# WAVE FIELD SYNTHESIS INTERACTION WITH THE LISTENING ENVIRONMENT, IMPROVEMENTS IN THE REPRODUCTION OF VIRTUAL SOURCES SITUATED INSIDE THE LISTENING ROOM

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**ABSTRACT**

Holophonic sound reproduction using Wave Field Synthesis (WFS) [1] aims at recreating a virtual spatialized sound scene in an extended area. Applying this technique to synthesize virtual sources located within an indoor environment can create striking audio effects in the context of virtual or augmented reality applications. However, interactions of the synthesized sound field with the listening room must be taken into account for they cause modifications in the resulting sound field. This paper enumerates some of these interactions according to different virtual scene configurations and applications. Particular attention is paid to the reproduction of the sound source directivity and to the reproduction of a room effect coherent with the real environment. Solutions for synthesizing the directivity of the source and the associated room effect are proposed and discussed around simulations, developpements and first perceptual validation.

## 1. CONTEXT

This research has been conducted in the context of the CARROUSO project [2] which is supported by European IST. It aims at providing methods and technologies to create or record a static or dynamic sound scene, to transfer it to a remote place where it can be reproduced with high fidelity regarding the original spatial and perceptual properties of the sound field.

Rendering of the sound scene focuses on Wave Field Synthesis in order to accurately restore spatial information and to maintain spatial coherence over a larger area in comparison with standard 5.1 or even stereo setups.

A commonly identified problem when rendering spatialized sound scenes is the compensation of the listening room. A general overview of the problem in the case of WFS rendering is described in a previous paper [3]. It is shown that, thanks to WFS properties, early reflections can be partially reduced over a large area in the listening room. Another quoted possibility is to take into account the acoustics of the listening environment and anticipate its consequences by pre-modifying the virtual acoustics parameters defined in the sound scene description.

In this paper, the room interaction problem is approached from a different standpoint. We consider the particular case where the WFS is used to create virtual sound sources located inside the listening environment. In order to achieve a fully convincing presence effect of the sound source, the room effect associated to the synthesized source should sound as coherent as possible with the actual acoustic properties of the listening environment. It is known for example, that in real situations the room effect will depend simultaneously on the shape and acoustical properties of the boundaries and also on the directivity characteristics of the source.

After reminding the general features of WFS rendering, the paper exhibits the main reasons for the discrepancy between the natural room effect and the room effect which is automatically generated when synthesizing the virtual sound source. It is shown for example, that this difference depends on the characteristics of the synthesized virtual sound source. The paper presents different solutions for improving the reproduction of sound sources located inside the listening environment.

Firstly, it addresses the problem of synthesizing the radiation pattern of the simulated sound source. This method has been implemented on a real WFS installation and some informal test could confirm its effect. Secondly, other methods are proposed in order to compensate for the absence of some important room effect contributions.

## 2. THREE DIMENSIONAL RADIATION OF LOUDSPEAKER ARRAYS USING WAVE FIELD SYNTHESIS

Wave Field Synthesis is a holophonic reproduction format derived from Huygens' principle and its mathematical formulations (Kirchoff Helmholtz and Rayleigh integrals). These formulations suggest the use of a continuous distribution of secondary sources located on a surface $S$ separating the source space, where primary sources are located, and the reproduction space, where the sound field produced by the primary sources is accurately recreated [4] [5].

Wave Field Synthesis is derived using an infinite plane for $S$ on which a continuous distribution of sources is placed.

Practical implementation of such a system involves several simplifications that modify the effective radiated sound field:

- reduction of the infinite plane to a line to focus the reproduction domain on the horizontal plane.
- restriction of the infinite line to a segment therefore limiting the area of correct reproduction.
- discretization of the distribution of sources that restricts the frequency band in which the sound field is correctly reproduced because of spatial aliasing effects.

These simplifications have influence on the effective three dimensional radiated soundfield:

- The reduction of the infinite plane to a line causes the emission of a soundfield that manifests a symmetry around the axis of the loudspeaker array.

- The restriction of the infinite line to a segment introduces windowing effects due to the visibility of the virtual sound source through the loudspeaker array. The loudspeaker array tends to focus the emitted sound field to the visibility area and diffraction occurs.
- The discretization of the distribution of sources involves a completely different behavior of the loudspeaker array above the spatial aliasing frequency (impossibility of focusing on the visibility area, "diffuse" soundfield).

## 3. INTERACTION OF VIRTUAL SOURCES WITH THE LISTENING ROOM

### 3.1. Analysis of a typical rendering situations

In order to introduce the problem addressed by this paper we consider two characteristic examples of a simple sound scene where the room interaction need to be accurately controlled. Both situations depicted on figure 1 refer to the reproduction of a virtual sound source within a concert hall and using a WFS array. In each case, the goal is to create the illusion of a sound source located on stage. The application could be either the superimposition of a phantom source within a live music ensemble, or the sound enhancement of one of the music instrument with an accurate spatial coherence between the real source and its enhanced sound.

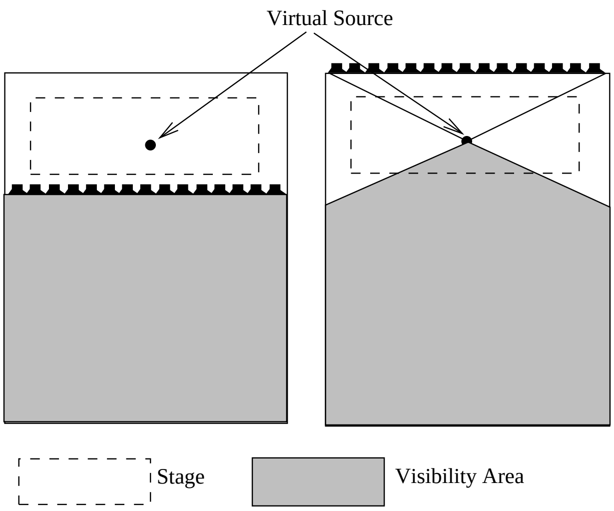


Figure 1: *WFS setups for creation of "on stage" virtual source*

On the left part of figure 1, the WFS array is installed in front of the stage (actually just above or below). Locating a virtual sound source on stage means giving the illusion to the listeners situated inside the reproduction area that a punctual sound source is emitting from behind the loudspeaker array. The reproduction of such virtual sources behind the transducer array is covered by Huyghens' principle. One can observe that the entire listening area is fed by the direct signal emitted by the virtual sound source.

On the right part of figure 1, the WFS array is installed behind the stage. Locating the virtual sound source on stage means giving the illusion that a punctual sound source is emitting in front of the loudspeaker array. This type of virtual source, refered as "focused source" is not covered by Huyghens' principle. However, using phase inversions, one is able to partially reconstruct the wave front emitted by a source situated in front of the WFS array. Obviously, the wave field cannot be correct between the virtual source position and the loudspeaker array. But, once again, the area where good reproduction can be expected may cover a large part of the audience as illustrated in figure 1.

### 3.2. Analysing discrepancy between real and virtual situations

Firstly, it is known that the radiation characteristics of an instrument is part of its acoustical signature and is important for auditory perception. On the one hand it is obviously responsible for the characteristics of the direct sound according to the orientation of the instrument. On the other hand, it will also influence the different room effect contributions : first reflexions and late reverberated field. All these aspects being clearly relevant for auditory perception it is interesting to look for an extension of WFS rendering that would address the synthesis of source radiation.

Secondly, it is clear from figure 1 that although the reproduction area can cover the whole audience area, some parts of the room boundaries are not lit up correctly by the synthesized sound field. In other words, if the sound field synthesized by the WFS was an exact reproduction of the one produced by the physical source, the room effect generated by the synthetic field would automatically be equivalent to the natural one. As described in part 2, the practical implementation of WFS has strong influence on the effective radiated soundfield in terms of spatial windowing and aliasing frequency.

For example, on the right part of figure 1 the major difference is the absence of the first order reflexion coming from the front wall since it receives no energy from the direct sound radiated by the virtual source. The side walls are also partially affected by windowing. One can observe that the frontal sections of the side walls are not fed by direct sound emanating from the reproduced source, as would be the case for a real source situated at the same position.

This, of course, is only true if the wave front being focused on the source by the louspeaker array is coherent, i.e. below the spatial aliasing frequency. Above the spatial aliasing frequency, loudspeakers situated along the front wall radiate high frequency energy along the side walls due to the diffuse properties of the aliased sound field. It can be remarked that the side walls also receive low frequency energy due to sound waves diffracted by the front loudspeaker array.

In light of these observations, we propose a method for compensating the lack of these room effect contributions in part 5.

## 4. DIRECTIVITY CONTROL OF VIRTUAL SOURCES

WFS usually considers virtual sources as monopoles or plane waves which is a limit case of a monopole at a large distance. True sources usually exhibit complex directivity characteristics. Therefore, realistic reproduction of a source should consider as well this aspect.

### 4.1. decomposition of source radiation

The 3 dimensional sound field radiated by a an acoustical source can be decomposed on spherical harmonics. These functions provide an orthogonal basis that can describe any radiation characteristics [6].

In the context of WFS, linear distribution of loudspeakers are used. Though radiating in 3 dimensions, the WFS loudspeaker array focuses on the correct reproduction in a horizontal plane. Therefore, the reproduction of a directivity with WFS should consider the 2D representative of spherical harmonics that are called cylindrical harmonics. There directivity functions are:

$$\begin{aligned} Y_m^1(\theta) &= \cos(m\theta) \quad pour\ m >= 0 \\ Y_m^{-1}(\theta) &= \sin(m\theta) \quad pour\ m >= 1 \end{aligned} \tag{1}$$

### 4.2. Multichannel equalization for WFS

Multichannel equalization for WFS reproduction has been introduced in [7]. Loudspeakers exhibit complex directivity characteristics that modify the effective radiated sound field. This process has been developed to compensate for this problem in the virtual source visibility area of the horizontal plane.

The sound field produced by the loudspeaker array is described with acoustical measurements of each driver by a microphone array. Impulse responses that correspond to the radiation of a target virtual source are specified at the microphone positions. A multichannel iterative procedure is used to obtain filters that minimize the quadratic error of the produced sound field at the microphone positions. Above the aliasing frequency, individual equalization of the drivers, combined with energy control of the produced sound field, is used.

In contrary to classical equalization techniques, this process controls *the produced sound field* in a given listening area and compensates accurately the angle dependent deficiencies of every element of the loudspeaker array.

The multichannel equalization process can be adapted to the reproduction of directive sources by specifying impulse responses that correspond to a given directivity. Using the fact that a directivity function can be decomposed in spherical/cylindrical harmonics, we propose to derive filters for a set of cylindrical harmonics for each virtual source positions. These filters are calculated in an offline process and are stored in a database that can be accessed by the virtual position and the cylindrical harmonics order.

A given directivity can thus be recomposed by applying the coefficients of its cylindrical harmonics decomposition to the calculated filters.

### 4.3. Reproduction of directive source using multichannel equalization

This process has been applied to WFS reproduction on MAP loudspeaker panels. The setup is composed of 4 adjacent MAPs that forms a 32 elements loudspeaker array. This setup has been measured on a linear microphone array made of 48 omnidirectional elements. The target source is located at 5 m from the origin of the coordinate system and is centred toward the loudspeaker array. It reproduces a cylindrical harmonic of order 5. The figure 2 displays the geometry of the setup and the position of the source.

Figures 3 and 4 display the impulse and frequency responses of the MAP array at the microphone positions. They have been obtained by processing the measured impulse responses of the MAP array with the filters obtained from the multichannel equalization process.

It can be noticed on figure 4 that the frequency response of the source is accurately reproduced up to the aliasing frequency (approximately 1200 Hz). Above that corner frequency, the sound field gets diffuse as for omnidirectional sources in WFS reproduction.

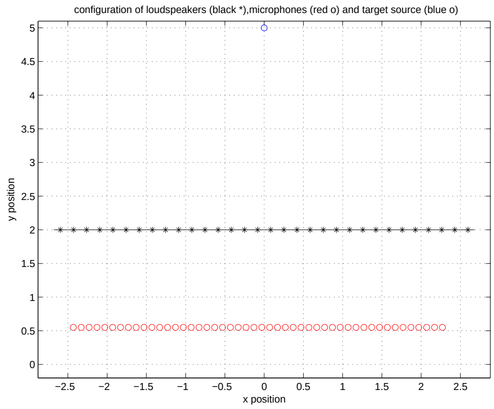


Figure 2: *MAP reproduction setup. Crosses correspond to the loudspeaker positions, red circles to the microphones and the blue circle to the target source*

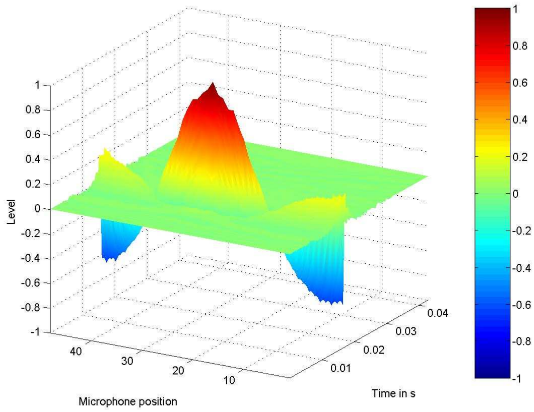


Figure 3: *Low pass filtered impulse responses of a 5th order cylindrical harmonics*

In figure 3, the impulse responses have been low pass filtered with a corner frequency at 1200 Hz (aliasing frequency). It can be seen that the 3 lobes are properly reconstructed below the aliasing frequency with the accurate phase properties.

## 5. PROPOSED METHOD FOR COMPENSATING LACK OF ROOM EFFECT IN THE CASE OF INSIDE SOURCES

This section describes an evaluation of the primary reflections that are absent when synthesizing focused sources using WFS. In [8] it is shown that first order image sources along the ceiling, floor, and back wall of the listening room can be approximated as being correctly reproduced by a WFS system. However, first order image sources along the front and side walls are absent. As a consequence, their progeny is also absent; this implies the absence of entire clusters of reflections originating from the frontal and lateral zones of the listening room.

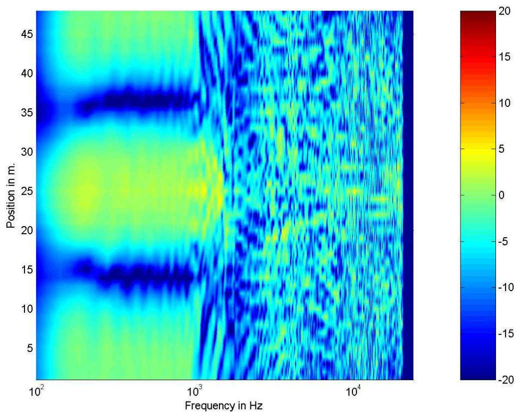


Figure 4: *Frequency responses of a 5th order cylindrical harmonics*

We propose an approach for recreating the primary reflections lacking along the front and side walls when reproducing focused sources by WFS:

- **Front wall:** One can generate a virtual image source on the other side of the front wall to artificially recreate the primary reflection that is present in the case of a real source. Seeing as this section of the room is invisible to direct sound radiated by the focused source at all frequencies, one must account only for absorption coefficient when adding the virtual image source.
- **Side walls:** By adding extensions to the loudspeaker array along the frontal sections of the side walls, one can also generate virtual image sources in these sections. The artificial reproduction of side wall reflections must however be restricted to the zone that was previously shown to be unfed by the direct source signal. Moreso, an assessment of the energy radiated by the frontal loudspeaker array onto the side walls at low frequencies (diffraction) and at high freqencies (spatial aliasing) should be made. This will allow us to determine the quantity of energy already present on side walls before reinjecting artificial image sources.

Figure 5 illustrates the injection of virtual image sources to account for the lack of primary reflections in WFS reproduction of focused sources. This automatically generates the progeny of these primary reflections and therefore reproduces a coherent room effect.

## 6. CONCLUSION

After having analysed the reproduction of virtual sources using a WFS system in an indoor environment, we have exhibited two principal lacks in the reproduction of inside sources: the radiation properties of the source and the lack of some contributions of the room effect. A method has been introduced for the synthesis of the sound source radiation based on the reproduction of a subset of cylindrical harmonics. The method relies on an adaptation of the multichannel equalization algorithm to compensate for the acoustical characteristics of the loudspeakers. We also described a method using virtual image sources to artificially inject early reflections that are otherwise absent in the WFS reproduction of inside sources. These techniques may allow for more realism in the resulting rendering.

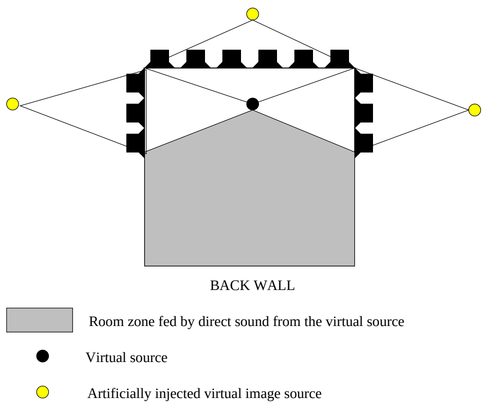


Figure 5: *Artificial injection of virtual image sources using loudspeaker arrays along front and side walls of the listening room.*

## 7. REFERENCES

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