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TESTING OF COMMERCIAL SOFTWARE TO GENERATE SIMULATED IMPULSE RESPONSES FOR PERSONAL SOUND ZONES SYSTEMS

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ABSTRACT

Personal Sound Zones (PSZ) systems are used to create customized listening areas using loudspeaker arrays, achieving listening zones with different audio signals, without headphones. For this purpose, these systems are optimized to obtain a filter bank, with a filter for each loudspeaker, so that the array can generate an area in space with a particular sound (*bright zone*) and another where the sound of that emission is cancelled (*dark zone*), and vice versa for another sound. One of the biggest challenges for the widespread use of PSZ systems is that the construction of those filters requires a large set of precise source-receiver impulse responses, i.e., one for each array loudspeaker and multiple receiver points in the potential listening areas. Measuring these impulse responses is, however, very time-consuming, and usually requires expensive and high-quality acoustical instrumentation. In this communication, we present preliminary results of testing the reliability of the use of commercial room acoustics simulation software to obtain the required set of impulse responses, without performing in situ measurements. We evaluate the influence of different simulation setups (e.g., emitter/receiver directivities, environmental conditions, transition order, model calibration, etc.) on the performance of a PSZ system, in terms of acoustic contrast.

Keywords: *personal sound zones, room impulse response estimation, commercial software, testing performance.*

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1. INTRODUCTION

Personal Sound Zones (PSZ) systems are used to create multiple individual listening zones in a shared space using specially controlled radiation by an array of loudspeakers [1]. In the simplest case, a loudspeaker array emits controlled signals to produce two independent sounds in two separate listening zones. These zones are called the *bright zone* and the *dark zone*. PSZ algorithms usually create these listening zones by constructive and destructive interference between the signals from the different loudspeakers in the array at the different listening positions, which are achieved by designing a multichannel filter for the loudspeaker array.

Hence, a significant impediment to the straightforward implementation of dynamic PSZ systems in real-world scenarios is the fact that the controlled emissions from the loudspeaker array depend not only on the sounds to be emitted, but also on a large set of transfer functions from the various loudspeakers in the array to a dense set of control positions in each of the zones. In addition, if the environment is not anechoic, the sound field generated in the room (i.e., depending on reflections, absorption and scattering of materials, and overall reverberation) can make it very challenging the design of the digital filters for the loudspeakers that achieve the required interference at the listening points. In those cases, instead of the transfer functions between the loudspeakers and the measurement points, which could easily be calculated analytically, the real room impulse responses (RIRs) between each loudspeaker and each point are required.

Due to the large number of RIRs to be obtained and the

need for very precise positioning of the transducers at the measurement points, impulse response measurement is a very time-consuming and labour-intensive task that cannot easily be extrapolated to dynamic situations. For this reason, simulations of impulse responses are often used in early research stages of audio systems solutions, instead of measurements, to validate algorithmic changes. For instance, simulated IRs have been recently used in the training of machine learning algorithms to improve the robustness of PSZ and sound zone control (SZC) systems [2–4]. In many cases, these RIRs are obtained with simple and research-focused algorithms whose calculation is solely based on Geometrical Acoustics (GA) theory (although not ideal due to phase-related caveats) and, in particular, on the Image Source Method (ISM) with a very reduced set of simulation options. For instance, in some of these simulators the design of rooms with arbitrary geometries is rather challenging, and the same occurs when defining the acoustic behaviors (i.e., absorption and scattering coefficients) of specific sections of the boundary surfaces, such as to including furniture, accounting for loudspeaker directivity, etc. However, several of these factors are expected to have a significant impact on the performance of PSZ systems in real-world environments.
However, although originally developed for other applications, several commercially available software solutions based on GA, characterized by relatively low computational cost, allow for the use of accurate geometric models, flexible definition of acoustic properties (e.g., material absorption and scattering), and possibility of including source directivity, among others.
This study aims to investigate whether the inclusion of various simulation parameters, often treated with limited accuracy in some simplified acoustic simulation tools, leads to the generation of simulated RIRs that significantly improve the performance of PSZ systems.

1.1 Method

To this end, a set of RIRs was measured in a controlled room using a linear array of loudspeakers and two rectangular arrays of microphones as it is shown in the top picture of Fig. 1.
A second set of measurements, using an omnidirectional source, was carried out at several positions in the same room as shown in Fig. 2 (picture of setup) and Fig. 3 (scheme of the measurement locations). These last responses were used to calibrate a GA simulation model in Odeon, as it will be explained in Section 2. Once the room model was calibrated, Odeon was used to replicate, by simulation, the RIRs measured with the setup formed by the loudspeaker and microphone arrays of Fig. 1.

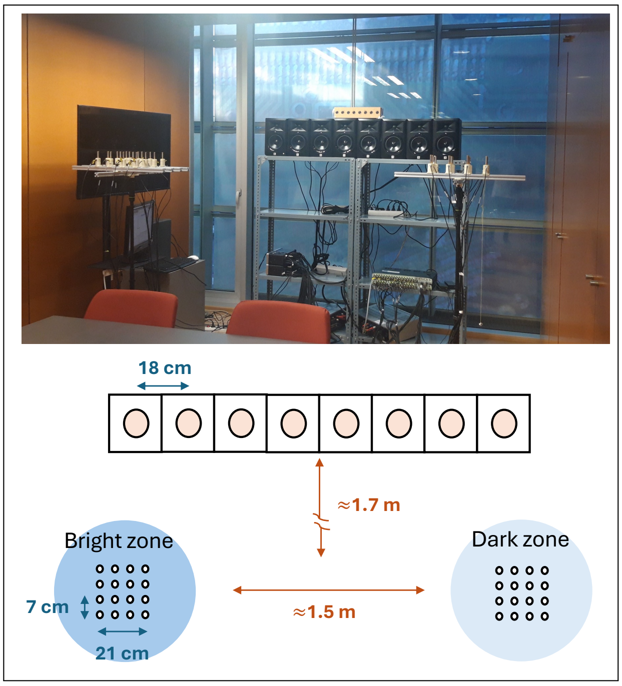


Figure 1: Picture (top) and scheme (bottom) of the experiment room for PSZ validation.

Then, we evaluated the performance of the PSZ system when the filters for the loudspeaker array were computed using the simulated RIRs under various modeling conditions. The Acoustic Contrast (AC), the ratio of the spatial-averaged energy obtained in the *bright* and *dark* zones respectively, has been calculated for simulated RIRs with and without source directivity, with and without atmospheric conditions modeling, using different transition orders (i.e., 0, 2 and 10), and considering both material-calibrated and uncalibrated room models. This approach enables a systematic analysis of the influence that relevant acoustic parameters can have on the reliability of PSZ system design, particularly when simulated data are used as a surrogate for real-world measurements in the early development stages.
For the definition of AC along the frequency range, consider $\mathbf{g}_l(n)$ the FIR filter designed by the PSZ system for the lth loudspeaker, and $\mathbf{h}_{li}^{\mathrm{B}}(n)$ and $\mathrm{h}_{li}^{\mathrm{D}}(n)$ the RIR between loudspeaker lth and microphone ith of the *bright* (B) and *dark* (D) zones, respectively. Then, assuming the

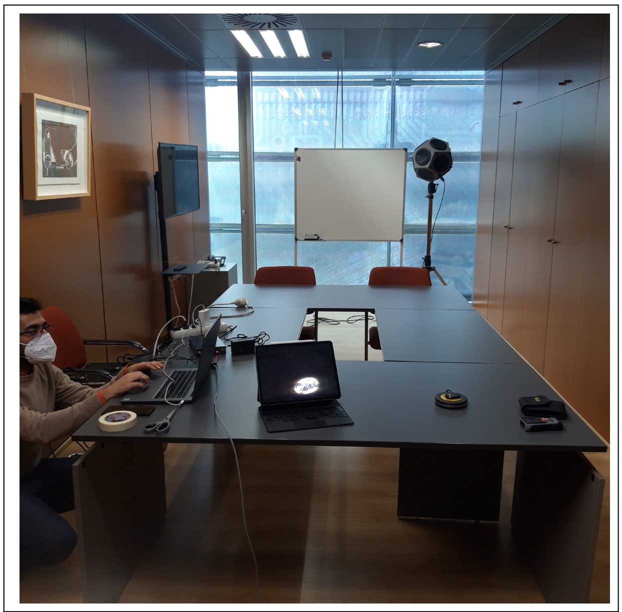


Figure 2: Experiment room with omnidirectional source during RIR capture for model calibration.

signal fed to the loudspeakers is an impulse, $\delta(n)$, the signal received at the ith microphone in both $\{\mathrm{B},\mathrm{D}\}$ zones is given by the superposition of the filtered signals emitted by the eight loudspeakers (see Fig. 1) as

$$p_i^{\{\mathrm{B,D}\}}(n) = \sum_{l=1}^{8} \mathbf{g}_l(n) * \mathbf{h}_{li}^{\{\mathrm{B,D}\}}(n)\,, \tag{1}$$

whose Fourier transform is given by

$$P_i^{\{\mathrm{B,D}\}}(f) = \sum_{l=1}^{8} G_l(f) H_{li}^{\{\mathrm{B,D}\}}(f)\,. \tag{2}$$

Consequently, the AC between the mean energy of the *bright* and *dark* zone for frequency f is defined as

$$\mathrm{AC}(f) = \frac{\frac{1}{M_B}\sum_{i\in B} |P_i^{\mathrm{B}}(f)|^2}{\frac{1}{M_D}\sum_{i\in D} |P_i^{\mathrm{D}}(f)|^2} = \frac{\sum_{i\in B} |P_i^{\mathrm{B}}(f)|^2}{\sum_{i\in D} |P_i^{\mathrm{D}}(f)|^2}\,, \tag{3}$$

where the number of microphones in the *bright* zone, M_B, and the *dark* zone, M_D, is 16 each.

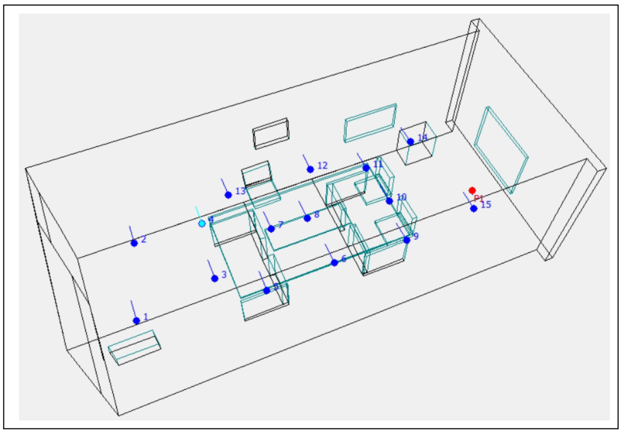


Figure 3: Odeon model with the omnidirectional sound source (red) and the receivers (blue).

2. COMMERCIAL SOFTWARE: ODEON

2.1 General description

The RIRs required to evaluate the impact of the various simulation features on the performance of the PSZ system were derived using the Odeon acoustic simulation software. Odeon is one of the fundamental acoustic simulation software designed for room modeling. At its core, Odeon is designed for simulating the acoustic behavior of enclosed spaces and for deriving room acoustical parameters, but it is not primarily intended to generate RIRs that are sound in terms of their phase and, therefore, that are ideal for many audio processing applications. As such, it relies on energy-based rather than pressure-based estimations of the sound field [4]. To construct impulse responses from reflectograms, Odeon assigns an arbitrary polarity to each reflection. However, in [4] it is said that this sign is consistently applied for a reflection across all receivers within the simulated environment.

Odeon applies GA theory to determine the acoustical behavior between virtual sources and receivers within a particular environment. Specifically, Odeon implements a hybrid geometrical acoustics algorithm that combines the ISM with ray-tracing techniques [5]. Early reflections are calculated using a method that blends the specular reflections from the ISM with a technique known as the Early Scattering Method (ESM). Beyond a certain transition order (to), Odeon employs a ray-based algorithm referred to as the Ray-Radiosity Method (RRM).

The long-standing development, widespread use, and commercial availability of Odeon make it highly acces-

sible and user-friendly. Furthermore, it provides extensive configuration options that enable energy-based estimations to closely approximate the perceptual implications of room acoustics, such as reverberation time, clarity, and spatial distribution of sound. However, it does not simulate the detailed sound field in the same way as some wave-based methods.
For example, the geometry of the room and the absorption and diffusion properties of boundary surfaces and objects within the space can be specified with a high degree of flexibility. The acoustic properties of sound sources can also be defined with considerable precision. In addition, Odeon allows for the inclusion of atmospheric conditions in the simulation environment, which can influence the propagation of sound. All these parameters are incorporated by Odeon in the calculation of propagation directions, arrival times, and the energy of reflections reaching a given receiver within the room.
All of this seemed to make Odeon an appropriate reference platform for systematically evaluating the impact of specific simulation parameters on system behavior, in contrast to more constrained simulation tools with reduced modeling granularity.

2.2 Parameters

Specifically, the following aspects were investigated:

- Room Calibration Accuracy: we evaluated the impact of using a plausibly dressed model (i.e., one in which surface materials were assigned based on expert knowledge) versus a calibrated model, in which the absorption properties of surfaces were optimized using built-in Odeon Genetic Material Optimizer [5] to achieve simulated room acoustical metrics (T_{20}, C_{50} and D_{50}) within approximately one Just-Noticeable Difference (JND) of the measured values near the PSZ receiver positions.
- Atmospheric Conditions: the influence of including actual atmospheric conditions, measured on the same day as the *in situ* RIR measurements, was assessed by simulating both with and without atmospheric conditions. This allowed for an analysis of the extent to which temperature and humidity could affect the PSZ performance with simulated RIRs.
- Transition Order: the effect of the transition order, which defines the switch from ISM + ESM to RRM [5], was analyzed by obtaining analogous RIRs with different transition orders of 0 (i.e., RRM alone), 2 and 10 ($t_o \in \{0,\ 2,\ 10\}$). Considering the temporal accuracy of ISM, it is expected to obtain better PSZ performance with ISM than with the stochastic RRM.
- Source Directivity: we examine the influence of the array directivity by comparing simulations assuming omnidirectional radiation with those incorporating the actual directivity patterns of the real transducers used in the PSZ array, a factor known to be critical for accurate sound field control.

3. TESTING

3.1 Room description

The experiment was conducted in a meeting room at the Audio Lab of the Institute of Telecommunications and Multimedia Applications (iTEAM) of the Universitat Politècnica de València (see Fig. 1 and Fig. 2) with approximate dimensions of $7.8\,\mathrm{m}$ (length) × $3.0\,\mathrm{m}$ (width) × $2.6\,\mathrm{m}$ (height).
Most of the room's surfaces are acoustically reflective, including a glass curtain wall located in the front wall and hard wooden side walls and floor. The ceiling consists of a suspended grid with metal-protected panels. The wall opposite the curtain wall features a wooden door, a window facing the corridor, and a wooden-paneled section. Additionally, the room contains a central wooden table and a set of chairs.
Two different sets of impulse responses were harvested in the room. The first, for which an omnidirectional sound source (as shown in Fig. 2) was used, captured RIRs with receivers distributed throughout the room, and was intended to be used for the calibration of the simulation model. Microphone positions are marked by blue points in Fig. 3. The second set of measured RIRs used the loudspeaker and microphone arrays shown in Fig. 1 and are meant to be used for PSZ validation. Geometrical distances between the loudspeakers and microphones inside their respective arrays, and between the line of speakers and the front line of microphones are also given in the scheme shown at the bottom of Fig. 1. Finally, the separation of the center points of the *bright* and *dark* zones was approximately $1.5\,\mathrm{m}$.
The room exhibits a reverberation time (T_{20}) ranging from $0.40\,\mathrm{s}$ to $0.62\,\mathrm{s}$ in the range from 125 to 4000 Hz. Clarity (C_{50}) and Definition (D_{50}) values were measured at $6.93\,\mathrm{dB}$ and 0.82 on average, respectively. Expected spatial variability in these parameters was observed de-

pending on source-receiver configuration and proximity to room surfaces.

3.2 RIR simulation design

A geometric model of the room was created in Odeon based on precise distance measurements, incorporating the room boundaries and all objects with acoustically representative surfaces. Elements with noticeable thickness were modeled accordingly, even when their dimensions were below typical modeling guidelines [6], given the simplicity and low surface count of the space. Surface materials were assigned based on expert knowledge.
The model was then duplicated and one version was calibrated using Odeon's Genetic Material Optimizer to minimize discrepancies in terms of T_{20}, C_{50} and D_{50} (measured vs simulated responses), obtaining differences close or below one Just-Noticeable Difference (JND) for the three parameters, particularly at receiver positions close to the PSZ grids' locations. Calibration used an omnidirectional source and receivers at positions that matched those of the first set of measurements (see Fig. 2 and Fig. 3).
Then, the loudspeaker and microphone arrays of the PSZ system were subsequently placed in both the calibrated and non-calibrated models for the extraction of simulated RIRs, matching their real position in the room (Fig. 1).
The loudspeakers' directivity patterns had previously been measured in anechoic chamber and were imported into Odeon with the $10°$ resolution supported by the software. Distinct directivity profiles were applied to central and side loudspeakers to account for the influence of the array's physical configuration on the radiation of adjacent transducers.
Atmospheric conditions measured on the day of the recordings (Fig. 1) were also incorporated into the simulation. In the model without atmospheric contribution, this feature was explicitly disabled in Odeon.
The transition order, which defines, as explained before, the switch between deterministic and stochastic reflection modeling, was varied from 0 to 10. This study reports results for orders 0, 2 (Odeon's default [5]), and 10.
The duration of the impulse response was set to $1000\,\mathrm{ms}$, sufficiently long relative to the reverberation of the room. In the auralization setup, the *unity HRTF* was selected to obtain omnidirectional impulse responses (regarding the receiver), and headphone inverse filters were disabled.
All other simulation parameters were left at Odeon's recommended defaults based on the characteristics of the model.

3.3 PSZ

As said before, PSZ systems aim to deliver a particular sound to the designated *bright* zone while canceling it out in the *dark* zone by using arrays of loudspeakers. To achieve this, a set of filters must be designed to process the audio signals that are fed to the loudspeakers. Various techniques have been explored to compute the filters for acoustic energy control. Among these approaches, the Acoustic Contrast Control (ACC) algorithm [7] stands out as the method capable of achieving the highest degree of isolation between the designated *bright* and *dark* zones. However, a notable limitation of the ACC approach is its inability to synthesize a specific target response within the *bright* zone. To address this shortcoming, the Weighted Pressure Matching (wPM) algorithm was proposed [8–10]. This technique offers the advantage of enabling the rendering of a target response in the *bright* zone, while still maintaining control over the acoustic energy in the *dark* zone. Therefore, the wPM algorithm has been used to design the PSZ filters and to compute the AC performance for each simulation condition.
By default, impulse responses exported from Odeon are individually normalized, removing the relative amplitude differences between responses, which is essential for interdependent systems such as PSZ. To address this, the responses were amplitude-compensated prior to their use in the PSZ's filter training to preserve their relative scaling. Compensation factors were extracted from Odeon's text output files.
Furthermore, a fixed number of samples was trimmed from the beginning of all impulse responses to compensate for the delay introduced by the internal filtering process of Odeon during the generation of RIRs [5]. This delay was experimentally determined in a virtual identical but anechoic room, based on the expected arrival time of the direct sound.

3.4 Results

This section presents the PSZ system performance results, in terms of AC (3), for the various simulation parameter configurations described earlier in Section 2.2. Unless explicitly stated otherwise, results correspond to the condition in which the PSZ filters' design was performed using Odeon-simulated RIRs, while validation was carried out with the set of real RIRs measured in the experimental room using the PSZ system. The order of presentation follows the logical sequence of decisions typically made when designing a virtual model and generating RIRs in

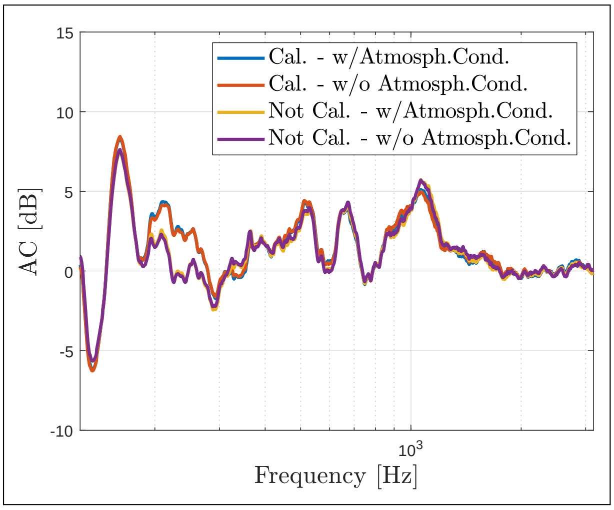


Figure 4: AC for different conditions: with or without model calibration and considering or not accurate atmospheric condition.

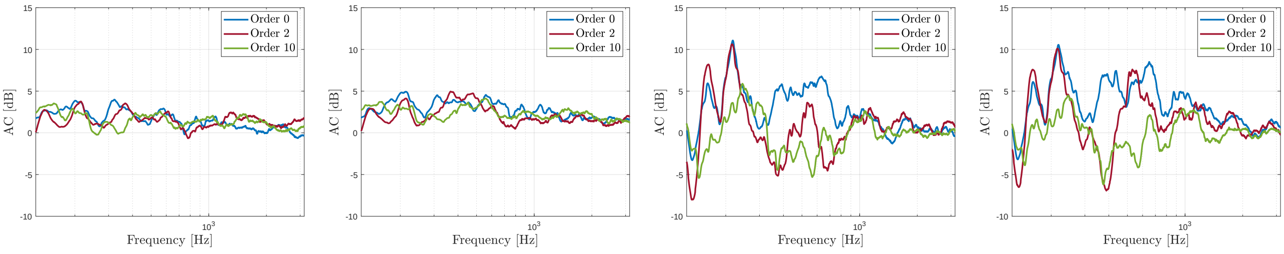
a simulation environment. Accordingly, results are first shown for the effect of model calibration and the inclusion of atmospheric conditions, followed by the impact of source directivity and transition order.

Due to space limitations and for the sake of brevity, the effects of model calibration and atmospheric conditions are reported only for transition order $to = 2$ and assuming omnidirectional loudspeaker directivity. This configuration was selected as the baseline for analyzing the impact of calibration and atmospheric conditions, since $to = 2$ is the default setting in Odeon and the use of omnidirectional sources avoids confounding the results with source directivity effects.

As shown in Fig. 4, model calibration labelled as "Cal." (i.e., adjusting the acoustic properties of the simulation surfaces to better match the behavior of them in the real room) can have a significant impact on system performance, even in comparison to an uncalibrated model ("Not Cal.") that already featured plausible material assignments. This outcome, while expected, shows that good calibration is fundamental to improve PSZ performance. This observation is consistent with the underlying mechanism of PSZ systems, which relies not only on the direct path but also heavily on early reflections to design the filters. When these early reflections have an amount of energy relevant in physical terms, the filters obtained with the simulated responses are more likely to generalize effectively to real-world conditions. In this regard, Odeon proves to be particularly useful, as it includes a built-in genetic optimization algorithm (Odeon Genetic Material Optimizer) that, given a set of measured RIRs, automatically adjusts the absorption coefficients of the model room surfaces to minimize discrepancies, in terms of JNDs, between simulated and measured room acoustic parameters across multiple receiver positions.

As it can also been seen in Fig. 4, the inclusion of atmospheric conditions in the model, labelled as "w/ Atmosph. Cond.", leads to a slight improvement in the performance of the PSZ system, in comparison to that obtained when the RIRs are simulated in Odeon with this feature disabled. However, it is considered that even this slight improvement should be highlighted, as its reduced relevance in this case is likely due to purely physical factors: since the loudspeaker array is relatively close to the sound zones, propagation losses in air are minimal. Nonetheless, given the negligible effort required to monitor and incorporate these parameters into the simulation, their inclusion is recommended, particularly in scenarios involving greater source-to-receiver distances, where such effects may become more relevant. In this regard, it is also recommended that acoustic simulation tools that do not currently support atmospheric conditions, consider implementing this feature in future releases.

The difference in AC when training the PSZ system with simulated RIRs that incorporate the actual directivity of the array loudspeakers, as opposed to assuming omnidirectional radiation, is shown in Fig. 5. It displays four subplots: (a) and (b) show AC results when training and validating with simulated RIRs using measured directivity (a) and omnidirectional (b) patterns, respectively, and will be explained later. Subplots (c) and (d) present the corresponding results when validation is performed using real RIRs. Interestingly, and as seen in the comparison between (c) and (d), incorporating real loudspeaker directivity (c) into the simulation did not yield a substantial improvement in this experiment. While some differences can be observed, especially in the frequency smoothness of the AC curve, they are not significant in magnitude. One plausible explanation is the relatively short source–receiver distance (approximately $1.7\,\mathrm{m}$), where the direct path dominates, and the impact of directivity on early reflections may be reduced. Nevertheless, this result needs further investigation, as loudspeaker directivity is a parameter with strong theoretical relevance and one that Odeon allows to be modeled with considerable precision, in contrast to simpler simulation tools.



(a) (b) (c) (d)

Figure 5: AC obtained when source directivity ((a) and (c)), or omnidirectional sources ((b) and (d)) are considered in the simulation model to compute filters $\mathbf{g}$ in (1). AC obtained when simulated ((a)-(b)) or real ((c)-(d)) RIRs, $\mathbf{h}_{li}$, have been used in (1).

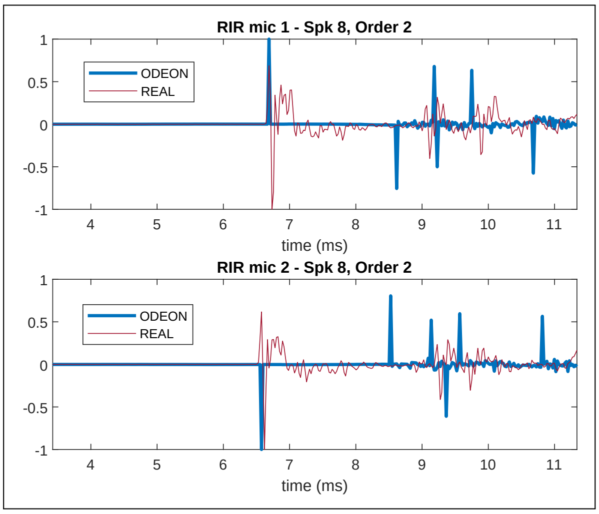


Figure 6: Comparison between simulated ($to = 2$) and real RIRs from loudspeaker 8 to microphones 1 (top) and 2 (bottom) of the *bright* zone. Responses are amplitude-normalized for visualization.

Finally, regarding the influence of the transition order, simulated RIRs with $to = 0$ yielded, in general, higher AC (see Fig. 5) than those obtained with higher transition orders (i.e., $to = 2$ and $to = 10$). While higher orders employ the IMS for early reflection prediction, which is typically expected to improve temporal accuracy in the description of the reflections and, therefore, in PSZ performance, a temporal analysis of the simulated RIRs (Fig. 6), in contrast to the measured ones, reveals a critical point: in our experiment, only for $to = 0$ the direct paths preserve consistent polarity across receivers, whereas in higher orders (see Fig. 6 for $to = 2$ and two different receivers), in contrast to what would expected considering [4], polarity appears randomized for all rays, including the direct path. This behavior is likely a key factor underlying the observed differences in PSZ performance across transition orders.

While a random polarity of the late reflections is theoretically unlikely to have a significant perceptual or functional impact, applying a random polarity to the early reflections, or even to the direct path, seems to cause severe degradation of the filters designed for array processing systems. Since early reflections, and particularly the direct path, play a critical role in the filter optimization, introducing random polarity at this stage may undermine the effectiveness of simulated RIRs for PSZ applications. For this reason, we recommend that simulation tools ensure consistent polarity, at least for the direct sound path.

To further investigate the impact of random polarity assignment in direct paths, additional results are presented in Fig. 5 (a) and (b) showing the PSZ performance when both training and validation are carried out using the same simulated RIRs. In principle, this configuration should yield high AC values, as the filter optimization and validation are based on identical data. However, the resulting AC remains relatively low, reinforcing the hypothesis that the random polarity of direct paths may impair system performance.

It is worth noting that the PSZ algorithm used in this study has achieved significantly higher AC values (12 dB in average) when both training and validation were performed using real measurements.

4. CONCLUSIONS

PSZ systems rely on large sets of impulse responses for filter training. However, acquiring these responses through *in situ* measurements is a highly demanding task, not often feasible prior to the installation of the PSZ system in specific environments.

For this reason, acoustic simulation algorithms, most commonly based on the Image Source Method, are frequently used to approximate these responses. However, many such algorithms do not allow for precise inclusion of key factors such as room-specific atmospheric conditions or source directivity.

In this study, we evaluated the influence of various simulation parameters on the performance of a real PSZ system, for which actual RIRs were available. Odeon was selected as the simulation platform due to its ability to accurately model atmospheric conditions and source directivity, offer user control over simulation methods, and perform automatic calibration to match the acoustic characteristics of a real space.

Results showed that calibrating the room model improved the quality of the simulated RIRs and led to better PSZ system performance. The inclusion of atmospheric conditions was also found to have a potentially meaningful effect. Surprisingly, little difference was observed in PSZ performance between using virtual omnidirectional sources and using the real directivity of loudspeakers in the simulation model, despite the theoretical expectation of a stronger impact. Finally, we found that the way Odeon seems to handle the polarity of early reflections, and especially the direct path for $to > 0$, can limit the usefulness of simulated RIRs for array processing applications. Besides this, overall, the extensive configurability of Odeon was found to be well-suited for the generation of simulated training data for PSZ applications. In this regard, we recommend alternative designers of RIR simulation algorithms to incorporate certain features, particularly those linked to source directivity, atmospheric conditions, and calibration capabilities.

5. ACKNOWLEDGMENTS

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