Audio Engineering Society

Convention Paper 10073

Presented at the 145th Convention
2018 October 17–20, New York, NY, USA

On the accuracy of audience implementations in acoustic computer modelling

Ross Hammond[1], Adam J. Hill[1], and Peter Mapp[2]

[1] *Department of Electronics, Computing and Mathematics, University of Derby, UK*

[2] *Peter Mapp Associates*

Correspondence should be addressed to Ross Hammond (R.Hammond@derby.ac.uk)

ABSTRACT

Performance venue acoustics differ significantly due to audience size, largely from the change in absorption and reflection pathways. Creating acoustic models that accurately mimic these changes is problematic, showing significant variance between audience implementation methods and modelling techniques. Changes in total absorption per person due to audience size and density makes absorption coefficients selection difficult. In this research, FDTD simulations confirm that for densely packed audiences, diffraction leads to a linear correlation between capacity and total absorption at low frequencies, while at high frequencies there is less increase in total absorption per person. The significance of diffraction renders ray-tracing inaccurate for individually modelled audience members and has further implications regarding accuracy of standard audience modelling procedures.

1 Introduction

The acoustics of performance venues differ significantly when occupied compared to unoccupied, and different audience characteristics such as density of occupation, clothing and posture produce variations to absorption [1,2,3,4]. Formulation of absorption coefficients for audiences is problematic and when considering audience size alone, measuring a group of people in accordance with ISO 354 [5] is often not suitable to be transferred to a larger audience due to the change in ratio between audience size and perimeter edges [6].

Several additional methods have been proposed including the use of many measurements from occupied and unoccupied concert halls, to determine average absorption coefficient values [7]. Screens can also be used during reverberation chamber measurements to cover the edges of the audience block [6] which was adapted to calculate the absorption of each audience surface by using measurements with and without screens [8]. Another method [9] uses two different coefficients, one for both an infinite audience area without edges and one for the perimeter length, calculated by taking a variety of measurements in different configurations.

A variety of conditions were tested within a reverberation chamber based on this theory, for a combination of audience characteristics, including differences due to audience density [1]. The effect of edges was found to be negligible for low occupation density rates, consequently meaning the sound absorption is a linear correlation with occupation. Within the 0.88pers/m^2 to 2.34 pers/m^2 density range tested for standing audiences, the absorption coefficients for 125Hz and 250Hz were found to be independent of the number of occupants. At higher frequencies absorption per person decreases as density increases. It is unclear if validation [2] can be accurately provided using acoustic models compared with physical measurements. To date, little work has been found on optimum methods of implementing audiences within acoustic models and if there are variances between commonly used techniques.

This work intends to identify and assess the variances between audience implementation techniques. Often, a standard audience absorption coefficient will be applied to a floor plane, floating plane or an audience brick, but it is expected that variances will exist between these techniques. Additionally, two different acoustic simulation methods will be investigated for audience modelling including geometrical ray-tracing/cone tracing and the finite-difference time-domain (FDTD) method. The undertaken work could also be applied to areas with public address systems that are tested without the presence of an audience or the public and validated using acoustic models.

2 Methodology

Several different methodologies were employed during this work. Initially, comparisons were made between audience implementation techniques in acoustic models using an industry standard electro-acoustic modelling program EASE [10]. This was completed in both a reverberation chamber model and the theatre 1 template which is a ~10,000m^3 theatre with inbuilt sound system including distributed delays and front fills (Fig 1).

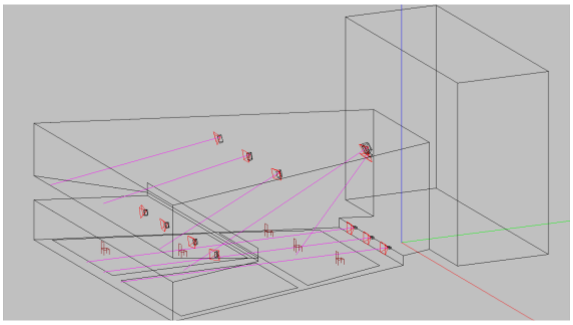

Figure 1. Theatre 1 template in EASE.

Assessments of the reverberation time and total absorption were made as well as derived equivalent absorption coefficients per person for the reverberation chamber. Differences to the Speech Transmission Index and impulse responses were also observed. The calculations from the simulated reverberation times were made in accordance with ISO 354 [5]. This required twelve impulse responses to be created, and reverberation times averaged, for each condition using four measurement positions and three source positions. The chamber is 450.59m^3 with surfaces assigned a 0.01 absorption coefficient, with 100% scattering to create a diffuse field. It was validated by inserting a known absorbing material and calculating the absorption coefficient based on the reverberation time of the empty and occupied chamber. A 25m^2 area was used for each implementation technique with a consistent 0.4 absorption coefficient across all frequency bands for the reverberation chamber, to assess any frequency dependence. Within the theatre 1 model, a standard audience absorption coefficient from EASE was applied to each implemented audience area. Implementations include an ‘audience brick’ (faces in the shape of a cuboid/polyhedron), floating planes and floor planes as shown in Fig 2 - 4. Four listener positions were used in the theatre model positioned left, centre and right of the centre line of the venue, close to the stage and a central position towards the back of the venue.

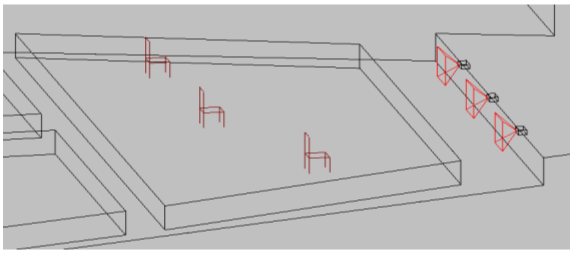

Figure 2. Audience brick implementation.

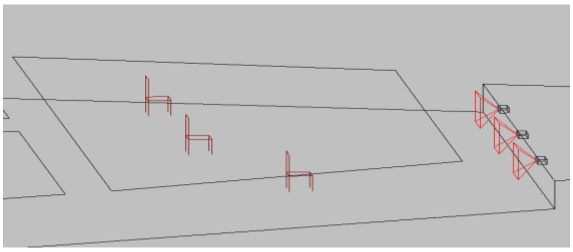

Figure 3. Floating plane implementation.

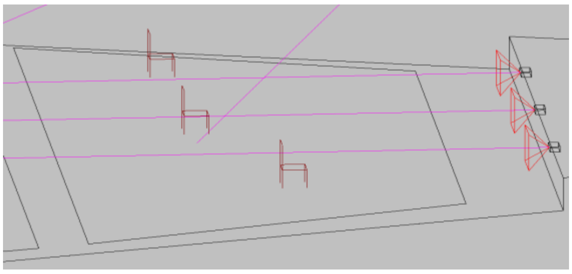

Figure 4. Floor plane implementation.

To assess the effect of audience density of population, audience 'columns' were inserted into the reverberation chamber at different densities within a fixed 25m^2 area. The columns were formed of a polygon with 24 sides, were 0.31m in diameter and extruded to a 1.7m height, as displayed in Fig 5. This simplified representation of an audience member does not provide realistic data but allows an insight into the absorption patterns expected by differing audience densities. The densities tested consist of 0.16 to 9 persons per m^2 in addition to testing a single audience column as a reference. Additionally, the same reverberation chamber model with audience columns was created in the software LowFAT [11] which utilizes the finite-difference time-domain (FDTD) modelling method with an upper frequency limit of 2kHz due to limited computational power and an 18th order Maximum Length Sequence (MLS) source signal. This allows the inclusion of diffraction effects within the simulations as opposed to geometrical cone-tracing. Additionally, five source positions were tested for a 7.84pers/m^2 density using LowFAT to observe if source position has an impact on how much diffraction affects absorption. This included directly above the audience columns at a distance of 2m and at 15° intervals.

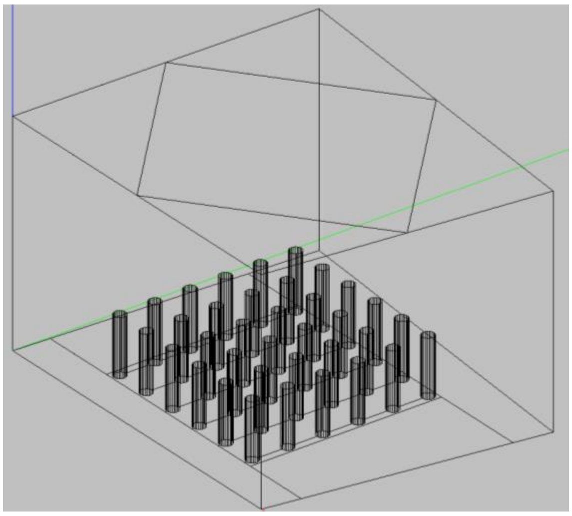

Figure 5. Reverberation chamber model with audience columns.

3 Audience implementation differences

The reverberation times (RT) of the reverberation chamber model calculated within EASE, with different audience implementations are found in Fig 6. As expected, the additional absorbing surface area from an audience brick and floating planes results in a reduction of reverberation time. This is a significant difference for low frequencies where air absorption is less of a contributing factor, with the RT more than doubling between audience brick and the floor plane approaches over the range 100-400Hz.

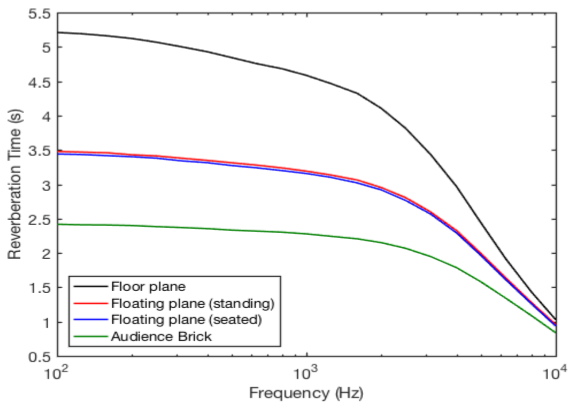

Figure 6. Reverberation chamber RT times.

The air absorption, which is included in EASE simulations, results in the reverberation times found in Fig 6 to be inconsistent with frequency. Calculating the corresponding total absorbing area [5], found in Fig 7, allows the absorption from the object in question to be calculated disregarding air absorption. This is approximately consistent across all frequencies for all implementations, which is to be expected as a 0.4 absorption coefficient was used for all frequencies to observe any frequency dependent effects. The cone-tracing technique used by EASE does not accurately show the physical effects of diffraction which would produce frequency differences.

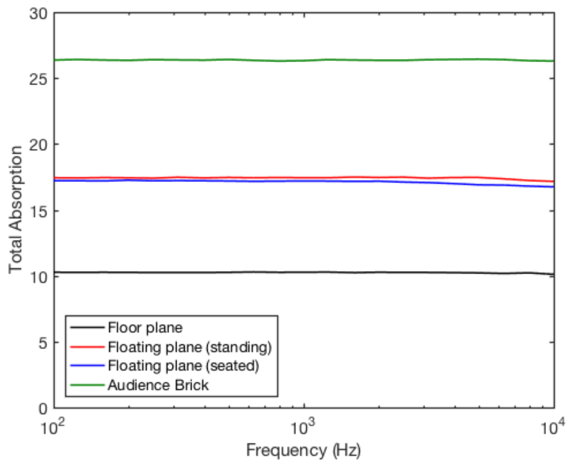

Figure 7. Reverberation chamber equivalent total absorbing area.

Fig 8 shows the reverberation times for different audience implementations within the theatre 1 template with all loudspeaker elements active. It is clear to see differences between each implementation with significantly less sound absorption from the floor plane. This is not necessarily due to the total absorbing area, since the floating planes would be very similar. It is more likely due to the position of the absorbing material in relation to the concentration of sound energy. This is supported by the differences between the floating planes which provide an identical amount of total absorbing area but are located at different heights. This could also allow additional sound energy to enter the space between the floor and the floating plane for higher positioned planes. The front-face of the audience brick provides additional absorbing material alongside the heightened position of the plane at standing height consequently meaning this implementation provides the most absorption.

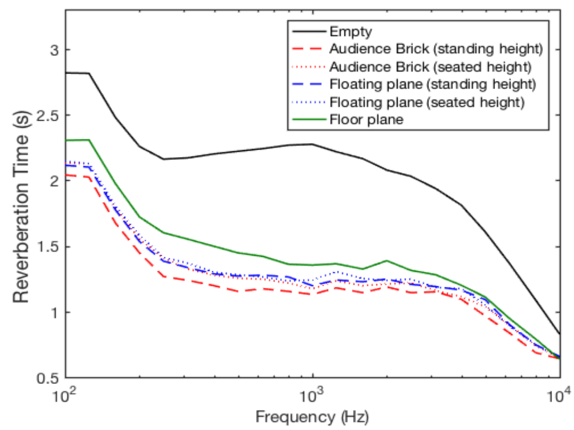

Figure 8. Theatre 1 average RT times.

Fig 9 and 10 display the differences in reverberation times between audience implementations of the single measurement positions front-left (stage right) and front-centre. All positions exhibit a similar amount of disagreement between implementations which removes the possibility that the differences in Fig 8 are due to averaging.

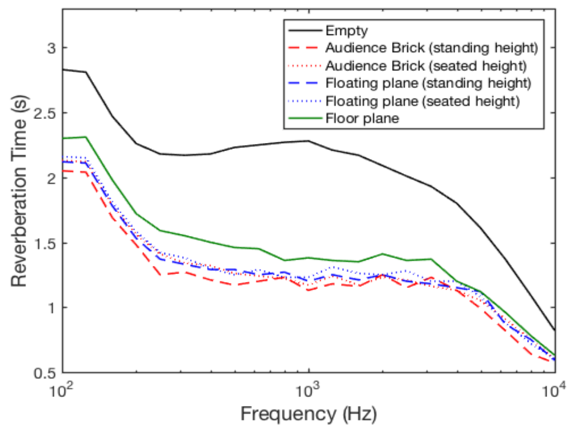

Figure 9. Theatre RT time, front-left position.

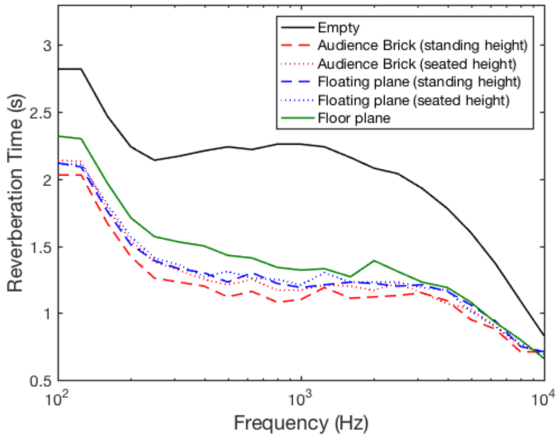

Figure 10. Theatre RT time, front-centre position.

Additional simulations were made with the front-fills/stage lip loudspeakers active, to observe changes when sources are positioned at approximately the same height as the audience. Fig 11 shows the reverberation times for the front-centre position, where significant variations can be seen. A substantial amount of the direct sound will be absorbed by the front face of the audience brick, resulting in a reduced reverberation time compared with other implementation techniques and compared with the same technique but the entire sound system active. The rays from the source are almost perpendicular with the floating plane at standing height causing less interaction and absorption. This demonstrates the inconsistent effects produced by audience implementations for differing source positions.

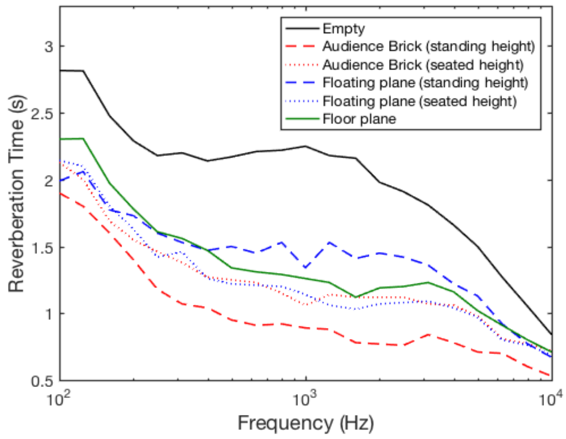

Figure 11. Theatre RT time, front-fill loudspeakers, front-centre position.

Observing the time domain is crucial to decipher alterations to the reflection pathway. Fig 12 through 14 show the impulse responses, with a 44.1kHz sample rate, of three implementation techniques at the front-centre position. Subtle changes to the discrete early reflections in both time and level could alter perception and intelligibility. Changes to the reflection pathway from using different techniques therefore needs to be carefully considered. It is clear that differences are present within the discrete reflections especially for the first early ground reflection.

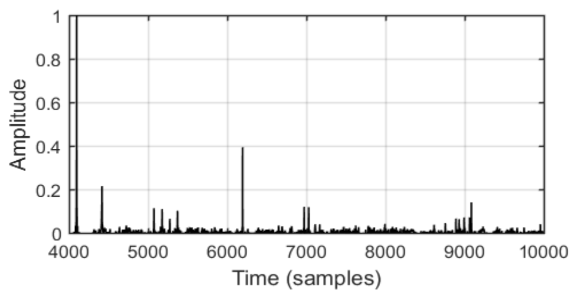

Figure 12. Impulse response floor plane.

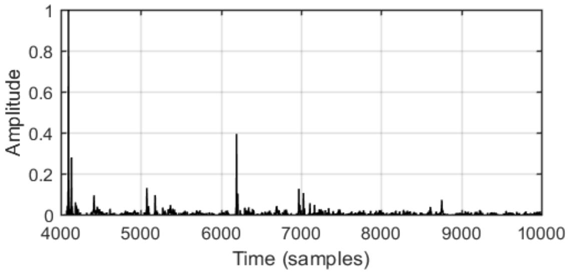

Figure 13. Impulse response floating plane.

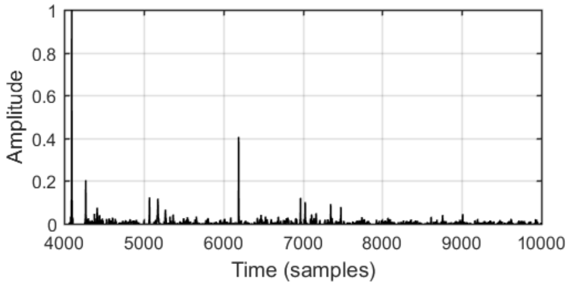

Figure 14. Impulse response audience brick.

The calculated Speech Transmission Index (STI) for each implementation when all loudspeakers are active is shown in Fig 15. Consistent variations exist of up to 0.08 STI between implementations. This is a significant difference both perceptually and potentially contractually when target STI values need to be achieved. The greater differences between the floor plane and floating plane also suggests that the position of this audience face is of greater importance than the total absorbing area, especially when there are directional loudspeakers and there is not an ideal diffuse field.

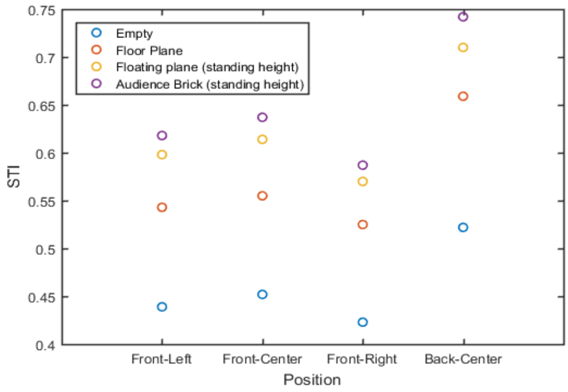

Figure 15. Speech Transmission Index.

Subsequently, Fig 16 shows the STI results for when the front-fill/stage lip loudspeakers are solely active. For all positions the floor plane has better measured intelligibility than the floating plane which is the opposite to when the entire sound system is active. It is suggested that most of the direct sound rays emitted from the sources which would otherwise interact with the audience, run parallel to the floating plane bypassing it, increasing the early and late reflection energy. Furthermore, sound energy can become trapped in-between the floor and floating plane, restricting essential early reflections. Towards the back of the venue, the audience brick implementation limits some direct sound energy due to blocking early reflection pathways.

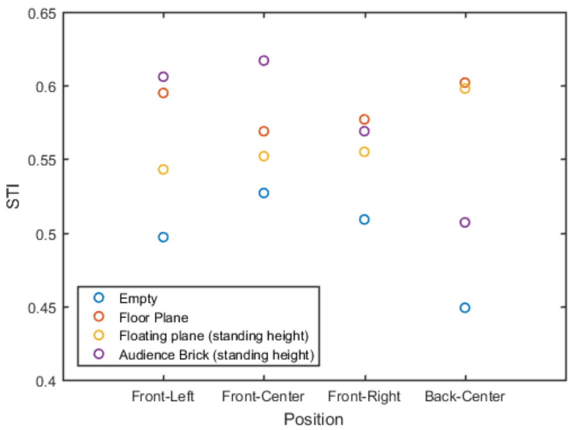

Figure 16. Speech Transmission Index (front-fill loudspeakers).

4 Modelling method differences

Fig 17 shows the resultant absorption coefficients (calculated per total polygon area) of different densities implemented via audience columns, calculated in EASE. The absorption coefficient applied to each column was kept consistent at 0.4 to show any frequency dependent effects. The calculated value of 0.4 at a capacity of 1 audience column validates the acoustic model and procedure. There are negligible differences between frequencies across all densities, which does not align with physical measurements [1]. This suggests the diffraction effects at low frequencies are not considered by software utilizing the ray tracing/cone tracing geometrical acoustic modelling techniques. For physical measurements, a greater amount of absorption per person/total polygon area occurs for low frequencies at higher densities. The reflection pathways for cone-tracing will mostly interact with the external columns, reducing the impact/absorption of the central columns, creating a lower overall absorption coefficient per person/total polygon area. Diffraction means the central columns provide a greater amount of absorption, although this depends on the frequency to density relationship.

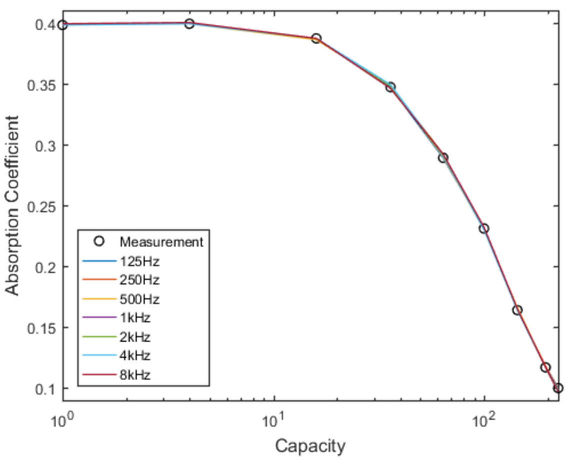

Figure 17. Audience density of occupation equivalent absorption coefficients from EASE simulations.

When the same simulations are carried out with FDTD, which incorporates the effect of diffraction, the frequency dependence is found, as seen in Fig 18. However, the creation of polygons within the software is less precise than within EASE, making the calculated absorption coefficients slightly less reliable. As expected, at low frequencies where wavelength is larger than the audience columns, the absorption per person/area is consistent as capacity increases which corresponds with previous research [1]. As frequency increases, less diffraction means the RT is closer to that of the cone-tracing technique. It is predicted that frequencies above 2 kHz, which was currently not practicable to compute, will continue to approach the RT response data from EASE. Research on metamaterials which suggests how filters can be created with scaled-down similar structures [12] could explain the irregular reduction of absorption at 500Hz, although further work is required to explore this hypothesis.

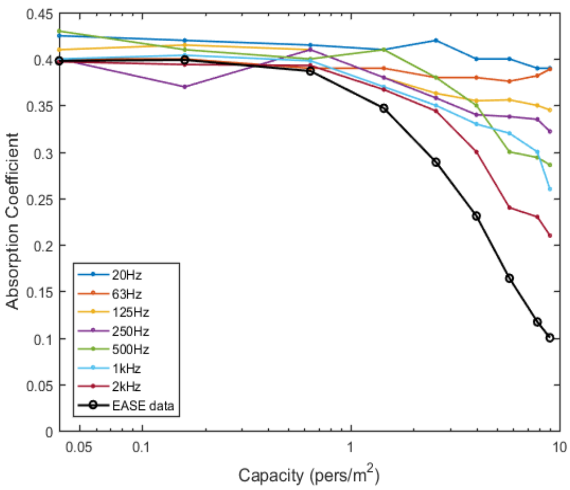

Figure 18. Audience density of occupation equivalent absorption coefficients from FDTD and average EASE data.

Fig 19 shows the equivalent absorption coefficients because of differences in diffraction caused by source position. Negligible effects occur at low frequencies but as the wavelength exceeds the diameter of the audience columns, position does appear to effect absorption. From above, higher frequencies will be absorbed at a higher rate, most likely due to interactions with a larger surface area of absorbing material. Off axis, less interaction with the absorbing audience columns and minimal diffraction due to short wavelengths means less absorption per column.

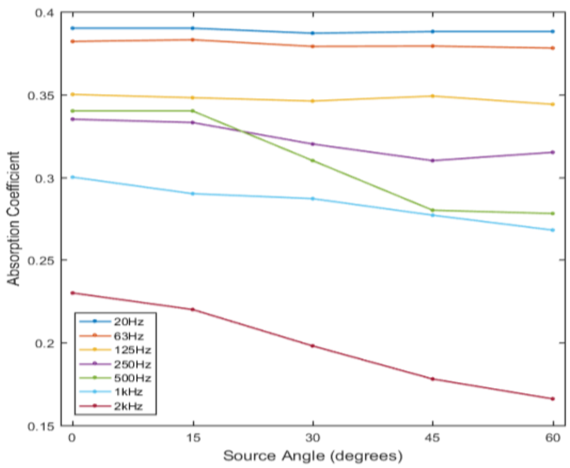

Figure 19. Absorption coefficients for 7.84 per/m^2 for source angles between 0° and 60°.

5 Conclusions

It is clear that implementations of audiences within acoustic models can create significant differences to total absorption, reflection pathways and intelligibility measurement. Audience bricks, floating planes and floor planes contain a different amount of total absorbing area as well as occupying a different area of space, affecting interaction with the sound.

Using individually modelled audience members would seem an optimal solution as the shape would be more realistic, despite the increased detail. However, this creates additional problems within common geometrical acoustic simulation software since diffraction is not adequately modelled and has been shown to be a key element to audience absorption.

Simulations using cone-tracing geometrical acoustic modelling techniques of audience columns arranged in different densities inside a reverberation chamber produced absorption that is independent of frequency, which does not support previous research. FDTD of the same conditions aligned with previous research that low frequency absorption per person is independent of density. As density increases, the absorption per person decreases for higher frequencies. It is suggested that diffraction causes this effect.

Ongoing future work will continue investigation using actual absorption coefficients, rather than using consistent values to identify frequency dependent effects. Additionally, physical measurements will allow development of transferable absorption coefficients for standing audiences for a variety of densities. The developed coefficients will be paired with audience implementation techniques for greater accuracy when creating acoustic models.

References

[1] Martellotta, F. D’alba, M. and Crociata, S. "Laboratory measurement of sound absorption of occupied pews and standing audiences", Applied Acoustics, vol. 72, no. 6, pp. 341-349, 2011.

[2] Martellotta, F. Crociata, S. and D’Alba, M. "On site validation of sound absorption measurements of occupied pews", Applied Acoustics, vol. 72, no. 12, pp. 923-933, 2011.

[3] Meyer, E. et al. “Uber einige messungen zur schallabsorption von publikum (On the measurements of sound absorption of audiences). Acustica 14:119–24, 1964.

[4] Kath, U. “"The Influence of Clothes on the Sound Absorption of Single Persons." Acta Acustica united with Acustica, 17.4, 234-237, 1966.

[5] ISO 354:2003 - Acoustics - Measurement of sound absorption in a reverberation room.

[6] Kath, U. and Kuhl, W. “Messungen zur schallabsorption von personen auf ungepolsterten stuhlen (Measurements of sound absorption of audience on unupholstered seats). Acustica 14:49–55, 1964.

[7] Beranek, L. L. “Audience and seat absorption in large halls”, The journal of the Acoustical Society of America, 32.6, 661-670, 1960.

[8] Davies, W. J. et al. “Measuring auditorium seat absorption”. J Acoust Soc Am 96(2):879–88, 1994.

[9] Bradley, J. S. “Predicting theater chair absorption from reverberation chamber measurements”, The journal of the Acoustical Society of America, 91(3), 1514-1524, 1992.

[10] AFMG. "Enhanced Acoustic Simulator for Engineers", [Online]. Available: http://ease.afmg.eu/. [Accessed: 30 May 2018].

[11] Hill, A. "LowFAT", [Online]. Available: http://adamjhill.com/lowfat/. [Accessed: 30 May 2018].

[12] Zhu, H. et al. “Metamaterial based embedded acoustic filters for structural applications." AIP Advances 3.9: 092121, 2013.