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COMPUTATIONAL DESIGN: ACOUSTIC SHELLS FOR ANCIENT THEATRES

Giovanni Augusto Bouvet[1] Louena Shtrepi[1] Elena Bo[1]
Tomás Méndez Echenagucia[2] Arianna Astolfi[1]
[1] DENERG - Department of Energy, Politecnico di Torino, Italy
[2] Department of Architecture - College of Built Environments, University of Washington, USA
giovanni.bouvet@gmail.com

ABSTRACT

After more than 2000 years since their construction, classical theatres still fulfil the purpose they were designed for. Unfortunately, their acoustics are often not optimal today, and that is the reason why modern performances mostly rely on electro-acoustic amplification systems. The aim of this work was to improve the acoustics of ancient theatres through the use of lightweight removable shells.

All the studies were carried out through optimizations in the Grasshopper 3D environment. To this aim, it was necessary to implement a suitable simulation model. Since the acoustics in open-air theatres differ both from free field and diffuse field in closed rooms a simple ISM (Image-Source Method) algorithm, partially based on François Canac's studies, has been developed. An evolutionary solver, Galapagos, has been deployed for the computational morphogenesis and optimisation of the acoustic shells.

The theatre of Tindari (Italy) was analysed, the optimisation criterion being the maximisation of listening positions receiving sufficient sound energy, i.e. sound pressure levels. The results highlighted that the model could be a fast and efficient help in early design stages, leaving space for further improvements.

1. INTRODUCTION

The modern use of ancient theatres as places of performance could help to maintain their role of cultural sites, as well as get funding for meeting the cost of maintenance and restoration [1-3]. Although there is still no certainty about how theatres sounded in ancient times, we know that their acoustics is often inadequate nowadays: their original structures have suffered deterioration, and the environment around them is far louder in these days than what it used to be in the ancient times.

UNESCO promoted several international norms and charters with the objective of developing a common model, where both conservation and modern usage could coexist. Among them, the Syracuse Charter [4] focuses its attention on the sustainable use of the theatres. Interestingly, it also gives recommendations about the acoustics, asserting that temporary structures can integrate the gaps in order to optimise the acoustic performance. This provided the inspiration for this work, trying to design lightweight removable acoustic shells for modern performance.

The first issue that came up was how to approach the research: the acoustical simulation of performance spaces is conventionally based on the application of indoor measuring standards [5]. However, studies [6-7] have shown that these do not correctly apply on large unroofed theatres, where the sound field is not diffuse, but it is more a result of the superimposition of the contribution of the direct sound and a few early reflections [8].

In a twenty-years-long research on Greek and Roman theatres, François Canac [9] defined the geometric functions that characterise the acoustic behaviour of their elements. His conclusions helped in structuring this research.

A 3D simulation was developed in order to simulate sound propagation in open theatres, and an acoustics shell was modeled and optimized by a form-finding genetic algorithm, a technique that has already proven effective in similar cases [10]. The theatre of Tindari (Italy) has been considered as a case study.

2. METHODS

The work can be divided into two phases. First, a simple Image-Source Method (ISM) algorithm has been developed in the Grasshopper 3D environment, in order to study different conditions in a generic theatre.

Secondly, the work consisted in the computational morphogenesis and optimisation of an acoustic shell, choosing the theatre of Tindari in Italy (see Fig.1) as a case study. The theatre, first built in the IV century B.C., has been extensively restructured over the years.

Figure 1. Theatre of Tindari.

A significant aspect of the research of Canac, which laid the basis of this work, was the opportunity to represent the geometry of the theatre in a simplified way: his theatres were analysed in their 2D sections, which included a straight scene wall, a raised stage, a plain orchestra and a cavea made of one or more sloping sections. The reflections of the individual elements were considered separately, and observations were made about their relationship using a geometric approach (see Fig. 2).

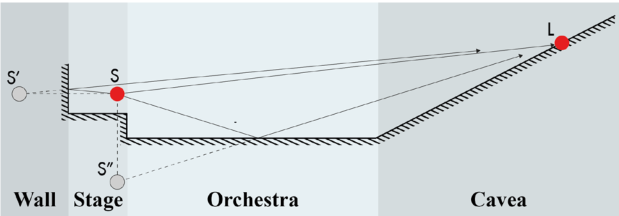

Figure 2. Canac's model.

It was possible to implement this schematization, in order to build a 3D model, and evaluate the energy contributions of the sound rays.

2.1 Implementation of a generic model

Canac's research consisted on on-site surveys and the study of scale models, with the aim to understand universal acoustic properties of many theatres. In the same way, in the preliminary stage, the objective of this work was the implementation of a generic model capable to cope with differently sized theatres.

All the work took place in Grasshopper 3D, a visual programming environment that runs within the Rhinoceros 3D application and operates real-time processing of data, enabling a quick feedback of the results.

A 3D model was implemented in order to react to the variation of several geometric parameters, which included the aspects needed to define the dimensions of the theatre: the height, slope and radius of the cavea and any diazoma, the length of the orchestra. All these parameters could be manually changed or stored in external dictionaries and automatically recalled.

Other parameters defined the height and width of the stage and the position of the sound source, able to move freely on the stage at a height of 1.6 m. In the first phase, a flat scene wall was considered.

Finally, other parameters defined the number and location of the listeners, evenly distributed on the seating sections.

Regarding to the theatre of Tindari, its dimensions were considered in the following way: the orchestra was modelled as a circle 25.5 m in diameter, half surrounded by the cavea, which presented an initial stepped section (two steps, with a total height of 2.3 m) followed by a sloping section with a height of 10.15 m and an angle of 27°.

Given the source and listener positions, the model draws direct and reflected sound rays, calculating their path lengths. First-order specular reflections were generated from three different surfaces: the stage floor, the orchestra and the scene wall. All of them were obtained through the image-source technique.

After a visibility check (i.e., in the model represented in Fig. 2 the stage reflection is missing), each wave should comply with specific conditions in order to be counted: its grazing angle must be larger than 4°, each reflected wave must arrive to the listener in a given time (50 ms for speech, 80 ms for music). The first condition takes into account all the sound rays absorbed by the crowd surrounding the listener, while the second one was a choice made in order to exclude late reflections, which could adversely affect the sound quality. Filters removed from the calculation all the rays that did not meet these constraints.

Contribution for each ray to the sound pressure level (L_p) was calculated using the formula:

$$L_p = L_W - 11 - 20\,log(r) + 10log\,(1-\alpha) + ID_\theta \quad (1)$$

and:

L_w has been set to a value of 80 dB(A) and 95 dB(A) for speech and music, respectively.

r is the path length of the sound ray, measured from the listener to the source (for direct waves) or to the reflected image-source (for reflections).

The sound absorption coefficient α has been set to 0.05 considering the single stone material of all surfaces [11]. It is important to notice that in equation (1) the term $10\,Log\,(1-\alpha)$ is not considered in the case of contribution of direct sound.

As Canac noticed, it is particularly important to keep the orchestra surface clear, i.e. with no obstacles, as its reflection strongly helps to strengthen the sound.

The source directivity index ID_θ has been set taking into account two different conditions: an omnidirectional source for music (e.g. resembling a small ensemble), a directive source for speech. In the latter case, contributions were calculated through the intersections of the sound rays with 3D speech balloons, which were modelled according to recent studies [12].

It was then possible to define the $L_{p,Tot}$ (dBA) received in each listening position, through the logarithmic sum of direct and reflected contributions, with the equation:

$$L_{p,Tot} = 10Log\left(10^{\sum_i \frac{L_{pi}}{10}}\right) \quad (2)$$

2.2 The role of the stage

Before starting the design phase, some questions arose regarding the ideal position of the stage and the effects of a raised stage floor.

All the combinations of height and distance of the stage in a certain range have been evaluated given a step of 0.5 m. These have been combined to other variables regarding the source directivity (an omnidirectional or directive source) and the source location (a central or lateral source location) (see Fig. 3).

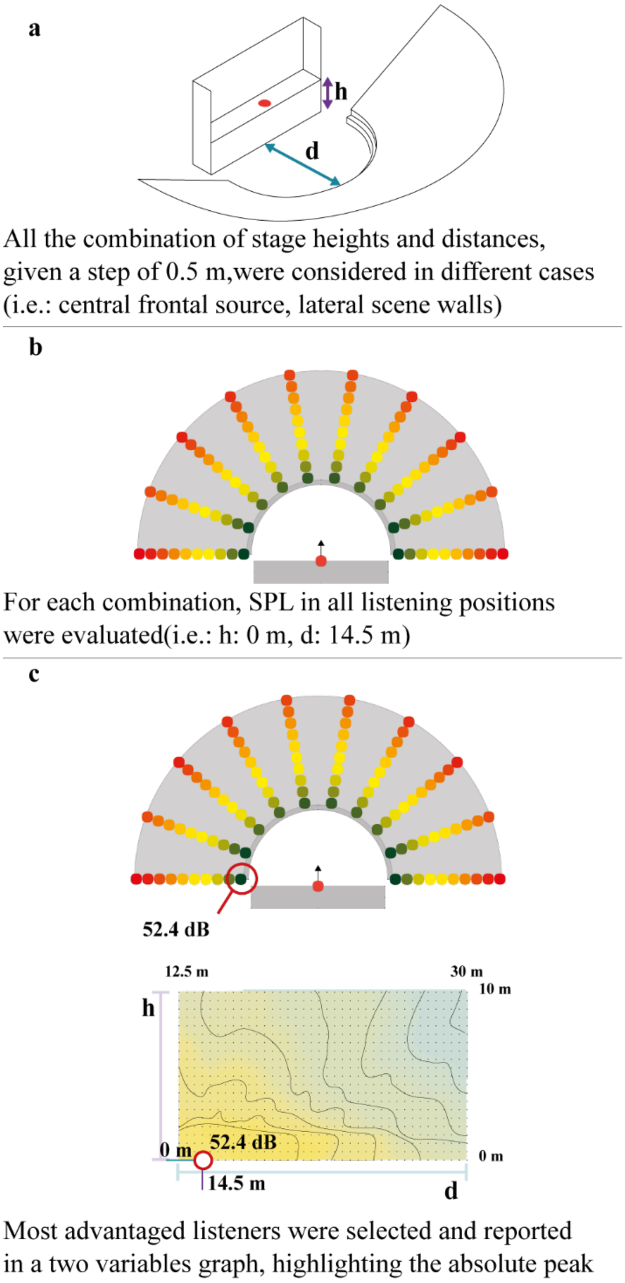

Figure 3. The analysis of the combinations of stage height and distance.

The results of this phase showed that the best performance is obtained with a ground level stage, the source being in the centre of the orchestra. Because of this, it was possible to simplify the model for the subsequent analyses: the stage building was removed, the source being placed directly on the orchestra floor. Consequently, it was not necessary anymore to take into account the stage and the orchestra reflections as separate contributions, only two first-order reflections types were considered in the study: the shell and the orchestra floor reflections.

2.3 Morphogenesis and optimisation

Subsequently, it was possible to begin the shell design for the Theatre of Tindari. The shell was defined as an extrusion of a freeform profile curve along a freeform curve path, firstly discretized into a matrix of 3x3 panels. MDF was chosen as a material, because of its low sound absorption coefficient ($\alpha_{500\text{-}1000Hz}$=0.05).

The model was further improved, in order to consider the reflections of each panel. In the previous studies, each listener could receive one reflection at best from each of the reflecting surfaces considered (scene wall, orchestra, stage). In contrast, the shell could direct several reflections to a single position, it was necessary to rearrange the data structure in order to assign each ray to the correct listener, keeping the possibility to change the number of panels or listening positions at a later phase.

Galapagos [13], an evolutionary solver included as a plug-in in Grasshopper, has been deployed for the generation of the acoustic shell. Many tests were conducted in order to be able to find the correct optimization criterion. The best results were obtained by considering the maximisation of the number of listening positions receiving a sufficient useful sound level, considered to be at least 10 dB higher than the measured background noise level, i.e. 34 dB(A).

Lastly, another evolutionary search process was conducted, in order to find the best configuration of the shell, which resulted in a matrix of 6x3 panels (see Fig. 4).

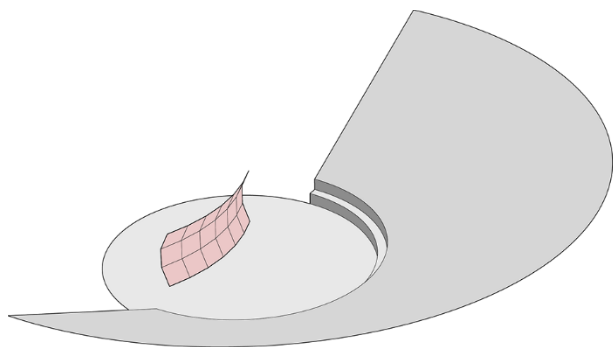

Figure 4. The resulting optimal configuration of the acoustic shell in the case of Tindari theatre.

2.4 Comparing simulations with source variables

The source considered had L_W=80 dB(A), it was oriented in a frontal direction using a speech directivity balloon and was placed 1.6 m high above the orchestra level, with an offset of 1 m on the right of the symmetry axis of the theatre in order to avoid focalisations. A polar array of 100 listeners was considered over the completely absorbing ($\alpha = 1$) cavea.

Three conditions were considered:

a – Current state: a sound absorption coefficient: $\alpha = 0.5$ was assigned to the orchestra [11].

b – Reflective orchestra: a reflective stage floor with a sound absorption coefficient of $\alpha = 0.05$ was assigned to the orchestra surface.

c – Reflective orchestra + shell (Fig. 4): the sound shell obtained from the previous analyses was added on the reflective orchestra.

3. RESULTS AND DISCUSSION

The results of the three conditions were compared, as it can be seen in Fig. 5, which shows the results found for a vocal source:

a – Current state: it showed that the higher rows could not receive an acceptable sound level, with a 29% unsatisfaction rating.

b – Reflective orchestra condition: it showed that the overall performance greatly improved, with an 89% satisfaction rating. Still, some of the highest and more lateral rows could not get enough sound energy to be included in the satisfied group.

c – Reflective orchestra + shell condition: it showed that the shell contribution managed to improve the sound levels for the most disadvantaged listeners, raising satisfaction rating to 96%.

The resulting shell, with its toroidal section shape, has proved able to enhance the sound levels, especially in the highest and most lateral positions,

It is interesting to consider the effect of the source offset with respect to the symmetry axis of the theatre: Fig.5 shows how in case a and b this results in higher sound levels in the nearest side listening positions, as distance remains the most important factor in their calculation.

In case c, on the contrary, best side positions are the most distant, which can take advantage from the geometry of the shell, as a larger number of reflections is concentrated on them. The results are reported in Tab. 1.

	a	b	c
Near side	74%	92 %	92%
Far side	68 %	86 %	100%

Table 1. Satisfaction rating (SPL received > 44 dBA) among listeners in two sides, as an effect of the source asymmetry (offset = 1m)

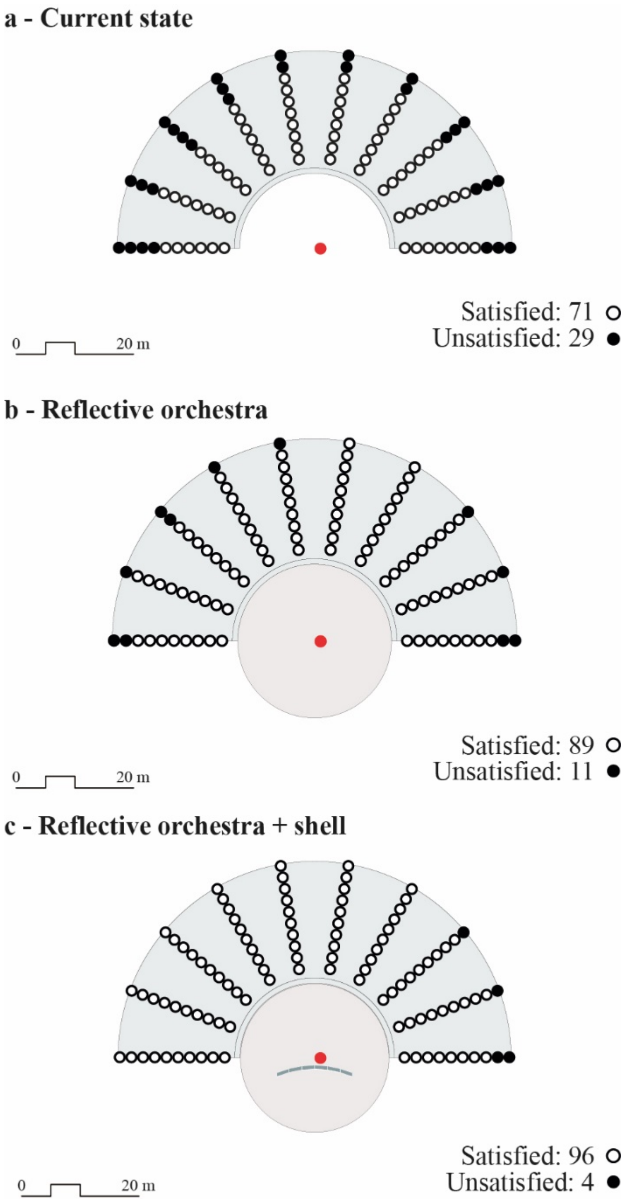

Figure 5. Satisfied listeners for speech source in three different conditions.

4. CONCLUSIONS

The aim of this work was to improve the acoustics of ancient theatres by using lightweight removable shells. The study combined parametric models, implemented in the Grasshopper 3D environment, with geometrical acoustic simulations in order to optimise the acoustic shell geometry. The geometrical studies of François Canac have been carefully developed over a 3D perspective and used in the case study of the theatre of Tindari (Italy). Only one objective acoustic parameter has been considered as an optimization objective, i.e. the number of satisfied listeners based on the maximisation of the sound pressure level at each receiver position.

The results of this work highlight that a simplified model can give good results and be a fast and efficient help in the early design stages. A toroidal-shaped shell has been shown to improve significantly the most critical listening positions, since it can direct favourable reflections on the most disadvantaged listeners.

Further investigations could be performed in other sites to test the acoustic efficacy of the shell designed here. Moreover, in-situ measurements might be of great importance to take into account also the real conditions of the sites in terms of their geometry and materials.

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