SOUND PROPAGATION DIRECTION CONTROL USING THREE CONFIGURATIONS OF TWO-DIMENSIONAL LOUDSPEAKER ARRAYS

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ABSTRACT

In this paper, several configurations of two-dimensional loudspeaker arrays for a system for controlling the sound propagation direction are proposed and the directivities of these array configurations are discussed. The system is theoretically based on the boundary surface control principle. Three loudspeaker arrangements (cross-shaped, circular, and square-matrix) and two control sensor configurations (circle and elliptic) are tested by numerical simulations. The results indicate that the square-matrix loudspeaker array has the highest directivity. Based on this, a real prototype of a square-matrix loudspeaker system is constructed. The measured directivity characteristics of the prototype are similar to those estimated by the numerical simulation.

1. INTRODUCTION

One of the goals of computer control of the direction of sound propagation is to realize the ability to provide high-quality sound to only a specified "listeners' area", while preventing sound propagation to the "outside zone". There are two techniques for achieving this; both employ a loudspeaker array. One method is based on the delay-and-sum algorithm [1], while the other is based on the "*boundary surface control principle*" (BSCP) [2,3]. Both methods use control sound sources constructed from loudspeaker arrays and control sensors composed of a reproduction control point and suppression control points. Using such systems, it has been difficult to achieve effective control of the sound propagation direction and clear dumping in the outside zone. The delay-and-sum algorithm is straightforward to design, but requires many loudspeakers with a large array unit to generate a high directionality. This problem can be overcome by using the method based on the BSCP [4], but it is difficult to determine the optimal arrangement of control sound sources and control sensors in this method.

We found that employing a loudspeaker array with a cross-shaped configuration and an elliptical configuration of suppression control points achieves better characteristics than using a conventional straight-line loudspeaker array [5]. In this paper, we present more detailed and extended results for two-dimensional loudspeaker array configurations by performing further investigations. Specifically, circular and square-matrix array configurations are tested and the directivity characteristics for these configurations are discussed.

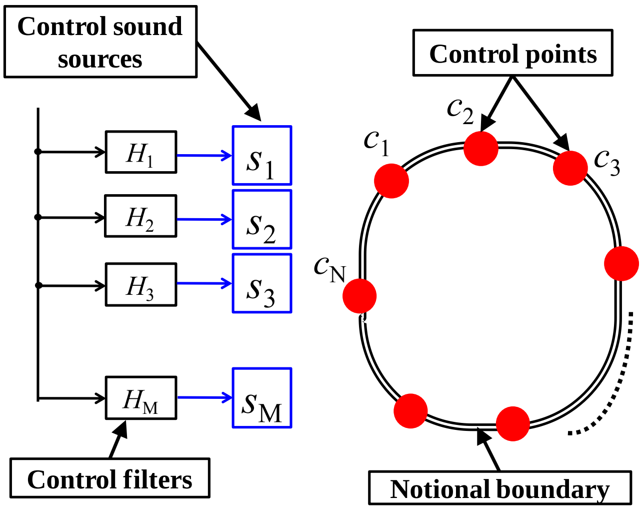

Fig. 1 Example of the conventional localized sound field control system: control sound sources (□), suppression control points (●)

We also construct a prototype of a loudspeaker array system and use it to demonstrate the feasibility of the proposed method.

In the following section, we briefly describe the conventional BSCP-based method and describe the theoretical aspects of the proposed method that employs a two-dimensional loudspeaker array and an elliptical acoustic boundary. In section 3, the feasibility of these techniques is verified by performing numerical simulations for several experimental conditions. Section 4 describes the design and test results of the prototype system. Conclusions are given in the final section.

2. METHOD

2.1 BSCP-Based Method

We first describe a basic method for a sound field control system and then explain a direction control system, both of which are based on the BSCP.

The BSCP states that the sound field characteristics in a certain area are determined by the acoustic pressure and the particle velocity on the surface boundary that encloses the area. **Fig. 1** shows a schematic illustration of an example of a conventional localized sound field control system that can

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create a quiet zone in the area outside the boundary by setting the sound pressure on the boundary to zero. The boundary is a notional boundary that consists of a certain number of control sensor points, as indicated in the figure. The sound pressures are controlled by the control filters that control the outputs from the loudspeaker array.

As indicated in **Fig. 1**, the system consists of loudspeakers (control sound sources), s_m, m=1,2,…,M, acoustic sensors (control points), c_n, n=1,2,...,N, and sound control filters, H_m, $m=1,2,...,M$. We denote the transfer function of the sound control filters by

$$H(\omega) = [H_1(\omega), H_2(\omega), \ldots, H_M(\omega)]^T \quad (1)$$

and the transfer function from the sound source s_m to the control point c_n by G_{mn}, that is

$$G(\omega) = \begin{bmatrix} G_{1,1}(\omega) & \cdots & G_{M,1}(\omega) \\ \cdots & \cdots & \cdots \\ G_{1,N}(\omega) & \cdots & G_{M,N}(\omega) \end{bmatrix} \quad (2)$$

When sound pressure values on the control points are denoted by

$$A(\omega) = [A_1(\omega), A_2(\omega), ..., A_N(\omega)]^T \quad (3)$$

the following relation is hold.

$$A(\omega) = G(\omega)H(\omega) \quad (4)$$

Here, $A(\omega)$ is the target characteristic to the realized. From eq.(4), $H(\omega)$ is obtained by

$$H(\omega) = G(\omega)^+ A(\omega) \quad (5)$$

where + indicates Moore-Penrose inverse. Coefficients of FIR filters for the control filters are derived by taking inverse Fourier transform of $H(\omega)$.

2.2 Arrangement of the Loudspeaker Array

Conventional loudspeaker array systems employ a straight-line array that inevitably creates two main lobes that are symmetric about the array line[6]. Therefore, the direction control ability of such systems is limited to 180 degrees because the other side of the array line has the same directivity characteristics. To overcome this limitation, we propose various configurations of loudspeaker arrays in a two-dimensional plane[7]. In this paper, three typical arrays (shown in **Fig. 2**) are tested. These arrays can form a main lobe that extends 360 degrees around the center of the loudspeaker array.

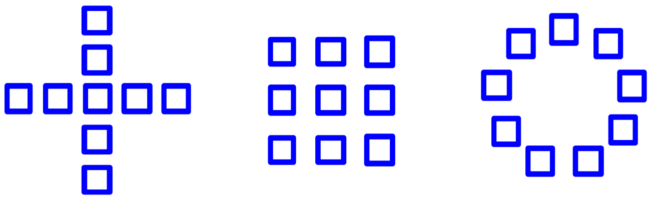


Fig. 2 Three types of the loudspeaker array .

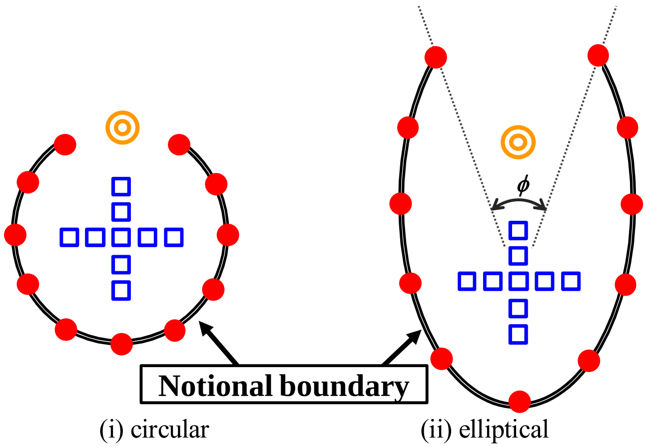


Fig. 3 Arrangement of control sensor points: control sound sources (□), reproduction control point (◎), suppression control points (●), aperture angle ϕ

2.3 Arrangements of the Control Sensor Points

The control sensor points consist of suppression control points and a reproduction control point that ensures sound reproduction characteristics. The suppression control points are located on the notional boundary and can be notional themselves if the acoustic environment of the area of interest is invariant.

Fig. 3(i) shows a typical arrangement of the control sensor points, where the notional boundary is circular and the reproduction control point is located on the main lobe direction. The suppression control points on the notional boundary are controlled to give a sound pressure of zero. This ensures that sound energy is reflected at the notional boundary and that the reflected energy flows to the opposite side past the center of the circle [8]. Thus, the sound energy is considered to be broadly distributed about the reproduction control point, making it difficult to form a sharp main lobe and to achieve clear dumping of the side lobes.

To overcome this problem, we introduce an elliptical notional boundary, and locate the center of the loudspeaker array at one focal point of the ellipse and the reproduction control point at the other focal point (see **Fig. 3**(ii)). Using this configuration, the energy reflected at the notional boundary accumulates at the other focal point.

In Fig. 3(ii), the reproduction control point is denoted by s_1, and the line between the reproduction control point and the center of the loudspeaker array is taken to be the x-axis and the line orthogonal to the x-axis at the center of the ellipse is taken to be the y-axis. The positions of the suppression control points s_m, $m=2,3,\ldots,M$ are then given by

$$(p_{s_m}^{(x)}, p_{s_m}^{(y)}) = (\alpha\cos\theta, \beta\sin\theta) \quad (6)$$

where α and β are the major and minor radii of the ellipse, respectively. θ represents the angle relative to the x-axis, which is given by

$$\theta = \frac{\pi}{2} + \frac{\pi(m-1)}{(M-1)} \quad (7)$$

The distance between the reproduction control point and the center of the loudspeaker array is given by

$$F = \sqrt{\alpha^2 - \beta^2} \quad (8)$$

In this arrangement, the acoustic energy reflected at the suppression control points accumulates at the reproduction control point (i.e., the other focal point), so that the main lobe is expected to be intensified.

2.4 Estimating Sound Control Filter Coefficients

The concrete procedure for estimating the coefficients of the sound control filters is based on the algorithm described in section **2.1**. At the reproduction control point, the reproduction $A_1(\omega)$ is equal to the system input, and at the other control point, the sound pressure should be zero, so that

$$A(\omega) = [1,0,0,\ldots,0]^T \quad (9)$$

Let r_{mn} denote the distance between sound source s_m and control point c_n. If r_{mn} is sufficiently small then the transfer function $G(\omega)$ defined by (2) is given by

$$G_{mn}(\omega) = \frac{1}{4\pi r_{mn}} \exp(-j\omega \frac{r_{mn}}{c}) \quad (10)$$

where c is the sound velocity and the free sound field is assumed. The control filter characteristics $H(\omega)$ can be estimated using (9), (10) and (5).

3. NUMERICAL SIMULATION

3.1 Experimental Conditions

The following three configurations for loudspeaker arrays were used: (a) *cross-shaped,* (b) *square-matrix,* and (c) *circular* (see **Fig. 2**). All three configurations contain the same number of loudspeakers. The distance between adjacent two loudspeakers is set to 5 cm. Two configurations of the control sensor points (i.e., suppression control boundaries) are tested: (i) *circular* and (ii) *elliptical* (see **Fig. 3**). In type (ii), α and β in eq. (6) are set to 100 cm and 86.6 cm, respectively.

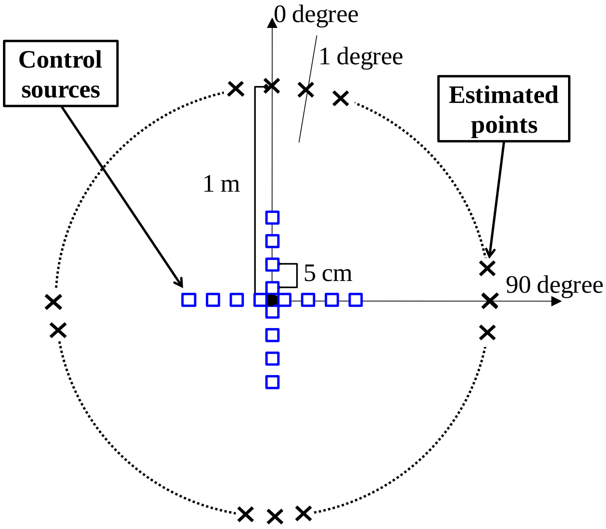


Fig. 4 Configuration of the control sources and estimated points used in the experiments.

Two aperture angles, ϕ=30 degrees and 180 degrees are tested in these experiments. These constants was adjusted experimentally. The directivity characteristics are estimated using a BSCP-based method.

The same coordinates are used as those given in section **2.2**, and an angle of 0 degrees indicates the direction of the x-axis. Two different directions for the main lobe (0 and 45 degrees) are specified in the experiments. The sound velocity is set to c=343.7 m/s, so that the Nyquist frequency is 6874 Hz. The sound pressures for impulse signals with a frequency band in the range 200 Hz to 6874 Hz are calculated. In every case, the reproduction control point is located 100 cm from the coordinate origin. Sound pressures are calculated for points in 1 degree intervals on the circumstance of a 100-cm-radius circle (see **Fig. 4**).

In addition, the sound pressure distribution in a 500 cm by 500 cm plane is calculated for every point in a 10-cm lattice.

3.2 Results

Fig. 5 shows the results for the three configurations of the loudspeaker array. It reveals the following:

(1) The square-matrix array, *(b)* has considerably stronger directivity than the other two configurations for every condition.

(2) The characteristics of the cross-shaped array vary depending on the specified propagation direction.

(3) On the other hand, those of the circular array are independent of the specified propagation direction.

The results for suppression control boundary configurations reveal the following:

(4) When the aperture angle is ϕ=30 degrees, no remarkable differences are observed between the results for arrays *(a), (b),* and *(c)* (see **Fig. 6**).

(5) When ϕ=180 degrees, the elliptical boundary exhibits relatively a sharp main lobe (see **Fig. 7**).

We can also confirm that the directivity is fairly well maintained for acoustic signals with frequency over 3437 Hz (=Nyquist freq./2).

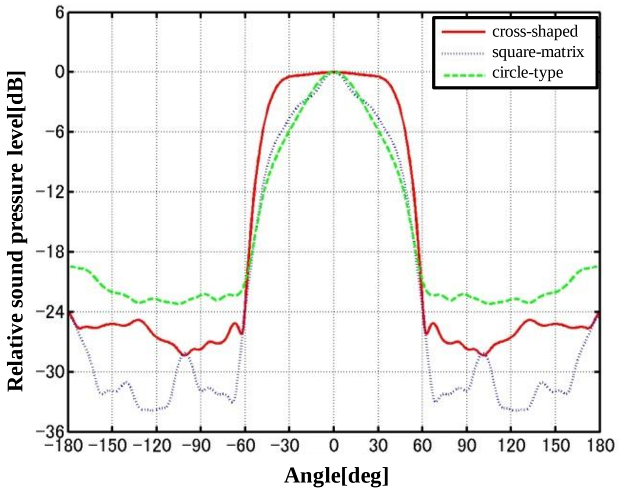


Fig. 5 Directivity characteristics estimated for the elliptic-type boundary, where ϕ=180 degree.

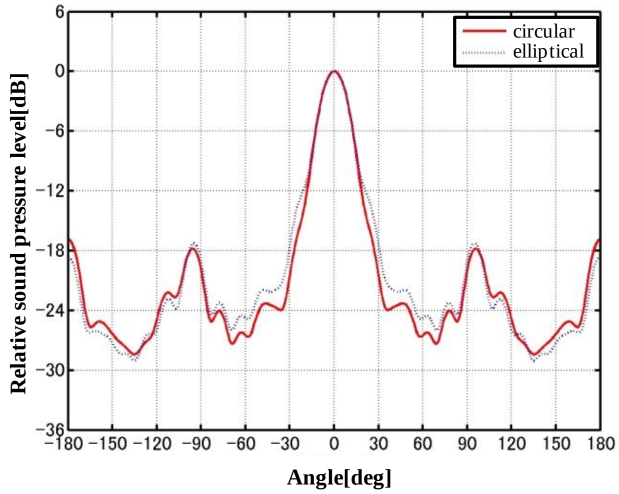


Fig. 6 Directivity characteristics estimated for the square-matrix-type loudspeaker array, where ϕ=30 degree.

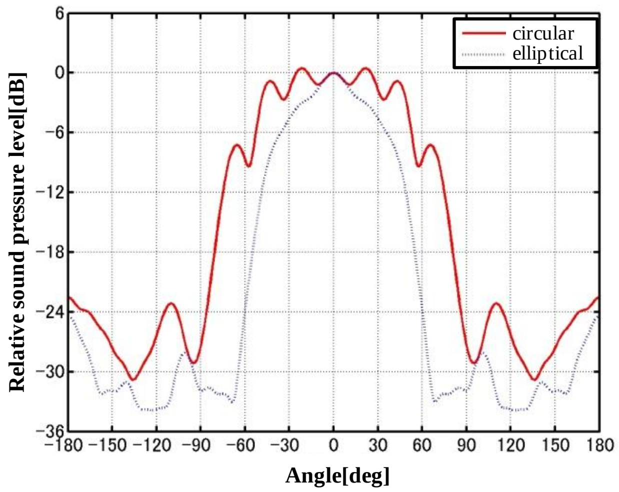


Fig. 7 Directivity characteristics estimated for the square-matrix-type loudspeaker array, where ϕ=180 degree.

4. REAL PROTOTYPE SYSTEM

4.1 System Design

As mentioned in subsection **3.2**, the square-matrix array has high directivity. Therefore, we constructed a prototype system based on this loudspeaker array configuration (see **Fig. 8**). This array consists of 4×4 loudspeakers each separated by an interval of 60 mm.

127 notional suppression control points are located on an elliptical boundary. The other configurations are essentially the same as those used in the numerical simulation described in section **3**. The control filters are constructed by 512-tap FIR filters.

4.2 Experimental Results

An impulse response that uses a TSP signal with a sampling frequency of 16 kHz is measured on the plane that covers the upper surface of the loudspeaker array. The measurement points are located on the circumference of a 50-cm-radius circle at intervals of 22.5 degrees.

Fig. 9 shows a comparison of the acoustic pressure distributions obtained by the numerical simulation and by measurements in a real plane. It shows good agreement between the two distributions. **Fig. 10** shows the directivity characteristics for several frequency bands; it reveals that frequency bands of 1.0 kHz to 2.5 kHz and 4 kHz to 5 kHz have high directivities. The measurement was done in a quite simple sound proof room, so that the experimental results were affected by the acoustic conditions in the vicinity of the device. However, they demonstrate the feasibility of the proposed method in a real plane.

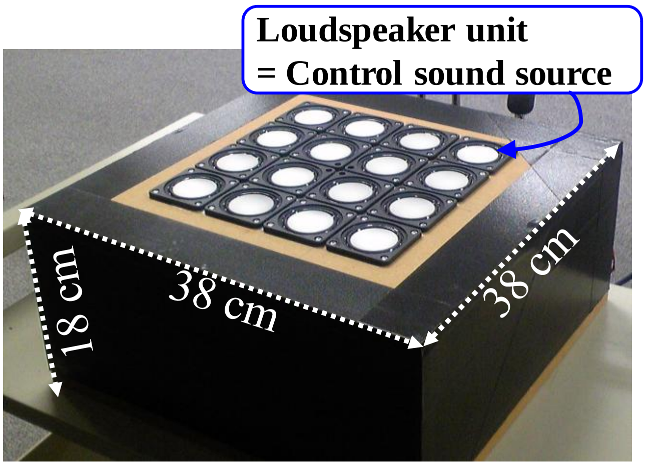
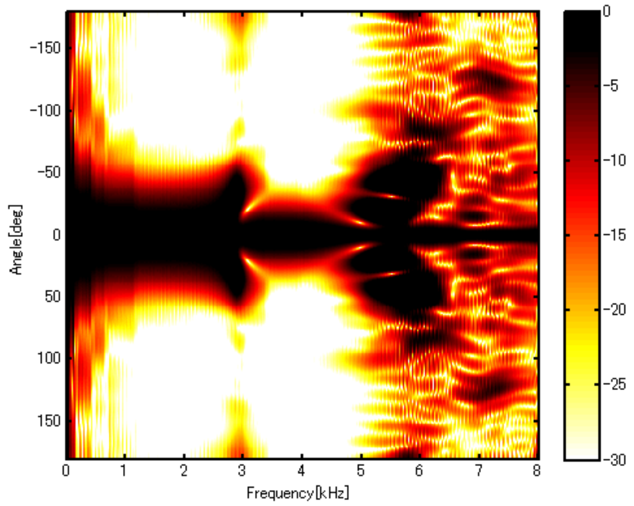
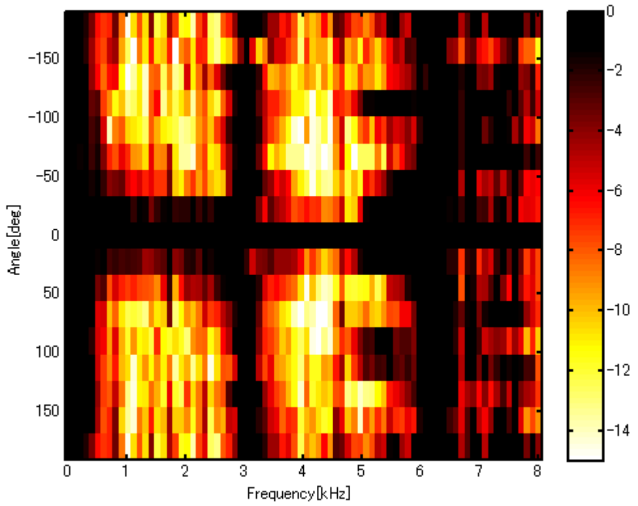


Fig. 8 Real prototype system employing the square-matrix-type of the loudspeaker array system. The side of the unit is 38 × 38 × 18 cm.



(a) Numerical simulation



(b) Measured value on the real plane.

Fig. 9 Comparative result between an acoustic pressure distribution of a numerical simulation and that of the measured value on the real plane.

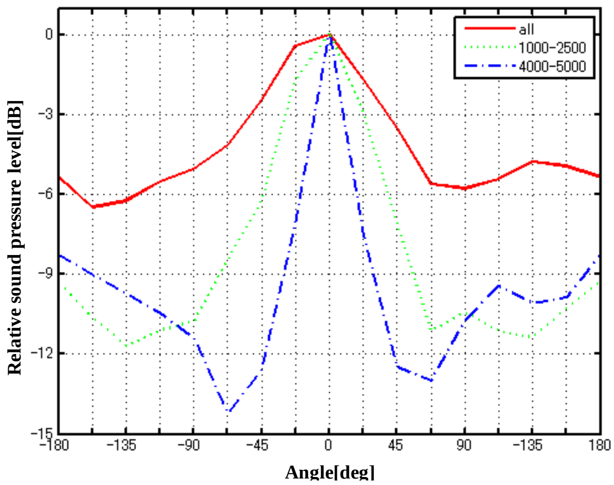


Fig. 10 Directivity characteristics for several frequency bands.

6. CONCLUSION

We have proposed three configurations for two-dimensional loudspeaker arrays for a sound propagation direction control system. We determined the directivities for these loud speaker array configurations in numerical simulation. The square-matrix configuration has the highest directivity. We constructed a prototype of this loudspeaker array configuration and confirmed that it has similar characteristics as those predicted by the numerical simulation. In the future, we will try to measure directivity characteristics of the prototype system using real acoustic conditions in the vicinity of the device.

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