Abstract

In the last decades we have seen an increased interest in the acoustics of ancient Greek and Roman theatres and much research has been performed on many of them. Research has mainly focused on modelling the acoustics of theatres and has shown various acoustical effects. However, only a limited number of in situ measurements have been available to validate the results. In this paper, results are presented of large-scale measurements which were performed in the Odeon of Herodes Atticus and the theatres of Epidaurus and Argos. The accuracy of these measurements is discussed in part one of this series of papers. Impulse response measurements have been conducted at respectively 200, 264 and 60 listener positions for 5 equal-angular dodecahedron sound source rotation steps at 2 source positions. In addition, binaural impulse responses were measured using an artificial head on respectively 10, 12 and 3 receiver positions. Finally, speech intelligibility measurements have been carried out in accordance with IEC 60268-16 using a ‘speech source’ that simulates a human voice. In the Odeon of Herodes Atticus, all measurements have been performed in the morning as well as in the evening, showing a minimal discrepancy well within the Just Noticeable Difference (JND) for every discussed parameter. This proves that it is legitimate to compare measurements collected during a full day under slightly different climate conditions. Results for the Odeon of Herodes Atticus show a uniform axisymmetric distribution over receiver positions of common acoustical parameters such as reverberation time, clarity, sound strength and spaciousness. For the theatre of Epidaurus this distribution is non-uniform due to the opposite-facing seating areas, which is in line with findings from research by others. The results of the speech intelligibility measurements show a declining trend for STI over distance, which contradicts some findings presented in literature.

1. Introduction

The ancient Greek theatres have been fascinating objects to many people for a long time. The theatres are renowned for their alleged exceptional acoustics. However, there is only little scientific support for this claim. In the past years, some research is done on the acoustics of Ancient Greek and Roman theatres, but only a few studies do include in situ measurements. A well-known example is the ERATO project (2003-2006) [1], during which researchers from several countries performed measurements in a large number of theatres. In a follow-up study, Gade & Angelakis (2006) [2] presented measurements of 30 to 45 source-receiver (SR) combinations in the theatre of Epidaurus using an omnidirectional source and receivers. Later, Psarras et al. (2013) [3] presented results of measurements performed in 2004 and 2011 in the same theatre while also using omnidirectional...
transducers. In this study, a total number of 28 SR combinations was measured in both an empty theatre and a theatre with audience. Another research is that of Vassilantonopoulos & Mourjopoulos (2009) [4] who measured 10 SR combinations in the Odeon of Herodes Atticus. Unfortunately, the use of a different type of sound source make the results hard to compare with the results form this study.

Often, in literature measurements are used to validate geometrical acoustical models in which acoustic mappings of ancient theatres are made [4,5]. The modelled mapping results can be seen as extrapolated results of the measurements. However, findings based on these modelled mappings have never been checked by real measured mappings. This research has aimed to obtain an acoustic mapping of the theatres by means of a large number of high quality impulse response (IR) measurements in accordance with ISO 3382.

In this paper, which is part of the Ancient Acoustics project [5-7], the results of large-scale in situ measurements (over 10,000 IR’s) in three different ancient Greek theatres are discussed. Measured theatres are the Odeon of Herodes Atticus (200 B.C.) which provides space for 5,000 people, the theatre of Epidaurus (400 B.C.) which contains 14,000 seats and the theatre of Argos (200 B.C.) which originally had a capacity of 20,000 seats. First the measurement method, setup and post processing are discussed, after which the results for the Odeon of Herodes Atticus and the theatre of Epidaurus are presented individually. Results of selected measurement positions in the theatre of Argos are presented in comparison with the results of comparable positions in the other two theatres. The paper will end with a discussion of the results and conclusions.

2. Measurement method

This section is a brief summary of the measurement method used in the three investigated theatres. An extensive discussion on the measurement method and setup is presented in part 1 of the series of papers on project Ancient Acoustics [5].

For all measurements, the setup consisted of two dodecahedron omnidirectional sound sources and a ‘speech source’ that simulates a human voice. IR’s were all captured by means of omnidirectional microphones connected to a sound recording device, except for binaural impulse responses (BIR’s) which were captured with an artificial head. During all measurements an exponential sweep was used as an excitation signal and the sound sources were rotated in 5 equal-angular steps to obtain an accurate average per receiver position. Sweep lengths of 21.8 s were used in the theatre of Epidaurus, while lengths of 43.7 s were used in the Odeon of Herodes Atticus and the theatre of Argos. During the measurements, meteorological conditions were continuously monitored. Finally, all measurements were post-processed in Dirac v6.0 and MATLAB.

![Figure 1: Measurement plans of the Odeon of Herodes Atticus (left), the theatre of Epidaurus (centre) and the theatre of Argos (right). Omnidirectional receiver positions are marked ‘o’, artificial head positions are marked ‘x’.

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To obtain an acoustic mapping of the seating area, the receivers are distributed over lines in distinct sections of the seating areas of the theatres. Lines where chosen instead of a random or more spread distribution to be able to compare the different sections. For the Odeon of Herodes Atticus, this resulted in a measurement grid of 200 receiver positions, equally distributed over 10 lines. In the theatre of Epidaurus, this was a grid of 264 receiver positions distributed over 12 lines. In the top half of the seating area the line of receivers was split in half to ensure a sufficiently dense measurement grid. The theatre of Argos only allowed for 4 lines of receivers, of which the centre lines both contained 20 receivers and the outer lines contained 10 receivers. This resulted in a grid of 60 receiver positions. One of the sound sources was placed in the centre of the orchestra of the theatres and one was placed diagonally backwards (in case of Odeon and Argos this was on the edge of the elevated stage). Both sound sources were placed at a height of 1.5 m, whereas the receivers had a height of 0.8 m above the seating. Except for the receivers on the orchestra, which had a receiver height of 1 m. Fig. 1 shows the detailed measurement plans for each of the investigated theatres.

3. Results and discussion

In this section, measured acoustic parameters like sound strength G, reverberation time T<sub>20</sub>, clarity C<sub>80</sub>, spaciousness IACC and speech intelligibility STI are presented and discussed. Acoustic parameters derived from the omnidirectional sound source measurements are averaged values of five equal-angular source rotations and are presented as single number values calculated in accordance with ISO 3382. Inspection of IR’s from 5 different source rotations has confirmed the importance of stepwise rotation of a dodecahedron sound source, as deviations in acoustic parameters of more than 1 JND have been observed in the 500-8kHz frequency range between individual measurements per receiver position. Additionally, 100% of the IR’s measured in the Odeon of Herodes Atticus and the theatre of Epidaurus have a minimum decay range (INR) of 35 dB [5] for the averaged 500-1000 Hz octave bands, necessary to be able to calculate all ISO 3382 parameters in this study within 1 JND error. For the theatre of Argos this is 96%. All measurements are performed in unoccupied theatres. Results for the Odeon of Herodes Atticus and the theatre of Epidaurus are presented as contour plots. The results for the theatre of Argos are presented as line plots as the density of the measurement grid is not fine enough to represent the results in contour plots.

3.1 Odeon of Herodes Atticus

Calculated results for G, T<sub>20</sub> and C<sub>80</sub> from measured IR’s in the Odeon of Herodes Atticus are presented in Fig. 2. For all figures, the results for sound source position S1 are shown on the left and for S2 on the right. In Fig. 2a one can see a uniform decline of the sound strength G of about 14 dB over the depth of the theatre for both sound source positions. The reverberation time T<sub>20</sub> shown in Fig. 2b ranges from a minimum of 1.2 s at the orchestra of the theatre to a maximum of 1.7 s in the seating area. Looking at the contour plots, one may say that the reverberation time has a relatively uniform axisymmetric distribution with an average reverberation time of 1.5 s and a standard deviation of 0.1 s. This does not change when placing the sound source at position S2, except for the orchestra positions where the reverberation time increases to 1.5 s. In Fig. 2c, the clarity C<sub>80</sub> shows a similar axisymmetric distribution for both sound source positions declining from 12 dB on the podium to 3 dB in the back of the seating area. The average clarity C<sub>80</sub> is 5.8 dB, with a standard deviation of 2.0 dB. When moving the sound source to position S2, the clarity in the orchestra and the first few seating rows on the right side drops to 6 dB. A thing to note is that the central placement of the sound source (S1) only effects the acoustics on the orchestra and the first few rows of the seating area. When the source is placed at position S2, parameters T<sub>20</sub> and C<sub>80</sub> both have values closer to the theatre’s average. For this source position, the minimum and maximum measured reverberation time values over all measurement positions are even within 1 JND of the theatre’s average value.
3.2 Theatre of Epidaurus

Fig. 3 depicts mappings of calculated results from measured IR’s in the theatre of Epidaurus. Much like in the Odeon of Herodes Atticus, the decline of the sound strength over distance is uniform throughout the theatre.

The mapping for $T_{20}$, shown in Fig. 3b, reveals a remarkable trend. It appears that for receiver positions in the opposite facing seating areas the reverberation time is on average 0.3 s higher than in the remaining part. The effect causes a significant non-uniform distribution, as opposed to the uniform distribution in the Odeon of Herodes Atticus. As a result, the average $T_{20}$ is 15-25% higher than findings in other research [2,3]. The average reverberation time $T_{20}$ for source position S1 is 1.3 s, with a standard deviation of 0.2 s. The effect can likely be attributed to the higher order reflections between the opposite facing seating rows. An inverse effect was presented by Gade & Angelakis [2], where simulation results showed a lower reverberation time in the opposite facing seating areas.

The higher reverberation time in the opposite-facing seating areas is also seen in the clarity $C_{80}$, depicted in Fig. 3c. Here, differences of 6 dB on average occur between the seating areas on the edge of the theatre and the remainder of the theatre. For the clarity the effect is persistent even when the sound source is placed at position S2. The average clarity over all measurement positions is 11.5 dB, with a standard deviation of 3.0 dB. In this study, no significant decline of clarity with increasing SR distance was found, which contradicts findings in literature [3].
3.3 Comparing the investigated theatres

3.3.1 Sound strength, reverberation time and clarity

In this section the measurement results of the theatre of Argos are presented and compared to the other measured theatres. Line measurements with a comparable angle towards the centre were chosen. Line E, F and B of respectively the Odeon Herodes Atticus, the theatre of Epidaurus and the theatre of Argos are plotted as function of the SR distance. Again, the results are presented as averaged values over 5 equal-angular source rotations and averaged for the 500-1000 Hz full octave bands.

From the results for Argos in Fig. 4, it can be deduced that the theatre of Argos is the theatre where the least amount of reflections occurs. The average reverberation time $T_{20}$ is 0.7 s, with a standard deviation of 0.1 s and the average clarity $C_{80}$ is 15.6 dB, with a standard deviation of 1.5 dB. Moreover, the decay of the sound strength $G$ with increasing SR distance comes close to the decay of sound in free field conditions. This may be clarified by the lack of overall curvature of the theatre, the degraded state of the theatre or the lack of a scene.

The T20 shows large deviation between the different theatres. In Argos the T20 is the lowest and appears to become more or less stable above 40 m SR distance. In the theatre of Epidaurus T20 increases with the SR distance and shows higher values in the ‘orchestra’ when the source is moved to S2. For C80 an increase is visible for S2 at 19-22 m SR distance, similar to the positions which showed an increase in G. As one would expect, the theatre of Argos shows the highest C80 and the Odeon of Herodes Atticus the lowest. The C80 appears to be flat above 30 m SR distance for the
3.3.2 Spaciousness

Fig. 5 shows the averaged values for spaciousness IACC$_{0-\infty}$ for the full octave bands 125-4000 Hz. Although the number of BIR measurement in Argos was limited in comparison with the other theatres, the results provide a general impression of the spaciousness in these theatres. From Fig. 5 it can be obtained that the highest values for IACC are measured in the theatre of Epidaurus, which corresponds to low spaciousness. Moreover, the standard deviation between the measured positions is low and the values are in line with measurement results in literature [3]. In the theatre of Argos the IACC$_{0-\infty}$ slightly declines and for Odeon Herodes Atticus the IACC$_{0-\infty}$ is even lower including a larger deviation. Furthermore, for Odeon Herodes Atticus source position S2 results in significantly lower IACC$_{0-\infty}$ values than for S1 above the 500 Hz band.
3.3.3 Speech intelligibility

Results of measured speech intelligibility in accordance with IEC 60268-16 are depicted in Fig. 6. The measurements have been conducted using a calibrated speech source at 1 m distance, placed at source position S1. The speech transmission index STI is subsequently calculated using averaged octave band background noise levels from measurements in the three investigated theatres (Table 1).

Fig. 6a shows STI for a normal vocal effort (60 dB(A)) as well as for a shouting vocal effort (82.3 dB(A)) in accordance with ANSI 3.5. One can see an overall declining trend for STI with increasing SR distance. This contradicts some findings presented in literature [2,3], where increasing or stable trends with increasing SR distance are shown. Even when shouting, which is the maximum achievable human speech level, declining trends remain visible. The lowest values for STI are found in the theatre of Argos, due to the little support of reflections and the highest SR distance. The more curved shape and better state of the theatre of Epidaurus seems to contribute to higher values for STI compared to the theatre of Argos. The highest values for STI are found in the Odeon of Herodes Atticus, where the listener may benefit from reflections from the scene behind the podium. Compared to the other theatres, higher values for STI are specifically found in the undermost seating areas. In Fig. 6b, pure acoustics-only STI is shown, i.e. with an assumed infinite Signal to Noise ratio (SNR). With this (artificial) assumption, exceptionally high values for STI are found. It is likely that aforementioned data from literature arose from similar calculations. In this acoustics-only case, it is clearly visible that speech intelligibility in the Odeon of Herodes Atticus is more influenced by the theatre acoustics compared to the other two theatres.

Table 1: Averaged background noise levels collected from measurements in all three theatres.

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_{eq} background [dB]</td>
<td>40.0</td>
<td>36.0</td>
<td>37.0</td>
<td>34.9</td>
<td>32.3</td>
<td>28.8</td>
<td>23.6</td>
<td>39.8</td>
</tr>
</tbody>
</table>

Figure 6: Measured speech transmission index STI for the corresponding line E, F and B of respectively the theatre of Odeon Herodotus Atticus, theatre of Epidaurus and Argos, as a function of the SR distance. (a) STI with a normal vocal effort (black) and shouted (grey), both with measured background noise level. (b) STI with infinitely high Signal to Noise Ratio. Results originate from a speech source placed at source position S1.
4. Conclusions

This study has aimed to obtain acoustic mappings of the investigated theatres by means of a large number of high quality IR measurements. This has helped to reveal acoustic phenomena that would otherwise not be visible in a smaller set of measurements. Additionally, the measured data is used for a parametric study on the material settings and geometrical accuracies of computational models and enable additional research which is covered in part 3 of the series of papers on project Ancient Acoustics [6]. From the results presented in this paper, the following can be concluded:

- The Odeon of Herodes Atticus has a uniform axisymmetric distribution of the acoustic parameters reverberation time $T_{20}$ and clarity $C_{80}$. From the three investigated theatres, speech is most intelligible here, which may result from the presence of the scene behind the podium.
- The acoustic mappings show a non-uniform axisymmetric distribution for the theatre of Epidaurus. This effect can be attributed to the opposite facing seating areas, which provide higher order late reflections. The large number of high quality measurements make it possible to find this effect and enable further research in accurately modelling the theatre and its acoustics.
- The results show the theatre of Argos to be the theatre where the least amount of reflections occurs. This may be attributed to the lack of curvature of the seating areas, the overall bad state of the theatre and the lack of a scene.
- The exceptional speech intelligibility found in literature was not found in this study. It is likely that the exceptional values arose from calculations with infinitely high speech levels and no background noise, as is shown in this paper.

This paper can be considered as a first overall presentation of the measured data. In a future study the data will be discussed in more detail, focussing on spectral and temporal effects.

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References