Virtual Source Reproduction Using Two Rigid Circular Loudspeaker Arrays

Yi Ren and Yoichi Haneda (The University of Electro-Communications)

Convention Paper 10120

ABSTRACT - In this paper, a virtual sound source reproduction method is proposed using two circular loudspeaker arrays with rigid baffles. This study aims to reproduce virtual sources in front of, or outside the loudspeaker arrays, with each array considered as an infinite-length rigid cylinder with loudspeakers attached to its surface. Transfer functions that consider the reflection between the two arrays are introduced, and the appropriate reflection times to be used in the transfer function are discussed. Using the pressure-matching method and circular harmonic expansion, several methods are proposed and compared via computer simulation.

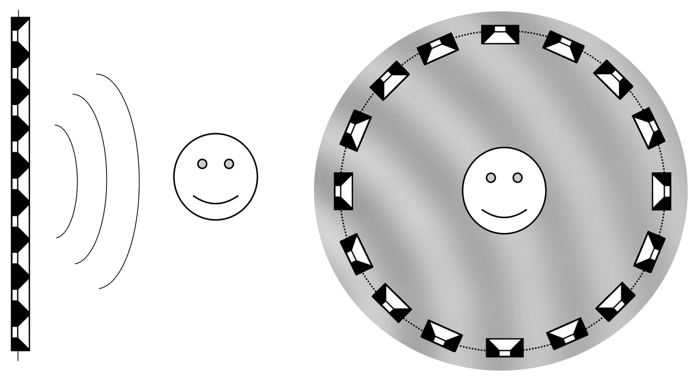
Introduction

Immersive Audio System

- Multichannel sound systems
- Binaural reproduction
- ***Sound field reproduction***

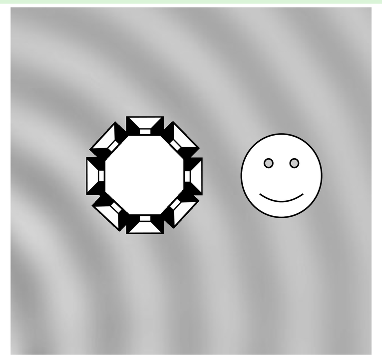
Virtual Source Reproduction

A particular case of sound field reproduction is virtual source reproduction where only known sources exist in the desired sound field. Conventional methods for virtual source reproduction with a circular loudspeaker array reproduce virtual sound **in front of a linear loudspeaker array** or **inside a circular loudspeaker array**.



- **Listeners are restricted to a limited area** or a very large-scale array is required.
- Reverberations in a real environment could cause errors in sound field reproduction inside a circular array.

Virtual Source Reproduction Exterior to a Circular Loudspeaker Array



Virtual source reproduction using a circular loudspeaker array reproduces virtual sound **outside the circular loudspeaker array**.

- **limitless listening area**
- reverberation in a real environment would result in a more natural sound.

To reproduce a virtual source exterior to the **circular loudspeaker array**, we set **control points** on a circle exterior to both the source and loudspeakers. By **reproducing the sound pressure at every control point**, the sound field could be reproduced when no source exists in the exterior area. A pressure matching method could be used to obtain the **driving function**.

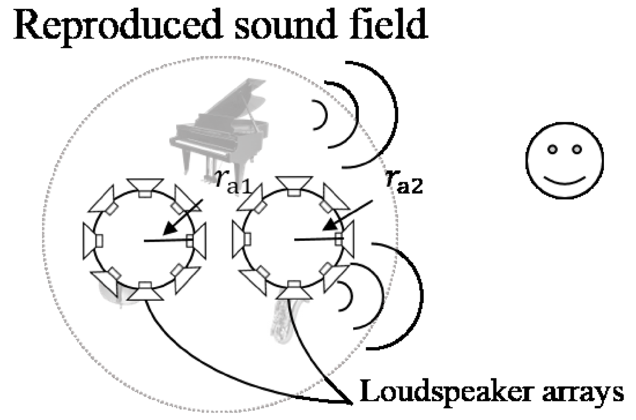
Pressure Matching

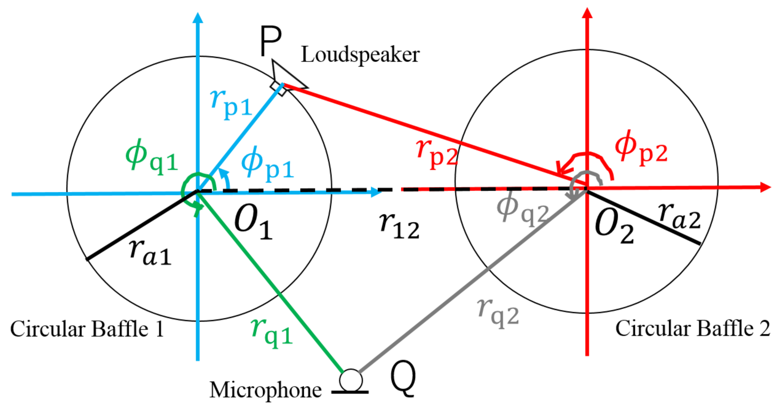
$$\mathbf{d} = \frac{\mathbf{G}^{\mathrm{H}}\mathbf{P}}{\mathbf{G}^{\mathrm{H}}\mathbf{G} + \lambda\mathbf{I}} \quad (1)$$

d: driving function; **G**: transfer function; **P**: desired sound field; **I**: identity matrix; λ: regularization parameter.

Virtual Source Reproduction Using Two Rigid Circular Loudspeaker Arrays

Using a circular loudspeaker array, it is only possible to reproduce a sound source within **limited distance** or **limited bandwidth**. Introducing one more circular loudspeaker array is considered effective for increasing the source distance.

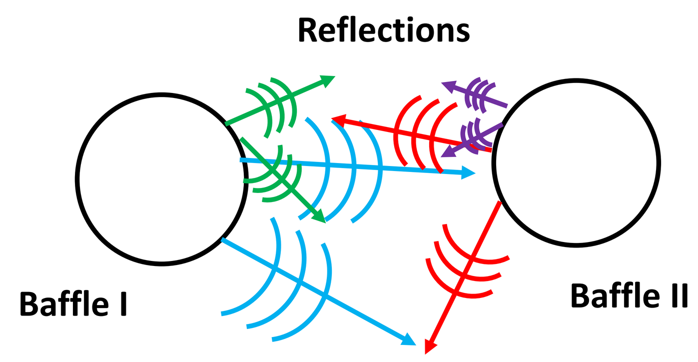




Coordinate System

Virtual Source Reproduction Using Two Rigid Circular Loudspeaker Arrays

However, sound would **reflect between two rigid circular baffles infinitely**, which complicates the transfer function G of the two rigid circular arrays.

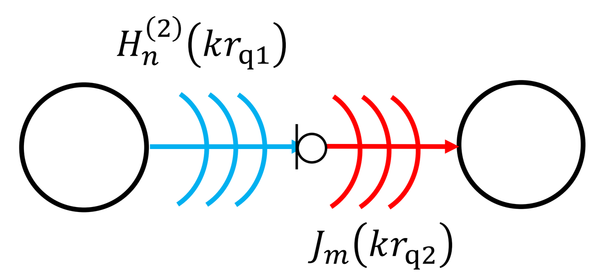


Interactions between Two Rigid Circular Baffles

Eq. (2) describes the **scattered sound** of baffle I, and Eq. (3) describes the **incident sound** of baffle II with the same value at a given position.

$$P_{1s}(r_{q1}, \phi_{q1}) = \sum_{n=-\infty}^{\infty} \gamma_{n,1} H_n^{(2)}(kr_{q1}) e^{jn\phi_{q1}} \quad (2)$$

$$P_{2i}(r_{q2}, \phi_{q2}) = \sum_{m=-\infty}^{\infty} \alpha_{m,2} J_m(kr_{q2}) e^{jm\phi_{q2}} \quad (3)$$



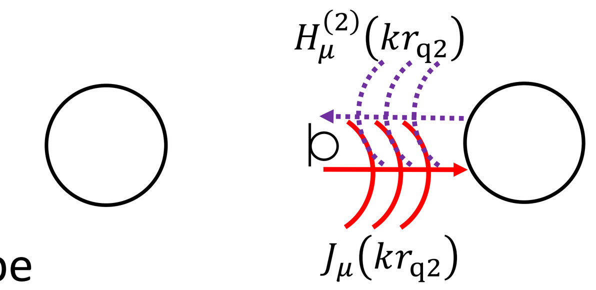
Eq. (4) could be obtained by using **Graf's Addition Theorem** and the properties of Bessel functions. Therefore, the relationship between Eqs. (2) and (3) could be expressed as Eq. (5)

$$H_n^{(2)}(kr_{q1}) e^{jn\phi_{q1}} = \sum_{m=-\infty}^{\infty} H_{n-m}^{(2)}(kr_{12}) J_m(kr_{q2}) e^{jm\phi_{q2}} \quad (4)$$

$$\alpha_{m,2} = \sum_{n=-\infty}^{\infty} H_{n-m}^{(2)}(kr_{12}) \gamma_{n,1} \quad (5)$$

The incident sound P_{2i} is then reflected by baffle II and becomes scattered sound P_{2s}.

$$P_{2s}(r_{q2}, \phi_{q2}) = \sum_{m=-\infty}^{\infty} \beta_{m,2} H_m^{(2)}(kr_{q2}) e^{jm\phi_{q2}} \quad (6)$$



The velocity of the normal direction would become 0 on the circumference of a rigid baffle and Eq.(7) could be obtained. Eq. (8) for the opposite reflections could be obtained in a similar manner.

$$\beta_{m,2} = -\frac{J_m'(kr_{a2})}{H_m^{(2)'}(kr_{a2})} \alpha_{m,2} = -\frac{J_m'(kr_{a2})}{H_m^{(2)'}(kr_{a2})} \sum_{n=-\infty}^{\infty} H_{n-m}^{(2)}(kr_{12}) \gamma_{n,1} \quad (7)$$

$$\beta_{m,1} = -\frac{J_m'(kr_{a1})}{H_m^{(2)'}(kr_{a1})} \sum_{n=-\infty}^{\infty} H_{m-n}^{(2)}(kr_{12}) \gamma_{n,2} \quad (8)$$

Transfer Functions Related to Two Rigid Circular Arrays

All sound reflections could be calculated using the proposed transformation. Then the transfer function could be expressed as **the sum of the direct sound and reflections**. For order n, Eqs. (7) and (8) could be considered as a kind of **convolution**. Therefore, we truncated the maximum order and reflection times and applied **vectorization** for faster simulations.

$$T_{n,m,1} = -\frac{J_m'(kr_{a1})}{H_m^{(2)'}(kr_{a1})} H_{m-n}^{(2)}(kr_{12}), \qquad T_{n,m,2} = -\frac{J_m'(kr_{a2})}{H_m^{(2)'}(kr_{a2})} H_{n-m}^{(2)}(kr_{12})$$

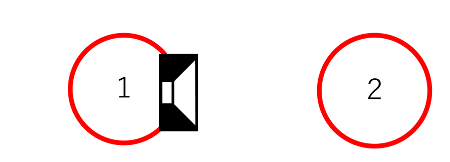
$$P_{111} = \boldsymbol{\psi}_1^{\mathrm{T}}\boldsymbol{\gamma}_1, P_{121} = \boldsymbol{\psi}_2^{\mathrm{T}}\mathbf{T}_2\boldsymbol{\gamma}_1, P_{112} = \boldsymbol{\psi}_1^{\mathrm{T}}\mathbf{T}_1\mathbf{T}_2\boldsymbol{\gamma}_1, P_{122} = \boldsymbol{\psi}_2^{\mathrm{T}}\mathbf{T}_2\mathbf{T}_1\mathbf{T}_2\boldsymbol{\gamma}_1$$

$$P_{221} = \boldsymbol{\psi}_2^{\mathrm{T}}\boldsymbol{\gamma}_2, P_{211} = \boldsymbol{\psi}_1^{\mathrm{T}}\mathbf{T}_1\boldsymbol{\gamma}_2, P_{222} = \boldsymbol{\psi}_2^{\mathrm{T}}\mathbf{T}_2\mathbf{T}_1\boldsymbol{\gamma}_2, P_{212} = \boldsymbol{\psi}_1^{\mathrm{T}}\mathbf{T}_1\mathbf{T}_2\mathbf{T}_1\boldsymbol{\gamma}_2$$

$$G_1 = P_{111} + P_{121} + P_{112} + P_{122} + \cdots$$

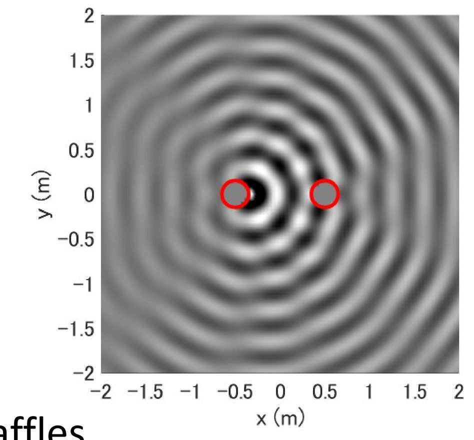
$$G_2 = P_{221} + P_{211} + P_{222} + P_{212} + \cdots$$

A wave field simulation was conducted and the results nearly match the FDTD results.

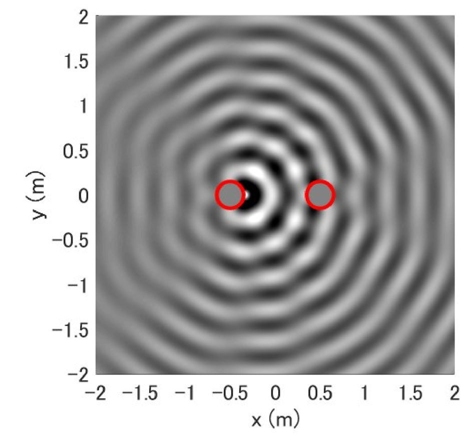


Model for simulation

Red circles represent rigid baffles



Proposed Method

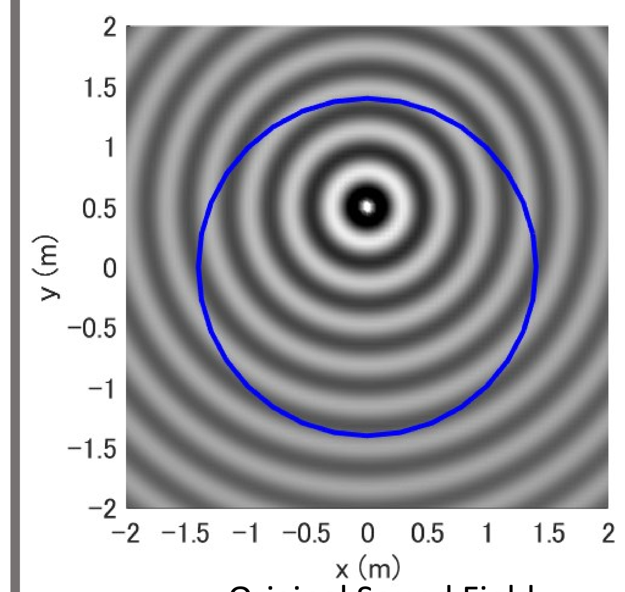


FDTD

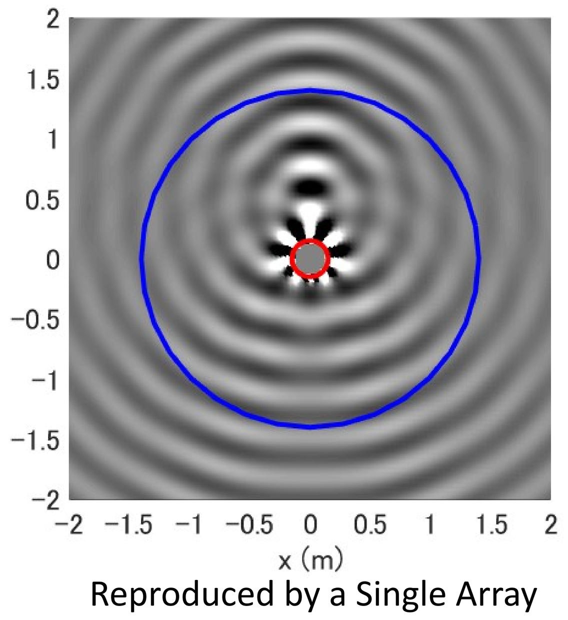
Results

Virtual Source Reproduction

Blue circles represent control points

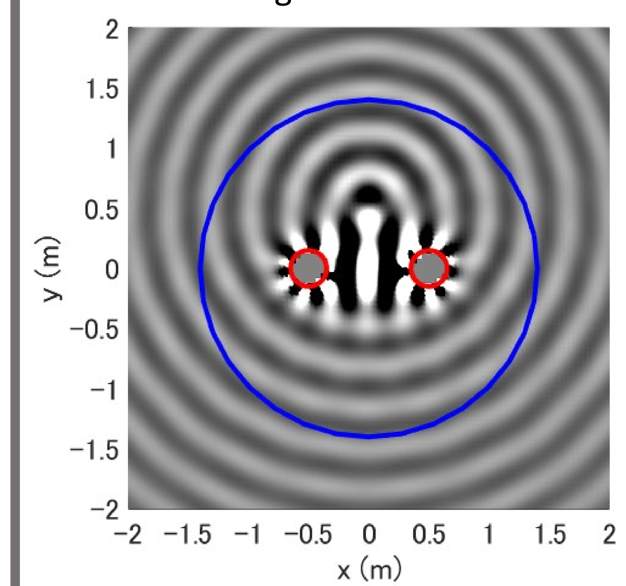


Original Sound Field

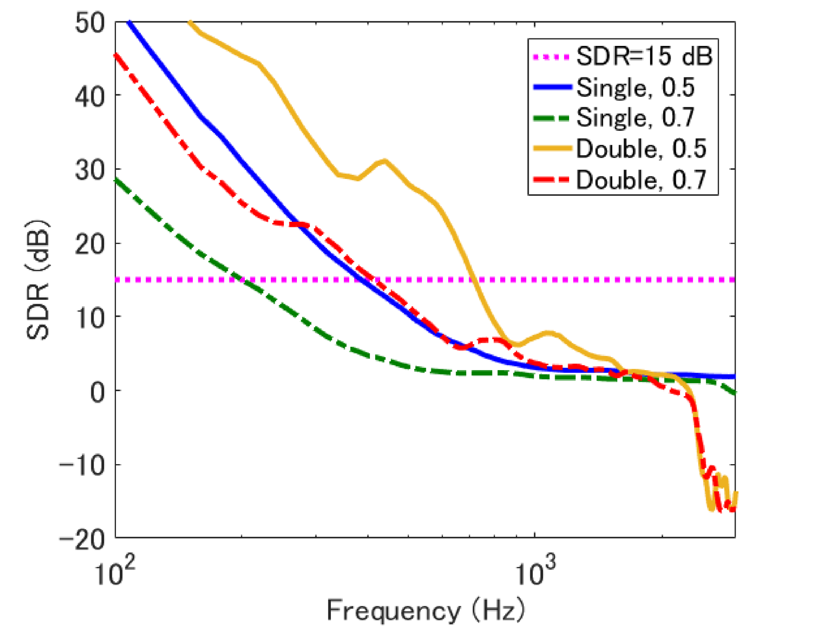


Reproduced by a Single Array

Frequency(fs)	1000 Hz
Pos. of source	(0 m, 0.5 m)
No. of control points	48
Radius of control points	1.4 m
No. of speakers(L)	30
Radius of array	0.15 m
Center of two baffles	(−0.5 m, 0 m), (0.5 m, 0 m)



Reproduced by Two Arrays



Single/Double: Single array (30 ch)/Two arrays (2×15 ch)
0.5/0.7: Distance of source r_s = 0.5 m/0.7 m

SDR (Signal-to-distortion ratio)

SDR was used to evaluate the reproduction accuracy. A reproduction with SDR greater that **15 dB** indicates a well-reproduced sound field and is considered as a threshold.

$$\mathrm{SDR\ [dB]} = 10\log_{10}\frac{\sum|P|^2}{\sum|P-\hat{P}|^2}$$

The **filter gain** was set to **0 dB** as a constraint.

Conclusion

We proposed several methods for reproducing a virtual source outside a loudspeaker array. It was confirmed that the proposed method can effectively reproduce the desired sound field, while using two circular loudspeaker arrays could provide better performance. A transfer function for the model with two rigid circular arrays was proposed and is considered practical.
A mode-matching method for the model with two circular arrays is considered for further research, and a prototype of this system is being built.