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On the Use of Ancient Open-Air Theatres for Modern Unamplified Performances: A Scale Model Approach

Nicola Prodi, Andrea Farnetani, Patrizio Fausti, Roberto Pompoli
Department of Engineering, University of Ferrara, Italy. nicola.prodi@unife.it

Summary
Ancient theatres are widely used today for modern performances including drama, music and ballets. Despite the state of conservation of the stage, the scenery is often designed with little care about its acoustical efficiency. To clarify the acoustical impact of these elements in ancient theatres, different stage settings were investigated by means of scale model measurements. The scale model is a 1:20 scale reproduction of the ancient theatre of Siracusa (Italy). It is conceived as modular structure so that different configurations of the cavea and of the stage can be reproduced. To investigate the stage-set effects, different groups of reflecting panels were arranged on the platform and an orchestra shell was tested too. The interplay of stage and theatre architecture was outlined by a systematic set of acoustical measurements.

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1. Introduction

In the years 2000 there has been a flourishing of studies and projects concerning the acoustics of western ancient theatres, and especially those in the Mediterranean basin. In particular the EU project ERATO [1] and the Italian project ATLAS [2] focused on these spaces of performance. Studies were devoted to better know how they sound, to auralize them under several configurations documented by archaeological evidences and to clarify their acoustical evolution during the course of history. One of the main outputs was a clear view of the interplay of acoustics and architecture in open-air theatres from the essential design of early Greek theatres to the more sophisticated Roman ones [3, 4, 5]. It was found by the present authors that typical acoustical conditions can be expected in accordance with a specific theatre layout. In particular Table I (taken from [5]) tells us that reverberation time, clarity for speech and strength relative to the direct sound can be grouped with sufficient precision according to peculiar architectural elements present in a given theatre, whose impact on the acoustics was thus isolated.

These findings were based on the joint analysis of in situ measurements in the remains of ancient theatres still in use and of scale model measurements performed on the 1:20 model of the theatre of Siracusa, south Italy. In fact this space is optimally documented from the archaeological point of view [6] and was quite fit to be used as a prototype of the evolution of acoustics across centuries. It is to be noted that the results obtained by both in situ and scale models measurements were generally consistent with the knowledge accumulated by systematic computer modelling of such spaces [7]. Furthermore it was documented how the tiers of steps make up a large part of the reverberant tail and thus the importance of steps geometry in the theatre acoustics was outlined [8]. Indeed some authors stated that the most intriguing acoustical effects experienced in the ancient open theatres can be traced back to the diffraction of sound on the steps, which acts as an amplification for relevant speech-related frequencies and attenuates the noise background [9, 10].

Notwithstanding the recent advances, other issues are to be tackled related to the ancient theatres. Two of the most prominent are the accurate numerical modelling of the wave field in the *cavea* (that is the main seating area) and, from an operational point of view, the optimization of the theatre space for modern performances. In fact ancient theatres are widely used today as concert halls, drama theatres and for a number of performances. Apart from the state of conservation and the layout of the theatre, the modern stage setting is designed mainly for scenographical purposes, disregarding its acoustical efficiency. Moreover, a sound system is often used to assist the performances.

In the current literature general criteria for the modern use are collected in [11] whereas more specific investigations on the effect of some typical drama sceneries and guidelines for the acoustical design are found in [12, 13]. In these latter cited works the sceneries are categorized into four families called “background wall”, “large objects”, “small orchestra objects” and “orchestra floor”. It was found that either a background wall or dense objects in

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Table I. (Taken from [5]). Values of the main acoustical parameters (Mid frequency averages) expected in unoccupied ancient open-air theatres depending on the architecture layout. ΔG_{free} indicates the level increase with respect to the free field decay.

Type	Real	Model	T_{Mid} [s]	$C50_{\text{Mid}}$ [dB]	ΔG_{free} [dB]
Complete Roman	Aspendos	Siracusa Roman and Hellenistic	1.64 ± 0.13	5.4 ± 2.3	5.7 ± 1.0
Roman or Greek w/o gallery and incomplete stage building	Taormina, Jerash	Siracusa Greek	1.13 ± 0.10	6.4 ± 2.0	4.9 ± 1.2
Greek w/o stage building	Delphi, Segesta	Siracusa Greek w/o stage building	0.45 ± 0.12	16.5 ± 2.1	2.9 ± 1.0

the orchestra could improve the acoustics and that a combination of two or more generic scenery categories could also lead to positive and partially additive effects.

This work has the task of tackling the modern use of ancient theatres by providing some evidences for guiding the adaptation of those spaces to unamplified performances. The underlying concept was to introduce least invasive elements such as reflectors in order to enhance the sound perception. To investigate the interaction between the architecture and the stage set a 1:20 scale model of the ancient theatre of Siracusa (Italy) was used. In fact, a scale model can take into account all the wave effects, including comb filtering and scattering from the steps of the cavea, that are not considered by a computer ray tracing model but are fundamental in this type of theatres. This work is a more extended presentation and discussion of the results outlined at the *Acoustics of Ancient Theatres Conference* in Patras, Greece (18–21 September 2011) [14]. Some information on the effect of a sound system on a group of theatre geometries is also summarized in [14].

2. Scale model

The ancient theatre of Siracusa, situated in the south of Italy, is one of the biggest theatres of the "Magna Grecia". The site had undergone major changes during its history and fortunately the excavations made it possible to trace with great detail three different layouts dating from the fifth century B.C. to the second century A.D., that is a Greek (SG), a Hellenistic (SH), and a Roman theatre (SR). The diameter of the *cavea* was 85 m for the SG with a 20° slope of the tiers and a capacity of 5000, and was 143 m for SH and SR with a tier slope increased to 25° for the first group of tiers only, while the capacity was 15000. In order to reproduce the historical configurations described above the scale model was designed as a modular structure obtained by assembling nine slices each covering 20° span in plan. Thanks to the modular design it was possible to add or remove some structural parts such as the tiers of steps, the gallery with columns, the different stage buildings, and it was thus possible to assemble each of the above theatres. Moreover also some hybrid configurations, which have no archaeological evidence, could be assembled to investigate the acoustical contribution of specific architectural elements. A 1:20 scale was chosen as the best possible compromise between the contrasting requirements of the space to settle the model on the one hand, and the measurable frequency range on the other hand.

Basically each 20° slice is subdivided into three main parts: the lower, the middle, and the upper tiers of steps. Additional movable parts were also designed to allow a modification of the *cavea* structure and to introduce the two *diazoma* (upper and lower walkways) added in Hellenistic and Roman theatres, respectively.

3. Tuning the natural acoustics

The scale model was firstly used to define some typical stage sets which may allow to enhance the acoustics of the ancient theatre for the needs of a musical performance or a play. In these cases the basic requirement is not to use a sound system but to make the most of the natural acoustics, and this was investigated in the work with the addition of passive reflective movable devices.

For this purpose a reference set-up of the scale model was fixed presenting the widest *cavea* (diameter 143 m) without any additional element such as the stage building or the gallery in the upper part. This "bare" condition is actually representative of many ancient theatres still in use and is not optimized for the acoustics in a large part of the audience. In particular, as detailed in the following and reported by in situ measurements in Delphi and Segesta (see Table I, last row), in this condition the expected reverberation time is very short, the strength is very low and the clarity is too high.

The target in the choice of the additional elements to put on the stage, was to provide the impulse response with some useful early reflections which could be integrated in the direct sound by Haas effect and hence increase the perceived loudness. On the other hand, also the circulation of the sound energy in the *cavea* should be increased to enhance the perceived reverberance and possibly to control an excess of clarity. In order to cover some typical layouts for music and drama three stage set-ups were defined and are showed in Figure 1. They can be briefly described as follows:

1. *Orchestra shell*: design of an orchestra shell having dimensions 16 m x 7.6 m x 7.4 m consisting of three side walls and a roof and containing diffusive elements. The roof angle can be adjusted to maximize the coverage of the audience.
2. *Trap. Large*: eight reflective screens 2 m large and 3 m high were arranged in a trapezoidal shape.

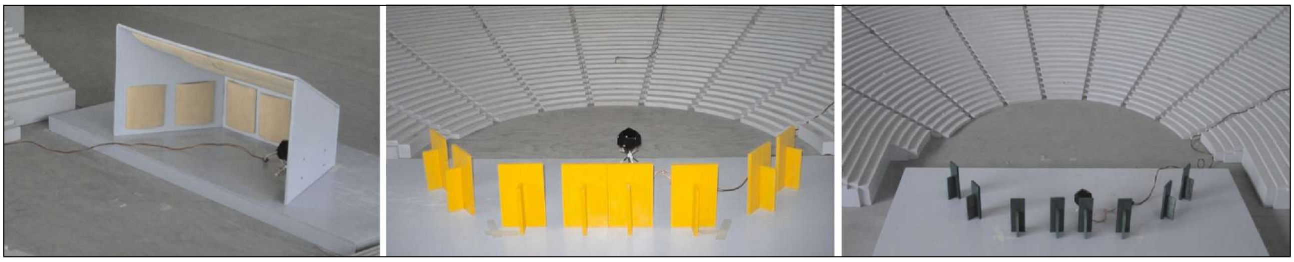

Figure 1. The three configurations of the stage: left, the orchestra shell; center, the large reflectors in trapezoidal plan; right, the small reflectors in the same plan arrangement.

3. *Trap. Small*: following the same plan of the previous configuration, 8 smaller modules 1 m large and 3 m high were used.

Though they are not placed in the orchestra but on the stage, the set-ups 2 and 3 could be categorized as "small objects" as defined in [12] whereas the other three types of scenery in the same computer study could not be considered here. The location of the reflectors followed the consideration that, in case a sufficiently wide stage is available (seldom added by means of a temporary structure), this is the area where the modern performance most commonly takes place.

3.1. Acoustical measurements

To characterize the three stage sets as well as the basic configuration of the theatre in term of acoustical parameters, an extensive set of acoustical measurements was made. The measures were taken with the theatre in the unoccupied condition. The measurement chain was the same as described in [5] and included a miniaturized dodecahedron and a ¼" microphone. This set-up allowed to cover a frequency range up to the 2 kHz octave band in full scale since over this frequency band the air absorption becomes too high to be accounted for effectively.

The placement of the sound source and of the receivers was as far as possible compliance with [15], though this technical reference is conceived for closed spaces. Firstly three positions for the source were selected: two of them were in line 1 m from the symmetry axis (front and rear respectively), and the third position was on the right side to form a triangle with the other two. Then, 11 receivers on the right part of the *cavea* were fixed, which were placed with equal spacing along three radial directions at 30°, 60° and 90° from the right border. To obtain the impulse responses a deconvolution technique was adopted, using exponential swept sine as excitation signal and rescaling the obtained IR in the time domain.

The impulse responses were then processed and the acoustical parameters were calculated. The spatial average of results over all receivers will be shown as a function of frequency from 125 Hz to 2 kHz together with the "Mid" values (arithmetical average of the 500 Hz, 1 kHz and 2 kHz octave bands). The spatial dispersion bars represented by the standard deviations of the measured values are also reported in the figures. Moreover, some results will be presented as a function of source-receiver distance.

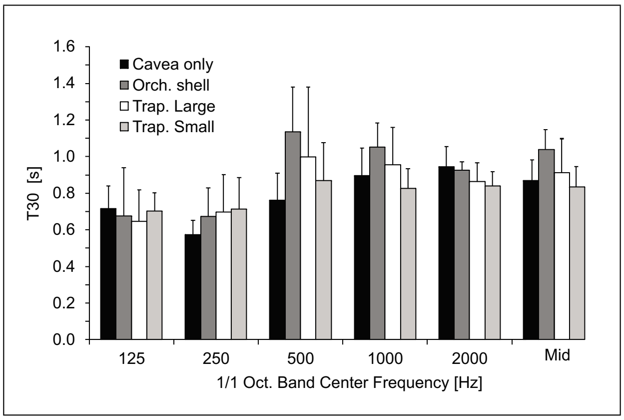

Figure 2. Comparison of reverberation time T30 values for the different stage-sets.

In the following the most significant results will be shown and discussed considering only the source S1 placed at 1 m from the fore stage and 1 m from the symmetry axis of the theatre.

3.1.1. Reverberation

In Figure 2 the reverberation time measured for the different configurations of the stage is shown. The bare configuration (*cavea* only) has a short reverberation, slightly higher at middle frequencies. Firstly it is to be outlined that this condition shows a reverberation higher than SG (having 85 m diameter compared to the present 143 m) and this is due to the increase of the scattered sound field which is most evident in the range of mid frequencies. The introduction of an orchestra shell produces some effects on T30 mostly at 500 Hz (+0.37 s) and 1 kHz (+0.15 s) but very little changes are observed at lower and higher frequencies.

The trapezoidal configurations increase the reverberant tail only at 250 Hz and 500 Hz. At 125 Hz and 2 kHz there is no remarkable difference from the basic condition, whereas at 1 kHz the values are slightly longer (Trap. large) or shorter (Trap. small). Anyway, since the spatial dispersion bars in the plot are quite overlapped, it appears that the differences in the values obtained for the different preparations are hardly distinguished from one another in most of the octave bands. As a consequence the control of reverberation by these simple means is difficult, though some limited improvement can be achieved. Actually a change in the energy circulation should be possible only with a change in the theatre layout, which is realized in the existing theatres when the stage wall is present and effective for this scope. Moreover it can be noted that this limit is more severe for musical performances rather than for drama, since a shorter reverberation can be better tolerated in the latter case.

3.1.2. Strength

This parameter allows a direct comparison of the setups concerning their ability to increase the sound level at the various audience positions. A convenient way to investigate this point is to trace the sound propagation for each set-up. Before presenting the results it is to be recalled that the course of the regression expected for the basic condition is very close to the free field with an increase close to 3 dB [5]. For this reason the data have been normalized in order to fix the value of G_{Mid} at the first location in the bare condition equal to its expected value of −2.9 dB. This location is at 19.73 m from the sound source due to the large orchestra space in between. Figure 3 shows the measured values after normalization: they are referred to as "expected strength" in the mid frequencies (Exp. G_{Mid}) and are thus reported as a function of source-receiver distance. The logarithmic regressions for each of the above set-ups is also included. From an inspection of the figure it can be seen that in most of the audience area the data are negative and this easily explains why G_{Mid} is probably the most critical parameter to deal with, since the competing background noise, even from the audience itself, could make the listening quite effortful.

Moreover in Figure 3 one can see that, in order to increase the parameter, the small panels are not enough: the large ones are needed. In fact, when using the larger reflecting panels, the improvement with respect to the basic configuration varies from 2 dB in the positions far from the stage (as far as 50 m) to 5 dB in the closer ones. Should the audience be located in the orchestra too (and thus much closer to the stage), a more marked improvement could be reached. Actually, if the orchestra is occupied, the farthest seats will miss the contribution from the flat reflective orchestra floor, which is the most prominent geometrical reflection immediately after the direct sound, especially for frontal source positions (see for instance Figure 4 in [16] where a typical impulse response for a similar combination is reported). This effect applies to all of the set-ups and is to be accounted for in the planning of the audience areas.

Although the orchestra shell has an effect similar to the large panels in most of the *cavea*, its performance is not as good as the panels in the farthest positions. Two reasons can explain this behaviour. Firstly the reflection from the shell roof should be accurately optimized and directed towards the higher rows of steps in the *cavea* also when the source is positioned in the frontal part of the stage. This need prompts for an adaptation of the orchestra shell to the theatre but this operation, which is technically feasible, is unlikely unless the device will be a resident infrastructure. A second reason for the worse performance of the shell in

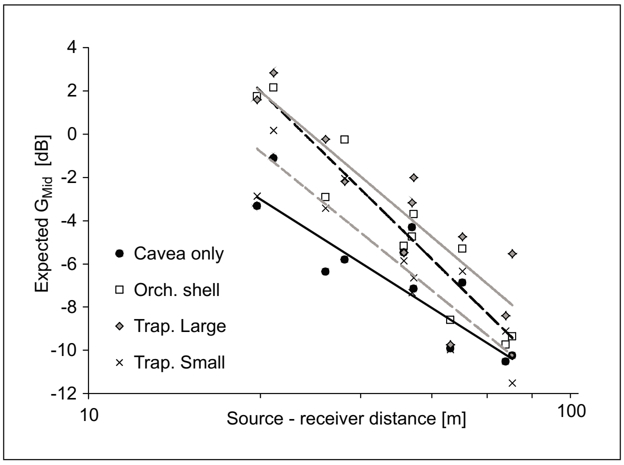

Figure 3. Expected Strength G_{Mid} as a function of source-receiver distance for the different stage preparations. The values are normalized to those measured in real ancient theatres with a similar geometry [5]. In particular the expected course of the basic configuration (named *cavea* only in the plot) is like the free-field propagation with a +3 dB bias. The logarithmic regressions are also included.

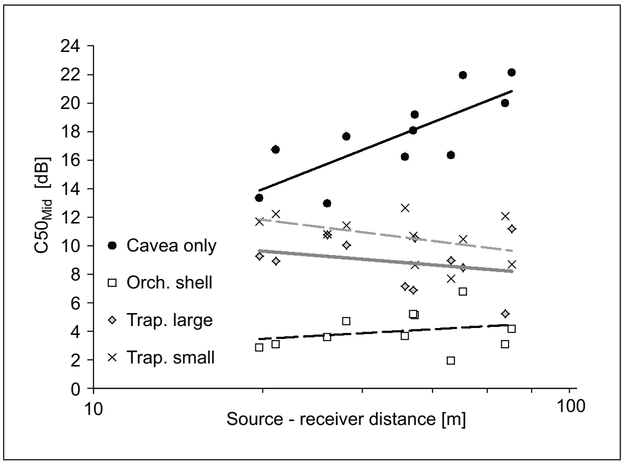

Figure 4. Clarity for speech $C50_{\mathrm{Mid}}$ as a function of source-receiver distance. Logarithmic regression lines are included.

the distant seats could be due to the type of the reflections occurring on the interior surfaces, which are sound diffusing. This is a well-known requirement for performers in order to avoid coloration of the orchestra sound, but the measures indicate that the reflected energy is more spread and not as effective in the distance.

3.1.3. Clarity

The analysis of clarity indicators C50 and C80 is useful to understand the change in the impulse response produced by the stage configurations. In Figure 4 and 5 the clarity parameters are reported as a function of source-receiver distance together with their linear regressions. In both cases the values in the basic condition are very far from a possible optimal range and the sound will result too dry especially for the musical signal. Furthermore the clarities increase with the distance from the source. Adding a few reflections from the stage set makes the regression

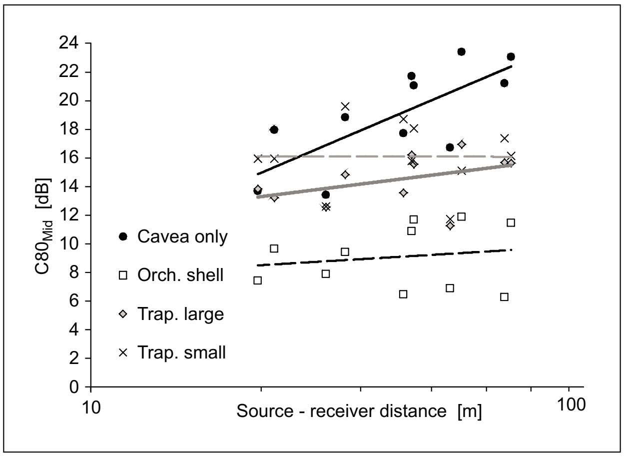

Figure 5. Clarity for music $C80_{Mid}$ as a function of source-receiver distance. Logarithmic regression lines are included.

lines much flatter. The improvement produced by the stage sets is very pronounced for C50. In this case, without considering the orchestra shell which is not compatible with a drama stage-set, the best solution is still the large panel configuration, as the clarity is 1 dB lower than using the small panels. Anyway, the overall values of C50 are slightly high and comparable with those found in the front rows of a closed theatre.

An improvement is visible also analyzing the C80 parameter with reference to the orchestra shell. The clarity decreases of more than 10 dB and in many positions the parameter is close to its optimal range for music. Also in this case the parameter takes values similar to those found in the first rows of a concert hall.

3.2. Discussion

Though not exhaustive due to the logistic limits of scale modeling, the experiments highlighted some important findings that can provide assistance in the adaptation of the natural acoustics to modern performances when starting from a bare, unfitted ancient theatre. In particular the reverberation cannot be effectively adjusted in a useful frequency range. On the contrary some existing coloration can be exalted by the added reflective surfaces as in the present case happened especially for the 500 Hz octave band. In this respect the relationship of this finding with the peculiar wave phenomena encountered in ancient theatres as described for instance in [10] calls for further analysis and modeling.

To obtain a substantial change in the reverberation it is necessary to alter the circulation of energy in the region of the *cavea* and this is only possible by revising the architecture (i.e. adding a back wall with or without side extensions, adding an upper reflective gallery or both).

The orchestra shell has better clarity results, but fails with the sound level at distant positions where the performance of the large panels is superior. On the other hand, optimizing the orchestra shell would surely improve its performance further, but this is unlikely to happen in practice. In fact the shell is a temporary installation which is not conceived for the specific theatre (or even for open-air theatres at all) and thus the adaptability which would be needed to optimize the acoustics can be hardly provided in this operational framework.

The necessity of larger reflective panels seems to characterize ancient open-air theatres and is consistent with the former computer model indications in [12]. It is to be remarked that usually in closed theatres (and concert halls in particular) a large number of small panels is generally preferred to a small number of large ones, at least for ceiling reflections [17]. The present case shows an effective alternative to implement when the most important issue is to provide sound energy to the remote listeners and the focus is not only on the quality of sound for performers.

It is believed that the present results can serve as the basis for optimizing the geometry and the location of the reflectors. Given in fact that, based on experience, logistic requirements (i.e. weight, handling, time needed for installation) will set an upper limit to the panel area which will be presumably not far from the present large panels (that is $6\,m^2$ each), it can be argued that the main parameters to work with in the assessment will be the number of panels to reduce the voids, and the splay of the lateral wings. In particular simple geometrical constructions can be implemented in order to better concentrate the sound in the central *cavea*, where most of the audience will gather in case of events with an occupancy far from the full capacity. In addition, more sophisticated panel designs, comprising for instance a forward adjustable inclination of an upper panel stripe, should allow to better direct the reflections to the farthest areas.

4. Conclusions

The lack of extended reflective surfaces in the stage area, which is quite common in ancient theatres due to their state of conservation, can be compensated for by adding few architectural elements to support the sound propagation and improve the listening conditions. This is more so also in consideration of the increase of the competing background noise at the sites, whose location is in many cases in the proximity of urban areas. An attempt was made in this work in this direction that is to investigate the possible benefits and the limits of passive strategies in the adaptation of acoustics to modern performances. Though the scale modeling could not cover as many configurations as necessary for a comprehensive analysis, several remarks can be done to give indications for the acousticians dealing with similar issues. Within natural acoustics few large reflecting panels arranged on the stage to delimit the performance area can be a good compromise compared to the smaller panels or even to an orchestra shell. In fact these elements are able to partially compensate for exceeding clarity, and increase the sound level to a certain extent with better performance in the farthest positions. The orchestra shell provides a better (that is lower) clarity but also a lower sound level in the distant locations. In any case the reverberation time cannot be corrected for effectively with these simple means.

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