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On the optimization of a mixed speaker array in an enclosed space using the virtual-speaker weighting method

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ABSTRACT

In order to achieve sound field reproduction in a wide frequency band, multiple-type speakers are used. The reproduction accuracy is not only affected by the signals sent to the speakers, but also depends on the position and the number of each type of speaker. The method of optimizing a mixed speaker array is investigated in this paper. A virtual-speaker weighting method is proposed to optimize both the position and the number of each type of speaker. In this method, a virtual-speaker model is proposed to quantify the increment of controllability of the speaker array when the speaker number increases. While optimizing a mixed speaker array, the gain of the virtual-speaker transfer function is used to determine the priority orders of the candidate speaker positions, which optimizes the position of each type of speaker. Then the relative gain of the virtual-speaker transfer function is used to determine whether the speakers are redundant, which optimizes the number of each type of speaker. Finally the virtual-speaker weighting method is verified by reproduction experiments of the interior sound field in a passenger car. The results validate that the optimum mixed speaker array can be obtained using the proposed method.

1. Introduction

The reproduction of spatial sound field has been a concern for decades. Among the sound field reproduction approaches, Higher-Order Ambisonics (HOA) [1–3] and Wave Field Synthesis (WFS) [4–6] are widely investigated. HOA and WFS can be considered to be a mode-matching approach and a surface integral approach respectively [7]. In practice, these approaches for sound field reproduction must cope with the limitations imposed by practical sound reproduction systems. Namely, they must be applied to discrete loudspeaker distributions of limited spatial support, varying directivity and possibly multi-path propagation, whereas the listening domains have a finite size. In an enclosed space, the reflection of the boundary also needs to be addressed while using these approaches.

While a sound field is reproduced in an enclosed space, a field-matching approach [7], which achieves the sound field reproduction through multiple sound pressure points matching, is a practical one. One of the earliest researches on field-matching approach was developed by Kirkeby and Nelson in 1993 [8]. Then, many studies focus on this approach [9–11]. In implementation, multiple-type speakers are always required in order to achieve sound reproduction in a wide frequency band. For instance, multiple-type actuators including bass shakers, subwoofers and loudspeakers, are used in order to

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achieve aircraft sound reproduction within 50 Hz–10 kHz [12]. At low frequencies 4 standard car audio loudspeakers and at high frequencies 8 headrest loudspeakers are used in order to achieve personal audio sound in the full audio band [13]. The importance of multiple-type speakers for sound reproduction has been addressed in these researches, but how to determine the position and number of each type of speaker remains a problem.

In order to minimize the leakage of acoustical energy and reproduction error, Lilis proposed a method of least-absolute shrinkage and selection operator (Lasso) to choose corresponding positions of loudspeakers at different frequencies [14]. Radmanesh proposed a two-stage algorithm combining Lasso and Least Squares (LS) for isolated wideband sound reproduction [15,16]. These two methods could optimize the speaker position, but the optimum number of the speakers of a mixed speaker array is difficult to be determined by lasso method.

Asano investigated the optimization of the speaker configuration in a wide frequency band based on the correlation of transfer function between the speaker and the control points, and Gram-Schmidt orthogonalization was used to calculate the correlation of transfer function [17]. Similar optimization idea was used to reduce the number of speakers and microphones [18], and it is found that the optimized source array obtained using this method could also achieve a good reproduction accuracy.

Khalilian described a constrained matching pursuit algorithm to optimize the speaker positions [19–21]. This algorithm firstly designs a target acoustic transfer function based on the desired sound field, then the positions of the loudspeakers are selected in order to make the actual acoustic transfer function best approximates the target one.

Some search algorithms, such as Genetic Algorithm (GA), Simulated Annealing Algorithm (SAA) and so on, are also considered in the optimization of sound reproduction systems. In order to find an optimal loudspeaker array for balancing the performance and robustness of three-dimensional (3D) audio system with cross-talk cancellation, Bai proposed a method combining Taguchi method and GA [22]. For achieving a personal audio system, Coleman evaluated the performance of varied control systems based on the contrast performance between bright and dark zones, array effort and planarity of sound field in the bright zone, and then adopted Sequential Forward-Backward Search (SFBS) to optimize the configuration of control system [23,24]. Olik investigated different system configurations for different personal sound reproduction with first order reflections [25]. Enumeration method is applied to provide design guidelines of loudspeaker configuration for personal audio system in a car cabin at high frequencies [26].

The above investigations have verified these search algorithms can effectively optimize the configuration of reproduction system, but mostly obtain asymmetric source array. Hardly any above method considers the optimization problem of a mixed speaker array in a wide frequency band. In this paper, a virtual-speaker weighting method is proposed to solve this problem. Section 2 describes the method to calculate the weights of loudspeaker array for spatial sound reproduction. Section 3 proposes a virtual-speaker model to quantify the controllability of the speaker array. The gain of the virtual speaker transfer function is used to determine the priority of candidate speaker positions, which optimizes the position of each type of speaker. The relative gain of the virtual-speaker transfer function is used to determine whether the speakers are redundant, which optimizes the number of each type of speaker. Section 4 describes the optimization of a multiple-type speaker array in a wide frequency band. Finally in Section 5, the experimental results validate that the optimum mixed speaker array obtained by the proposed method can achieve a good reproduction accuracy.

2. Sound field reproduction in an enclosed space

Field-matching approach is applied for reproducing a desired sound field in an enclosed space. The reproduction process is shown in Fig. 1. It is shown that the process can be divided into two stages. In the first stage, a microphone array is used to

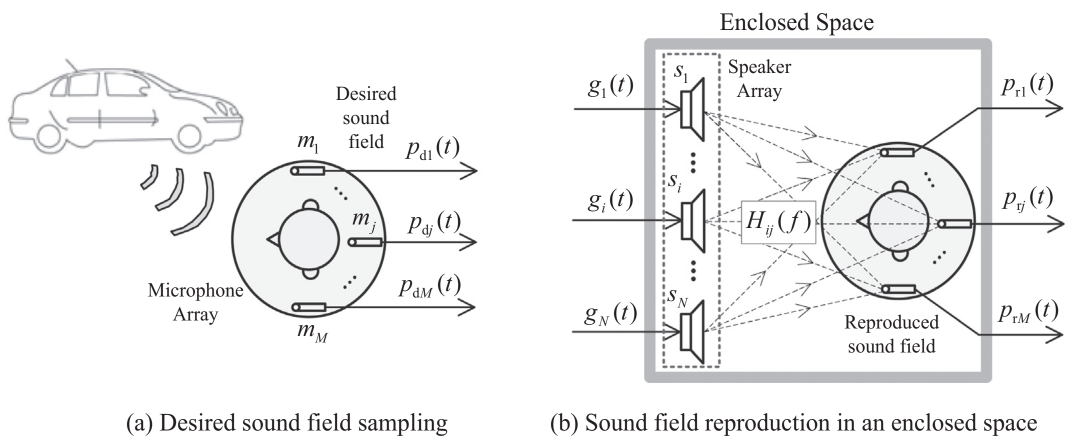

Fig. 1. Schematic diagram of sound field reproduction in an enclosed space.