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Immersive audio inside the Greek-Roman theatre of Tyndaris: comparison between past, current and future conditions

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ABSTRACT
The acoustics applied to the ancient monuments has been found to be of great interest, especially when other disciplines interface with the sound perception of virtual reality. This paper deals with the digital reconstruction of the acoustic conditions related to the Greek-Roman theatre of Tyndaris through its historical architectural evolution from the 4th century BCE. The auralization of the selected audio recording has been applied to four different scenarios, representing the theatre in its past original condition (PC), in the current conditions (CC), in a future condition (FC) that includes an acoustic shell on the orchestra area, and in a hypothetical condition with the original scene preserved, but the current degraded cavea (SC). The absorption coefficients of the digital model have been calibrated based on the measured results of the current condition. These data have been used as input for the PC and FC models. The same source-receivers set-up has been used in the three conditions. Furthermore, a listening test has been submitted to 12 volunteers who have been involved in the assessment of the subjective acoustic parameters, that is, the Intensity, Reverberation, Clarity, Tonal Balance, Listener envelopment, Apparent source width, Distance and the source localization in the virtual environment.

Keywords: Ancient theatres, subjective acoustic tests, Auditory VR

1. INTRODUCTION

During the last decade, a growing interest towards the use virtual reality to make our cultural heritage more accessible has emerged. One of possible application of this tool is the evaluation of the effect of architectural interventions on the acoustic performance of historical buildings during the design process (1). The purpose of this work is to investigate the benefits of comparing a methodic evaluation conducted with the objective parameters, given by ISO 3382-1:2009, with the subjective data gathered through listening tests with spatialized audio in virtual reality in the case study of different conditions of an ancient open-air theatre.

The acoustic simulation tools are nowadays easily available to a wide variety of audience, composed also of non-experts who approach the most developed technology given its contained costs. This situation occurs also in specific contexts, spanning from the acoustic space design to the reconstructions of non-existing buildings (archaeo-acoustics), including the virtual world of the gaming industry (2). However, if the latest generation of technology creates new research opportunities for the experts in acoustics, at the same time it can potentially raise several concerns on the accuracy and reliability of the acoustic simulations. On this basis, the issues can be faced especially when there is a lack of a fully understanding of critical acoustic problems pertaining to both simulation algorithms and modelling techniques (3).

Postma and Katz have described the potentials of auralization in virtual reality applied to historical

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reconstruction in (4) and (5).
Moreover, acoustic simulations for particular spaces such as ancient theatres present several challenges (6). It has been shown that the objective acoustic parameters (ISO 3382-1:2009) do not fully describe the acoustic characteristics (7), thus a more “listening” - related approach could be used to reach accurate acoustic models of existing conditions as well as to investigate acoustic effects for any adaptive reuse (8).

This paper proposes the integration of Ambisonic auralization and its applications in an adaptive reuse project related to the ancient theatre of Tyndaris. The theatre has been considered in its past original condition (PC), in the current conditions (CC), in a future condition (FC) that includes an acoustic shell on the orchestra area, and in a hypothetical condition with the original scene preserved (SC). A description of the shape and the geometrical characteristics, including material choices, for the proposed acoustic shell is also developed. Furthermore, the methodologies to achieve reliable results in open-air theatres have been developed and explored along with a careful calibration procedure of the three specific conditions.

2. MATERIALS AND METHODOLOGY

2.1 Case study overview

The ancient theatre of Tyndaris is located on the seaside of Sicily, specifically on a cliff facing the natural landscape of the Tyrrhenian Sea at a height of 180 m. It is surrounded by the ruins of the ancient city of Tyndaris that was founded in 396 BCE by Greeks. The birth of this Greek colony was specifically due for retaining the exiles of the nearby city of Messenia (modern Messina).

The shape of this theatre has considerably changed throughout the centuries. In particular, during the 4th century BCE a scenic building was added to close-up the orchestra, and during the late imperial age of the Roman empire substantial modifications have been made to adapt the theatre to host the performance of gladiators’ spectacles and fights against wild beasts.

After important natural events, like landslides and earthquakes, the Greek theatre was buried for several centuries until the archaeological excavations occurred in 1838 and continued between 1960 and 1998.

Nowadays the theatre hosts also artistic performance, but its existing acoustic state is compromised by many factors: the lack of the original scenic building, responsible of useful reflections supporting the actor's voice, the absence of a large part of the steps of the cavea and the general deterioration of the materials, impacting the reflectivity, and the increasing noise levels of the surroundings due to traffic.

2.2 Calibration process

The measured results herein used for the calibration process are related to the acoustic survey carried out in September 2015 by the Applied Acoustics Research Group of the Department of Energy of the Politecnico di Torino, extensively described in (9).

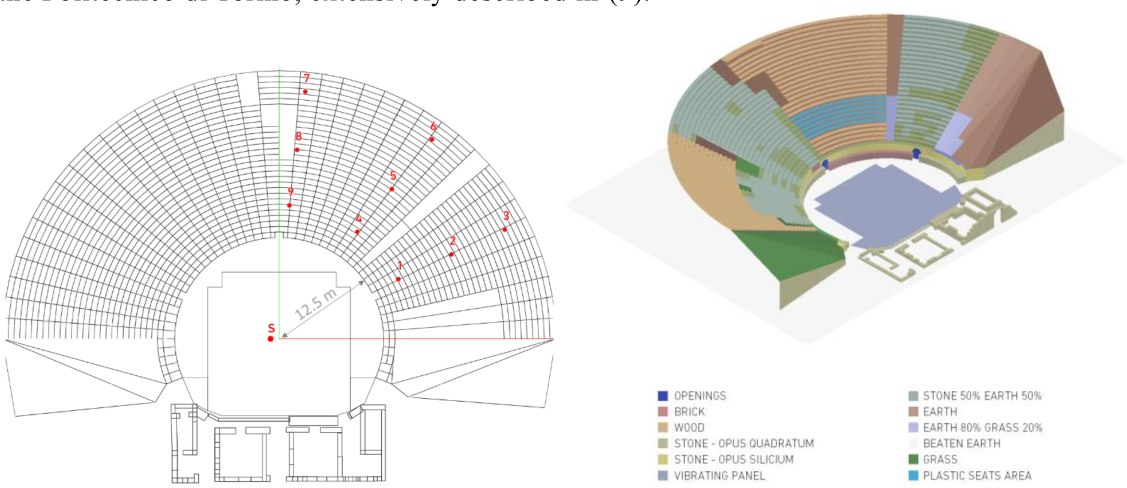

Figure 1 – a) Source and receiver positions in Ramsete.

b) Axonometric view of the calibration model showing the mapping of the materials in the current situation.

The chosen software for the simulations is Ramsete, a widely employed geometrical acoustics (GA) software based on pyramid tracing, an evolution of the conical beam tracing (10).

The same number and location of source and receivers have been used during the measurements and in Ramsete, in order to proceed with the calibration process of the absorbing and scattering coefficients of the materials placed in the theatre, which was done by trial and error.

This paper makes use of the results used in previous research studies, that have validated an acoustic model reflecting the existing conditions of the theatre by tuning the spectra of the measured values of the main acoustic parameters with those obtained by the digital simulation (11). All the materials in the model have been mapped as shown in Figure 1b.

Table 1 summarises the absorption coefficients applied to the materials used for the acoustic calibrations. The sound absorption coefficients are affected by a high level of uncertainty as reported by Vorländer (12) especially due to the consistent aging effect of the materials.

Table 1 – Sound absorption coefficients.

	63	125	250	500	1000	2000	4000	8000
OPENINGS	1	1	1	1	1	1	1	1
BRICK	0.2	0.2	0.2	0.1	0.05	0.05	0.05	0.05
WOOD	0.4	0.4	0.3	0.2	0.04	0.02	0.02	0.02
STONE - OPUS QUADRATUM	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
STONE - OPUS SILICIUM	0.36	0.36	0.39	0.43	0.43	0.47	0.49	0.47
STONE 50% EARTH 50%	0.31	0.25	0.28	0.29	0.2	0.15	0.15	0.15
EARTH	0.25	0.35	0.42	0.43	0.3	0.21	0.25	0.25
EARTH 80% GRASS 20%	0.39	0.35	0.38	0.39	0.25	0.2	0.2	0.3
BEATEN EARTH	0.25	0.22	0.35	0.35	0.22	0.1	0.15	0.2
GRASS	0.2	0.25	0.36	0.37	0.38	0.28	0.19	0.18

The calibration procedure is based on the principles proposed in (4). The following description highlights the details of the geometrical acoustic (GA) model construction. In particular:

- The impulse responses (IRs) have been used like a reference point for the calibration process. In this case, measured values are gathered from the 2015 survey.
- A 3D model has been realised by using AutoCAD 2022, allowing a reconstruction of the theatre reporting the most relevant geometrical features and details (13). Specifically, a number of 2261 faces have been modeled in the DXF format file, then exported to be used in Ramsete.
- A material mapping has been performed based on a photogrammetry of the site and wide-angle photos. Reflecting the conditions existing during the measurements, the cavea was in part covered by wooden benches and plastic chairs; the orchestra instead was covered by a wooden platform.
- The reverberation time (T20) and strength (G) are the main acoustic parameters that have been considered sufficient for the calibration process (14). The tuning of the values, developed like an iterative process, has been completed when the difference between measured and simulated values is within 5% and 1 dB, respectively (15).

2.3 Construction of PC and FC models

From the CC model calibration, shapes of the architectural components and materials were modified to create the virtual reconstruction of the past conditions (PC) resembling the Hellenistic configuration of the theatre, as shown in Figure 2.

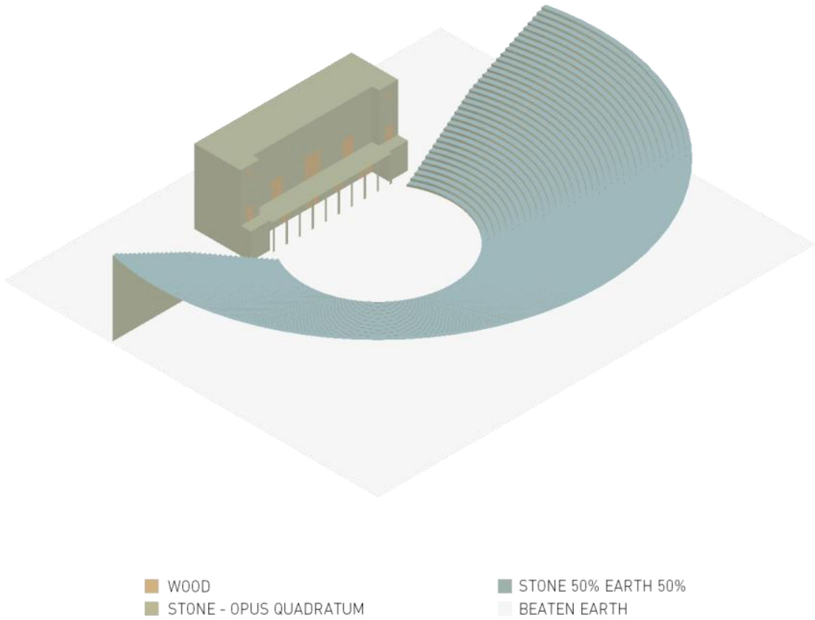

Figure 2 – Axonometric view of models used for the simulation of the Hellenistic configuration (PC).

The solution chosen for the project of adaptive reuse has already been proposed in 2016 by Giovanni Bouvet (16). It consists of a scenic structure that takes advantage of the Canac's Law to provide the early reflections useful for increasing the loudness of the sound signal. This future scenario was named FC.

The innovation of the reuse design project is based on a new acoustic shell characterised by a curved shape. This reflecting surface was generated by an evolutionary solver (i.e. Galapagos), a plugin for Grasshopper deploying computational morphogenesis, using a simple Image Source Method (ISM) algorithm, partially based on François Canac's studies.

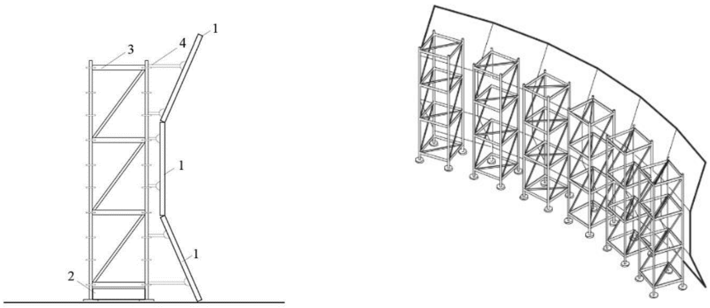

Figure 3 – Structure of the acoustic shell

The shape of this geometry has been developed considering the recommendations of the Syracuse Charter (17), asserting that temporary structures can integrate through gaps in order to optimise the acoustic performance: the modular approach of the singular components allows for a lightweight removable structure that does not impose any permanent impact on the archaeological site.

One additional fourth modelling scenario (SC) was created by transporting the scenic building from PC to CC to assess the impact of the scenic building on the sound field without the reverberation generated by fully intact cavea of PC.

2.4 Ambisonic auralizations

From each of the four simulations, and for the selected source and listener positions, one IR was exported to create the auralizations for the listening test. The IRs were exported from the receiver point R5 in B-format with an ambisonic order of 3 (3OA – 16 channels). They were then used for the convolution of two anechoic recordings, one speech sample and one music sample, using the multichannel convolution matrix VST plugin X-MCFX running inside the sound processing program Plogue Bidule.

The resulting tracks, each with 16 channels, were then muxed with a 360° video made by rendering an equirectangular image of a 3d model of the corresponding scene, centred around the receiver point R5 in Blender. The mux was realized with FB360 Encoder, a free software developed by Facebook that is able to use a 3OA track to create a .mkv file with 10 audio channels that can be read by a Meta Quest 2 in standalone mode.

2.5 Listening test

The resulting immersive scenes have been compared in a subjective listening test, structured as an AB comparison (18) presented inside the virtual reality environment using a Head Mounted Display (HMD), specifically a Meta Quest 2, and open headphones (Sennheiser HD 650).

Twenty-four auralization pairs were created, 8 of which were presented in a random order to each participant. Each pair was followed by a set of 3 questions, presented inside the immersive video:

1. How different are the two signals on a scale of 0 to 10?
2. What kind of difference did you perceive? (Multiple choice answer: Intensity, Reverberation, Clarity, Tonal Balance, Listener envelopment, Apparent source width, Distance)
3. Which signal did you prefer between first and second?

The listening methodology has been used also in other studies and has been extensively described in (5). Twelve participants, self-evaluated normal hearing subjects aged between 22 and 32, were given written instructions before the test, including the definitions of the perceptual attributes required to answer the second questions. An extensive description of the same attributes can be found in (5); they were also given two training pairs before starting the test and they were allowed to replay each comparison as much as they needed. Their progress was constantly followed, taking advantage of the wireless screen mirroring capability offered by the Meta Quest 2.

At the end of the test, participants were asked to remove the HMD to answer a last question about the position of the sound source. Participants were provided a tablet showing the planimetry of the theatre where they could draw freely with a stylus to indicate the position and dimensions of the source.

All of the listening test sessions have been conducted inside the anechoic chamber of the Politecnico di Torino in order to avoid any external disturbing noise. Closed headphones would have been equally efficient at preventing distraction, but they would have impaired communication between the tester and the subject.

Figure 4 – a) Set-up fore listening test in the anechoic room at Politecnico di Torino.

b) Rendering of the 3D model of the theatre in the current condition with the addition of an acoustic shell corresponding to FC.

3. RESULTS

3.1 Objective parameters comparison

Figures 5, 6 and 7 show a comparison of CC, PC and FC based on the main objective parameters considered during the simulations.

The virtual reintegration of the missing parts of the cavea, together with the reconstruction of the frons scaenae in PC, generated a noticeable increase of the T_{20} and G and drastic decrease of C_{50} and C_{80}. The effectiveness of the reflective shell in FC is proved by an average increment of G of 1.8 dB and a better Clarity of speech, +2.4 dB on average for C_{50}, compared to CC; yet this improvement could be unperceivable for a common spectator.

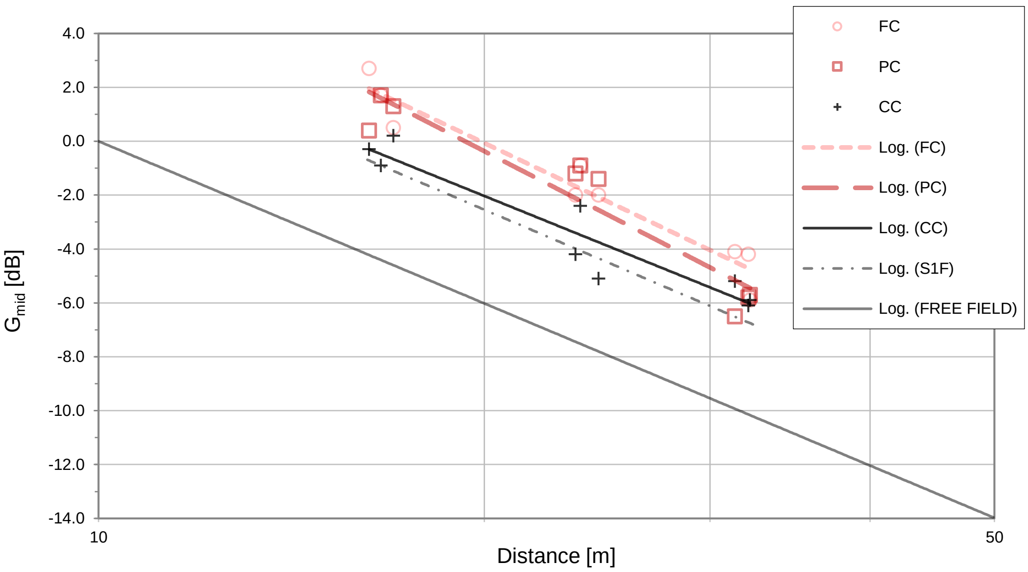

Figure 5 – Comparison of the values of G_{mid} for CC, PC and FC.

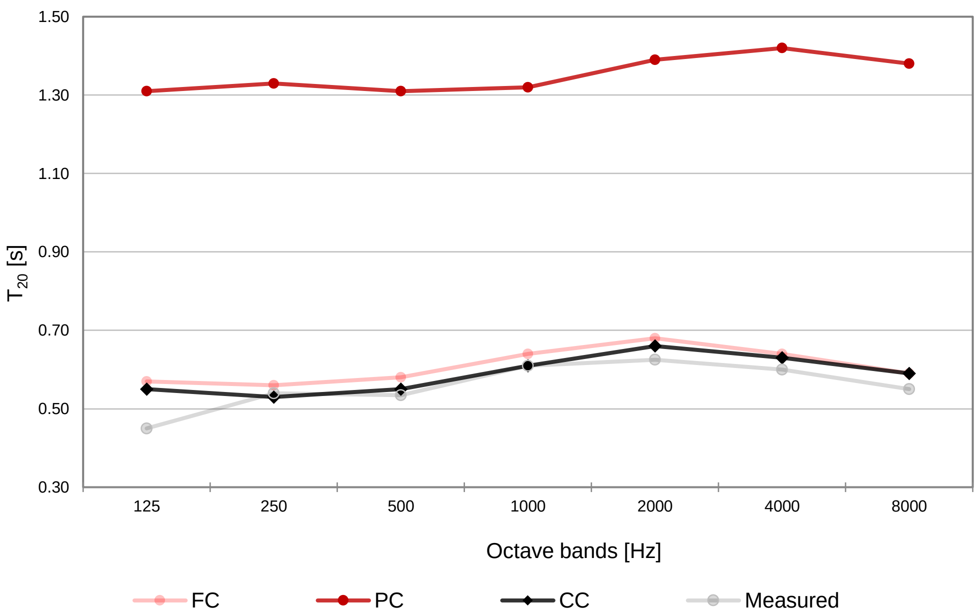

Figure 6 – Comparison of the values of T_{20} for CC, PC and FC.

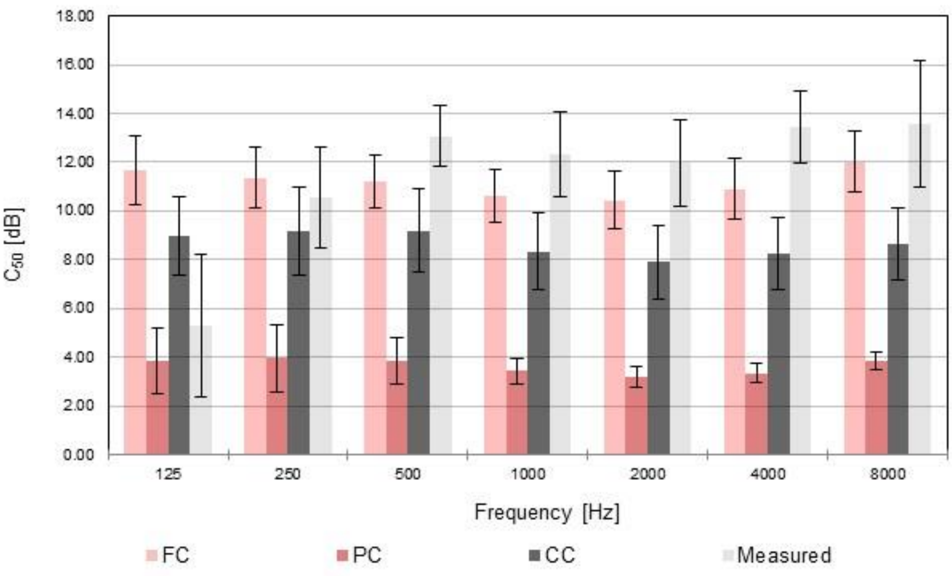

Figure 7 – Comparison of the values of C_{50} for CC, PC and FC.

3.2 Subjective comparison

The results of the listening test show a clear preference of FC over CC, especially when comparing speech auralizations; in this case FC was preferred 75% of the times, suggesting that the impact of the acoustic shell on the sound field could be noticeable for the audience. The more reverberant scenery of PC was still preferred over the other two, even for speech, although the participant reported a noticeable decrease of clarity.

Eleven of the twelve participants were able to clearly identify the position of the sound source at the center of the orchestra when asked at the end of the session.

Being allowed to replay the audio pair as much as they needed was very useful for the participants since most of them expressed an initial sense of disorientation. Many subjects also reported they were not sure if they were basing their preferences on visual or auditory input.

4. CONCLUSIONS

Aim of this preliminary study was to investigate the benefits of comparing a methodic evaluation conducted with the objective parameters, given by ISO 3382-1:2009, with the subjective data gathered through listening tests with spatialized audio in virtual reality in the case study of ancient open-air theatre

The answers given by the subjects of the listening test result useful to evaluate the accuracy of the geometrical-acoustic models. Moreover, they confirm the previous assumptions based on the analysis of objective parameters. However, given the limited number of participants (=12) the reliability of the results must be further investigated with more listeners that would allow to apply more advanced statistical methods. Some of the critical aspects of the test were related to the repeatability of the result s when the participants were asked to evaluate the same auralization pair twice, and to the influence of the visual stimulus on the evaluations. Future research will focus on reducing these uncertainties in order to be able to take advantage of subjective listening tests to evaluate possible projects of adaptive reuse and to create accurate reconstructions of past configurations of the historically valuable buildings of our cultural heritage.

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