P2-4 Numerical Analysis of Radiated Sound Field of Spherical Loudspeaker with Variable Radiation Characteristics

- Estimation of Size and Shape of Musician's Sound Image by Sound Source Search -

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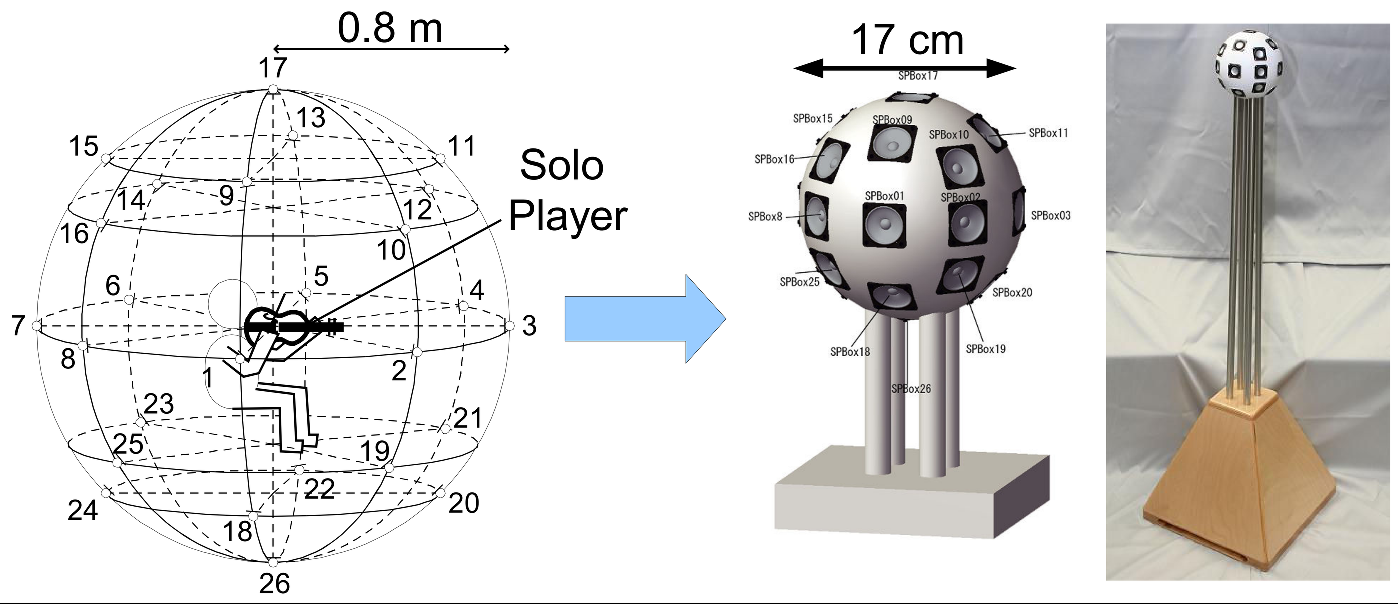
1. INTRODUCTION

Our Ultra-Realistic Audio Technique

- Depict **the presence of an object** at a given position
- Listeners around an object can listen to the sound generated by the object

Spherical Loudspeaker with Variable Radiation Characteristics



Aim of Study

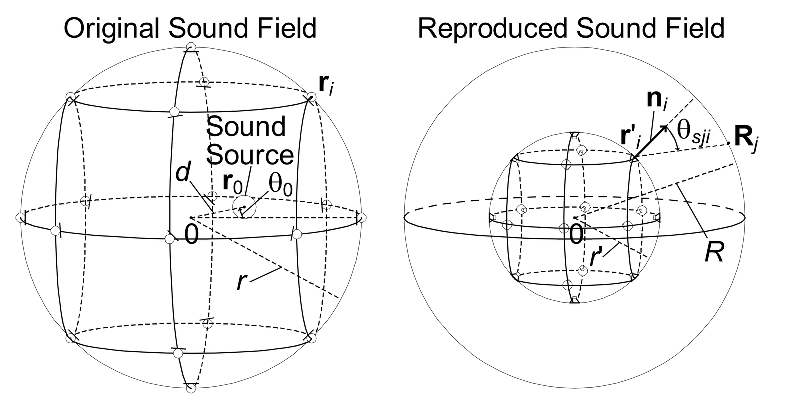
- Computer simulation
  - + Analyze the radiated sound field generated by the spherical loudspeaker
- Sound source search
  - + Estimate the position of multiple point sound sources

The size and shape of the musician's sound image depicted by the spherical loudspeaker are evaluated

2. COMPUTER SIMULATION

Simulation Environment

- M(=26) microphones
  - + $\mathbf{r}_i$: On a sphere of radius r(=0.8 m)
- M(=26) loudspeaker units
  - + $\mathbf{r}'_i$: On a sphere of radius r'(=0.085 m)



- N(=162) observation points
  - + $\mathbf{R}_j$: On a sphere of radius R(=1 m)

Azimuth and Elevation angles of Microphones and Loudspeaker Units

i	θ_i [°]	ϕ_i [°]	i	θ_i [°]	ϕ_i [°]	i	θ_i [°]	ϕ_i [°]
1	0	0	9	0	45	18	0	-45
2	45	0	10	45	30	19	45	-30
3	90	0	11	90	45	20	90	-45
4	135	0	12	135	30	21	135	-30
5	180	0	13	180	45	22	180	-45
6	-135	0	14	-135	30	23	-135	-30
7	-90	0	15	-90	45	24	-90	-45
8	-45	0	16	-45	30	25	-45	-30
			17	--	90	26	--	-90

Calculation of Sound Pressures

- Sound source $s(t)$
  - + Sine wave (amplitude A, frequency f)
- Recorded signals $x_i(t)$
  - + $d_{i0}(=|\mathbf{r}_i-\mathbf{r}_0|)$: Distance between sound sources and microphones
  - + $\mathbf{r}_i$: Position vector of microphones
  - + $\mathbf{r}_0$: Position vector of sound sources
  - + c: Sound velocity

$$x_i(t)=\frac{1}{d_{i0}}s\left(t-\frac{d_{i0}}{c}\right)=\frac{A}{d_{i0}}\sin\left\{2\pi f\left(t-\frac{d_{i0}}{c}\right)\right\}$$

- Sound pressure in observation points
  - + M: Number of loudspeaker units
  - + $d_{ji}(=|\mathbf{R}_j-\mathbf{r}'_i|)$: Distance between loudspeaker units and observation points
  - + $\mathbf{r}'_i$: Position vector of loudspeaker units
  - + D_{sji}: Radiation directivity of loudspeaker units

$$p(\mathbf{R}_j,f,t)=\sum_{i=1}^{M}\frac{D_{sji}}{d_{ji}}x_i\left(t-\frac{d_{ji}}{c}\right)=\sum_{i=1}^{M}\frac{D_{sji}A}{d_{ji}d_{i0}}\sin\left\{2\pi f\left(t-\frac{d_{ji}+d_{i0}}{c}\right)\right\}$$

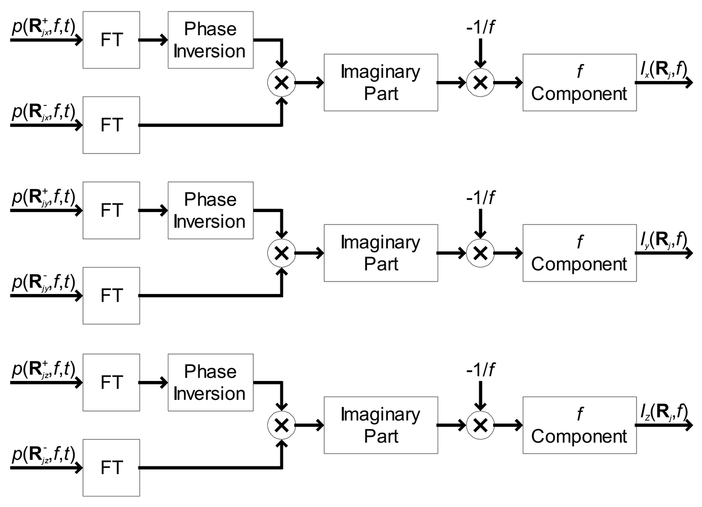
Calculation of Sound Intensity vectors

- Direction of sound intensity vectors
  - + Correspond to arrival direction of 1 sound source

$$\mathbf{I}(\mathbf{R}_j,f)=\{I_x(\mathbf{R}_j,f),I_y(\mathbf{R}_j,f),I_z(\mathbf{R}_j,f)\}^T$$

- Calculation by cross-spectral method
  - + 3 directions are calculated by 6 sound pressures
  - + $p(\mathbf{R}^{\pm}_{jx},f,t),p(\mathbf{R}^{\pm}_{jy},f,t),p(\mathbf{R}^{\pm}_{jz},f,t)$

$$\mathbf{R}^{\pm}_{jx}=\mathbf{R}_j\pm(\Delta,0,0)^T$$
$$\mathbf{R}^{\pm}_{jy}=\mathbf{R}_j\pm(0,\Delta,0)^T \quad \Delta=0.001\text{ m}$$
$$\mathbf{R}^{\pm}_{jz}=\mathbf{R}_j\pm(0,0,\Delta)^T$$



Parametric Conditions

Sound source amplitude (A)	1
Sound source frequency (f)	125, 250, 500, 1000, 2000, 4000, 8000, 16000 Hz
Sound source position ($\mathbf{r}_0$)	$(d\cos\theta_0, d\sin\theta_0, 0)^T$
Sound source distance (d)	0, 0.2, 0.4, 0.6 m
Azimuth angle of sound sources (θ_0)	0, 45°
Sound velocity (c)	340 m/s
Normal unit vector of loudspeaker units ($\mathbf{n}_i$)	$\mathbf{r}'_i/\lvert\mathbf{r}'_i\rvert$
Radiation directivity of loudspeaker units (D_{sji})	Omnidirectional, Decay 6 dB, Decay 12 dB, Real

(Omnidirectional) $D_{sji}=1$

(Decay 6 dB) $D_{sji}=\frac{3+\cos\theta_{sji}}{4}$

(Decay 12 dB) $D_{sji}=\frac{5+3\cos\theta_{sji}}{8}$

(Real) $D_{sji}=\begin{cases}1 & (f=125,250,500)\\ \frac{3+\cos\theta_{sji}}{4} & (f=1000,2000)\\ \frac{5+3\cos\theta_{sji}}{8} & (f=4000,8000,16000)\end{cases}$

$$\cos\theta_{sji}=\frac{\mathbf{n}_i\cdot(\mathbf{R}_j-\mathbf{r}'_i)}{|\mathbf{n}_i||\mathbf{R}_j-\mathbf{r}'_i|}$$

Estimation of Positions

- Estimated position $\mathbf{r}_E$

$$\mathbf{r}_E=\frac{1}{FN}\sum_{f}\sum_{j=1}^{N}\left\{\mathbf{R}_j+\frac{\mathbf{I}(\mathbf{R}_j,f)}{p(\mathbf{R}_j,f)}\right\}$$

- + N(=162): Number of observation points
- + F(=8): Number of frequencies
- + $\mathbf{R}_j$: Position vector of jth observation point
- + $\mathbf{I}(\mathbf{R}_j,f)$: Sound intensity vector in $\mathbf{R}_j$
- + $p(\mathbf{R}_j,f)$: Mean-square sound pressure in $\mathbf{R}_j$

$$p(\mathbf{R}_j,f)=\sqrt{\frac{1}{T}\int_0^T\{p(\mathbf{R}_j,f,t)\}^2dt}$$

- + T: Period

Simulation Results

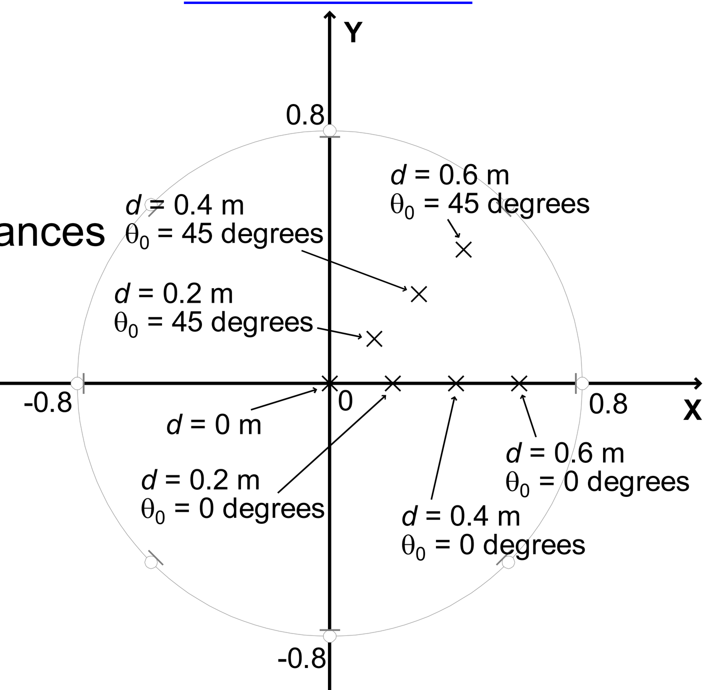
- Estimated sound source positions
  - + Same as the position of inputted positions
- Estimated sound image positions
  - + Distances are less than sound source distances

The general size of the musician's sound image is scaled down to the size of the spherical loudspeaker

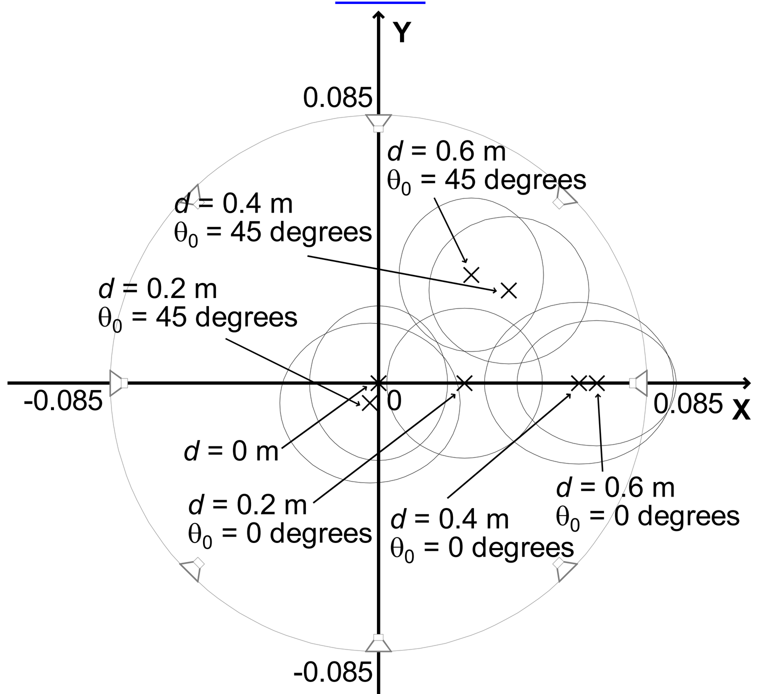
- Size of confidential intervals
  - + 1/4 of the spherical loudspeaker

The sizes of individual point sound images are scaled up significantly

Sound Source



Real

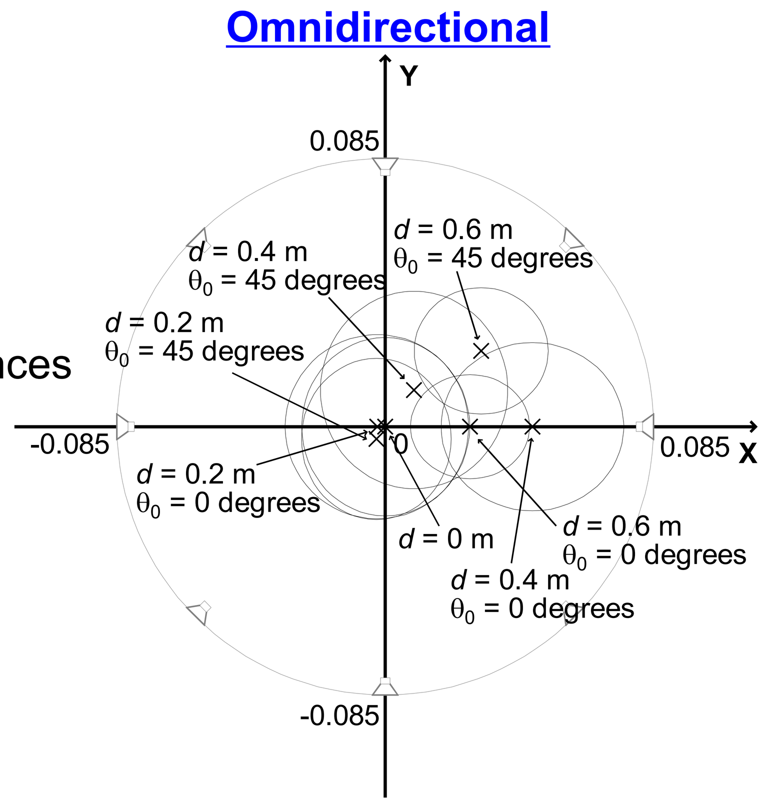


Effect of Radiation Directivity of Loudspeaker Units

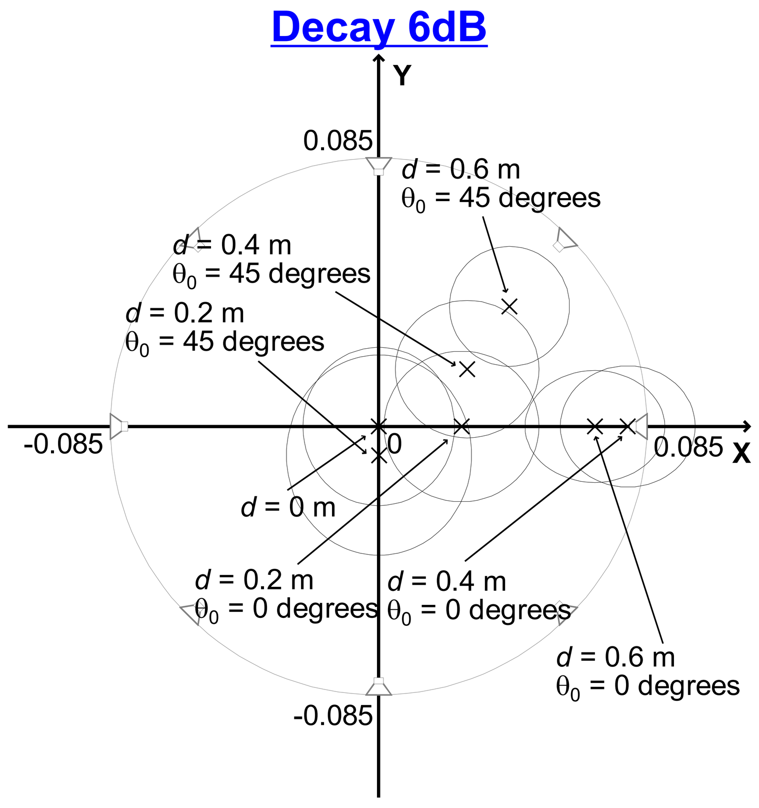
- Omnidirectional
  - + Estimated distances bias to zero meter
- Decay 6dB or Decay 12dB
  - + Estimated distances are similar to inputted distances

The shape of the musician's sound image can be accurately maintained if the radiation directivity of the loudspeaker units is sharply set toward the outside of the loudspeaker

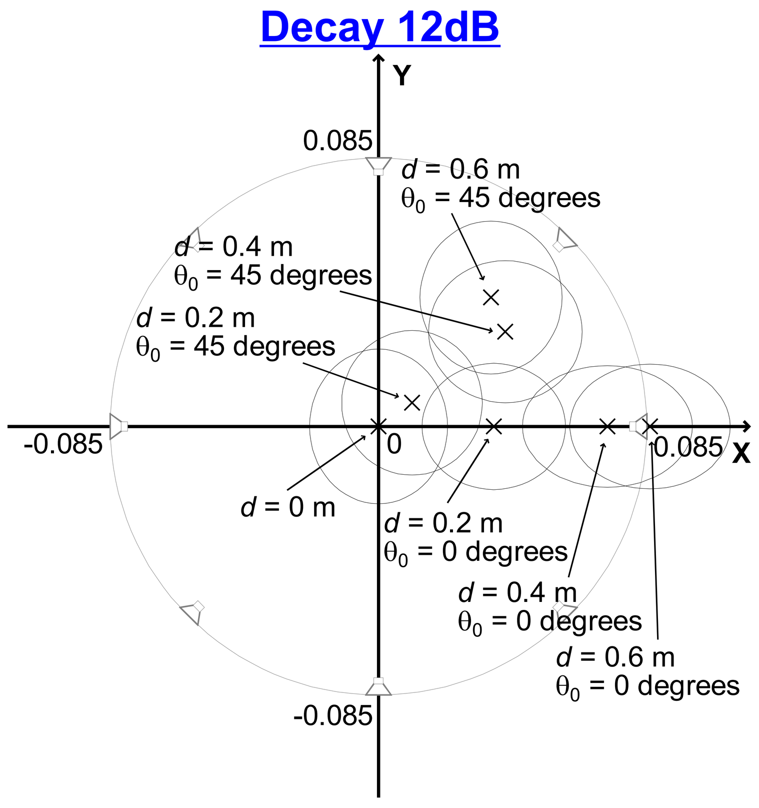
Omnidirectional



Decay 6dB



Decay 12dB



3. CONCLUSION

- Computer simulation was performed
  - + The radiated sound field reproduced by a spherical loudspeaker with variable radiation characteristics was numerically analyzed
- The position of multiple sound images was estimated by the sound source search technique
- The size and shape of the musician's sound image depicted by the spherical loudspeaker was evaluated
  - + **The general size of the musician's sound image was scaled down to the size of the loudspeaker**
  - + **The size of individual point sound sources was scaled up significantly if a musician has multiple point sound sources**
  - + **The shape of the musician's sound image was accurately maintained if the radiation directivity of the loudspeaker units was sharp**
- Future work
  - + Numerical evaluation of the effect of the developed spherical loudspeaker on the radiation characteristics of the musician's sound image