Journal of Sound and Vibration 358 (2015) 1–19

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Positioning actuators in efficient locations for rendering the desired sound field using inverse approach

Wan-Ho Cho [a,*], Jeong-Guon Ih [b], Takeshi Toi [c]

[a] Center for Fluid Flow & Acoustics, Division of Physical Metrology, Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon 305-340, Republic of Korea

[b] Center for Noise and Vibration Control (NoViC), Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Republic of Korea

[c] Department of Precision Mechanics, Chuo University, Tokyo 112-8551, Japan

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form
30 June 2015
Accepted 29 July 2015
Handling Editor: P. Joseph
Available online 31 August 2015

ABSTRACT

For rendering a desired characteristics of a sound field, a proper conditioning of acoustic actuators in an array are required, but the source condition depends strongly on its position. Actuators located at inefficient positions for control would consume the input power too much or become too much sensitive to disturbing noise. These actuators can be considered redundant, which should be sorted out as far as such elimination does not damage the whole control performance significantly. It is known that the inverse approach based on the acoustical holography concept, employing the transfer matrix between sources and field points as core element, is useful for rendering the desired sound field. By investigating the information indwelling in the transfer matrix between actuators and field points, the linear independency of an actuator from the others in the array can be evaluated. To this end, the square of the right singular vector, which means the radiation contribution from the source, can be used as an indicator. Inefficient position for fulfilling the desired sound field can be determined as one having smallest indicator value among all possible actuator positions. The elimination process continues one by one, or group by group, until the remaining number of actuators meets the preset number. Control examples of exterior and interior spaces are taken for the validation. The results reveal that the present method for choosing least dependent actuators, for a given number of actuators and field condition, is quite effective in realizing the desired sound field with a noisy input condition, and in minimizing the required input power.

1. Introduction

The goal of sound field control using multichannel audio systems is to render a desired sound field condition for a specific purpose and there have been various methods suggested to this end. However, due to constraints associated with cost and space requirements, only a limited number of acoustic actuators, such as 5.1 and 7.1 channel systems, have been used in commercial systems despite significant developments in spatial audio techniques.

* Corresponding author. Tel.: +82 42 868 5872.
E-mail address: chowanho@kriss.re.kr (W.-H. Cho).

http://dx.doi.org/10.1016/j.jsv.2015.07.037
0022-460X/

Among the various spatial audio techniques, the direct rendering techniques based on an inverse approach using least-square solutions [1] has benefit to render arbitrary shaped sound field if the desired condition is given in terms of the sound pressure distribution. The inverse approach uses the inversion of a transfer matrix that describes the relation between the actuators and the field points. The transfer matrix can be obtained not only through direct measurement but also through numerical estimation. As an advanced form of the inverse approach, the boundary surface control method was suggested for obtaining the desired sound field by matching the sound pressure conditions for the boundary surface of the target region [2,3]. Recently, a technique based on modularization of the transfer matrix was suggested for determining the acoustic characteristics of the actuator conditions and the listening space with actual subsystems that are controllable in practical situations [4,5].

The efficient placement of an array system is suggested for the manipulation of virtual sources, such as the amplitude panning technique [6] and wave field synthesis technique [7,8]. However, the positioning of acoustic actuators in efficient locations has not been discussed for direct rendering based on the inverse approach. In many cases of research purpose, the loudspeaker array surrounding the control region, such as circular array is widely used for a wide area control [9–11]. In some practical applications, the existing loudspeakers installed in the cabin [12] were used to improve spatial perception without adding or moving any loudspeakers. There are some special cases in which an efficient position is relatively clear; these include the headrest for a personal audio system that delivers different sounds to people in different seats in a car cabin [13]. In general, a setup with a large number of actuators is thought as useful for precise control; however, too many actuators can make the system unstable [5] because various types of noise and modeling errors are existed and amplified in real situations. Thus, a method for the proper positioning of the acoustic actuator is required for practical applications.

In this paper, a strategy for the proper positioning of actuators in using the inverse technique for sound field rendering is proposed to assure a well-conditioned transfer matrix. Generally, some modeling errors can be introduced in a transfer matrix and a certain amount of disturbing noise will exist in the input signal. And, when obtaining the desired sound field condition for a large area over a wide frequency range, the number of field points is typically much larger than the number of actuators. In this case, the transfer matrix becomes ill-conditioned. For these reasons, conditioning of the transfer matrix is essential to obtain a robust solution against modeling errors and disturbing noise. Here, several approaches to obtain a stable solution in a rank deficient matrix equation are considered and applied for the positioning actuators in efficient locations.

2. Theoretical background

2.1. Inverse approach for a sound field rendering

Sound field rendering using an inverse array design method is based on a least-square problem that is used to minimize the error between the desired sound field condition and the sound field rendered by the array system. In the transfer matrix between the acoustic actuator input and the field points to be controlled, many sub-transfer matrixes are included as transfer paths for the signal. If the transfer matrix describing the relationship between the input to the actuator array and the output at the control region is given by **G**, the response at the field **H** is described by [5]

$$\mathbf{H} = \mathbf{G}\mathbf{A}_F, \tag{1a}$$

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_{s,1} & \mathbf{G}_{s,2} & \cdots & \mathbf{G}_{s,N} \end{bmatrix} \begin{bmatrix} \mathbf{T}_1 Z_1 \\ \mathbf{T}_2 Z_2 \\ \vdots \\ \mathbf{T}_N Z_N \end{bmatrix}. \tag{1b}$$

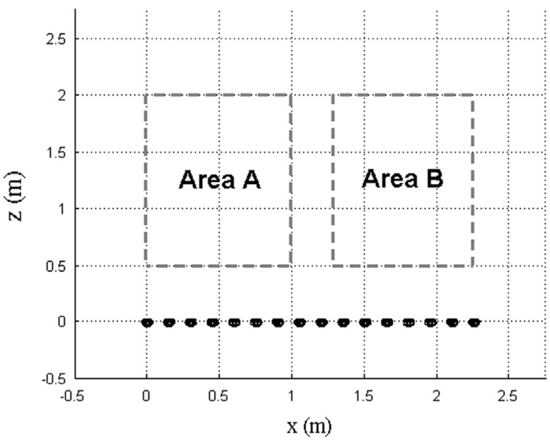

Fig. 1. Configuration of the source array system and control region.