SPHERICAL MICROPHONE ARRAY WITH MULTIPLE NULLS FOR ANALYSIS OF DIRECTIONAL ROOM IMPULSE RESPONSES

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ABSTRACT

A spherical microphone array is presented which incorporates multiple nulls in the beampattern for analysis of directional room impulse responses. Improved performance is achieved compared to spherical arrays with regular beampatterns due to the ability to attenuate undesired room reflections. Formulation of the multiple-null spherical array processing is presented, both in the space and spherical harmonics domains. The paper concludes with experimental investigation using impulse response data measured in an auditorium.

Index Terms— Microphone array, spherical harmonics, room acoustics, beamforming, null-steering.

1. INTRODUCTION

Spherical microphone arrays [1] have been studied recently for several applications, one of which is room acoustics. The spherical microphone array realizing three-dimensional beamforming with rotational symmetry facilitates spatial and directional analysis of sound fields in rooms and auditoria. Gover et al presented a spherical microphone array and incorporated beamforming for directional sound-field analysis in rooms [2]. Rigelsford and Tennant designed a volumetric array and implemented beamforming for acoustic imaging in a room [3]. Park and Rafaely [4] and Rafaely et al [5], used a scanning spherical microphone array around rigid and open spheres to analyze the sound field in auditoria using plane-wave decomposition [6] and directional impulse responses [5].

In the studies presented above, fixed beamformers were employed for the spatial filtering, which was rotated to various look directions to realize directional analysis. In this paper the advantage of using beamforming with multiple nulls designed to suppress significant room reflections from directions other than the look direction is investigated. As early reflections compose a significant part of the room impulse response [7], placing spatial nulls in their direction can produce directional impulse responses with improved signal-to-noise ratio (SNR) compared to fixed beamforming.

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The paper presents development of a multiple-null beamformer, formulated both in the space domain and in the spherical harmonics domain, and investigates its application to directional room acoustics analysis using experimental data. Performance is compared to a regular beamformer [8].

2. SPHERICAL ARRAY PROCESSING

Spherical microphone array processing is revised in this section. The results presented here are then used in the following sections. The reader is referred to previous work for a more comprehensive presentation of the topic [9, 10].

Consider a spherical microphone array which samples the sound pressure on a sphere. The array output can be calculated either in the space domain or in the spherical Fourier transform domain as [9]:

$$y = \sum_{j=1}^{M} p(kr, \Omega_j) w^*(k, \Omega_j) = \sum_{n=0}^{N} \sum_{m=-n}^{n} p_{nm}(kr) w^*_{nm}(k), \tag{1}$$

where k is the wavenumber, r the array radius, p the sound pressure, w the complex conjugate of the array weighting function w^*, and p_{nm} and w_{nm} their spherical Fourier transforms [11]. The complex conjugate has been used to simplify the notation [9, 12]. M is the number of spatial samples, or microphones, and N is the array order. In this paper we neglect aliasing errors in order to simplify the analysis. The effect of sampling, aliasing errors and sampling configurations are discussed in more detail in [9, 13].

Array equations can be written in a matrix form by defining the following vectors:

$$\mathbf{p} = [p(kr, \Omega_1), p(kr, \Omega_2), ..., p(kr, \Omega_M)]^T \tag{2}$$

is the $M \times 1$ vector of pressure signals at the microphones, and

$$\mathbf{w} = [w_1, w_2, ..., w_M]^T \tag{3}$$

is the corresponding $M \times 1$ vector of weights. Similar vectors can be defined in the spherical harmonics domain.

$$\mathbf{p}_{nm} = [p_{00}, p_{1(-1)}, p_{10}, p_{11}, ..., p_{NN}]^T \quad (4)$$

is the $(N+1)^2 \times 1$ vector of the spherical harmonics coefficients of the pressure, and

$$\mathbf{w}_{nm} = [w_{00}, w_{1(-1)}, w_{10}, w_{11}, ..., w_{NN}]^T \quad (5)$$

is the $(N+1)^2 \times 1$ vector of the spherical harmonics coefficients of the weights.

Array output can now be written in a matrix form:

$$y = \mathbf{w}^H \mathbf{p} = \mathbf{w}_{nm}^H \mathbf{p}_{nm}. \quad (6)$$

Array beampattern is typically calculated as array output assuming the sound field is composed of a single unit-amplitude plane-wave, such that [11]:

$$p_{nm}(kr) = b_n(kr) Y_n^{m^*}(\Omega_0), \quad (7)$$

where b_n is a function of array configuration, with available analytical expressions [11, 14], Ω_0 is the plane-wave incident direction, and Y_n^m is the spherical harmonics basis function of order n and degree m [11].

Array manifold vectors, used in the standard array processing literature [12], which represent the microphones output typically due to a plane wave, are given by

$$\mathbf{v} = [v_1, v_2, ..., w_M]^T, \quad (8)$$

where each element is given by

$$v_j = \sum_{n=0}^{N} \sum_{m=-n}^{n} b_n(kr) Y_n^{m^*}(\Omega_0) Y_n^m(\Omega_j). \quad (9)$$

Similarly, array manifold vector can be written in the spherical harmonics domain, given by

$$\mathbf{v}_{nm} = [v_{00}, v_{1(-1)}, ..., v_{NN}]^T, \quad (10)$$

where each element is given by

$$v_{nm} = b_n(kr) Y_n^{m^*}(\Omega_0). \quad (11)$$

Array response to a unit amplitude plane wave arriving from Ω_0 can now be written as

$$y = \mathbf{w}^H \mathbf{v} = \mathbf{w}_{nm}^H \mathbf{v}_{nm}. \quad (12)$$

3. MULTIPLE-NULL SPHERICAL ARRAY BEAMFORMING

Spherical microphone arrays can be used to measure directional room impulse responses [5], by applying beamforming. When setting the array look direction at the direct sound or one of the major room reflections, we would like to detect that reflection without distortion. This can be achieved by designing array output to be unity in response to a plane wave from the desired look direction [12], i.e.

$$\mathbf{w}^H \mathbf{v}_0 = 1, \quad (13)$$

where $\mathbf{v}_0$ denotes $\mathbf{v}$ involving direction Ω_0, the desired look direction. At the same time, we would like to reduce contributions from other directions. As room impulse responses typically include strong early reflections, we could reduce the contributions from these reflections by setting array output from these directions to zero, i.e.

$$\mathbf{w}^H \mathbf{v}_l = 0, \quad l = 1, ..., L, \quad (14)$$

with L denoting the number of nulls to be placed in the array beampattern. Defining

$$\mathbf{V} = [\mathbf{v}_0, \mathbf{v}_1, ..., \mathbf{v}_L], \quad (15)$$

we can now formulate the following problem with the aim of finding the multiple-nulls beampattern weights:

$$\mathbf{w}^H \mathbf{V} = \mathbf{c}, \quad (16)$$

with

$$\mathbf{c} = [1, 0, ..., 0]^T \quad (17)$$

a vector of length $L+1$. A least-squares solution can be applied to (16) to find the coefficients, i.e.

$$\mathbf{w} = \mathbf{V}^{\dagger} \mathbf{c}, \quad (18)$$

where $\mathbf{V}^{\dagger}$ is the pseudo-inverse of $\mathbf{V}$. A similar formulation can be written in the spherical harmonics domain, due to the equivalence in formulation presented in section 2. Matrix $\mathbf{V}_{nm}$ can be defined in a similar manner to matrix $\mathbf{V}$, and the set of equations:

$$\mathbf{w}_{nm}^H \mathbf{V}_{nm} = \mathbf{c}, \quad (19)$$

can be solved by

$$\mathbf{w}_{nm} = \mathbf{V}_{nm}^{\dagger} \mathbf{c}. \quad (20)$$

As arrays in practice typically employ spatial over - sampling [5, 6], vector $\mathbf{w}_{nm}$ and matrix $\mathbf{V}_{nm}$ will be of lower dimensions compared to $\mathbf{w}$ and $\mathbf{V}$, and so the spherical harmonics formulation may be more efficient.

4. EXPERIMENTAL INVESTIGATION

Multiple-null beamforming was compared to regular beamforming ($w_{nm}^* = Y_n^m(\Omega_l)/b_n$) [6, 8], for directional room impulse response analysis using measured data. The experiment is detailed in [5], a brief review is presented here. A loudspeaker was placed on the stage at the Sonnenfeldt auditorium, Ben-Gurion Univeristy, and a scanning dual-sphere [14] microphone array was placed at the seating area. The radii of the two spheres were 0.4 and 0.43 meters, with 882 microphone positions on each sphere. Data was taken by measuring the impulse response from the loudspeaker to the microphone array, and its Fourier transform was used for $p(kr, \Omega_j)$ in this work. The original paper employed delay-and-sum beampattern [10] for analysis of directional impulse responses, and in this paper it is compared to similar analysis using multiple-null beamforming, both of spherical harmonics order $N = 10$, in the frequency range 500-2800 Hz.

Table 1 presents details of six early room reflections, including the direct sound, taken from [5]. Multiple-null beamforming was realized by setting the array look direction to one of these six waves, and setting nulls at directions of the other five waves. Figures 1 and 2 present the regular and multiple-nulls beampatterns, respectively, both with look direction at the direct sound. Although the beampatterns look similar, the multiple-null beampattern has zeroes, or low response, at the directions of the five room reflections, denoted by "$\times$" marks on the figures. Note that the beampatterns actually realized included $|b_n|$ terms to improve low frequency robustness [10], which might modify the beampatterns at low frequencies.

Figures 3 presents three directional room impulse responses for look directions corresponding to waves 1, 4, and 6 in Table 1. Results for both beampatterns are presented, including SNR values with the signal represented by 6 msec time window around the desired reflection, and noise represented by the remainder of the impulse response. The figure shows that improved SNR can be achieved with the multiple-null beamformer. In particular, Figs. 3b and 3c show that the multiple-null array better attenuates undesired reflections (reflections other than near the "∇" mark).

5. CONCLUSION

A spherical microphone array with a multiple-null beampattern was developed in this paper, with formulations both in the space and the spherical harmonics domains. This beampattern was used for analysis of measured directional room impulse responses, showing improved performance over a regular beampattern. The study of methods for automatic identification of significant undesired reflections, leading to automatic multiple null-steering [12], and their use in room acoustics analysis are proposed for future study.

6. REFERENCES

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No.	τ	θ	ϕ	Path
1	28.3	96.4	25.7	Direct
2	42.5	57.9	25.7	Ceiling reflector I
3	46.0	36.4	25.7	Ceiling reflector II
4	48.3	92.1	42.9	Left stage wall
5	57.2	92.1	300.0	Right auditorium wall
6	63.7	92.1	68.6	Left auditorium wall

Table 1. Summary of data for the plane-wave decomposition analysis, taken from [5]. For each of the six waves, the table shows the arrival time (τ, msec), the arrival direction (θ, ϕ, degrees), and the physical path followed in the auditorium from the source to the array.

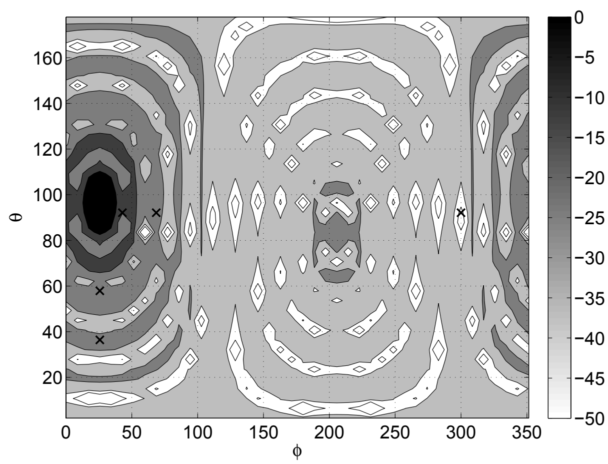


Fig. 1. Regular beampattern.

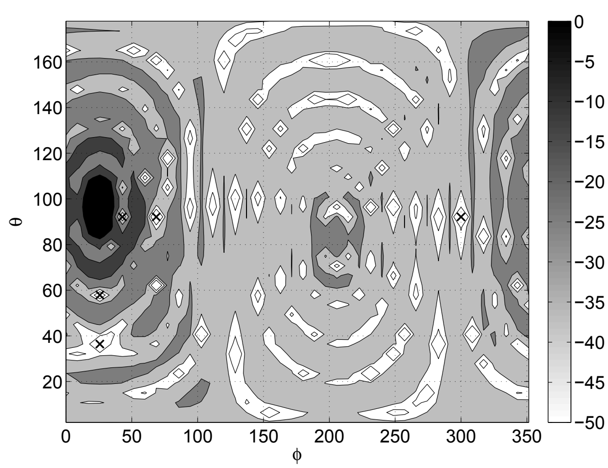
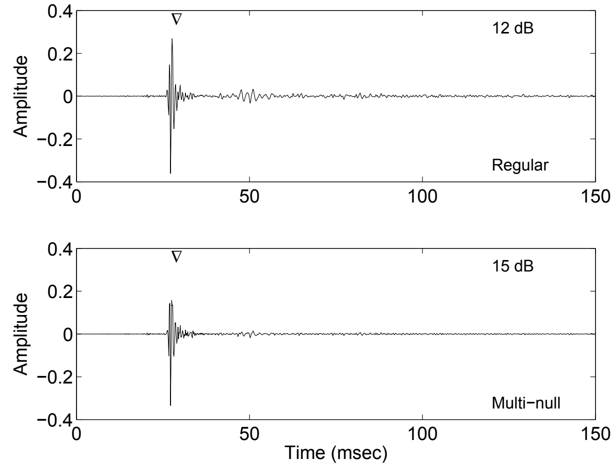
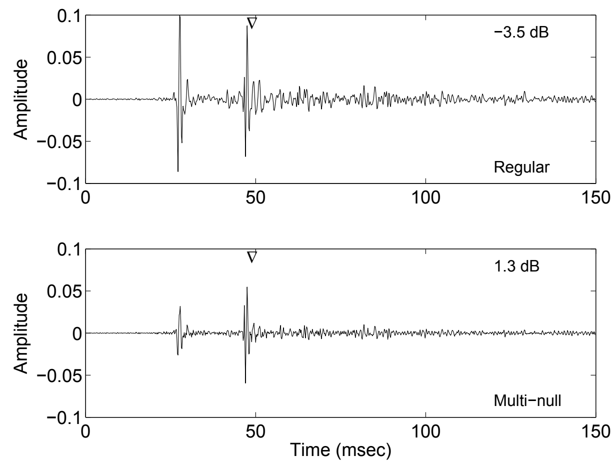


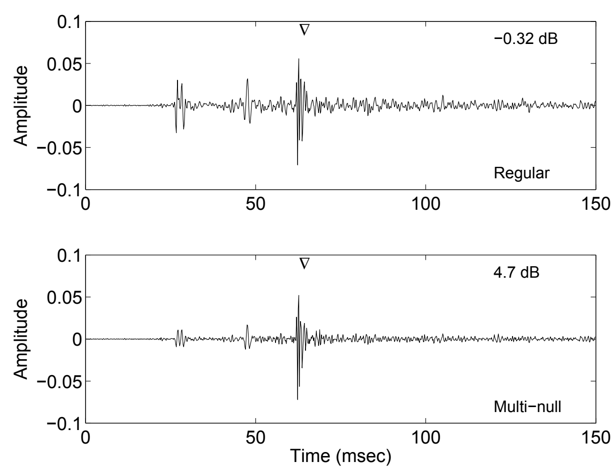
Fig. 2. Multiple-null beampattern.



(a)



(b)



(c)

Fig. 3. Directional impulse responses with look directions as denoted in Table 1: (a) wave 1, (b) wave 4, (c) wave 6. "∇" marks waves arrival times, dB values denotes SNR, and beampattern type is denoted on the figure.