AASP-P6.9

DIRECTIVITY SYNTHESIS WITH MULTIPOLES COMPRISING A CLUSTER OF FOCUSED SOURCES USING A LINEAR LOUDSPEAKER ARRAY

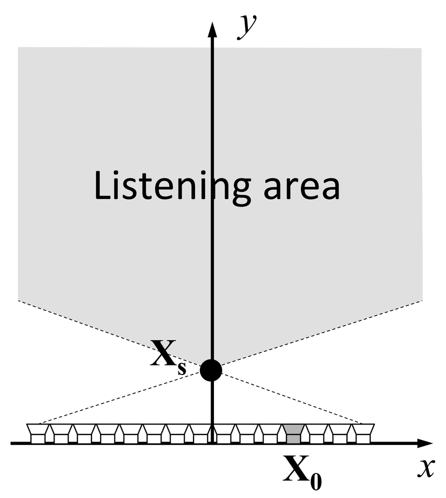
Kimitaka Tsutsumi[1,2], Yoichi Haneda[2], Ken'ichi Noguchi[1], Hideaki Takada[1]
[1]Nippon Telegraph and Telephone Corporation, Japan, [2]The University of Electro-Communications, Japan

Goal: Create sound fields from directional sources in the listening areas of focused sources with linear loudspeaker array.
Question: How can we introduce directivity to virtual sound sources between a loudspeaker array and audience seats?

Proposed: 1. Create a cluster of focused sources to form multipoles in the listening area.
2. Analytical conversion of circular harmonics into weights for each multipole.
Results: Reproduced directivity on the basis of multipoles comprising multiple focused sources.

Introduction

- Virtual sound sources closing in on the audience seats for live viewings and theaters
- Focused source method [1]: Creating sound fields from monopole sources between audience seats and a linear loudspeaker array



- Sound field and driving function

$$P(\mathbf{r}) = \int_{-\infty}^{\infty} D(\mathbf{x}_0,\mathbf{x}_s) G_{2D}(\mathbf{r}-\mathbf{x}_0)\, d\mathbf{x}_0$$

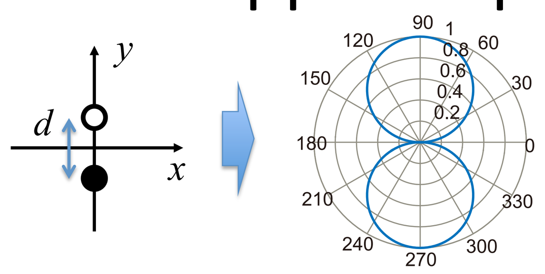
$$D(\mathbf{x}_0,\mathbf{x}_s) = -\frac{jk}{2} c_0 \frac{y_0 - y_s}{|\mathbf{x}_0 - \mathbf{x}_s|} H_1^{(1)}(k|\mathbf{x}_0 - \mathbf{x}_s|)$$

- Limited listening areas due to the nature of sound focusing
- Accurate reproduction of sound directivities help the audience feel more realistic sensations [2]
- Our goal: Creating sound fields from directional sources in the listening areas of focused sources

Multipole

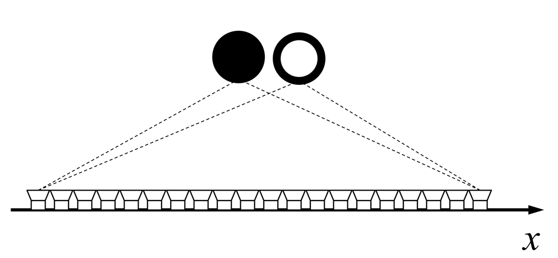
- Multipole: Directional source comprising a collection of point sources with opposite phases

$$S(\mathbf{r}) = \sum_{m,n} d_{mn} \cdot \frac{\partial^{m+n}}{\partial x^m \partial y^n} G(\mathbf{r})$$

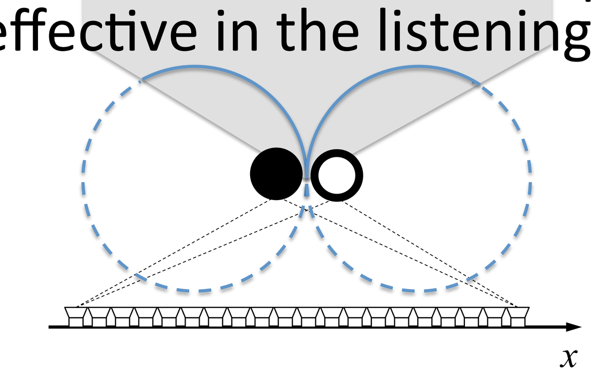


- Sound field from a multipole reproduced by a cluster of focused sources

Create multiple focused sources



Sound field of the multipole effective in the listening area



Proposed method

- Basic idea: The analytical conversion of circular harmonic coefficients into weights for each multipole
  - Circular harmonic decomposition of arbitrary sound fields in 2D

$$S(\mathbf{x}) = \sum_{\nu=-\infty}^{\infty} \breve{S}_\nu^{(2)} H_\nu^{(2)}(kr) e^{j\nu\alpha} = \sum_{\nu=-\infty}^{\infty} \breve{S}_\nu^{(2)} H_\nu^{(2)}(kr) (\cos\alpha + j\sin\alpha)^\nu$$

Euler's formula

By applying binomial expansion

$$S(\mathbf{x}) = \breve{S}_0^{(2)} H_0^{(2)}(kr)$$
$$+\sum_{N=1}^{\infty}\sum_{m=1}^{N} j^{N-m} \cdot \binom{N}{m} \cdot \breve{S}_N^{(2)} H_N^{(2)}(kr) \cdot \cos^m\alpha \cdot \sin^{N-m}\alpha$$
$$+\sum_{N=1}^{\infty}\sum_{m=1}^{N} (-j)^{N-m} \cdot \binom{N}{m} \cdot \breve{S}_{-N}^{(2)} H_{-N}^{(2)}(kr) \cdot \cos^m\alpha \cdot \sin^{N-m}\alpha$$

- Taylor's expansion at the origin of the coordinate

$$S(\mathbf{x}) = \sum_{N=0}^{\infty}\sum_{m=0}^{N} \left.\frac{\partial^N S(\mathbf{x})}{\partial x^m \partial y^n}\right|_{\mathbf{x}=0} \frac{x^m \cdot y^n}{m!n!} \Rightarrow \sum_{N=0}^{\infty}\sum_{m=0}^{N} \left.\frac{\partial^N S(\mathbf{x})}{\partial x^m \partial y^n}\right|_{\mathbf{x}=0} \frac{\cos^m\alpha \cdot \sin^n\alpha}{m!n!}$$

where $d = m + n$ — On the unit circle

- By comparing coefficients of the term $\cos^m\alpha \cdot \sin^n\alpha$

$$\left.\frac{\partial^{m+n} S(\mathbf{x})}{\partial x^m \partial y^n}\right|_{\mathbf{x}=0} = j^n (m+n)! \left\{ \breve{S}_{m+n}^{(2)} H_{m+n}^{(2)} + (-1)^n \breve{S}_{-m-n}^{(2)} H_{-m-n}^{(2)} \right\}$$

- The driving functions for sound fields from a sound source based on superposition of multipoles

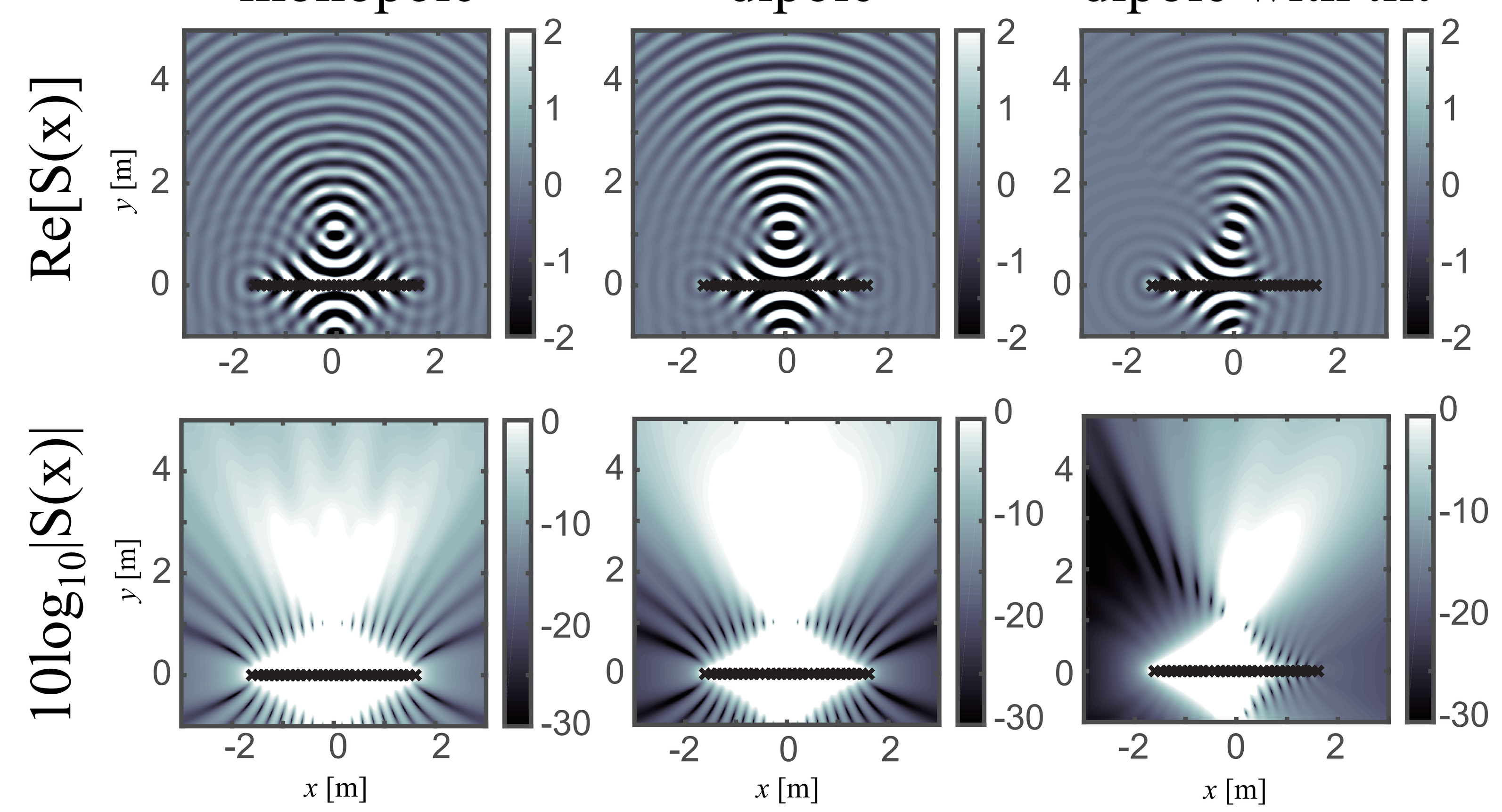
$$D(\mathbf{x}_0) = \sum_{m,n} \sum_{\substack{\mathbf{x}_s^{m,n} \in X^{m,n} \\ g_s^{m,n} \in G^{m,n}}} \left.\frac{\partial^{m+n} S(\mathbf{x})}{\partial x^m \partial y^n}\right|_{\mathbf{x}=0} \cdot \frac{g_s^{m,n}}{(jdk)^{m+n}} \cdot \frac{D(\mathbf{x}_0, \mathbf{x}_s^{m,n})}{m!\cdot n!}$$

$$X^{m,n} = \left\{ (x^m, y^n) \,\middle|\, x^m = x^{m-1} \pm \Delta, y^n = y^{n-1} \pm \Delta \right\}$$

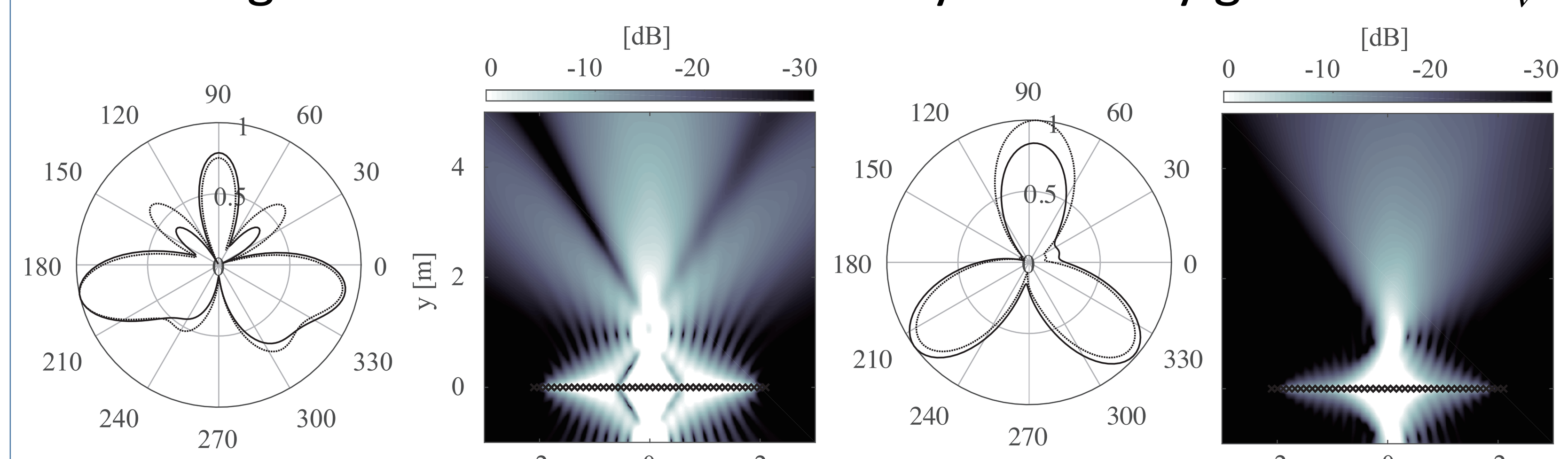
$$G^{m,n} = \left\{ g^{m,n} = g^m \cdot g^n \,\middle|\, g^m = (\pm 1) g^{m-1} \right\}$$

Computer simulations

- Sound field reproduction of monopoles and dipoles comprising focused sources (sine waves)
  - 41-ch linear array with 0.1 m intervals, f = 1 kHz
  - virtual sound sources at (x,y) = (0, 1)



- Directional source on the basis of superposition of multipoles comprising a cluster of focused sources
  - Simulation setup: same as the above cases
  - The order of circular harmonics and multipole: N = 4
  - Original sound field: modeled by randomly generated $\breve{S}_\nu^{(2)}$



Normalized |S(x)| on the unit circle — $10\log_{10}|S(x)|$ — Normalized |S(x)| on the unit circle — $10\log_{10}|S(x)|$

Selected references

[1] S. Spors +, AES Conv. 127, 2009. [2] K. Maki +, AST. Vol. 67, 2011.