AN INVESTIGATION INTO THE ACOUSTICS OF THE ODEON OF HERODES ATTICUS

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1 INTRODUCTION

An increased interest in the study of the acoustical properties of ancient performance spaces has been reported in recent years. The revival and reproduction of the sound of historical monuments can nowadays be achieved by means of computer modelling software as well as in situ measurements in the view to clarify their acoustic evolution over time[1]. This work has also been encouraged by a number of charters, guidelines and projects put forward from 1931 till nowadays [2], [3].

With the advent of Virtual Reality technologies and 3D environments of high level of detail and accuracy, a realistic representation and navigation within those monuments can also be achieved. This remote real-world experience can serve educational purposes and enhance visitor experience in museums and historical exhibitions.

This study investigates the acoustics of an ancient Greek Odeon; the Odeon of Herodes Atticus. Odea were ancient Greek and Roman roofed theatres mainly intended for recitations of an ode (song), hence the name of the structure “Odeon” or “Odeion” as it is also found in the current literature [4], [5].They were often funded by private bodies and tended to be smaller in size compared to the open-air theatres of the same era, but comprised a more elaborate internal décor than the latter [6].

The Odeon of Herodes Atticus (hereafter Odeon HA) is located in Greece in the western part of the ancient Athenian city, Acropolis and it was built by Herodes Atticus, a rich Greek aristocrat and sophist, between 160-169 A.D. It was considered the highest building in the country and its capacity could accommodate up to 6000 people.

In and around 267 A.D. the Odeon was burned down[6]. The restoration of this ancient monument started taking place in 1950 but the final reconstruction did not include the roof or several other structural elements. As a theatre, it has been used mainly during the summer period (April to late September) for various events and performances since its reconstruction.

The first investigations into to the identity, structure and history of the theatre date back to 1752 as published in [7], however, further work was undertaken by several researchers up to the present day. Initial speculations with respect to the roofed version of the theatre were published in 2002. The roof was believed to cover part of the theatre. As such, in Vassilantonopoulos and Mourjopoulos [4] simulation, the acoustics of a partially roofed theatre has been studied.

Recent investigations by Manolis Korres, have proved the existence of a roof which covered the theatre in full as [6]. Based on the latest evidence, this study aimed to investigate the difference in acoustic characteristics of the roofed Odeon HA, both when empty as well as 85% occupied by an audience. The results of the latter were then used in a Virtual Reality environment in which the user is given the opportunity to navigate within the theatre and “listen” to the space.

In-situ measurements were not in the scope of this assessment due to a festival taking place in the Odeon at the time of investigation. Hence, the geometrical acoustic model of the open version (current state), which formed the basis of the roofed version of the Odeon, was created and calibrated using data from in-situ measurements and simulations undertaken in 2004, 2009 and

2016 by other researchers [4], [8], [9]. The calibration is therefore an approximation of the real-world scenario.

2 METHOD

2.1 Software

A dimensionally accuracy 3D model of the theatre was created in SketchUp 2017. The SketchUp to CATT extension, SU2CATT was used to import the the 3D Model into CATT Acoustic v9 for acoustic modelling.

The model was run through the TUCT™, raytracing element of CATT-Acoustic. As the model contains significant open sections, the analysis uses the third algorithm available in the software as recommended in [10]. In this mode ray splitting is used for all reflections along the specular path. The model was run with an initial number of 50000 rays. The temperature in the Odeon was set to 25˚ Celsius (typical room temperature) and humidity at 50%.

The optimum values for the acoustic indices studied in this report relating to the type of performances that the Odeon was constructed for are given in Table 1. Those are derived from data and analysis conducted in [11]–[15].

Table 1: Optimum Values in Odea for the Selected Parameters

Optimum Values		
T30	C80	G
0.7 – 2.3	-2 – 3	>3

2.2 Model Design

Based on drawings provided in [6], all dimensions and most of the architectural details were scaled and modelled with a high level of accuracy in the corresponding software. According to findings in the study conducted by Nielsen *et al.*[16], "*A detailed seating area with rows and steps allows horizontal reflections between seat rises and proscenium resulting in higher accordance with measured data*". An illustration of the details of the interior of the theatre is shown in Figure 1.

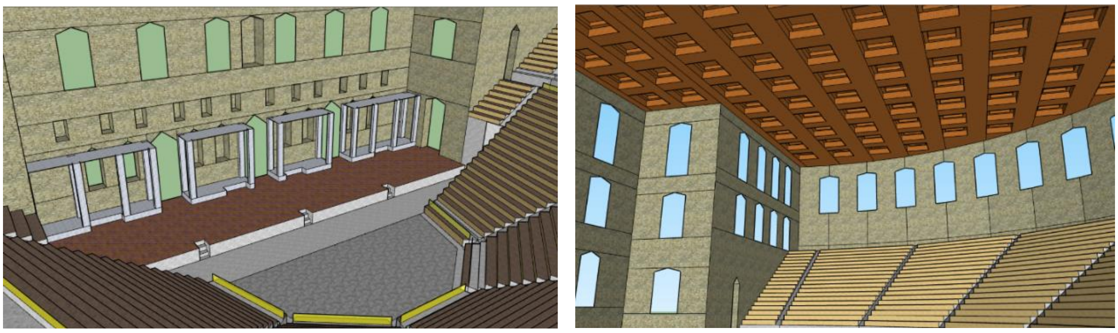

Figure 1: Details of the Theatre Model

2.3 Sound Source & Receivers

This report concerns the assessment of a human voice and its propagation across the theatre. A natural singing voice with directional characteristics and spectrum suggested in ODEON software is used. The sound source was positioned 1.7m above the stage floor aiming at the centre of the audience. The overall SPL was set to 75dB(A), which corresponds to a loud voice [1]. A number of receivers at key positions were selected across the upper and lower cavea with head direction aiming at the sound source which was located as above. Receiver points were selected only on one side of the theatre, as a similar distribution of sound would be expected in the other half due to the symmetry of the structure. The receivers' height used for the audience mapping was set to 0.8 meters above the seating area, representing the height of the ears of a seated person.

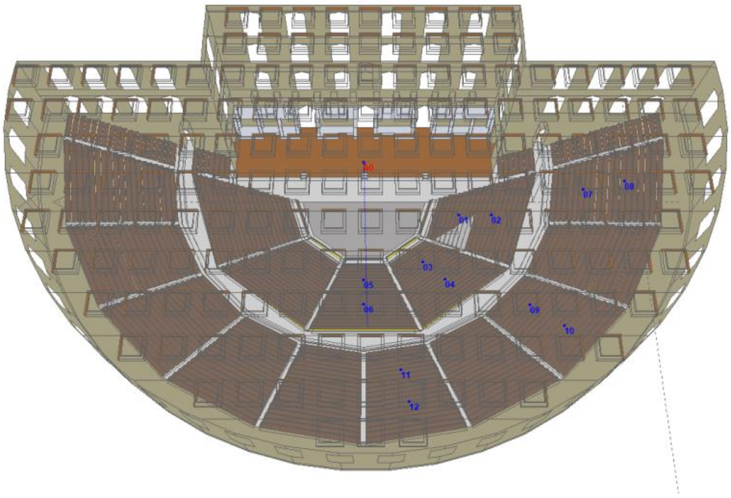

Figure 2: Location of Source & Receivers

The exact positions of the selected source and receivers are shown in Figure 2. A0 represents the sound source in red, whereas the receivers are shown in blue with numbers 01-12.

2.4 Materials

The selection of the materials assigned to the modelled surfaces was based on information found in [6]. The absorption and scattering coefficients rely on data found in [17] and on the studies which conducted in-situ measurements and simulations [4], [8], [9], [18].

It has been assumed that the Odea had open windows for natural daylight and ventilation purposes, therefore, the open windows along with the seated audience were the main absorptive elements within the space [11].

The average values for the absorption and scattering coefficients chosen for this model are tabulated below.

Table 2: Average Absorption and Scattering Coefficients

Surface	**Material**	**Absorption**	**Scattering**
Building Stage	Porous Stone	0.2	0.9
Stage	Wood	0.1	-
Orchestra	Marble	0.02	0.55
Cavea	Marble	0.02/0.7*	0.55
Surrounding Back Walls	Porous Stone	0.2	0.9
Roof	Wood	0.1	-
Décor on Stage	Marble	0.02	0.55

*Absorption used for the occupied version of the roofed theatre.

[1] Based on level data provided by CATT – Acoustics between 125Hz and 4kHz Octave band.

3 RESULTS & DISCUSSION

The results of the average T30, C80, G and STI values over the 500Hz and 1kHz octave bands of the selected receiver positions for the empty state of HA (EHA) and occupied state of HA (OHA) are shown in Table 3.

Table 3: Simulated Values for the Selected Receivers

Receiver	T30		C80		G		STI	
	EHA	OHA	EHA	OHA	EHA	OHA	EHA	OHA
R1	3,0	2,2	-3,7	0,9	6,1	1,2	0.42	0.59
R2	3,0	2,1	-6,4	-2,1	5,5	0,1	0.34	0.51
R3	3,0	2,1	-3,3	1,6	5,5	1,0	0.43	0.61
R4	3,1	2,1	-6,2	-0,8	4,9	-0,1	0.39	0.54
R5	3,1	2,1	-1,7	3,5	6,6	3,0	0.49	0.66
R6	3,1	2,0	-1,7	3,1	6,5	3,2	0.49	0.66
R7	3,1	2,1	-7,1	-2,6	4,4	-1,1	0.30	0.47
R8	2,9	2,0	-6,8	-1,1	3,4	-1,8	0.28	0.46
R9	3,0	2,1	-7,4	-2,4	4,1	-2,1	0.31	0.48
R10	3,1	2,1	-4,9	-1,5	4,1	-1,8	0.34	0.46
R11	2,9	2,1	-6,2	-0,1	4,3	-0,2	0.34	0.53
R12	3,0	2,1	-6,1	-0,8	3,4	-1,7	0.32	0.52

The predicted average reverberation times for the EHA and OHA were approximately 3s and 2s respectively. Only little variation in the values of the above parameter was observed across the theatre. The higher reverberation time in the EHA is related to the energy of the late reflections and lack of absorptive surfaces, compared to the occupied version of the theatre. An illustration of the above is given in Figure 3, which shows the energy of the common reflections for a selected receiver; here R12. The main contributors to the energy buildup within the theatre space are the orchestra pit; roof; stage building and the back walls (Figure 4**)**. Analysis has demonstrated that after the first and second order of specular reflections, the energy of a number of reflections in the OHA at receive position R12 is significantly reduced compared to the energy at the empty state.

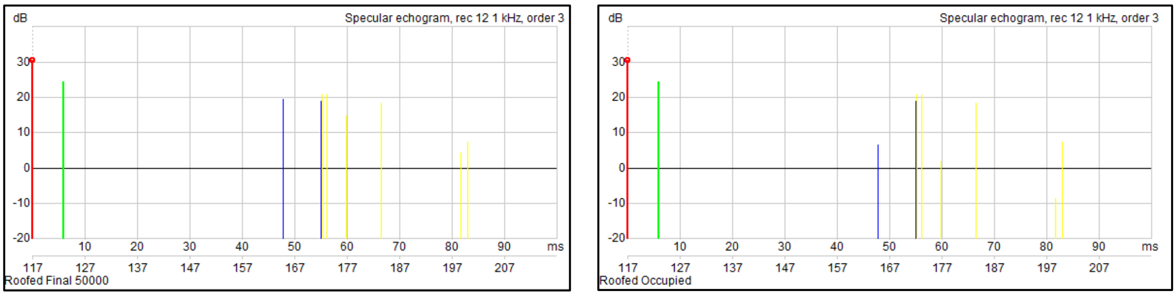

Figure 3: Energy of Specular Reflections. EHA (left) & OHA (right)

The reduction of 1 second observed between the two versions of the theatre is clearly a result of the additional absorption induced by the simulated seated audience in the cavea. The above figures are in agreement with the values reported in literature for similar structures [4], [14], [19], [20] and within the optimum values for musical performances for the case of the OHA.

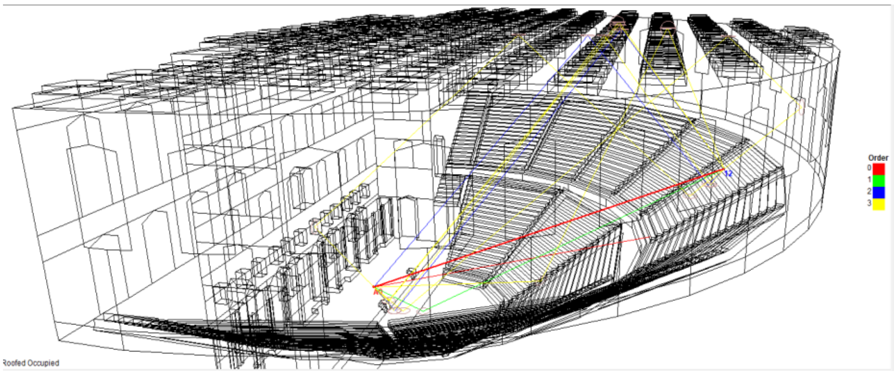

Figure 4: Image Source Capture of 1st-3rd order of Reflections for R12

The acoustic mapping of Clarity (C80) within the two theatre versions is shown in Figure 5. Clarity in the OHA was significantly higher than in the EHA, ranging approximately between -13 and 15 dB. The same parameter was limited to values between -14 and 6 dB in the EHA. An increase of the order of 3dB to 8dB was observed in [21] for the simulated Odea in a full state compared to the theatre versions without audience. Here, the increase in the C80 values due to the additional absorption induced by the introduction of audience covering 85% of the cavea seems to be of the order of 5.8dB on average.

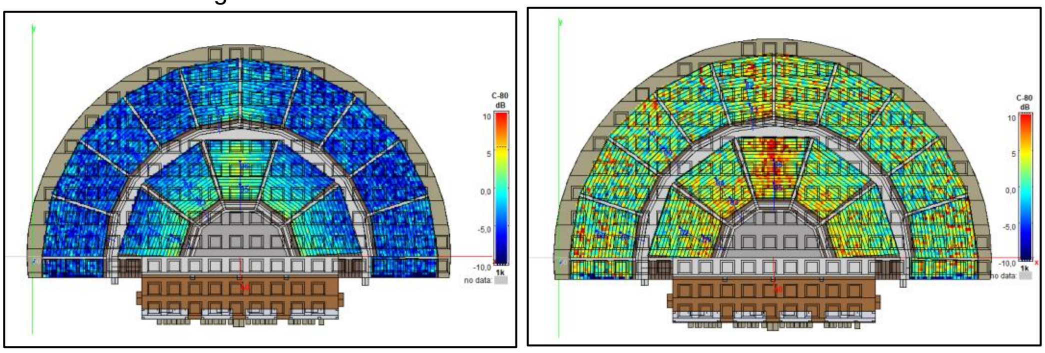

Figure 5: Distribution of C80 in EHA (left) and OHA (right)

The acoustic mapping of Strength on the audience planes is shown in Figure 6.

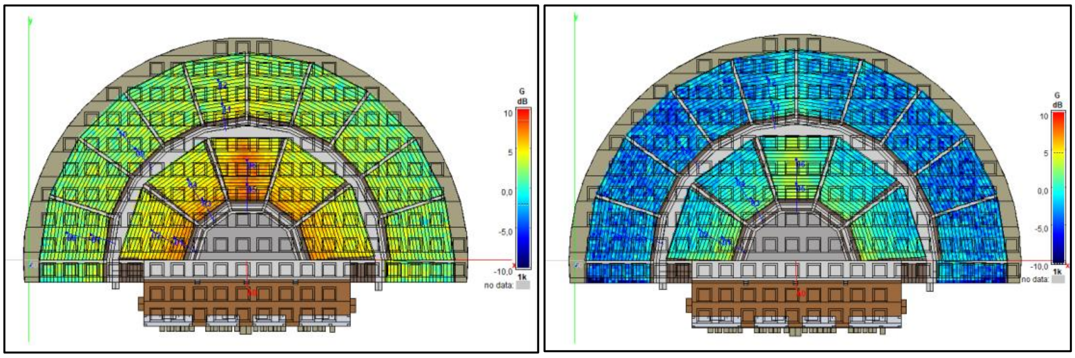

Figure 6: Distribution of G in EHA (left) and OHA (right)

Based on the above, an amplification of minimum 5dB and maximum 9dB can be observed in the central area of the modelled theatres and more specifically around locations R6 and R5 in both simulations, which is above the 3dB threshold for the proposed optimum values (*see Table 1*). A gradual decrease in those values is observed as we are heading away from the source. The lowest values of strength are -2dB for the EHA and -12dB for the OHA at the far end of the theatre. Optimum strength values are, therefore, achieved mainly at the central area of the lower cavea. The front rows of the cavea receive significant sound pressure level due to the close distance from the source, hence minimal energy dissipation. In addition strong reflections arriving from the stage building, seating area and orchestra pit provide some amplification of the sound as shown in Figure 7. The average difference between the two simulations is of the order of 5dB.

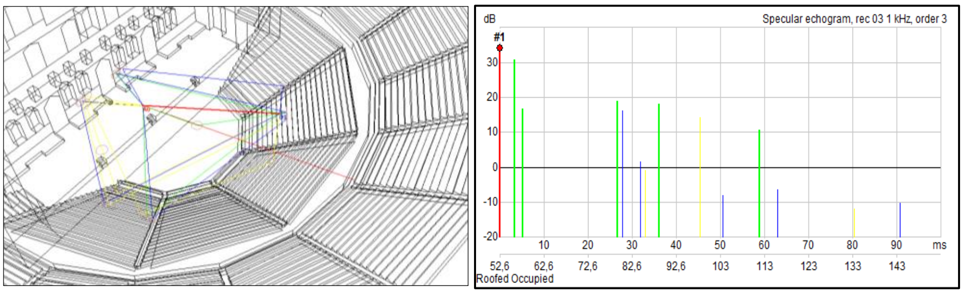

Figure 7: Reflections at Location R3

Finally, an illustration of the Speech Transmission Index and its distribution across the seating area, as per the proposed speech intelligibility assessment scale, is shown in Figure 8.

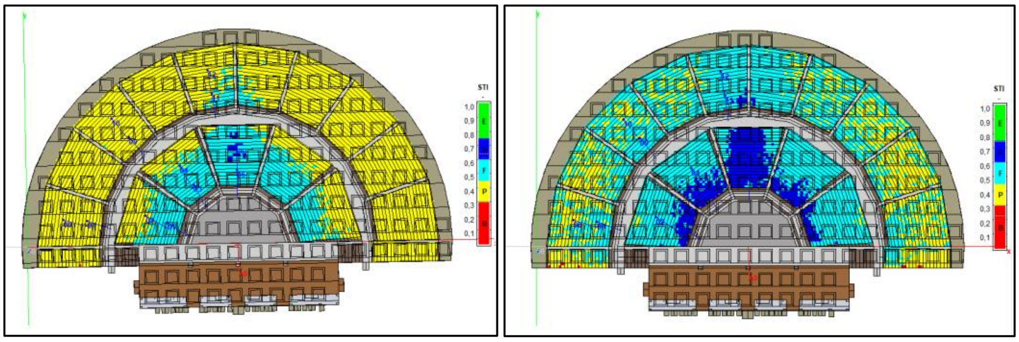

Figure 8: Distribution of STI in EHA (left) and OHA (right)

The average STI within the OHA was approximately 0.5, whereas a decrease of 0.1 was observed in the absence of the audience. Based on the above, speech intelligibility across the EHA and OHA was classified as “poor” and “fair” respectively. It should be noted that the greatest values of this parameter are observed at the central positions as well as the lowest part of the lower cavea. Similar STI values have been observed in simulated theatres of similar structure and type[21].

4 APPLICATIONS IN A VIRTUAL REALITY ENVIRONMENT

This section is a brief description of the practical implementation of the above model in a virtual reality environment. The aim was to provide an opportunity for virtual navigation within the interior of the roofed occupied version of the theatre which would include both visual and sonic stimuli in order to achieve an immersive virtual reality experience.

The model design was enhanced and embellished with additional features created by the author as well as retrieved from a Sketchup model of the theatre available to public and uploaded to www.3dWarehouse.sketchup.com by Vasilis Iakovidis. The additions included external features of the theatre as well as internal decorations, such as sculptures, ancient Greek pillars as well as avatars on stage and audience area. An illustration of the above are shown in Figure 9.

The game engine used was Unreal Engine 4 (UE4). UE4 is a platform used by various commercial games and is currently free for public use. It allows development of games by its users and collaborates with third party audio engines, such as Steam Audio which is developed by Valve Corporation. This plugin is currently offered free in game engines for a more enhanced experience and editing of the audio aspects of games. Sophisticated features include the implementation of

Head Related Transfer Function (HRTF) used for spatialised audio as well as computational reverberation effects. The above characteristics have been accounted for within the project.

Figure 9: Interior Design of the Odeon

Sound stimuli was added both to the internal and external areas of the theatre. Those comprised environmental sounds (birds, rusting of leaves, and short-length day aspects) as well as audience chatter, the sound of the character's footsteps and finally the convolved signals extracted from CATT and imported into the UE4 at the studied listening positions.

Appropriate materials were assigned to each surface allowing for some audio interaction whilst the character is walking in the surrounding spaces. With the exception of the footsteps' sounds, the rest of the audio stimuli was edited using features available in UE4 and the Steam Audio plugin. Attenuation settings allowing fall off distances with logarithmic sound attenuation up to a selected distance from the sources, combined with advanced spatialization based on real time computations of binaural HRTFs offered with the Steam Audio plugin were applied. An illustration of the world created within the UE4 is shown in figure 10.

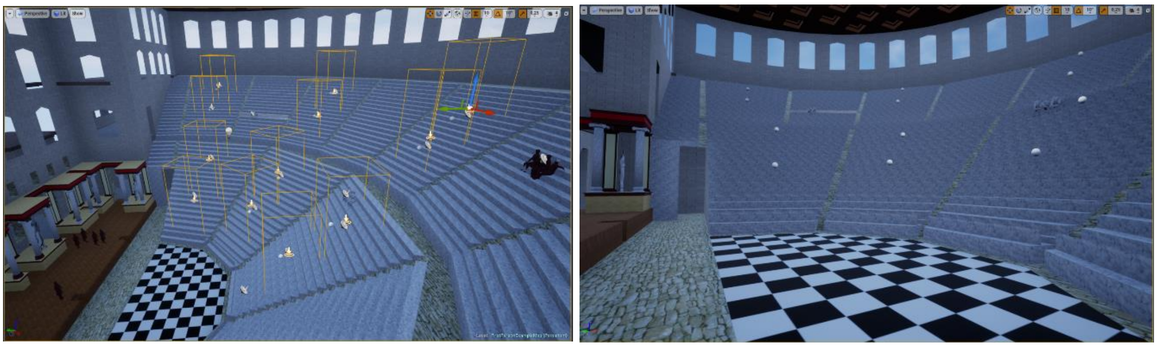

Figure 10: Internal Space from the Editor's Perspective (left) and the Gamer's Perspective (right)

5 CONCLUSIONS

This study has investigated the acoustics of the ancient Greek Odeon of Herodes Atticus in relation to four acoustic indices; Reverberation Time, Clarity, Sound Strength and Speech Transmission Index. The simulations were based on drawings provided in [6], and the geometrical acoustic model was analysed in CATT – Acoustic v9. Analysis of the acoustic behaviour of the modelled theatre, on the basis of the aforementioned acoustic indices, including the effect of audience occupying 85% of the seating area and comparisons with the empty state were undertaken.

The theatre demonstrated a good acoustic response when occupied. Reverberation time and Clarity were found to be within the optimum values for musical performances in the majority of the locations across the theatre. High speech intelligibility as well as sound strength would be expected in central positions and the lower cavea areas. On the contrary, the empty theatre would be over-reverberant for musical events. Poor speech intelligibility, on average, as well as low clarity and sound strength values were observed across the theatre, but the central and closest to the source positions for the latter parameter. In all, the results were in agreement with published data for similar structures and type of performance spaces.

The impulse responses obtained at the selected receiver positions in the occupied theatre were exported in the Unreal 4 games' engine, where a virtual reality environment including virtual navigation with audio embedded elements was created. Further work includes the enhancement of the 3D model by adding audio-visual aspects, which would improve the general experience in the virtual reality environment.

6 ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Greek association "DIAZOMA" for their guidance and support in relation to the provision of important information with regard to the Odeon of Herodes Atticus. Special thanks to Dr Manolis Korres, professor of history of architecture at the National Technical University of Athens and author of the book "The roof of Herodion" (In Greek: «Η στέγη του Ηρωδείου») which we've extensively used in this study, for his time and guidance regarding the analysis of architectural drawings provided within his book.

7 REFERENCES

1. L. Savioja and U. P. Svensson, "Overview of geometrical room acoustic modeling techniques," *J. Acoust. Soc. Am.*, vol. 138, no. 2, pp. 708–730, 2015.
2. N. Haddad, "Criteria for the assessment of the modern use of ancient theatres and odea," *Int. J. Herit. Stud.*, vol. 13, no. 3, pp. 265–280, 2007.
3. Gugliermetti, Bisegna, and Monaco, "Acoustical Evolution of the Roman Theatre of Ostia," *Build. Acoust.*, vol. 15, no. 2, pp. 153–167, 2008.
4. S. L. Vassilantonopoulos and J. N. Mourjopoulos, "The acoustics of roofed ancient odeia: The case of Herodes Atticus Odeion," *Acta Acust. united with Acust.*, vol. 95, no. 2, pp. 291–299, 2009.
5. M. Bieber, *The History of the Greek and Roman Theatre*. Princeton University Press, 1981.
6. M. Korres, *I stegi tou Irodiou kai alles gigadies gefiroseis*. Athens: Melissa, 2014.
7. J. Stuart and N. Revett, *Antiquities of Athens: Measured and Delineated by James Stuart, FRS and FSA, and Nicholas Revett, Painters and Architects*. Princeton Architectural Press, 1763.
8. C. A. Goussios, C. V Sevastiadis, G. M. Kalliris, and G. V Papanikolaou, "The Acoustics of Ancient Greek Odea," in *AES 116th Convention*, 2004.
9. N. Hoekstra, B. Nicolai, B. Peeters, C. Hak, and R. Wenmaekers, "Project Ancient Acoustics Part 2 of 4 : Large-Scale Acoustical Measurements in the Odeon of Herodes Atticus and the Theatres of Epidaurus and Argos," in *ICSV 2016 - 23rd International Congress on Sound and Vibration: From Ancient to Modern Acoustics*, 2016, pp. 1–8.
10. I Rees, "Common Pitfalls in Computer Modelling of Room Acoustics," in *Proceedings of the Institute of Acoustics*, 2016, vol. 38 Pt.1.
11. J. H. Rindel and M. Lisa, "The ERATO project and its contribution to our understanding of the acoustics of ancient Greek and Roman theatres," in *The Acoustics of Ancient Theatres Conference Patras, September 18-21, 2011*, 2011.
12. G. Iannace, A. Trematerra, and M. Masullo, "The large theatre of pompeii: Acoustic evolution," *Build. Acoust.*, vol. 20, no. 3, pp. 1–6, 2013.
13. G. Iannace and A. Trematerra, "The rediscovery of Benevento Roman Theatre Acoustics," *J. Cult. Herit.*, vol. 15, no. 6, pp. 698–703, 2014.
14. U. Berardi, G. Iannace, and L. Maffei, "Virtual reconstruction of the historical acoustics of the Odeon of Pompeii," *J. Cult. Herit.*, vol. 19, no. January, pp. 555–566, 2016.
15. M. Aretz and R. Orlowski, "Sound strength and reverberation time in small concert halls," *Appl. Acoust.*, 2009.
16. M. L. Nielsen, J. H. Rindel, and C. Christensen, "Predicting the Acoustics of Ancient Open-Air Theatres: the Importance of Calculation Methods and Geometrical Details," *Balt. Acoust. Meet.*, 2004.
17. M. Vorländer, *Auralization*. 2008.
18. C. Van Loenen, M. Van Der Wilt, A. Diakoumis, R. Wenmaekers, C. Hak, and K. Hooymans, "Project ancient acoustics part 3 of 4: Influence of geometrical and material assumptions on r ay-based acoustic simulations of two ancient theatres," in *ICSV 2016 - 23rd International Congress on Sound and Vibration: From Ancient to Modern Acoustics*, 2016.
19. R. Dragonetti, C. Ianniello, F. Mercogliano, and R. Romano, "The acoustics of two ancient roman theatres in Pompeii," in *19th INTERNATIONAL CONGRESS ON ACOUSTICS*, 2007, no. September.
20. J. H. Rindel, "Roman theatres and revival of their acoustics in the ERATO project," *Acta Acust. united with Acust.*, vol. 99, no. 1, pp. 21–29, 2013.
21. J. H. Rindel, "Roman theatres and revival of their acoustics in the ERATO project," *Acta Acust. united with Acust.*, vol. 99, no. 1, pp. 21–29, 2013.