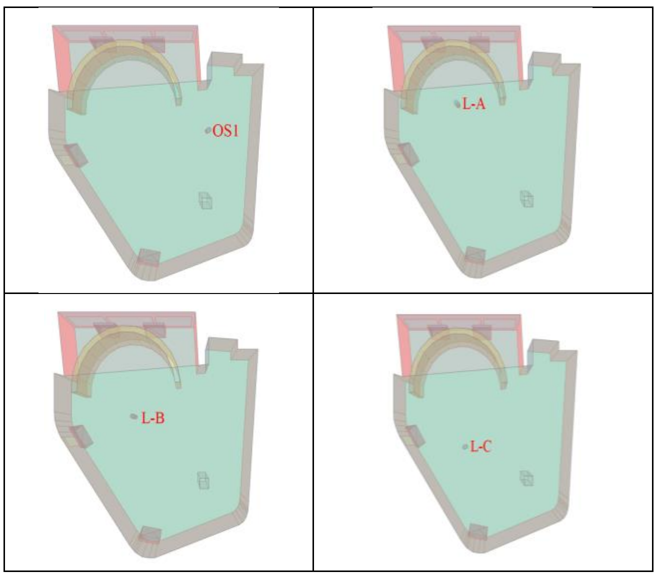


Figure 9: Source locations for the Gallery simulations.

A sample SPL distribution at 500 Hz for source location L-B is shown Figure 10 below. The lowest sound level is behind the large curve surface and if the shadow region is not included, the deviation will be smaller. Similar behaviour was observed for the different source location and other frequencies.

The results for the Church are presented in Table 2 below. The three source locations are highlighted in Figure 11 below.

The table shows the difference between the minimum and maximum SPL in the Church with the source placed in three different locations within the Church. The maximum deviation is 4.8 dB and the minimum deviation is 3.4 dB. A sample SPL distribution at 500 Hz for source location S-B is shown Figure 12 below. The lowest sound level is near the back of the Church. Similar behaviour was observed for the different source location and other frequencies.

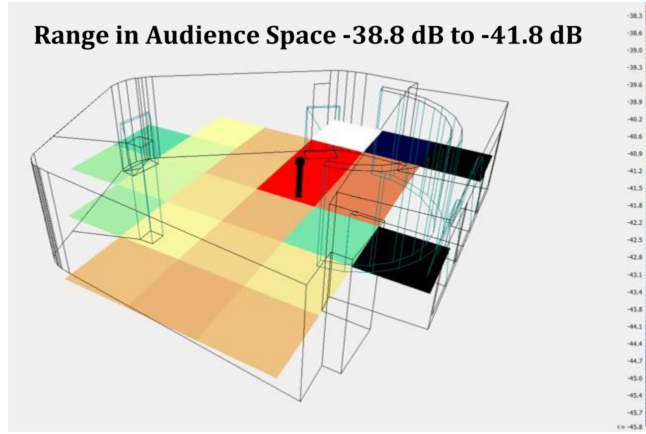


Figure 10: Simulation of SPL variation at 500 Hz in the Gallery.

Table 2: SPL variation across the Anglican Church, dB

Band Frequency, Hz	125	500	2 K
Source – A (Fig.11)	4	4	4
Source – B (Fig.11)	4.2	3.8	3.8
Source- C (Fig.11)	3.4	4.8	3.4

Figure 11: Source locations for the Church simulations.

The results of Table 2 and Figure 12 showed that the curved ceiling of the Church had minimal impact on SPL variation in the audience area except the fact the SPL decayed from front to the back. The reasons are outlined below. It is, conventionally, believed that the sound in enclosed spaces becomes diffused after a short distance away from the source of sound.

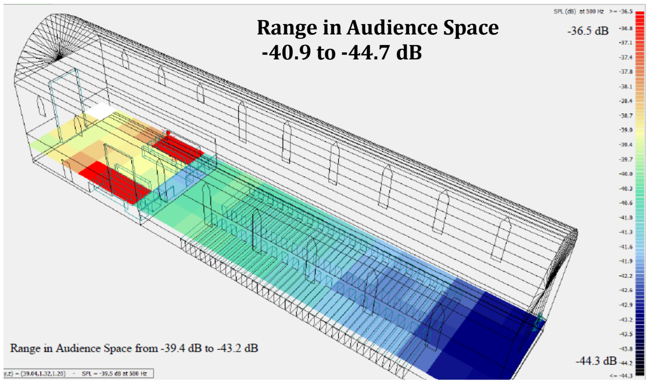


Figure 12: Simulation of SPL variation at 500 Hz in the Church.

But Gade's study on the room acoustics of Danish concert halls hinted at the notion that reflected sound pressure levels in concert spaces decreased as the receiver moved further away from the source [11]. The 'revised theory' of sound level in rooms was derived from early research of Barron [5, 12]. The revised theory states that reflected sound is not constant throughout an audience space, but decreases as a function of source-receiver distance.

Finally, the results for Wigmore Hall are presented in Table 3 below. The table shows the difference between the minimum and maximum SPL in the audience area with the source placed in five different locations within Wigmore Hall. The maximum deviation is 4.4 dB and the minimum deviation is 2.6 dB.

A sample SPL distribution at 500 Hz for source located inder the dome on the stage is shown Figure 13 below. The lowest sound level is near the back of the hall. Similar behaviour was observed for the different source location and other frequencies.

The results of Table 3 and Figure 13 showed that the curved ceiling and domed stage of Wigmore Hall had minimal impact on SPL variation in the audience area except the fact the SPL decayed from front to the back. The reasons for the SPL variation were discussed already.

Table 3: SPL variation across Wigmore Hall, dB

Band Frequency, Hz	**125**	**500**	**2 K**
Source-back of stage under dome	2.8	2.6	3.5
Source at middle of stage	3.8	3.5	3.6
Source-at front of stage	4.2	3.9	3.8
Source-5 on stage (Unoccupied)	4.0	3.3	2.7
Source-5 on stage (Occupied)	4.4	2.5	2.8

6 Conclusions

Impact of curved spaces was investigated in the two-part papers. Three interior spaces with curved surfaces were selected as test cases for the investigation. Part I of the two-part papers applied a Hybrid-Image-Ray analysis to evaluate the impact in mid-to-high-frequencies.

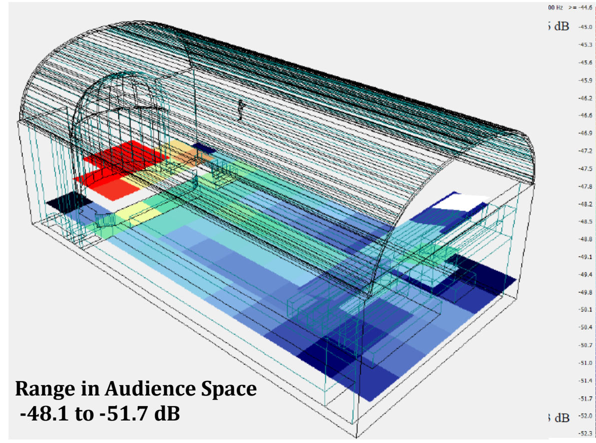


Figure 13: Simulation of SPL variation at 500 Hz in Wigmore Hall.

The results presented in Section 4 clearly indicated that concave surfaces have no negative impact on SPL distribution throughout the audience space. Beyond the focal plane, curved envelopes diffuse SPL equally throughout the enclosed spaces. The results also confirmed the 'revised theory' that SPL reduces as a function of source-receiver distance even in closed spaces.

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