Influence of the Listening Room on Spectral Properties of Wave Field Synthesis

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Introduction

The derivation of most sound field synthesis techniques assumes an anechoic listening room. Without significant effort this cannot be fulfilled in practical installations. As a consequence of the additional reflections imposed by the listening room, the synthesised sound field differs from the target sound field. This contribution discusses the implications of a reflective listening room on the sound field created by Wave Field Synthesis (WFS) with focus on spectral changes. Results from simulations using the image source model (ISM) and measured room impulse responses (RIRs) of a multi-channel loudspeaker array, both with varying wall absorption, are presented. From these simulations conclusions on perception of colouration are drawn. Room reflections smooth the comb filtering effects caused by spatial aliasing due to a discretised secondary source distribution. This can alleviate the system-induced colouration. In a small room, room modes cause colouration in the low frequency range. The excitation of room modes in WFS depends on type and position of the virtual source.

Limitations of Wave Field Synthesis in practice

WFS aims at synthesising a desired sound field usually inside a secondary source distribution (SSD) [1]. In practice, this technique suffers from violations of theoretical assumptions. One is the reduction to monopoles only on the SSD leaving out the dipoles demanded by theory. This simplification is due to the fact that monopoles can be approximated quite well by loudspeakers in a closed box while dipole loudspeakers are difficult to construct. With monopoles only the desired sound field inside the SSD can be achieved nevertheless, but now an outer field arises that would have been cancelled when utilising dipoles as well. The existence of the outer field is relevant in practice because a WFS array is typically installed in a reflective environment here termed a listening room instead of being employed under free field conditions as theory demands. The outer field is then reflected back inside the SSD and changes the target sound field.

Another violated assumption from theory is the impossibility of a continuous SSD. Instead, discrete loudspeakers have to be used which constitutes spatial sampling along the SSD and leads to spatial aliasing artefacts [2]. When considering broadband excitation, these artefacts form additional wave fronts that follow the desired first wave front. The additional wave fronts appear to be similar to room reflections as they are delayed and filtered copies of the direct sound [3]. Both the first wave front as well as the artefacts are reflected by the surrounding listening room which leads to an unnatural and dense RIR of a virtual source as the spatial aliasing artefacts fill in the early reflections of the room [4]. The reflected spatial aliasing artefacts show their impact also in the frequency domain which is discussed in this contribution.

Spectral standard deviation as predictor for colouration

Due to the spatial aliasing artefacts, WFS shows comb filter-like spectral fluctuations above the so-called aliasing frequency which depend on the spacing of the loudspeakers as well as on the positions of virtual source and receiver [2]. The spectral fluctuations are the reason for the colouration of this reproduction technique. For quantifying the extent of the spectral fluctuations, the standard deviation (STD) of the magnitude spectrum in dB can be used. This quantity has also been used to serve as a predictor for colouration in various studies alongside another measure based on the autocorrelation function [5]. It has in particular been proven as a suitable predictor for colouration in a room-in-room scenario [6] as well as in WFS under free field conditions [7].

Spectral properties of virtual sources in a listening room

The spectral properties of WFS in a listening room are assessed by simulations of virtual point sources synthesised by discrete linear loudspeaker arrays inside simple rectangular rooms. The contribution of the room is either simulated by the ISM [8] or based on measured RIRs. Loudspeaker driving functions have been calculated using the Sound Field Synthesis Toolbox[1] [9].

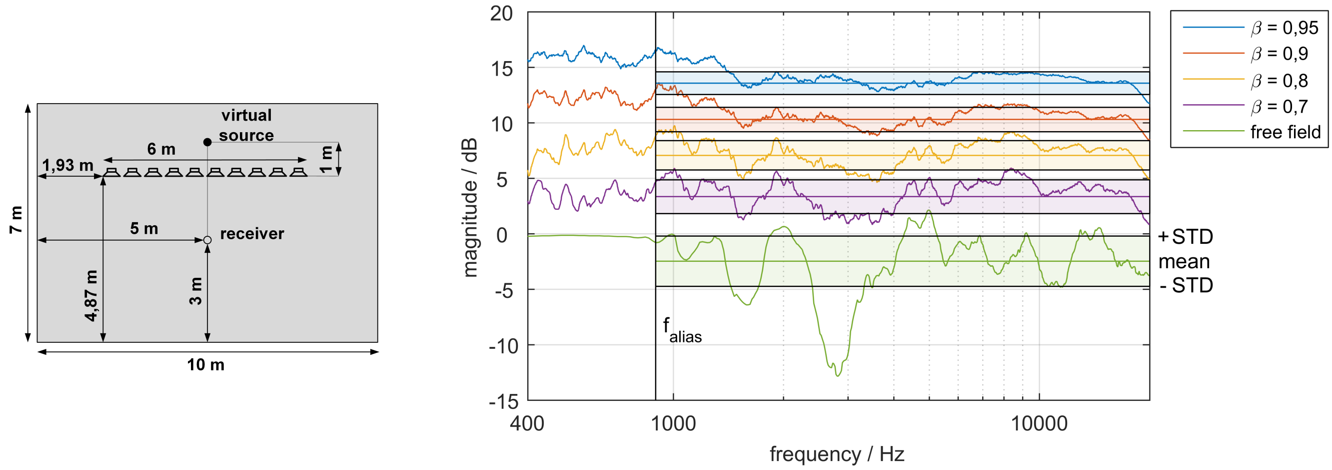
Setup for simulated loudspeaker RIRs

The setup for room simulations with the ISM is shown in fig. 1 (a). The linear loudspeaker array is 6 m long and consists of 31 loudspeakers spaced by 20 cm. The slight asymmetry of the setup avoids too idealised results of the ISM. With the smallest distance of a source or receiver to a wall of only 1.40 m, low frequency evaluations of the results are not valid due to approximations of the ISM. The walls of the room are assigned with frequency independent reflection coefficients β equal to all walls.

Results for simulated loudspeaker RIRs

Fig. 1 (b) shows the results of simulating the frequency response of the virtual point source at the receiver po-

[1] `http://github.com/sfstoolbox/sfs-matlab`, release 2.3.0



(a) Setup of linear array of 31 monopoles in listening room. Height of room is 3 m. Array is positioned 1,60 m above the ground with virtual source and receiver in the same horizontal plane.

(b) Magnitude responses of the virtual source at the receiver position for varied uniform reflection coefficients of the listening room of fig. 1 (a) and in free field. Standard deviations (STD) and means above the aliasing frequency f_{alias} have been calculated based on linearly spaced frequency bins. Magnitude responses are smoothed in third-octave bands and have been shifted along the y-axis for ease of inspection.

Figure 1: Simulation of a virtual point source in a listening room simulated with the image source model with varied reflection cofficients compared to free field conditions – setup and resulting magnitude responses.

sition of the setup in fig. 1 (a) for different reflection coefficients of the walls of the listening room compared to free field conditions. The magnitude responses are smoothed in third-octave bands and shifted along the y-axis for ease of inspection. As can be seen, the desired sound field in the free field case shows strong spectral fluctuations above the aliasing frequency. In comparison, the magnitude responses for WFS in the listening room show less spectral fluctuations the higher the reflection coefficient becomes. Thus, it can be concluded that room reflections are smoothing the spectral fluctuations caused by spatial aliasing.

To quantify this effect, the STDs of the magnitude responses in dB have been calculated. While calculation based on logarithmically spaced frequency bins might be more suitable for the auditory system, the STDs calculated here based on linearly spaced frequency bins sufficiently demonstrate the effect of reduction of the spectral fluctuations. The STDs are included in fig. 1 (b) as intervals around the means of the magnitude responses in dB starting from the aliasing frequency f_{alias}. It can be seen that the STD is getting smaller with increasing reflection coefficient of the walls of the listening room. Fig. 2 shows this effect with the STD dependent on reverberation time. The reverberation times have been calculated for the room of fig. 1 (a) for several reflection coefficients in between $\beta = 0.7$ and 0.95 according to Sabine [10] via the equivalent absorption area. The results show clearly that stronger reflections decrease the spectral fluctuations quantified by the STD of the magnitude response in dB above f_{alias}. As the STD is a predictor for colouration, it can be concluded that reflections reduce the colouration induced by the reproduction technique WFS due to spatial aliasing.

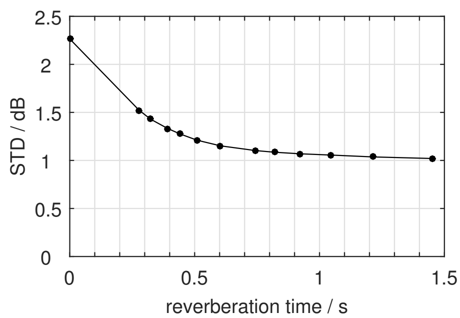
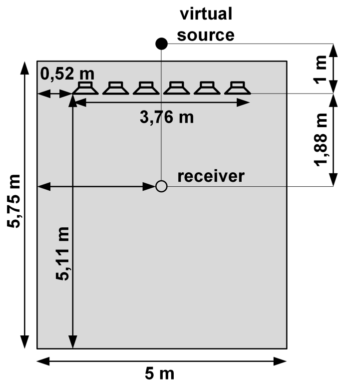


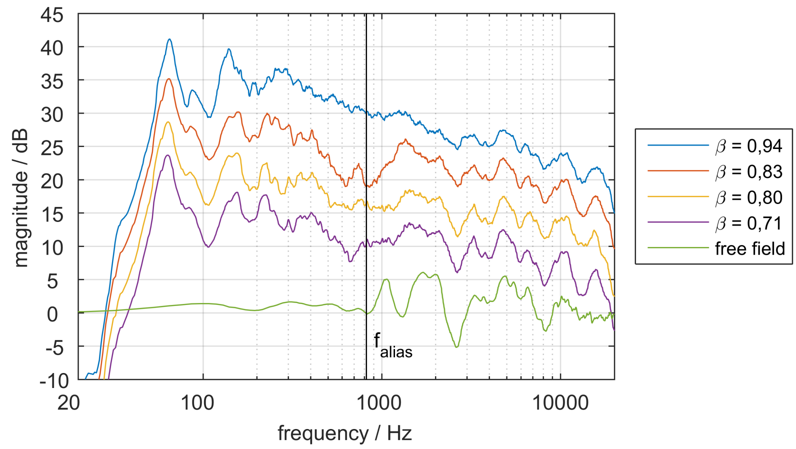
Figure 2: Standard deviations (STD) of magnitude responses in dB above the aliasing frequency of the virtual source for the setup in fig. 1 (a) over reverberation time. Black points indicate available data points.

Setup for measured loudspeaker RIRs

The setup for synthesis of a virtual source out of measured RIRs of the array loudspeakers is depicted in fig. 3 (a). A linear array of 16 loudspeakers type Neumann KH 120 A is placed in a basically rectangular room. With an effective array length of 3.76 m, the loudspeaker spacings are approx. 25 cm, but they are not equidistantly spaced due to construction of the array with trusses. Three walls of the room and the ceiling are plastered, only the wall opposite the array is a drywall. The wall properties have been varied by applying different configurations of broadband absorbers. The following configurations have been used, listed in descending order in terms of strength of reflections:



(a) Setup of linear array of 16 loudspeakers in real listening room. Height of room is 3 m. Array is positioned 1,59 m above the ground with virtual source and receiver in the same horizontal plane.



(b) Magnitude responses of the virtual source at the receiver position for different absorber configurations in the listening room of fig. 3 (a) converted to uniform reflection coefficients and in free field. Magnitude responses are smoothed in third-octave bands and have been shifted along the y-axis for ease of inspection.

Figure 3: Simulation of a virtual point source in a listening room represented by measured room impulse responses compared to free field conditions – setup and resulting magnitude responses.

- no absorbers,
- broadband absorbers at the walls (in total 15.48 m^2),
- broadband absorbers at walls and ceiling (in total 20.64 m^2),
- additional absorbers of pyramid-shaped foam with 7 cm depth (additional 8 m^2) placed below the broadband absorbers at the walls.

A detailed description of the measurement can be found in [11]. The RIRs along with binaural RIRs of the KEMAR manikin at different receiver positions are available as a free database[2].

Results for measured loudspeaker RIRs

The results for the synthesis of a virtual source out of measured RIRs of the array loudspeakers is shown in fig. 3 (b). The magnitude responses are again smoothed in third-octave bands and shifted along the y-axis for ease of inspection. For the four absorber configurations, reflections coefficients β have been calculated out of measured reverberation times in a simplified way via the equivalent absorption area and the reverberation time formula according to Sabine.

Above the aliasing frequency the same trend as in the case of simulated RIRs can be seen: The stronger the reflections, the more the spectral fluctuations caused by spatial aliasing are smoothed although there are some deviations from this finding, e.g. above 10 kHz.

[2] `http://dx.doi.org/10.14279/depositonce-87.6`

Behaviour at low frequencies

At low frequencies in a small room, room modes become evident as can be seen in fig. 3 (b). In contrast, the magnitude response of WFS in free field is almost linear with only slight deviations due to the truncation of the array to a finite length. The room modes cause colouration of the virtual source below the aliasing frequency. Fig. 4 shows the magnitude responses of the RIRs of all 16 array loudspeakers of the setup in fig. 3 (a), as well as the magnitude responses for two virtual sources: the virtual point source of fig. 3 (a) and a virtual plane wave travelling perpendicular to the array. As can be seen, the extent of the formation of the room modes differs for the two virtual sources. This is due to the fact that the loudspeakers are driven with different gains and delays depending on the type or position of the virtual source and thus the superposition of the loudspeakers turns out differently. This implies that the excitation of room modes for WFS in a small listening room does not only depend on the position of the loudspeakers and the receiver but also on the virtual source. From this it can be concluded that virtual sources are colourated differently by room modes.

Discussion and outlook

While room reflections lead to reduced colouration above the aliasing frequency in WFS, the lower frequency range can suffer from additional colouration introduced by the room. In the case of small listening rooms, this includes colouration caused by room modes. The implications of this different behaviour at low and high frequencies are not clear from the above simulations, i.e. it is unknown if overall the colouration of WFS in a listening room is greater, reduced or just a different kind of colouration compared to the free field situation. The study [12] concernced with stereophonic reproduction which is subject to comb filter effects as well and first results from [13] for WFS suggest, though, that system induced colouration is alleviated by a reflective environment.

Furthermore, it is not known to which extent of reduction of colouration above the aliasing frequency reflections lead. Therefore, it is necessary to conduct listening tests to determine this relation. Moreover, the threshold of perception of listening room reflections in WFS or just noticable differences are of interest as well.

The STD of the magnitude response is a rather coarse measure for colouration and has not in every study proven as a good predictor for this perceptual attribute, cf. [5]. It seems therefore advisable to use a more sophisticated method to predict colouration by means of an auditory model. The model of [14], that has been used for WFS in free field, appears as a suitable model, but it might be necessary to extend it as reverberation could introduce new aspects that are missing in the model.

Perception in rooms also includes the phenomenon of binaural decolouration [15]. However, this effect does not seem to play a role in the perception of WFS [7, 16] although the spatial aliasing artefacts show similarities to reflections. In future research, it would therefore be interesting to study if binaural decolouration is coming into effect for WFS in reflective environments.

Conclusions

Reflections of the listening room alleviate the spectral fluctuations and thus the colouration of WFS due to spatial aliasing caused by discretisation of the secondary source distribution. This can be quantified by calculating the STD of the magnitude response of a virtual source synthesised by WFS in a listening room. Below the aliasing frequency, colouration by the room itself is apparent including the excitation of room modes which additionally depends on the virtual source.

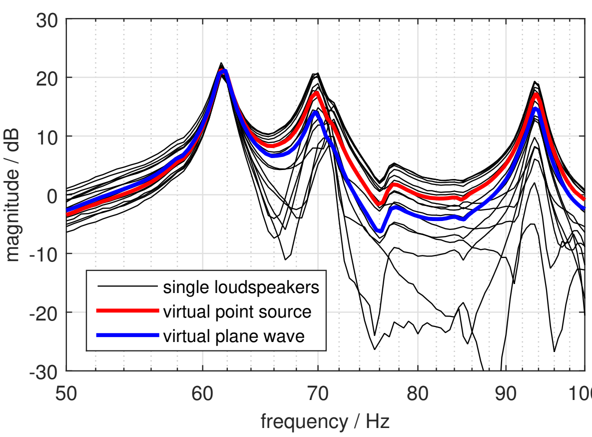


Figure 4: Low frequency magnitude responses for the setup in fig. 3 (a) of the 16 loudspeakers, the virtual point source depicted in the figure and a virtual plane wave travelling perpendicular to the array. The response of the virtual point source has been normalised to the lowest mode at approx. 61 Hz.

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