Acoustic measurements of the Roman theatre of Pompei by mapping the sound reflections

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***Abstract*— The city of Pompei has been always subject to archaeological works during the last decades. However, the theatre that has been discovered in the urban environment has one of the best preserved *cavea*, although it lacks most of the *scaenae frons*. This paper deals with the acoustic measurements undertaken to study the behavior of this important monument through the main acoustic parameter outlined by ISO 3382-1, and to detect the direction of the early and late reflections characterizing the reverberation. This latest approach enabled the possibility to investigate the sound propagation thought the space with the employment of a multichannel spherical array microphone. The recorded impulse response (IR) has been analyzed in such a way to create an overlay video, given by the overlapping of the 360° image taken at the receiver position with the contour level of the sound decay after the impulse.**

Keywords—acoustic parameters, spherical array microphone, spatial PCM sampling, Roman theatre, impulse response.

I. Introduction

The development of the measuring technologies represents a great help for the researchers who actively attend deep studies on the ancient architectural patrimony. As such, the possibility to understand the direction of arrival of the sound rays during the IR is now possible to be achieved besides a description of the architectural characteristics of these performing arts places. The intention of this paper is to complete the acoustic characterization of the Roman theatre of Pompei, one of the ancient open-air theatres located in southern Italy as part of the Roman empire.

II. Historical Background

The city of Pompei has been taken to light after the excavations works started during the 17th century [1]. The city has been buried since 79 AC under the lava of the volcano Vesuvius. Pompei was one of the most florid cities of the Greek-Hellenistic expansion, under the influence of the Samnites [1].

The first shape realized for this theatre was a U plan layout, by having the stage and the scenic building (the places where the actors played) separated by the *cavea* (reserved to the audience) [2]. Afterwards, the summa *cavea* has been connected to the scenic building through the construction of the *tribunalia* that are the terraces created above the vomitoria which gave the access to the orchestra on the opposite sides of its diameter [3].

Originally the *cavea* was realized in marble sheet by covering the seats, but its reconstruction is composed of bricks [2]. The *summa cavea* is crowned by a top gallery (ambulatory) which today only the west side has been erected, as shown in Fig. 1.

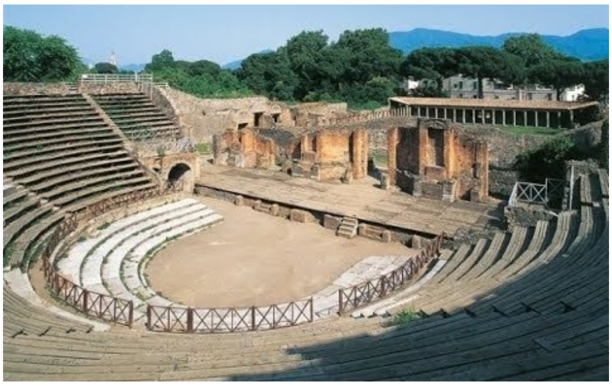

Fig. 1. Great theatre of Pompei.

The scenic building had a core structure made of brick, but externally the walls should be covered by marble [1]. The *scaenae frons* has never entirely rebuilt, and some removable wooden planks supported by a metallic structure is nowadays used to host live performance that includes lyrics, jazz and pop styles [2].

III. Architectural Features

The Great theatre of Pompei had an original capacity of up to 5000 spectators distributed across the *ima* and *summa cavea*, nowadays reduced to 2200. The diameter of the orchestra is 10 m long, while the outer diameter of the entire *cavea* measures 58 m [3].

The steps of the *cavea* were in marble, as the top gallery and the scenic building. This latest one should be composed of three main doors, by having the central one arched and the laterals squared [2]. The cavea was separated by the scenic building in Hellenistic period, and only with the Romans they became unified through the extension of the top corridor linking both areas [1]. For this occasion, the *cavea* has been extended as long as it represented and organic space overall.

The scenic building should be composed of different orders of columns, in Tuscanic style for the first level, Ionic and Corinthian for the elevated ones, as discovered in many other Roman theatres [4][5].

The proscenium was the area where the actors performed during the shows. It was composed of a wooden deck approximately 1.2 m above the orchestra level [6][5].

Table 1 summarizes the architectural features of the Great theatre of Pompei.

TABLE I. ARCHITECTURAL CHARACTERISTICS OF THE GREAT THEATRE OF POMPEI

Description	Features
Type of plan layout	U shape
Original capacity (No. of seats)	5000
Actual capacity (No. of seats)	2200
Total volume (m^3)	26468
Stage building (m) [L × W]	22.6 × 6.7

IV. MEASUREMENTS

An acoustic survey was undertaken inside the theatre to understand the acoustic behavior of the existing volume through the objective parameters obtained in line with the standard requirements outlined in ISO 3382-1 [7]. During the surveys, thermo-hygrometric conditions were taken in consideration [8]. The acoustic survey was carried out with the following equipment:

- Equalised omnidirectional loudspeaker (Look Line);
- Microphones:
  a) Binaural dummy head (Neumann KU-100);
  b) B-Format (Sennheiser Ambeo);
  c) Omnidirectional microphone (Bruel&Kjaer);
  d) 32-channel spherical array (Mh Acoustic em32 Eigenmike®);
- Personal Computer connected to the loudspeaker and all the receivers.

The sound source was placed at 1.3 m from the finished floor, and it was placed on the proscenium. The receivers were installed at the height of 1.2 m from the relative finish floor across the *cavea*. The excitation signal emitted by the sound source was the Exponential Sine Sweep (ESS) [9] having a duration of 15 s in a uniform sound pressure level for the range between 40 Hz and 20 kHz. The measurements were undertaken in unoccupied conditions [10].

Fig. 2 shows the positions of the sound source and the receivers placed during the survey.

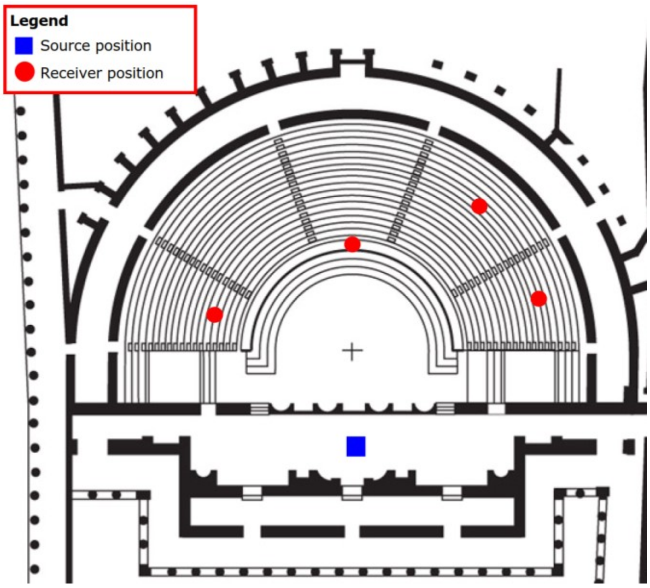

Fig. 2. Scheme of the equipment location during the acoustic measurements in the Roman theatre of Pompei.

V. RESULTS

A. Traditional parameters

The recorded ESS signals have been processed by using the plugin Aurora suitable for Audition 3.0 [11]. The acoustic parameters as defined by the standard ISO 3382-1 and herein introduced are the following: early decay time (EDT), reverberation time (T_{20}), clarity indexes (C_{50} and C_{80}), definition (D_{50}), and strength (G). These acoustic parameters are reported in the octave bands between 125 Hz and 4 kHz, considered as the average results of all the measurement positions.

Fig. 3 to Fig. 7 show the graphs related to the main acoustic parameters for the data gathered by the survey undertaken inside the Roman theatre of Pompei.

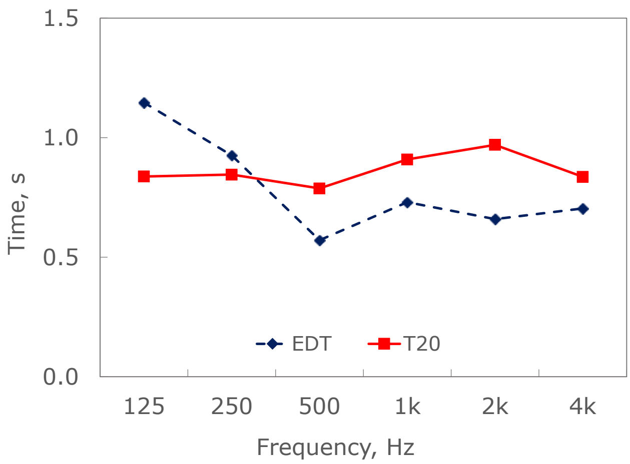

Fig. 3. Measured results of Early Decay Time (EDT) and Reverberation Time (T_{20}).

Fig. 3 shows the frequency response of the EDT and T_{20} parameters. The averaged value of the T_{20} is approximately 1 s, which is comparable with other ancient open-air theatres of Roman style [12]. On this basis, the Roman theatre of Pompei has a response suitable for both speech and musical performance, even if the latest one would require preferably a higher reverberation time [13].

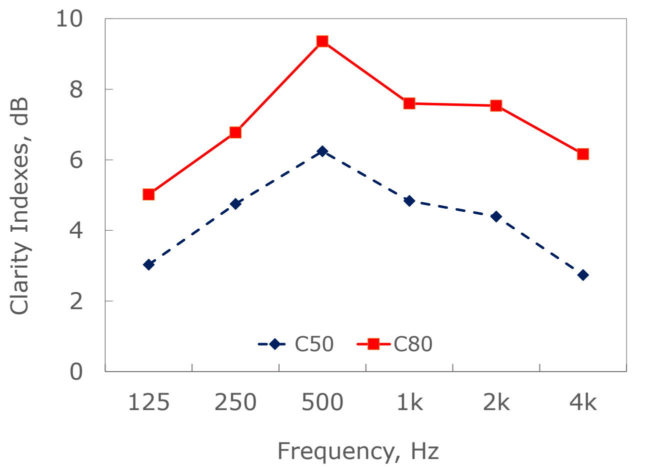

Fig. 4. Measured results of clarity indexes (C_{50} and C_{80}).

By literature [14], the optimum values for speech clarity index (C_{50}) are indicated to be ≥ 3 dB. In the Roman theatre of Pompei this parameter fluctuates between +3 and +6 dB, with a spike at 500 Hz. Based on results of Fig. 4, the good response of C_{50} has been achieved at all frequencies bands, with a short fall at 125 Hz and 4 kHz.

In terms of music (C_{80}), the optimum values as defined by literature should be comprised between -2 and +2 dB, according with Jordan [15]. This target has not been achieved in any frequency bands, found to be above the upper range limit. Translated in other words, the music would be very clear, especially at 500 Hz.

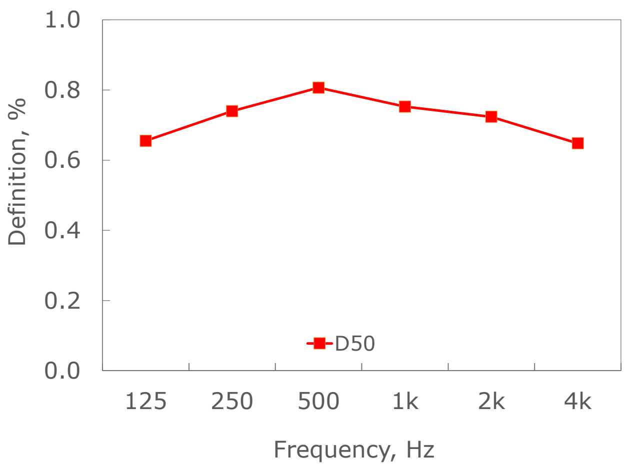

Fig. 5. Measured results of Definition (D_{50}).

As per research studies [16], a good speech definition is achieved for values higher than 0.5 (i.e. 50%), while the optimum values for music definition are considered those that are lower than 0.5 (i.e. 50%). On this basis, the results obtained in the Roman theatre of Pompei are found to be around 0.7 (70%) across all the frequency bandwidth. This means that the listening conditions are very suitable for speech, even if the outcome is also good for music.

In terms of strength (G) Fig. 6 shows the energy response obtained inside the theatre. Values have been compared by grouping the data acquired across the *cavea*.

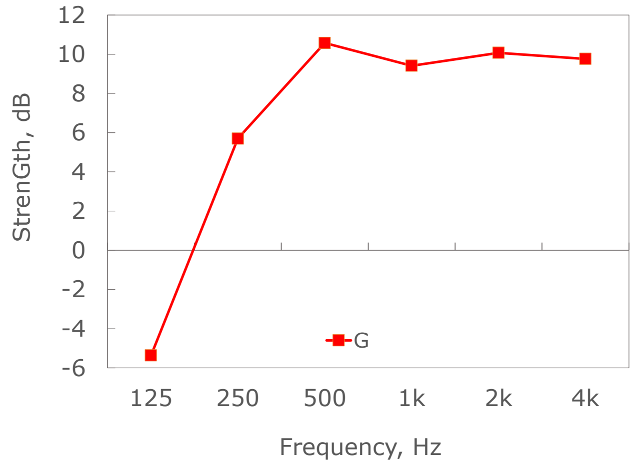

Fig. 6. Measured results of strength (G).

By averaging the values of all the measuring points, the best strength is obtained at mid-high frequencies range while it results weak at 125 Hz. This means that listeners have light difficulties in hearing a *fortissimo* for bass sounds [13]. As such, the players (especially singers) should put more effort in obtaining a good performance at the bass tones.

Considering the strength in function of the distance existing between the source and the receiver, Fig. 7 shows the results related to measured positions selected across the *cavea*.

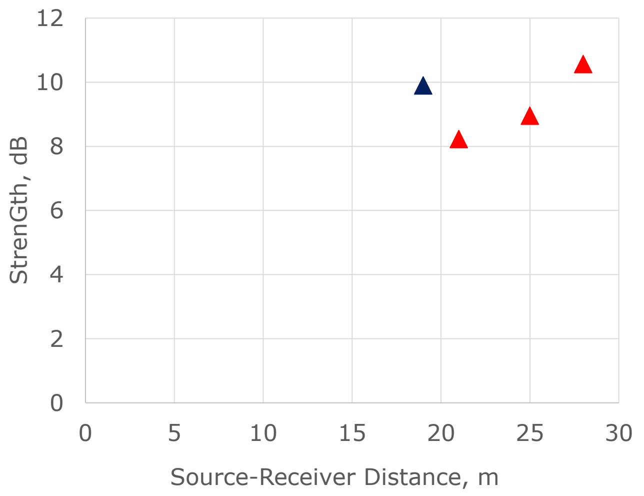

Fig. 7. Results of strength (G) related to the stalls area.

Fig. 7 shows a good G response at the seats located across the *cavea*, achieving values between 8 and 11 dB. In particular, the trend line of G related to the all measured positions increases proportionally with the distance: the greater is the distance the higher is G. However, the exception is given by the blue triangle located at 19 m from the sound source; in this position (i.e. nine steps above the orchestra level on the western side of the *cavea*) G is higher than other locations at the same height. This is due to the presence of the ambulatory and the gallery still survived at the top of this wedge, as it is visible in Fig. 8. The construction coronating this corner of the *cavea* contributes to increase the strength because of representing strong reflecting surfaces for the sound rays [17][18].

Fig. 8. View of the Roman theatre of Pompei highlighting the presence of the ambulatory and the gallery on the western side of the *cavea*.

B. *Acoustic analysis of 3D sound maps*

The utilization of the em32, given its configuration to be a spherical array microphone, allow the elaboration of 360° sound maps, obtained for each source-receiver combination. Such maps allow to understand the specific role that specific surfaces inside the theatre interact with the sound waves, from the direct to the late reflections including their energy intensity [19][19].

This different data analysis, that completes the overview obtained by showing the graphs related to the main acoustic parameters, is obtained by combining the IR recorded by the multichannel microphone and the panoramic view represented in an equirectangular format [20]

The result obtained is a color map overlay showing the soundwaves arriving to the receiver from all the possible spherical directions. The video has been realized by processing 1024 samples at 48 kHz sampling rate [19].

The different sound energy has been represented by contour levels of a range of colors going between red tinge and blue-violet shades, representing a high and a poor energy, respectively.

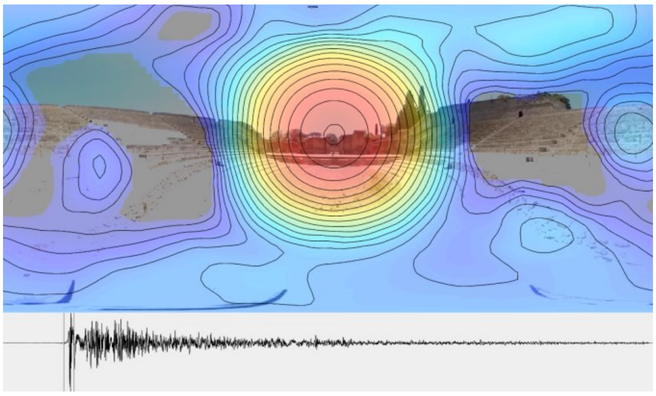

Fig. 9. Acoustical map showing the direct sound arriving to the receiver.

Fig. 9 show the direct soundwave arriving to the receiver placed at the center of the first step of the *ima cavea*. It is visible how the sound comes from the sound source placed on the floor of the proscenium.

The following shot, shown in Fig. 10, represents the early reflections hitting the steps of the *cavea* and climbing upwards. This phenomenon is typical of Roman and Greek theatres already studied with this methodology by the authors [20]. The outcomes reflects what has been investigated by researchers about the geometry of semicircles concentric increasing with a constant dimension of the steps [21][22].

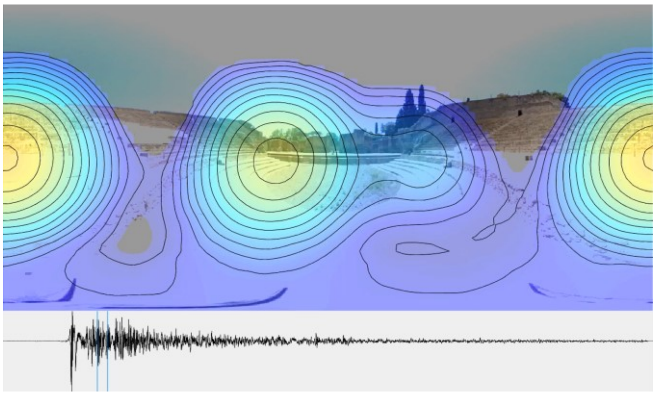

Fig. 10. Acoustical map showing the early reflections.

VI. CONCLUSIONS

This paper deals with the results obtained by the acoustic survey undertaken in the Great theatre of Pompei. Measurements based on ISO 3382-1 were conducted in situ in unoccupied conditions and by considering the outdoor thermo-hygrometric conditions.

Overall, the results obtained from the measurement campaign showed that the theatre has a good response for speech performance, with some difficulties at low frequencies in terms of strength that require the singers to put more effort at the bass tones. The theatre results having a good response also in terms of music, being in the average of other ancient theatres used for modern uses.

The acoustic study of the main parameters has been extended to analyze the specific path of the sound rays. These results could be possible by the utilization of the multichannel spherical array microphone that determine the directivity of the soundwaves based on the uniform distribution of the capsules on the spherical front.

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