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MEASUREMENTS AND ANALYSIS OF THE ACOUSTICS OF THE ANCIENT THEATRE OF EPIDAURUS

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Abstract

Results are presented from recent acoustic measurements performed in the ancient open theater of Epidaurus. These measurements were obtained using modern techniques, allowing evaluation of numerous acoustic parameters for the theatre, such as: Clarity C-80, Definition D-50, RASTI, LEF, etc. These measurements and results are also compared to those obtained from a computer acoustic simulation of the theatre's acoustics. The analysis of the results, illustrates many novel aspects of the theatre's acoustic properties, such as the pattern and mechanism for the early reflections, the spectral response of the theatre, aspects of time-frequency response interaction and aspects of the spatial impression. The results restate the well-known exceptional acoustic quality of the theatre for speech, with speech intelligibility remaining nearly perfect at all listener positions.

Keywords

Epidaurus theatre, acoustic measurements

1. Introduction

The renowned exceptional acoustics of the Ancient Theatre of Epidaurus, raise the interest both of experts and ordinary visitors. Occasionally, there have been acoustic measurements of the theatre [1,2], but in the past mainly because of equipment limitations, those have highlighted only a few aspects. This paper was originally presented in Greek [3] and it is given here in edited, English version. It provides detailed measurements for a variety of listening positions, allowing for a better understanding of the theatre's acoustic characteristics. Simultaneously, there is a comparison of these results with computer acoustic simulations for the same source - receiver positions as those used for the measurements [4]. Given that a more recent paper [5] has introduced an analytic approach for describing the theatre's acoustic performance, the current work provides results that can verify those theoretical findings.

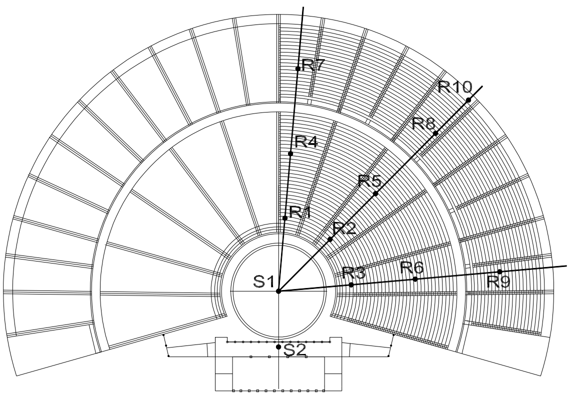


Figure 1- Plan view of the theatre with tested source (S_N) and receiver (R_N) positions

2. Measurement Methodology

The acoustic measurements of the theatre were performed on 28th April of 2004 by two research groups of the University of Patras (from the Dept. of Electrical & Computer Engineering. and Mechanical & Aerospace Engineering) and were based on modern measurement methods using laptop and sound card (RME), WinMLS and B&K Dirac software, omni-directional B&K and ACO Pacific microphones and ATC SMC 20-2 Active Monitor as a sound source. The measurements were obtained from positions shown in Figure 1, at exact locations and distances that were also employed in an earlier study based on computer simulation [4]. The sound source was placed at a height of 1.5 m, in the centre of the stage ("orchestra", position S1), and also displaced 5m closer to the koilon (position S2). The excitation signal (both MLS and sinusoidal sweep) was generated at a level of 105 dB –SPL/1m, while the environmental noise was in average around 55 dB (40 dB(A)). From the measured responses, the anechoic response of the source system was deconvolved.

3. Results

3.1 Time domain composition of sound field

The sound field of the theatre is formed by early distinct reflections and significant amount of diffracted sound energy that decays fairly shortly, (approximately after 200 ms) to the noise floor level, noting that a 40 dB decay is observed within approx.60 ms from the direct signal arrival (see Figure 2).

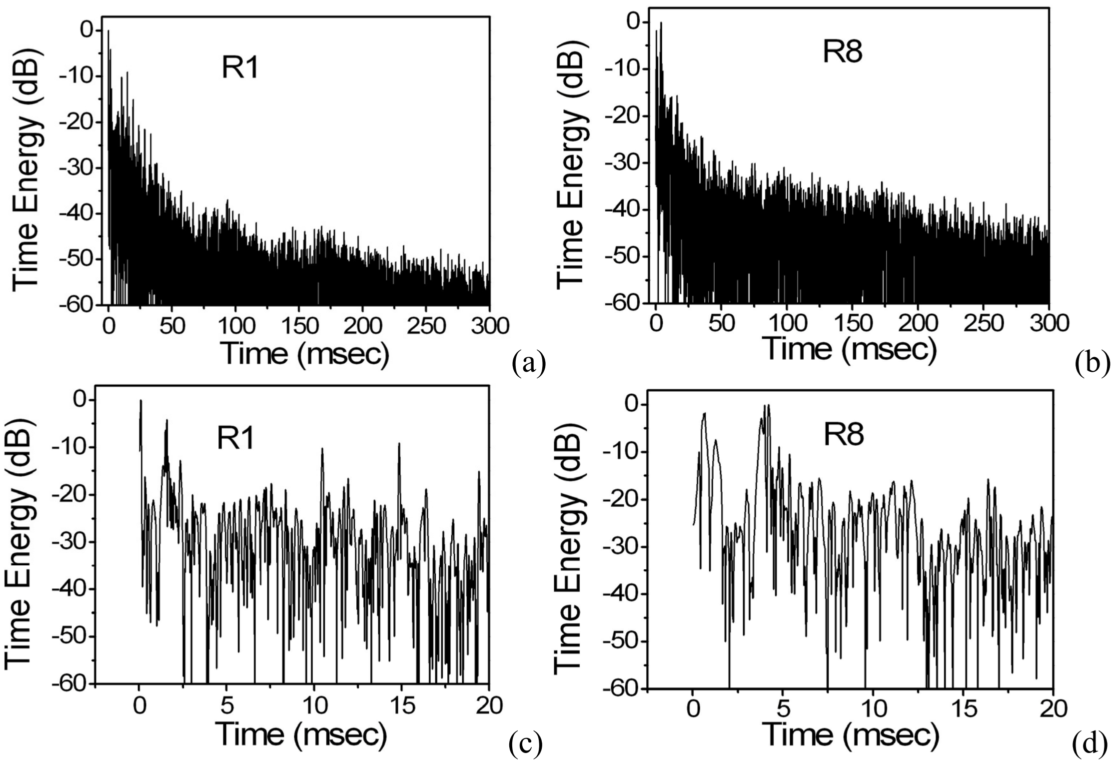


Figure 2 - Impulse Response (normalized energy in dB) for the source in the centre of the stage (S1) and for the receivers positions R1 ((a) and (c)) and R2 ((b) and (d)). Responses are after deconvolution by the anechoic response of the excitation source

Observing the measurements in Figure 2, but also via the simulations for the same positions (Figure 3), the following conclusions can be drawn: for close to the source positions (R1, R2, R3) the first reflection arrives approximately 1,7 ms after the direct signal and is generated from the stage floor (Figs 2(c), 3(a)). The second reflection arrives at about 6 ms and comes from the listener's front aisles. Second order reflections also arrive approximately at 11 and 16 msec. A different arrival mechanism is observed for the distant positions (R7, R8, R9): the first reflection arrives at 1,3 ms, generated by the front seating aisles (benches) of the listener (Figs 2(d), 3(b)). The second reflection arrives approximately at 3,5 - 4 ms from the floor of the orchestra. Significantly, for such distant positions scattered and specular early reflections seem to focus and generate useful to speech intelligibility energy. Nevertheless, in all cases, from Fig.2 it is clear that the early reflections decay by approx. 40 dB within 60 ms, hence contributing to speech intelligibility by enhancing the perception of the direct signal.

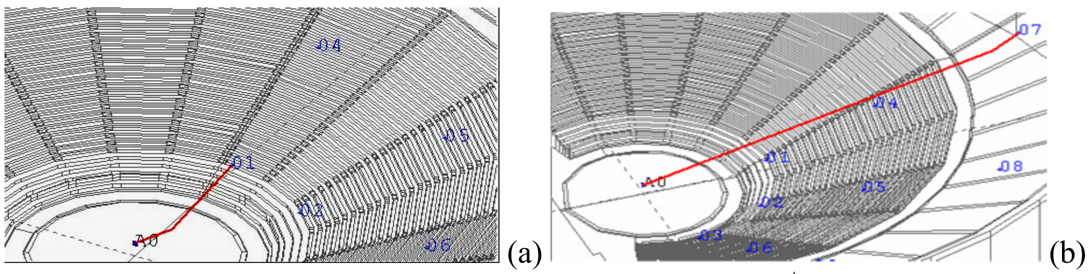


Figure 3 - Illustration of the generation mechanism for the 1st reflection at different receiver positions of the theatre of Epidaurus: (a) position R1 (b) position R7.

3.2 Frequency domain composition of sound field

The acoustics of theatre impose a characteristic frequency response to sound signals. As is shown in Figures 4 (a),(b) for measurements obtained with the source at the centre of the stage, the frequency response is characterized by a significant dip at 170-200 Hz (due to floor reflection cancellation, more pronounced for the distant positions), a resonance at the region 500-1000 Hz for the close receiver positions and additional peaks appearing at 300 and 1500Hz for the distant positions. At the same time, for all receiver positions the low frequency region 80-150 Hz, close to male speech pitch, is also transmitted with sufficient amplitude and volume.

The broad form of the spectral response does not change drastically with either the receiver distance or angle. However, when the source is moved to the front of the orchestra (near the first aisles), then it was observed that both the dip and resonance region is shifted towards lower frequencies (from 800Hz to 600Hz). These characteristics and the largely invariant with the position response, can be beneficial for transmitting speech signals, since the important for intelligibility, frequency region around 1 KHz is strongly amplified. The very low frequency region of speech is retained in amplitude ensuring that the voice volume and source size is well- preserved. The non-significant for intelligibility frequency region above the male speech pitch is reduced in energy, whilst higher formant regions are amplified. At high frequencies, there is an expected attenuation, which should be more pronounced in the presence of audience (such measurements were not performed here).

Based on the above observations and considering the time-frequency response of the theatre (Figure 5), it is obvious that the mechanism of the early reflections from the floor of the orchestra and from scattered energy from the seat rows as was mentioned above and in [5], is responsible for the characteristic spectral amplification effect which reverberates and decays for up to 150-200 ms approximately, while for subsequent intervals, the dense diffuse reflections, generate a significantly flatter spectrum.

Figure 5 also shows -additive to the response- low frequency noise below the region of excitation, (e.g. 10 Hz) possibly due to air currents, which in the past has been related to the "good acoustics" of the theatre. As shown, such noise components are additively combined with the late response (after the 150 ms) to generate the flattening of the spectrum which appears as ambient decay well-below the level of the early signal.

3.3 Acoustic Definition (D-50), Clarity (C-80) and Intelligibility (RASTI)

In Figure 6, the results of measurements are given for all distances and angles along with the results of acoustic simulations of the theatre for the same positions [3]. Considering the Definition D-50 (Figure 6 (a)) and Clarity C-80 (Figure 6 (b)) it can be observed that the acoustic performance is good, regardless of the source-receiver distance. The empty theatre achieves remarkable speech intelligibility with measured RASTI close to 95%, clarity is more than 15dB, while for central and middle positions ($\theta = 50°$, $\theta = 45°$) this parameter increases with distance, suggesting the beneficial reallocation of the early/late reflection energy ratio.

It is significant that the corresponding simulations, although they indicate similar range of values, seem to present lower performance, especially for the lateral positions. The small difference between measurement and simulation may be due to the fact that the simulation is based on smooth surfaces and simplified models of reflection diffraction. In contrast, the measurements correspond to the material of the surfaces at its current, eroded state.

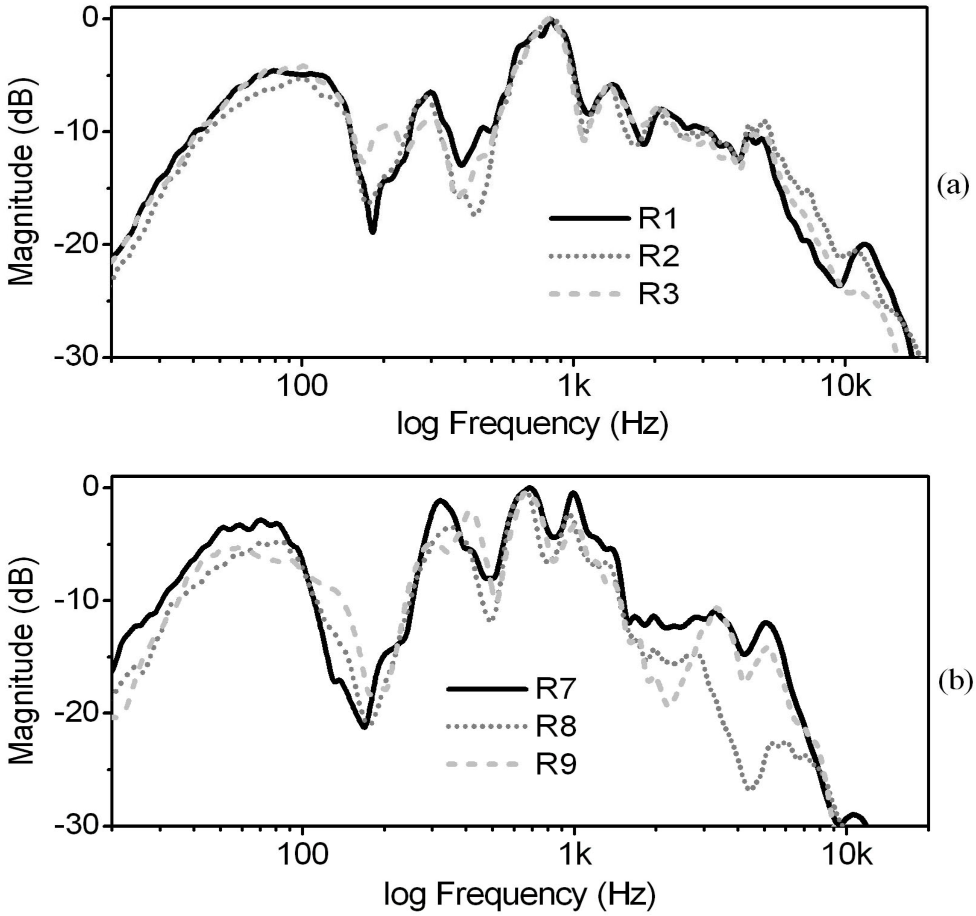


Figure 4 – Normalised magnitude frequency response of the theatre at: (a) close positions / different angles and (b) distant positions / different angles.

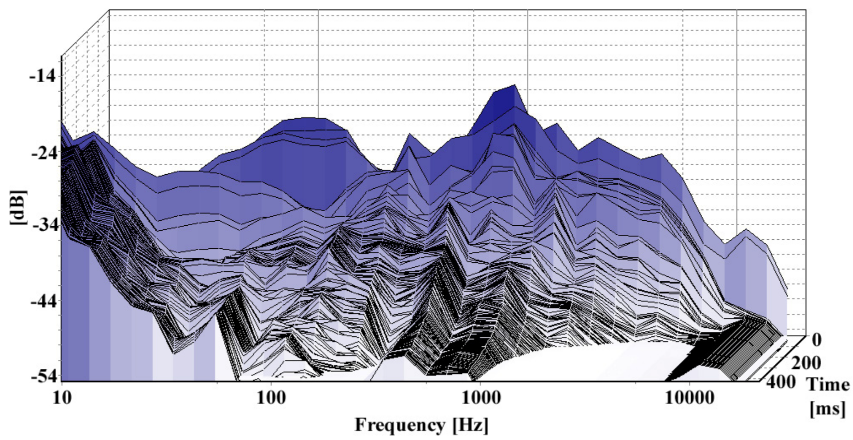
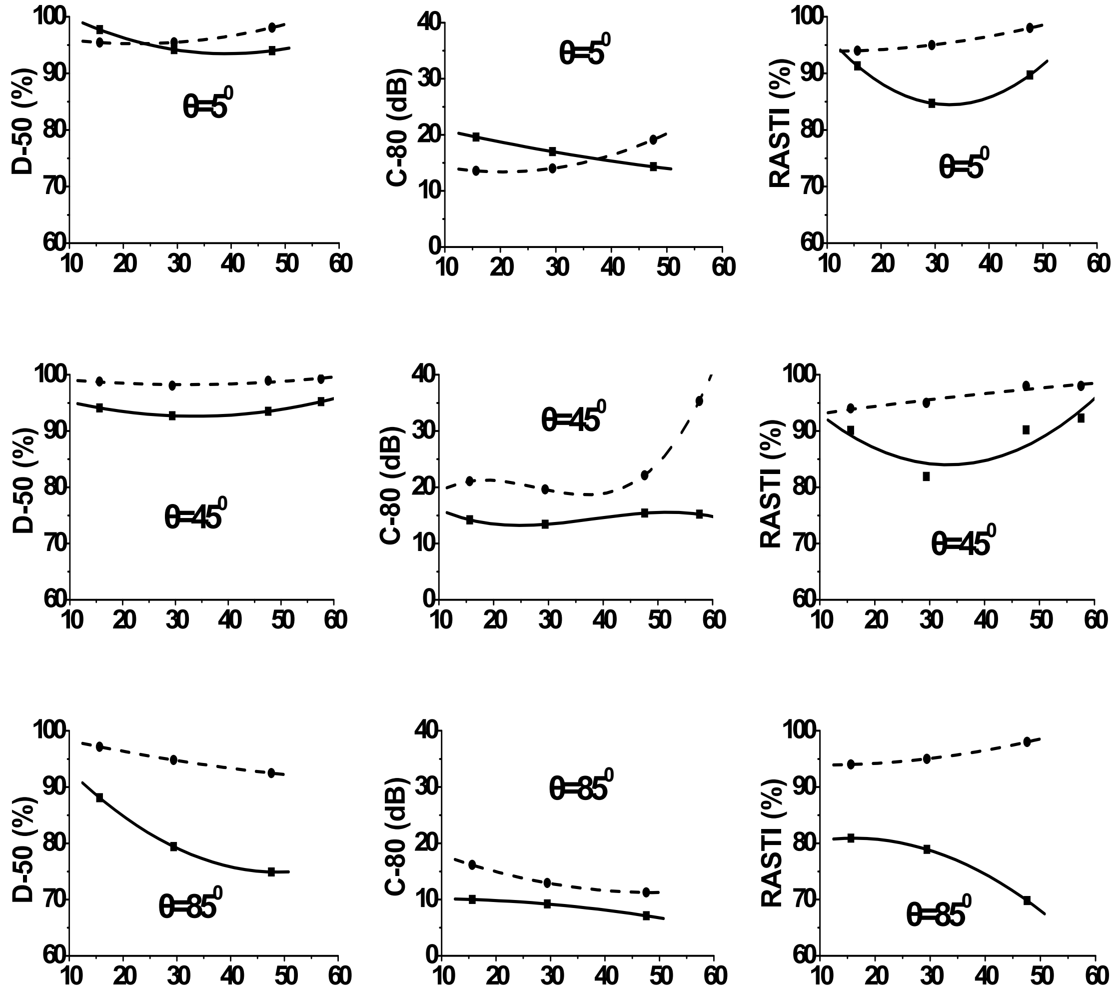


Figure 5 - Time-frequency analysis of the response for receiver position R1.

Similarly, excellent is the measured intelligibility of speech via RASTI (Figure 6 (c)), which appears to be independent of distance and angle in all cases being close to the ideal (nearly 100%). The results confirm the excellent acoustic behaviour of the theatre for speech reproduction.



Distance from source (m)

(a) (b) (c)

Figure 6 - (a) Definition D-50, (b) Clarity C-80, (c) Speech Intelligibility RASTI, as function of receiver distance and angle from the source (in the centre of the stage). The results are from – – measurements and from —— simulations [ ].

3.4 Spatial Impression

The results from simulations show that lateral reflections appear to reach listeners with progressively sharper angles, for increasing the distance from the source (as shown in Figure 7 and discussed in [1,3]). This result, combined with early arrival times of beneficial focused reflections (indicated by the increasing with distance D-50 and C-80 parameters shown in Fig. 6(a) (b)), produce a beneficial effect on speech intelligibility in these far receiver positions (Figure 6(c)). As was found in [3], the contribution of lateral energy with distance, is less severe for side positions in the koilon.

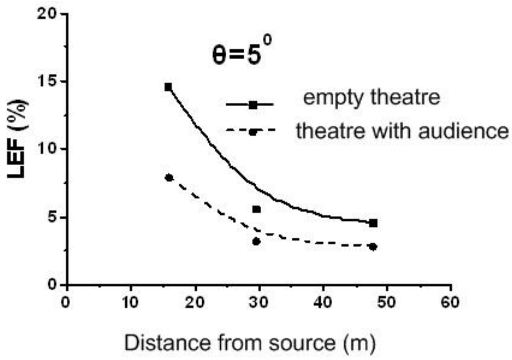


Figure 7 – Lateral Energy Fraction (LEF) versus the distance to the central positions of the receiver (from simulation)

4. Conclusions

(a) The measurements confirm the theatre's excellent acoustics and speech intelligibility, for all the typical listener positions tested here.
(b) The early reflections from the floor of the stage (orchestra) and the front of the benches (aisles) contribute to useful energy for the speech signals. For positions on the upper part of the koilon, there is also a phenomenon of focused early reflections. The energy of early reflections decays by approx. 40 dB within 60 ms, hence enhancing speech intelligibility by supporting the directly transmitted signal energy.
(c) A lower-level sound field component, decaying for approx. 300 ms, is generated by dense diffracted reflections, which are mostly amplified by the sides and the horizontal surfaces of the koilon. The arrival angle of these reflections is most acute for the far listening positions. This provides a low-level ambience to the generated sounds.
(d) The frequency response of the theatre emphasises the region of 500 Hz – 1,5 KHz, and this resonance effect lasts for approximately 200 msec. There is a prominent response dip at approx. 200Hz, which is mainly due to the ground reflection, affecting the earliest temporal structure of the generated sound. The spectrum flattens after approximately 200 ms, while there is also additive low frequency noise modulation (around 10 Hz) possibly due to air currents.
(e) The excellent values of C-80, D-50 and RASTI, which appear to improve for the distant positions, indicate the positive contribution of these early reflection, but also the beneficial effect of the diffracted sound field which appears to be underestimated by geometric acoustics –based computer models of the theatre.

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