CONCAVE SURFACES AND ACOUSTICS OF PERFORMANCE SPACES PART II – WAVE ANALYSIS

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Résumé

La croyance conventionnelle nous amène à penser que le fait d'avoir des surfaces concaves comme enveloppe d'une pièce occupée ne produit pas un son de qualité. L'effet du point focal des surfaces concaves peut provoquer des niveaux de pression acoustique élevés, des colorations et des échos. Cependant, tout au long de l'histoire, de nombreuses pièces avec des grandes surfaces incurvées semblent produire de bonne acoustique. Des recherches récentes ont suggéré de procéder à une analyse des ondes pour établir l'impact des surfaces concaves. Contrairement à la partie I de cette étude, l'évaluation de la distribution des niveaux de pression acoustique dans les pièces à surfaces concaves, a été réalisée en résolvant l'équation des ondes. La raison principale en est que la théorie de rayon image n'est valide qu'à des fréquences supérieures à la fréquence de coupure de Schroeder. La théorie des ondes est utilisé e pour les fréquences inférieures à 100 Hz. La modélisation par éléments finis a été appliquée pour résoudre le problème de la distribution du niveau de pression acoustique dans les pièces présentant des surfaces concaves. Dans cette étude, trois lieux ont été étudiés : la galerie Paul Cocker à l'Université Ryerson à Toronto, l'église Anglicane St. Pauls à Toronto, et le Wigmore Hall à Londres. Les résultats pour trois fréquences de basses (25 Hz, 50 Hz et 100 Hz) ainsi que leur combinaison seront présentés dans cette étude.

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

Abstract

Conventional wisdom states that having concave surfaces as the envelope of any occupied space does not produce good sound. The focussing effect of concave surfaces can cause high sound pressure levels, coloration, and echoes. However, throughout history there have been many enclosed rooms with large curved surfaces as envelopes that seem to produce good acoustics. Recent research suggested that wave analysis must be undertaken to establish the impact of concave surfaces. In contrast to Part I of the current investigation, evaluation of the sound pressure level distribution, in rooms with concave surfaces, was performed by solving the governing wave equation. The main reason is that the image-ray theory is valid only at frequencies greater than the Schroeder cut-off frequency. The wave theory is used for frequencies lower than 100 Hz. Finite element modelling was applied to solve for the sound pressure level distribution within rooms with concave surfaces. Three spaces, the Paul Cocker Gallery in Ryerson University, Toronto, St. Pauls Anglican Church in Toronto and Wigmore Hall in London were investigated in this study. The results for three low frequencies (25 Hz, 50 Hz and 100 Hz) as well as their combination will be presented in this paper.

Keywords: Concave surfaces; focussing; wave theory; sound pressure level distribution; acoustic simulation.

1 Introduction

It is a textbook truism that concave surfaces within confined spaces focuses sound whereas convex surfaces diffuse sound. On the other hand, many churches, opera theatres, auditoriums, and concert halls alike were designed with curved features from an architectural perspective. Many of these performance spaces were seen to provide acceptable and satisfactory acoustic character and focusing was found to be not an issue.

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. In Part II, wave analysis was conducted to evaluate acoustic performances in low frequencies in auditoria with curved envelopes. The results are highlighted below. Full details of the investigations can be gleaned from the research report by Johnston-Iafelice [1].

2 Background

The rationale for the current investigation was detailed in Part I of the two-part papers. The main thrust for the study was the anecdotal observation by O'Keefe during a performance in Runnymede United Church in Toronto. He noted a strong and positive subjective response to a base note of the 'G String (37 Hz)' even though he was sitting away from the focal plane. Brief details of O'keefe's subjective perception were discussed in Part I of the paper. The current investigation was undertaken to answer the

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truisms accorded to concave surfaces in performance spaces.

3 Case Study Spaces and Wave Analysis

Three spaces were chosen for the investigation. They, as shown in Figures 1, 2, and 3, are: a) Paul Cocker Gallery situated within the Architectural Science Bulding, Ryerson University, Toronto; 2) St. Martin-in-the-Fields Anglican Church, Toronto; and 3) Wigmore Hall in London England.

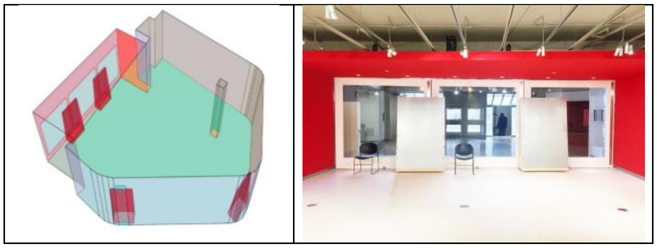


Figure 1: Paul Cocker Gallery, Ryerson University, Toronto.

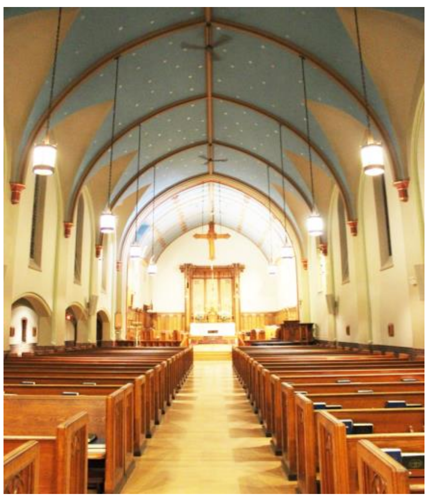


Figure 2: St. Martin in the Fields Anglican Church, Toronto.

Figure 3: Wigmore Hall, Lonmdon, 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 2 and 3.

The room acoustics software, ODEON, was used in Part I of the two-part papers [2]. Room acoustics software conventionally use a Hybrid-Image-Ray method to evaluate the results in band frequencies up to 8000 Hz. However, the hybrid method loses accuracy in low frequency below a cut-off frequency, called Schroeder frequency, given by Equation 1 below.

$$f_s = 2000\sqrt{\frac{T_{60}}{V}} \quad (1)$$

Where, V is the volume of the space and T_{60} is the reverberation time. The main thrust of our investigation was the 'G String' event observed in Runneymede United Church. Hence, low frequency analysis was undertaken through wave theory where the exact wave equations were solved using a finite element method (FEM). The FEM solutions were evaluated applying a commercially available powerful multi-physics softaware, COMSOL [3]. FEM divides the solution region into a number of elements (i.e., meshing), and solves the governing equation with a pre-set source defined. A simple example of the meshing of Wigmore Hall with a point source within the stage area, below the cupola, is shown in Figure 4 below.

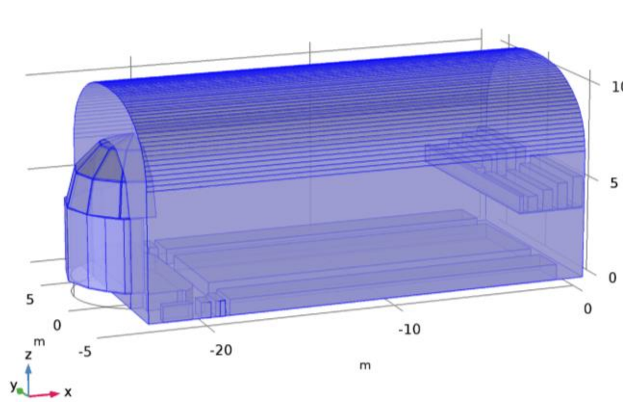


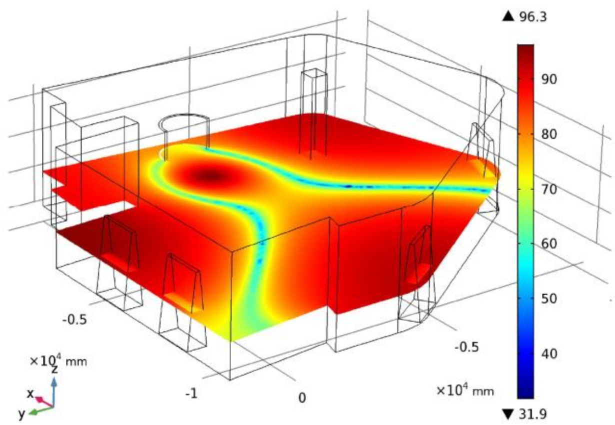
Figure 4: An Example of COMSOL FEM meshing of Wigmore Hall.

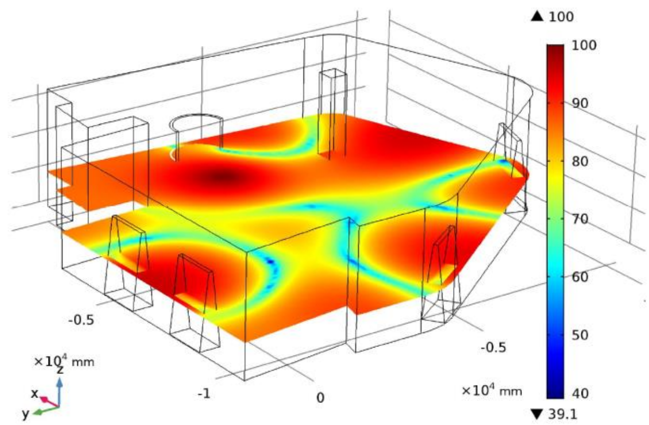
4 Results and Discussion

A point source was placed at different locations of the interior space of the three test cases; the Gallery, the Church and Wigmore Hall, and the Sound Pressure Level variation were evaluated along a horizontal plane as well as a vertical plane. The FEM results are highlighted below.

4.1 Paul Cocker Gallery

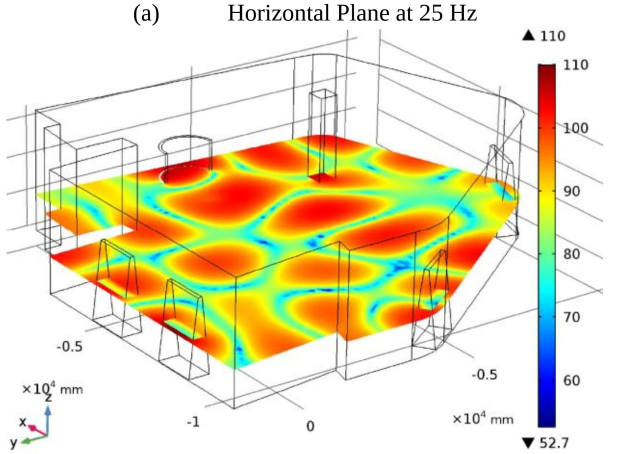
It must be noted that the Gallery does not contain any interior concave surfaces. Hence, three different curved surfaces were fabricated and placed within the gallery. The results for one of the curved spaces are highlighted in the figures below.

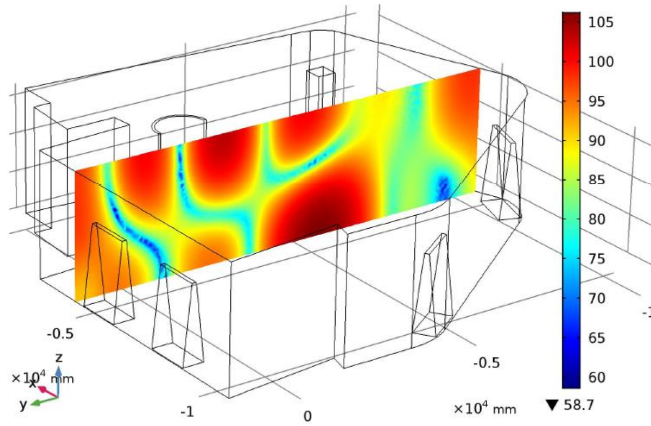




(a) Horizontal Plane at 25 Hz

(b) Horizontal Plane at 50 Hz





(c) Horizontal Plane at 100 Hz

(d) Vertical Plane at 100 Hz

Figure 5: SPL distribution for the Gallery, Source outside the curve.

Results for SPL variation with the source outside the concave surface are shown in Figure 5. The results for 25 Hz, 50 Hz and 100 Hz, along a horizontal plane, are shown in Figures 5a, 5b and 5c respectively. Results for 100 Hz, along a vertical plane, are shown in Figure 5d.

The main observation is that the concave surface did not focus the sound and the SPL variation is mainly controlled by the room modes. Similar results for the point source placed inside the focal plane of the concave surface are shown in Figure 6 below.

Similar observation can be gleaned from Figure 6 that the concave surface has no impact on the SPL variation.

4.2 St. Martin-in-the-Fields Anglican Church

Results for SPL variation with the source near the main altar of the Church is shown in Figure 7. The results for 25 Hz, 50 Hz and 100 Hz, along a horizontal plane, are shown in Figures 7a, 7b and 7c respectively. Results for 100 Hz, along a vertical plane, are shown in Figure 7d.

The main observation is that the concave surface did not focus the sound and the SPL variation is mainly controlled by the room modes

4.3 Wigmore Hall

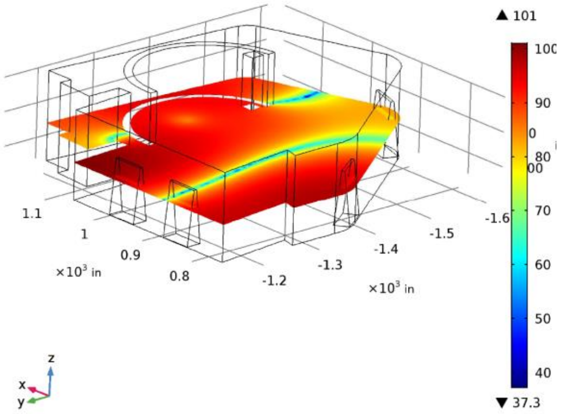
Results for SPL variation with the source on the stage below the cupola are shown in Figure 8. The results for 25 Hz, 50 Hz and 100 Hz, along a horizontal plane, are shown in Figures 8a, 8b and 8c respectively. Results for 100 Hz, along a vertical plane, are shown in Figure 8d.

The main observation is that the concave surface did not focus the sound and the SPL variation is mainly controlled by the room modes. Similar results were observed for both the Gallery and the Church.

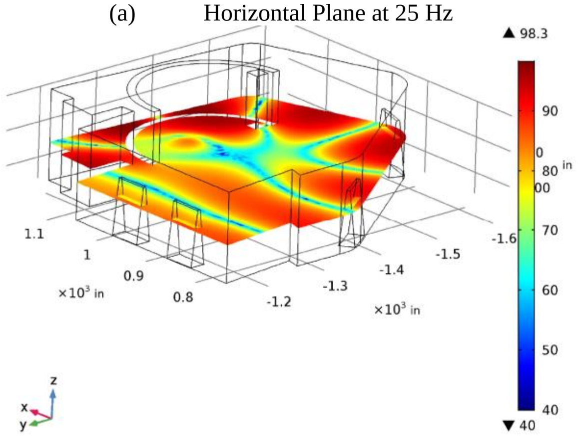
It must be also pointed that the results presented in Figures 5, 6, 7, and 8 were for single frequencies. However, in actual performances, each note is accompanied by its harmonics and sub-harmonics and single tones are never generated. Hence, the actual SPL variation will be a combination of many frequencies, being generated simultaneously.

4.4 Discussions

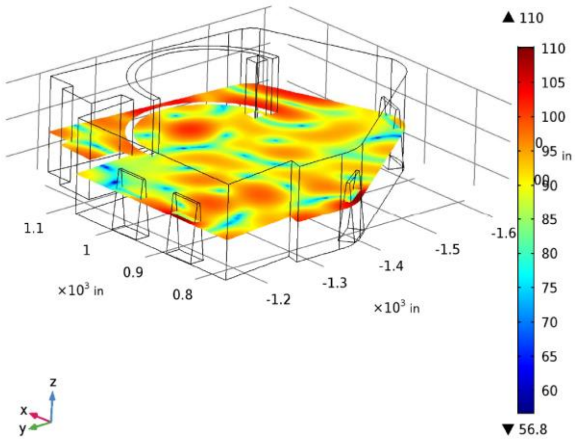
It must be pointed out that the focussing effect of the concave surfaces depend on the size of the surface and the wavelength (λ) of the generated sound as shown by Vercammen [4. 5]. Results for 25 Hz (λ = 13.6 m), 50 Hz (λ = 6.8 m), and 100 Hz (λ = 3.4 m) were presented in this paper. And hence results for the Gallery is truly valid for 100 Hz. The results for Wigmore Hall and the Church are valid for 50 Ha and 100 Hz and on the borderline for 25 Hz. However, the results were presented for all the three frequencies to show the behaviour trend of concave surfaces at low frequencies.



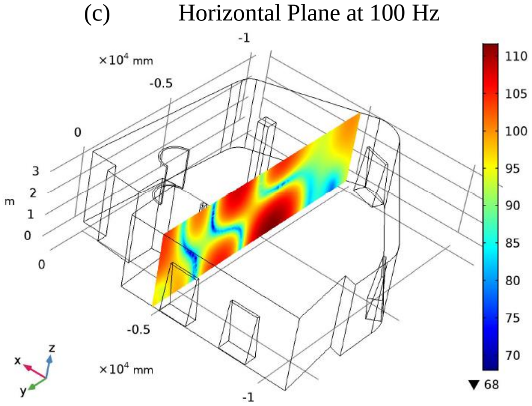
(a) Horizontal Plane at 25 Hz



(b) Horizontal Plane at 50 Hz

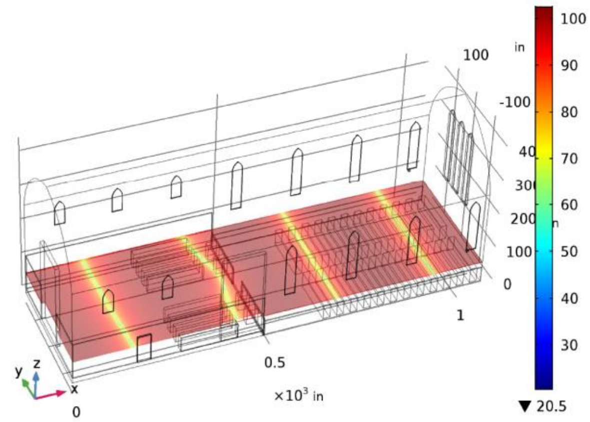


(c) Horizontal Plane at 100 Hz

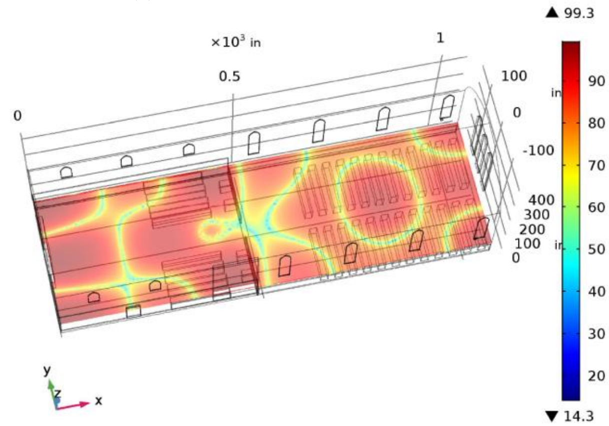


(d) Vertical Plane at 100 Hz

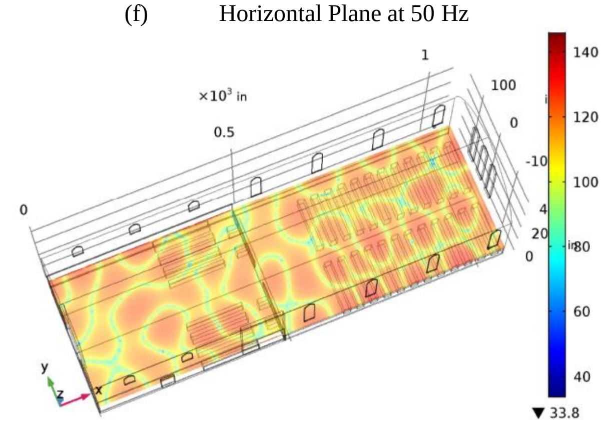
Figure 6: SPL distribution for the Gallery, Source inside the curve.



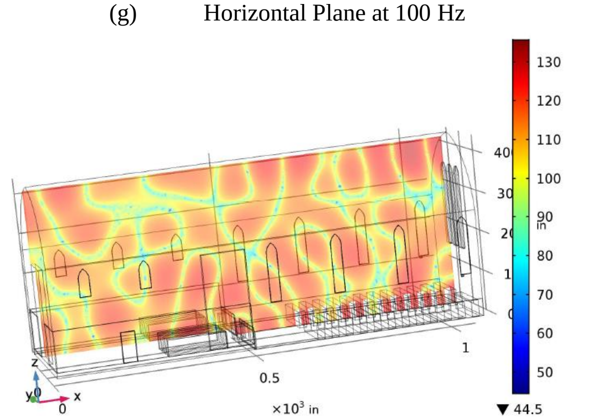
(e) Horizontal Plane at 25 Hz



(f) Horizontal Plane at 50 Hz

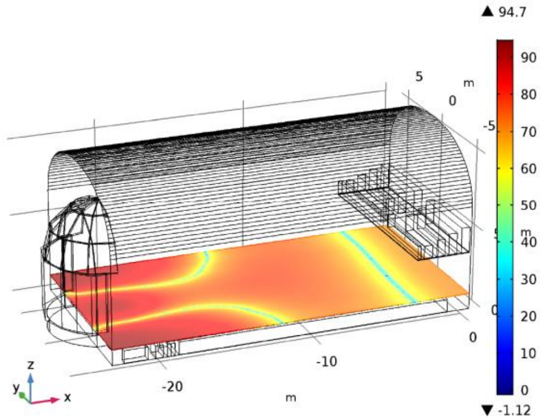


(g) Horizontal Plane at 100 Hz

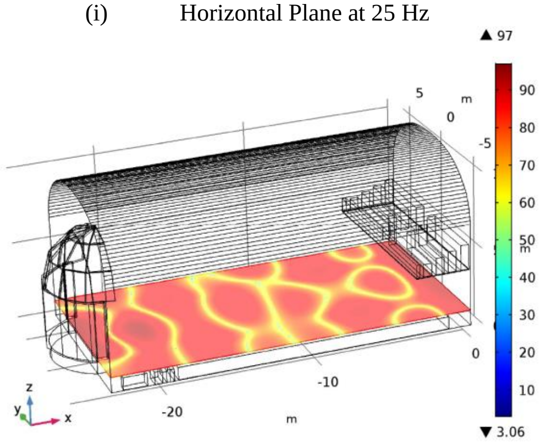


(h) Vertical Plane at 100 Hz

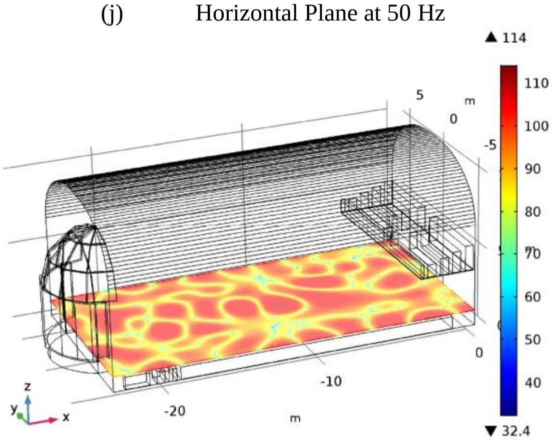
Figure 7: SPL distribution for the Anglican Church.



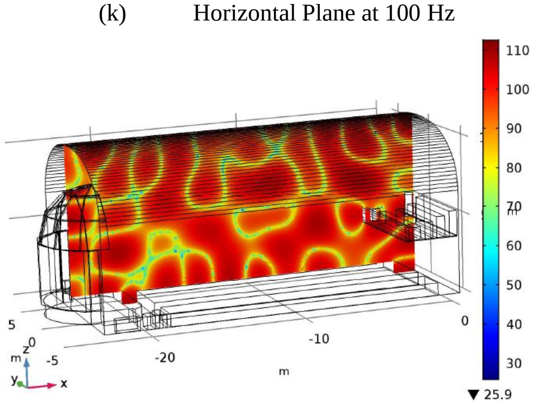
(i) Horizontal Plane at 25 Hz



(j) Horizontal Plane at 50 Hz



(k) Horizontal Plane at 100 Hz



(l) Vertical Plane at 100 Hz

Figure 8: SPL distribution for the Wigmore Hall.

5 Conclusions

Impact of curved spaces was investigated. Part II of the two-part papers applied a wave analysis to evaluate the impact in low-frequencies. The results presented in Section 4 clearly indicated that concave surfaces have no negative impact on SPL distribution throughout the audience space. In addition, SPL at low frequencies is dominated by the room modes.

Acknowledgements

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References

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