Reproduction of nearby sound sources using high-order Ambisonics: Implementation and evaluation

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Introduction

A known challenge in loudspeaker-based auralization such as wave-field synthesis (WFS) or high-order Ambisonics (HOA) is the reproduction of nearby sound sources. Considering a real sound source that moves closer than 1 meter to a listener, a significant change in the wave curvature can be observed which in turn produces a significant increase in the interaural level differences. In order to accommodate for this near-field effect, a near-field compensated (NFC) method has been previously proposed for HOA [3], which in theory should allow the reproduction of sound sources that are significantly closer than the radius of the playback loudspeaker array.

The NFC method applies near-field coding filters to Ambisonic components and can lead to very large loudspeaker signals at low frequencies for very close sources. Therefore, in practice, angular weighting windows (AWWs) are introduced after applying NFC filters [1][3].

The main cue in the perception of nearby sound sources outside the median plane is the large low-frequency interaural level differences (ILDs)[2], which needs to be reproduced by NFC-HOA. This manuscript investigates the effect of different existing AWWs by simulating the corresponding sound fields and ILDs. Based on this analysis, a new improved weighting window is proposed. Finally, the technical applicability of the different AWW approaches is assessed by measuring ILDs with a dummy head using an example loudspeaker array inside an acoustically damped room.

Near field compensated HOA

NFC-HOA allows for the reproduction of virtual point sources by applying near field coding filters to HOA components. These filters are described by a ratio of spherical Hankel functions of the second kind h_m^- and depend on the source distance from the center of the array ρ_s and the radius of the loudspeaker array R. They are described for 2D and 3D reproduction up to order M for each degree $0 \leq m \leq M$ by:

$$H_m^{NFC(\rho_s,R)}(k) = \frac{h_m^-(k\rho_s)}{h_0^-(k\rho_s)} \frac{h_0^-(kR)}{h_m^-(kR)} \quad (1)$$

where $k = 2\pi f/c$ is the wavenumber. Figure 1 shows the amplitude and phase response of example NFC filters.

For close sources and high orders, NFC filters show very large gains at low frequencies which are problematic to produce with loudspeakers. In addition, in real rooms, these large signals do not compensate one anther to provide the desired pressure value in the center of the loudspeaker array. Therefore, in practical realizations, angular weighting windows are used to restrict the amplitude of the NFC filters at low frequencies, and particularly at high orders. At least two different implementations can be found in the literature: (i) high pass filters ('hp') with specific cut-off frequencies (Daniel [3]) and (ii) cosine window ('coswin') shaped filters (Arhens and Spors [1]). In this paper, a new AWW is introduced and referred as regularization function ('reg'), which is described by:

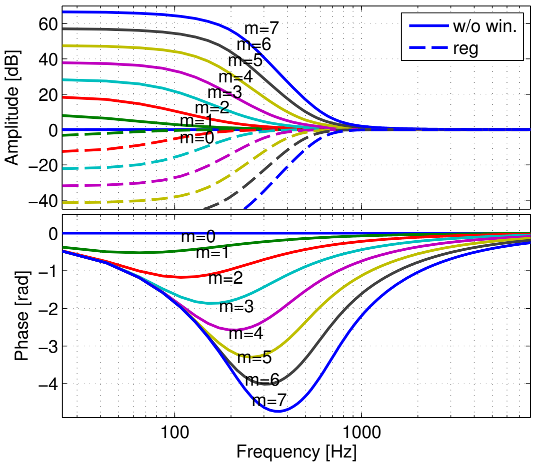

Figure 1: Frequency response of NFC filters for $m = 0$ to 7, for a virtual source at $\rho_s = 0.5$ m and a loudspeaker array radius of $R = 1.5$ m. The dashed line represents the resulting NFC filter with the regularization function.

$$w_m^{reg} = \frac{2}{1 + \left|H_m^{NFC(\rho,R)}\right|^2} \quad (2)$$

The resulting amplitude spectra of the weighted NFC filters is plotted in the top panel of figure 1 (dashed lines) for different Ambisonics orders. The three mentioned AWWs provided different attenuation of the NFC filters and their performance is analyzed in the following sections.

Sound field simulations

Simulations of reconstructed sound fields with 2D NFC-HOA for a source at $\rho_S = 0.5$ m and a circular 32-loudspeaker array ($R = 1.5$ m) are plotted in figure 2 for an Ambisonic order of $M = 15$ with the three considered AWWs and without weighting (noted 'w/o win'). Contours represent the 25% absolute error. The circle at the origin of the loudspeaker array indicates the typical dimension of a human head.

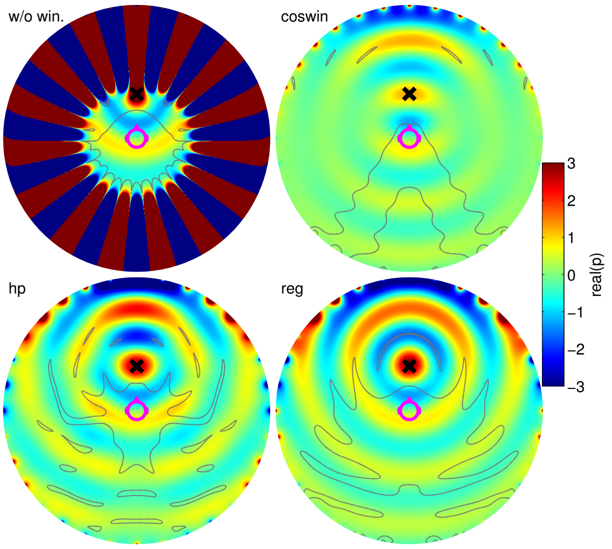

Figure 2: Instateneous pressure of 2D NFC-HOA reproduced sound source at 0.5 m (cross marker) for a frequency of $f =$ 600 Hz

Without angular weighting (top left panel), large pressure values can be observed for distances further than the virtual source. In the case that the playback room introduces some reverberation, this large pressure will disturb the reproduced sound field at the listener's location. As expected, the use of all AWWs leads to a significant reduction of the pressure in this area. Considering the area inside the error contours for the different AWWs, the 'coswin' window produces the smallest area and the proposed regularization function the largest area. Hence, NFC-HOA with the proposed regularization function successfully reproduces the sound field from a nearby source over the largest area.

Interaural level differences

Listener's ear signals were simulated by using KEMAR HRTFs for a circular array of 18 loudspeakers ($R =$ 1.4 m). This represents the ideal condition with a perfectly anechoic listening room and a perfectly aligned listener in the center of the array. Interaural level differences (ILDs) are plotted in figure 3 for $M = 7$ and for a source at azimuth $\theta = 90°$ and distance $\rho_S = 0.15$ m.

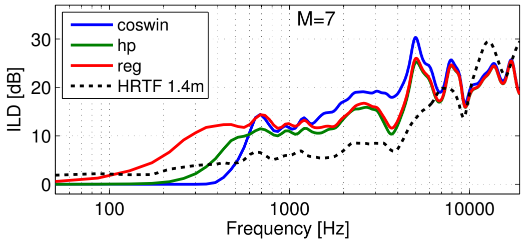

Figure 3: ILDs for NFC-HOA in ideal conditions.

The regularization function (red line) is the only one able to provide low-frequency ILDs larger than for distant sources (dashed curves). According to Brugart et al [2], these low-frequency ILDs are of particular importance for distance perception of nearby sound sources.

In practice, loudspeaker arrays are often placed in acoustically-damped rooms (not perfectly anechoic) and the listener's head is not perfectly aligned at the center. Therefore, a dummy head was used to record binaural signals in the "SpaceLab" facility at DTU for the same virtual source ($\theta = 90°$, $\rho_S = 0.15$ m) that was reproduced with NFC-HOA over a circular 16-loudspeaker array. The corresponding ILDs are plotted in figure 4 for the three considered weighting windows.

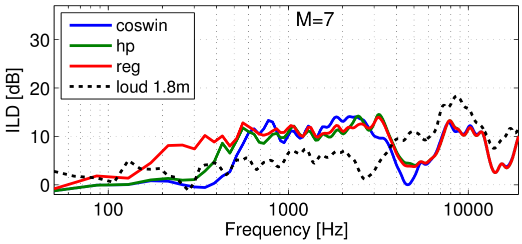

Figure 4: Recorded ILDs for NFC-HOA.

In non-ideal conditions, lower ILDs are produced for all considered windows. The regularization window is again the only one able to provide low frequency ILDs. For frequencies larger than 600 Hz, all three windows provide similar ILDs for this virtual source.

Summary and conclusions

The present study investigated the effect of different weighting windows on the sound field as well as on the corresponding auditory cues (ILDs) in ideal and realistic loudspeaker playback conditions. Moreover, a novel regularization window was proposed as an angular weighting window for NFC-HOA, which showed a number of advantages over other existing weighting windows:

- Reproduced sound fields showed a larger acceptable reconstruction area.
- Large ILDs were obtained at low frequencies which is an important auditory cue for estimating the distance of nearby sources [2].
- These large ILDs were also recorded in a practical loudspeaker installation.

The performance of the proposed regularization function should be further assessed by a distance perception experiment.

References

[1] Ahrens, J. and Spors, S. (2009). "Spatial encoding and decoding of focused virtual sound sources," 1st Ambisonics Symposium.

[2] Brungart, D. (1999). "Auditory localization of nearby sources. III. Stimulus effects," J. Acoust. Soc. Am., 106, 3589.

[3] Daniel, J. (2003). "Spatial sound encoding including near field effect: Introducing distance coding filters and a viable, new Ambisonic format," 23rd Int. Conf. of the Audio Eng. Soc.