

MULTIZONE 2D SOUNDFIELD REPRODUCTION VIA SPATIAL BAND STOP FILTERS

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ABSTRACT

Any attempt to create multiple independent soundfields in separate zones over an extended region of open space results in unintended interference in a given zones from other zones. In this paper, we design spatial band stop filters to suppress interzone interference in the regions of interests and pass the desired soundfields with no distortion. This is achieved by using the higher order spatial harmonics of one zone to cancel the undesirable effects of the lower order harmonics of the same zone on the other zones. We illustrate the work by designing and simulating a 2D two-zone soundfield.

Index Terms— soundfield reproduction, multizone, cylindrical harmonic expansions, spatial band stop filters.

1. INTRODUCTION

Reproduction of multiple independent soundfields in separate zones over an extended region of open space is a challenging problem. There are many potential applications such as simultaneous entertainment systems in cars, sound systems in exhibition centers, and personal loudspeaker systems in shared office environments. Recently, we proposed a framework to recreate multiple 2D soundfields at different locations within a single circular loudspeaker array by cylindrical harmonics expansions and angular filtering [1]. However, reproduction is difficult in the cases when zones are in-line with each other or too close to each other. In this paper, we attempt to solve this problem by designing spatial band stop filters to cancel the induced effect from one zone to another.

There are plethora of activities related to single zone spatial soundfield reproduction based wave field synthesis (WFS) [2, 3] and Spherical/Cylindrical harmonic based techniques [4, 5]. However, there is only a limited number of work reported in the literature on multizone spatial soundfield reproduction in the literature. In Microsoft Research TechFest 2007, Tashev demonstrated a speaker array project, called ‘Personal Audio Space’ [6]. A linear loudspeaker array consisting of sixteen inexpensive speakers was used to demonstrate that sound waves cancel each other out in one area and become amplified in another. In 2008, Poletti has proposed a 2D multizone surround sound systems using the least squares pressure matching approach [7], where the investigation is mainly based on simulation results. Recently, we proposed a generalized framework to achieve spatial multizone soundfield reproduction. The key techniques of this framework are the spatial harmonic coefficient translation from individual desired soundfields

to a single global co-ordinate system and the application of appropriate angular windowing. However, the windowing process consumes extra spatial modes (harmonics) and caused reduced dimensionality in the reproduction region, resulting in some limitations in the multizone soundfield reproduction. i.e., reproduction failed in the cases when reproduction zones are in-line or too close to each other.

In this paper, we attempt to solve this problem by designing spatial band stop filters to suppress interzone interference in the regions of interests and pass the desired wavefields with no distortion. This is achieved by using the higher order harmonic modes of one zone to cancel the undesirable effects on the other zones induced from the lower order modes. Specifically, we (i) express the induced coefficients from the other zones due to the lower order modes of the first zone, then (ii) use the higher order modes of the first zone to cancel these unwanted terms and obtain the filtering modal coefficients, (iii) express each soundfield in terms of coefficients containing the desired soundfield coefficients and the filtering coefficients and (iv) finally translate each soundfield to a single global co-ordinate system and use existing single zone soundfield reproduction technique to reproduce the desired multizones with an array of loudspeakers. For simplicity, we formulate a two-zone system model. Simulation result demonstrates favorable performance.

2. SYSTEM MODEL

Suppose there are two spatial zones and corresponding 2D (height invariant) desired spatial soundfields to be reconstructed. Let the radius of zone 1 and zone 2 be r_1 and r_2 respectively, whose origins \mathcal{O}_1 and \mathcal{O}_2 are located at r_{z1} and r_{z2} from a global origin \mathcal{O} as shown in Fig. 1. The distance between \mathcal{O}_1 and \mathcal{O}_2 is denoted as r_0 . r_{c1} and r_{c2} are the radii we will refer to in Section 3.2. The loudspeakers are placed on a circle with radius $R_p \geq r$ from \mathcal{O} . The loudspeaker weight at angle ϕ_p is denoted as $\rho_p(\phi_p, k)$, where $k = 2\pi f/c$ is the wavenumber, f is the frequency, and c is the speed of sound propagation.

3. HARMONIC EXPANSIONS: DESIRED SOUNDFIELD

We assume any arbitrary observation point within the circular spatial reproduction zone to be $\mathbf{x} \equiv (\|\mathbf{x}\|, \phi_x)$, we can write the desired 2D (height-invariant) soundfield for the first zone by using cylindrical harmonic expansions as [5]

$$S^{d(1)}(\mathbf{x}; k) = \sum_{n=-N_1}^{N_1} \alpha_n^{d(1)}(k) J_n(k\|\mathbf{x}\|) e^{jn\phi_x}, \quad (1)$$

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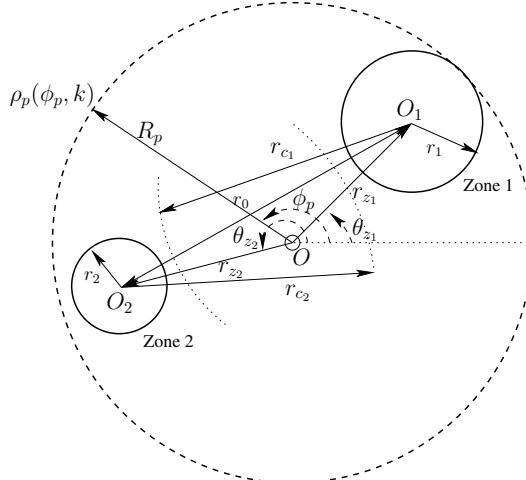


Figure 1: Geometry of two-zone sound reproduction system.

where $J_n(\cdot)$ are the Bessel functions of order n , and $\alpha_n^{(1)}(k)$ are a set of coefficients uniquely representing the desired soundfield of the first zone, which are mode limited¹ to $N_1 = \lceil kr_1/2 \rceil$ [8, 9].

3.1. Coefficients translation theorem

Theorem 1 Let $\{\alpha_n^{(1)}(k)\}$ be a set of coefficients of a soundfield with respect to a co-ordinate systems whose origin is at $(r_0, \theta^{(12)})$ with respect to a second co-ordinate system, where the two co-ordinate systems have the same angular orientation. Then the corresponding soundfield coefficients with respect to the second co-ordinate system is given by

$$\alpha_n^{(2)}(k) = \alpha_n^{(1)}(k) * T_n^{(12)}(r_0, \theta^{(12)}; k), \quad (2)$$

where $T_n^{(12)}(r_0, \theta^{(12)}; k) \triangleq J_n(kr_0)e^{-jnr^{(12)}}$ and '*' denotes the convolution.

Here we define the notation $T_n^{(12)}$ as the translation process from the first zone with respect to the co-ordinate system of the second zone while $T_n^{(21)}$ as the translation process from the second zone with respect to the co-ordinate system of the first zone. The proof is published in [1].

3.2. Spatial band stop filter

Consider two soundfields in two spatial zones as in Fig. 1. Due to propagation of sound waves, there are undesirable interference from one zone to the other. The concept of *spatial band stop filtering* is to cancel this interference; i.e., to filter the propagating soundfield of the first zone over the second zone and vice versa. Let the desired soundfield in zone 1 expressed in cylindrical harmonic expansion as in (1) with $2N_1 + 1$ soundfield coefficients $\alpha_m^{(1)}(k)$. However, these lower order modes have non-zero soundfield outside the zone 1 which includes zone 2. Due to the inherent properties of Bessel functions² higher order models ($> N_1$) of (1)

¹That is, the desired sound field is entirely described by $2N_1 + 1$ lowest modes

²Higher order Bessel functions are high pass

will have zero contribution to the zone 1. Hence, we use these higher order modes of (1) to cancel the effects of lower orders on zone 2 effectively creating a spatial band-stop filtering. Below, we use the spatial harmonic coefficient translation theorem 1 to derive this theory.

We can express the soundfield induced on zone 2 due to the soundfield on zone 1 with respect to the co-ordinate system at the centre of zone 2 by the translation theorem 1. Thus, the the induced coefficients at zone 2 due to the lower order modes of zone 1 are given by $\alpha_m^{(1)}(k) * T_m^{(12)}$. Now consider a set of higher order coefficients with respect to zone 1 given by $\gamma_m^{(1)}(k)$ for $N_{c_1} < |m| < N_0$. The induced soundfield on zone 2 due to these higher orders is $\gamma_m^{(1)}(k) * T_m^{(12)}$. Thus, the resulting total soundfield coefficients in zone 2 due to both lower and higher orders are given by

$$\beta_m^{(2)}(k) = \alpha_m^{(1)}(k) * T_m^{(12)} + \gamma_m^{(1)}(k) * T_m^{(12)}. \quad (3)$$

The higher order modes turning on between the spatial region of radii r_{c_1} and r_0 (referred in Fig. 1) correspond to mode numbers $N_{c_1} = \lceil kr_{c_1}/2 \rceil$ and $N_0 = \lceil kr_0/2 \rceil$ respectively [9].

We write the convolution as a summation

$$\beta_m^{(2)}(k) = \sum_{n_1=-N_1}^{N_1} \alpha_{n_1}^{(1)}(k) T_{m-n_1}^{(12)} + \sum_{N_0 \leq \|n_2\| \leq N_{c_1}} \gamma_{n_2}^{(1)}(k) T_{m-n_2}^{(12)}. \quad (4)$$

Now, we express (4) in matrix form as

$$\beta^{(2)}(k) = \mathbf{A}^{(1)}(k) \boldsymbol{\alpha}^{(1)}(k) + \mathbf{G}^{(1)}(k) \boldsymbol{\gamma}^{(1)}(k), \quad (5)$$

where

$$\begin{aligned} \beta^{(2)}(k) &\triangleq [\beta_{-N}^{(2)}(k), \dots, \beta_N^{(2)}(k)]^T, \text{ for } N = N_0 - N_{c_1} \\ \boldsymbol{\alpha}^{(1)}(k) &\triangleq [\alpha_{-N_1}^{(1)}(k), \dots, \alpha_{N_1}^{(1)}(k)]^T, \\ \boldsymbol{\gamma}^{(1)}(k) &\triangleq [\gamma_{-N_0}^{(1)}(k), \dots, \gamma_{-N_{c_1}}^{(1)}(k), \gamma_{N_{c_1}}^{(1)}(k), \dots, \gamma_{N_0}^{(1)}(k)]^T, \\ \mathbf{A}^{(1)}(k) &\triangleq \begin{pmatrix} T_{-N+N_1}^{(12)} & \cdots & T_{-N-N_1}^{(12)} \\ T_{-N+N_1+1}^{(12)} & \cdots & T_{-N+1-N_1}^{(12)} \\ \vdots & \ddots & \vdots \\ T_{N+N_1}^{(12)} & \cdots & T_{N-N_1}^{(12)} \end{pmatrix}, \end{aligned} \quad (6)$$

and $\mathbf{G}^{(1)}(k)$ is given in (8) displayed on the top of next page. Note that we use the translation property,

$$T_m^{(12)} \triangleq J_m(kr_0)e^{-jmr^{(12)}} = 0 \text{ for } \|m\| > N_0, \quad (7)$$

to force number of entries in (8) to zero.

For perfect filtering, i.e., zero soundfield interference on zone 2, we need $\beta^{(2)}(k) = [0, \dots, 0]^T$. Thus, we use the least squares method to solve (5) as

$$\boldsymbol{\gamma}^{(1)}(k) = -[\mathbf{G}^{(1)T}(k) \mathbf{G}^{(1)}(k)]^{-1} \mathbf{G}^{(1)T}(k) \mathbf{A}^{(1)}(k) \boldsymbol{\alpha}^{(1)}(k). \quad (9)$$

Similarly, we can repeat the process for the second zone and obtain the filtering coefficients of the second zone $\gamma_m^{(2)}(k)$.

$$\mathbf{G}^{(1)}(k) = \begin{pmatrix} T_{N_0-N}^{(12)} & T_{N_0-N-1}^{(12)} & \cdots & T_{N_0-2N}^{(12)} & T_{-N_0}^{(12)} & 0 & \cdots & 0 \\ T_{N_0+1-N}^{(12)} & T_{N_0-N}^{(12)} & \cdots & T_{N_0-2N+1}^{(12)} & T_{-N_0+1}^{(12)} & T_{-N_0}^{(12)} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ T_{N_0}^{(12)} & T_{N_0-1}^{(12)} & \cdots & T_{N_0-N}^{(12)} & T_{-N_0-N}^{(12)} & T_{-N_0-N+1}^{(12)} & \cdots & T_{-N_0}^{(12)} \\ 0 & T_{N_0}^{(12)} & \cdots & T_{N_0-N+1}^{(12)} & T_{-N_0-N-1}^{(12)} & T_{-N_0-N}^{(12)} & \cdots & T_{-N_0-1}^{(12)} \\ \vdots & \ddots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & T_{N_0}^{(12)} & T_{-N_0-2N}^{(12)} & T_{-N_0-2N+1}^{(12)} & \cdots & T_{-N_0-N}^{(12)} \end{pmatrix}. \quad (8)$$

3.3. Desired global soundfield

We are now writing the soundfield coefficients of the first zone as

$$\tilde{\alpha}_m^{(1)}(k) = \begin{cases} \alpha_m^{d(1)}(k) & \text{for } -N_1 < m < N_1 \\ \gamma_m^{(1)}(k) & \text{for } N_{c1} < |m| < N_0 \end{cases}, \quad (10)$$

where the soundfield coefficients $\tilde{\alpha}_m(k)$ contain both the desired soundfield coefficients of zone 1 and filtering coefficients canceling the undesirable effects from zone 2. The modes distributions are illustrated in Fig. 2. Similarly, we can obtain the soundfield coefficients of the second zone $\tilde{\alpha}_m^{(2)}(k)$.

Then we translate each soundfield with respect to the global co-ordinate system [1]. Since these modes are layered, we can add them together and obtain the corresponding desired soundfield coefficients in global co-ordinates

$$\begin{aligned} \beta_m^d(k) &= \beta_m^{d(1)}(k) + \beta_m^{d(2)}(k) \\ &= \tilde{\alpha}_m^{(1)}(k) * T_m^{(10)}(r_{z_1}, \theta_{z_1}; k) + \tilde{\alpha}_m^{(2)}(k) * T_m^{(20)}(r_{z_2}, \theta_{z_2}; k), \end{aligned} \quad (11)$$

where $T_m^{(10)}(r_{z_1})$ and $T_m^{(20)}(r_{z_2})$ are mode limited to $N_{z_1} = \lceil \ker_{z_1}/2 \rceil$ and $N_{z_2} = \lceil \ker_{z_2}/2 \rceil$, respectively. We can now write the desired global soundfield using cylindrical harmonic expansion as

$$S^d(\mathbf{x}; k) = \sum_{m=-\infty}^{\infty} \beta_m^d(k) J_m(k\|\mathbf{x}\|) e^{jm\phi_x}, \quad (12)$$

where \mathbf{x} refers to any observation point within the circular spatial zone $\|\mathbf{x}\| \leq R_P$.

Once the desired soundfield coefficients for the global region $\beta_m^d(k)$ are known, the two-zone reproduction problem is now reduced to reproduction of the desired soundfield (12) over the entire region. We can apply any of the existing single zone sound reproduction techniques to obtain the loudspeaker weights $\rho_p(\phi_p, k)$.

4. ERROR ANALYSIS

For this analysis, we assume that a suitable loudspeaker array is able to recreate the soundfield given by (12) with the soundfield coefficients given by (11). We can mathematically write the reproduced soundfield in zone 2 in terms of coefficients with respect to the co-ordinate system of zone 2 as

$$\beta_m^d(k) * T_m^{(02)} = \tilde{\alpha}_m^{(1)}(k) * T_m^{(10)} * T_m^{(02)} + \tilde{\alpha}_m^{(2)}(k) * T_m^{(20)} * T_m^{(02)} \quad (13)$$

where we omit the arguments of T_m for convenience.

From (16) in Appendix, $T_m^{(20)} * T_m^{(02)} = 1$ and $T_m^{(10)} * T_m^{(02)} = T_m^{(12)}$, thus we write (13) as

$$\beta_m^d(k) * T_m^{(02)} = \tilde{\alpha}_m^{(1)}(k) * T_m^{(12)} + \tilde{\alpha}_m^{(2)}(k). \quad (14)$$

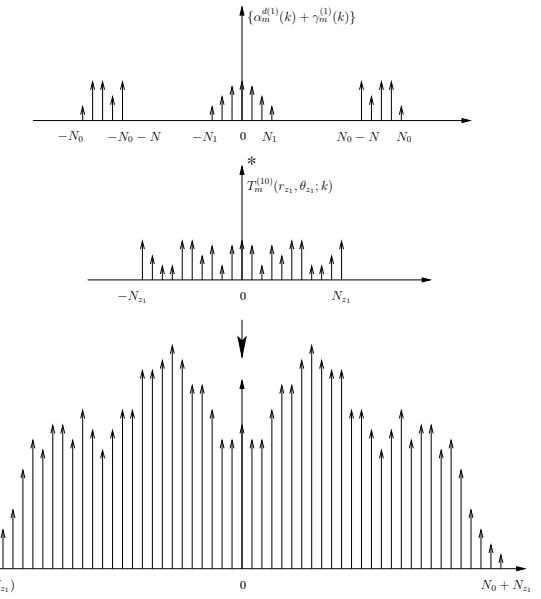


Figure 2: Illustration of modes distributions for desired global soundfield, where $\alpha_m^{d(1)}(k)$ are the desired soundfield coefficients of zone 1, $\gamma_m^{(1)}(k)$ are the filtering coefficients and $T_m^{(10)}(r_{z_1}, \theta_{z_1}; k)$ refers to the translation process from zone 1 to the global soundfield.

Note that $\tilde{\alpha}_m^{(2)}(k)$ gives the desired sound field and using (10) and (3), we get

$$\tilde{\alpha}_m^{(1)}(k) * T_m^{(12)} = \beta_m^{(2)}(k). \quad (15)$$

However, we made $\beta_m^{(2)}(k) = 0$ for lower order modes in our spatial filter design. The above analysis reveals that the translation and band stop filtering process will not induce any additional errors. The reproduction errors may be introduced due to the truncation and loudspeaker reproduction.

5. SIMULATION

In this paper, we use a simple example to illustrate the ability to reproduce a 2D two-zone soundfields using the spatial band stop filters. We consider two circular reproduction zones of radii 0.15m which are in-line with each other. Zone 1 and Zone 2 are both 0.75m away from the global origin \mathcal{O} . The desired soundfields are monochromatic plane wave of frequency of 1000 Hz arriving from 45° and 135° respectively. According to the di-

mensionality of spatial soundfield reconstruction [1], the minimum number of loudspeakers P required to reconstruct the field is $2 * \lceil k\epsilon[r_0/2 + \max(r_1, r_2)]/2 \rceil + 1$. In this case, we place 80 loudspeakers on a circle of 1.5m while we calculate loudspeaker weights using the least squares method, and the resulting reproduced field is shown in Figure 3. 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 loudspeaker array. 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 reproduced error in this case is 10%.

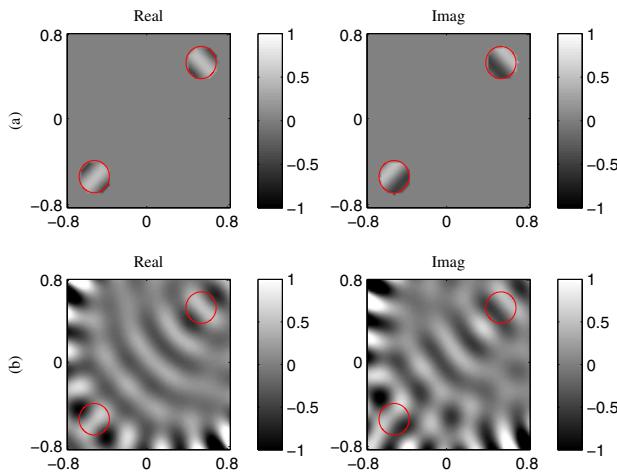


Figure 3: Reproduction of a 2D multizone soundfield for two reproduction zones of radius 0.15m, frequency of 1000Hz. $\theta_{z_1} = 45^\circ$, $r_{z_1} = 0.75$ m and $\theta_{z_2} = 225^\circ$, $r_{z_2} = 0.75$ m. (a) desired field, and (b) reproduction field. 80 loudspeakers are equally spaced on a circle of $R = 1.5$ m.

6. CONCLUSION

In this paper, we design spatial band stop filters to suppress interzone interference in the region of interest and pass the wavefield with no distortion. This is achieved by using the higher order modes of one zone to cancel the undesirable effects on the other zones induced from the lower order modes. Simulation result demonstrates good reproduction in the case when reproduction zones are in-line and close to each other. These are preliminary results of our investigation on spatial multizone reproduction.

7. APPENDIX: TRIANGULAR TRANSLATION IDENTITY

We derive the following translation theorem for three co-ordinate systems:

Theorem 2 Let $T_m^{(21)}$, $T_m^{(20)}$, and $T_m^{(01)}$ be the translation operators between co-ordinates systems 0, 1, and 2 as defined by Theorem 1. Then we have

$$T_m^{(21)} = T_m^{(20)} * T_m^{(01)}. \quad (16)$$

According to the Translation Theorem 1,

$$T_m^{(20)} = J_m(kr_{z_2})e^{-jm\theta_{z_2}}, \quad (17)$$

$$T_m^{(01)} = J_m(kr_{z_1})e^{-jm(\theta_{z_1}+\pi)} \quad (18)$$

$$T_m^{(21)} = J_m(kr_0)e^{-jm(\theta^{(21)}+\pi)} = J_m(kr_0)e^{jm\theta^{(21)}}. \quad (19)$$

Thus, $T_m^{(20)} * T_m^{(01)}$

$$= \sum_{m=-\infty}^{\infty} J_m(kr_{z_2})e^{-jm\theta_{z_2}} J_{n-m}(kr_{z_1})e^{-j(n-m)(\theta_{z_1}+\pi)} \quad (20)$$

Using the translation identity [10], (20) now becomes

$$T_m^{(20)} * T_m^{(01)} = J_m(kr_0)e^{-jm\theta^{(12)}} = J_m(kr_0)e^{jm\theta^{(21)}} = T_m^{(21)}.$$

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