Proceedings of 20th International Congress on Acoustics, ICA 2010

23–27 August 2010, Sydney, Australia

Multizone soundfield reproduction using multiple loudspeaker arrays

Yan Jennifer WU (1) and Thushara D. Abhayapala (1)

(1) School of Engineering, Research School of Information Sciences & Engineering,
The Australian National University, Canberra, Australia

PACS: 43.60. Uv Model-based signal processing

ABSTRACT

Multizone soundfield reproduction with various potential applications has recently drawn attentions in acoustic signal processing. In this paper, we seek to recreate two or more distinct 2D soundfields simultaneously at different spatial regions using multiple loudspeaker arrays. The basic ideas from the cross-talk cancelation systems were applied to determine the loudspeaker weights by the Least Squares method. Simulation results demonstrate favorable performance.

INTRODUCTION

Personalized sound environments are becoming increasingly important to the entertainment and audio industries. Using *spatial multizone soundfield reproduction*, an individual sound environment can be produced to each listener inside an enclosure without physical isolations or the use of headphones. Spatial multizone soundfield reproduction is a conceptually challenging problem in acoustic signal processing, as currently most of the existing techniques [1, 2, 3, 4, 5, 6] concentrate on a single zone.

In [7], we have proposed a framework to recreate multiple 2D (height invariant) soundfields at different locations by analyzing the problem with cylindrical harmonics expansions. The key concept is to derive an equivalent global multizone soundfield so that spatial multizone soundfield reproduction can be reduced to the reproduction of a single soundfield over the entire region. In [8], we have designed spatial band stop filters to suppress interzone interference in the regions of interests and pass the desired wavefields with no distortion. The extension of reproduction of a given spatial soundfield without altering a nearby quiet zone was shown in [9]. In the above-mentioned approaches, we attempt to solve the 2D multizone problem using a single array of loudspeakers. In this paper, we seek to explore the possibility of recreating two or more distinct 2D soundfields simultaneously at different spatial regions using multiple loudspeaker arrays.

We apply the basic ideas from the cross-talk cancelation system, where two loudspeakers are used to reproduce soundfields at listeners' ears. To perform crosstalk cancelation, the acoustic transfer functions between each loudspeaker and each ear are required. The design task is to obtain the filtering weights to reproduce the desired signals at ears [10]. Most of the crosstalk cancelation systems [11, 12, 13, 14] are based on Least Squares techniques [15]. In this paper, we extend this idea in the context of soundfield reproduction; we intend to determine the loudspeaker weights by the Least Squares Method so that desired soundfields can be generated simultaneously at different spatial regions.

From the simulation result, this approach offers a better solution for allocating spatial zone positions than the method proposed in [7, 8]. The favorable simulation results of non-circular loudspeaker arrays demonstrate the fact that circular loudspeaker arrays are not compulsory requirements for the loudspeaker configurations as long as the loudspeakers are placed on or outside the regions of interest.

The paper is structured as follows. In the second section, we present the system model for multizone soundfield reproduction using two or more loudspeaker arrays. In the third section, the loudspeaker weight design is presented by equating the desired soundfields to the actual soundfields. Finally, we present the simulation results of multizone soundfield reproduction using multiple circular loudspeaker arrays and multiple non-circular loudspeaker arrays.

Notation

Throughout this paper, we use the following notations: matrices and vectors are represented by upper and lower bold face respectively, e.g., $\boldsymbol{H}$ and $\boldsymbol{\rho}$. The symbol $\breve{\boldsymbol{H}}$ is used to denote a sub-matrix. The superscript $^{(q,q')}$ used in terms is used to represent a mathematical relationship between the qth zone and the q' zone. The imaginary unit is denoted by $i(=\sqrt{-1})$.

SYSTEM MODEL

Suppose there are Q non-overlapping 2D (height-invariant) desired spatial zones and corresponding spatial soundfields to be reproduced. As shown in Figure 1, the radius and the origin of the qth spatial zone are denoted as $R_z^{(q)}$ and $\mathscr{O}_q$ respectively, where $\mathscr{O}_q$ is $(r^{(q0)}, \theta^{(q0)})$ with respect to the global origin $\mathscr{O}$. Any arbitrary observation point within this circular qth spatial zone is denoted as $\boldsymbol{x}^{(q)}$. Note, there is no specific requirement for the loudspeaker array configuration as long as the loudspeakers are placed on or outside the circle of radius $R_z^{(q)}$ for each loudspeaker array. The weight of the pth loudspeaker of the qth loudspeaker array is denoted as $\rho_p^{(q)}$, where $k = 2\pi f/c$ is the wavenumber, f is the frequency and c is the speed of sound propagation. We denote $\boldsymbol{y}_p^{(2,q)}$ as the distance from the pth loudspeaker at the second zone to the arbitrary observation point $\boldsymbol{x}$ with respect to the origin of the qth zone, and so forth.

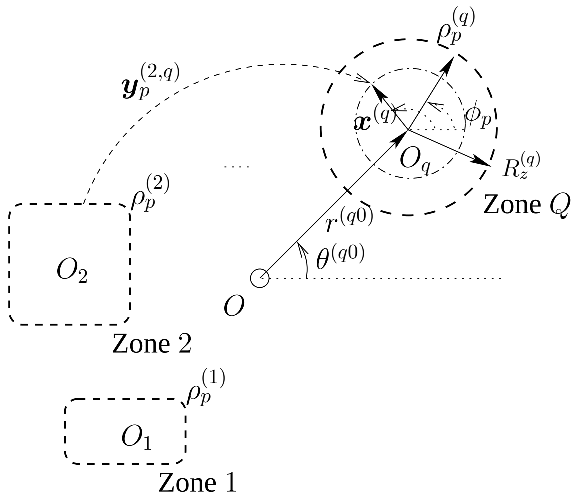

Figure 1: Geometry of the multizone sound reproduction system using multiple loudspeaker arrays. The radius and the origin of the qth spatial zone are denoted as $R_z^{(q)}$ and $\mathcal{O}_q$ respectively, where $\mathcal{O}_q$ is $(r^{(q0)}, \theta^{(q0)})$ with respect to the global origin $\mathcal{O}$. Any arbitrary observation point within this circular qth spatial zone is denoted as $\boldsymbol{x}^{(q)}$. The loudspeaker weight at angle ϕ_p of the qth loudspeaker array is denoted as $\rho_p^{(q)}$. We denote $\boldsymbol{y}_p^{(2,q)}$ as the distance from the pth loudspeaker at the second zone to the arbitrary observation point $\boldsymbol{x}^{(q)}$ with respect to the origin of the qth zone.

Desired Soundfields: Cylindrical Harmonic Expansions

We can express any arbitrary 2D (height invariant) qth desired sound field at a point $\boldsymbol{x}_p \equiv (\|\boldsymbol{x}^{(q)}\|, \phi_x^{(q)})$ inside the qth region from $\mathcal{O}_q$ as [5, 7]

$$S^{\mathrm{d}(q)}(\boldsymbol{x}^{(q)}, k) = \sum_{m=-\infty}^{\infty} \alpha_m^{\mathrm{d}(q)}(k) J_m(k\|\boldsymbol{x}^{(q)}\|) e^{im\phi_x^{(q)}}, \quad (1)$$

where $J_m(\cdot)$ are the Bessel functions of order m, and $\alpha_m^{\mathrm{d}(q)}(k)$ are a set of coefficients for the qth desired soundfield.

Note that the representation (1) has an infinite number of orthogonal modes, this series expansion can be truncated due to the properties of the Bessel functions and the fact that the soundfield has to be bounded within a spatial region where all sources are outside [16].

Thus, we truncate (1) to

$$S^{\mathrm{d}(q)}(\boldsymbol{x}^{(q)}, k) = \sum_{m=-M_q}^{M_q} \alpha_m^{\mathrm{d}(q)}(k) J_m(k\|\boldsymbol{x}^{(q)}\|) e^{im\phi_x^{(q)}}, \quad (2)$$

where the desired soundfield of the qth spatial zone is mode limited to M_q,

$$M_q = \lceil k e R_z^{(q)}/2 \rceil. \quad (3)$$

Actual Soundfield

As shown in Figure 1, there are P_q loudspeakers located at $\boldsymbol{y}_p^{(q)}$ $(p = 1, \ldots, P_q)$ from the origin of the qth zone O_q on the qth loudspeaker array. Assume that no loudspeaker is inside any of the spatial zones of interest. The composite reproduced soundfield at the qth zone consists of fields due to loudspeaker arrays from zone 1 to zone Q. Let $\rho_p^{(q)}(k)$ be the signal weights required from the pth loudspeakers of the qth zone to achieve these desired fields. Thus, the reproduce soundfield within the qth zone at a point $\boldsymbol{x}^{(q)}$ from O_q is given by

$$\begin{aligned} S^{\mathrm{a}(q)}(\boldsymbol{x}^{(q)}, k) = & \sum_{p=1}^{P_1} \rho_p^{(1)}(k) \frac{i}{4} H_0^{(1)}(k\|\boldsymbol{y}_p^{(1,q)} - \boldsymbol{x}^{(q)}\|) \\ & + \sum_{p=1}^{P_2} \rho_p^{(2)}(k) \frac{i}{4} H_0^{(1)}(k\|\boldsymbol{y}_p^{(2,q)} - \boldsymbol{x}^{(q)}\|) \\ & + \ldots \\ & + \sum_{p=1}^{P_q} \rho_p^{(q)}(k) \frac{i}{4} H_0^{(1)}(k\|\boldsymbol{y}_p^{(q,q)} - \boldsymbol{x}^{(q)}\|), \end{aligned} \quad (4)$$

where the number of loudspeakers placed around zone 1 to zone Q is P_1 to P_q respectively, and $\boldsymbol{y}_p^{(1,q)}$ denotes the distance from the pth loudspeaker at the first zone to the observation point $\boldsymbol{x}$ with respect to the origin of the qth zone, and so forth. Here we have assumed that the loudspeakers are infinitely long point cylinders. Note, the fundamental solution to the Helmholtz wave equation [17] in 2D is $(i/4)H_0^{(1)}(k\|\boldsymbol{y} - \boldsymbol{x}\|)$ where the source is at $\boldsymbol{y}$ and the observation point is at $\boldsymbol{x}$, and $H_m^{(1)}(\cdot)$ is the Hankel function of the first kind.

Also, we recall the addition theorem for cylindrical harmonics [17]

$$H_0^{(1)}(k\|\boldsymbol{y} - \boldsymbol{x}\|) = \sum_{m=-\infty}^{\infty} H_m^{(1)}(k\|\boldsymbol{y}\|) J_m(k\|\boldsymbol{x}\|) e^{im\phi_{xy}} \quad \text{if } \|\boldsymbol{y}\| > \|\boldsymbol{x}\| \quad (5)$$

where ϕ_{xy} is the angle between the vectors $\boldsymbol{x}$ and $\boldsymbol{y}$.

Then we use (5) in (18) to write the actual soundfield in basis expansion form

$$S^{\mathrm{a}(q)}(\boldsymbol{x}^{(q)}, k) = \sum_{m=-\infty}^{\infty} \alpha_m^{\mathrm{a}(q)}(k) J_m(k\|\boldsymbol{x}^{(q)}\|) e^{jm\phi_x^{(q)}}, \quad (6)$$

where

$$\begin{aligned} \alpha_m^{\mathrm{a}(q)}(k) = & \frac{i}{4} \Big(\sum_{p=1}^{P_1} \rho_p^{(1)}(k) H_m^{(1)}(k\|\boldsymbol{y}_p^{(1,q)}\|) e^{im\angle \boldsymbol{y}_p^{(1,q)}} \\ & + \sum_{p=1}^{P_2} \rho_p^{(2)}(k) H_m^{(1)}(k\|\boldsymbol{y}_p^{(2,q)}\|) e^{im\angle \boldsymbol{y}_p^{(2,q)}} \\ & + \ldots \\ & + \sum_{p=1}^{P_q} \rho_p^{(q)}(k) H_m^{(1)}(k\|\boldsymbol{y}_p^{(q,q)}\|) e^{im\angle \boldsymbol{y}_p^{(q,q)}} \Big), \end{aligned} \quad (7)$$

and we define the notation $\angle \boldsymbol{y}_p^{(1,q)}$ as the angle of the pth loudspeaker of the first zone with respect to the origin of the qth zone, and so forth.

If we are to design loudspeaker weights, we can equate the desired soundfields to actual soundfields at each spatial zone, i.e.,

$$S^{\mathrm{d}(q)}(\boldsymbol{x}^{(q)}, k) = S^{\mathrm{a}(q)}(\boldsymbol{x}^{(q)}, k), \text{ for } q = 1, \ldots, Q \text{ and } k \in [k_l, k_u], \quad (8)$$

where k_l and k_u are the wavenumbers corresponding to lower and upper end of the frequency band of interest.

Thus, using (1), (6), and (7), we have

$$\alpha_m^{\mathrm{d}(q)}(k) = \frac{i}{4}\Big(\sum_{p=1}^{P_1} \rho_p^{(1)}(k) H_m^{(1)}(k\|\boldsymbol{y}_p^{(1,q)}\|) e^{im\angle \boldsymbol{y}_p^{(1,q)}} + \sum_{p=1}^{P_2} \rho_p^{(2)}(k) H_m^{(1)}(k\|\boldsymbol{y}_p^{(2,q)}\|) e^{im\angle \boldsymbol{y}_p^{(2,q)}} + \ldots + \sum_{p=1}^{P_q} \rho_p^{(q)}(k) H_m^{(1)}(k\|\boldsymbol{y}_p^{(q,q)}\|) e^{im\angle \boldsymbol{y}_p^{(q,q)}} \Big), \quad (9)$$

for $m = -\infty, \ldots, \infty$, and $p = 1, \ldots, P_q$ as the condition for exact reproduction. Required loudspeaker weights can be calculated from (9) by forming a series of equations.

LOUDSPEAKER ARRAY DESIGN

We would like to achieve Q possibly different soundfields over Q distinct spatial zones simultaneously without interfering each other. Thus, we construct (9) for each q as simultaneous equations and write them in matrix form

$$\boldsymbol{\alpha}^{\mathrm{d}}(k) = \boldsymbol{H}(k)\boldsymbol{\rho}(k), \quad (10)$$

where

$$\boldsymbol{\alpha}^{\mathrm{d}}(k) = [\alpha_{-M_1}^{\mathrm{d}(1)}(k), \ldots, \alpha_{M_1}^{\mathrm{d}(1)}(k), \alpha_{-M_2}^{\mathrm{d}(2)}(k), \ldots, \alpha_{M_2}^{\mathrm{d}(2)}(k), \ldots, \alpha_{-M_q}^{\mathrm{d}(q)}(k), \ldots, \alpha_{M_q}^{\mathrm{d}(q)}(k)]^T, \quad (11)$$

$$\boldsymbol{\rho}(k) = [\rho_1^{(1)}(k), \ldots, \rho_P^{(1)}(k), \rho_1^{(2)}(k), \ldots, \rho_P^{(2)}(k), \ldots, \rho_1^{(q)}(k), \ldots, \rho_P^{(q)}(k)]^T. \quad (12)$$

and

$$\boldsymbol{H}(k) = \frac{i}{4}\begin{pmatrix} \breve{\boldsymbol{H}}^{(1,1)}(k) & \breve{\boldsymbol{H}}^{(2,1)}(k) & \cdots & \breve{\boldsymbol{H}}^{(q,1)}(k) \\ \breve{\boldsymbol{H}}^{(1,2)}(k) & \breve{\boldsymbol{H}}^{(2,2)}(k) & \cdots & \breve{\boldsymbol{H}}^{(q,2)}(k) \\ \vdots & \vdots & \ddots & \vdots \\ \breve{\boldsymbol{H}}^{(1,q)}(k) & \breve{\boldsymbol{H}}^{(2,q)}(k) & \cdots & \breve{\boldsymbol{H}}^{(q,q)}(k) \end{pmatrix}, \quad (13)$$

where $\breve{\boldsymbol{H}}^{(1,1)}(k)$ is a sub-matrix

$$\breve{\boldsymbol{H}}^{(1,1)}(k) = \begin{pmatrix} \breve{H}_{-M_1}^{(1,1)}(k, \boldsymbol{y}_1) & \cdots & \breve{H}_{-M_1}^{(1,1)}(k, \boldsymbol{y}_P) \\ \breve{H}_{-M_1+1}^{(1,1)}(k, \boldsymbol{y}_1) & \cdots & \breve{H}_{-M_1+1}^{(1,1)}(k, \boldsymbol{y}_P) \\ \vdots & \ddots & \vdots \\ \breve{H}_{M_1}^{(1,1)}(k, \boldsymbol{y}_1) & \cdots & \breve{H}_{M_1}^{(1,1)}(k, \boldsymbol{y}_P) \end{pmatrix}, \quad (14)$$

and we define

$$\breve{H}_{-M_1}^{(1,1)}(k, \boldsymbol{y}_1) = H_{-M_1}^{(1)}(k\|\boldsymbol{y}_1^{(1,1)}\|) e^{-iM_1\angle \boldsymbol{y}_1^{(1,1)}}. \quad (15)$$

The total number of loudspeakers $P = P_1 + P_2 + \ldots + P_q$ specifies whether the linear system (10) can be solved exactly or not. For each desired soundfield, we have $2M_p + 1$ soundfield coefficients, thus a total of $M \equiv \sum_{p=1}^{P}(2M_p + 1)$ coefficients is required to accurately reproduce the soundfield.

In general the system (10) can only be satisfied exactly if $P \geq M$. Therefore, the number of loudspeakers required for exact reproduction of the desired soundfield

$$P \geq \sum_{q=1}^{Q} 2M_q + 1. \quad (16)$$

The matrix of loudspeaker weights $\boldsymbol{\rho}(k)$ can be solved by the following well-known solution

$$\boldsymbol{\rho}(k) = \boldsymbol{H}^{\dagger}(k)\boldsymbol{\alpha}(k), \quad (17)$$

where $\boldsymbol{H}^{\dagger}(k) = (\boldsymbol{H}(k)^H \boldsymbol{H}(k))^{-1}\boldsymbol{H}(k)^H$ is the Moore-Penrose Pseudo Inverse of $\boldsymbol{H}(k)$.

However, if $\boldsymbol{H}(k)$ is poorly conditioned, which could be the case for most multizone systems, there would be no solution to the matrix. The conditioning of $\boldsymbol{H}(k)$ is determined primarily by the loudspeaker geometry and positions of spatial regions relative to one another. However, Single Value Decomposition (SVD) [18] or regularization [19] may be used to improve the robustness of the Least Squares solution.

The corresponding reproduced soundfield can be obtained by

$$S^{\mathrm{a}}(\boldsymbol{x}^{(q)}; k) = \sum_{q=1}^{Q}\sum_{p=1}^{P} \rho_p^{(q)}(k) \frac{i}{4} H_0^{(1)}(k\|R_p^{(q)}\hat{\boldsymbol{\phi}}_p^{(q)} - \boldsymbol{x}^{(q)}\|), \quad (18)$$

where $H_0^{(1)}(k\|\cdot\|)$ is the zeroth order Hankel functions of the first kind, $\hat{\boldsymbol{\phi}}_p^{(q)} = (1, \phi_p^{(q)})$ and $R_p^{(q)}\hat{\boldsymbol{\phi}}_p^{(q)}$ denotes the loudspeaker position of the qth spatial region.

SIMULATION

Two-zone Soundfield Reproduction using Circular Loudspeaker Arrays

In the first example, we consider two circular reproduction zones of radii 0.4 m which are in-line with each other in free field. Zone 1 and Zone 2 are both 0.6 m away from the global origin $\mathscr{O}$. The desired soundfields consist of 50 random plane waves at 1000 Hz. We use random planewaves to avoid the system being affected by the incoming wave source directions. According to the dimensionality of spatial soundfield reconstruction [5], the number of loudspeakers P_q required for array q is $2 \times \lceil k(R_z^{(q)}) \rceil + 1$. In this case, we equally place 17 loudspeakers on a circle of 0.4 m for each loudspeaker array. We calculate loudspeaker weights using the method proposed in the previous section. The resulting reproduced field is shown in Figure 2. The top two plots show the real and imaginary parts of the desired two-zone soundfield, and the bottom two plots show the soundfield reproduced by the circular loudspeaker arrays. The reproduced two-zone soundfield corresponds well to the desired multizone soundfield where the zone boundaries of the two reproduction regions are indicated in two circles.

The reproduction error in the qth zone is defined as

$$\varepsilon^{(q)}(R_z^{(q)}, k) \triangleq \frac{\int_0^{R_z^{(q)}}\int_0^{2\pi} |S^{\mathrm{d}(q)}(R^{(q)}, \Omega^{(q)}; k) - S^{\mathrm{a}(q)}(R^{(q)}, \Omega^{(q)}; k)|^2 d\Omega^{(q)} dR^{(q)}}{\int_0^{R_z^{(q)}}\int_0^{2\pi} |S^{\mathrm{d}(q)}(R^{(q)}, \Omega^{(q)}; k)|^2 d\Omega^{(q)} dR^{(q)}}. \quad (19)$$

In this case, the reproduction error is 1.53%.

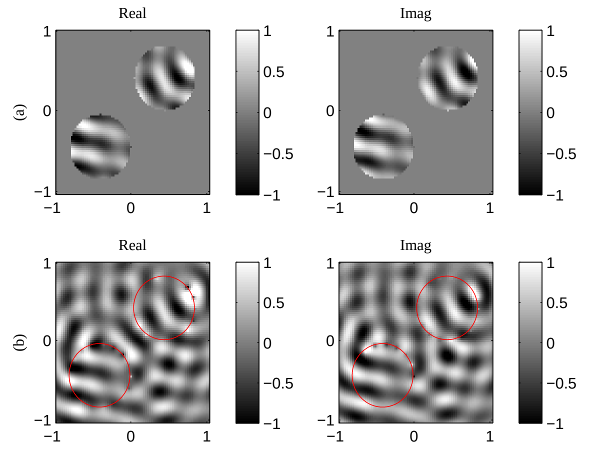

Figure 2: Reproduction of a 2D two-zone soundfield with radius 0.4 m each using two circular loudspeaker arrays. The desired soundfields consist of 50 random plane waves at 1000 Hz. Two zones are located at $\theta^{(10)} = 135°, r^{(10)} = 0.6$ m and $\theta^{(20)} = -45°, r^{(20)} = 0.6$ m respectively. (a) Desired field, and (b) reproduced field. We have equally placed 17 loudspeakers on a circle of 0.4 m for each loudspeaker array. The reproduced error in this case is 1.53%.

Reproduction Error with Distance

We investigate the performance of a soundfield with two reproduction zones of radius 0.4 m each by plotting the reproduction errors with different zone separation in distance. The desired soundfields consist of 50 random plane waves at 1000 Hz. Two loudspeaker arrays each consists of 17 equally placed loudspeakers on a circle of 0.4 m. We realize that the reproduction will not fail as long as these two zones have around 0.1 m separation. As compared to the multizone soundfield reproduction technique proposed in [7, 8], this method offers a better solution for allocating spatial zone positions.

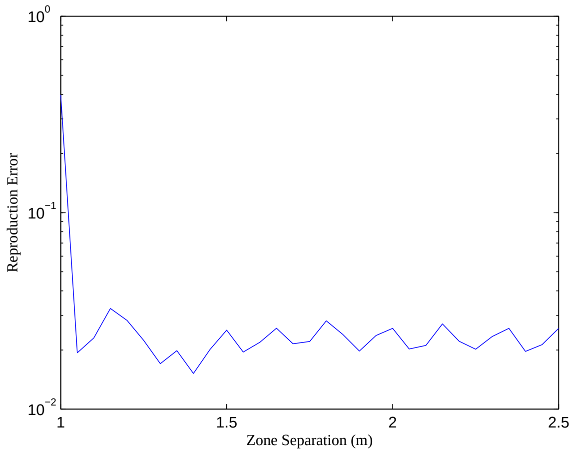

Figure 3: Reproduction error with different zone separation (in distance) for two circular reproduction zones with radius 0.4 m each using two loudspeaker array. The desired soundfields consist of 50 random plane waves at 1000 Hz. We have equally placed 17 loudspeakers on a circle of 0.4 m for each loudspeaker array.

Multizone Soundfield Reproduction using Circular Loudspeaker Arrays

In this example, we consider three circular reproduction zones with radius 0.4 m each in free field using three loudspeaker arrays as shown in Figure 4. We equally place 17 loudspeakers on a circle of 0.4 m for each loudspeaker array. Three zones are located at $\theta^{(10)} = 45°, r^{(10)} = 0.6$ m, $\theta^{(20)} = 165°$, $r^{(20)} = 0.6$ m and $\theta^{(30)} = -75°, r^{(30)} = 0.6$ m respectively. The desired soundfields consist of 50 random plane waves at 1000 Hz. The top two plots show the real and imaginary parts of the desired soundfield, and the bottom two plots show the real and imaginary parts of the reproduced soundfield. In this case, the reproduction error is 4.6%.

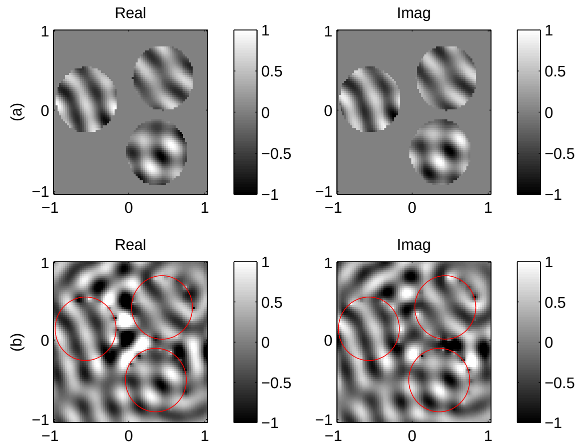

Figure 4: Reproduction of a 2D three-zone soundfield with radius 0.4 m each in free field using three loudspeaker arrays. Three zones are located at $\theta^{(10)} = 45°, r^{(10)} = 0.6$ m, $\theta^{(20)} = 165°, r^{(20)} = 0.6$ m and $\theta^{(30)} = -75°, r^{(30)} = 0.6$ m respectively. (a) Desired field, and (b) reproduced field. The desired soundfields consist of 50 random plane waves at 1000 Hz. We equally place 17 loudspeakers on a circle of 0.4 m for each loudspeaker array. The reproduction error in this case is 4.6%.

Two-zone Soundfield Reproduction using Non-circular Loudspeaker Arrays

In this section, we seek to recreate the desired soundfields using non-circular loudspeaker arrays. As mentioned in the “System Model" Section, circular loudspeaker arrays are not compulsory requirements for the loudspeaker configurations as long as the loudspeakers are placed on or outside the circle of radius $R_z^{(q)}$. For demonstration purpose, we use square-shape loudspeaker arrays as they provide better performance than the rectangular-shaped loudspeaker arrays. Based on the same parameters for the desired soundfields as shown in previous two-zone example, we use two square-shaped loudspeaker arrays with 17 loudspeakers on each. The number of loudspeakers used is the same as the one used in the two-zone example. The size of the square-shaped loudspeaker array is 0.8 m × 0.8 m. We equally place 5 loudspeakers with 0.16 m separation on one side of the square-shaped loudspeaker array and the remaining 12 loudspeakers on the other three sides with 0.2 m separation respectively. The loudspeaker weights of these two square-shaped loudspeaker array are calculated using the method proposed in the “Loudspeaker Weights Design” Section. The resulting reproduced field is shown in Figure 5. The top two plots show the real and imaginary parts of the desired two-zone soundfield, and the bottom two plots show the soundfield reproduced by the square-shaped loudspeaker arrays. The reproduced two-zone soundfield corresponds well to the desired multizone soundfield where the zone boundaries of the two reproduction regions are indicated in two circles. The reproduction error calculated based on (19) is 1.87%.

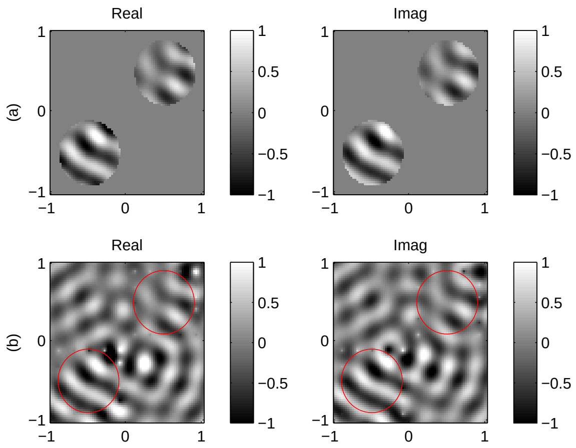

Figure 5: Reproduction of a 2D two-zone soundfield with radius 0.4 m each using two square-shaped loudspeaker arrays. The desired soundfields consist of 50 random plane waves at 1000 Hz. Two zones are located at $\theta^{(10)} = 135°, r^{(10)} = 0.6$ m and $\theta^{(20)} = -45°, r^{(20)} = 0.6$ m respectively. (a) Desired field, and (b) reproduced field. The size of the square-shaped loudspeaker array is 0.8 m $\times$ 0.8 m. For each loudspeaker array, we equally place 5 loudspeakers with 0.16 m separation on one side of the square-shaped loudspeaker array and equally place the other 12 loudspeakers on the other sides with 0.2 m separation. The reproduction error in this case is 1.87%.

CONCLUSION

This paper has investigated the soundfield reproduction performance to recreate two or more distinct 2D soundfields simultaneously at different spatial regions using multiple loudspeaker arrays. The basic ideas from the cross-talk cancelation systems were applied to determined the loudspeaker weights by the Least-squares method. From the simulation result, this approach offers a better solution for allocating spatial zone positions. The favorable simulation results of non-circular loudspeaker arrays demonstrate the fact that circular loudspeaker arrays are not compulsory requirements for the loudspeaker configurations as long as the loudspeakers are placed on or outside the regions of interest.

REFERENCES

[1] O. Kirkeby and P.A. Nelson, "Reproduction of plane wave sound fields", *Journal Acoustics Society America*, Vol.94, No.5, 2992–3000, November, 1993.

[2] A.J. Berkhout, D.de Vries and P. Vogel, "coustic control by wave sound field synthesis", *Journal of Acoustic Society America*, Vol.93, 2764–2778, 1993.

[3] S. Spors, R. Rabenstein and J. Ahren, "The theory of wave field synthesis revisited", in *Proc. the AES 124th convention*, Amsterdam, The Netherlands, May, 2008.

[4] D.B. Ward and T.D. Abhayapala, "Reproduction of Plane Wave Sound Field Using an Array of Loudspeakers", *IEEE Trans. Speech, Audio Processing*, Vol 9, No.6, 697–707, September, 2001.

[5] Y.J. WU and T.D. Abhayapala "Theory and Design of Soundfield Reproduction Using Continuous Loudspeaker Concept", *IEEE Trans. Speech, Audio and Language Processing* January, Vol. 17, No. 1, 107–116, 2009.

[6] M. Poletti, "Three-Dimensional Surround Sound Systems Based on Spherical Harmonics", *Journal Audio Engineering Society*, No.11, Vol.53, 1004–1025, November, 2005.

[7] Y.J. WU and T.D. Abhayapala, "Simultaneous Soundfield Reproduction at Multiple Spatial Regions", in *Proc. the AES 128th convention*, May, 2010.

[8] Y.J. WU and T.D. Abhayapala, "Multizone 2D Soundfield Reproduction Via Spatial Band Stop Filters", *Proc. IEEE Workshop on Applications of Signal Processing to Audio and Acoustics, WASPAA'2009*, 309-312. New Paltz, NY, October, 2009.

[9] Thushara D. Abhayapala and Yan Jennifer WU, "Spatial Soundfield Reproduction with Zones of Quiet", in *Proc. the AES 127th convention*, New York, U.S.A, October, 2009.

[10] T. Betlehem,"Acoustic Signal Processing Algorithms for Reverberant Environments", *Ph.D. thesis*, Research School of Information Sciences and Engineering, Australian National University, Canberra, ACT, August 2005.

[11] P.A. Nelson and S.J. Elliott, *Active control of sound*, Acadmic, London, 1992.

[12] S.M Kuo and G.H Canfield, "Dual-channel audio equalization and cross-talk cancellation for 3-D sound reproduction", *IEEE Trans. Consum. Electron.*, vol. 43, no. 4, pp. 1189-1196, November 1997.

[13] A. Mouchtaris, P. Reveliotis, and C. Kyriakakis, "Inverse filtering design for immersive audio rendering over loudspeakers", *IEEE Trans. Multimedia*, vol. 2, no. 2, pp. 77-87, June 2000.

[14] S. Miyabe, M. Shimada, T. Takatani, H. Saruwatari, and K. Shikano, "Multichannel inverse filtering with selection and enhancement of a loudspeaker for robust sound field reproduction", in *Proc. International Workshop on Acoustic Echo and Noise Control, IWAENC'2006*, Paris, France, Sept 2006.

[15] Y. Huang, J. Benesty, and J. Chen, "On crosstalk cancellation and equalization with multiple loudspeakers for 3D sound reproduction", *IEEE singal process. letters*, vol. 14, no. 10, pp. 649-652, 2007.

[16] R.A. Kennedy, P. Sadeghi, T.D. Abhayapala and H.M. Jones, "Intrinsic Limits of Dimensionality and Richness in Random Multipath Fields", *IEEE Trans. Signal Processing*, Vol.55, No.6, 2542–2556, June, 2007.

[17] D. Colton and R. Kress, *Inverse Acoustic and Electromagnetic Scattering Theory*, Springer, New York, second edition, 1998.

[18] S.M.A Salehin and T.D. Abhayapala, "Localizing lung sounds: Eigen basis decomposition for localizing sources within a circular array of sensors", to appear in *Journal of Signal Processing*, DOI:10.1007/s11265-009-0435-3.

[19] M. Poletti, "Robust Two-Dimensional Surround Sound Reproduction for Nonuniform Loudspeaker Layouts", *Journal Audio Engineering Society*, No.7/8, Vol.55, 598–610, July/August, 2007.