THE ACOUSTICS OF THE CASSINO ROMAN THEATRE

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Résumé

Dans cet article, les caractéristiques acoustiques du théâtre romain de Cassino sont discutées. Le théâtre a été construit à l'époque impériale,puis, après les invasions barbares, il fut abandonné et détruit. Il a été reconstruit ces dernières années. Une source sonore placée sur la scène et dans l'orchestre a été utilisée et les caractéristiques acoustiques conformes à la norme ISO 3382 ont été mesurées. Le théâtre a un temps de révérence court égal à 0,6 seconde car le mur de la scène n'a pas été reconstruit. Cependant, en saison estivale, le théâtre est utilisé pour des spectacles musicaux utilisant des systèmes d'amplification électro-acoustiques pour avoir une bonne acoustique

Mots clefs: théâtres antiques, temps de réverbération, scène, orchestre, cave, acoustique des salles.

Abstract

In this paper, the acoustic characteristics of the ancient Roman theatre of Cassino are discussed. The theatre was built during the Imperial Age and was abandoned and destroyed after the Barbaric invasions. The theatre has been rebuilt in recent years and it is currently used for summer events ad performance. To measure the acoustic characteristics of this ancient theatre, the authors used a spherical omnidirectional sound source placed on the stage and in the orchestra. The results show that nowadays the theatre has a short reverberation time equal to 0.6 seconds due to the lack of the stage wall, which has not been rebuilt. The weak sound strength justifies the use of electro-acoustic amplification systems which during the summer season, are adopted to improve the acoustic experience in this ancient theatre.

Keywords: ancient theatres, reverberation time, archeoacoustics, scena, orchestra, cavea, room acoustics.

1 Introduction

In ancient times, theatrical buildings were built to provide performances with a better vision and listening conditions [1-3]. The theatres built in Greece were resting on the slope of a hill with a concentric stepped structure. This configuration improved the visual experience and allowed a better distribution of the sound. Vitruvius, in the ancient book "*De Architectura*", provides some rudimental principles of architectural acoustics, which support many of the features found in ancient theatres [4-6]. To improve the acoustics, Vitruvius suggested to place vases (*echeia*) under the steps; this fascinating hypothesis, today finds applications with acoustic resonators used for correcting the acoustics of modern theatres. The acoustics of the ancient theatres was mainly due to the regular arrangement of the aligned semi-circular steps and to the regular geometries which acted as diffusing surfaces. The diffused sound field in ancient theatres guaranteed good acoustic conditions, as repetitively reported in recent studies [7, 8].

During the imperial period, more than a thousand theatres were built [9]. Theatres were not only buildings for performances as they were places for political and religious meetings. In fact, all the cities of the Roman Empire had a theatre, and the richest citizens contributed financially to its construction. Theatrical performances were offered by rich men to gain the people's consent and political power.

Several measures were used to improve the acoustics of the theatres, such as covering the orchestra with square marble slabs, so to obtain a better diffusion of incident sound. The scena became a building with columns, stuccos, and plasters. The rows of columns, arranged on several levels, created diffusing surfaces that improved the propagation of sound. While the scena building was covered with a canopy to increase early reflections of sound towards the *cavea*. The presence of the scena building allowed a better distribution of the sound in the cavea. In fact, the voice of the actor was reflected by the scena building and then returned to the audience sitting in the cavea. The theatres were used during the summer season and to protect the spectators from the summer heat, the cavea was covered with awnings (*velaria*) [10]. The size of the scena building covered the maximum height of the cavea in order to enclose the scena and the cavea in a single body. Furthermore the size of the scena of Roman theatres was doubled compared to that of Greek theatres. Figure 1 shows a reconstruction of the scena, orchestra, and cavea of the ancient Roman theatre. In this paper the acoustic characteristics of Roman Theatre of Cassino are discussed.

The city of Cassino in Italy was very important during the Imperial Empire, because it was located along the most important communication routes with Rome. This explains

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the construction of important buildings such a large theatre and the amphitheatre inside the walls of the ancient city. Figure 2 shows the aerial view with evidence of the theatre and amphitheatre of Cassino by Google maps.

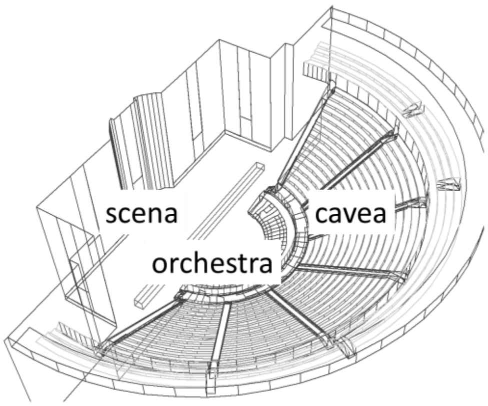

Figure 1: Main elements of the Roman theatre: the scena, the orchestra and the cavea.

Figure 2: Aerial view with the position of the theatre (left) and amphitheatre (right) in the current state by Google maps.

The Roman theatre of Cassino was built in the first century BC, during the Augustan period. The cavea stands on the slope of a hill and is oriented to the South - East. The ground plan and the orchestra are semi-circular. Subsequent historical events led it to being abandoned and demolished.

Figure 3 shows the ground plan of the theatre in current state, with the main dimension and the principal elements (scena, orchestra, and cavea).

While Figure 4 shows the ground plan of the theatre before the restoration (1900) in this period only few elements of the structures had been preserved; and after the restoration (2007) [11].

Figure 5 shows the theatre during the restoration works. The restoration involved only a few parts of the cavea and was completed in 2000. In its current state, the theatre has a semi -circular orchestra with a diameter of 10 m; the cavea with an external diameter of 56 m; and the scena of 5.0 m x 27.4 m. Only nineteen steps have been rebuilt, compared to the origin, in stone and mortar, with height of 0.40 m and depth of 0.70 m, so the cavea has a slope of 30°. The current capacity is about 1,000 spectators.

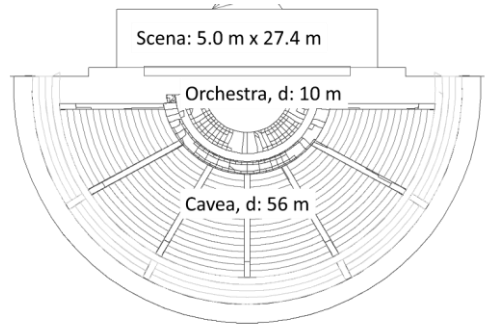

Figure 3: Ground plan of the theatre in the current state, with the main dimension and the principal elements (scena, orchestra, cavea).

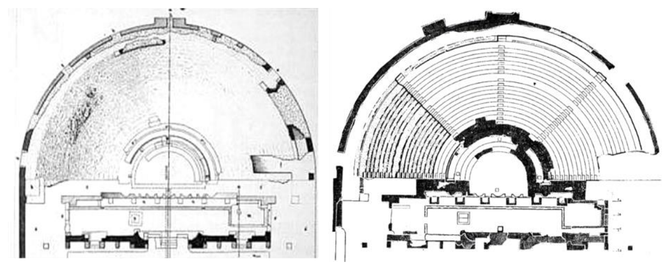

Figure 4: Ground plan of the theatre before the restoration work (left) in 1900, and after the restoration (right) in 2007 [11].

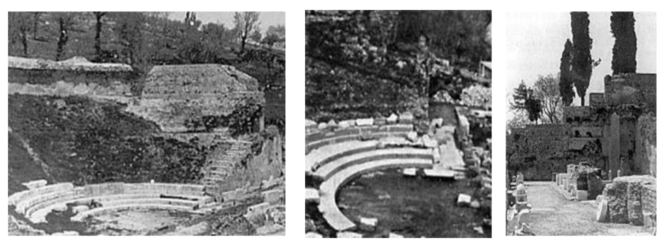

Figure 5: The theatre during the restoration work [11].

Figures 6 and 7 show the side and front view of the theatre in its current state respectively [12].

Figure 6: Front view of the theatre in the current state.

2 Acoustic measurements

To evaluate the acoustic characteristics of the theatre, acoustic measurements were carried out in accordance with literature practice [13] and the standard ISO 3382 [14]. A spherical omnidirectional sound source was placed on the scena at a height of 1.5 m from the floor, in the actor position.

Figure 7: Side view of the theatre in the current state.

The sound source was fed with a MLS signal, by impulse response technique. The acoustic procedure and the post processing methodology were similar to those used to study other theatres [15-20]. The impulse response was detected with an omnidirectional microphone (GRAS 40 AR endowed with the preamplifier 01 dB PRE 12 H) placed at a height of 1.2 m. The receiving points were placed on the I, V, IX, XV and XIX steps, in order to obtain information from varying distances from the sound source, along the three radial directions in the cavea. Figure 8 shows the position of the sound source on the scena, and the receiver points in the cavea set out along three radial directions. The distances of the receiver points from the sound source on the scena were: I step 13 m; V step 17 m; IX step 19 m; XV step 23 m and XIX step 27 m.

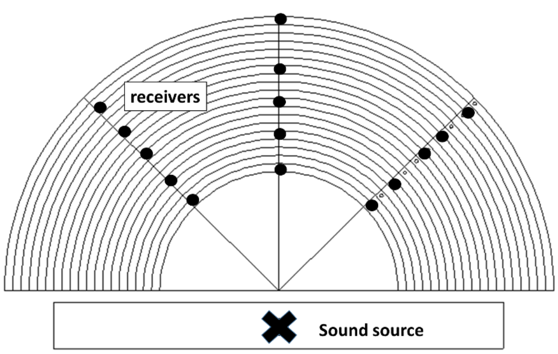

Figure 8: Position of the sound source (**x**) on the scena and the five receivers (•) in the cavea.

During the acoustic measurements, the theatre was empty; the measured noise level was equal 35 dBA. Figures 9 shows the sound source on the scena during the acoustic measurements. The impulse responses were analysed with the software Dirac 4.0. The acoustic parameters defined in the standard ISO 3382 that were analyzed are the reverberation time (T_{30}), early decay time (EDT), sound strength (G), clarity (C_{80}), definition (D_{50}), and sound transmission index (STI).

While Figure 10 shows the sound source on the scena and measurement microphones in the cavea for the measurement of G (strength, dB), for a total of ten receivers.

Figure 9:Sound source on the scena during the measurements.

The typical suggested values of the different monaural acoustic parameters for both speech comprehension and music listening are discussed in [21]:

- T_{30} should assume values below 1.0 second for a clear perception of speech, while it could assume values around 2.0 seconds for music listening preference;
- C_{80} should have a higher value if the goal is to separate initial sounds from diffuse ones, making discrete sounds stand apart from each other. In a sound field which is not completely diffuse, C_{80} is uncorrelated to reverberation time. For the purposes of good listening conditions of music, it is generally reported that C_{80} should be in a range between -2 dB and 2 dB, while it is expected to be above 2 dB if speech perception is a priority;
- D50 may assume values from 0 to 1.0, but for a good speech comprehension, it should have values above 0.5;
- STI represents the degree of the amplitude modulation in a speech signal, with them both referring to the distortion in speech signals caused by reverberation, echoes, and background noise. Values of STI greater than 0.5 represent favorable speech intelligibility conditions.

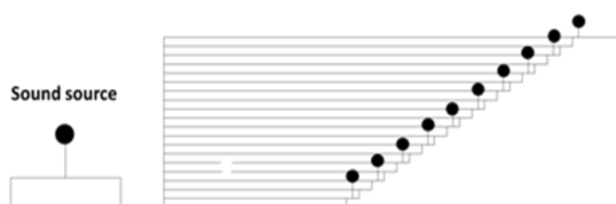

Figure 10: Sound source on the scena and measurement microphones in the cavea for the measurement of G, for a total of ten receivers.

Table 1 shows a synthesis of the optimal acoustic values for different listening conditions.

Table 1: Optimal acoustic parameter values for different listening conditions.

Parameters	EDT, s	T30, s	C80, dB	D50
Values for musical performances	1.8 < EDT < 2.6	1.6 < T30 < 2.2	-2 < C80 < 2	< 0.5
Values for speech performances	1.0	0.8 < T30 < 1.2	> 2	> 0.5

3 Acoustic results

For the fifteen receivers, with the sound source on the scena: Figure 11 shows the average measured values of T30 with the standard deviation; Figure 12 shows the average measured values of EDT, with the standard deviation; Figure 13 shows the average measured values of C80, with the standard deviation; Figure 14 shows the average measured values of D50, with the standard deviation. The measured values confirm that the lack of a roof and backstage wall led to a few sound reflections with short reverberation time, as highlighted in values below 0.5 second of T30. The average value of C80 is equal to 13 dB, while the average value D50 is equal to 0.9. The STI is equal to 0.85 [22-26]. Acoustic measurements show that the theatre, in the actual configuration, cannot be used for opera or symphonic music, since the scena, with no rear wall, prevents any sound reflections, and the listeners only perceive the direct sound. To improve acoustics of the theatre, some screens should be installed at rear of the scena, so as to allow for sound reflection. Figure 15 shows the impulse response on step VII with the effects of the multiple reflections due to the diffraction on the sound on the steps. The multi-reflections of the sound generate a diffusion of the incident sound in all directions, distributing the sound field evenly. Each edge of the steps emit a sound like a secondary sound source. The seats are regular surfaces so are an acoustic filter that passes sound coming from the scena at the expense of surrounding noise.

In open-air theatres, the parameter G (strength, dB) assumes a special significance for the assessment of acoustics. G represents the subjective level of sound and it is defined as the gain from sound pressure level, which is produced by the same spherical omnidirectional sound source, with the same power level (Lw), in a free field at a distance of 10 m from the sound source. To measure the acoustic parameter G, the spherical omnidirectional sound source was calibrated and the sound power level Lw (dB) was measured through the "substitution method" with an reference sound source. The procedure consists of a comparison of the sound pressure level in octave band of a noise source under test with those of the calibrated reference sound source. The reference sound source consists of a centrifugal fan driven by a powerful asynchronous motor type B&K 4204 [27, 28].

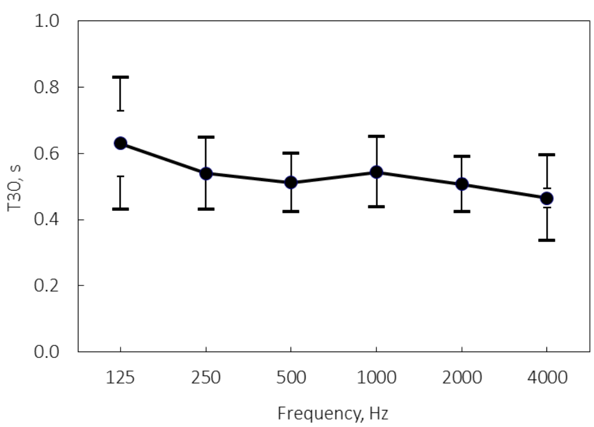

Figure 11: Average values and relative standard deviations of T30.

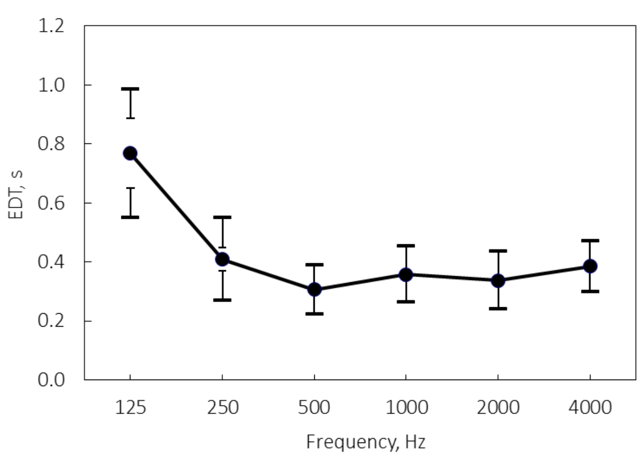

Figure 12 :Average values and relative standard deviations of EDT.

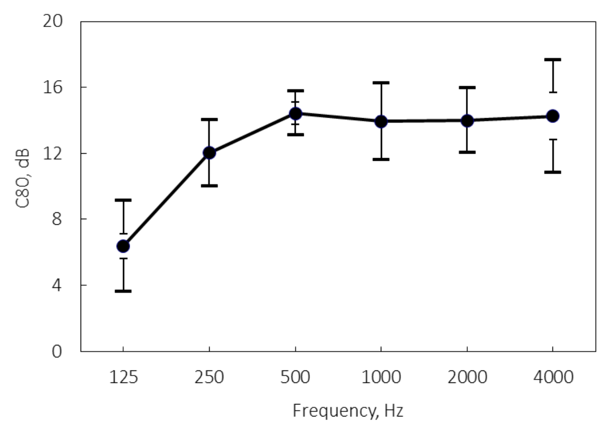

Figure 13: Average values and relative standard deviations of C80.

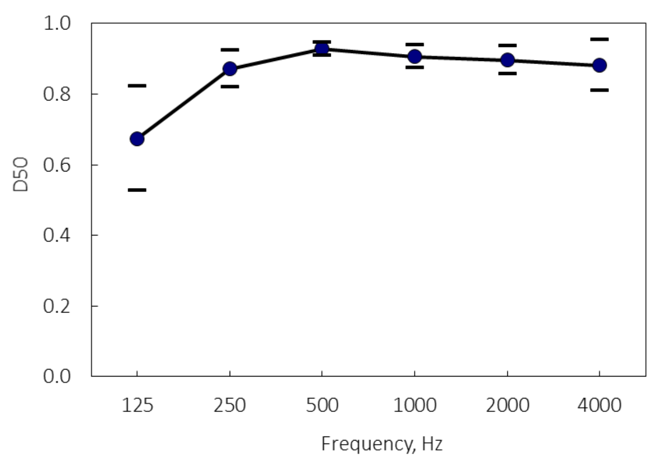

Figure 14: Average values and relative standard deviations of D50.

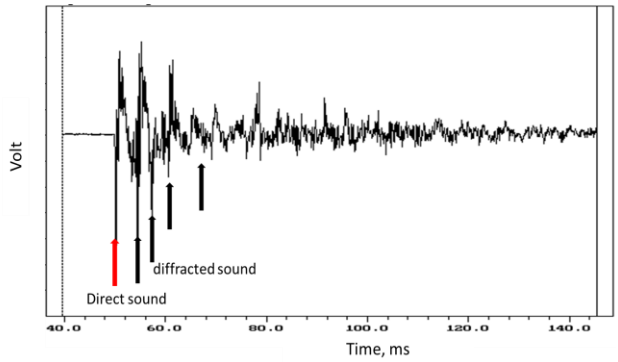

Figure 15: Impulse response on step VII, multi reflections are due to the diffraction on the sound on the steps.

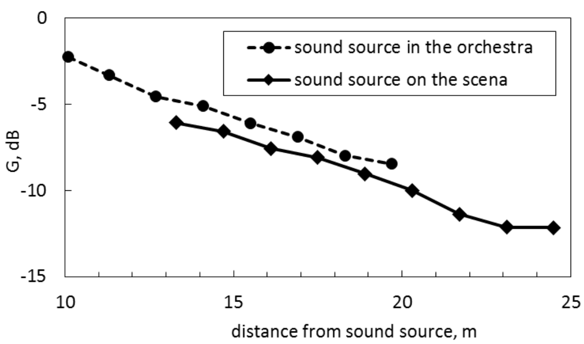

Figure 16: Average value of G along the cavea, with the sound source on the scena and in the orchestra.

The calibration procedures were carried out in a closed large room, and than the set-up was preserved. With the same Lw "calibration" set-up, the sound source was feed during the measurements in the theatre. The acoustic parameter G (strength, dB) was calculated with the following formula:

$$G = Lp - Lw + 31 \text{ (dB)}$$

where Lp (dB) is the sound pressure level detected in the cavea along on the ten steps (Figure 10). Lw (dB) is the sound power level of the spherical sound source. Figure 16 shows the average values of the G, measured along the three directions in the cavea, when the spherical sound source is placed on the scena and in the orchestra.

Based on the sampled results, the spatial distributions of the acoustic parameters were obtained in the cavea. Figure 17 shows the map of T30 at the frequency of 1000 Hz. The reverberation is very low and does not exceed 1.0 second due to the absence of reflective surfaces, while slightly increase only in the upper part of the cavea. Then Figure 17 shows the map of C80 at the frequency of 1000 Hz. Finally, Figure 17 shows the map of D50 at the frequency of 1000 Hz, in the theatre, approaches the unit value. However, with modest variations, the average spatial distribution suggests that the theatre has excellent behaviour for speech understanding [29].

The spatial distribution of the acoustic characteristics is not uniform. In the reconstruction of the theatre some walls are taller than others and this effect generates non-symmetrical sound reflections, resulting in an uneven spatial distribution.

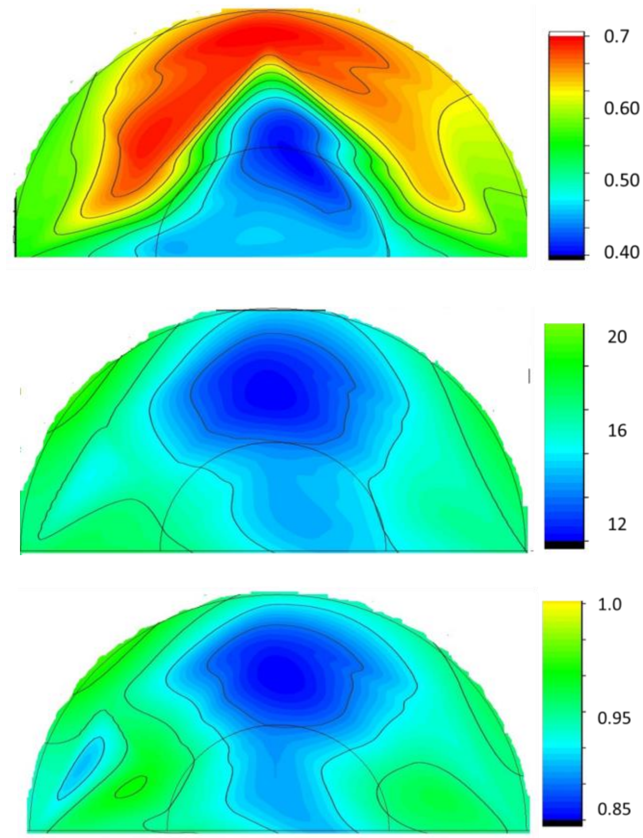

Figure 17: Maps (top to down) of T30 (s), C80 (dB), and D50 at the frequency of 1000 Hz.

4. Discussion

In order to assess the acoustic characteristics of the theatre of Cassino in the actual configuration, a comparison was conducted with the acoustic parameters measured in empty conditions into the open-air theatres of Pompeii (large theatre and Odeon), Benevento, Posillipo, Taormina, Segesta and Siracusa [30-35]. The average values of the monaural parameters at the mid-frequency bands of 500 Hz and 1.0 kHz are reported in Table 2.

Table 2. Acoustic parameters averaged at mid-frequency bands of 500 Hz and 1.0 kHz measured in some ancient theatres in empty conditions.

Theatres	T_{30} [s]	C_{80} [dB]	D_{50} [-]	Cavea diameter [m]
Benevento	0.9	8.0	0.78	93
Cassino	0.6	19.0	0.91	53
Pompeii (large theatre)	0.9	6.0	0.70	60
Pompeii (Odeon)	1.0	9.5	0.8	30
Posillipo	1.1	3.0	0.70	47
Taormina	1.9	1.17	0.53	110
Segesta	0.5	16.0	0.90	63
Siracusa	1.2	13.0	0.90	140

From the comparison with the other reconstructed open type theatres, the Cassino theatre has the shortest reverberation time, due to the geometric characteristics. The cavea has not been completely rebuilt, so even the scena building walls have not been rebuilt. The absence of reflective surfaces does not generate a reverberant field. The theatre has few sound reflections, for its current use, all the events involving the use of sound amplification with loudspeakers. A possible solution to improve the acoustics of the theatre would be the installation of temporary structures of high-density PVC sheets with reflective characteristics, so that the sound incident on the sheets can be sent back into the cavea.

5. Conclusions

The paper reports the acoustic measurements in the Roman theatre of Cassino. The theatre has been partially rebuilt and it is nowadays used for theatrical performances. The acoustic measurements show that the absence of reflective surfaces, such as the walls of the scena building, makes the acoustics insufficient. In fact, the values of the reverberation time do not exceed 1.0 second, and also it is measured a low sound strength value (G, dB). Nowadays during modern performances, sound amplification systems with loudspeakers are used. Not surprisingly, the historical atmosphere and the suggestion of these places make the listener forget the acoustic limits of these theatres or the diffuse use of loudspeakers. However, there is no doubt about the fascination of performance in these theatres that attract a large number of spectators inside the cavea of the ancient theatre. So, the recovery of the ancient theatres allows these buildings to be the cultural centre of the shows in the summer season.

References

[1] G. C. Izenour, *Theatre Design*, McGraw-Hill, New York, 1977.

[2] P. Arnott, *An introduction to the Greek theatre*, Springer, 1991.

[3] P. Wilson, *The Greek theatre and festivals: documentary studies*, Oxford University Press on Demand, 2007.

[4] W.C. Sabine, *Collected Papers On Acoustics*, Cambridge Harvard University Press, 1923.

[5] M.P. Vitruvio, *De Architectura*.

[6] P. Zanker, *La città romana*, Laterza, 2013.

[7] N. F Declercq; C. S. A Dekeyser. Acoustic diffraction effects at the Hellenistic amphitheater of Epidaurus: seat rows responsible for the marvelous acoustics, *J. of the Acoustical Society of America* 121(4), 2011-2022 (2007).

[8] T. Lokki; A. Southern; S. Siltanen; L. Savioja, Acoustics of Epidaurus – Studies With Room Acoustics Modelling Methods, *Acta Acustica* 99, 40 – 47 (2013).

[9] F. Sear, *Roman Theatres: An Architectural Study*, OUP Oxford, 2006.

[10] F.R.d Alfano; G. Iannace; C. Ianniello; E. Ianniello, "Velaria" in ancient Roman theatres: Can they have an acoustic role? Energy Build. 95, 98–105, (2015). https://doi.org/10.1016/j.enbuild.2015.03.010

[11] G.F. Carettoni, Il teatro romano di Cassino, *in Notizie degli scavi di antichità* 1939, 99-141.

[12] C. Pisani Sartorio, P. Rossetto Ciancio, *Teatri greci e romani. Alle origini del linguaggio rappresentato. Censimento analitico*. Seat Torino, 1994.

[13] F. Canac, *L'acoustique des theatres antiques. Ses enseignements*. Editions du centre national de la recherche scientifique, Paris, 1967.

[14] ISO 3382-1:2009: *Acoustics - Measurement of room acoustic parameters*.

[15] G. Iannace; A.Trematerra, The rediscovery of Benevento Roman Theatre Acoustics, *Journal of Cultural Heritage* 15(6), 698, (2014).

[16] U. Berardi; G. Iannace; L. Maffei, Virtual reconstruction of the historical acoustics of the Odeon of Pompeii, *Journal of Cultural Heritage* 19, 555-566 (2016).

[17] A. Trematerra; S. Paternuostro; I. Lombardi, Virtual reconstruction and sound field simulation of the Odeon of Posillipo. *16th Conf. Applied Mathematics*, APLIMAT 2017; Bratislava; Slovakia; 2017.

[18] U. Berardi. A double synthetic index to evaluate the acoustics of churches, Archives of Acoustics, 37, 4 (2012).

[19] U. Berardi; E. Cirillo; F. Martellotta.A comparative analysis of energy models in churches, Journal Acoustical Society of America, 126, 4 (2009).

[20] R. S. Shankland, Acoustics of Greek theatres, *Physics Today* 26, 30–35 (1973).

[21] M. Barron, *Auditorium Acoustics and Architectural Design*, E&FN SPON London, 1993.

[22] J. H. Rindel, Roman Theaters and the Revival of Their Acoustics in the ERATO Project, *Acta Acustica* 99, 21-29 (2013).

[21] S. L. Vassilantonopoulos; J. N. Mourjopoulos, A study of ancient Greek and Roman theater acoustics. *Acta Acustica united with Acustica* 89(1), 123-136 (2003).

[23] K. Chourmouziadou; J. Kang, Acoustic evolution of ancient Greek and Roman theatres. *Applied Acoustics* 69, 514-529 (2008).

[24] A. C. Gade; M. Lisa; C. Lynge; J.H. Rindel, Roman Theatre Acoustics; Comparison of acoustic measurement and simulation results from the Aspendos Theatre, Turkey. *In Proc. ICA 2004*.

[25] G. Iannace, U. Berardi, F. De Rossi, S. Mazza, A. Trematerra and G. Ciaburro. Acoustic Enhancement of a Modern Church. *Buildings* 9, 83, (2019).

[26] U. Berardi, G. Iannace and A. Trematerra. Acoustic treatments aiming to achieve the Italian minimum environmental criteria (CAM) standards in large reverberant classrooms. *Canadian Acoustics / Acoustique canadienne* 47(1), 73-80 (2019).

[27] https://www.bksv.com/en/products/transducers/ acoustic/sound-sources/reference-4204

[28] ISO 3747:2011: *Determination of sound power levels of noise sources using sound pressure Comparison method for use in situ*.

[29] U. Berardi; G. Iannace, The acoustic of Roman theatres in Southern Italy and some reflections for their modern uses. *Applied Acoustics* 170, 107530 (2020).

[30] G. Iannace; A. Trematerra, The acoustic effects of the audience in the modern use the of ancient theatres. Jurnal Teknologi 80(4), 147-155 (2018).

[31] A. Farnetani; N. Prodi; R. Pompoli, On the acoustics of ancient Greek and Roman theaters. *J. of the Acoustical Society of America* 124(3), 1557-1567 (2008).

[32] E. Bo; A. Astolfi; A. Pellegrino; D. Pelegrin-Garcia; G.E. Puglisi; L. Shtrepi; M. Rychtarikova, The modern use of ancient theatres related to acoustic and lighting requirements: Stage design guidelines for the Greek theatre of Syracuse. *Energy and Buildings* 95, 106-115 (2015).

[33] L. Tronchin; F. Merli; M. Manfren, On the acoustics of the Teatro 1763 in Bologna. *Applied Acoustics* 172, 107598 (2021).

[31] L. Tronchin; F. Merli; M. Manfren; B. Nastasi, The sound diffusion in Italian Opera Houses: Some examples. *Building Acoustics* 27(4), 333–355 (2020).

[34] G. Ciaburro; G. Iannace; I. Lombardi; A. Trematerra. Acoustic Design of Ancient Buildings: The Odea of Pompeii and Posillipo. Buildings 10, 224 (2020). https://doi.org/10.3390/buildings10120224

[35] G. Iannace; A. Trematerra, The audience effect on the acoustics of ancient theatres in modern use. In Proc. of 142nd *Audio Engineering Society International Convention* 2017, AES 2017.