Near-field sound propagation based on a circular and linear array combination

Takuma OKAMOTO, National Institute of Information and Communication Technology, Japan

1. Introduction

- Personalizing listening areas using multiple loudspeakers
  - Multiple sound zones (*e.g.* T. Okamoto ICASSP 2014)
  - Near-field sound propagation
    - Localized sound area is only generated near loudspeakers and sound energy is quite low apart from the loudspeakers
- Conventional near-field sound propagation methods and their problems
  - Evanescent wave reproduction (H. Itou *et al.* WASPAA 2011, ICASSP 2012)
    - Attenuation property cannot be controlled
  - Using double circular arrays (J.-H. Chang *et al. J. Acoust. Soc. Am.* 2012)
    - Only horizontal control
    - Least squares approach and very ill-conditioned

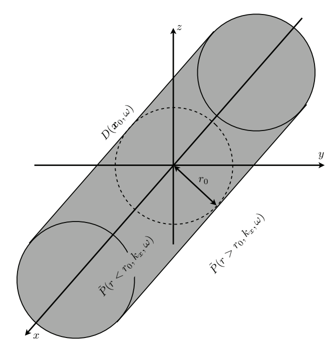
Proposed method for 3-dimensional near-field sound propagation

Sound pressure radiated from a circular sound source outside the circle is completely canceled out using a linear sound source with stable analytical solution

2. Preparations for proposed method

- Sound field produced by a cylindrical sound source

$$P(\boldsymbol{r},\omega)=\int_0^{2\pi}\int_{-\infty}^{\infty} D(\boldsymbol{r}_0,\omega)G_{3\mathrm{D}}(\boldsymbol{r}-\boldsymbol{r}_0,\omega)r_0dx_0d\phi_0,$$



  - 2D spatial Fourier transform

$$\tilde{P}_n(r,k_x,\omega)=2\pi r_0\tilde{D}_n(k_x,\omega)\tilde{G}_n(r-r_0,k_x,\omega)$$

$$\tilde{G}_n(r<r_0,k_x,\omega)=-(j/4)H_n^{(2)}(k_r r_0)J_n(k_r r)$$

$$\tilde{G}_n(r>r_0,k_x,\omega)=-(j/4)H_n^{(2)}(k_r r)J_n(k_r r_0)$$

Property I: The radiation property produced by a cylindrical source outside the cylinder is different from that inside the cylinder

- Sound field produced by a linear sound source

$$P_{\mathrm{L}}(\boldsymbol{r},\omega)=\int_{-\infty}^{\infty}D_{\mathrm{L}}(\boldsymbol{x}_0,\omega)G_{3\mathrm{D}}(\boldsymbol{r}-\boldsymbol{x}_0,\omega)dx_0$$

  - Spatial Fourier transform

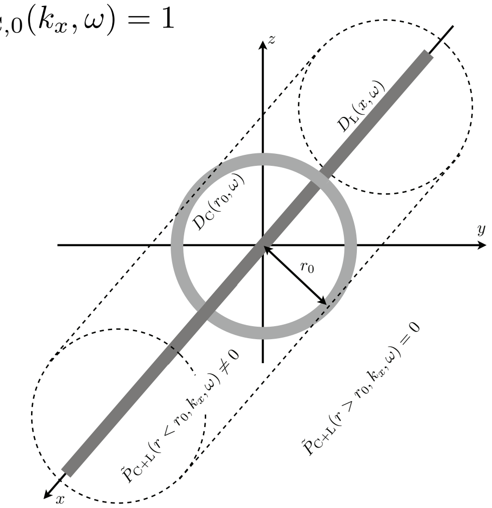
$$\tilde{P}_{\mathrm{L}}(r,k_x,\omega)=\tilde{D}_{\mathrm{L}}(k_x,\omega)\tilde{G}_{\mathrm{L}}(r,k_x,\omega)\qquad \tilde{G}_{\mathrm{L}}(r,k_x,\omega)=-\frac{j}{4}H_0^{(2)}(k_r r)$$

Property II: The sound pressure produced by a linear source is radiated axisymmetrically to the x-axis and only has 0-th order component

3. Proposed method

- Analytical formulation
  - Driving faction of a circular sound source (must also only has 0-th order)

$$D_{\mathrm{C}}(r_0,\omega)=\begin{cases}1 & (x=0)\\ 0 & (x\neq 0)\end{cases}=\delta(x)\quad \xrightarrow{\mathcal{F}_x}\quad \tilde{D}_{\mathrm{C},0}(k_x,\omega)=1$$



  - Sound field produced by a circular sound source

$$\tilde{P}_{\mathrm{C},0}(r<r_0,k_x,\omega)=-(j\pi r_0/2)H_0^{(2)}(k_r r_0)J_0(k_r r)$$

$$\tilde{P}_{\mathrm{C},0}(r>r_0,k_x,\omega)=-(j\pi r_0/2)H_0^{(2)}(k_r r)J_0(k_r r_0)$$

  - Driving function of a linear sound source

$$\tilde{P}_{\mathrm{L}}(r,k_x,\omega)=-\tilde{P}_{\mathrm{C},0}(r>r_0,k_x,\omega)$$

$$\tilde{D}_{\mathrm{L}}(k_x,\omega)=-2\pi r_0J_0(k_r r_0)$$

  - Total produced sound field

$$\tilde{P}_{\mathrm{C+L}}(r>r_0,k_x,\omega)=0\quad \textit{Completely cancelled!!}$$

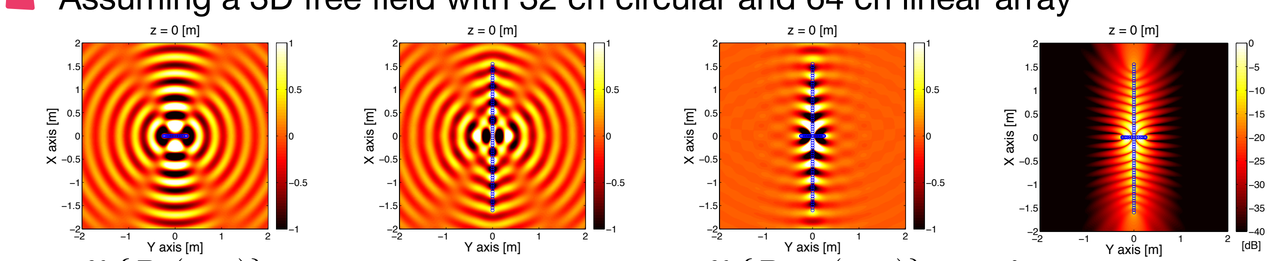
$$\tilde{P}_{\mathrm{C+L}}(r<r_0,k_x,\omega)=-\frac{j\pi r_0}{2}\left(H_0^{(2)}(k_r r_0)J_0(k_r r)-H_0^{(2)}(k_r r)J_0(k_r r_0)\right)\quad \textit{Not cancelled}$$

  - Stable driving function of a linear sound source

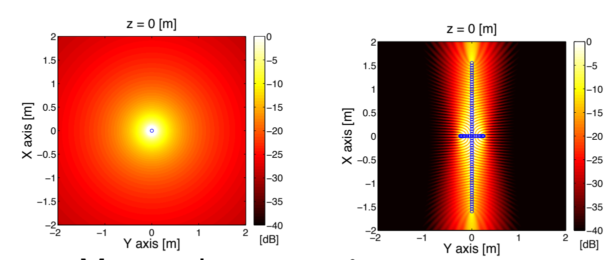
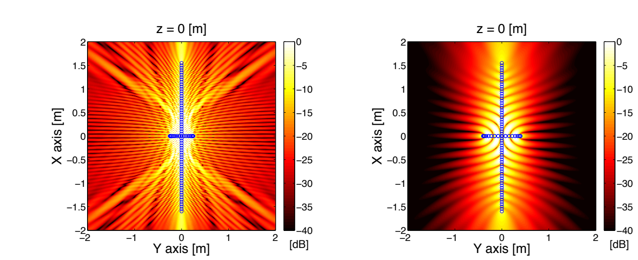
$$\tilde{D}_{\mathrm{L}}(k_x,\omega)=0 \text{ for } k_r^2=k^2-k_x^2<0 \qquad D_{\mathrm{L}}(x,\omega)=-2r_0\frac{\sin\left(k\sqrt{x^2+r_0^2}\right)}{\sqrt{x^2+r_0^2}} \text{ for } |k|>|k_x|$$

4. Computer simulations

- Assuming a 3D free field with 32 ch circular and 64 ch linear array



$\Re\{P_{\mathrm{C}}(\boldsymbol{r},\omega)\}$ $\Re\{P_{\mathrm{L}}(\boldsymbol{r},\omega)\}$ $\Re\{P_{\mathrm{C+L}}(\boldsymbol{r},\omega)\}$ $f=1000, r_0=0.25$

Monopole $f=3000, r_0=0.25$ $f=5000, r_0=0.25$ $f=1000, r_0=0.40$

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