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2.5D localized sound zone generation with a circular array of fixed-directivity loudspeakers

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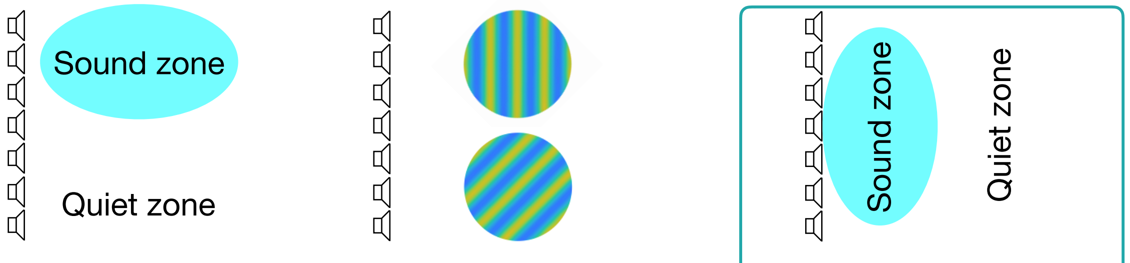
1. Introduction

- **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)
  - Dimension mismatch between a linear array and a point source (JIHMSP 2017)
    - Problem: Higher order modal control and many loudspeakers are required
- **Proposal: Dimension mismatch between a circular array and a point source**
  - 2.5D exterior field synthesis with a circular array of fixed-directivity loudspeakers
    - Introducing fixed-directivity loudspeakers for avoiding forbidden frequencies
    - Fewer loudspeakers for only controlling 0-th and 1-st order components

2. Proposed analytical formulation

- **Exterior sound field produced by circular fixed-directivity sound source**

$$S_1(r,\theta,\phi) = \int_0^{2\pi} D_1(\phi_1) T(\boldsymbol{r},\boldsymbol{r}_1) d\phi_1 \quad \xrightarrow{\mathcal{F}} \quad \mathring{S}_{m,1}(r) = 2\pi \mathring{D}_{m,1} \mathring{T}_m(r,r_1)$$

$$\mathring{T}_m(r_>,r_1) = jk \sum_{n=|m|}^{\infty} h_n(kr) j_{n,1}(a,r_1) \frac{2n+1}{4\pi} \frac{(n-|m|)!}{(n+|m|)!} P_n^{|m|}(0)^2$$

$$j_{n,1}(a,r_1) = a j_n(kr_1) + j(1-a) j'_n(kr_1)$$

- **Exterior sound field produced by fixed-directivity sound source at array center**

$S_0(r,\theta,\phi) = D_0 T(\boldsymbol{r},\boldsymbol{r}_0)$ $D_0 = 1$ for simplicity and $r_0 = 0$ centered origin

$$S_0(r,\theta,\phi) = \frac{e^{jkr}}{4\pi r}\left\{a + (1-a)\left[1+\frac{j}{kr}\right]\cos\alpha\right\}$$

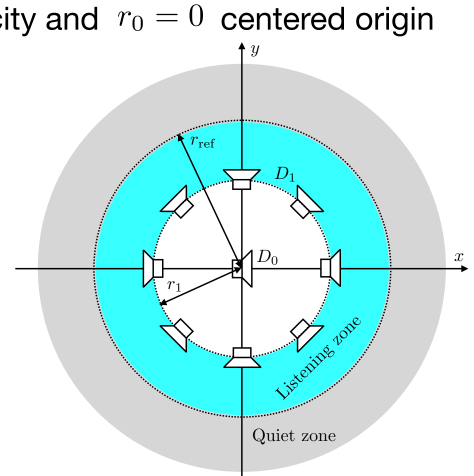
$$= a\frac{jk}{4\pi} h_0(kr) - (1-a)\frac{k}{4\pi} h_1(kr)\cos\alpha$$

only has 0-th and 1st order components

$\mathcal{F}$

$$\mathring{S}_{0,0}(r) = a\frac{jk}{4\pi} h_0(kr)$$

$$\mathring{S}_{\pm1,0}(r) = -(1-a)\frac{k}{8\pi} h_1(kr)$$



3. Analytical driving function of circular source

- **Driving function in 2.5D spherical harmonic spectrum domain**
  - Cancelling horizontal sound field produced by D_0

$$\mathring{D}_{0,1} = -\frac{\mathring{S}_{0,1}(r_{\mathrm{ref}})}{2\pi \mathring{T}_0(r_{\mathrm{ref}},r_1)} = -a\frac{jkh_0(kr_{\mathrm{ref}})}{8\pi^2 \mathring{T}_0(r_{\mathrm{ref}},r_1)}$$

$$\mathring{D}_{\pm1,1} = -\frac{\mathring{S}_{\pm1,1}(r_{\mathrm{ref}})}{2\pi \mathring{T}_{\pm1}(r_{\mathrm{ref}},r_1)} = (1-a)\frac{kh_1(kr_{\mathrm{ref}})}{16\pi^2 \mathring{T}_{\pm1}(r_{\mathrm{ref}},r_1)}$$

- **Localized sound zone in horizontal plane**
  - $S_{0+1}(r,\phi) = 0$ for $r = r_{\mathrm{ref}}$

$$S_{0+1}(r,\phi) = \sum_{m=-1}^{1} \mathring{S}_{m,0+1}(r) e^{jm\phi}$$

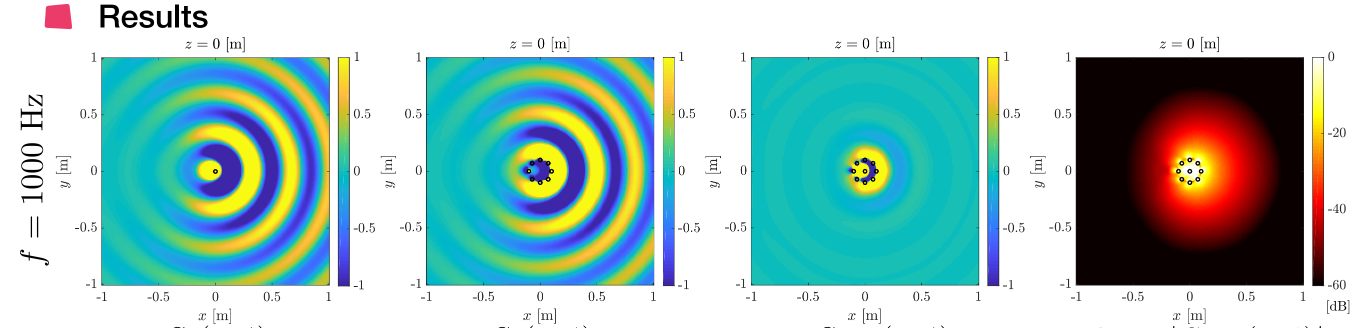
$$= a\frac{jk}{4\pi}\left\{h_0(kr) - h_0(kr_{\mathrm{ref}})\frac{\mathring{T}_0(r,r_1)}{\mathring{T}_0(r_{\mathrm{ref}},r_1)}\right\} - (1-a)\frac{k}{4\pi}\left\{h_1(kr) - h_1(kr_{\mathrm{ref}})\frac{\mathring{T}_{\pm1}(r,r_1)}{\mathring{T}_{\pm1}(r_{\mathrm{ref}},r_1)}\right\}\cos\phi$$

- **Driving signals of circular array of fixed-directivity loudspeakers**

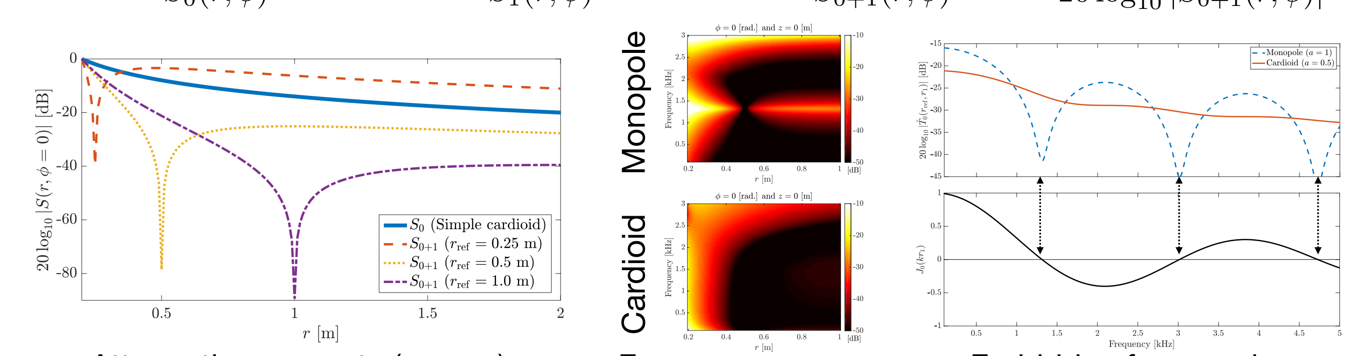
$$D_1(\phi_l) = \sum_{m=-1}^{1} \mathring{D}_{m,1} e^{jm\phi_l} = -a\frac{jkh_0(kr_{\mathrm{ref}})}{8\pi^2 \mathring{T}_0(r_{\mathrm{ref}},r_1)} + (1-a)\frac{kh_1(kr_{\mathrm{ref}})}{8\pi^2 \mathring{T}_1(r_{\mathrm{ref}},r_1)}\cos\phi_l$$

4. Computer simulations

- **Simulation condition**
  - Circular array of 8 loudspeakers with $a = 0.5$ (cardioid), $r_{\mathrm{ref}} = 0.5$ m and $r_1 = 0.1$ m
- **Results**



$S_0(r,\phi)$ $S_1(r,\phi)$ $S_{0+1}(r,\phi)$ $20\log_{10}|S_{0+1}(r,\phi)|$



Attenuation property ($\phi = 0$) Frequency response Forbidden frequencies

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