3D localized sound zone generation with a planar omni-directional loudspeaker array

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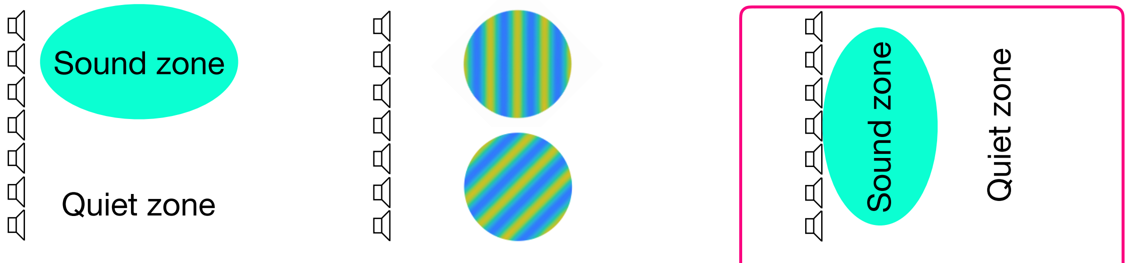
1. Introduction

Generating personalized sound zones with loudspeakers



(a): Contrast control (b): Multizone sound field (c): Localized sound zone

Conventional methods of localized sound zone generation

- Evanescent wave production (H. Itou et al., WASPAA 2011, ICASSP 2012)
- Circular and linear array combination (T. Okamoto, ICASSP 2015, JIHMSP 2017)
  - Problem: Higher order modal control and many loudspeakers are required
- Dimension mismatch between a linear array and a point source (JIHMSP 2017)
  - Problem: Undesired sound pressures are propagated to elevation angles

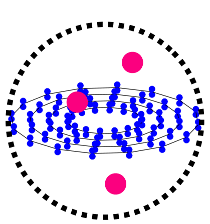
Proposal: 3D localized sound zone generation with a planar loudspeaker array

- Sound pressures produced by a loudspeaker are cancelled by using multiple co-centered circular arrays
  - Only controlling 0-th order spherical harmonic component $\breve{B}_0^0$
  - Omni-directional loudspeakers are sufficient instead of monopole pairs
  - Implemented with fewer loudspeakers than other methods

2. 3D sound field control with a planar array

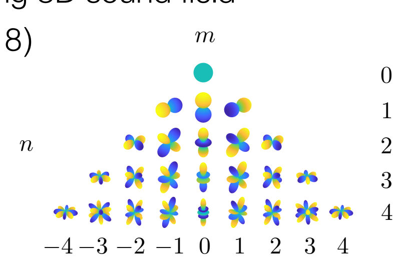
Active noise control with a planar first-order loudspeaker array

- Sound pressures propagated from noise sources are cancelled by using multiple co-centered circular arrays (-> This is also 3D localized sound zone generation)
  - Vertical monopole pairs are required for controlling 3D sound field (B. Bu et al., IEEE/ACM TASLP 2018)



Monopole: $\breve{B}_n^m$ for $n+|m|$ even

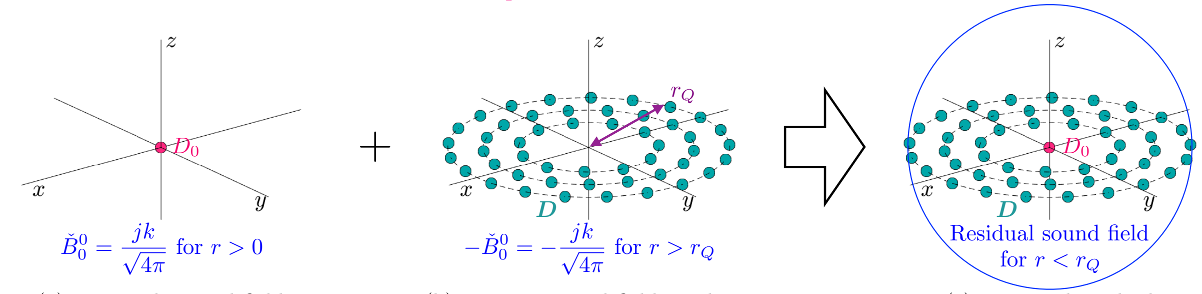
Dipole: $\breve{B}_n^m$ for $n+|m|$ odd



Strategy of proposed method

- Noise sources are located on horizontal plane: $\breve{B}_n^m$ has only $n+|m|$ components
  - Omni-directional loudspeakers are sufficient (T. Okamoto, ICASSP 2019)

3. Proposed method



(a) Monopole sound field (b) Exterior sound field synthesis (c) Proposed method

3D sound field control with multiple co-centered omni-directional circular arrays

- Spherical harmonic expansion of 3D exterior sound field

$$S(r,\theta,\phi) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \breve{B}_n^m h_n(kr) Y_n^m(\theta,\phi)$$

- Sound field produced by circular arrays

$$S_1(r,\theta,\phi) = \sum_{q=1}^{Q}\int_0^{2\pi} D(r_q,\phi_0)\, G(\boldsymbol{r},\boldsymbol{r}_q)|_{\theta_0=0} d\phi_0 = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \left[2\pi jk \sum_{q=1}^{Q} \mathring{D}_{m,q} \mathcal{P}_n^{|m|}(0) j_n(kr_q)\right] h_n(kr) Y_n^m(\theta,\phi)$$

- Driving signals of circular arrays

$$\breve{B}_n^m + 2\pi jk \sum_{q=1}^{Q} \mathring{D}_{m,q} j_n(kr_q)\, \mathcal{P}_n^{|m|}(0) = 0 \qquad (j_n(kr_q)\,\mathcal{P}_n^{|m|}(0) \rightarrow U_n^{|m|}(r_q))$$

$$\mathring{\boldsymbol{D}}_m^{\mathrm{even}} = \frac{1}{2\pi jk}\left(\boldsymbol{U}_{|m|}^{\mathrm{T}}\boldsymbol{U}_{|m|}\right)^{-1}\boldsymbol{U}_{|m|}^{\mathrm{T}}\breve{\boldsymbol{B}}_m^{\mathrm{even}}$$

(Complex number)

Proposed method

- Sound field produced by a center loudspeaker

$$S_0(r,\theta,\phi) = D_0 G(\boldsymbol{r}, r_0=0) = D_0 \sum_{n=0}^{0}\sum_{m=-n}^{n} \frac{jk}{\sqrt{4\pi}} h_n(kr) Y_n^m(\theta,\phi) = D_0 \frac{e^{jkr}}{4\pi r}$$

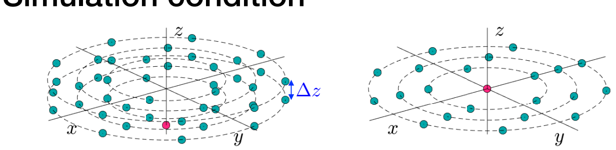
- Driving signals of circular arrays

$$\breve{\boldsymbol{B}}_0^{\mathrm{even}} = -\left[\frac{jk}{\sqrt{4\pi}}, 0, \cdots, 0\right]^{\mathrm{T}} \qquad \boldsymbol{J}_0 = [j_0(kr_1), j_0(kr_2), \cdots, j_0(kr_Q)]^{\mathrm{T}} \qquad \mathring{\boldsymbol{D}}_0 = \boldsymbol{D} = -\frac{1}{8\pi^2}\left(\boldsymbol{U}_0^{\mathrm{T}}\boldsymbol{U}_0\right)^{-1}\boldsymbol{J}_0$$

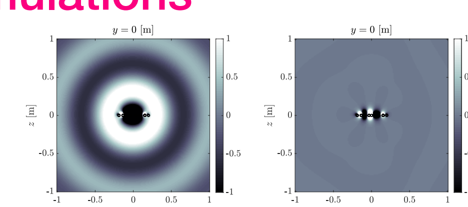
(Real number)

4. Computer simulations

Simulation condition

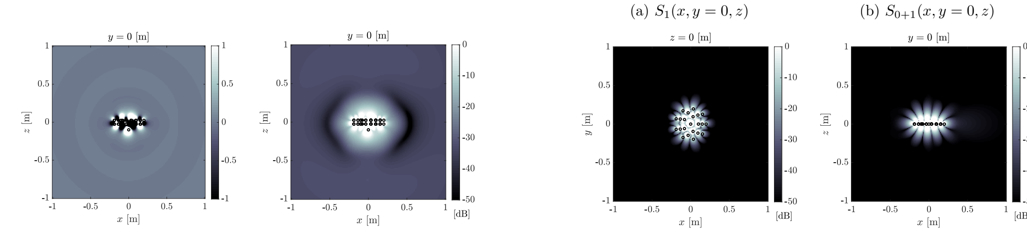


(a) Method with monopole pairs (b) Proposed method



(a) $S_1(x, y=0, z)$ (b) $S_{0+1}(x, y=0, z)$

Results



(a) $S_{0+1}(x, y=0, z)$ (b) $20\log_{10}|S_{0+1}(x, y=0, z)|$ (c) $20\log_{10}|S_{0+1}(x, y, z=0)|$ (d) $20\log_{10}|S_{0+1}(x, y=0, z)|$

Monopole pairs (43 ch) Proposed (22 ch)

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