ACOUSTICAL MEASUREMENTS IN ANCIENT GREEK AND ROMAN THEATRES

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ABSTRACT

Acoustical measurements were conducted in two ancient theatres–one Greek and one Roman–the origin of modern opera houses and drama theatres. The Delphi theatre (Greece) does not have a stage building, while the Taormina theatre (Italy) has a partially remaining stage building behind the orchestra. The effect of the stage building on the sound field was determined in terms of the temporal and spatial factors of the sound field. It was found that the stage building affects and the magnitude of the interaural cross-correlation function (IACC). In addition to the reflection from the orchestra floor and the stage tower, scattered and reverberant sound from the audience area were observed.

1. INTRODUCTION

In ancient architectural acoustics, the concepts of reverberation, interference, echo disturbance, and clarity of voice were described [1], Ancient Greek and Roman theaters are the origin of the modern opera houses and drama theatres [2, 3]. An ancient Greek theater consists of the *theatron, consisting of the audience seating and exiting aisles,* and the *orchestra, a flat acting area*. An ancient Roman theater added a large stage building behind the *orchestra, patterned after later Greek (Hellenistic) theatres*. This stage building provides to the audience area with strong reflections to reinforce the direct sound, and such reflections improve source loudness and speech intelligibility.

It is often considered that the sound field of the ancient theater consists of the direct sound and only single reflection from the ground and is similar with the sound field of open space [4]. The presence of scattered and reverberant sound is assumed negligible. It is important to achieve the intelligibility of speech and vocal source in an ancient theater. Such intelligibility was maintained since there are no lateral and upward reflections, and reverberation in the outdoor sound field. However, it is reported that the unoccupied seats and the heads of the audience also scattered sound to adjacent areas [5]. Reverberation in a Greek theatre model was shown to be a significant part of the acoustical response [6].

In this study, acoustical measurements were performed in typical ancient Greek and Roman theatres to clarify the effect of the stage tower. To evaluate the quality of sound fields, binaural impulse responses were measured using the methods which are used to evaluate a modern auditorium and then acoustical parameters of the sound field were calculated.

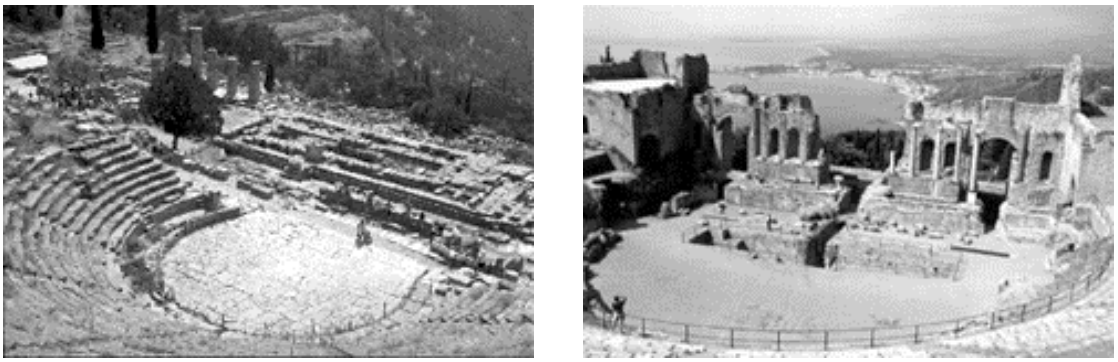


Figure 1. Ancient theatres measured. Left: Delphi; Right: Taormina.

2. EXPERIMENTAL PROCEDURE

Acoustical measurements were conducted in the Delphi theatre (5000 seats) and the Taormina theatre (5400 seats) (Figure 1). The plans of these theatres are shown in Figure 2. The Delphi theatre does not have a stage building, while the Taormina theatre has a stage behind the orchestra. Many of the seats (cavea) of the Delphi theatre were carved out of the rock. In the Taormina theatre, the frontal section of seating (M01, M04 and M07) consists of seating planks on a temporary steel frame which has a high degree of acoustic transparency. The middle seating area (M02, M05 and M08) consists of cut stone, and rear (M03, M06 and M09) consists of the wood benches.

The test signal was a log sine sweep with a duration 20 s (sampling frequency: 48 kHz). Frequency range was from 80 to 18000 Hz. The log sine sweep was radiated from an omni-directional loudspeaker located at the centre of the orchestra. A human head with two small

condenser microphones at each ear entrance was used as a receiver. During the measurements, the stage was completely empty. The measurements were conducted in an unoccupied condition. All the measurement devices were controlled by a laptop PC. Orthogonal physical factors in accordance with Ando's subjective preference theory of a sound field were analyzed [7].

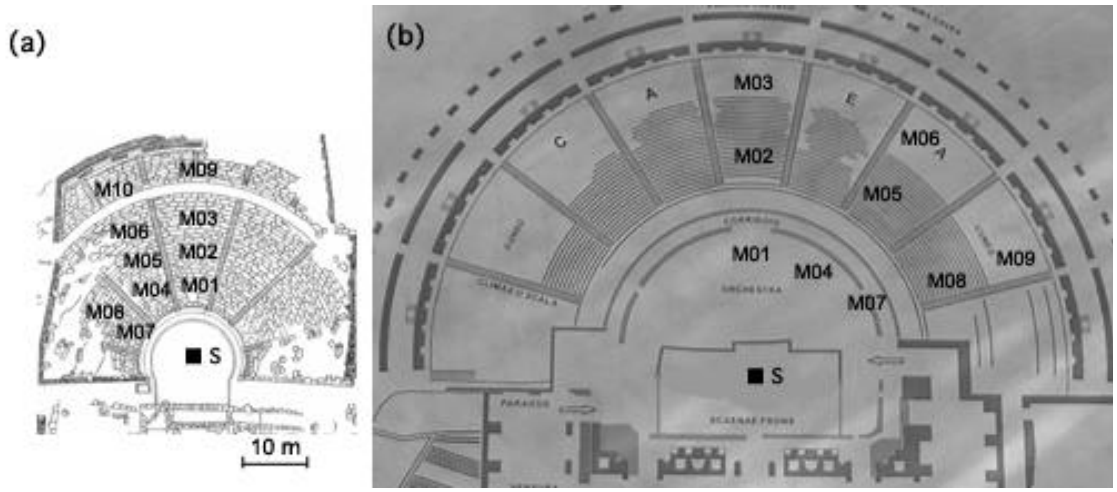


Figure 2. Sound source (S) and receivers (M01-M10). (a) Delphi; (b) Taormina.

3. RESULTS AND DISCUSSION

3.1 Impulse Responses

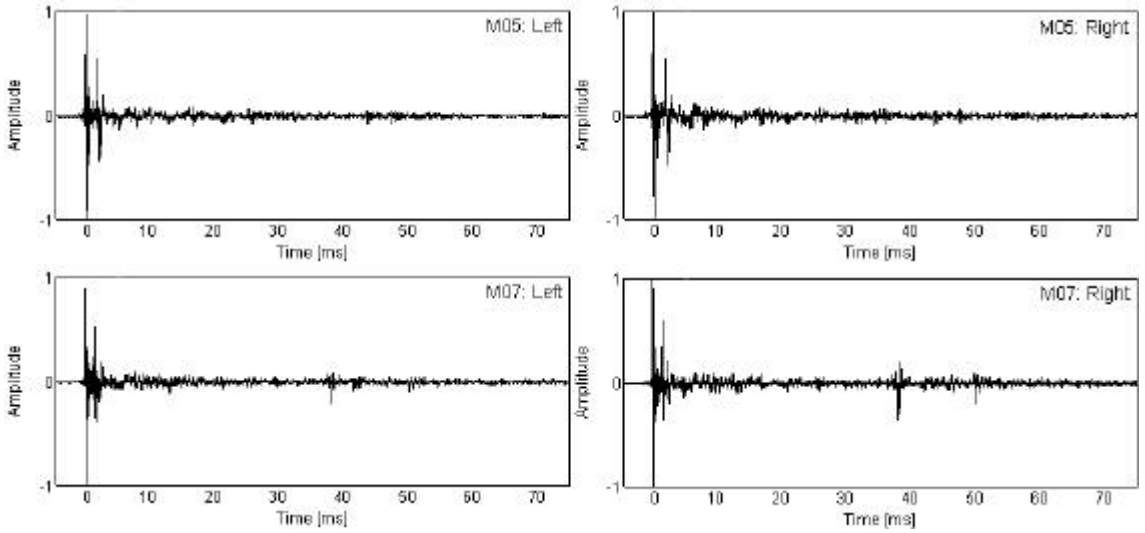
Figure 3 shows binaural impulse responses as typical examples of the measurements. In the Delphi theatre, only the single reflection of about 2 ms from the orchestra floor was observed at the receiver positions except for the side seat. Strong reflections of about 40 ms were observed in the side seats (M07 and M08). These were also observed in the 1:10 scale model and are likely from the seating area.

In the Taormina theatre, the reflections with periodical delay times up to 20 ms were observed at the seat in the middle row (M02, M05, and M08). These may be from the seating area which is constructed of stone.

3.2 Subsequent Reverberation Time

Examples of measured reverberation curve at 500 Hz are shown in Figure 4. Both are the open theatre and not diffuse sound field, therefore, the decay has a non-exponential behavior below 250 Hz. It can be seen that the decay of the Delphi theatre is steeper that those of the Taormina theatre. The sound field decay of the Delphi theatre begins immediately after the reflection from the floor. The acoustical decay is sustained by scattering from the stone seats. Measured subsequent reverberation time T_{sub} is shown in Figure 5. Linear regression for initial 20-dB attenuation is calculated by a logarithmic transformation of the integrated decay curve. For Delphi theatre, the values of T_{sub} were at about 0.5 to 0.6 s at mid frequencies (500 Hz and 1 kHz, averaged). For Taormina theatre, the values of T_{sub} are longer, increasing to around 0.9 to 1.0 s. These reverberation times would be considered optimum for speech and vocal music [7, 8].

Delphi



Taormina

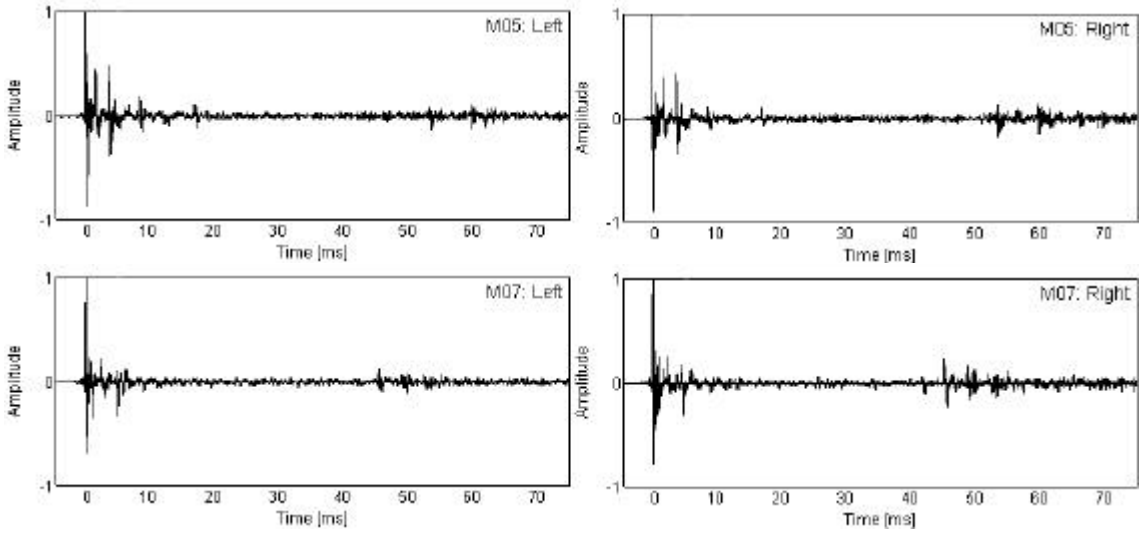


Figure 3. Binaural impulse responses as typical examples of the measurements.

(a) (b)

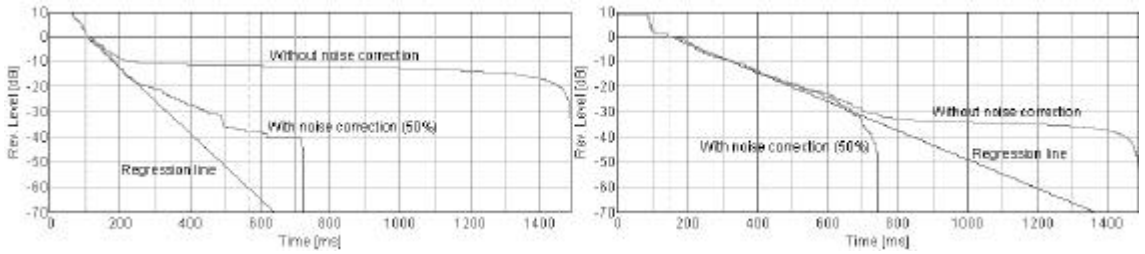


Figure 4. Decay curves for reverberation obtained by Schroeder's method as typical examples of the measurements. (a) Delphi (at M05) (b) Taormina (at M07).

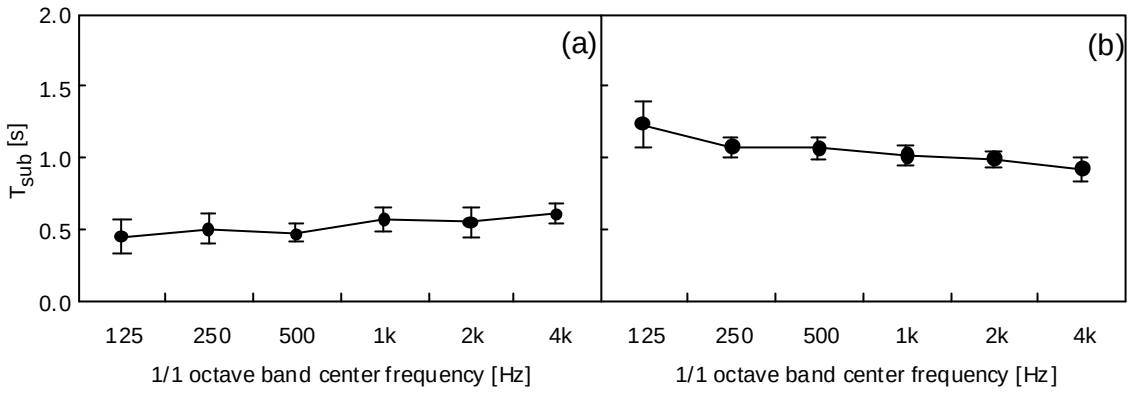


Figure 5. Results for T_{sub}. Average value of 10 receiver positions and standard deviations are indicated. (a) Delphi; (b) Taormina.

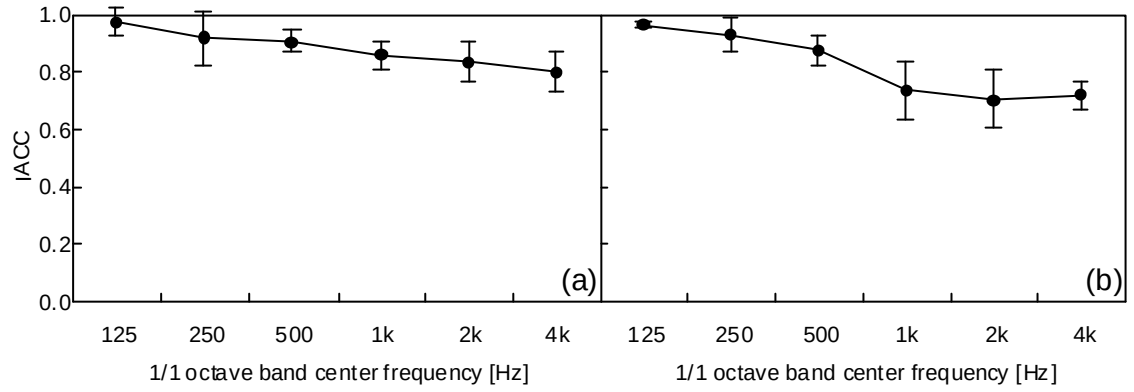


Figure 6. Results for IACC. Average value of 10 receiver positions and standard deviations are indicated. (a) Delphi; (b) Taormina.

3.3 IACC

Figures 6(a) and 6(b) show the measured IACC as a function of the 1/1 octave band center frequency for both theatres. The IACC results show a large value (more than 0.70 on average) for the IACC in all frequency range investigated in two theatres. However, a significant difference between two theatres was observed in the frequency range above 500 Hz. The IACC measured in Taormina Theatre is smaller than that in Delphi. In Taormina, the values of IACC in the front area (M01, M04, and M07) at the frequencies between 250 Hz and 2 kHz were larger than those in the middle and rear areas. Not only the stage building behind the source, but also the masonry walls of the stage sides provide the reflections to decrease IACC. The values of interaural time delay τ_{IACC} were less than 0.10 ms at frequencies greater than 250 Hz at the receiver positions except for the M07 of Taormina theatre, thus resulting in a horizontal balance of the sound field.

5. REMARKS

To clarify the true nature of the sound fields of the ancient theatres, acoustical measurements were conducted in a Greek and Roman theatre. The stage building on the sound field was shown to have an affect in terms of both the temporal and spatial factors of the sound field. The stage reflections increase the magnitude of the interaural cross-correlation function (IACC). Reflections from the orchestra floor and the stage tower were observed, and also scattered and reverberant as well. For Delphi theatre, the values of T_{sub} were at about 0.5 to 0.6 s at mid frequencies (500 Hz and 1 kHz, averaged). For Taormina theatre, the values of T_{sub} were at about 0.9 to 1.0 s. These reverberation times would be considered optimum for speech and vocal music in today's opera and drama theatres.

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