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# Plane wave decomposition as a tool for interactive modification of measured sound fields and their adaptation to different reproduction systems

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## ABSTRACT

The plane wave decomposition of sound fields recorded by microphone array measurements delivers a detailed view on their spatio-temporal structure. For the analysis of room impulse response measurements, different spatial resolutions can be used for the time sections of direct sound, early reflections and diffuse reverberation. The early part of the sound field is analyzed using a high spatial resolution, while the late part is analyzed using a lower spatial resolution. Sound engineers and acousticians can use a visualization of the analysis results to determine room characteristics. In this paper, an approach for the interactive modification of measured impulse responses for auralization purposes is presented. In addition to analysis, plane wave decomposition is a powerful tool for the synthesis of different sound fields. Methods for efficient reproduction of (modified) impulse responses, by multi-channel systems driven by virtual main microphone signals, and by binaural setups will be discussed.

## INTRODUCTION

Room simulation based on impulse responses is well established in the field of audio engineering and sound design. Several tools are available and several projects have been dedicated to the optimization of measurement and recording techniques [1]. Hulsebos [2] has proposed the use of circular microphone arrays for auralization and developed ideas and methods to do this auralization in Wave Field Synthesis (WFS) format. However, in his work the interactive modification of such measurements was not covered. Tools that are available today do not provide possibilities to include direction dependency of room characteristics in the modification process. For the measurement of room impulse responses several systems and methods have been proposed. In measurement situations these are often used simultaneously [1]. As a result, different reproduction systems require different data and the modification of the impulse responses is related to the specific reproduction system. The system proposed in this paper aims to offer interaction possibilities based on direct interaction with a graphical representation of impulse responses. The sound engineer should be given the same direction dependent room design possibilities for different reproduction scenarios including WFS, multi-channel audio and binaural reproduction. The system utilises visualization, interaction and processing models, which are known to engineers from their recording practice and adapt them as close as possible to make use or their knowledge and experience.

## PLANE WAVE DECOMPOSITION

### Principles

To enable a reproduction system independent interaction, analysis of the spatio-temporal structure of the sound field with high spatial resolution is required. One possibility is to calculate a plane wave decomposition of the microphone array measurement. The calculation of plane wave decomposition of circular array measurements has been studied by Spors, Hulsebos et al.

[2] [3]. This is the basis for interaction and adaptation. In this work we use a plane wave decomposition based on cylindrical harmonics. However, the principles described in this paper are not limited to this kind of pre-processing. Interaction and adaptation can also be applied to three dimensional analysis and measurements. Because of the used circular measurement system and for practical reasons like measurement time, a two-dimensional approach has been chosen. The measurement of a circular array with an outward pointing cardioid microphone can be expressed as a combination of a pressure-sensitive monopole microphone and a velocity-sensitive dipole microphone [4]:

$$S(k_\varphi,\omega,R) = \frac{1}{2}\left(P(k_\varphi,\omega,R) + j\rho c V_n(k_\varphi,\omega,R)\right). \qquad \text{(Eq. 1)}$$

$P(k_\varphi,\omega,R)$ and $V_n(k_\varphi,\omega,R)$ are the pressure and the normal velocity on the perimeter with radius $R$ of the microphone array. In [5] it is shown that, based on the measurement, in case of a source free volume, the response of the microphone can be expressed as:

$$S(k_\varphi,\omega,R) = Q(k_\varphi,\omega)\left[H^{(1)}_{k_\varphi}(kR) + H^{(2)}_{k_\varphi}(kR) - jH^{(1)'}_{k_\varphi}(kR) - jH^{(2)'}_{k_\varphi}(kR)\right]. \qquad \text{(Eq. 2)}$$

$Q(k_\varphi,\omega)$ are the expansion coefficients of the sound field in terms of cylindrical harmonics while $H^{(1)}_{k_\varphi}$ and $H^{(2)}_{k_\varphi}$ are Hankel functions of the first and second kind; $k$ is the wave number, $k_\varphi$ is an integer indicating the order of the cylindrical harmonics. $H^{(1)'}_{k_\varphi}$ and $H^{(1)'}_{k_\varphi}$ are the derivatives of the Hankel functions. It can be shown that, in far field approximation, the plane wave decomposition of the sound fields in terms of cylindrical harmonics is given by Eq.3, while $\varphi$ represents the angle of incidence of the plane wave:

$$S_\infty(\varphi,\omega) = \frac{1}{\pi}\sum_{k_\varphi}(-j)^{k_\varphi}\, Q(k_\varphi,\omega)e^{jk_\varphi\varphi}. \qquad \text{(Eq. 3)}$$

**Limitations**

The plane wave decomposition is limited by two main factors. The aperture of the measurement array gives a lower limit of the usable frequency range and an upper limit exists as:

$$f_n = \frac{c}{2\Delta x} = \frac{cn}{4\pi R}. \qquad \text{(Eq. 4)}$$

In case of a circular array with 512 measurement positions $n$ on a 1m radius $R$ the upper frequency limit is $f_n \approx 13.5kHz$. In case of a circular array measurement the plane wave decomposition is limited to give an exact result only for the horizontal direction. This can be enhanced as presented in [5] and overcome by the use of 3D arrays and corresponding plane wave decomposition [6]. For a detailed discussion on the limitations of cylindrical harmonic decomposition the reader is referred to [3].

**Visualization and Interaction**

The plane wave decomposition (PWD) allows analyzing the sound field inside the reconstruction area of the array used for the impulse response measurement in terms of horizontal directions. This makes it a suitable tool for intuitive visualization and interaction. By plotting the plane wave decomposition in a circular surface, the sound engineer can easily identify directions of high energy (reflections). For sharper imaging, Hulsebos proposed the focusing of the plane wave decomposition; if applied in a travel-time dependent way the visualization as a whole becomes very sharp. A focussing decomposition was presented in [13] and adapted to circular arrays in [2]. Figure 1A presents the plane wave decomposition of a measured sound field in a circular plot. After applying the travel-time dependent focusing and a reduction of angular bandwidth to 64 directions the result presented in figure 1B can be used for visualization. Beside this direction dependent visualization it is possible to extrapolate the impulse response in the middle of the array with virtual microphone techniques using omni-directional virtual microphones as described later in this paper. Such an extrapolated single impulse response can be used to analyze general room parameters like reverberation time etc. Based on the plane wave decomposition, the sound field can be modified direction dependently. This enables the modification of spaciousness-related parameters such as lateral efficiency From a sound design point of view new possibilities are introduced, e.g., creating virtual rooms with different reverberation times for different directions or a definition depending on the direction. It has to be emphasized again that these new principles are not limited to a signal processing approach based on cylindrical plane wave decomposition.

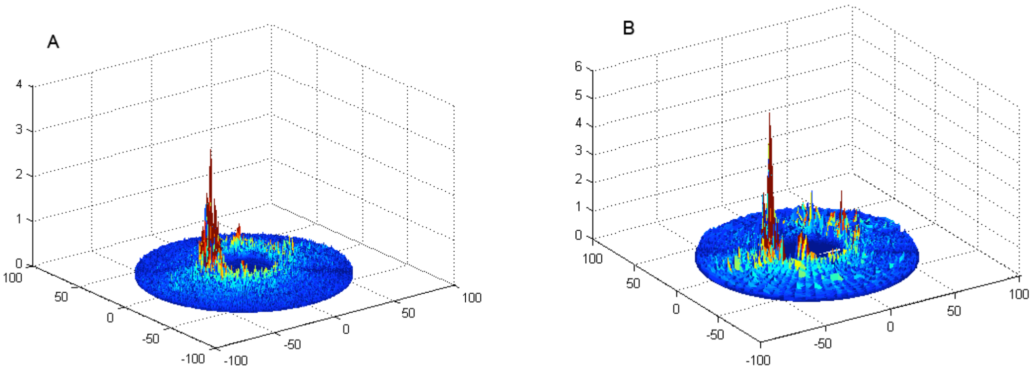

Figure 1: Visualization of the early part of a measured impulse response including direct sound. A: Plane wave decompositions in a circle plot. B: Plane wave decompositions with moving focusing and reduced angular resolution (The x-axis and y-axis indicate the traveling distance in meter the z-axis the amplitude).

The interaction in the spatial domain follows the well-known interaction principles "*select and modify*". In detail the following steps are required for the sound designer:

- Select an angle area (From one PWD direction to the whole room)
- Select a time range
- Choose a tool for the visualization and modification of the selected area, e.g., with a filter envelope as proposed in [7]
- Process and deselect

Figure 2 presents the plane wave decomposition with a selected area in a red frame and the resulting impulse response, which will be modified.All modifications are applied to the direction dependent impulse responses separately.

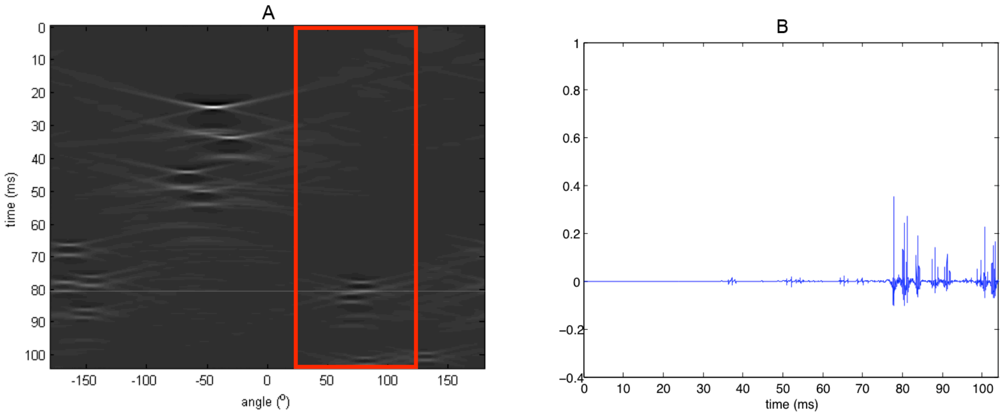

Figure 2: Simulation of a mirror image source model.
A: Plane wave decompositionsin a user-selected area. B: Corresponding impulse response for interactive modification in a frequency range of 500Hz to 10kHz

## REPRODUCTION AND ADAPTATION TO DIFFERENT REPRODUCTION SYSTEMS

The plane wave decomposition and its modification can be adapted to different reproduction systems. Adaptation to a WFS system [8] has been proposed by Hulsebos [2]. Hulsebos also proposed an adaptation to a multi-channel speaker layout. In the present work a new system is proposed for the adaptation to multi-channel systems – the use of virtual microphones and the adaptation for a binaural reproduction.

### Virtual microphones

High quality recording of a real acoustic environment for multi channel reproduction evolves the use of room microphones or/and main microphones. Since the beginning of stereophonic recording and reproduction several microphone setups like AB, XY or ORTF have been proposed. These techniques are also common in surround recording by using a combination of 2 stereo configurations for the left and right channel and the left surround and right surround channel [14]. Based on the knowledge in 2-channel stereo recording several proposals have been made for stereophonic surround systems like 5.1 setups. Setups proposed by Theile and Wittek [15], Williams [12] et al. are well established and their characteristics are known by the sound engineers. Baarsch proposed in [9] the use of microphone setups as panning laws. He described a system to pan dry sources by defining a virtual main microphone using arbitrary directivities, positions and direction of microphones. The system makes use of the sound engineer’s knowledge in terms of positioning dry sources. In case of room reproduction the plane wave decomposition can be used to create an arbitrary directivity pattern in the horizontal plane, analogue to the adaptation of the B-Format to virtual microphone characteristics [10]. In contrast to the possibilities of the B-Format which is used to generate directivities by combining 1st order directivities of figure-of eight microphones in three directions with an omnidirectional microphone, the plane wave domain is not limited to generate coincident virtual microphones. The coincident microphone configurations are achieved by applying a direction dependent weighting [2]. To generate the impulse response of a non-coincident main microphone setup the plane wave decomposition is extrapolated to the required microphone positions. This is possible in the range of the reconstruction area of the recording array. Figure 3 presents a block diagram of the required processing steps. The processing is done in the frequency domain.

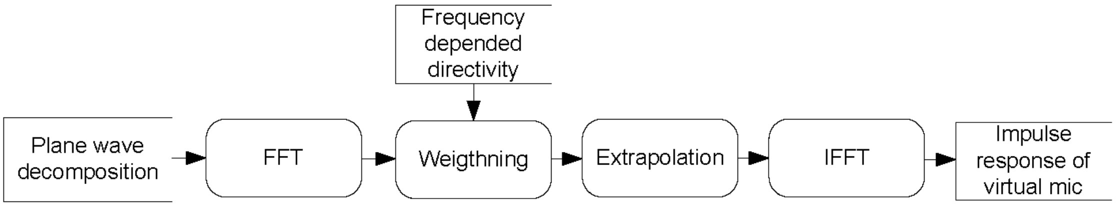

Figure 3: Block diagram for the virtual microphone processing.

The sound pressure in a point $P(r,\theta,\omega)$ can be extrapolated to any position based on plane wave decomposition by the use of:

$$P(r,\theta,\omega)=\int_{0}^{2\pi} S_{\infty}(\varphi,\omega)e^{-jk\,r\cos(\theta-\varphi)}d\theta \quad . \qquad \text{(Eq. 4)}$$

In addition to the extrapolation with an omnidirectional characteristic an ideal frequency independent directivity of the virtual microphone can be introduced in the equation using:

$$g(\varphi)=\beta+(1-\beta)\cos(\varphi+\alpha) \quad \text{With} \quad \beta\in[0,1] \;\; \alpha,\varphi\in[0,2\pi] \qquad \text{(Eq. 5)}$$

Using the factor $\beta$ the directivity can be varied between omnidirectional and figure-of-eight. To enable a rotation of the virtual microphone the rotation angle $\alpha$ has to be introduced. For a more realistic microphone simulation, $g(\varphi)$ can be made frequency dependent $G(\varphi,\omega)$ using the characteristics of known microphones resulting in:

$$P(r,\theta,\omega) = \int_0^{2\pi} G(\varphi,\omega) S_\infty(\varphi,\omega) e^{-jk\; r\cos(\theta-\varphi)} d\theta \quad . \qquad \text{(Eq. 6)}$$

The results of the processing are presented in figure 4. The basis was a two-dimensional mirror image source model for which the impulse response on a circle of 1m radius and 512 positions were calculated. Figure 4A shows the response of the first microphone of the circle. After calculating the plane wave decomposition and an extrapolation to the position of the first microphone we get the result presented in figure 4B. This figure presents the ideal case. In real situations errors are introduced by three-dimensional components in the sound field, which will not be extrapolated properly. The most prominent events have to be separated and extrapolated taking the characteristics of elevated sources into account like described earlier [5]. Another error source is the limited bandwidth of such a measurement, which was also explained. Figure 4C and 4D present a simulation and extrapolation for a three-dimensional mirror image source model of the same room as before.

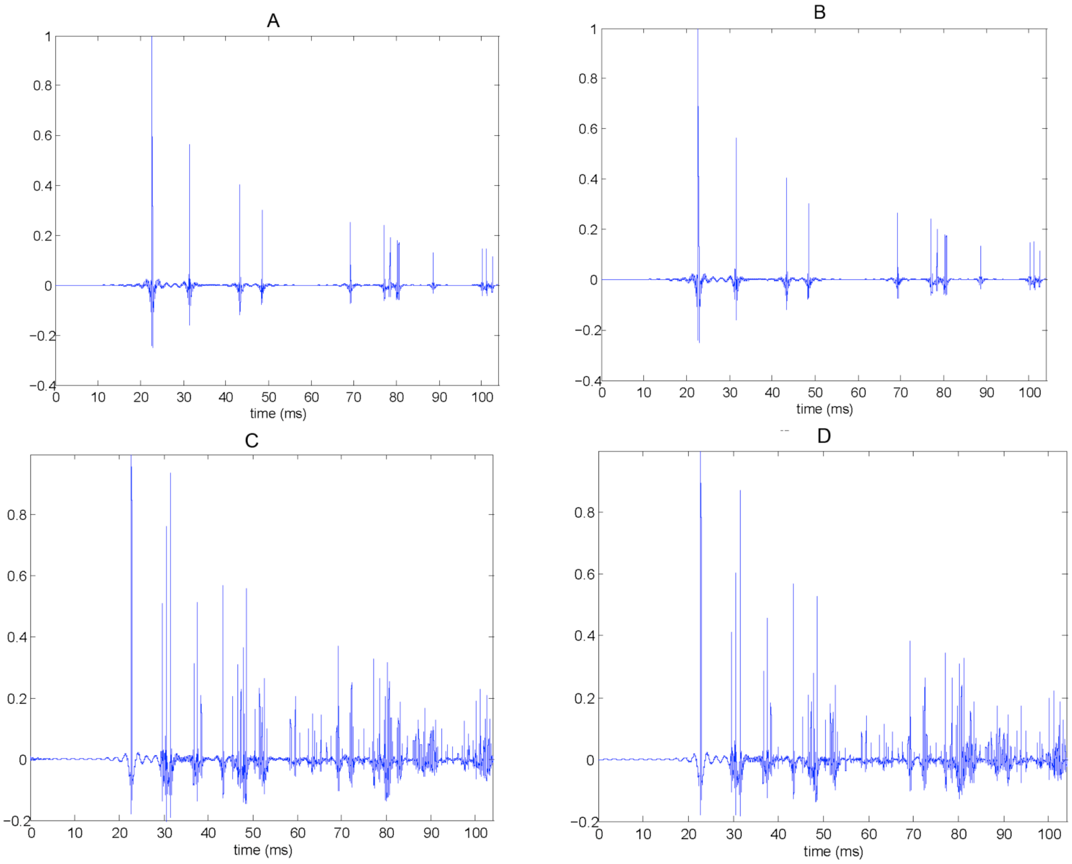

Figure 4: Simulated impulse responses of a 2D-MISM (A/B) and a 3D-MISM (C/D).
A/C: First impulse response of a simulated circular array measurement.
B/D: Virtual microphone impulse response for the same position.
All diagrams show the frequency range from 500Hz to 10kHz.

## Binaural reproduction

Another possibility for audio reproduction are binaural systems. In previous work a system for the binaural measurements of acoustic environments has been presented [11]. The binaural room scanning enables the data based simulation of acoustic environments. In such a system a reproduction situation is measured with a dummy head in high angle resolution. In the reproduction situation a head tracker is used to detect the position of the listener's head and the correct measured head related transfer function (HRTF) is picked and convolved with the input signal. The measured data always depend on the dummy head or a person used for the measurement. By combining circular array measurements with such technique this restriction can be overcome. One important point is the simplification to one horizontal layer in case of a circular array. How different array measurements can be combined is out of the scope of this paper but can be one solution. In case of a binaural reproduction the plane wave decomposition can be used in combination with head related transfer functions. To obtain the impulse responses for the left and right ear $P_L(\omega)$, $P_R(\omega)$ the plane wave decomposition components are convolved with their corresponding HRTFs $H_L(\varphi,\omega)$ and $H_R(\varphi,\omega)$ as well as integrated of the angle of incidence:

$$P_L(\omega) = \int_0^{2\pi} H_L(\varphi,\omega) S_\infty(\varphi,\omega) d\varphi \qquad \text{(Eq. 7)}$$

$$P_R(\omega) = \int_0^{2\pi} H_R(\varphi,\omega) S_\infty(\varphi,\omega) d\varphi \qquad \text{(Eq. 8)}$$

Because of this two step approach the measured data of the room are independent of the used HRTFs, which can be changed and individualized without repeating the room measurement. The comparison of this approach with binaural measurements is part of current research.

## CONCLUSIONS AND FUTURE WORK

In this paper a method for interactive modification of plane wave decompositions was presented. Besides the interaction and visualization an adaptation to different reproduction systems has been shown. The proposed methods provide the basis for an interactive room sound design system. In the next step of this research the proposed methods will be analyzed based on measurements and subjective tests. The efficient storage of the measurement data is also part of the future work.

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