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Ancient Greek theatre – impulse response simulation

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ABSTRACT

Based on Vitruvius' "De Architectura libri decem" about proportions of the Greek theatre supplemented with the size data from Epidaurus, we reconstruct the impulse response and process the recordings of ancient and modern music. All theatres preserved till today, had sound deficiencies which Vitruvius recommended to solve using bronze vases. The wooden theatres didn’t have these deficiencies so simulating their impulse response gives us the effect intended by the old masters. The simulated impulse response can be used for filtering music signal to achieve this effect.

Keywords: acoustic reconstruction, Vitruvius' design of ancient theatres, diffusion into walls

1. INTRODUCTION

The reconstruction of ancient theatre acoustics is the topic raising a vivid interest among researchers, professionals, students and general audience. The long-term motivation for this work was to discover what effect is caused by the ancient theatre as its design seems to be optimally chosen from other options. Thus, it may indicate subjective quality effect which could be important in modern music as well.

The field is vividly investigated in different aspects and different methods of simulation.

The concept of simulation of the impulse response of the theatre in Epidaurus was investigated already in [1]. The lower frequencies were modelled with Finite-Difference Time-Domain method, while higher with beam tracing. Thus, the impulse response was reconstructed. The authors correctly took into account the existence of the stage which is not preserved in the theatre.

Another research on Epidaurus theatre was reported in [2]. The approach undertaken there is to perform measurements of the sound propagating from the middle of orchestra or from the point close to it analyzed in the positions of receivers installed at the various locations on the theatre’s cavea. The study fosters the results about speech intelligibility across the whole cavea. Also the occupation of the cavea by auditors does not have much impact on the acoustical properties of the theatre.

The topic was also covered by the research project ERATO under the EU 5th Framework “Preserving and using cultural heritage”, Project ICA3-CT-2002-10031 running from 1 February 2003 to 31 January 2006 [3].

Another example to the fact that the field is vividly investigated are the results of N. Declercq and C. Dekeyser [4] or the material in Nature based on their work. [5] Let us observe that here the propagation is analyzed by the calculation of amplitudes of the propagating signals of the specific frequencies, so the time-frequency effects are not taken into account.

The paper [6] discusses the influence of the stage building on the acoustical properties of the theatres in Greece.

The focus of our work was also to transfer the simulation result into the signal processing algorithm that would yield an experimental way to validate the conjecture that the Greeks had great experience in acoustics and sound arrangements despite the relatively poor technical means they had at disposal. Another important contribution was to focus on time-frequency effects known today in modern psychoacoustics that have a crucial impact on the subjective impression of music. As the core material for analysis we certainly used the findings of the acousticians working in the field and gathering the measurement results but we also kept in mind that the important source of information is "De architectura. Libri Decem" by M. Vitruvius Polio [7], who in Book V gives a quite precise account how a theatre with good acoustics has to be built, adding a special emphasis that the way it's built results in the sound propagating in the optimal way and providing most of the pleasure to the auditorium.

Let us review the above research papers from the perspective of the contents of Vitruvius’ description. In [1] the authors did not include the closing wall behind the stage that should be as high as the roof of porticus. The paper [6] also does not include the wall only the building behind the stage. The wall behind the stage and

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its important acoustical influence is discussed in [7].

As for the research in [2] the authors did not, however, consider Vitruvius' recommendation to equip the stone theatre with resonating vessels.

In the current paper we also do not take into account the resonating vessels. Instead, we assume the theatre material to be wood. As explained in Vitruvius' description, the wooden theatres did not require the vessels.

It should be mentioned also that the theatre of Epidaurus belongs to the type called by Vitruvius "Greek theatre" so the venue constructed for the musical performances. Thus the feature it has is the propagation of the music.

The known solution [4] analyzes only the impact of the antique theatre for the specific frequencies and does not take into account the delays. Moreover, it relates to the preserved parts of the theatre but does not take into account those that were in use but have not been preserved till our times, and that were still designed to have an acoustical influence.

The approach from [8] is based on the measurements of the impulse responses, which however are prone to errors due to the noise and the measurement conditions. The accuracy of the measurement is most probably .001, so -60 dB. We simulate the Impulse Response which for most of the delays up to 2 sec is under -60 dB.

Our approach considers the time-frequency structure of the processed signal and of the reconstructed impulse response and as such results in high accuracy reconstruction.

The paper is organized as follows. In Section 2 we give an overview of the method, while Section 3 contains the examples and applications. We end with some conclusions.

2. THE METHOD

Our approach to the reconstruction of the acoustical properties of ancient theatres relies on the simulation of impulse responses with which then the sound of music is digitally filtered. The impulse responses are pure simulation not based on the other measurements, but based on the actual geometrical properties of the ancient theatre. Thus, we are able to approximate the sound conditions as they were in the original theatre despite the erosion and the partially preserved elements of the construction.

Our approach is to reconstruct the impulse response (up to 2 sec of delay) and apply it as FIR – Finite Impulse Response – via convolution to the signal of original music. To obtain the Impulse Response we simulate trajectories propagating from the initial point (the actor's lips, the actor standing on the middle of the edge of the stage) following the geometric acoustic rules and registered if within 2 sec they reach the endpoint (the ears of the person sitting in the middle of the first row).

When the generated trajectory hits the walls of the theatre, we model the propagation of the sound in the theatre walls. The paradigm here is to exploit the wave – particle duality which assumes the propagation according to diffusion equation – contrary to D'Alembert equation which results in the geometric acoustics rules of propagation. The solutions to the diffusion equation are Wiener processes trajectories, over which the delay and attenuation are evaluated [9].

Reconstruction of the impulse response up to 2 sec allows to consider the time – frequency effects like dynamic changes in pure tones propagation. The delays and attenuations are computed over every straight line segment of the trajectory (so called partial delays and attenuations) and then combined – delays added and attenuations multiplied – to get the final values for the trajectory. The attenuations for different trajectories with the same delay are added. Thus, we obtain for the specific delays the specific sum of attenuations. So, we arrive at the overall Impulse Response.

The simulation is based on generating the trajectories in the air by means of forward ray tracing (see [10]) and supplemented by generating the trajectories in the theatre walls as we assume part of the energy is consumed to traverse the walls and comes back to the original wave with some delay. Hence, if we want to reconstruct the impulse response with the length up to 2 seconds, we need to take into account the sound propagating to the walls.

Thus, we supplement the standard forward ray tracing method with the trajectories through the walls analyzed according to Feynmann-Kac theorem. [9] And we apply this method to the geometries provided by the plan of the actual ancient theatres.

2.1 Forward ray-tracing

From the initial point we generate the trajectories composed of the segments of sound propagation in air and of the segments of sound propagation in the material of the walls. The sound propagation in the air follows the rules of the geometrical acoustics.

The amplitude is inversely proportional to the distance the sound wave is propagating to during the segment of trajectory between the subsequent reflection points. Thus, the attenuation F is proportional to the distance travelled:

$$F = S. \tag{1}$$

where S - the distance travelled by the sound in the segment of trajectory.

The next except the first segments that cross the air are selected consistently with the rule that the angle of reflection is equal to the angle of incidence.

The simulation takes into account that the sound is perceived by a human, the ability of sound localization is modelled by using Head Related Transfer Function [11].

2.2 Diffusion model

The fragment of trajectory is randomly selected from the 3-dimensional Gaussian distribution with mean 0 and standard deviation depending on (proportional to) the speed of sound in the respective material.

$$W(n)(x,y,z) \sim \mathcal{N}\left(0, \frac{V}{N^{1/2}}\right). \qquad (2)$$

2.3 Delay/attenuation pairs

We assume the propagation in the air when the wave leaves the wall and travels a short distance in the air. The attenuation F and the delay T are given by the formulae:

$$F = SD^{1/3} \qquad (3)$$

$$T = \frac{S}{V}, \qquad (4)$$

where V - the sound velocity in the component (air/wood),

S - the distance travelled by the sound in the component,

D - the density of the component.

2.4 Wall material

The light wood (pine, fir, spruce) has a density of 400-500 kg/m^3 and the respective sound velocity is 4000-5000 m/s. The choice of density 400 kg/m^3 and the sound velocity 4000 m/s is, in our opinion, a good representation of the true material.

2.5 Design

The design of the theatre was implemented as C++ functions into the C++ code CEZAM performing ray tracing algorithm. The effects of propagation of the sound inside of the wall material were simulated in R (also for the multiple reflections) as pairs of attenuations and delays – see equations (3-4) – and recorded as an additional input to C++ software.

2.6 Theatre proportions

The theatre proportions are found according to the description from Vitruvius [7] and the size of the theatre in Epidaurus. The theatre is assumed to be built from 10 cm thick wood and to have a closing wall behind the stage. Other details follow description from Vitruvius' Book V. It should be mentioned that in Epidaurus the higher part of seats was added only in Roman times. Earlier there was a colonnade. So, in the simulation we assume the theatre building with the closing wall and colonnade. Hence, the length of the seats is corrected as in Table 2.7.1.

The useful modification is to place the sound source in the orchestra where the choral parts were performed from.

The geometry of the theatre is mostly transparent so it is fairly straightforward to prepare the code implementing the function returning for the three-dimensional data the value 1 for the air found at these coordinates, 2 for wood and 0 for the open space above the theatre building. The most important features that were to be implemented are the angle of the audience, the angle of the slope and the size of seats.

We needed also another function to return the direction of the normal to the theatre surface.

2.7 Measurement data

The measurement data comes from the paper [4] and was supplemented with the data from Vitruvius' description of the Greek theatre: the angle of audience and the height of stage

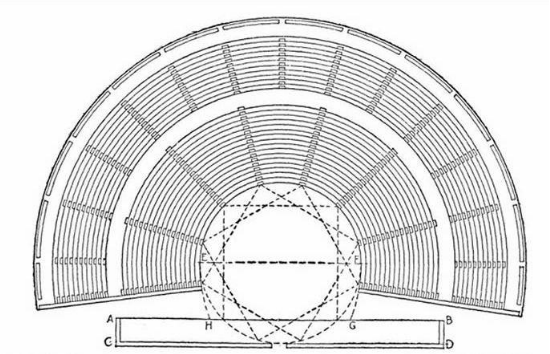

Figure 1 – Ancient Greek theatre according to Vitruvius' description

2.7.1 Data from Epidaurus

Table 1

Parameter	Unit	Value
Width of the seats	meter	.746
Height of the seats	meter	.367
Slope of the theatre	degrees	26.6
Distance between centre of the orchestra and lower seat row	meters	22.63
Length of the seats	meters	49.88
Length of the seats (corrected)	meters	44.78

2.7.2 Data from Vitruvius' description of the Greek theatre

Table 2

Parameter	Unit	Value
The angle of audience	degrees	210
Height of the stage	meter	3-3.6

3. EXAMPLES AND APPLICATIONS

3.1 Available solutions

The presented algorithm was coded into an Android application designed to imitate the described effect of ancient theatre acoustics. Also, if a shorter delay is needed (Android has got this parameter around 250ms), a software implementation on the Texas Instruments DSP C6748 hardware device (with 10 ms delay) was implemented.

The impulse response of the reconstructed ancient theatre acoustics is available with the VST tools like SIR or others.

3.2 The music applications

In pilot tests the difference of the original and the processed signal is described as "richer, deeper, and more reverberation." To support that we can plot the spectrogram of the song “*La voce del silenzio*” sung by Andrea Bocelli. The parameters of the time-frequency decomposition: Hamming window, in ERB (equivalent rectangular bandwidth - a perception based frequency scale), window length 50 ms, overlap 95% (i.e. redundancy 20). The software used is STX [12],[13].

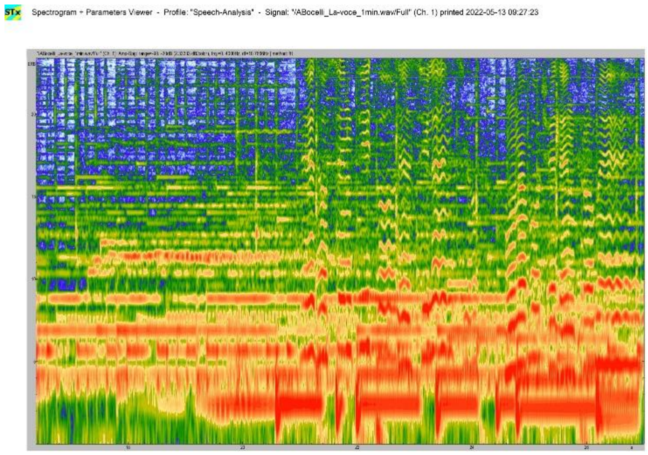

Figure 2 – Spectrogram of the original recording “La voce del silenzio” by Andrea Bocelli.

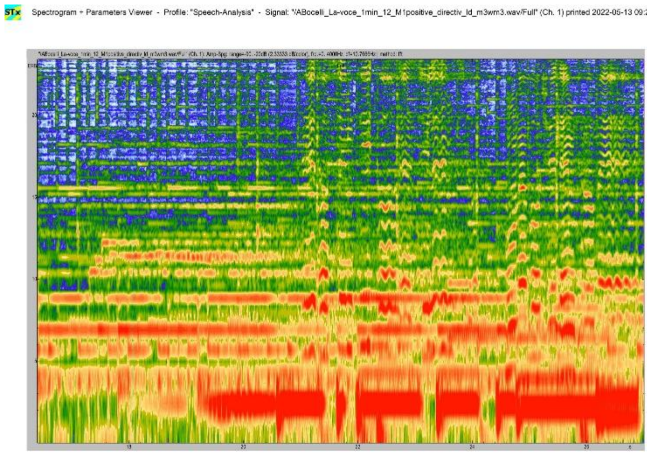

Figure 3 – Spectrogram of the recording “La voce del silenzio” by Andrea Bocelli processed by the simulated impulse response of the Greek theatre.

4. CONCLUSIONS

We introduced the method consisting in implementing the proportions of the Greek theatre and simulating the effect of propagation of the sound into walls by means of Wiener process. We simulate the trajectories from the stage to the middle of the first row and convolve the music signal with the obtained Impulse Response. The result has got plausible features that were analyzed.

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