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Broadband Direction Estimation Method utilizing Combined Pressure and Energy Gradients from Optimized Microphone Array

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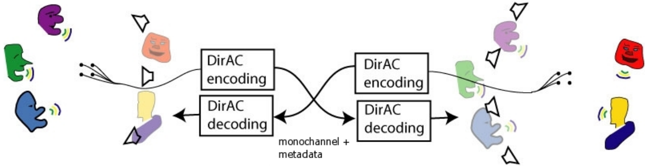
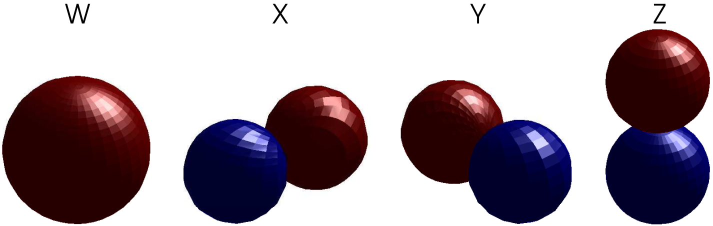
Introduction

- Direction of arrival (DOA) of sound
  - Source localization, beamforming/spatial filtering
  - Parametric spatial audio coding
- Large scale of methods for estimating DOA
  - MUSIC, ESPRIT, time differences of microphone signals, ...
- DOA based on sound intensity vector (energetic analysis)
  - Applied here with Directional Audio Coding (DirAC) for recording and reproducing spatial sound



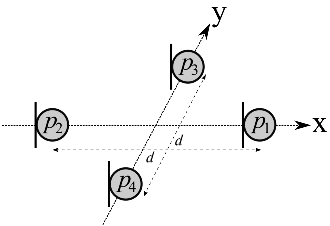
Direction estimation in energetic analysis

- Based on active sound intensity vector $\boldsymbol{I}_a$
  - Direction and magnitude of the net flow of sound energy
  - $p \times \vec{\mathbf{u}}$ (pressure times particle velocity)
- DOA$(t, f) = \frac{-\mathbf{I}_a(t,f)}{\|\mathbf{I}_a(t,f)\|}$ (opposite dir. to intensity vector)
- Pressure and velocity with B-format microphone signals



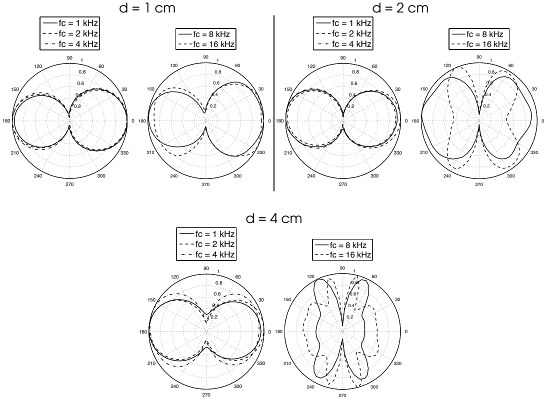
Square microphone array

- Four omnidirectional microphones in square
  - Miniature microphones
  - Mics. placed a few centimeters apart from one another
- Horizontal B-format signals (omni W, dipoles X and Y)
  - Pressure gradients: X = p_1 - p_2, Y = p_3 - p_4
  - W = $\mathbf{mean}(p_1, p_2, p_3, p_4)$



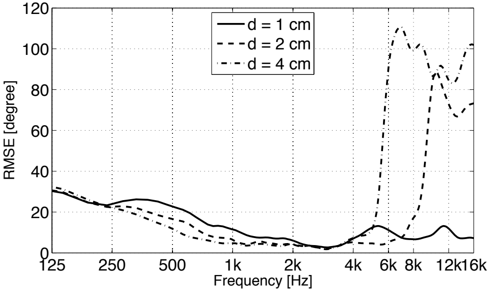
Issues

- Deformed dipoles above spatial-aliasing frequency f_{sa}
  - Depend on spacing, $f_{\mathrm{sa}} = \frac{c}{2d}$ (c = speed of sound)



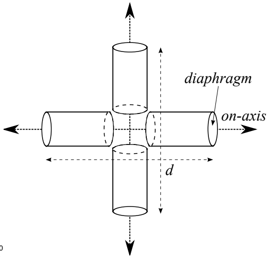
Issues

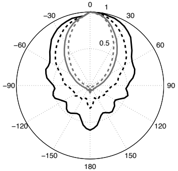
- Spatial aliasing
  $\Rightarrow$ erroneous DOA estimation at high frequencies
- Self-noise of microphones
  $\Rightarrow$ erroneous DOA estimation at low frequencies
- Error for DOA estimation expressed as RMSE

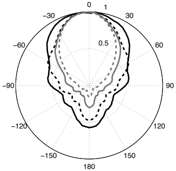


Microphone array providing acoustic shadowing

- Array of omnidirectional microphones with large housing
  - ⇒ Shadowing at high frequencies
  - ⇒ Inter-microphone level differences
- Could shadowing be utilized in energetic analysis to estimate DOA?







Left: dir. patterns for AKG mic. (diaph 2.1cm) at 5, 8, 12.5, and 16 kHz

Right: dir. patterns for G.R.A.S mic. (diaph 1.27cm) at 8, 10, 12.5, and 16 kHz

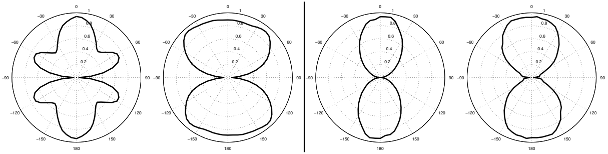
Direction estimation using energy gradients

- Sound intensity approximated using energy gradients

$$\widetilde{I}_x(t,f) = |P_1(t,f)|^2 - |P_2(t,f)|^2$$
$$\widetilde{I}_y(t,f) = |P_3(t,f)|^2 - |P_4(t,f)|^2$$

- Dir. patterns at 12 kHz (1/3-oct. band)

Pressure gradient | Energy gradient



AKG | G.R.A.S | AKG | G.R.A.S

- PEG method:

  Intensity vectors with pressure and energy gradients at low and high frequencies, respectively ⇒ DOA from intensity vectors

Spacing optimization of microphone array

- Idea: match spatial-aliasing frequency f_{sa} with the frequency-limit f_{lim} for using the energy gradients
  - f_{sa} depends on inter-microphone distance
  - f_{lim} depends on diaphragm size of the microphone
- Directivity index (DI): on-axis pickup energy vs. total pickup energy (integrated over all directions)

$$DI(f, ka) = 10 \log_{10}(\Delta L(f, ka))$$

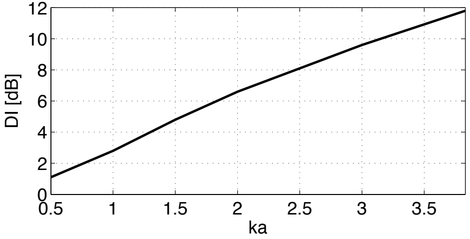
- DI depends on ratio of diaphragm circumference and wavelength:

$$ka = \frac{2\pi r}{\lambda},$$

where r is the radius of the diaphragm and $\lambda = c/f_{\mathrm{lim}}$

Spacing optimization of microphone array

- DI as a function of ka for omnidirectional microphone

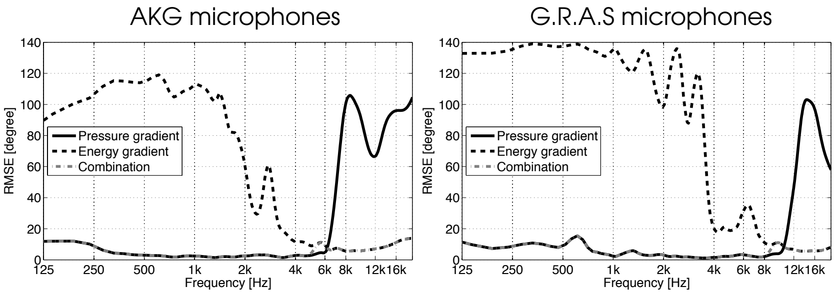


- Optimized spacing between microphones in array:

$$d_{\mathbf{opt}} = \frac{\pi r}{ka}$$

Evaluation

- Evaluation of PEG method and spacing optimization
  - Array of AKG mics. (diaph 2.1 cm) ⇒ spacing d_{opt} = 3.3 cm
  - Array of G.R.A.S mics. (diaph 1.27 cm) ⇒ spacing d_{opt} = 2 cm
- Error for DOA estimation expressed as RMSE



Summary

- DOA of sound estimated from sound intensity vectors (p and $\vec{\mathrm{u}}$ from B-format signals)
- Array of four omni microphones providing B-format signals
  - X- and Y-dipoles as pressure gradients
  - Spatial aliasing $\Rightarrow$ erroneous DOA estimation at high freq.
- Broadband DOA estimation method (PEG) proposed
  - Energy gradients $\Rightarrow$ overcomes spatial aliasing issue
  - Inter-mic. level differences (caused by shadowing of mics)
- Method to optimize mic. array for PEG
  - Inter-mic. distance based on the size of diaphragm
- Evaluation: PEG produces reliable DOA estimation at the entire audio freq. range using optimized mic. array

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The Academy of Finland (Projects #105780 and #119092) and Fraunhofer Gesellshaft IIS have supported this work. The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement no [240453].