"Sound Cask" - A new dimension of the sound reproduction based on the boundary surface control -

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ABSTRACT

The sound reproduction system based on the boundary surface control principle makes possible a physically close sound reproduction and has a high performance of spatial reproduction such as sound localization and sound distance. Based on these features, we have researched and developed a 3-D sound field sharing system in order to make possible a deeper level of telecommunication through music. We need space large enough for a musical performance with the sound reproduction system and real-time convolution system for 3-D sound reproduction based on the boundary surface control principle. In this paper, we introduce a system architecture of 3-D sound field sharing system for musical performance, specifically a "Sound Cask" which serves as the basis for sound reproduction and has 96 loudspeakers installed omnidirectionaly.

1. INTRODUCTION

There has been considerable research and development on sound field reproduction based on the boundary surface control principle since Ise proposed it in 1993[1]. In recent years, it has become easier to record and reproduce sounds with multiple channels. We have already developed a three-dimensional (3-D) sound reproduction system based on the boundary surface control principle using a 62 channel-loudspeaker system and a C_{80} fullerene-shaped 70 channel microphone array[2]. This 62 channel reproduction system achieved high performance of sound reproduction based on the results of psychological and physical experiments.

As an example of a sound reproduction system application, we proposed a sound field sharing system that enables telecommunication as if we were in the same room. In this system, we can simultaneously experience the same reproduced sound field and communicate with voice which is convolved with transfer functions of the primary sound field. Research results indicate that the sound field sharing system with 62 loudspeakers makes speech communication more natural by adding spatial information to the voice.

The features of the sound field sharing system are most effective in communication such as music performance which is concerned with spatial information. In this paper, we introduce a "sound cask" to make possible a distant ensemble performance based on the boundary surface control principle.

2. SOUND FIELD REPRODUCTION BASED ON THE BOUNDARY SURFACE CONTROL PRINCIPLE

In 1993, Ise proposed the boundary surface control (BoSC) principle which is a 3-D sound reproduction method based on the Kirchhoff-Helmholtz integral equation and inverse system[1, 3, 4]. Figure 2 shows its basic concept.

We are considering reproduction of a sound field at recorded area V in the primary field into reproduced area V' in the secondary field. Given that V is congruent with V', the following equations hold.

$$|r' - s'| = |r - s| \quad (s \in V, r \in S, s' \in V', r \in S') \qquad (1)$$

where S and S' denote a boundary of the recorded area and a boundary of the reproduced area respectively. If we denote the sound pressure in V and V' as $p(s)$ and $p(s')$

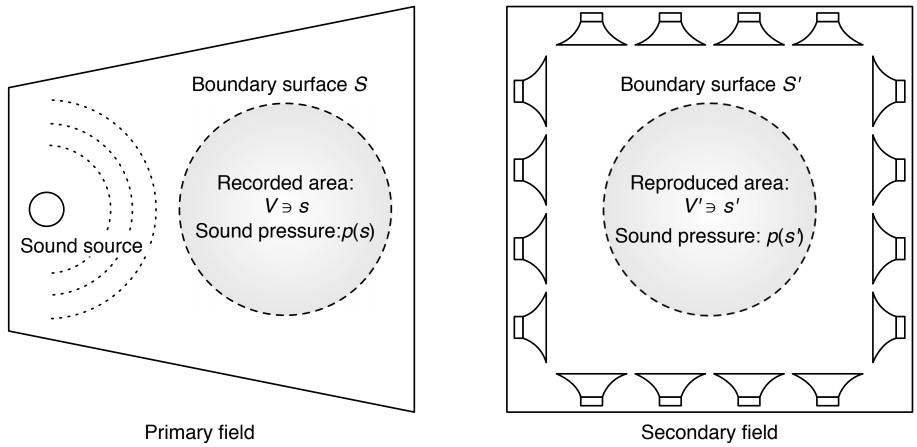

Fig. 1: Concept of the boundary surface control principle.

respectively, $p(s)$ and $p(s')$ are denoted by the following equations.

$$p(s) = \int\int_S G(r|s)\frac{\partial p(r)}{\partial n} - p(r)\frac{\partial G(r|s)}{\partial n} dS \quad s \in V \tag{2}$$

$$p(s') = \int\int_{S'} G(r'|s')\frac{\partial p(r')}{\partial n} - p(r')\frac{\partial G(r'|s')}{\partial n} dS' \quad s' \in V' \tag{3}$$

where n and n' denote normal vectors on S and S' respectively. By applying the equation 1, we obtain the following relationships of Green's function and its gradient:

$$G(r|s) = G(r'|s') \tag{4}$$

$$\frac{\partial G(r|s)}{\partial n} = \frac{\partial G(r'|s')}{\partial n'} \tag{5}$$

Hence, it follows that if the sound pressure and its gradient on each boundary are equal to each other, then the sound pressures in each area are also equal to each other from equations 2 and 3. This is expressed as

$$\begin{aligned} &\forall r \in S, \forall r' \in S', \\ &p(r) = p(r'), \frac{\partial p(r)}{\partial n} = \frac{\partial p(r')}{\partial n'} \\ &\Longrightarrow \forall s \in V, \forall s' \in V', \quad p(s) = p(s'). \end{aligned} \tag{6}$$

By considering this as a boundary value problem, from the uniqueness of the solution it follows that either the sound pressure value or its gradient value are sufficient to determine the value for both[5].

Another sound reproduction method using the Kirchhoff-Helmholtz integral equation is a wave field synthesis[6]. However, a characteristic of the boundary surface control principle is that a closed surface configuration is not restricted because of the inverse system.

3. SOUND FIELD SHARING SYSTEM

As an example of application of the BoSC system, we introduce a sound field sharing system using more than one BoSC system. A sound field sharing system is a telecommutation system that allows us to communicate with each other as if we were in the same room. Figure 4 shows the basic concept.

The system creates the same sound field for each speaker, thus enabling communication in the same sound space. The background sound (N_A,N_B) that is recorded in the shared sound fields, for example, birds singing or rustling leaves in the nature are convolved with the inverse system and then reproduced simultaneously in each secondary field. Each speaker is immersed in the background sound as if they were in the same place.

Furthermore the voice of each speaker in the secondary field is recorded and then reproduced in the shared sound field. The reproduced voices in the shared sound field are recorded by microphone arrays ($W_{A\rightarrow B}$, $W_{B\rightarrow A}$) and convolved with the inverse system and then reproduced in the other speaker's secondary sound field. This process

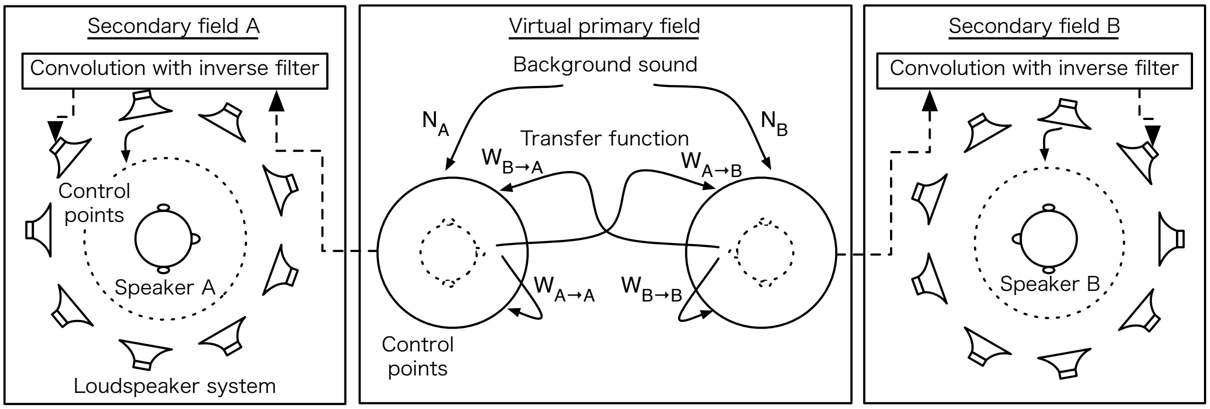

Fig. 2: Concept of the sound field sharing system.

adds spatial information to the speaker's voice such as sound reflection in the shared sound field and the other speaker's position. Similarly, how the speaker hears his or her own voice depends on the spatial information. Therefore, the reproduced voice in the shared sound field is recorded by the speaker's own microphone array ($W_{A\to A}$, $W_{B\to B}$) and then reproduced in the speaker's own secondary sound field after convolution with the inverse system. However, this requires removal of the direct sound in the shared sound field.

If there is no need to reproduce the background sound (N_A,N_B) in real time, the background sound can be reproduced after recording. For voice communication between systems, the voice is convolved with transfer functions from a loudspeaker to the other microphone array ($W_{A\to B}$, $W_{B\to A}$) and to the speaker's own microphone array ($W_{A\to A}$, $W_{B\to B}$) in the shared sound field. Then, the convolved voices are added and reproduced in the secondary field. However, in the latter transfer function, a direct sound effect must be removed.

In previous studies, we developed a sound field sharing system using the BoSC system with 62 channel loudspeakers[2, 8]. The BoSC system allows us to perceive the direction of reproduced voice. The system transmits voice direction in a three-person conversation by changing the transfer functions in accordance with the speaker's facing angle[9]. Only 24 loudspeakers were used to reproduce voice between the systems to avoid a large amount of calculations[10].

4. SOUND CASK

The main characteristic of the BoSC system is its ability to reproduce a sound field not by points but three-dimensionally. A listener can freely move his or her head, so that the system can provide high performance of spatial information reproduction such as conveying sound localization and sound distance[11]. Based on these system features, as an example of a more effective application of the BoSC system, we introduce a "sound cask" to make possible an ensemble performance in a distant environment.

Figure 4 shows a picture of the sound cask. In the horizontal direction, the sound cask is shaped like a regular nonagonal cask. Hence, except for floor and ceiling planes, the sound cask has no parallel sides. This characteristic shape has the effect of suppressing acoustic modes inside the sound cask.

With internal dimensions of 1950 mm in diameter at the central horizontal plane and 2150 mm in height, the sound cask is large enough for a player to play wind and stringed musical instruments inside the system. A Total of 96 full-range loudspeakers are installed omnidirectionaly except for the floor plane. Six loudspeakers are installed on the ceiling plane. The loudspeakers installed on the wall surface are divided into six layers based on their height, with 9 loudspeakers allotted to each of the top and the bottom layers, and 18 loudspeakers allotted to each of the remaining layers. The average interval between layers is around 350 mm. The average interval between loudspeakers in the horizontal direction is around

Fig. 3: Sound cask

Fig. 4: BoSC microphone array placed in the sound cask for measuring transfer functions to design the inverse system.

540 mm at the top and bottom layers, and around 330 mm at all other layers. In a conventional 62-channel BoSC system, loudspeakers are installed around the upper body of a listener. However, in the sound cask, loudspeakers are installed to cover the whole body of a listener. Therefore, this is expected to improve the sound reproduction performance in the vertical direction.

Additionally, the wall parts of the sound cask are modularized and can be dismantled when transporting the system. The system is divisible into nine parts in the horizontal direction where each part forms a side of a regular nonagon. The walls of the sound cask are divisible into three (top, middle and bottom) parts in the vertical direction. For sound absorbing material, we use priwool (with a thickness of $120mm$ and a density of $32kg/m^3$) to satisfy both effectivity and comfort. The noise barrier

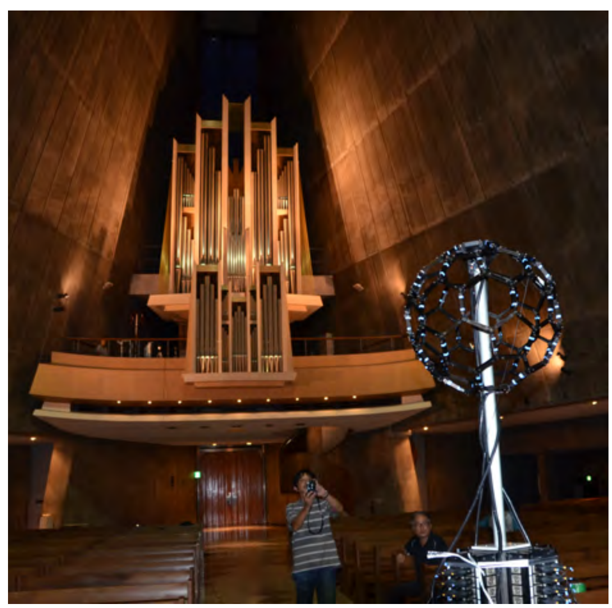

Fig. 5: Recording with BoSC microphone arrays in Tokyo cathedral.

performance of the system is Dr-20. We also considered the ease of inverse system design by shortening reverberation time.

Figure 4 shows the BoSC microphone array used for recording sound fields and measuring transfer functions. The BoSC microphone array is designed to have the same configuration as C_{80} fullerene. Eighty omnidirectional microphones (DPA 4060BM) are installed at the node of the fullerene. The diameter of the microphone array is about 46 cm and is large enough to enclose a listener's head.

For sound field recordings with the BoSC microphone system, we need an 80-channel recording system. A common PC-based multichannel recording system puts restrictions on recording place options because it requires an external power supply. To avoid this issue, a portable 80 channel sound recording system has been constructed and used for recording the sound outdoors and at other places[12].

Figure 4 shows the flow of sound signals in the sound cask system. The loudspeakers in the sound cask are driven by digital amplifiers installed at the bottom of the sound cask. The computer sends a voice sound signal to the other system through the network.

The computer obtains sound field data to be shared with other participants from the recorded sound field database. By preliminarily convolving the sound field data with the inverse system, the system only play the data to reproduce the sound field.

The sound of musical performance to be transferred among the systems needs to be convolved with transfer functions that are measured in the primary sound field. The musical performance recorded inside the system is convolved with the transfer functions from a sound source to control points corresponding to the other listener's virtual position in the primary field ($[w_j]_{A\to B}$, $[w_j]_{B\to A}$). To reproduce the sound reflection of a player's musical performance, we convolved the performance sound with the transfer functions from a sound source to control points corresponding to the player's virtual position in the primary field ($[w_j]_{A\to A}$, $[w_j]_{B\to B}$). Hence, in this case, a direct sound must be removed from the transfer functions. Also, the recording of a musical performance inside the system needs an echo canceler.

The sound reproduction performance of the sound cask is being researched physically and psychologically. Preliminary research indicates that the sound cask system has higher sound reproduction performance than a conventional 62 channel sound reproduction system.

5. CONCLUSIONS

In this paper, we introduced a "sound cask" to make possible an ensemble performance in a distant environment based on the boundary surface control principle. In the future, we will research sound reproduction performance of the sound cask with consequent focus on sound field sharing communication using the system architecture introduced in this paper.

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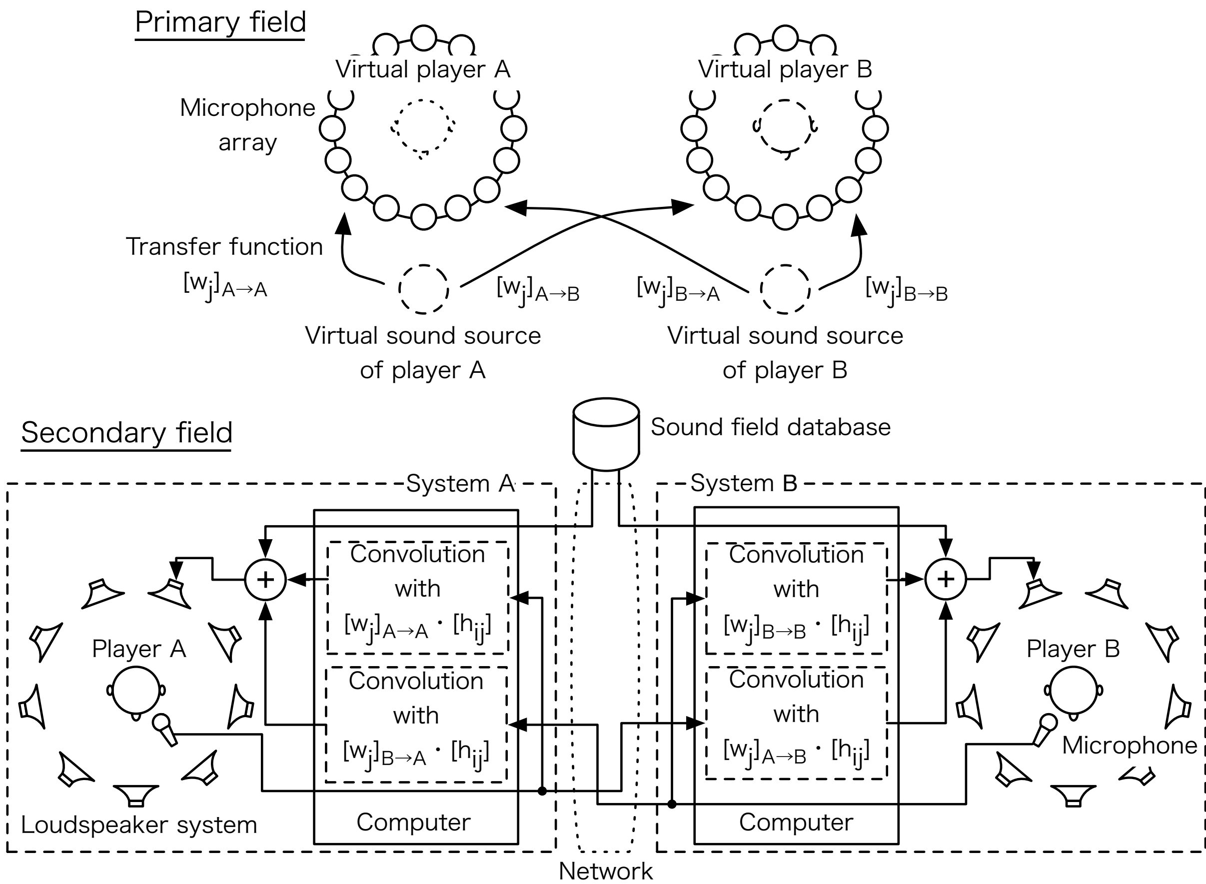

Fig. 6: Sound signal flow of the sound field sharing system with sound cask.

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