2.5D LOCALIZED SOUND ZONE GENERATION WITH A CIRCULAR ARRAY OF FIXED-DIRECTIVITY LOUDSPEAKERS

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ABSTRACT

This paper provides an analytical approach to generating localized sound zone close to loudspeakers in the horizontal plane using a circular array of fixed-directivity loudspeakers and an additional loudspeaker based on sound source dimension mismatch. A circular loudspeaker array and an additional loudspeaker located on the array center are simultaneously produced in mutual opposite phase. As a result, the propagated sound pressure at the reference circle for 2.5-dimensional sound field synthesis is completely cancelled, but that near the circular array is not compensated and localized sound zone generation is realized. The driving signals of the circular array of fixed-directivity loudspeakers and the produced sound pressures are analytically derived. The results of computer simulations indicate the effectiveness of the proposal. By taking the acoustic source-receiver reciprocity into account, the proposed filter coefficients of loudspeakers are also directly used for close-talking microphone array with directional microphones in the horizontal plane.

Index Terms— 2.5D sound field control, localized sound zone, circular loudspeaker array, spherical harmonic expansion, Ambisonics.

1. INTRODUCTION

Generating a personalized sound zone by using loudspeakers is an important and attractive acoustic communication technique. To realize a personalized sound zone, many approaches have been proposed, and are broadly categorized into two main approaches. The first controls the acoustic contrast or the energy between two spaces [1–8]. In addition, an extended approach controls multiple sound fields [9–17] so that they are simultaneously synthesized for different zones in space. These methods typically control sound zones away from the loudspeakers.

In another approach, a localized sound zone is generated near loudspeakers so that audible sound pressure is only propagated close to them but at very low amplitudes beyond the reference distance. In this paper, this approach is called localized sound zone generation.

Several methods for localized sound zone generation have been proposed. One is based on evanescent wave reproduction [18] using linear or circular arrays of loudspeakers [19, 20]. An analytical method using a linear and circular loudspeaker array combination has been proposed for 3-dimensional (3D) localized sound field propagation [21, 22]. In addition, an analytical approach using a linear loudspeaker array and an additional monopole directivity loudspeaker based on sound source dimension mismatch has also been provided [23]. These methods, however, require a large number of loudspeakers since they are based on higher-order modal control in the angular and cylindrical harmonic spectrum domains. To address the problem, this paper extends a previous method based on sound source dimension mismatch with a linear array [23] into an analytical approach with a circular array of fewer loudspeakers.

Sound field synthesis systems are frequently simplified for synthesis in the horizontal plane. The sound sources are then arranged on a line or a circle. In actual implementations, 3D monopole sources instead of 2D line sources are usually employed for the sound sources. Such approaches are called 2.5D sound field synthesis [7, 24–29]. 2.5D sound field synthesis with a linear or a circular sound source can only synthesize correct sound pressure at the reference line or circle. In a previous method with a linear array [23], the sound pressure produced by a point source is cancelled by a linear array at the reference line and localized sound zone generation in the horizontal plane near the linear array can be realized by the residual sound pressure between the point source and linear array.

In the proposed approach, the sound pressure produced by a loudspeaker is cancelled by a circular loudspeaker array and localized sound zone generation in the horizontal plane near the circular array can also be realized.

In exterior sound field control with single-layer monopole source distributions, however, a forbidden frequency (Bessel-zero) problem occurs [7, 18]. For considering actual loudspeaker directivity [27, 30, 31] and avoiding the forbidden frequency problem, a circular array of fixed directivity loudspeakers [30] is introduced in the proposal as in 2D sound field recording with a circular radial directional microphone array [32, 33]. By locating an additional fixed-directivity loudspeaker on the array center, the proposal can generate a localized sound zone in the horizontal plane by controlling only the 0-th and first order components of 2D cylindrical harmonic spectrum and the number of loudspeakers for the circular array can be reduced compared with conventional higher-order modal control methods [20–23].

In addition, by taking the acoustic source-receiver reciprocity [22] into account, the proposed filter coefficients of loudspeakers are directly employed for close-talking microphone array [34–36] with directional microphones [32] in the horizontal plane.

2. PROPOSED ANALYTICAL FORMULATION

2.1. Sound field produced by circular fixed-directivity sound source

A continuous circular fixed-directivity sound source distribution with radius r_1 centered at the origin on the x-y plane is considered instead of a circular array of fixed-directivity loudspeakers (Fig. 1).

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A sound field synthesized by a continuous circular sound source is given as

$$S_1(r,\theta,\phi) = \int_0^{2\pi} D_1(\phi_1) T(\boldsymbol{r}, \boldsymbol{r}_1) d\phi_1, \tag{1}$$

where $D_1(\phi_1)$ is the driving function of the circular source and $T(\boldsymbol{r}, \boldsymbol{r}_1)$ is the transfer function from sound source position $\boldsymbol{r}_1 = [r_1,\ \pi/2,\ \phi_1]$ to receiver position $\boldsymbol{r}$. Similar to previous works [27, 31], $T(\boldsymbol{r}, \boldsymbol{r}_1)$ is modeled as a weighted combination of a monopole and a dipole with the main lobe pointing away from the center. Under the free-field assumption, $T(\boldsymbol{r}, \boldsymbol{r}_1)$ is given as

$$T(\boldsymbol{r}, \boldsymbol{r}_1) = \frac{e^{jk|\boldsymbol{r}-\boldsymbol{r}_1|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}_1|} \left\{ a + (1-a) \left[1 + \frac{j}{k|\boldsymbol{r}-\boldsymbol{r}_1|} \right] \cos\alpha \right\}, \tag{2}$$

where $j = \sqrt{-1}$, k is the wavenumber, a is the first-order weighting parameter and α is the angle from the loudspeaker axis. As in previous works [27, 30], (2) for $r > r_1$ is represented by the spherical harmonic expansion [18] and given as

$$\begin{aligned} T(\boldsymbol{r}_>, \boldsymbol{r}_1) = jk \sum_{n=0}^{\infty} \sum_{m=-n}^{n} h_n(kr) \{ a j_n(kr_1) \\ - j(1-a) j_n'(kr_0) \} Y_n^m(\theta,\phi) Y_n^m(\pi/2, \phi_1)^*, \end{aligned} \tag{3}$$

where j_n and j_n' are the n-th order spherical Bessel function and its radial derivative, h_n is the n-th order spherical Hankel function of the first kind [18], and

$$Y_n^m(\theta,\phi) = \sqrt{\frac{(2n+1)}{4\pi} \frac{(n-|m|)!}{(n+|m|)!}} P_n^{|m|}(\cos\theta) e^{jm\phi} \tag{4}$$

is the m-th order spherical harmonics of the n-th degree, and $P_n^{|m|}$ is the $|m|$-th order associated Legendre polynomial of the n-th degree [37].

As in analytical 2.5D higher-order Ambisonics [24,25,27], when the cylindrical harmonic expansion is applied to (1) with $\theta = \pi/2$, the circular convolution theorem holds and (1) is represented as

$$\mathring{S}_{m,1}(r) = 2\pi \mathring{D}_{m,1} \mathring{T}_m(r, r_1). \tag{5}$$

In addition, the 2.5D spherical harmonic expansion of transfer function $T(\boldsymbol{r}, \boldsymbol{r}_1)$ for $r > r_1$ is derived from (3) and given as

$$\mathring{T}_m(r_>, r_1) = jk \sum_{n=|m|}^{\infty} h_n(kr) j_{n,1}(a, r_1) Q_n^m P_n^{|m|}(0)^2, \tag{6}$$

where

$$j_{n,1}(a, r_1) = a j_n(kr_1) + j(1-a) j_n'(kr_1), \tag{7}$$

$$Q_n^m = \frac{2n+1}{4\pi} \frac{(n-|m|)!}{(n+|m|)!}. \tag{8}$$

In (7), the radial derivative of the n-th order spherical Bessel function is analytically obtained from the following relationship [18]:

$$j_n'(x) = j_{n-1}(x) - \frac{n+1}{x} j_n(x). \tag{9}$$

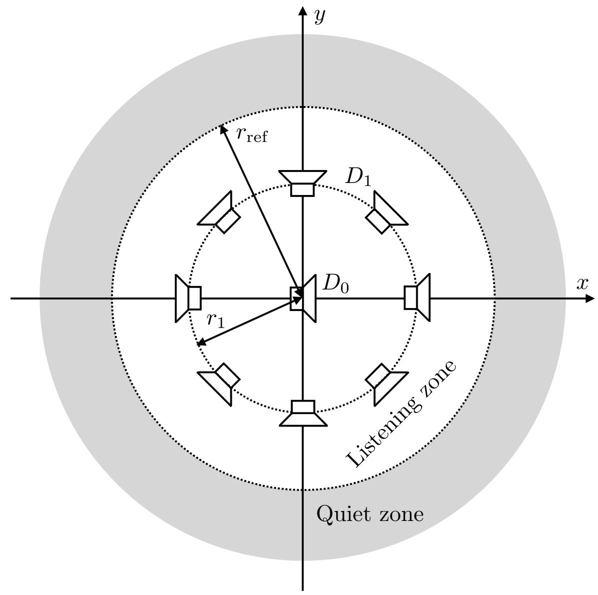


Fig. 1. Arrangements of a circular array of fixed-directivity loudspeakers with radius r_1 and driving signals D_1, an additional loudspeaker located on the array center with driving signal D_0, and listening and quiet zones. r_{ref} is a reference radius for deriving D_1 in 2.5-dimensional sound field control.

2.2. Sound field produced by fixed-directivity sound source at circular source center

A sound field produced by a fixed-directivity sound source located at $\boldsymbol{r}_0 = [r_0,\ \theta_0,\ \phi_0]$ is given as

$$S_0(r,\theta,\phi) = D_0 T(\boldsymbol{r}, \boldsymbol{r}_0), \tag{10}$$

where D_0 is the source driving function. After that, D_0 is set to 1 for simplicity. When $\boldsymbol{r}_0$ is located on the origin (Fig. 1), $r_0 = 0$ and $S_0(r,\theta,\phi)$ is represented as

$$\begin{aligned} S_0(r,\theta,\phi) = T(\boldsymbol{r}, 0) &= \frac{e^{jkr}}{4\pi r} \left\{ a + (1-a) \left[1 + \frac{j}{kr} \right] \cos\alpha \right\} \\ &= a \frac{jk}{4\pi} h_0(kr) - (1-a) \frac{k}{4\pi} h_1(kr) \cos\alpha, \end{aligned} \tag{11}$$

where the relationships [18]

$$h_0(x) = \frac{e^{jx}}{jx} \quad \text{and} \quad h_1(x) = -\frac{(j+x)e^{jx}}{x^2}$$

are introduced.

When the mainlobe of the dipole component is along the x-axis (Fig. 1), $\alpha = \phi$ and the 2D cylindrical harmonic expansion of $S_0(r,\theta,\phi)$ on the x-y plane is obtained as

$$\mathring{S}_{m,0}(r) = \frac{1}{2\pi} \int_0^{2\pi} S_0(r, \pi/2, \phi) e^{-jm\phi} d\phi. \tag{12}$$

From (11), $\mathring{S}_{m,0}(r)$ obviously has only the 0-th and first order components and represented as

$$\mathring{S}_{0,0}(r) = a \frac{jk}{4\pi} h_0(kr), \tag{13}$$

$$\mathring{S}_{\pm 1,0}(r) = -(1-a) \frac{k}{8\pi} h_1(kr), \tag{14}$$

where

$$\frac{1}{2\pi}\int_0^{2\pi}\cos\phi e^{\pm j\phi}d\phi = \frac{1}{2}. \tag{15}$$

2.3. Driving function of circular source

To cancel the sound pressure produced by the fixed-directivity sound source with D_0 located at the origin on the x-y plane at a reference radius r_{red} by using the circular sound source, driving function of the circular source D_1 is analytically derived (Fig. 1).

From (5), (13) and (14), D_1 also has only the 0-th and first order components and given as

$$\mathring{D}_{0,1} = -\frac{\mathring{S}_{0,1}(r_{\mathrm{ref}})}{2\pi\mathring{T}_0(r_{\mathrm{ref}},r_1)} = -a\frac{jkh_0(kr_{\mathrm{ref}})}{8\pi^2\mathring{T}_0(r_{\mathrm{ref}},r_1)}, \tag{16}$$

$$\mathring{D}_{\pm1,1} = -\frac{\mathring{S}_{\pm1,1}(r_{\mathrm{ref}})}{2\pi\mathring{T}_{\pm1}(r_{\mathrm{ref}},r_1)} = (1-a)\frac{kh_1(kr_{\mathrm{ref}})}{16\pi^2\mathring{T}_{\pm1}(r_{\mathrm{ref}},r_1)}. \tag{17}$$

The 2D cylindrical harmonic spectrum of the residual sound pressure produced by D_0 and $D_1(\phi_1)$ is also analytically derived as

$$\mathring{S}_{0,0+1}(r) = a\frac{jk}{4\pi}\left\{h_0(kr) - h_0(kr_{\mathrm{ref}})\frac{\mathring{T}_0(r,r_1)}{\mathring{T}_0(r_{\mathrm{ref}},r_1)}\right\}, \tag{18}$$

$$\mathring{S}_{\pm1,0+1}(r) = -(1-a)\frac{k}{8\pi}\left\{h_1(kr) - h_1(kr_{\mathrm{ref}})\frac{\mathring{T}_{\pm1}(r,r_1)}{\mathring{T}_{\pm1}(r_{\mathrm{ref}},r_1)}\right\}. \tag{19}$$

When $r = r_{\mathrm{ref}}$, the residual sound pressure is completely 0. In the proposed approach, a horizontal localized sound zone is generated by residual sound field

$$\begin{aligned} S_{0+1}(r,\phi) &= \sum_{m=-1}^{1}\mathring{S}_{m,0+1}(r)e^{jm\phi} \\ &= a\frac{jk}{4\pi}\left\{h_0(kr) - h_0(kr_{\mathrm{ref}})\frac{\mathring{T}_0(r,r_1)}{\mathring{T}_0(r_{\mathrm{ref}},r_1)}\right\} \\ &- (1-a)\frac{k}{4\pi}\left\{h_1(kr) - h_1(kr_{\mathrm{ref}})\frac{\mathring{T}_{\pm1}(r,r_1)}{\mathring{T}_{\pm1}(r_{\mathrm{ref}},r_1)}\right\}\cos\phi \end{aligned} \tag{20}$$

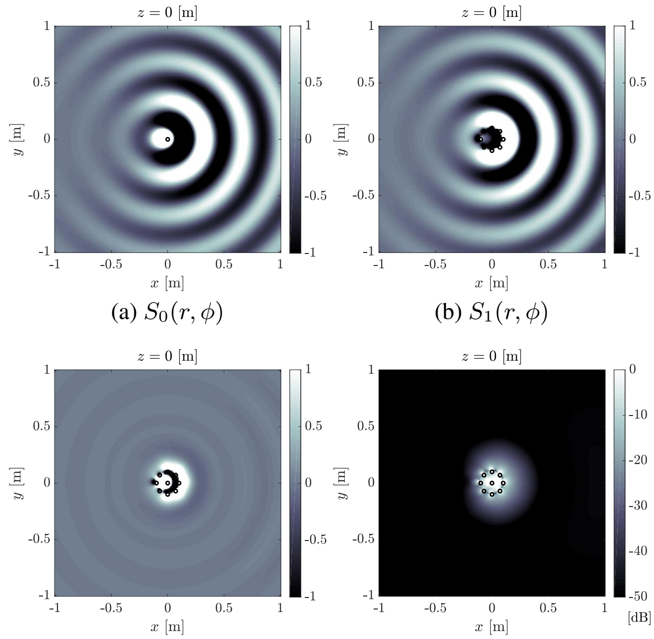
for $r < r_{\mathrm{ref}}$ where $\mathring{T}_{-1}(r,r_1) = \mathring{T}_1(r,r_1)$.

2.4. Driving signals of circular array of fixed directivity loudspeakers

A continuous circular source is finally discretized into a circular array of fixed-directivity loudspeakers (Fig. 1). The driving signal of each loudspeaker at ϕ_l in the temporal frequency domain is analytically obtained as

$$\begin{aligned} D_1(\phi_l) &= \sum_{m=-1}^{1}\mathring{D}_{m,1}e^{jm\phi_l} \\ &= -a\frac{jkh_0(kr_{\mathrm{ref}})}{8\pi^2\mathring{T}_0(r_{\mathrm{ref}},r_1)} + (1-a)\frac{kh_1(kr_{\mathrm{ref}})}{8\pi^2\mathring{T}_1(r_{\mathrm{ref}},r_1)}\cos\phi_l. \end{aligned} \tag{21}$$

When the number of loudspeakers is L, order m of the 2D cylindrical harmonic spectrum can be calculated up to $M = \lfloor(L-1)/2\rfloor$,



(a) $S_0(r,\phi)$ (b) $S_1(r,\phi)$ (c) $S_{0+1}(r,\phi)$ (d) $20\log_{10}|S_{0+1}(r,\phi)|$

Fig. 2. Results: (a) sound field $S_0(r,\phi)$ produced by D_0 with cardioid directivity ($a = 0.5$), (b) sound field produced $S_1(r,\phi)$ by D_1 with $L = 8$ loudspeakers, $r_1 = 0.1$ m, $a = 0.5$ and $r_{\mathrm{ref}} = 0.5$ m, (c) residual sound field $S_{0+1}(r,\phi)$ produced by D_0 and D_1, and (d) sound pressure level of residual sound field $20\log_{10}|S_{0+1}(r,\phi)|$ produced by D_0 and D_1. $f = 1$ kHz and black circles are loudspeakers.

where $\lfloor\cdot\rfloor$ is the floor function [7,24,27]. In the proposed approach, $M = 1$ and the minimum number of L is 3 and the proposal can be theoretically implemented by $3 + 1 = 4$ fixed-directivity loudspeakers. The proposed approach, therefore, can be realized by using fewer loudspeakers compared with conventional higher-order modal control methods [20–23].

3. COMPUTER SIMULATIONS

Computer simulations evaluated the proposed approach. In all the simulations, a three-dimensional free field was assumed. The speed of sound c was 343.36 m/s. For taking actual loudspeaker size into account, a circular array of $L = 8$ (rather than 3) cardioid directivity loudspeakers ($a = 0.5$) with radius $r_1 = 0.1$ m and an additional cardioid directivity loudspeaker ($a = 0.5$) located on the array center were introduced. The spatial Nyquist frequency of the circular array was about $f_{\mathrm{Nyq}} = 2.19$ kHz. n in (6) was truncated to 100.

The results of sound field in the x-y plane produced by D_0, D_1 and $D_0 + D_1$ with $r_{\mathrm{ref}} = 0.5$ m for temporal frequency $f = 1$ kHz are shown in Fig. 2. In addition, the results of sound pressure level $20\log_{10}|S(r,\phi)|$ produced by D_0 and $D_0 + D_1$ with $r_{\mathrm{ref}} = 0.5$ m, and $r_{\mathrm{ref}} = 0.25$, 0.5, and 1 m for $\phi = 0$, $z = 0$ m and $f = 1$ kHz where $20\log_{10}|S(r,\phi = 0)|$ with $r = 0.2$ m was set to 0 dB for all conditions are plotted in Fig. 3. As in a previous method with a linear loudspeaker array [23], the result of Fig. 3 shows that the produced sound pressure is completely cancelled at set reference radius r_{ref}. If r_{ref} is small ($= 0.25$ m), the distance attenuation property is precipitous, but the produced sound pressure level at $r >$

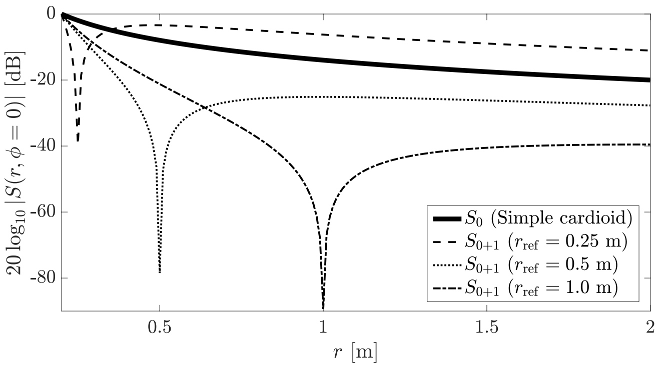
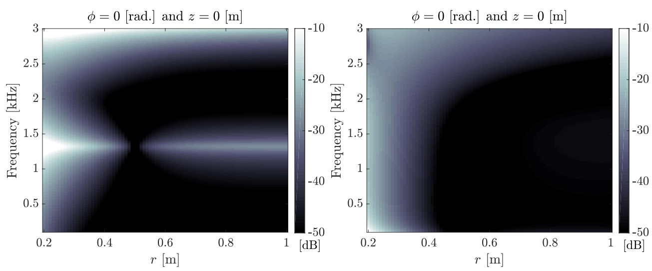


Fig. 3. Results of sound pressure level $20\log_{10}|S(r,\phi)|$ produced by simple cardioid loudspeaker with $a = 0.5$ and proposal with $a = 0.5$, $L = 8$ loudspeakers, $r_1 = 0.1$ m, and $r_{\rm ref} = 0.25$, 0.5, and 1 m for $\phi = 0$, $z = 0$ m and $f = 1$ kHz where $20\log_{10}|S(r,\phi = 0)|$ with $r = 0.2$ m is set to 0 dB for all conditions.



Monopole ($a = 1$) Cardioid ($a = 0.5$)

Fig. 4. Results of sound pressure level distribution for monopole ($a = 1$) and cardioid ($a = 0.5$) directivity conditions with $L = 8$ loudspeakers, $r_1 = 0.1$ m, $r_{\rm ref} = 0.5$ m, $\phi = 0$ and $z = 0$ m where spatial Nyquist frequency of circular array is about 2.19 kHz.

$r_{\rm ref}$ is increased again because the distance attenuation properties between sound sources D_0 and D_1 are quite different. $r_{\rm ref}$ must be set to an optimal value (= 0.5 or 1.0 m). From the results of Figs. 2 and 3, the proposed method with an optimal reference radius can then generate a localized sound zone compared with a simple cardioid loudspeaker.

To compare the proposed approach using cardioud directivity loudspeakers ($a = 0.5$) with that using simple monopole directivity ones ($a = 1$), Figure 4 shows the results of sound pressure level distribution for monopole and cardioid directivity conditions with $r_{\rm ref} = 0.5$ m, $\phi = 0$ and $z = 0$ m for 100 Hz $\leq f \leq$ 3 kHz and 0.2 m $\leq r \leq$ 1.0 m. Although the proposal with cardioud directivity can stably realize localized sound zone up to spatial Nyquist frequency $f_{\rm Nyq} = 2.19$ kHz, that with simple monopole directivity is quite unstable because of the forbidden frequencies similar in a previous work [7]. Figure 5 plotts the results of 0-th order $20\log_{10}|\mathring{T}_0(r_{\rm ref}, r_1)|$ in (6) and 0-th order Bessel function $J_0(kr_1)$ [18] for monopole ($a = 1$) and cardioid ($a = 0.5$) directivity conditions with $r_1 = 0.1$ m and $r_{\rm ref} = 0.5$ m. The result indicates that the instability with monopole directivity loudspeakers just corresponds to $J_0(kr_1) = 0$ and $\mathring{T}_0(r_{\rm ref}, r_1)$ with cardioud directivity ($a = 0.5$) is more stable than that with monopole directivity ($a = 1$).

Consequently, the proposed analytical approach with fixed-

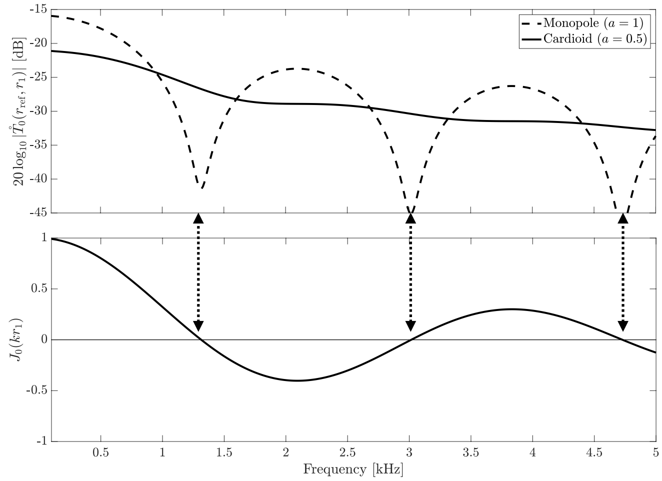


Fig. 5. Results of $20\log_{10}|\mathring{T}_0(r_{\rm ref}, r_1)|$ and $J_0(kr_1)$ for monopole ($a = 1$) and cardioid ($a = 0.5$) directivity conditions with $r_1 = 0.1$ m and $r_{\rm ref} = 0.5$ m.

directivity loudspeakers and an optimal reference radius can effectively generate a localized sound zone in the horizontal plane without forbidden frequencies by using fewer loudspeakers compared with conventional higher-order modal control methods [20–22]. Future work includes the evaluation of the sound pressure radiated to the vertical direction as conducted in a previous method with a linear array [23].

4. CONCLUSIONS

This paper proposed an analytical method for generating localized sound zone near loudspeakers in the horizontal plane with a circular array of fixed-directivity loudspeakers and an additional loudspeaker based on sound source dimension mismatch. The driving signals of the circular array of fixed-directivity loudspeakers and the produced sound pressures were analytically derived. The proposal can effectively generate a localized sound zone in the horizontal plane by using fewer loudspeakers compared with conventional higher-order modal control methods. The results of computer simulations suggested the effectiveness of the proposal.

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