Effects of Directivity of Microphones and Loudspeakers on Accuracy of Synthesized Wave Fronts in Sound Field Reproduction Based on Wave Field Synthesis

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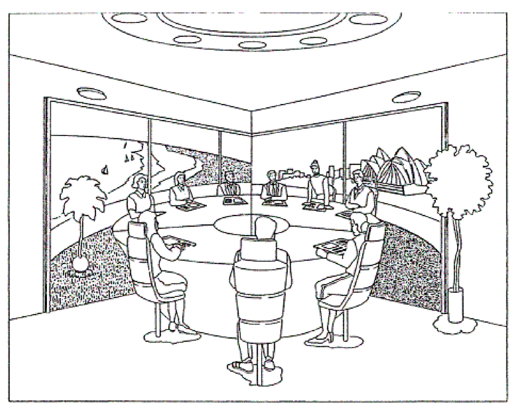
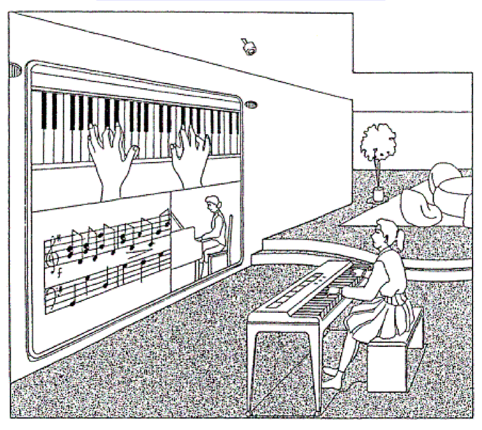
1. INTRODUCTION

Sound field reproduction

- More realistic than ordinary systems
  - Ordinary system…TV-phone, 5.1ch audio
- Tele-conference
  - Meeting in the same room
  - There are others in front of the person
- Tele-ensemble
  - Ensemble in the same place
  - There are others in front of the person

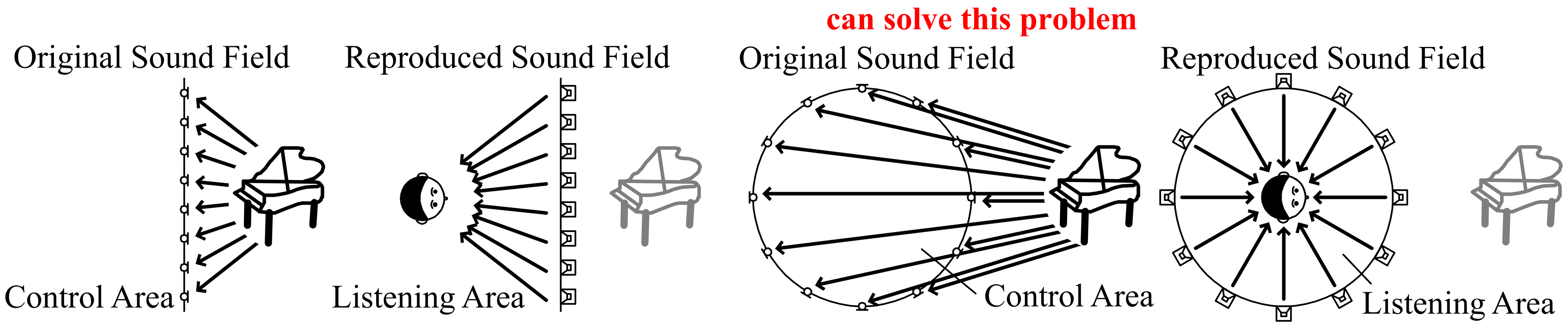
Tele-conference **Tele-ensemble**





Wave field synthesis

- Ordinary studies
  - Arrays are placed in a line
  - Piano sound of a listening area only comes from the frontal direction
- Surround system
  - Arrays are placed around areas
  - Sound of a listening area comes from all directions
  - **The directivity of microphones and loudspeakers can solve this problem**



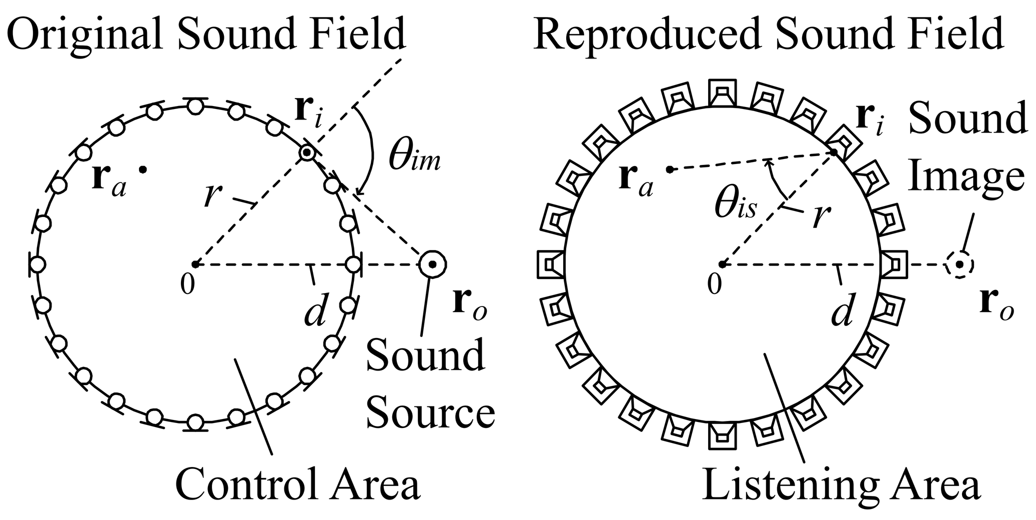
Aim of study

- The effect of the directivity of microphones and loudspeakers on the accuracy of synthesized wave fronts are evaluated by computer simulation
  - Shape of arrays…circle and square

2. COMPUTER SIMULATION - CIRCULAR AREA -

Environmental condition

- Original sound field
  - Free field
- Directivity of microphones
  - Toward the outside of control area
- Directivity of loudspeakers
  - Toward the inside of listening area



- Source signal $s(t) = \sin 2\pi f t$
- Sound pressure in original sound field

$$p_o(\mathbf{r}_a, f, t) = \frac{1}{|\mathbf{r}_a - \mathbf{r}_o|}\sin\left\{2\pi f\left(t - \frac{|\mathbf{r}_a - \mathbf{r}_o|}{c}\right)\right\}$$

- Channel signal of ith microphone

$$x_i(t) = \frac{D_{im}}{|\mathbf{r}_i - \mathbf{r}_o|}\sin\left\{2\pi f\left(t - \frac{|\mathbf{r}_i - \mathbf{r}_o|}{c}\right)\right\}$$

- Sound pressure in reproduced sound field

$$p(\mathbf{r}_a, f, t) = \sum_{i=1}^{M}\frac{D_{is}}{|\mathbf{r}_a - \mathbf{r}_i|}x_i\left(t - \frac{|\mathbf{r}_a - \mathbf{r}_i|}{c}\right)$$

$$= \sum_{i=1}^{M}\frac{D_{is}D_{im}}{|\mathbf{r}_a - \mathbf{r}_i||\mathbf{r}_i - \mathbf{r}_o|}\sin\left\{2\pi f\left(t - \frac{|\mathbf{r}_a - \mathbf{r}_i| + |\mathbf{r}_i - \mathbf{r}_o|}{c}\right)\right\}$$

$\mathbf{r}_o$: Position vector of sound source
$\mathbf{r}_i$: Position vector of microphones
$\mathbf{r}_a$: Position vector of both areas
D_{im}, D_{is} : Directivity of microphones and loudspeakers

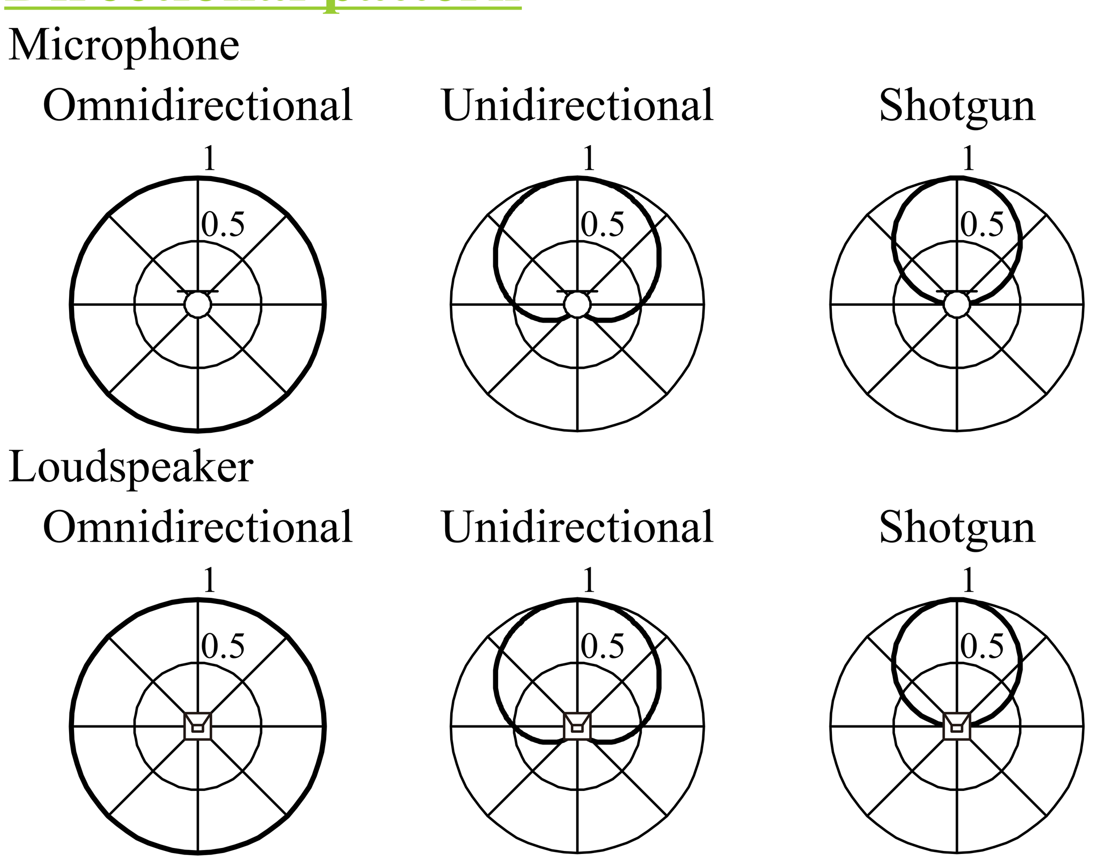
(Omnidirectional)	(Omnidirectional)
$D_{im} = 1$	$D_{is} = 1$
(Unidirectional)	(Unidirectional)
$D_{im} = \frac{1+\cos\theta_{im}}{2}$	$D_{is} = \frac{1+\cos\theta_{is}}{2}$
(Shotgun)	(Shotgun)
$D_{im} = \begin{cases}\cos\theta_{im} & (\theta_{im} \le 90^\circ)\\ 0 & (\theta_{im} > 90^\circ)\end{cases}$	$D_{is} = \begin{cases}\cos\theta_{is} & (\theta_{is} \le 90^\circ)\\ 0 & (\theta_{is} > 90^\circ)\end{cases}$

Parametric condition

Total numbers (M)	630
Source frequency (f)	125, 177, 250, 354, 500, 707, 1000, 1414, 2000, 2828, 4000, 5657, 8000 Hz
Source distance (d)	3, 10, 100 m
Radius of areas (r)	2 m
Sound velocity (c)	340 m/s
Directivity (D_{im}, D_{is})	Omnidirectional, Unidirectional, Shotgun

$$\mathbf{r}_0 = \begin{pmatrix} d \\ 0 \end{pmatrix}, \mathbf{r}_a = \begin{pmatrix} r_x \\ r_y \end{pmatrix} (r_x^2 + r_y^2 < r^2), \mathbf{r}_i = \begin{pmatrix} r\cos\frac{2\pi i}{M} \\ r\sin\frac{2\pi i}{M} \end{pmatrix}$$

Directional pattern



Simulation Results

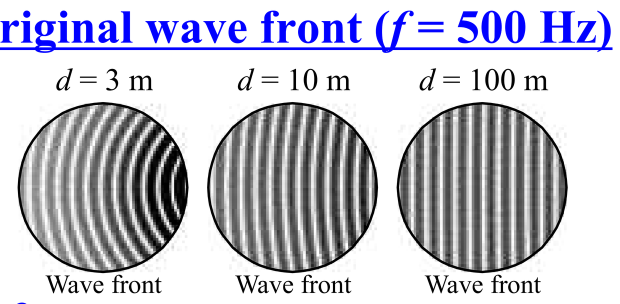
- Omnidirectional microphone
  - Wave fronts aren't reproduced well
- Unidirectional and shotgun microphone
  - Wave fronts are reproduced well

Wave fronts can be accurately reproduced if the unidirectional and shotgun microphone are applied

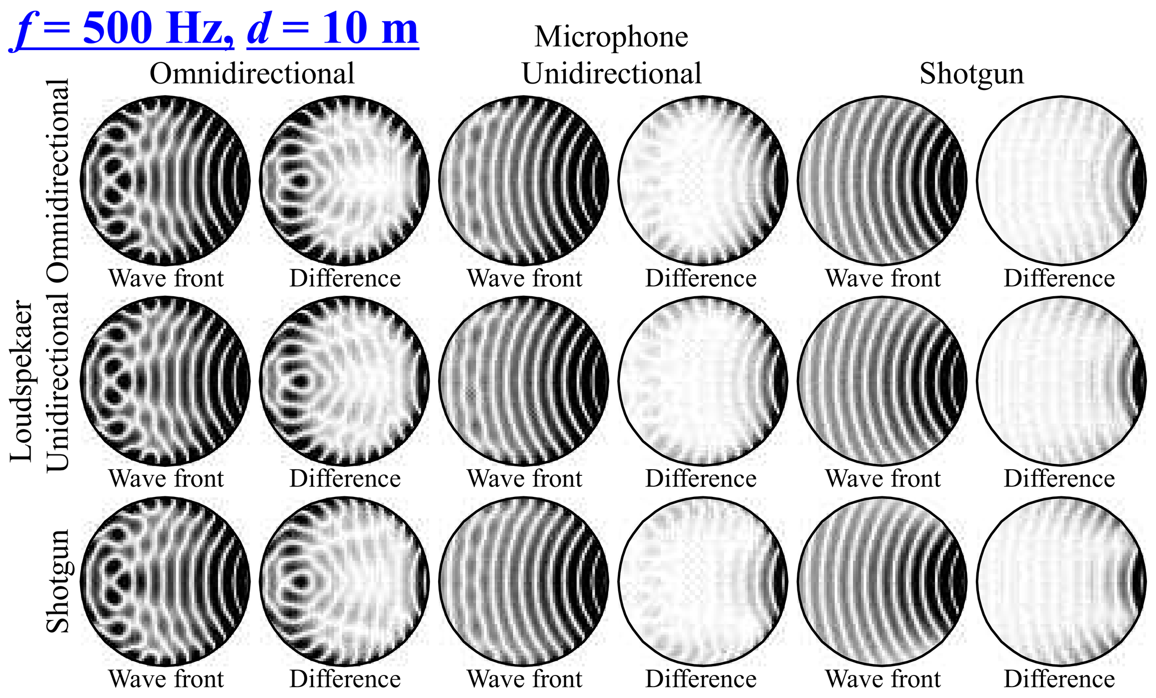
- Loudspeaker
  - Wave fronts are always reproduced well in the all directivity conditions

The directivity of microphones contributes to the accuracy of synthesized wave fronts

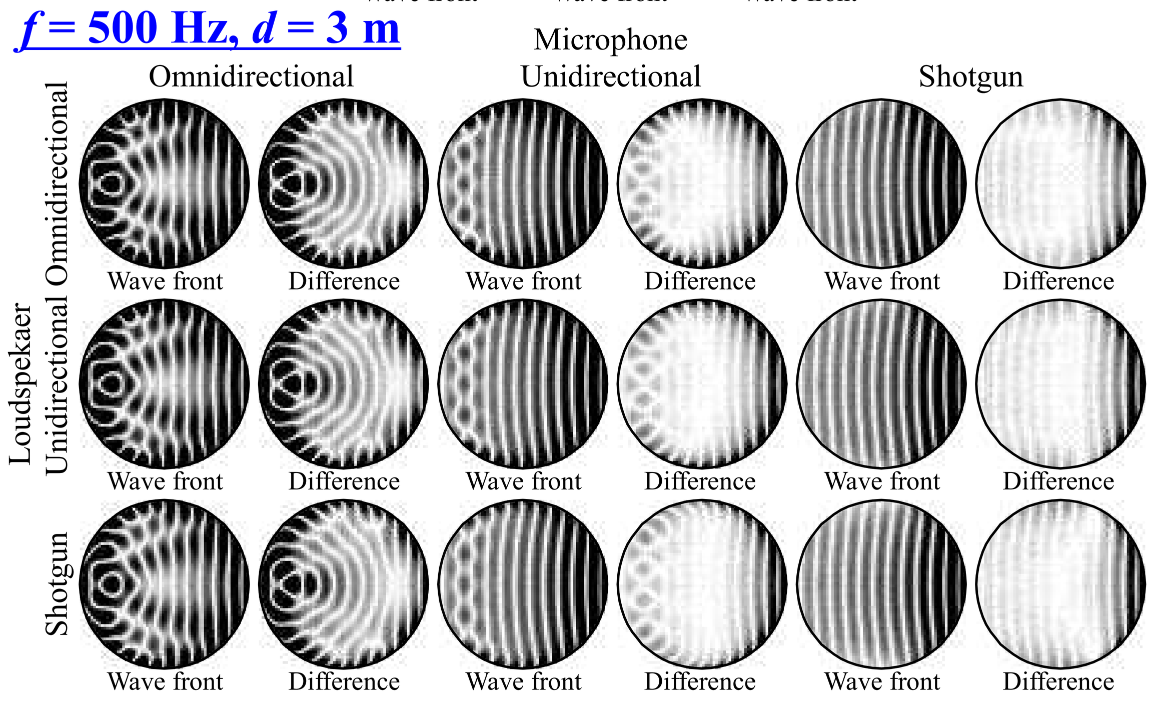
Original wave front (f = 500 Hz)



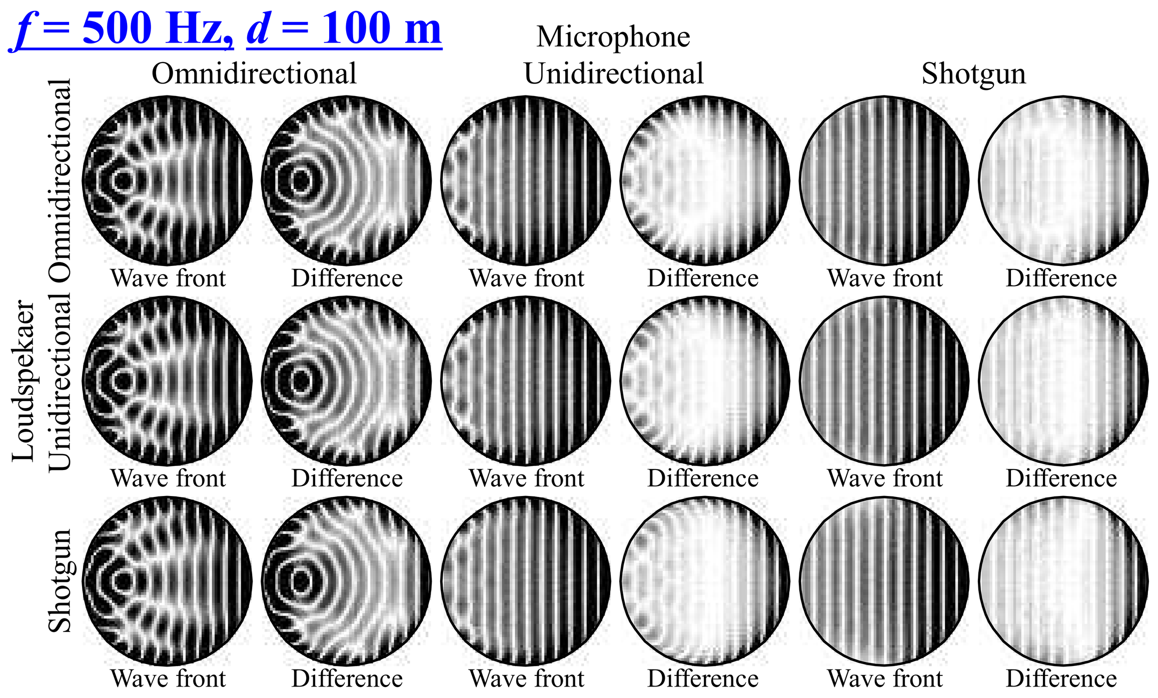
f = 500 Hz, d = 10 m



f = 500 Hz, d = 3 m



f = 500 Hz, d = 100 m

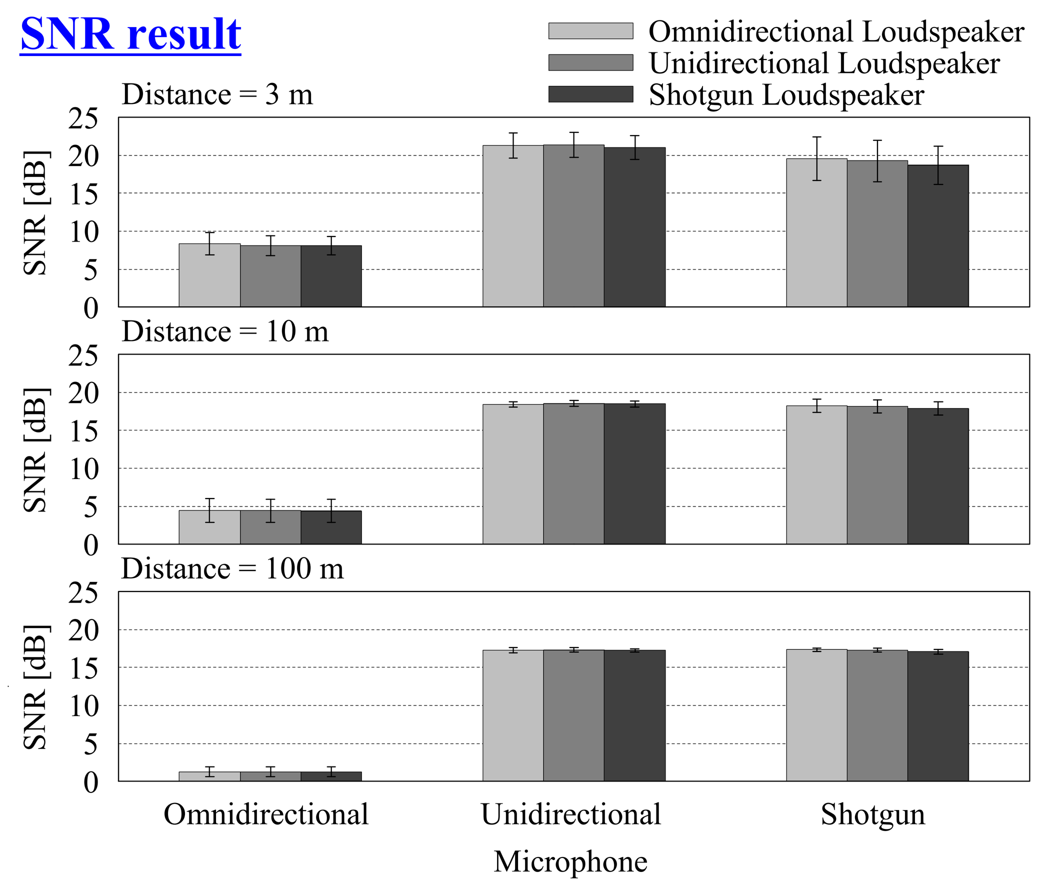


Evaluation by SNR

- SNR(Signal-to-Noise Ratio)
  - Range of $\mathbf{r}_a$: $r_x^2 + r_y^2 < 1^2$
  - F(= 13): Number of frequencies

$$\mathrm{SNR[dB]} = \frac{1}{F}\sum_f\left[10\log_{10}\frac{\sum_{\mathbf{r}_a}\{p_o(\mathbf{r}_a, f, 0)\}^2}{\sum_{\mathbf{r}_a}\{p(\mathbf{r}_a, f, 0) - p_o(\mathbf{r}_a, f, 0)\}^2}\right]$$

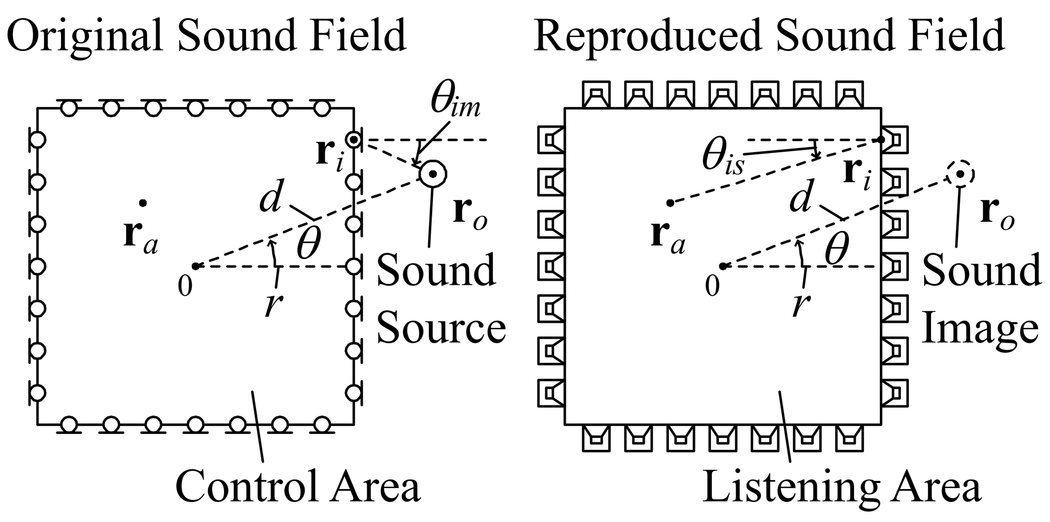
SNR result



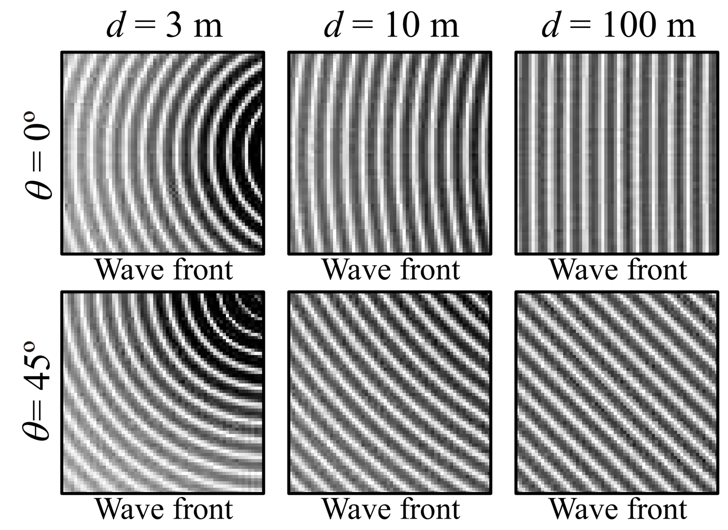
3. COMPUTER SIMULATION - SQUARE AREA -

Environmental condition

- Original sound field
  - Free field
- Directivity of microphones
  - Toward the outside of control area
- Directivity of loudspeakers
  - Toward the inside of listening area



Original wave front (f = 500 Hz)



Parametric condition

Total numbers (M)	800
Source frequency (f)	125, 177, 250, 354, 500, 707, 1000, 1414, 2000, 2828, 4000, 5657, 8000 Hz
Source distance (d)	3, 10, 100 m
Source Azimuth (θ)	0, 45
Side of square ($2r$)	4 m
Sound velocity (c)	340 m/s
Directivity (D_{im}, D_{is})	Omnidirectional, Unidirectional, Shotgun

$$\mathbf{r}_0 = \begin{pmatrix} d\cos\theta \\ d\sin\theta \end{pmatrix}, \mathbf{r}_a = \begin{pmatrix} r_x \\ r_y \end{pmatrix} (|r_x|, |r_y| < r),$$

$$\mathbf{r}_i = \begin{cases} \left(-r + \frac{r}{100} i \quad -r\right)^T & (i = 1 - 200) \\ \left(r \quad -r + \frac{r}{100}(i - 200)\right)^T & (i = 201 - 400) \\ \left(r - \frac{r}{100}(i - 400) \quad r\right)^T & (i = 401 - 600) \\ \left(-r \quad r - \frac{r}{100}(i - 600)\right)^T & (i = 601 - 800) \end{cases}$$

Simulation Results

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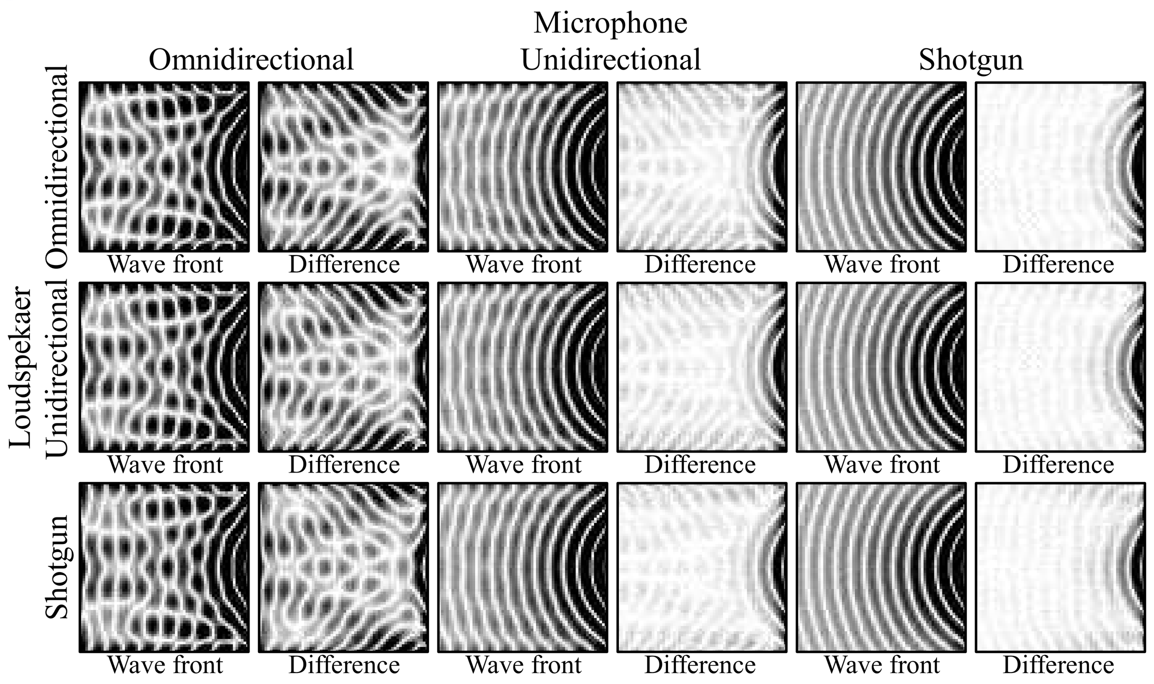
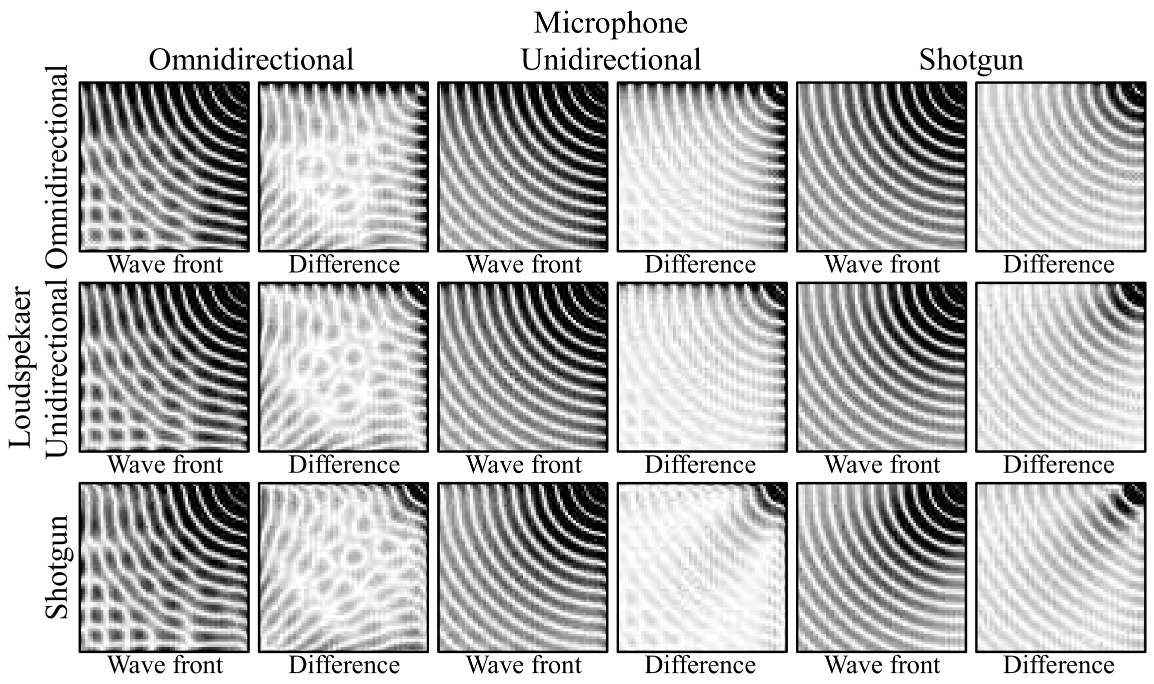
The directivity of microphones contributes to the accuracy of synthesized wave fronts

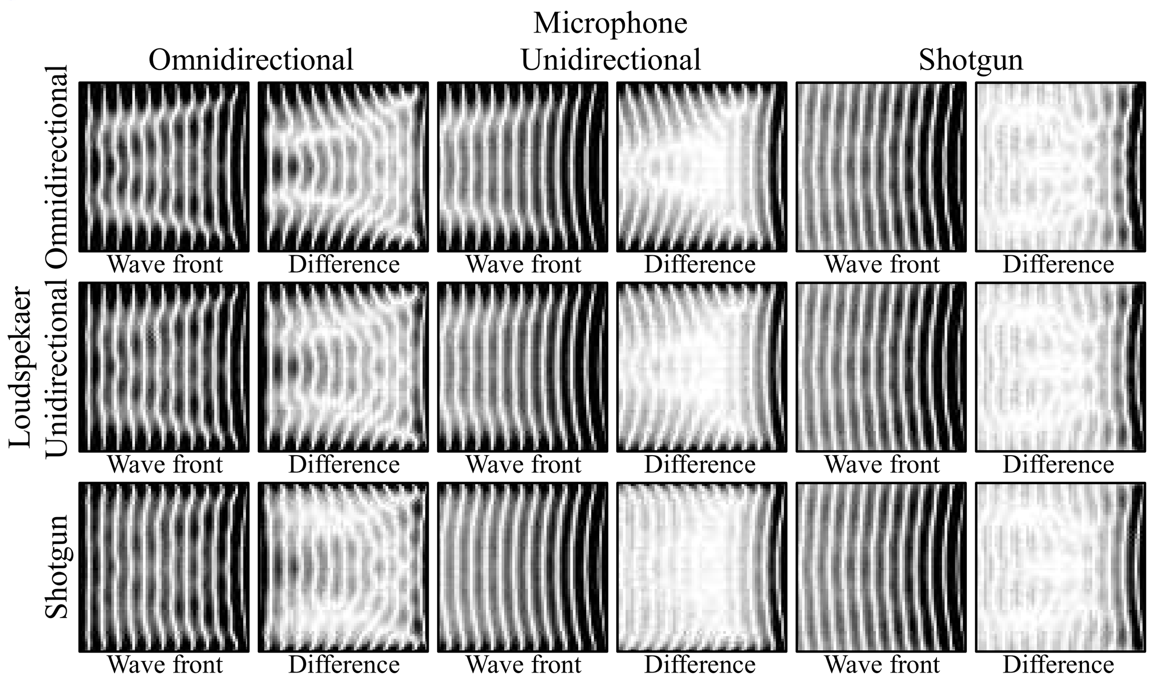
f = 500 Hz, d = 3 m, θ = 0°



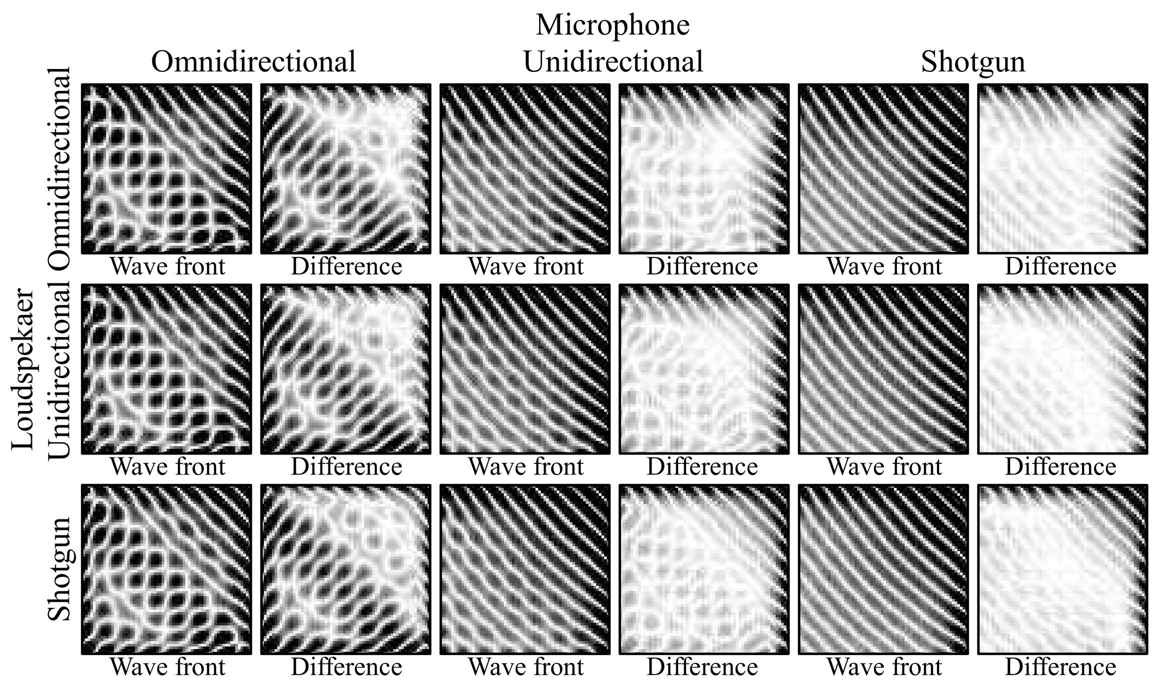
f = 500 Hz, d = 3 m, θ = 45°



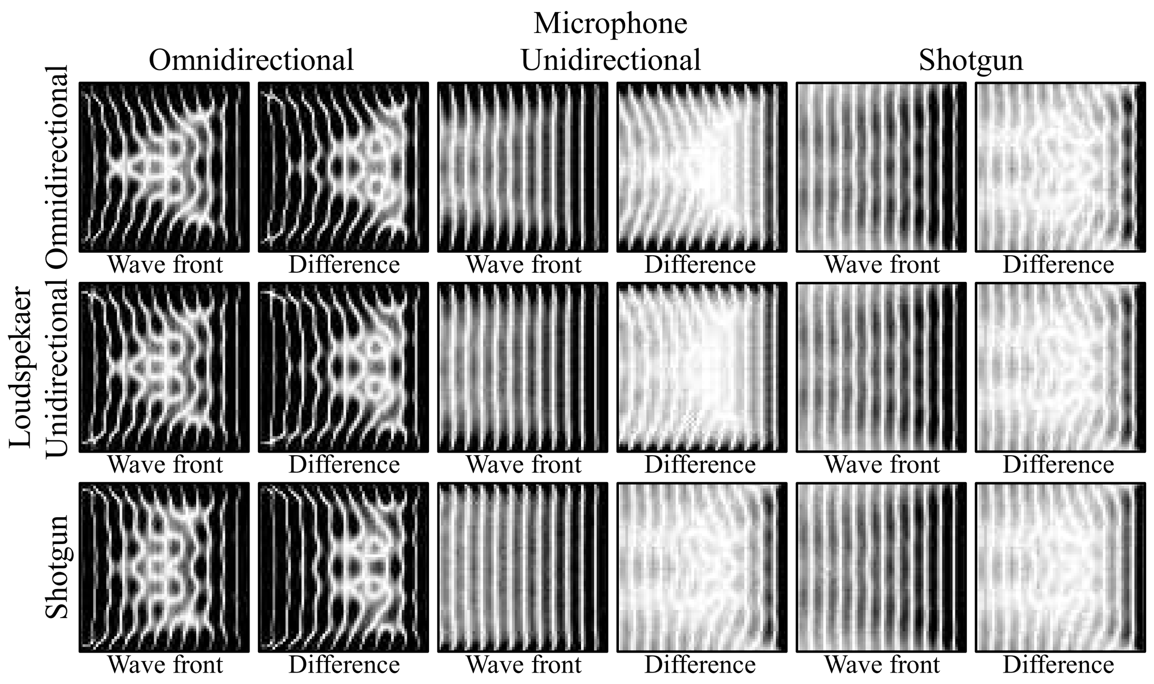
f = 500 Hz, d = 10 m, θ = 0°



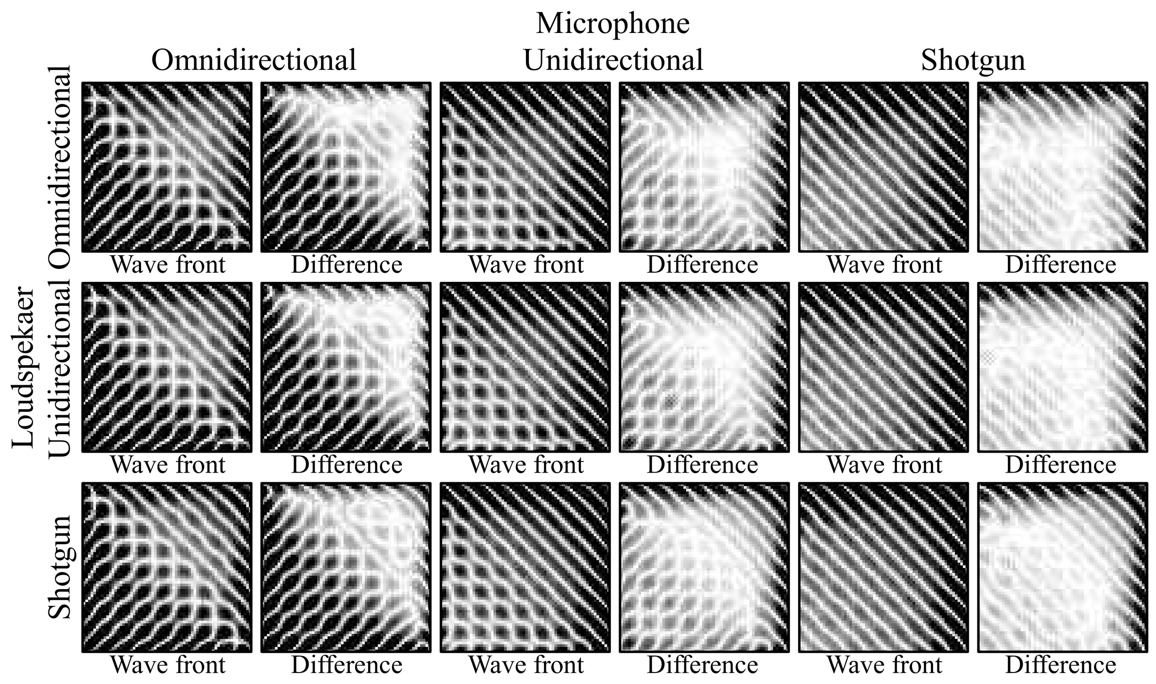
f = 500 Hz, d = 10 m, θ = 45°



f = 500 Hz, d = 100 m, θ = 0°



f = 500 Hz, d = 100 m, θ = 45°

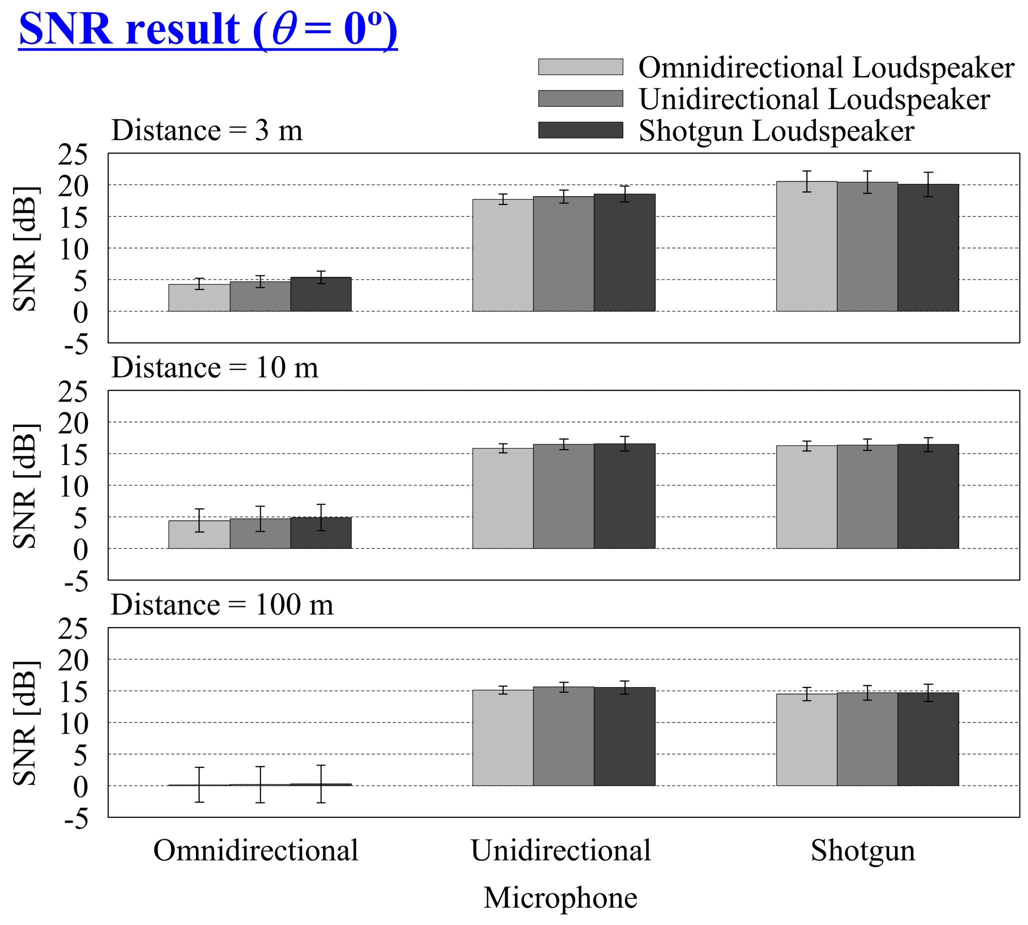


Evaluation by SNR

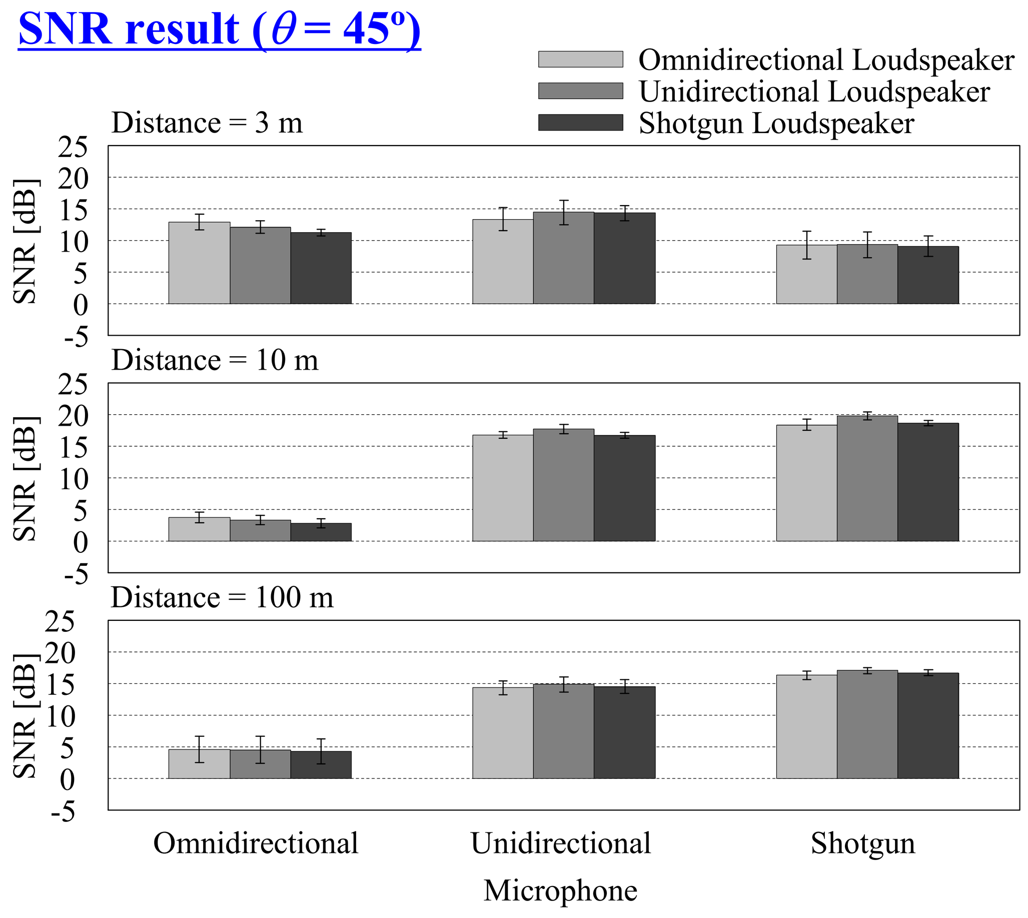
- SNR(Signal-to-Noise Ratio)
  - Range of $\mathbf{r}_a$: $|r_x|, |r_y| < 1$
  - F(= 13): Number of frequencies

$$\mathrm{SNR[dB]} = \frac{1}{F} \sum_f \left[10\log_{10} \frac{\sum_{\mathbf{r}_a} \{p_o(\mathbf{r}_a, f, 0)\}^2}{\sum_{\mathbf{r}_a} \{p(\mathbf{r}_a, f, 0) - p_o(\mathbf{r}_a, f, 0)\}^2} \right]$$

SNR result (θ = 0°)



SNR result (θ = 45°)



4. CONCLUSION

- **Computer simulation was performed in order to evaluate the effect of the directivity of microphones and loudspeakers on the accuracy of synthesized wave fronts in sound field reproduction based on wave field synthesis**
- As the result of two cases (the area of a circle and a square), it was shown as follows:
  - **There is almost no effect of the directivity of loudspeakers**
  - **Accurate wave fronts can be reproduced when a unidirectional and shotgun microphone are applied**
- Future works
  - The effect of the directivity of microphones and loudspeakers in the three-dimensional space
  - The accuracy of synthesized wave fronts when the loudspeaker array is placed in a reverberant room