LOCALIZED SOUND REPRODUCTION USING CIRCULAR LOUDSPEAKER ARRAY BASED ON ACOUSTIC EVANESCENT WAVE

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ABSTRACT

We present a localized sound reproduction method in which sound energy is high in specified target areas and low everywhere else. Such a system needs to reproduce a sound which attenuates faster than a point source. Our study focuses on an acoustic evanescent wave that has faster distance attenuation. The evanescent wave can be generated when a wave transmitted at subsonic speed between two media. Previously, we used a linear loudspeaker array to reproduce the evanescent wave. Nevertheless, since this method requires a line source of infinite length, a large number of loudspeakers are needed to realize sufficiently fast distance attenuation. To reduce the number of loudspeakers, we propose an evanescent wave reproduction method by using a circular loudspeaker array. Computer simulation results show that our method achieves faster distance attenuation than a point source and reduces the number of loudspeakers to less than that of the linear loudspeaker array.

***Index Terms*—** evanescent wave, fast distance attenuation, localized sound reproduction, circular loudspeaker array

1. INTRODUCTION

The purpose of our study was to develop a sound reproduction system for personalizing a listening area. This system can localize a sound field around one specific location so that the sound energy outside the target area is low, while the sound energy in the target area is high. An application of this work is to provide a private music listening area for users located at arbitrary positions. If the sound can be delivered to a specific place in a teleconference situation in an open office area, the speech from a remote location can be provided to only the conference participants.

A number of methods based on the theory of active control of sound [1] have been proposed [2, 3, 4, 5] for a localized sound reproduction. In these methods, control points are located in three-dimensional (3D) space. The sound energy at each control point is controlled so that it is equal to the preferred energy. However, since these methods have not yet accomplished controlling the listening area precisely, they causes sound leakage among control points. This is probably because these methods don't follow physical laws.

An evanescent wave is a physical phenomenon that decays exponentially with distance [6]. It can be observed in cases such as vibrating plates, wave reflection, and wave transmission between two different media. According to sound field reproduction methods based on wave field synthesis [7, 8, 9], evanescent waves are spatial aliasing artifacts and are undesirable. However, since these methods target reproduction of pure plane waves, and evanescent waves have faster amplitude decay, the contribution of the evanescent wave is considered negligible. In our work, we reproduced pure evanescent waves at an audio frequency band. Previously, we used a linear loudspeaker array to reproduce an acoustic evanescent wave [10]. However, since our previous method using linear array requires a line source of infinite length in principle, a large number of loudspeakers are needed to realize sufficiently fast distance attenuation.

To overcome the above problem, we focus on the evanescent wave in a cylindrical coordinate system, and propose a new reproduction method by using a circular loudspeaker array. We derived a driving signal for each loudspeaker to reproduce only the evanescent wave. Experimental results show that evanescent waves can be reproduced only with our method. We also show the relationship between the circumference wave number and the number of loudspeakers of the proposed evanescent wave reproduction system.

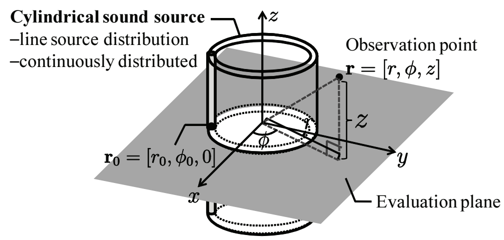

Fig. 1. Cylindrical coordinate system and set up of cylindrical sound source

2. ACOUSTIC EVANESCENT WAVE IN CYLINDRICAL COORDINATE SYSTEM

We used a cylindrical coordinate system $\mathbf{r} = [r, \phi, z]^T$ as in Fig. 1. Assuming sound fields along the z-axis as constant, we restrict an evaluation plane to the $z = 0$ plane only. When a cylindrical sound source whose radius is r_0 exists, as shown in Fig. 1, the sound field at observed point $\mathbf{r}$ $(r > r_0)$ is expressed as [6],

$$P(r, \phi, \omega) = \sum_{n=-\infty}^{\infty} \mathsf{P}(r_0, n, \omega) \frac{H_n^{(2)}(kr)}{H_n^{(2)}(kr_0)} e^{-jn\phi} , \qquad (1)$$

where ω is the angular frequency of the sound source, k is the wave number of the sound source, n is the circumferential wave number, $H_n^{(2)}(\cdot)$ is n-th order second kind Hankel function, $\mathbf{r}_0 = [r_0, \phi_0, 0]^T$ is the position of the line source of the $z = 0$ plane, and $\mathsf{P}(r_0, n, \omega)$ is the spatial spectrum of $P(r_0, \phi, \omega)$ with respect to ϕ.

When the circumferential wave number n is much greater than kr, the second kind Hankel function can be approximated as,

$$H_n^{(2)}(kr) \simeq j\sqrt{\frac{2}{\pi n}}\left(\frac{ekr}{2n}\right)^{-n} \quad (n \gg kr) \ . \tag{2}$$

If we choose one of n which satisfies $n \gg kr$ as n_{eva} and use Eq. (2), Eq. (1) can be rewritten as,

$$P(r, \phi, \omega) \simeq \mathsf{P}(r_0, n_{\text{eva}}, \omega)\left(\frac{r}{r_0}\right)^{-n_{\text{eva}}} e^{-jn_{\text{eva}}\phi} \ , \tag{3}$$

where $\mathsf{P}(r_0, n_{\text{eva}}, \omega)$ is a constant, $\left(\frac{r}{r_0}\right)^{-n_{\text{eva}}}$ is the distance attenuation term, and $e^{-jn_{\text{eva}}\phi}$ is the circumferential variation of the sound pressure. Equation (3) shows that attenuates followed as a power of n_{eva} with respect to r, which is called an acoustic evanescent wave generated by the cylindrical sound source.

3. PROPOSED METHOD FOR REPRODUCING EVANESCENT WAVES BY USING CIRCULAR ARRAY

3.1. Sound field reproduction in cylindrical coordinate system

The sound field reproduced by a continuous cylindrical sound source (Fig. 1) can be definitely expressed by

$$P(r, \phi, \omega) = \int_0^{2\pi} D(\phi_0, \omega) G(\mathbf{r} - \mathbf{r}_0, \omega) r_0 d\phi_0 \ , \tag{4}$$

where $D(\phi_0, \omega)$ is the driving signal for the cylindrical source, and $G(\mathbf{r} - \mathbf{r}_0, \omega)$ is the spatio-temporal transfer function between the line source located at $\mathbf{r}_0$ and the observation point $\mathbf{r}$.

Applying a spatial Fourier transform to Eq. (4) with respect to ϕ yields the sound field in the spatial frequency domain as

$$\mathsf{P}(r, n, \omega) = 2\pi r_0 \mathsf{D}(n, \omega) \cdot \mathsf{G}(r, n, \omega) \ . \tag{5}$$

Equation (5) shows that if the desired sound field $\mathsf{P}(r, n, \omega)$ and spatial transfer function $\mathsf{G}(r, n, \omega)$ is known, we can derive the driving signal for the cylindrical sound source. The driving signal in the spatial frequency domain is given as [9],

$$\mathsf{D}(n, \omega) = \frac{1}{2\pi r_0} \cdot \frac{\mathsf{P}(r, n, \omega)}{\mathsf{G}(r, n, \omega)} \ . \tag{6}$$

Normally, The spatial spectra of the transfer function is given as [9]

$$\mathsf{G}(r, n, \omega) = \frac{1}{4j} J_n(kr_0) H_n^{(2)}(kr) \ , \tag{7}$$

where $J_n(\cdot)$ is n-th order first kind Bessel function. To reproduce the evanescent wave by using Eq. (6), we need to calculate the spatial spectra of the evanescent wave $\mathsf{P}(r, n, \omega)$.

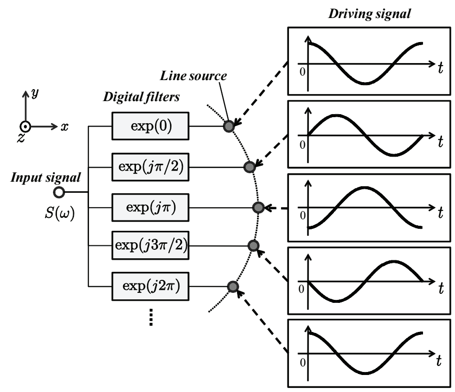

Fig. 2. Illustration of driving signal in time domain for each line source

3.2. Derivation of driving signal for reproducing acoustic evanescent waves

The spatial spectrum of the evanescent wave is given by the Fourier transform of Eq. (1) with respect to ϕ :

$$\mathsf{P}(r, n, \omega) = \mathsf{P}(r_0, n, \omega) \frac{H_n^{(2)}(kr)}{H_n^{(2)}(kr_0)} \ . \tag{8}$$

From Eq. (3), we have to choose n which satisfies $n > kr_0$ as n_{eva} to reproduce the evanescent wave. This condition can be described as,

$$P(r_0, n, \omega) = \delta(n - n_{\text{eva}}) \cdot S(\omega) \ , \tag{9}$$

where $S(\omega)$ is an temporal spectrum of the input signal. Substituting Eqs. (7), (8), and (9) into Eq. (6), the driving signal for reproducing the evanescent wave in the spatial frequency domain is given as

$$\mathsf{D}(n, \omega) = \frac{2j}{\pi r_0} \frac{\delta(n - n_{\text{eva}}) \cdot S(\omega)}{J_n(kr_0) H_n^{(2)}(kr_0)} \ , \tag{10}$$

and that in the temporal frequency domain is given as

$$D(\phi_0, \omega) = \frac{2j}{\pi r_0} \frac{e^{-jn_{\text{eva}}\phi_0}}{J_{n_{\text{eva}}}(kr_0) H_{n_{\text{eva}}}^{(2)}(kr_0)} \cdot S(\omega) \ . \tag{11}$$

Equation (11) has a circumferential variation term of sound pressure $e^{-jn_{\text{eva}}\phi_0}$ which depends on ϕ_0. This indicates that, if each line sound source is driven by an input signal with each phase shifted as shown in Fig. 2, we can reproduce the evanescent wave.

3.3. System configuration for proposed method

For practical implementation, the cylindrical line source distribution has to be replaced with a circular point source distribution and spatially discretized. The spatial transfer function $G(\mathbf{r} - \mathbf{r}_0, \omega)$ of a line source is approximated by that of the point source as,

$$G(\mathbf{r} - \mathbf{r}_0, \omega) \simeq \sqrt{\frac{2\pi|\mathbf{r} - \mathbf{r}_0|}{jk}} \cdot \frac{e^{-jk|\mathbf{r} - \mathbf{r}_0|}}{4\pi|\mathbf{r} - \mathbf{r}_0|} \ . \tag{12}$$

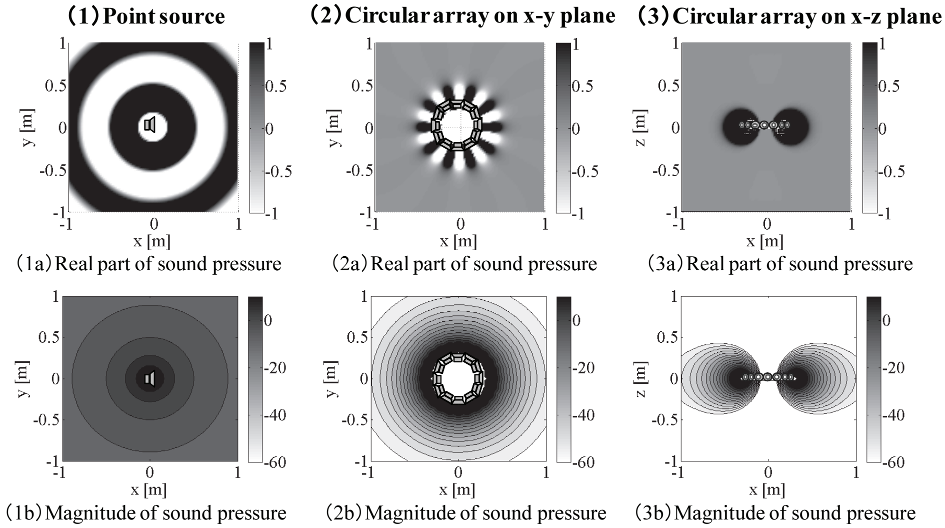

Fig. 4. Sound pressure distribution using point source and proposed method

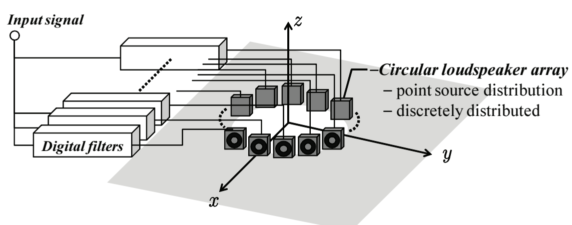

Fig. 3. Set up of circular loudspeaker array located on $x - y$ plane. Source distribution is discrete

Substituting Eqs. (11) and (12) into Eq. (4), the relationships among the driving signal for each loudspeaker is given as,

$$D_{\text{eva}}(\phi_0, \omega) = \sqrt{\frac{8jR_{\text{ref}}}{\pi k r_0^2}} \frac{e^{-jn_{\text{eva}}\phi_0}}{J_{n_{\text{eva}}}(kr_0) H^{(2)}_{n_{\text{eva}}}(kr_0)} \cdot S(\omega) \; . \quad (13)$$

We can obtain the real-valued driving signals in time domain by applying inverse Fourier transform with respect to ω. We implemented the evanescent wave reproduction system with a circular loudspeaker array and digital filters, as in Fig. 3. The system consists of N_{spk} digital filters and N_{spk} monopole loudspeakers arranged at equiangular intervals in the ϕ-direction.

4. COMPUTER SIMULATION EXPERIMENT

We evaluated the sound field reproduced using the proposed method. The sound pressure was evaluated on the $z = 0$ plane for $x \in [-1, 1], y \in [-1, 1]$ and $y = 0$ plane for $x \in [-1, 1], z \in [-1, 1]$ as shown in Fig. 3. The distance attenuation was also evaluated from $r = 0.5$ m to $r = 1.0$ m as shown in Fig. 3. The distance attenuation is a measure of how the magnitude attenuates when moving away from the system in the direction of r. Note that the sound pressures of all the results were normalized so that the sound pressure at $r = 0.5$ m was 0 dB.

In this section, we show the basic performance of our proposed method, the relationship between the number of loudspeakers and the circumferential wave number, and the frequency response at listening area.

Table 1. System configuration for experiment

Input frequency f_{in}	500 [Hz]
Number of loudspeakers N_{spk}	24
Radius of circular array r_0	0.3 [m]
Circumferential wave number n_{eva}	10
Referential distance R_{ref}	0.2 [m]

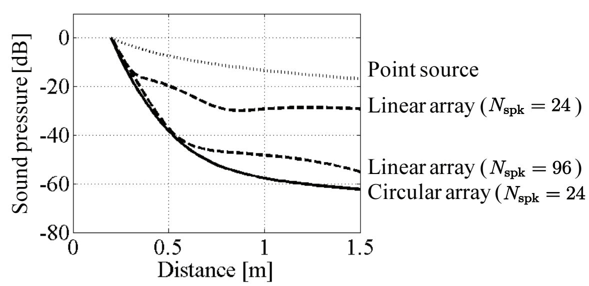

Fig. 5. Comparison results of distance attenuation using linear array and circular array

4.1. Basic performance of proposed method

To investigate the basic performance of the proposed method, we compared the sound pressure distributions reproduced by the proposed method and a point source arranged at the original point. The point source has an attenuation depending on the inverse square law of the distance. The experimental conditions are listed in Table 1.

The simulation results are shown in Fig. 4, which suggest that the reproduced sound of the proposed method attenuated faster than that of the point source. Note that there is no sound leakage along the z-direction.

4.2. Reduction in the required number of loudspeakers

In this section, we discuss whether we can reduce the number of loudspeakers by using the proposed method.

Figure 5 shows the comparison results of distance attenuation using linear and circular loudspeaker arrays. The distance attenuation property of the circular 24-loudspeaker array is similar to that of the 96-loudspeaker linear array, and that of the linear 24-loudspeaker array is worse. Therefore,

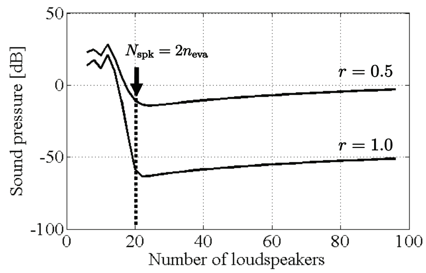

Fig. 6. Sound pressure observed at few listening points with varying number of loudspeakers

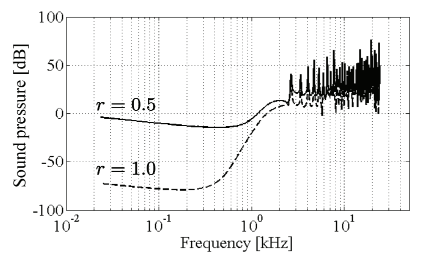

Fig. 7. Comparison results of frequency response between two listening areas

using a circular loudspeaker array, which reduces the required number of loudspeakers.

4.3. Effect of spatial discretization

The proposed method uses spatially discrete loudspeakers. We investigated the effect of spatial discretization. Sound pressures at a few observed points were evaluated when the number of loudspeakers was varied. The other conditions are listed in Table 1.

As shown in Fig. 6, there is a threshold number at which performance suddenly change. This is related to the spatial sampling theory of ϕ, that is, the loudspeaker interval is less than or equal to the circumferential wave length as,

$$\frac{2\pi r_0}{N_{\mathrm{spk}}} \leq \frac{1}{2} \cdot \frac{2\pi r_0}{n_{\mathrm{eva}}} \Rightarrow \therefore N_{\mathrm{spk}} \geq 2n_{\mathrm{eva}} \; . \qquad (14)$$

Note that the threshold number in Fig. 6 is equal to the lower limit in Eq. (14).

4.4. Frequency response at listening area

We simulated the frequency responses of the reproduced sound at a few listening areas. Frequency responses observed at $r = 0.5$ m and $r = 1.0$ m were evaluated. The other conditions are listed in Table 1.

The results in Fig. 7 show that the amount of attenuation depends on the input frequency. When the input frequency is low, the amount of attenuation is large. However, when the input frequency is high, the amount of attenuation become smaller.

4.5. Observed sound signal at listening area

We compared the amount attenuation of the observed sound signal between the point source and the proposed method.

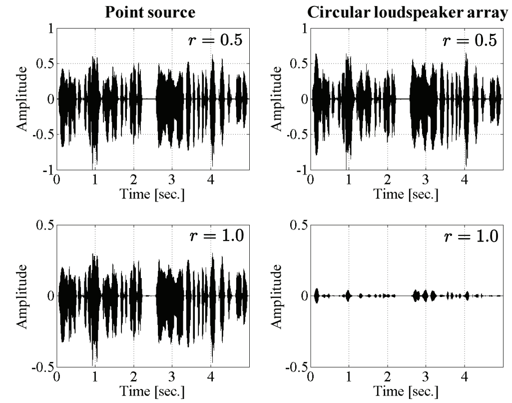

Fig. 8. Illustration of observed signals at two listening areas. Note that amplitude at $r = 1.0$ m is half as large as at $r = 0.5$ m.

Figure 8 shows comparison results of the listened signal waveforms between the point source and circular array. We used a speech signal band-limited from 200 Hz to 1 kHz as the input signal. Compared to the amplitude at $r = 1.0$ m, the amplitude of the proposed method is smaller than that of the point source.

5. CONCLUSION

We presented an acoustic sound reproduction method for an evanescent wave that has a fast distance attenuation property. We had proposed an evanescent wave reproduction method by using a linear loudspeaker array, but it required a large number of loudspeakers. To reduce the number of loudspeakers, we used a circular loudspeaker array and derived a driving signal for each loudspeaker based on the spectral division method. A computer simulation was performed to evaluate the performance of the proposed method. The results showed that our method produces faster distance attenuation without sound leakage at every direction, which reduces the required number of loudspeakers.

6. REFERENCES

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