PERCEPTUAL COMPARISON OF TWO DIFFERENT SIMULATION ALGORITHMS APPLIED ON THE EXAMPLE OF AN OPEN-AIR THEATRE

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1 INTRODUCTION

The present interest in the acoustics of ancient open-air theatres is related to the recent developments in archeoacoustics[1-2]. This is a new research field focused on the acoustics of ancient structures used for a specific purpose, as rituals or speaking and musical performances. Greek and Roman open-air theatres are obviously considered in this category, as one of the most ancient and recognized form of auditorium. Thus, the main question is: which is the nature of the remarkable acoustics of these theatrical structures?

The first investigations on open-air theatres acoustics go back to 1967, when Françoise Canac published his book[3] about twenty-years-long research on Roman and Greek theatres. Canac attributed the reason of their incredible acoustic to the absence of the roof, responsible of a dispersion of annoying late reflections inside the theatre. This postulate is actually one of the starting points for the contemporary study of ancient open-air theatre acoustics. In fact, the absence of a roof structure causes a remarkable decrease of the amount and density of sound reflections within the theatrical space. This was confirmed by real and on scale model measurements[4], which revealed the characteristics of Impulse Responses (IRs) in open-air theatres: their reflection path is mainly composed by the direct sound, between the sound source and a receiver, and two major reflections, coming from the *orchestra* floor and the stage building, if the latter survived; after those first reflections, the IRs show a group of distributed reflections with much smaller amplitude, which are mainly caused by the scattering of sound on the tiers of steps in the sitting area (*cavea*)[5].

This specific sound field makes problematic the usage of the standard[6] room acoustic parameters, such as Reverberation Time (RT), Early Decay Time (EDT), Clarity (C_{80}), Definition (D_{50}) or Sound Strength (G). These standards refers to in-door environments, thus more insight is needed for investigation of open-air theatres. In previous researches the use of ISO acoustical parameters was discussed for the characterizations of open-air spaces. A recent research[7] sustained that conventional reverberation parameters (RT and EDT) should be not considered in the acoustic characterization of unroofed auditorium, providing that the correct spatial information is given. Therefore, the C_{80} is higher respect indoor conditions range, while the G decay strongly depends on the distance of the receiver from the source, but also from the stage building[8].

Assumed that ancient theatres are non-standard acoustic spaces, a query that still needs to be deeply investigated is the suitability of room acoustics prediction software in open-air cases. For closed spaces, the reliability of prediction software has always been object of discussion and continuous studies[9-10], whose aim was to calculate objective results with a sufficiently good fit with real measurements. Since their findings showed the importance of correct sound diffusion and scattering coefficients set up, similar investigations should be proposed also on open-air theatre, where scattering assumes a relevant role. Moreover, referring to other studies[11] on comparison of recorded/ simulated stimuli, this kind of analysis could be implemented with perceptual assessment through listening tests.

Thus, the research presented in this article concerns the comparison of *in situ* measurements and simulated data from two prediction software algorithms, Odeon version 13.1 and CATT-Acoustic version 9. This analysis was achieved on the example of the ancient Greek theatre of Syracuse. Six different alternatives were simulated, with different scattering coefficient values (s = 0.25, 0.55, 0.75) and absorption coefficients (α_w = 0.05, 0.10) applied to the *cavea* stone. Firstly, a comparative analysis on the measured and simulated IRs was carried out, allowing a subsequent comparison between objective room acoustical parameters. Secondly, a subjective investigation was conducted on auralized speech and music stimuli obtained from same measured and simulated IRs. The survey was presented to expert listeners via headphones and the results were analysed taking into consideration the comparison with objective results.

2 CASE STUDY

2.1 The Greek theatre of Syracuse

The ancient Greek theatre of Syracuse in its actual condition was considered as study case in this investigation (Fig. 1a). It dates to the fifth century B.C and the geometry of the survived part shows the *cavea* with a diameter of around 105 m, which extends radially and symmetrically around the *orchestra* in a plane semi-circle of 29 m diameter; some parts of the last rows are missing, as the building stage (or *scaena frons*) is not anymore preserved. The *cavea* can be distinguished three zones: *ima*, *media* and *summa cavea*. Each part is divided from the other by a specific boundary element. Starting from the orchestra, the *ima cavea* corresponds to the first twelve steps and it has a slope of 22.5°. After a higher step of 0.86 m, it becomes *media cavea* and the slope changes to 20.8°. A large passage, called *diàzoma*, bounds this part and subsequently the *summa cavea* begins, keeping the same average slope. Recent measurements were carried out by the Department of Energy of the Politecnico di Torino in bare conditions (Fig. 1b).

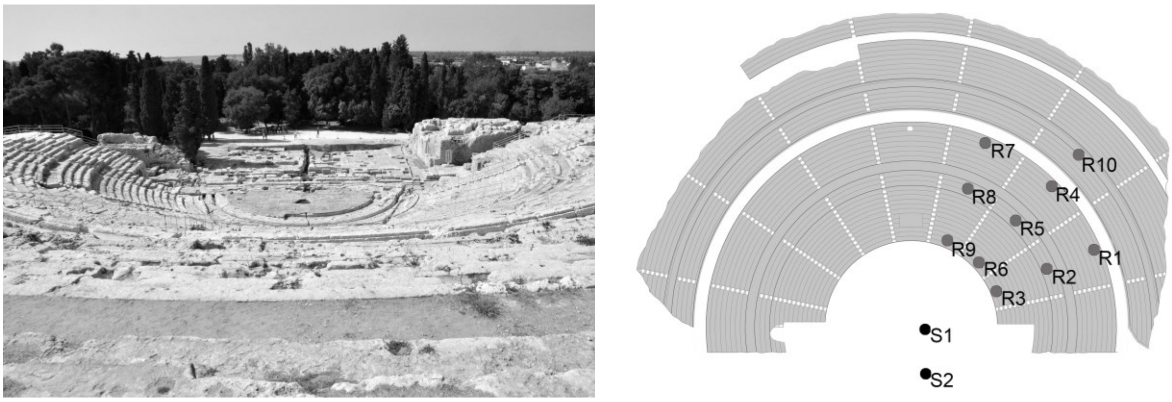

Figure 1. a) Greek theatre of Syracuse, actual condition; b) Measurement set up

2.2 *In situ* acoustical measurements

The measurements were realized with a strong impulsive source (firecracker) in two positions: S1, which was shifted of 1 m from the centre of the *orchestra* on the symmetrical axis, in order to avoid acoustical focus[12]; S2, which was located 7.6 m behind S1. A custom-made tripod was used to keep the firecrackers at the height of 1.5 m. Ten receiver positions were disposed on three axis of the *cavea*, 1.2 m high. In each position two type of receivers were used: an omnidirectional microphone (Shoeps CMC 5-U) and binaural microphone/ headphones (Roland CS 10-EM). The binaural microphones were worn always by the same person: in order to keep its head fixed in the same position, it was also used a custom-made headrest and chair.
The use of a strong impulsive source was necessary in order to guarantee a positive Signal-to-Background Noise Level Ratio (SNR). Due to wind and environmental noises, measured Background Noise Level was equal to 45 dB(A) in unoccupied condition at the last row of receivers.
Firecrackers acoustical properties were previously tested in another open-air theatre (Tyndaris) with same set up[13]. In that case, lower BNLs allowed performing measures in same source-receivers positions, both with firecrackers and a dodecaedrical source (e-sweep technique). The two measurement methods were compared and similar results were asserted in direct sound IRs spectral analysis.

3 SIMULATION METHOD

3.1 Simulation tools

Simulations were performed with two geometrical acoustic based software: Odeon version 13.1 and CATT-Acoustic version 9.
Odeon version 13.1[14] uses a hybrid calculation method: early reflections are calculated by a mixture of Image Source Method (ISM) and Ray-Tracing Method (RTM) with stochastic scattering process using secondary sources; late reflections are calculated by using a special RTM, where the secondary sources radiate energy locally from the surfaces and they are assigned with a frequency-dependant directionality, according to the vector based scattering method (the so-called “Reflection Based Scattering Coefficient”). The secondary sources may have a Lambert, Lambert Oblique or Uniform directivity, depending on the properties of the reflection as well as the calculation settings.
CATT-Acoustic version 9[15] is a selection of room acoustic prediction and auralization programs, where CATT-A is the main program handling modeling, surface properties and directivity libraries while TUCT is the main prediction and auralization program. TUCT[16] (The Universal Cone Tracer) offers several algorithms depending on the room case, ranging from basic to advanced, and various levels and combinations of diffuse ray split-up: first algorithm is based on stochastic diffuse rays, while second and third algorithm on actual diffuse rays split-up; the difference between them is that latter one takes the ray split-up a step further with lower random run to run variation.

3.2 General settings

Software MATLAB version R2015b[17] was used to create a parametric open-air theatre script; the script outputs are two identical 3D *cavea* models, one suitable for Odeon (.dxf file) and the other for CATT-Acoustic (.geo file). In order to reduce the simulation time, the theatre geometry was simplified and designed as symmetric. Then, other elements were added, as shown in Figure 2. The lateral parts are the rests of the ancient entrances to the *orchestra* area: the caves were simulated as apertures (α_w = 0.9; *s* = 0). The floor includes *scaena frons* (ancient stage) and *orchestra* area: it was divided in two parts in order to take into account the presence of ruins in stage area (grass absorption; s = 0.8), while the *orchestra* floor still keeps its reflective properties (concrete absorption; s = 0.2). Finally, it was necessary to insert Odeon model in a boundary box[14], with α_w= 1 absorbing walls to simulate the open-air conditions.
In the prediction models, omnidirectional source and omnidirectional/ binaural receivers were defined as in the measurements, considering the theatre as unoccupied. Only source S1 and receiver R6 combination was considered in objective and subjective analysis (Fig. 2) presented in this article. Six alternatives were performed in each software considering different type of *cavea* stone, thus material properties were modified as follows:

- Scattering coefficient *s* of *cavea* stone: 0.25, 0.55, 0.75;
- Absorption coefficients α_w of *cavea* stone: 0.05, 0.10.

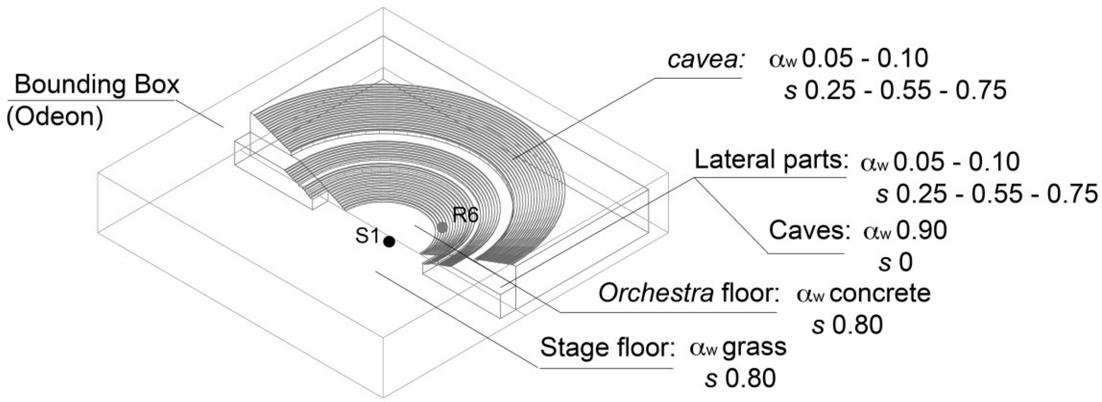

Figure 2. Theatre’s 3D model inserted in the boundary box, source-receivers and materials setup

In order to enable comparison between alternatives, the same settings were considered for all the simulations: 100 dB source sound power level, 1500 ms of impulse response length, 4 millions of rays. Specifically, in Odeon the Transition Order (TO) was limited to 1 to eliminate further image sources except the floor reflection[18]; despite this, a previous study[19] recommend instead TO equal to 2. About the scattering coefficients, Uniform directivity was enhanced, given that in this case Lambert and Oblique Lambert tends to radiate all power of 1^{st} order reflections out of the geometry. In CATT-Acoustic the third algorithm of calculation was chosen, as the most indicated for problematic open-air cases; diffuse reflections were introduced (surface + edges), while diffraction edges option was disabled (even if suggested in this case) in order to take into account the deep damages of the steps in actual conditions. Moreover, it was necessary to avoid in auralizations a typical “metallic” sound, coming in nature as echo from perfect periodical structures[20] and already attested in other ancient theatres simulations with CATT-Acoustic[21].

4 OBJECTIVE ANALYSIS

4.1 Comparative analysis on the impulse responses

An objective study was conducted on the two kinds of acoustic software under identical conditions. Measurements results were calculated and averaged from two consequent firecrackers IRs, while 6 simulated alternatives were performed in each software. Then, standard room acoustic parameters were calculated by analyzing measured and simulated IRs with software Dirac version 5[22] and Aurora version 44[23]. The following parameters were predicted for each model: Early Decay Time (EDT), Reverberation Time (T_{20}), Clarity (C_{80}) and Sound Strength (G). Their analysis was performed by comparing parametric results versus frequency. Moreover, as seen in reference[19], the following equation (1) was applied to evaluate the Error between measured and simulated Acoustic Parameters (AP). The Just Noticeable Difference (JND) for each room acoustic parameter is stated in ISO 3382-1[6].

$$Error = \frac{|AP\ measured - AP\ simulated|}{JND}\ [-] \qquad (1)$$

4.1.1 Objective results

Figures 3, 4, 5 and 6 report compared parametric values from measurements and software data (from now on called generally A and B). The frequencies interval chosen is 125 – 8 kHz, within the Internal Noise Ratio (INR)[6] was attested during measures; only in case of T_{20},125 Hz values* were not in compliance with standards. Symbols circle, rhombus and triangle refer to *s* of the simulated *cavea* stone, respectively 0.25, 0.55, 0.75, while continuous and spotted lines to α_w 0.10 and 0.05.

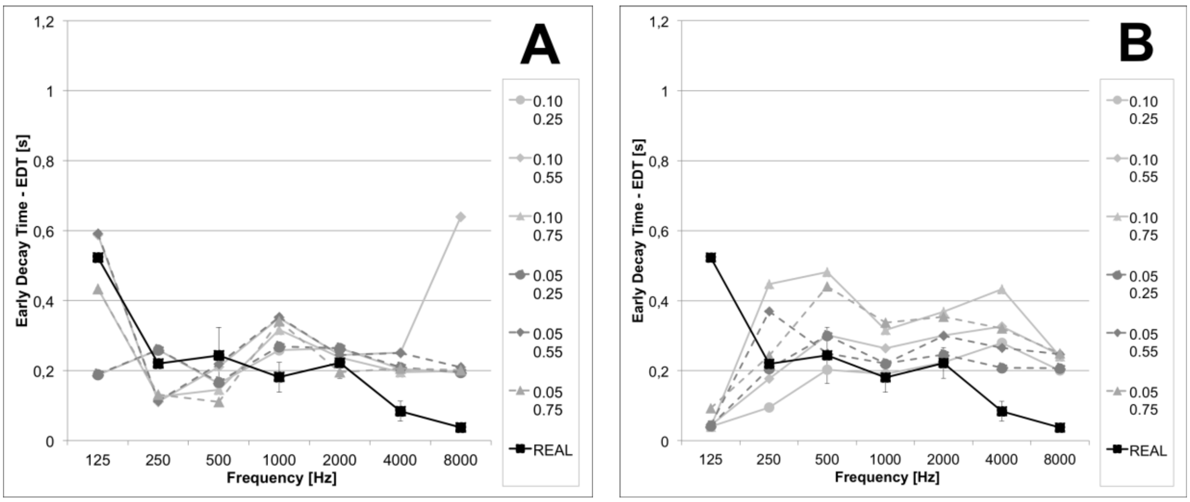

Figure 3. a) EDT values versus frequencies calculated for software A; b) for software B

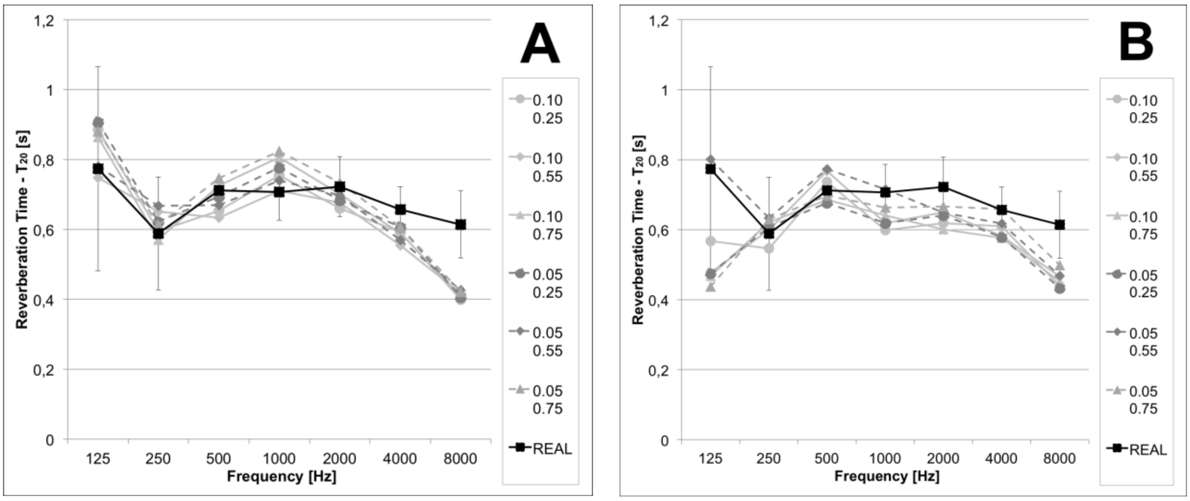

Figure 4. a) T_{20} values versus frequencies calculated for software A; b) for software B
*125 Hz values not in compliance with ISO 3382-1[6] in terms of INR

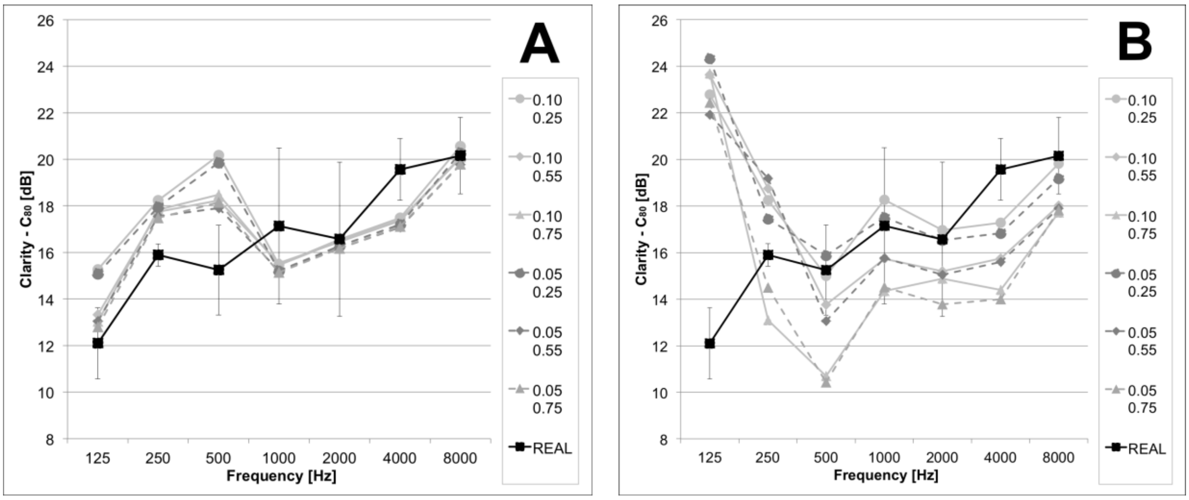

Figure 5. a) C_{80} values versus frequencies calculated for software A; b) for software B

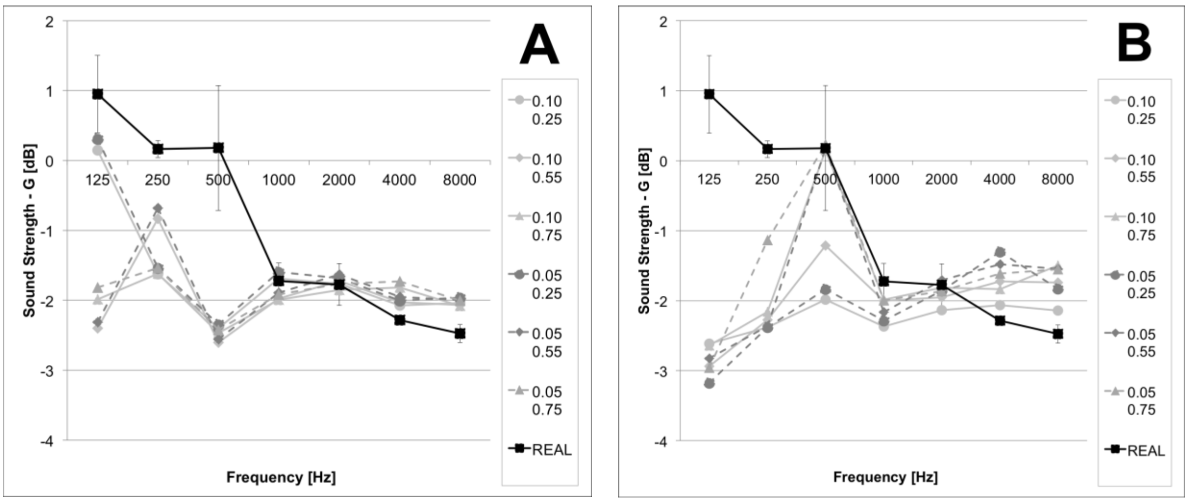

Figure 6. a) G values versus frequencies calculated for software A; b) for software B

For measurements values, Standard Deviation is reported on bars: it attests data variability at lower frequencies, especially in T_{20} and G values, due to open-air conditions.
Table 1 shows the Error with respect to the measured values, calculated for central frequencies (500 – 1kHz). Each alternative evaluated for A and B software is reported; values that do not respect the JND limits are in light grey.
Bold letters A and B evidenced in light grey are indicated as best simulated results, with EDT, T_{20} and C_{80} parameters under JND (G values were excluded since they revealed great variability at 500 Hz). In software A, coefficient *s* equal to 0.55 seems to be responsive in matching measured values, while in software B similar results are obtained with *s* equal to 0.25, for both coefficient α_w 0.10 and 0.05. With s equal to 0.75 slightly enhances are obtained in one case, but values except EDT are close to exceed JND limit.

Table 1. Error [-] between measured and simulated Acoustical Parameters ($AP_{500-1kHz}$).

Acoustical Parameters	α_w = 0.10 ; *s* = 0.25		α_w = 0.10 ; *s* = 0.55		α_w = 0.10 ; *s* = 0.75	
	A	**B**	**A**	**B**	**A**	**B**
EDT	0.0	0.1	0.3	0.3	0.1	0.8
T_{20}	0.1	0.6	0.5	0.2	0.8	0.7
C_{80}	1.6	0.4	0.7	1.4	0.8	3.7
G	1.8	1.9	2.1	1.4	2.0	0.7

Acoustical Parameters	α_w = 0.05 ; *s* = 0.25		α_w = 0.05 ; *s* = 0.55		α_w = 0.05 ; *s* = 0.75	
	A	**B**	**A**	**B**	**A**	**B**
EDT	0.0	0.2	0.3	0.1	0.1	0.8
T_{20}	0.4	0.9	0.1	0.5	1.1	0.4
C_{80}	1.3	0.5	0.4	1.8	0.5	3.7
G	1.7	1.8	2.0	0.8	1.9	0.6

5 SUBJECTIVE INVESTIGATION

5.1 Perceptual comparison

The following part of the research was conducted as a pilot study, which aimed at determining perceptual evaluation of auralized IRs compared to real ones in ancient theatres. The purpose is to understand if the differences assessed through objective standard parameters are perceivable subjectively. Moreover, the auralization could represent an instrument to detect typical sound phenomena of open-air theatre, as the echo.
This preliminary study was realized within 5 expert listeners through headphones, referring to same source-receiver combination analysed (S1-R6).

5.2 Stimuli preparation

The stimuli were created by convolving the binaural IRs obtained from Odeon and CATT-Acoustic simulations and those recorded in field. For binaural simulated IRs, Kemar Head-Related Transfer Function (HRTF)[24] was chosen as unique HRTF matching in both the prediction software. In order to remove the effect of the ear canal, in line with measurements documentation in field, it was then applied a diffuse-field equalization already present in the software. No headphones filtering was performed, since the frequency response of the headphones used during tests was already evaluated as acceptably flat. Recorded IRs were obtained with binaural microphone/ headphones (Roland CS 10-EM): they have been post-processed and cleaned, but it was not necessary to apply any inverse filter since the direct sound was already flat in frequency. This is confirmed by Figure 7, which shows the spectral continent of direct sound from simulated and recorded IRs (reported as omnidirectional for sake of easier comparison).
Two samples of anechoic recordings were chosen on the basis of contemporary typical performances in open-air theatres: a speaking person and an orchestra track ("Water Music Suite" – Handel/ Harty, Osaka Philarmonic Orchestra, Anechoic Orchestral Music Recordings, Denon). The speech sample was selected with sufficient signal energy in the frequency range from the 63 Hz to

the 2 kHz octave bands, while the music samples until 4 kHz; length chosen was 6 s. Finally, the same level was defined for each sample, in order to avoid effects of loudness.

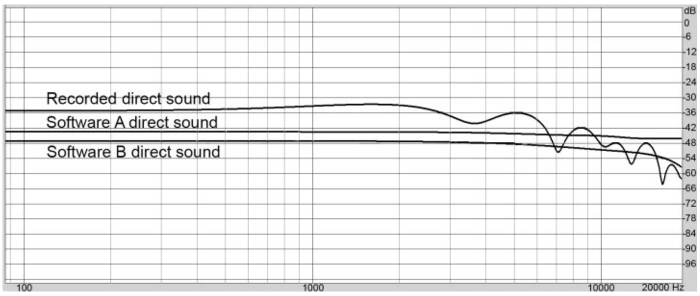

Figure 7. Spectral contents of direct sound, simulated and recorded omnidirectional IRs (0-20kHz). Direct Sound level was not normalized among the signal.

5.3 Subjective survey results

A first proposal of listening test was developed, through software IND-LisTEn[25] and the ABX Comparison Test was chosen. A and B are two signals: the question proposed is to recognize the X, which is another signal corresponding to A or B. In this case, signal A was an auralized stimulus simulated from Odeon or CATT-Acoustic, while signal B was the auralized stimulus recorded in field.

The test was organized in the anechoic chamber of the Department of Energy at Politecnico di Torino (Italy). The setup consisted in one computer position, a sound card Tascam US-144 and professional headphones Sennheiser HD600. Two samples from each software were chosen on the basis of the previous objective simulations best results:

- α_w = 0.10 ; s = 0.25
- α_w = 0.10 ; s = 0.55

Eight alternatives were obtained (2 samples from Odeon + 2 samples from CATT-Acoustic; 2 anechoic stimuli). Since the low number of listeners, 4 repetitions were introduced, for a total of 32 combinations that resulted in a 20 min of test length.

This first pilot test showed that simulations auralizations are perceived as different from those obtained in the real theater, as it was possible for each listener to correctly recognize signal X. However, it was common opinion that some simulated samples proposed in the test were quite similar to real measurements. These samples were lately recognized as the binaural IRs calculated with software B in conditions α_w = 0.10 and s = 0.25.

Thus, software B auralized samples with low scattering value (0.25) were generally recognized as the closest to real listening conditions.

6 CONCLUSIONS

The research presented in this article is based on the hypothesis that in open-air theatres scattered and diffuse reflections from the sharp edges of the stone seats play a significant role in the auditory perception. *In situ* measurements and simulations with two kinds of acoustical prediction software were conducted to investigate this argument.

Firstly, omnidirectional and binaural acoustical measurements were realized in the ancient theatre of Syracuse, chosen as study case; a strong impulsive sound source was provided in order to guarantee good SNR and sharp IRs. Then, prediction tools Odeon version 13.1 and CATT-Acoustic version 9 were both evaluated in their suitability to obtain good fit with real measurements from objective and subjective point of view. Geometrical details in the modelling part were confirmed as fundamental element of the simulation task. Six alternatives were proposed modifying *cavea* material characteristics (s and α_w values).

As objective results, the parametric study showed good matches between measured and calculated values for both software, but it was not possible to recognize a common trends with respect to the alternatives proposed. About the perceptual comparison conducted, the auralizations were firstly useful to reveal hidden sound effects due to specific parameters (i.e. metallic impression due to diffraction). The pilot test suggested a possible common link with objective parameters results. It also constitutes the basis for newer tests with different setups and more specific questions.

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