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Time-frequency diffraction acoustic modeling of the Epidaurus theatre

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ABSTRACT

This work investigates the contribution of sound diffraction in the acoustics of the ancient theatres, with reference to the theatre of Epidaurus. It is increasingly evident that in such theaters, the most important elements in the acoustic field are related to sound diffraction at the edges of the tiers, especially for the distant listener positions. For computational reasons, this study is limited to a 3D model of an elementary slice of the "koilon", evaluated in the time and frequency domains. The analysis accounts for direct, reflected, diffracted and mixed reflection - diffraction paths, and calculates the theatre's acoustic response in various positions along the tiers. The model contains detailed parametrisation of the seat geometry and allows for comparisons by including or neglecting diffraction in the composite acoustic field.

The contribution of the diffracted sound to the total sound field is evaluated through the estimation of energy-based acoustic parameters and the frequency response. The differences that occur in the typical acoustic parameters by accounting for diffraction are discussed. The ascending and descending components of the sound field are also analyzed regarding their composition and contribution to the predicted speech intelligibility.

Keywords: Epidaurus theatre, diffracted sound, speech intelligibility

1. INTRODUCTION

The significance of wave diffraction for the analysis of many acoustic propagation phenomena is only recently receiving attention, one prominent case study being the acoustics of the ancient open amphitheatres [1-7]. Diffracted acoustic components in the ancient theatres is not coincidental, but in period, it appears to be a designed property. A description by only surviving relevant text by Marcus Vitruvius Pollio (approx. 70-15 B.C.) [8], states that: *"…the height of the benches and the radius of the cavea (koilon) must be designed in such a way so that the sound reaching the listeners will be harmonic and clear without any interferences….*". Such design principles by the ancient architects are most prominent for the Epidaurus theatre, especially for the choice of a double slope to account for the extended upper koilon, as was also illustrated by Canac [9]. The tier edge-generated diff∑raction for this theatre was analytically studied more recently by Declercq and Dekeyser [2] employing a geometric-based acoustic modelling method incorporating multiple orders of diffraction and concluded that the backscattered sound from the cavea "…*amplifies high frequencies more than low frequencies*..". However, this prediction is contradicted by in-situ measurements [10] as is also the claim that this is responsible for the theatre's exceptional speech intelligibility. However, [2] introduced an important geometric metric for the "periodicity" for each amphitheatre's properties as a predictor for the 2nd order diffraction contribution to the spectral response. Farnetali et al. [6,7] studied open theatre reflection-diffraction effects with measurements both in-situ and in scale models. Additional effects from the ground floor and cavea tier steps specular reflections and edge diffraction were also studied in [9,10,11]. The significance of modelling diffraction paths during simulations of the acoustics of the ancient theatres was demonstrated by Economou and Charalambous [1], whilst Kaleris et. al. [5] also examined diffraction effects on a detailed 2D section of the theatre profile following a precise calibration of the simulation parameters to measured impulse responses. Such approach allowed categorization of specular reflections, edge diffraction and their combinations, considered also an "ascending" or "descending direction" along the cavea. It was found that the significant diffracted sound field has non-negligible impact on the theatre's acoustics by enhancing low-mid frequency energy (as opposed to the Declerq work [2]) and increasing speech intelligibility. Subsequent work by Menounou et. al. [3,4] provided a method for predicting and identifying propagation paths and elaborated on the concept of reflective and diffractive paths for the Epidaurus geometry. This analytic solution in frequency and/or time domain thereafter referred to as the Diffraction Kernel [4].

Even though diffraction-related simulations are recently becoming feasible via available software, e.g. [12, 13], complex 3D geometries such as a complete model of an ancient theatre entail heavy computational load, especially for higher order diffraction paths. Here,

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to assist implementation of efficient filter-like representations of diffraction propagation, the above analytic Diffraction Kernel (DF) is incorporated into the study of Epidaurus theatre acoustics focusing on the detailed evaluation of such reflection / diffraction effects in the receiver position. A precise matching of the measured theatre's time and frequency responses to the simulated responses is achieved, allowing for the first time the detailed examination for the relative contribution of reflective and diffracted components on the response and spectral profile. The proposed simplified diffraction kernel model provides an efficient linear filter platform to simulate and evaluate spatial acoustic properties, allowing also binaural representation for such soundfield components.

2. THE AMPHITHEATRE'S SOUND FIELD

2.1 Time and frequency response analysis

From past work [5, 7, 9-11] it is evident that the sound
field of open-air amphitheatres is generated via the combination of different reflection, diffraction and propagation mechanisms. Here, with the aid of the theatre's computer model (see Section 3) such mechanisms can be visualized and for simplicity are categorized in 3 classes, as:

a) **direct (δ) and early reflected paths (*r*)** formed from different order reflections (Fig.1(a))
b) **diffracted paths (*d*)** originating from the source. As can be seen in Fig. 1(b), due to the double slope of Epidaurus' koilon, diffraction paths are generated via 2 upwards moving mechanism (purple line): one from the lower diazoma tiers and one from the upper diazoma tiers, just below the listener. Additionally, there are downwards moving diffractions (yellow line), generated by tiers above the listener. For the more distant listener positions, such paths are fewer.
c) **reflected and diffracted paths (*rd*)** originating from reflection in the orchestra (Fig. 1 (c)) and upwards moving diffractions from lower and upper diazoma tiers (cyan line) and downwards moving diffractions from the tiers above the listener (orange line). These latter paths arrive at later instances (e.g. beyond 100msecs) and having low amplitudes will not be considered further in this analysis.

To express these linear combinations of the individual components in the time-domain soundfield s, in a simplified fashion we can write:

$$s \approx \delta + r + d + rd \qquad (1)$$

and for a direct signal $s(t) = \delta(t)$ implying a time shift that places $s(t)$ at t=0, the general form of the impulse response received at any position of the koilon, based on the mechanisms of eq(1), will be:

$$h(t) = \delta(t) + \sum_{r=1}^{N_r} A_r\, h_r(t-\tau_r) + \sum_{d=1}^{N_d} A_d\, h_d(t-\tau_d) + \sum_{rd=1}^{N_{rd}} A_{rd}(h_r * h_d)(t-\tau_{rd}) \qquad (2)$$

where $h_r(t)$ is the response of the reflective surface material, τ_r is the time delay of the reflection relative to the direct signal and A_r is the amplitude attenuation due to the propagation distance, i.e.: $A_r = \frac{r_0}{r_0 + c\tau_r}$ with $c = 343m/s$ being the the speed of sound in air and r_0 the distance between source and receiver for the specific path. Similarly, $A_d = \frac{r_0}{r_0 + c\tau_d}$ is the amplitude attenuation of each contributing edge diffraction source due to its propagation and τ_d is diffracted signal's propagation time.

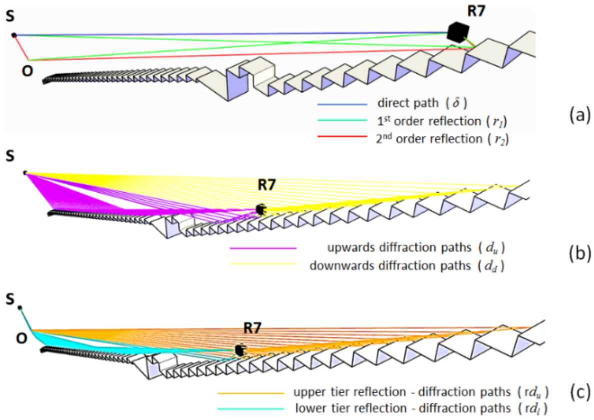

Figure 1–simulations of three acoustic path classes for the Epidaurus soundfield between source (S) located at the orchestra (O) centre and receiver (R7 as defined in [5,10]): (a) direct and early reflections, (b) only diffractions, (c) reflection and diffractions

The simulations indicate the significant contribution from diffractions following the reflection from the orchestra. These composite reflected – diffracted paths are described by the last term of eq. (1), with the amplitude attenuation and time constants A_{rd} and τ_{rd} respectively, while their temporal profile can be described by the convolution of the reflection and diffraction kernels, i.e: $h_{rd}(t) = h_r(t) * h_d(t)$. In this analysis, diffusion effects, either due to discrete reflections or due to the late reverberation tail, as well as ambient noise will not be cosnidered. In practice, the direct path component will diversify from the ideal delta function excitation, potentially exhibiting excitation
Source-dependent time, frequency and directivity response. Direct Fourier Transformation of eq. (2) provides the complex Transfer Function of the path to the specific receiver:

$$H(\omega) = 1 + \sum_{r=1}^{N_r} A_r\, H_r(\omega)e^{i\omega\tau_r} + \sum_{D=1}^{N_d} A_d\, H_d(\omega)e^{i\omega\tau_d} + \sum_{rd=1}^{N_{rd}} A_{rd}\, H_d(\omega)H_r(\omega)e^{i\omega\tau_{rd}} \qquad (3)$$

where $H_r(\omega)$ is the spectral profile of the reflecting surface which depends on the acoustic characteristics of the material and $H_d(\omega)$ is the spectral profile of the diffraction kernel. It occurs that the spectra of the composite reflected-diffracted paths result from the multiplication between the reflected and the diffracted kernels' spectra.

3. MODEL IMPLEMENTATION

As can be seen in Fig.2, the theatre's model utilized both generic simulation s/w [12] as well as custom s/w for modeling the theatre's soundfield [13]. Generic s/w was mostly used for setting up the 3D geometry (a full-scale model implemented via OTL), studying and identifying transmission paths (eq. 2) and their corresponding attenuation parameters.

The path parameters were fed into custom MATLAB [14] code that numerically evaluates the combined response (eq. (1)) using also the diffraction kernel proposed in [3,4].

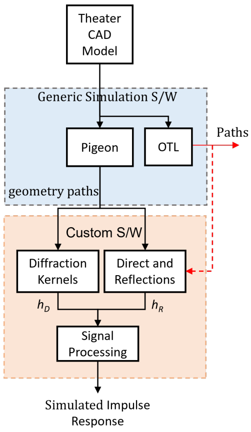

Figure 2 – approach for simulation of the theatre's soundfield

4. RESULTS

4.1 Time domain model and soundfield analysis

The model's output follows computer evaluation of the theatre's impulse response (see eq. (1)) for the appropriate listener position, assuming an omni(directional) source at the centre of the orchestra. As was shown in [5], the model geometrical parameters were fine-tuned in order to match the actual response measurements made in -situ [10]. Here, a comparison between model predictions and actual measurements are shown for position R7 as shown in Fig.3

The model appears to predict very accurately the theatre's early IR, noting that higher order reflection, diffraction and their combinations, along with diffusion and noise were not considered. Given that the model predicts accurate the composite theatre's IR, it is now feasible to separate, trace and examine separately the contributions of the individual mechanism described in Section 2.1.

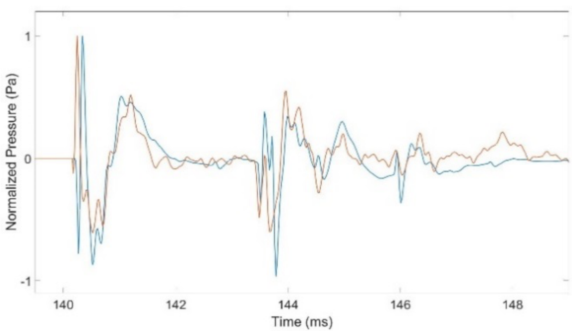

Figure 3 – comparison between model IR simulation and actual IR measurement for position R7 (first 50msec)

Figure 4 shows such a model-derived IR decomposition, noting also that the direct path has been component has been represented by the source actual pseudo-anechoic IR as was used during the in-situ measurement.

The analysis clearly illustrates that accumulated diffraction energy arrives from the lower tiers immediately

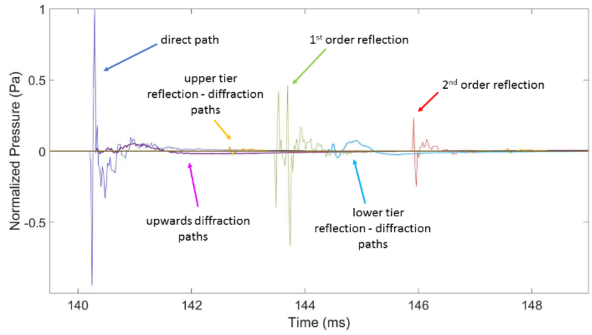

Figure 4 – decomposition of the model IR into separate soundfield components (first 50msec)

after the direct signal. Similarly, significant diffraction path energy is generated also from the reflection on the orchestra floor, arriving within 6mesec after the direct signal. Such contribution is stronger for the more distant positions in the upper diazoma and as was found in [5] to increase the early IR level and improve speech intelligibility.

4.2 Frequency domain model and soundfield analysis

From the estimated IRs, the spectra were extracted and a typical (1/12 octave smoothed) version is compared to the in-situ measured spectrum as is shown in Fig.5.

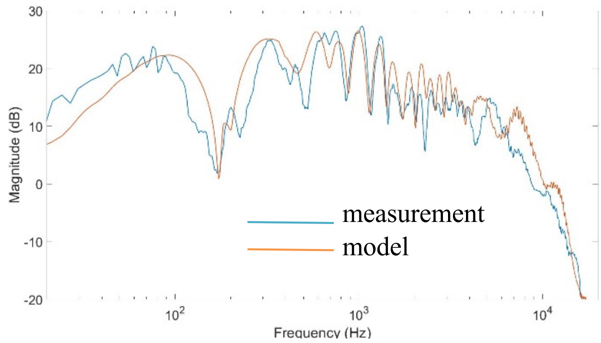

Figure 5 – comparison between model response spectrum and actual measurement for position R7

It is clear that the model provides sufficiently accurate estimation of the theatre's spectral response and thus it is feasible to expand the modeled spectrum into the individual components according to eq. (3), as is shown by Fig 6. Here it is shown that the diffracted paths enhance spectral content in the low and mid frequency range, hence improving SNR at this range and the speech intelligibility.

4.3 Speech intelligibility

Table 1 shows the Speech Transmission Index (STI) for four different source levels and assuming a NR-35 ambient noise profile, calculated from the simulated impulse responses at position R7. Here, STI is evaluated considering different components of the impulse response, **i.e.**: $\delta+r$, $\delta+r+d$ and $\delta+r+d+rd$, **(**see eq. (1)**)**. The diffractions both from the direct and the reflections were found to increase STI especially for weak source levels.

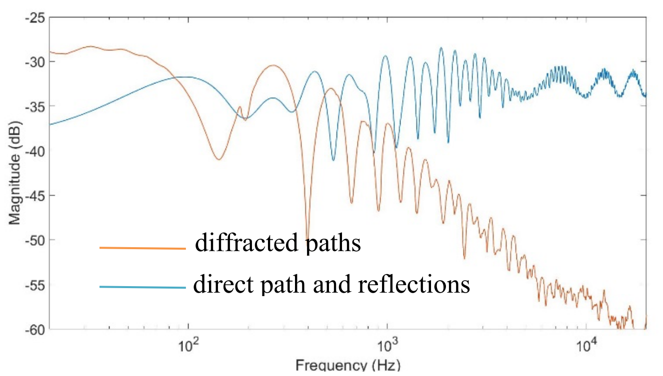

Figure 6 – decomposition of the model spectral response into separate soundfield components

Table 1 – STI for different source levels and for the different propagation mechanisms

	δ+r	δ+r+d	δ+r+d+rd
86 dB	0.999	1	1
70 dB	0.933	0.946	0.949
65 dB	0.805	0.825	0.836
60 dB	0.644	0.666	0.674

5. CONCLUSIONS

Following an ellaborate analysis appoach of the different sound propagation mechanisms in the Epidaurus theatre, a detailed study of the properties and contribution of the direct, reflected, diffracted paths, along with their combinations has been presented. The analyis is based on a simulation model derived from precise calibration of its parameters to in-situ measured impulse responses. Such a controlled simulation platform allows for precise matching of the estimated response both in time and spectracl domain to the measurements, as well as categorisation of specular reflections, edge diffraction and their combinations, along with the direction of arrival to the receiver (considered here as following an ascending or descending direction).

This analysis reveals a more detailed diffraction mechanism which here due to lack of space was discussed specifically for one receiver position in the middle of the second cavea (R7). As was shown, for the upper cavea (koilon) which has a steeper slope than the lower cavea section, the direct signal generates edge diffraction components from the rows just below the listener which arrive nearly simultaneously with the direct signal. The orchestra floor reflection also generates diffracted components, but in this case, these are produced from the rows of the lower cavea section. All these upwards moving signals arrive at close instances after the direct signal leading to an increase in the level of the total signal that significantly contributes to the speech intelligibility, especially given the reduction of the level of the direct signal at such distance. An additional second order diffraction mechanism appears to be formed by the back of each seating row which, although arriving nearly simultaneously with the previous components, increases the overall early signal level. Here it was verified that the total theatre response is composed from significant diffracted sound field component. The edge diffraction spreads and increases the early time response and contributes to the low-mid frequency energy of the overall spectral response of the theatre, a result that questions the findings in [2]. Such contribution in the low-mid frequency range appears to increase the speech intelligibility, especially for the distant listener positions and for weaker source signals.

6. REFERENCES

[1] P. Economou, P. Charalampous, "The Significance of Sound Diffraction Effects in Simulating Acoustics in Ancient Theatres", Acta Acustica united with Acustica, Vol.99, 2013.
[2] N. Declerq, C. Dekeyser, "Acoustic diffraction effects at the Hellenistic amphitheatre of Epidaurus", J.Acoust.Soc.Am. 121(4), 2007.
[3] P. Menounou, et.al. "A Virtual Source Method for the prediction of the sound field around rigid obstacles", EURONOISE conf., 2021.
[4] P. Menounou, P. Nikolaou, , "Analytical model for predicting edge diffraction in the time domain". J. Acoust. Soc. Am., Vol. 142 (6), 3580 (2017)
[5] K. Kaleris et. al., "Wave-based acoustic modeling of the Epidaurus theatre", EURONOISE conf., 2018.
[6] A. Farnetani, N. Prodi, R. Pompoli, "On the acoustics of ancient Greek and Roman theatres", J.Acoust.Soc.Am. 124 (3), 2008.
[7] A. Farnetani, N. Prodi, P. Fausti, "Validation of a numerical code for the edge diffraction on a scale model of an ancient theatre", The Acoustics of Ancient Theatres Conference, 2011.
[8] Vitruvius. The ten books on architecture (translated by Morgan MH). London/Cambridge, MA: Harvard University Press; 1914.
[9] F. Canac, "L'acoustique des théâtres antiques", published by the CNRS, Paris, 1967.
[10] S. Vassilantonopoulos, et.al., "Measurement and Analysis of the Acoustics of Epidaurus", The Acoustics of Ancient Theatres Conference, Patras, 2011.
[11] T. Lokki, et.al., "Studies of Epidaurus with a hybrid room acoustics modelling method", The Acoustics of Ancient Theatres Conference, Patras, 2011.
[12] Olive Tree Lab, PE. Mediterranean Acoustics Research and Development, https://www.mediterraneanacoustics.com/olive-tree-lab-suite.html (ac. 08.05.22)
[13] A. Erraji, J. Stienen, M. Vorländer, The image edge model, Acta Acustica, Volume 5, 2021.
[14] MATLAB (2022), version R2022a, Natick, Massachusetts: The MathWorks Inc.