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Horizontal 3D sound field recording and 2.5D synthesis with omni-directional circular arrays

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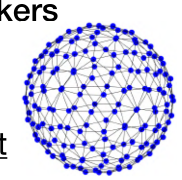
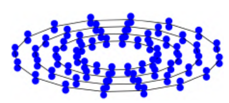
1. Introduction

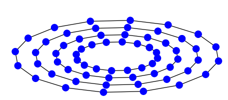
- **3D Sound field recording and synthesis with microphones and loudspeakers**
  - Wave field synthesis (WFS) with planar arrays
  - Higher-order Ambisonics (HOA) with spherical arrays
    - A huge number of elements are required and impractical arrangement



- **Horizontal sound field synthesis with linear and circular loudspeaker arrays**
  - 2.5D sound field synthesis
    - Array geometry is 2D but radiation property of loudspeakers is 3D: -> 2.5D
    - Restriction: Only sound pressures on reference line or circle are synthesized
- **Conventional sound field recording methods for 2.5D synthesis**
  - Assuming 2D sound field (e.g. S. Koyama *et al.*, IEEE TASLP 2013, JASA 2016)
    - Actual sound field is not 2D but 3D
  - 3D sound field recording with 3D arrays (e.g. T. Okamoto, WASPAA 2017)
    - Spherical arrays (=a huge number of microphones) are required
  - 3D sound field recording with a planar microphone array (H. Chen *et al.*, JASA 2015)
    - Differential microphones or microphone pairs are required



- **Proposed method: Horizontal 3D sound field recording with omni-directional circular arrays for 2.5D synthesis**
  - Only estimating spherical harmonic spectrums $\breve{A}_n^m$ for $n+|m|$ even is sufficient since 2.5D synthesis also only requires $\breve{A}_n^m$ for $n+|m|$ even components



2. Horizontal 3D sound field recording

- **Horizontal 3D sound field recording with omni-directional circular arrays**
  - 3D sound field on horizontal plane

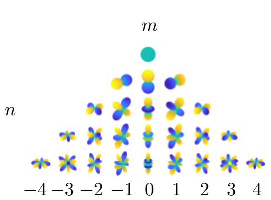
$$S(r,\pi/2,\phi)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n}\breve{A}_n^m j_n(kr)\mathcal{P}_n^{|m|}(0)e^{jm\phi}\qquad \mathcal{P}_n^{|m|}(0)=0 \text{ for } n+|m| \text{ odd}$$

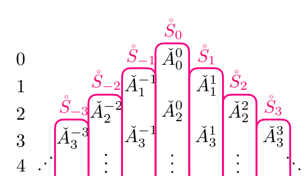
- Vertical derivatives of $\mathcal{P}_n^{|m|}(0)$ are required for recording entire 3D sound field
  - 2D cylindrical harmonic spectrums of sound field recorded by a circular array

$$\mathring{S}_m(r)=\frac{1}{2\pi}\int_0^{2\pi}S(r,\pi/2,\phi)e^{-jm\phi}d\phi$$

- Multiple radii R_q with maximum order N

$$\mathring{S}_m(R_q)\simeq\sum_{n=|m|}^{N}\breve{A}_n^m j_n(kR_q)\mathcal{P}_n^{|m|}(0)$$

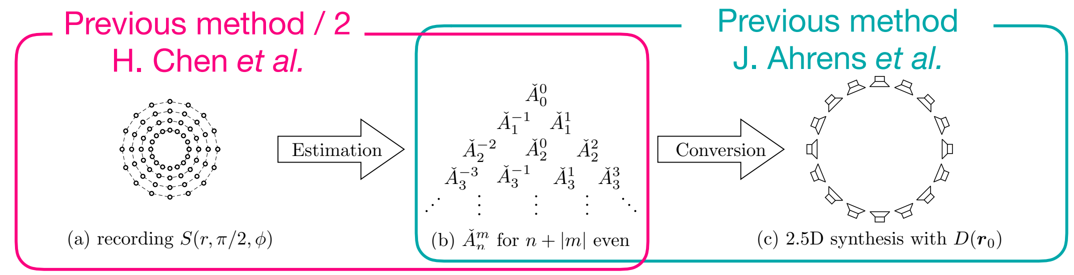




- Spherical harmonic spectrums $\breve{A}_n^m$ for $n+|m|$ even of 3D sound field

$$\mathring{\boldsymbol{S}}_m=\boldsymbol{U}_{|m|}\breve{\boldsymbol{A}}_m^{\text{even}}\quad\Rightarrow\quad\breve{\boldsymbol{A}}_m^{\text{even}}=\left(\boldsymbol{U}_{|m|}^{\mathrm{T}}\boldsymbol{U}_{|m|}\right)^{-1}\boldsymbol{U}_{|m|}^{\mathrm{T}}\mathring{\boldsymbol{S}}_m$$

- Only using omni-directional microphones is sufficient for even components



Scheme of proposed method (without new formulations)

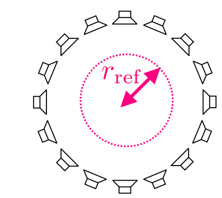
3. 2.5D synthesis with a circular loudspeaker array

- **2.5D HOA with a circular array** (J. Ahrens *et al.*, Acta Acust. Acust. 2008)
  - Sound field produced by a circular source

$$S(r,\theta,\phi)=\int_0^{2\pi}D(\boldsymbol{r}_0)G_{3D}(\boldsymbol{r},\boldsymbol{r}_0)\,r_0\,d\phi_0\quad\xrightarrow{\mathcal{F}}\quad\mathring{S}_m(r_{\text{ref}})=2\pi\mathring{D}_m\mathring{G}_m(r_{\text{ref}},r_0)$$

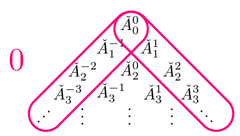
- Analytical driving function

$$\mathring{D}_m=\frac{\mathring{S}_m(r_{\text{ref}})}{2\pi\mathring{G}_m(r_{\text{ref}},r_0)}=\frac{\sum_{n=|m|}^{\infty}\breve{A}_n^m j_n(kr_{\text{ref}})\mathcal{P}_n^{|m|}(0)}{2\pi\sum_{n=|m|}^{\infty}jkj_n(kr_{\text{ref}})h_n(kr_0)\mathcal{P}_n^{|m|}(0)^2}$$



- Applying L'Hôpital's rule for $r_{\text{ref}}=0$

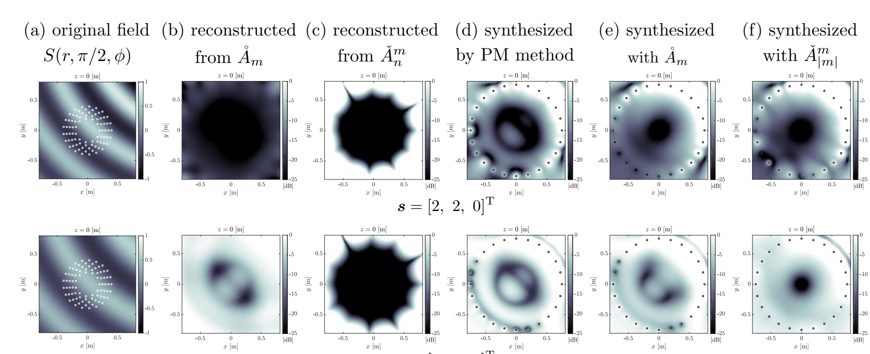
$$\mathring{D}_m\Big|_{r_{\text{ref}}=0}=\frac{\breve{A}_{|m|}^m}{2\pi jkh_{|m|}(kr_0)\mathcal{P}_{|m|}^{|m|}(0)}\qquad r_{\text{ref}}=0$$



4. Computer simulations

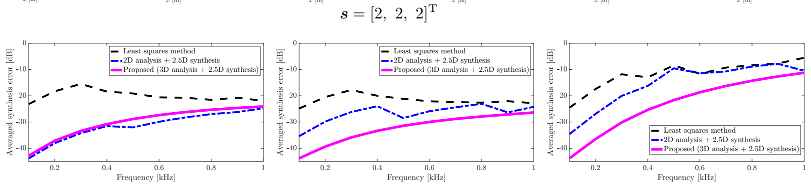
- **Simulation conditions**
  - Radii of five circular arrays: 0.4, 0.35, 0.3, 0.25 and 0.2 m
  - Target frequency band: 1 kHz and maximum order: $N=\lceil ekR_{q,\max}/2\rceil=10$
  - Number of microphones: 21+19+17+15+11=83 (less than $(N+1)^2=121$)
  - Comparison with pressure matching (PM) and 2D analysis-based methods
- **Results**
  - Reconstruction and synthesis errors

$$10\log_{10}\frac{|S_{\text{org}}(\boldsymbol{r})-S_{\text{rec/syn}}(\boldsymbol{r})|^2}{|S_{\text{org}}(\boldsymbol{r})|^2}\qquad f=500\text{ Hz}$$



- Averaged synthesis error

$$\frac{1}{\pi r^2}\int_0^r\int_0^{2\pi}10\log_{10}\frac{|S_{\text{org}}(\boldsymbol{r})-S_{\text{syn}}(\boldsymbol{r})|^2}{|S_{\text{org}}(\boldsymbol{r})|^2}d\phi dr\qquad r\le 0.2\text{ m}$$



(a) $\boldsymbol{s}$: 2D plane wave (b) $\boldsymbol{s}=[2,\ 2,\ 0]^{\mathrm{T}}$ (c) $\boldsymbol{s}=[2,\ 2,\ 2]^{\mathrm{T}}$

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