Physical and Perceptual Properties of Focused Sources in Wave Field Synthesis

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Motivation

- focused sources are virtual sources that are located within the listening area
- stunning effect of wave field reconstruction techniques (with limitations)
- first analysis of their properties for WFS [Spors et. al, NAG/DAGA 2009]
- here extension towards 2.5-dimensional reproduction and perceptual properties
Wave Field Synthesis for Linear Arrays

Application of Huygens-Fresnel principle to sound reproduction in a half-space $V$

- continuous linear distribution $\partial V$ of monopole sources (secondary sources)
- strength (driving function) of secondary sources is given by Rayleigh integral
- in practice spatial discrete distribution of loudspeakers as secondary sources
- secondary point sources for 2D reproduction $\Rightarrow$ 2.5D WFS
Wave Field Synthesis for Linear Arrays

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Properties of WFS for Non-Focused Sources

**Two/three-dimensional WFS**
- exact reproduction for continuous distribution of secondary sources
- spatial sampling of secondary source distribution
  - may lead to artifacts
- truncation of secondary source distribution
  - limited listening area, may lead to artifacts

**Additional errors of 2.5-dimensional WFS**
- secondary source dimensionality mismatch (point vs. line source)
  - amplitude errors, spectral errors (can be corrected by $\sqrt{jk}$-equalization)
- out of reproduction plane listeners
  - amplitude errors, localization errors

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**Time-Reversal Acoustic Focusing**
- based on reciprocity of wave equation
- aims at accumulation of energy in time and space
- direction of wave propagation not explicitly taken into account
- size of focus point for free-field propagation $\approx \lambda/4$

$t = -0.58 \text{ ms}$

$t = 1.5 \text{ ms}$
Acoustic Focusing in WFS

- typical realization in WFS by modeling acoustic sink at focus point
- results in converging wave field towards focus point, diverging after
- source must be located between listeners and loudspeakers for correct auralization
- sensible selection of active secondary sources (listener dependent)

$$t = -0.58 \text{ ms}$$

$$t = 1.5 \text{ ms}$$

Geometry used for Simulations and Experiments

- 2.5-dimensional reproduction with WFS
- loudspeaker distance $\Delta x = 0.15 \text{ m}$, array length $L = 10$ resp. $L = 30 \text{ m}$
- focused source position $x_s = (0 \ 1) \text{ m}$, listener positions indicated by ●
- aliasing frequency (wrt driving function) $f_{al} \approx 1140 \text{ Hz}$
Reproduction of Monochromatic Focused Source

\( f_s = 1 \text{ kHz} \)

\[
[x_s = (0\ 1) \text{ m}, \Delta x = 0.15 \text{ m}]
\]

\[
[x_s = (0\ 1) \text{ m}, \Delta x = 0.15 \text{ m}]
\]
Reproduction of Monochromatic Focused Source
\( f_s = 5 \text{ kHz} \)

\( \mathbf{x}_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m} \)

Reproduction of Monochromatic Focused Source
\( f_s = 10 \text{ kHz} \)

\( \mathbf{x}_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m} \)
Evanescent vs. Propagating Contributions

\( f_s = 2 \text{ kHz} \)

\[ x_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m} \]

Amplitude Distribution of Reproduced Wave Field
Parallel to x-axis for \( y = 3 \text{ m} \)

\[ x_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m} \]
Amplitude Distribution of Reproduced Wave Field
Along y-axis for \( x = 0 \) m

\[ y \rightarrow [m] \]
\[ \text{Amplitude} \]

\[ \text{focused source} \]
\[ \text{real source} \]

\[ [x_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m}] \]

WFS Pre-equalization for Focused Sources

- 2.5D reproduction with WFS requires \( \sqrt{\frac{k}{\pi}} \) pre-equalization
- pre-equalization is only necessary up to the aliasing frequency
- problem: aliasing frequency varies strongly with listener/source position

\[ [x_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m}, L = 30 \text{ m}, \text{w/o pre-equalization}] \]
Reproduction of a Bandlimited Focused Source

\( b_s = 1 \text{ kHz} \)

\[ [x_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m}, L = 30 \text{ m}] \]

\( b_s = 20 \text{ kHz} \)

\[ [x_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m}, L = 30 \text{ m}] \]
Impulse Response at Listener Position

Listener position $x = (0 \ 3) \ m$

$[x_s = (0 \ 1) \ m, \Delta x = 0.15 \ m, \ L = 30 \ m]$

Impulse Response at Listener Position

Listener position $x = (2 \ 4) \ m$

$[x_s = (0 \ 1) \ m, \Delta x = 0.15 \ m, \ L = 30 \ m]$
Impulse Response at Listener Position

Listener position $x = (5\ 4)\ m$

\[x_s = (0\ 1)\ m, \Delta x = 0.15\ m, L = 30\ m\]

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Impulse Response at Listener Position

Listener position $x = (10\ 4)\ m$

\[x_s = (0\ 1)\ m, \Delta x = 0.15\ m, L = 30\ m\]

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Impulse Response at Listener Position

Listener position $x = (15 \ 4) \text{ m}$

![Graph showing impulse response at listener position](image)

$x = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m}, L = 30 \text{ m}$

Spatio-Temporal Properties of Pre-Echos

Total length of array $L = 10 \text{ m}$

- **earliest pre-echo**
  - ![Graph showing earliest pre-echo](image)

- **direction/strength of pre-echos**
  - ![Graph showing direction/strength of pre-echos](image)

$x = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m}$
Spatio-Temporal Properties of Pre-Echos

Total length of array $L = 30$ m

- **Perceptual Relevance of Pre-Echos**
  - pre-echos arrive from different directions than focused source
  - wave fronts from pre-echos have lower levels than focused source

**Precedence effect:** The direction of a perceived sound is not altered by echos,
- arriving from different directions,
- occurring in a time window of 1-40 ms after the leading wave front and
- not exceeding more than 10-15 dB level difference.

**Potential consequences for perception of focused sources**
- direction of first wave front may determine perceived source direction
- perception of more than one source or a distributed source
- additional sources are filtered versions of focused source
- artifacts will be more obvious for transient signals

\[ x_s = (0 \ 1) \text{ m}, \Delta x = 0.15 \text{ m} \]
Results from Informal Listening Experiment

Design of informal listening test

- dynamic (head-tracked) binaural resynthesis of a linear WFS system
- source material: female speech, cello, castanets
- 5 listener positions for long array, 3 for short array
- 5 expert listeners freely described differences between stimuli and reference

Subjective experiments confirm the theoretical findings

- almost no artifacts close to / in front of focused source
- distortions are audible as comb filter effects, smearing of transients, chirping and whistling sounds
- artifacts often have different direction of incidence than focused source
- many subjects reported more than one source or one wide source

Summary and Conclusions

Main findings

- no sampling artifacts at focus point, distortions are increasing with distance
- pre-echos from different directions than focused source
- lead to perceptually (severe) distortions
- coloration of source signal due to extremely changing aliasing frequency for moving focused sources/listeners

Further work

- formal listening experiment
- thresholds for audibility of pre-echo artifacts
- methods to reduce perceptual impact of artifacts