

Minimization of environmental acoustic effects: an intangible design element of Greek theatres

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Abstract – This study aims at unveiling intangible design principles that may have directed positioning and construction of the classic Greek theatres, whose exceptional acoustic quality is still recognized nowadays. The attention is focused on the possible general design solutions adopted by Greek builders to minimize the acoustic background noise generated by the interaction between the theatre structure and the environment. For this task, a simplified vibroacoustic metrological model has been developed to infer the effects of the interaction between local environmental factors (e.g. the orography) and ancient Greek theatre structures. The model has been used to characterize the Greek theatre of Taormina to show, on a metrological basis, the key intangible elements that could have directed its design and construction.

I. INTRODUCTION

Greek theatres have always aroused great wonder for the quality of their acoustics, since, despite the high number of spectators (> 10,000 in the case of Epidaurus theatre), it is possible to hear the performances held in the center of the orchestra very clearly [1,2]. Many studies tried to motivate the combination of performance practices with acoustics functionality, going into very deep details, like the measurement of local diffractive acoustic phenomena, such as theatres step edges sound diffraction and diffusion [3]. Nevertheless, these studies are based on advanced measurement techniques and models but provide only technical characterizations of Greek theatres acoustic functionality, often leaving completely uninvestigated the reasons behind a theatre construction.

The lack such typology of knowledge becomes evident when trying to build an up-to-date understanding of a heritage asset coherent with the present cultural heritage vision of a monument, since it requires the integration of material and intangible aspects within the framework of a multidisciplinary cultural, structural and environmental context [4,5].

The present hyper-specialized fragmentation of disciplines in studying monuments provides effective technical support to evaluate their material properties but does not allow the development of a multi-disciplinary interpretation that synergically integrates the present historical evolutionary vision within the framework of its

contemporary culture, know-how and practices. A typical example is the acoustic characterization of a Greek theatre within the audio band only (20 Hz - 20 kHz). This band-limited analysis, in fact, may introduce strong limitations to the understanding of Greek knowledge of acoustics applied to architecture, since it is well known that the body perception of “*sound*” goes beyond the human ear sensitivity, synthesis of the more general human body interaction with the environment [6,7].

This change of perspective may produce very interesting results but requires abandoning the old concept of physical metrology as a mere set of technical solutions, extending metrology to production and validation of innovative historical and archaeological hypotheses. In the case of Greek theatres, it requires studying and interpreting the historical-evolutionary vision related to their design, although specialized to different local environmental and social contexts (*genius loci*).

A direct consequence of this innovative approach is that the role of metrology is no more limited to the functional characterization of ancient Greek theatres, but it is extended to help in providing hints and demonstrations useful to understand the intangible reasons of their structural design.



Fig. 1. Picture of the Epidaurus Theatre, Greece (source: Google Earth)

A metrological vibroacoustic study complementary to the classic archaeological-documentary vision may add

new elements in understanding the intangible rules underlying the Greek theatres design, overcoming the pure technical and structural methods of analysis, aligned with the classical concept of *techné* (ἡ τέχνη) as a combination of both intellectual and manual skills.

This innovative metrological approach is applied to the ancient Greek theatre of Taormina (Sicily region, Italy), providing, for the first time, an interpretation of the observed functional implication of its design only on the basis of a metrological model of its acoustic-environmental interaction, implemented on geometrical physics features coherent with the culture of the time. This approach allows us to highlight the key elements that, based on experiential know-how, directed both its design and construction methods. The adopted case study, despite its specificity, represents the application of a methodological vision, which is perfectly applicable to all the other ancient Greek theatres.

II. THE GEOMETRICAL PHYSICS MODEL

The method implements a geometric physical model, that, even if simplified, appears suitable to unveil some of the intangible elements, that are at the base of the uncoupling of the acoustics of the theatre from the environment and the spectators' acoustic forcing.

A. Geometric structure of a Greek theatre

There are several applications of the ancient Greek concept of *techné* as practical knowledge, witnessed through different heritage objects and practices, as demonstrated in other works [8]. One of the strong elements on which Greeks relied was geometry, as a metrological approach to the characterization of nature such as acoustics and optics, that were already mastered in Greek culture and still represent key elements of the modern scientific culture. This is why, prior to consider the vibroacoustic implications, this study started from a qualitative-quantitative analysis of the visible geometric elements, synthesized by geometric shapes and of the similarity among Greek theatre structures build in different places.

The first evidence is that all classic Greek theatres have a very similar geometry (Fig. 2), consisting of an almost circular *cavea*, generally but not always positioned on the sides of hills, necessary to support the weight of the stands, avoiding very demanding constructions, making the most of the orographic characteristics of the place. In terms of simple geometric structure, a Greek theatre can be globally synthesized as an inverted (hollow) conical-truncal geometric air container (structure), with the widest base facing upwards.

Physically, the theatre shape acts as an air “*container*”, made of a series of virtual air cylinders, whose number is equal to the seat rings number, positioned one above the other, each one geometrically characterized by equal height (seat height), but with a radius discontinuously increasing upwards (at each seat level) of a quantity equal

to the seat width. The contiguous virtual cylindrical air layers contained within the theatre freely interact with each other, the highest with the surrounding air environment of the upper part (highest ring), the lowest with ground (lowest ring).



Fig. 2. Typical structure of a Greek theatre based on Dionysus theatre (Athens, Greece)

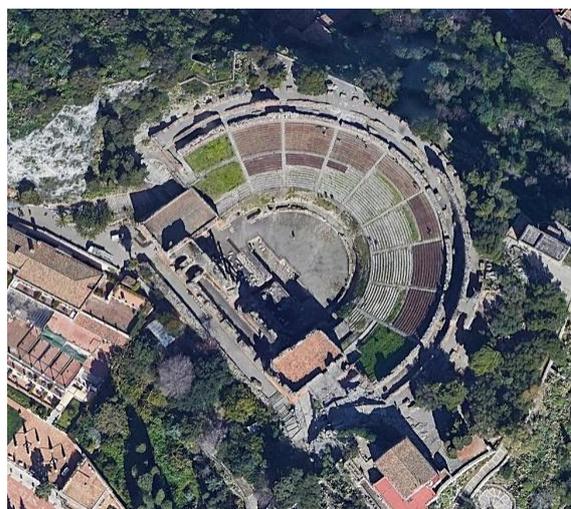


Fig. 3. Picture of the Greek Theatre of Taormina (source: Google Earth).

The theatre has a truncated cone structure (Fig. 4, yellow), sectioned frontally to produce a half-cone structure if seen in its vertical plane projection. The theatrical performances were always oriented towards the built semi-space, toward the truncated cone structure. The unbuilt side is closed by a proscenium, geometrically interpretable as a plane, that separates the inner acoustic area of the *cavea* from the external environment. This is technically coherent with Greek theatrical representation typology, always oriented in the direction of a semi-space.

Nevertheless, albeit very roughly, the proscenium can be considered as a symmetric plane in geometric architecture, relevant for its internal acoustic function as air space delimitation, screen against external environmental pressure forcing.

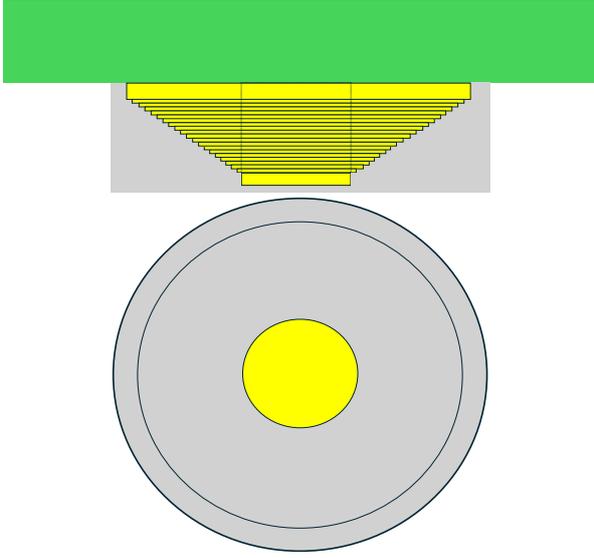


Fig. 4 Geometric vibracoustic model of an ancient Greek theatre.

B. The theatre as an acoustic resonator

The theatre structure, whose geometric simplified representation is shown in Fig.4, can be considered as an acoustic resonator, whose acoustic modes are identical to the ones of a hypothetical full un-sectioned structure. Its acoustic behavior in terms of modes has a perfect counterpart in optics (with optical modes) with a Fabry-Perot cavity made of circular mirrors, with one of the circular mirrors replaced by a plane positioned in the cavity plane of symmetry [9]. This hypothesis allows easy solutions of the acoustic wave equation for the determination of the acoustic modes of the theatre resonance “cavity” applied to a multiple cylindrical superimposed geometry.

Despite the approximate evaluation of acoustic resonance modes, this model surely allows us to get information about the frequency band involved by the lower acoustic modes based on a well-assessed metrological model. These modes are the relevant ones in relation to environmental forcing factors.

Considering the orchestra as the base of a virtual cylinder closed in the lower part (ground) and opened in the upper part (tangential to free air layer) (Fig. 4, green rectangle), whose height is equal to the depth of the theatre itself, then the classical solution of the acoustic wave equations in cylindrical coordinates for a cylinder opened on one side (virtual cylinder) leads to the definition of its internal resonance frequencies, f_{jmq} , synthesized by the relation

$$f_{jmq} = \frac{v_s}{2\pi} \sqrt{\left(\frac{\alpha_{jmq}}{R}\right)^2 + \left(\frac{q\pi}{AL}\right)^2} \quad (1)$$

where v_s is the speed of sound in air, R and L are the radius and length of the cylinder, j , m and q are the indices (non-negative integers) that refer to the eigenvalues of the radial, azimuthal and longitudinal modes respectively and where α_{jmq} is the j -th zero of the derivative of the m -th Bessel function. The most important modes for the acoustic quality of the theatre are the radial ones (α_{j00}), that are the modes “directed” towards the spectators, whose frequency values do not depend on the height of the air cylinder, while the highest radial resonance frequency is relative to the inner air cylinder, characterized by the lowest radius. It is just worth underlining that the higher acoustic modes have less relevance in the formation of an acoustic background noise within the theatre since, as typically happens in resonators, they exhibit lower amplitudes and much higher dispersion coefficients than the fundamental mode, as it will be also clear in the following.

Reiterating that the simplified geometric acoustic model presented is based on hypotheses aimed at keeping on one hand adherence to experimental reality, on the other one a simplified geometric representation aimed at a geometric understanding of the problems of the acoustic interaction between theatre and environment, it is evident that the acoustic coupling of the theatre with the outside can only occur through the upper layer (last cylinder of air).

What is, instead, a very relevant feature that can be derived from the model is that the lowest frequency acoustic mode, evaluated using typical data for a subset of Greek theatres, is always below the limit of the audible acoustic band (20 Hz). Hence, the quality of the acoustics within the theatre mainly appears to depend only on the environmental forcing.

Therefore, the positioning of the theatre must satisfy a very important (intangible) construction criterion: to avoid external pressure forces (winds), which could act inside the space delimited by the *cavea* and by the stage. From a purely physical point of view, this can be obtained only for tangent pressure forces (parallel to the ground), limiting the coupling to the sole effects of internal friction between the horizontal surfaces of the layers, as described in the model of the theatre, and to the surrounding environment. Therefore, the knowledge of the orography of the place in connection with direction and speed of the main local winds becomes a fundamental parameter in the design of a Greek theatre in view of minimizing their interaction, and, consequently, the background acoustic noise.

III. THE GREEK THEATRE OF TAORMINA

A. The theatre geometry

The theatre of Taormina is the second in Sicily, after that of Syracuse, in terms of size. Its geometry follows the classic geometries of a Greek theatre: it was dug into the rock and located on a slope. A semicircular space (*kōilon*) was occupied by the spectators, while in the centre there is

the orchestra, the place of the chorus, and on the opposite side of it the skenè, or stage building, the place where the actors changed. The orchestra is accessed through two uncovered entrances, the pàrodoi, which separate the stage building from the cavea. In front of the skenè, there is the proskènion, or the stage where the actors performed. At the top of the steps there is a double portico, covered by a vault. Thirty-six small niches are open onto the wall of the portico, perhaps used to house some statues. Originally there was only a small central construction, expanded in the first half of the 2nd century AD to 109 meters in diameter, with an orchestra with a diameter of 35 meters. The cavea is divided into nine sectors by eight staircases and has a double gallery, with an arched portico and an internal granite colonnade and a depth of about 20 m. The theatre has undergone several restorations over the centuries, particularly in the 19th century, when the columns on the stage were repositioned.

B. The theatre acoustic modes

We evaluated the frequencies of the inner and outer cylinders using the dimensions of the main geometric elements of the Taormina Theatre, demonstrating that the main modes are well within the infrasound band. The results of the main acoustic modes are shown in Table 1, assuming a sound speed equal to $v_s = 333 \text{ m/s}$.

Table 1. Lowest Resonance Acoustic Modes of the Taormina Theatre.

R = 17.50 m	f_{100min} 11.95 Hz	f_{010min} 5.75 Hz	f_{001min} 8.57 Hz
	f_{200min} 21.88 Hz	f_{020min} 9.53 Hz	f_{002min} 17.15 Hz
R = 54.50 m	f_{100min} 3.84 Hz	f_{010min} 1.84 Hz	f_{001min} 8.57 Hz
	f_{200min} 7.03 Hz	f_{020min} 3.06 Hz	f_{002min} 17.15 Hz

Due to the shape of the cavea and to the contiguity of the cylindrical air layers, the effective acoustic resonance frequencies can be much better represented by a continuum, even if the variations in radius are discrete, being discrete the radius increase from one ring to another. Nevertheless, it is also indisputable, due to the contiguity and the thickness of the layers and the energy dissipation to the air damp, that the attenuation coefficient of the higher modes is very high.

C. The orographic position of the theatre and the wind directions

Based on the obtained results, the quality of the acoustics within an ancient Greek theatre appears to largely depend on the capacity of uncoupling the low frequency acoustic modes of the theatre from the low frequency environmental forcing (winds). Hence, the positioning of the theatre becomes very relevant and a very important

intangible criterion: to avoid the interaction of external pressure forces inside the space delimited by the cavea and the stage. From a purely physical point of view, this effect is minimum when forcing is low (low intensity wind) and/or when the forcing direction is parallel to the ground plane, since external coupling may happen only by friction between the horizontal layers delimiting the theatre and the surrounding environment itself.

Therefore, the design of a Greek theatre required an effective knowledge of the orography of the place, but, above all, the knowledge of main winds directions and speeds, which, as we will see later in the case of the theatre of Taormina, could generate important couplings.



Fig. 5. Panoramic view of the Taormina Theatre. Note the position of the theatre, built-in the mountain to minimize the forcing effect of winds (source: Google Earth).

An altitude analysis of the theatre's position shows in a direct way that the Taormina Theatre North-West side is protected by a mountain higher than the theatre, the South-West side is protected by the proscenium, while the remaining sides are protected by the upper theatre ring wall and by trees (Fig.5).

D. The mean wind directions and intensities

The demonstration of this intangible hypothesis, that is the position and the orientation of the Taormina Theatre are functional to the minimization of the environmental forcing, requires the knowledge of the local main and prevailing periodic winds related to the orography of the place.

Fig. 6 shows both the position of the theatre (left) and the statistics of wind direction and intensity of a year period in Taormina (right). Although limited in time and not referred to the temple construction period, the diagram shows that globally the theatre appears to be well oriented. This approximation is deemed to be acceptable by the literature [10]. In fact, the North-West side of the theatre, affected by the strongest winds throughout the year, is protected by the mountains, the South-East side is protected by the upper circle of the theatre walls, the other

two sides, characterized by small winds, are protected by the proscenium and by the wall and the wood behind the rear side.

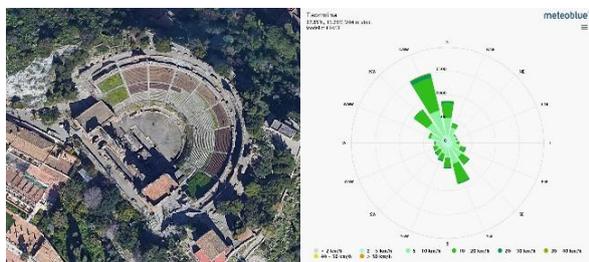


Fig. 6. (a) Position of the Theatre of Taormina (source Google Earth); (b) statistics of wind direction and intensity of a year period in Taormina (right). The wind rose was retrieved from the web page <https://www.meteoblue.com> under Creative Commons license (BY-NC) [accessed on: 27 Apr 2025].

For completeness, Fig. 7 shows the superposition of the wind rose statistics and the picture of the Taormina theatre.

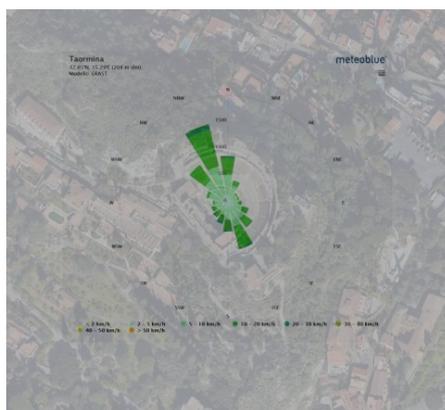


Fig. 7. Superposition of the wind rose statistics and the picture of the Taormina Theatre with superimposed the statistics of wind direction and intensity of a year period in Taormina. The wind rose was retrieved from the web page <https://www.meteoblue.com> under Creative Commons license (BY-NC) [accessed on: 27 Apr 2025].

IV. CONCLUSIONS

This study demonstrated the Greeks followed intangible rules to minimize the effects of environmental forcing elements to protect their construction and get the maximum acoustic performances.

This is the case of ancient Greek theatres, that although built in open space, appear to have an unsurpassed acoustic quality. A study with a simple vibroacoustic model shows that in the case of ancient Greek theatres their design is characterized by a relevant intangible component, that is

the minimization of the acoustic environmental infrasound forcing. In fact, the minimization of the background acoustic noise coupled with the absence of internal echo due to the large attenuation of the acoustic modes in the audio band, renders the Greek theatres an example of high-quality acoustic design.

This hypothesis has been demonstrated for the Greek theatre of Taormina, whose position and orientation has been explained according to the model, metrological demonstration of such a relevant intangible rule.

REFERENCES

- [1] Barkas, N., “The Contribution of the Stage Design to the Acoustics of Ancient Greek Theatres,” *Acoustics*, Vol. 1, No. 1, 2019, pp. 337–353. <https://doi.org/10.3390/acoustics1010018>
- [2] Chourmouziadou, K., and Kang, J., “Acoustic Evolution of Ancient Greek and Roman Theatres,” *Applied Acoustics*, Vol. 69, No. 6, 2008, pp. 514–529. <https://doi.org/10.1016/j.apacoust.2006.12.009>
- [3] Chourmouziadou, K., and Kang, J., “Simulation of Surface Diffusion and Diffraction in Open-Air Theatres,” *Institute of Acoustics - 6th International Conference on Auditorium Acoustics 2006*, 2006, pp. 97–108.
- [4] United Nations Educational, Scientific and Cultural Organization (UNESCO), “Basic Texts of the 2003 Convention for the Safeguarding of the Intangible Cultural Heritage,” 2022. Retrieved 9 January 2022. https://ich.unesco.org/doc/src/2003_Convention_Basic_Texts-_2022_version-EN_.pdf
- [5] Barone, F., Casazza, M., and Romano, R., “Vibroacoustic Heritage Monitoring with a Standalone System,” *Acta IMEKO*, Vol. 12, No. 3, 2023, pp. 1–6. <https://doi.org/10.21014/actaimeko.v12i3.1472>
- [6] Barone, F., Casazza, M., and Romano, R., “Standalone Detector for Vibroacoustic Heritage Monitoring,” presented at the 2022 IMEKO TC4 International Conference on Metrology for Archaeology and Cultural Heritage, Consenza, ITALY, 2023. <https://doi.org/10.21014/tc4-ARC-2022.041>
- [7] Ozga, A., “Scientific Ideas Included in the Concepts of Bioacoustics, Acoustic Ecology, Ecoacoustics, Soundscape Ecology, and Vibroacoustics,” *Archives of Acoustics*, Vol. 42, No. 3, 2017, pp. 415–421. <https://doi.org/10.1515/aoa-2017-0043>
- [8] Yin, D., “Was Plato Against Art?: Plato’s Concept of Technē (Art) and the Pre-Socratic Philosophical Term of Phusis (Nature); [柏拉图反对艺术 (Art) 吗? ——柏拉图的技艺 (technē) 思想和古希腊的自然 (phusis)],” *Theoretical Studies in Literature and Art*, East China Normal University Press, 38, 6, 2018, pp. 175–184.
- [9] Chen, Y., Tang, Y., Liu, X., Zhong, C., Liang, Y., and

Wu, Y., “Liquid-Level Measurement Using a Fabry–Perot Interferometer With a Transfer Mechanism,” *IEEE Sensors Journal*, Vol. 25, No. 9, 2025, pp. 15071–15079.
<https://doi.org/10.1109/JSEN.2025.3550496>

[10] Murray, W. M., “Do Modern Winds Equal Ancient Winds?”, *Mediterranean Historical Review*, Vol. 2, No. 2, 1987, pp. 139–167.
<https://doi.org/10.1080/09518968708569525>