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Three-dimensional sound field simulation using the immersive auditory display system "Sound Cask" for stage acoustics

Kanako Ueno[a], Maori Kobayashi[b], Haruhito Aso[c], Shiro Ise[d]

[a] Meiji University, Japan, uenok@meiji.ac.jp
[b] Meiji University, Japan, te11001@meiji.ac.jp
[c] Meiji University, Japan, ce53001@meiji.ac.jp
[d] Tokyo Denki University, Japan, iseshiro@mail.dendai.ac.jp

Abstract

A three-dimensional (3D) sound field simulation system using the immersive auditory display system, "sound cask," has been developed for creating a virtual environment that would reproduce the 3D acoustics of concert halls for musicians. The simulation system is based on the boundary surface control principle. The original sound field was measured using a microphone array consisting of 80 omnidirectional microphones (DPA 4060BM) installed at the nodes of the C80 fullerene structure. The virtual sound field was then constructed in a cask-shaped space (approx. 2 x 2 m), with 96 channel full-range loudspeakers (FOSTEX FE103EN) installed in the space. The 3D acoustic waves of music, including the acoustic condition on the stage, were created virtually inside the sound cask. For this, the first step was to design inverse filters of the MIMO (Multi-Input Multi-Output) system between the 96 loudspeakers and 80 microphones located in the sound cask. Next, the inverse filters, and the impulse responses measured in actual concert halls and signals from instruments played by musicians, were convolved. Room acoustic indices between the actual and virtual conditions were compared to test the validity of the simulation results. Furthermore, subjective experiments involving professional musicians were performed, and the subjects' impressions of the sound quality, spatial size, and effect of reverberation were investigated. This paper presents the features of the sound field simulation system based on the results of objective and subjective experiments.

Keywords: stage acoustics, sound field simulation, real-time sound field reproduction

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1 Introduction

The effects of room acoustics on musicians on stage can be investigated using a three-dimensional (3D) sound field simulation system in which the acoustics can be changed freely and quickly. To make subjects feel as though they were playing on a real stage, Ueno et al. developed a sound field simulation system that employs a six-channel recording and reproduction technique for solo performances [1] and ensemble performances with two players [2]. This simulation system has been used in experimental studies on the effect of the room acoustics on the musicians’ subjective auditory impression [1,3] and performance [4].

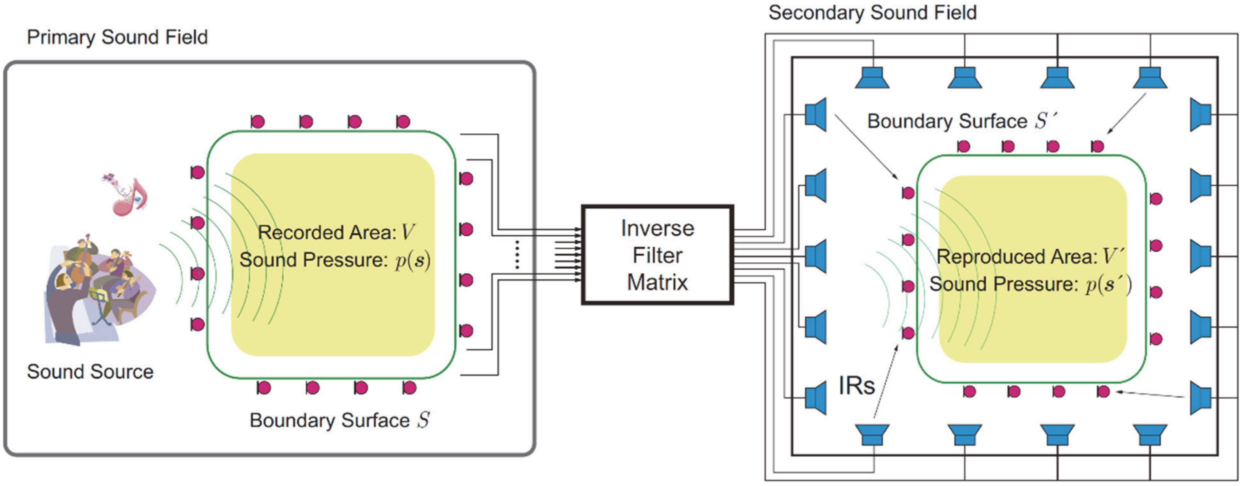
Meanwhile, starting in 2011, the sound cask, an immersive auditory system that consists of 96 loudspeakers driven by the output of an inverse filter and the design of which is based on the boundary surface control principle, has been developed [5]. The ability of the sound cask to create a highly accurate 3D sound field was investigated by physical measurement and by psychological and physiological experiments [5-7]. In this paper, we present the experimental results of using the sound field simulation system that includes the sound cask to simulate onstage acoustics. We conducted physical measurements on the performance of the system and obtained the evaluation of the system by the musicians.

2 The sound cask and its theoretical basis

The boundary surface control (BoSC) principle (Fig. 1) was used to create the 3D sound field in the sound cask [8]. The sound pressures at surface S are reproduced at surface S' in the secondary sound field via an inverse filter matrix, which is determined from the impulse responses of all possible combinations of loudspeakers and microphones. By combining the Kirchhoff-Helmholtz integral equation and the theory of inverse systems, the BoSC system can accurately reproduce a 3D sound field surrounded by a closed boundary surface.

The BoSC system comprises the BoSC microphone system (Fig. 2, left) and the reproduction room, namely, the sound cask (Fig. 2, right). First, the BoSC microphone system records the sound pressure on the surface of a volume defined by the BoSC microphone array. Next, the recorded signals are convolved with a set of inverse filters. Finally, the loudspeaker array in the sound cask accurately recreates the sound field in other locations by reproducing the convolved signals. In the BoSC system, the inverse filters are determined by an inverse system of a transfer function matrix measured for each loudspeaker and microphone pair.

The configuration of the BoSC microphone array is the same as that of a C80 fullerene. An omnidirectional microphone (DPA 4060BM) is at each of the 80 nodes of the fullerene. The diameter of the microphone array is approximately 46 cm. The area of the BoSC system to be reproduced is the region enclosed by the microphone array; thus, the system can reproduce a 3D sound field surrounding the head of a listener. Consequently, listeners can perceive sound images created within the sound field that are not adversely affected by head movements.



Source: (Omoto, 2015 [5])

Fig. 1 Concept of the boundary surface control principle with an inverse filter matrix

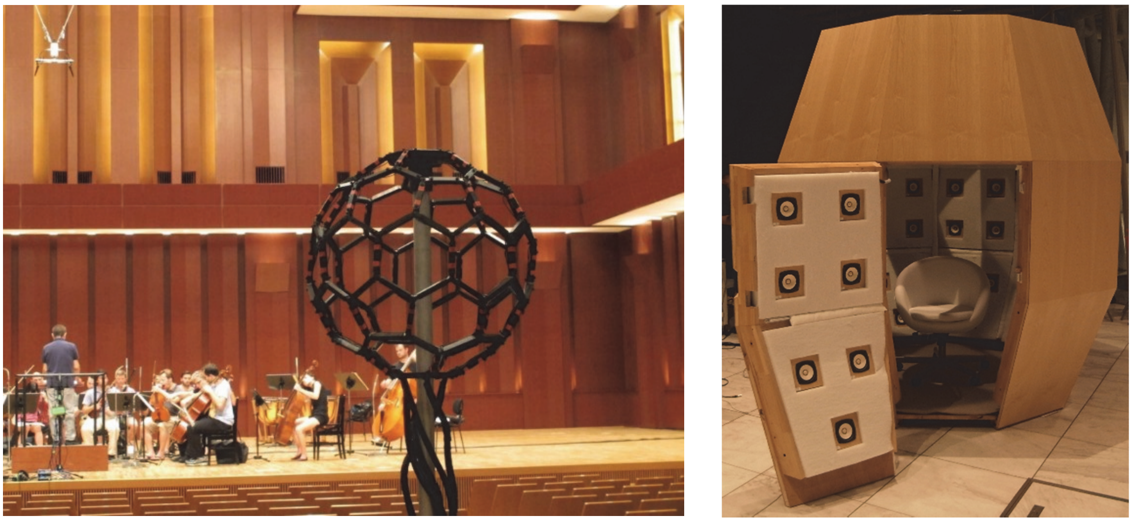


Fig. 2 The BoSC system comprises the BoSC microphone system (left) and the sound cask (right)

The sound cask (approximately 2 m x 2 m, $H = 2.2$ m) has a nonagonal horizontal cross section, and vertically its surfaces are set at three different angles to avoid parallel surfaces, except for the floor and ceiling. Its 96-channel sound field reproduction system comprises 96 full-range loudspeakers (FOSTEX FE103EN) installed in all the surfaces except the floor. The loudspeakers are installed in the walls in six rows, with 9 loudspeakers in the top and the bottom rows and 18 loudspeakers in each of the remaining four rows. The 6 loudspeakers are installed on the ceiling.

3 Sound field simulator for concert hall acoustics

3.1 Theoretical examination [9]

As shown in Fig. 3 (left), the source signal U generated from a loudspeaker, assumed an instrument of a player on a concert hall stage in the primary field, passes through the transfer functions $[F_j]$. The BoSC microphone is located at the position of the player. The transfer function is given by $[F_j] = [D_j] + [R_j] (\in C^{1\times M})$, where $[D_j]$ is the direct sound and $[R_j]$ is the reverberant sound. In the simulated field, as in the primary field, after the source signal U is picked up by a microphone for the musical instrument, the output signal $\hat{X}$ of the microphone is convolved using the FIR filter $[Q_i]$ $(\in C^{1\times N})$ in real time. Driving the loudspeakers in the sound cask with the filter output $[S_i]$ $(\in C^{1\times M})$ reproduces the same sound field as the primary field in the region surrounding the head of the listener (Fig. 3, right).

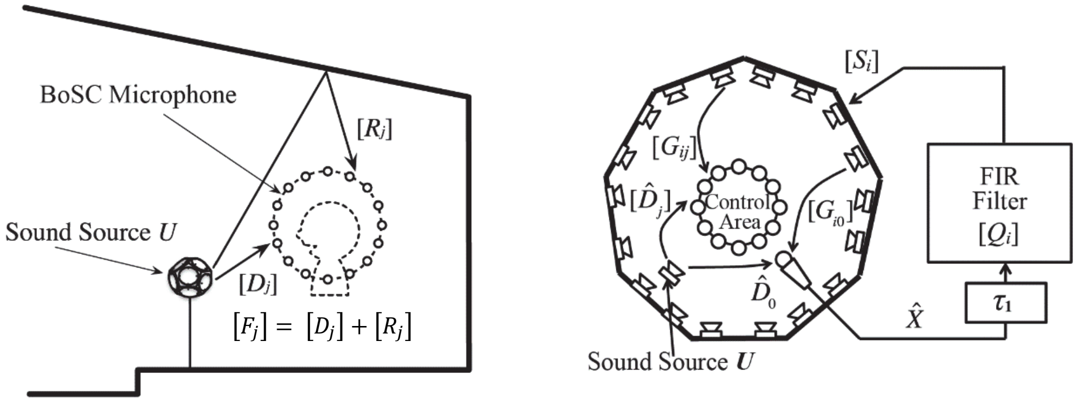


Fig. 3 Impulse response measured in the primary sound field (left) and the structure of the sound field simulator system using the sound cask (right)

From these conditions, the FIR filter $[Q_i]$ is expressed as

$$[Q_i] = \frac{[R_j][G_{ij}]^{-1}}{\hat{D}_0 + [R_j][G_{ij}]^{-1}[G_{i0}]} e^{j\omega\tau_1} \tag{1}$$

where τ_1 is the delay time of real-time computing of the FIR filter $[Q_i]$. Assuming that the microphone for the musical instrument is located near the sound source, we obtain $\hat{D}_0 \gg [R_j][G_{ij}]^{-1}[G_{i0}]$. Furthermore, the transfer function from the source to the microphone for the musical instrument is just the delay τ_2, i.e., $\hat{D}_0 = e^{-j\omega\tau_2}$. Then, the FIR filter $[Q_i]$ is expressed as

$$[Q_i] \cong [R_j][G_{ij}]^{-1} e^{j\omega(\tau_1+\tau_2)}, \tag{2}$$

where $[G_{ij}]$ $(\in C^{N\times M})$ is the transfer function matrix from *i*-th loudspeaker in the reproduced sound field to *j*-th microphone on the surface S'.

By considering the causality of the inverse system, we need to assume the delay time τ_h caused by the inverse system. Instead, the reflective sound $[R_j]$ can be shifted τ_r earlier, i.e., $[R'_j] = [R_j]e^{j\omega\tau_r}$. Therefore, actual FIR system $[Q'_i]$ is given as

$$[Q'_i] = [R'_j][H_{ji}] = [R_j][G_{ij}]^{-1} e^{j\omega(\tau_r-\tau_h)}, \tag{3}$$

where $[H_{ji}]$ ($\in C^{M\times N}$) is the inverse system of the transfer function $[G_{ij}]$ considering the causality mentioned above. $[Q_i] = [Q'_i]$ in eq.(2) and eq.(3) holds when $\tau_1 + \tau_2 = \tau_r - \tau_h$.

3.2 Experimental system

For the primary sound field, impulse responses were measured in three concert halls, the parameters of which are given in Table 1. The inverse filter $[H_{ji}]$ was calculated in the frequency domain, the conditions of which are given in Table 2. Figure 4 shows the experimental setup of the sound field simulator. The microphone for the musical instrument (H = 1.45 m) was a small omnidirectional microphone (DPA-4060) located on a wall inside the sound cask. Another omnidirectional microphone (H = 1.2 m) located at the center of the sound cask and the dodecahedral loudspeaker source (Brüel & Kjaer Type 4292, H = 0.9 m) were set in a manner identical to that used to measure the acoustics in real concert halls. The distance between the center of the sound source and the microphone was approximately 0.4 m, then we assume τ_2 =0. We used a Desktop PC to calculate the real-time convolution of the FIR filter, the delay time of which is τ_1 =11ms. The sampling frequency of all the signals was 48 kHz.

Table 1: Concert halls measured as the primary sound field

Hall	Seats	Volume [m^3]	Reverberation time [s]*	
			Stage	Audience area
A	492	4,500	1.2	1.4
B	1,192	9,500	1.2	1.5
C	1,871	17,445	1.8	2.1

*Measured value for 2 octave band of 500 and 1 kHz

Table 2: Calculation condition of FIR filter $[Q'_i]$

τ_r : Shift time of the reflective component	25 ms
Truncating length of the impulse response $[G_{ij}]$	2048 point
Tap length of the inverse filter $[H_{ji}]$	4096 point
τ_h : Delay time of the inverse filter	14 ms
FFT point to calculate the inverse filter	8192 point

Acoustic feedback occurs in the sound field simulator because of the microphones inside the sound cask. This feedback causes an echo and leads to instability of the system, thereby degrading the accuracy of the reproduced sound field. We suppressed the acoustic feedback by manipulating the inverse system design algorithm, whereby we introduced an additional control point called the "null space", where the sum of all signals from the loudspeakers is equal to zero. Figure 5 shows the results of an octave band analysis of the musical signal at the reference microphone. By using the inverse filter that creates the null space, the sound pressure level can be suppressed over all ranges of frequency bands. Specifically, the suppression level of the center frequency of 500 Hz is about 30 dB between the signals measured with and without the null space. However, the suppression level is lower in the higher-frequency bands [10].

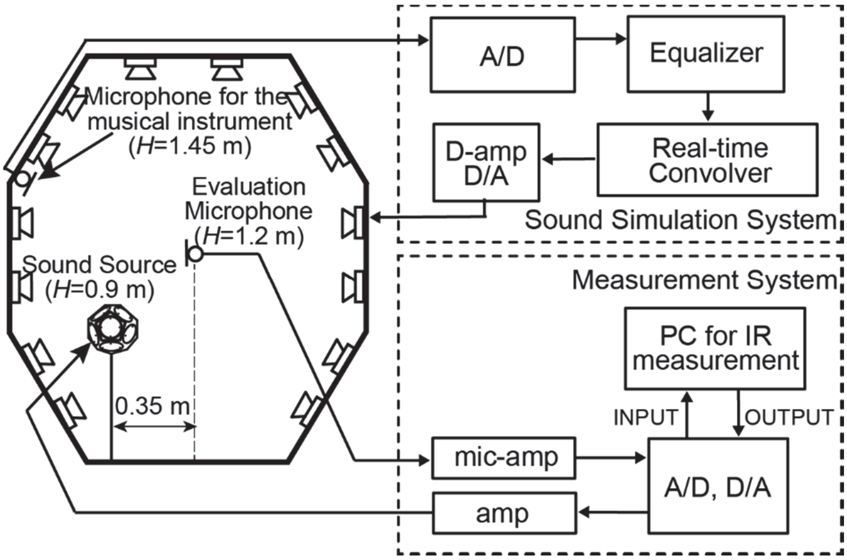
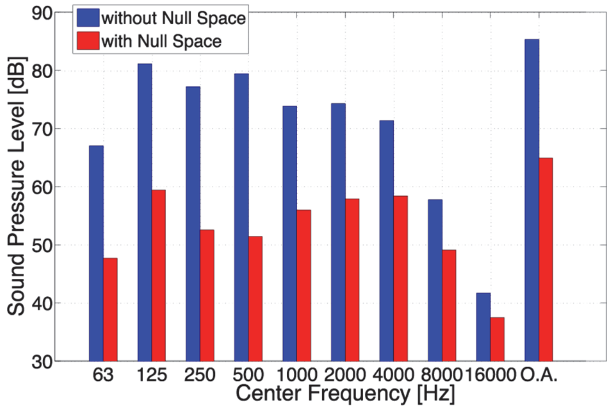


Fig. 4 Experimental setup of the sound field simulator



Source: (Kohno, 2015, [10])

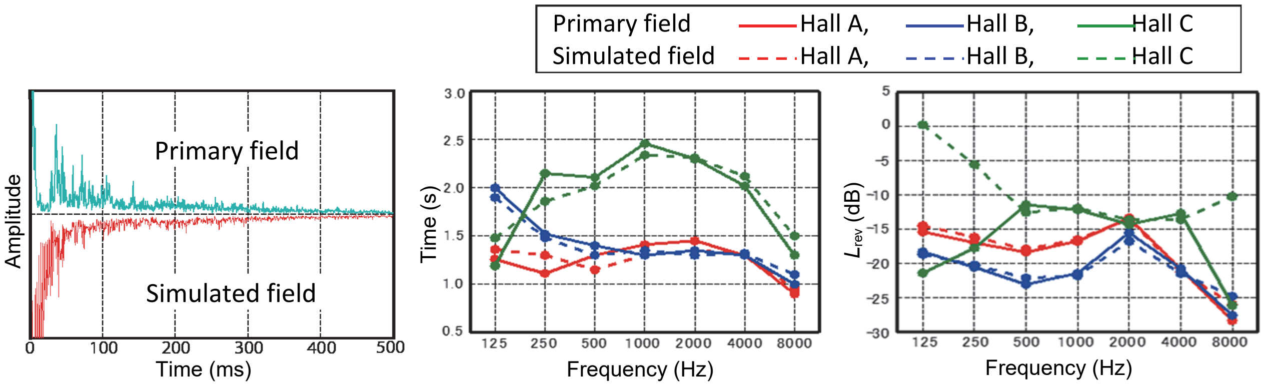
Fig. 5 The effect of feedback cancellation

In designing the sound field simulator, the frequency characteristic of the microphone for the musical instrument is not flat because of the frequency characteristic inside the sound cask. To improve the performance of the sound field simulator, an equalizer was installed to correct the frequency response of the instrumental microphone input.

3.3 Acoustical properties of the simulated sound field

To realize the actual strength of the reverberation at the position of the performer, we adjusted the relative level of the reverberation reproduced by the 96 loudspeakers to the direct sound. The reverberation time and the reverberation energy L_{rev} in the frequencies of each octave band were calculated from the impulse response measured in the sound field simulator. In these calculations, the direct sound energy of the impulse response is calculated from the energy within the time span between the arrival time of the direct sound and 10 ms later. The reverberation energy is calculated as the proportion of energy after 100 ms to the direct sound energy. Figure 6 compares the primary field with the simulated field for Hall A in an echo diagram [Fig. 6(a)], with respect to reverberation time [Fig. 6(b)], and with respect to reverberation energy [Fig. 6(c)]. The solid lines in Figs. 6(b) and (c) indicate the primary fields (actual concert halls) and dashed lines indicate the simulated fields.

Figure 6(a) shows that there were strong reflections from the floor and reflective surfaces of the loudspeakers up to 30 ms in the simulated sound field. The results in Figs. 6(b) and (c) show that both the reverberation time and the reverberation energy in the simulated sound field closely correspond to those in the primary field, except for L_{rev} of the low and high frequencies in Hall C where the reverberation was very strong.



(a) Echo diagram (Hall A) **(b) Reverberation time** **(c) L_{rev}**

Fig. 6 Acoustical properties measured in the simulated sound field

4 Subjective experiment by professional musicians

4.1 Procedure

To obtain the auditory impressions of musicians on the naturalness and presence (reality) of the sound field, we had ten professional musicians (four flutes, one clarinet, one oboe, one trumpet, two violins, and one violoncello) participate in a performance experiment. In addition, we tested one flute fabricator. To check the sound of the virtual stage, a subject sat at the center of the simulated sound field (Fig. 7) and played his/her instrument as a free test performance and then played a predetermined phrase within 1 min. After the performance of each test for each hall condition, the experimenter opened the sound cask door and asked the subject to give his/her auditory impression.

4.2 Results and discussion

Table 3 presents examples of comments made by a flute player and a violin player. They described each hall condition using various viewpoints such as auditory perception of space, reverberation properties, sound propagation characteristics, and preference for performance.

All subjects were able to distinguish the three stage conditions and reported the auditory impression of each condition on the sound of the instrument, reverberation, and in which hall they preferred to perform. Figure 8 shows the number of subjects who chose each condition as the best and the worst in which to perform; the opinions of the subjects were divided. The subjects gave negative comments about reverberation in the nonpreferred conditions, such as “the reverberation is artificial as in the recording studio” and “I cannot form the spatial image in my mind”. However, all subjects had the impression that the most preferred condition in which to perform was real and natural, as if they were playing on the stage in a real concert hall. Musicians evaluated the preferred condition with favorable comments such as “the reverberation is pleasant”, “performance in the reverberation is enjoyable,” and “the sound reaching the audience area can be imaged”.

Fig. 7 Musician in the sound cask during the performance experiment

The players tended to judge the concert halls to be smaller than the actual size of the primary sound field. This may be attributed to the strong reflections observed within the first 30 ms [see Fig. 6(a)]. However, most players commented that “the spatial volume could be felt as in the actual concert hall” in the preferred condition.

After conducting the experiment to evaluate the sound field simulator, we questioned on the opinion of the musicians on the use of the simulation system. Various scenarios such as preconcert rehearsal, sound check in the audience area, recordings, selection of a musical instrument for purchase in a shop, music lessons of the candidates for a professional position, were proposed. Several players pointed out that the system is highly recommendable for a rehearsal room as its reverberation is effective at removing excess strain on the body that naturally occurs in a rehearsal room without reverberation.

Moreover, the recorded sound of the predetermined phrase during the experiment convolved with the impulse responses measured by the BoSC microphone in the audience area of each concert hall was presented to each subject so that he/she could virtually listen to his/her own performance in the audience area. Musicians also expressed great expectation on such application of the sound field simulation system.

Table 3: Example comments by the participants

Hall	Flute player	Violin player
A	Smallest of the three halls. Low-frequency notes are very easy to play.	Reverberation is like that in a church. This hall has about 200 seats. Returned sound is felt artificial.
B	Response from the hall is fast. Large hall with loud returning sound. I can check the played sound with certainty and easily make out nuances. It is the easiest hall in which to perform.	It is felt like the reverberation was around the stage. The hall is relatively large but I cannot get a clear image of it.
C	I feel that the sound is dry around me and reverberates farther away. I cannot check the played sound. It is not easy to perform in this hall. I can easily image the audience area. The sound goes forward.	Middle size or large concert hall. I sensed that the sound was flying forward. I can play without any feeling of strangeness. I prefer the conditions of this hall to perform.

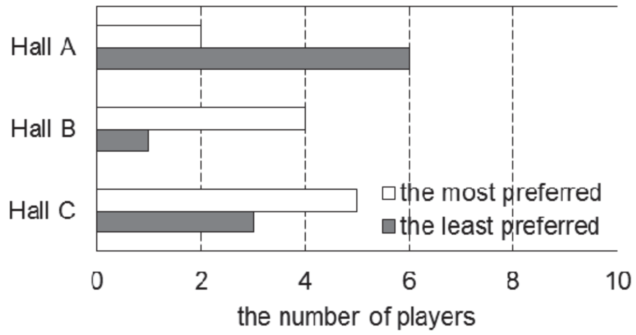


Fig. 8 Preferences of the musicians of the three hall conditions

5 Conclusions

To simulate the 3D sound field on the stage of a concert hall, a sound cask was developed based on the boundary surface control principle and its usefulness to the musician was examined by conducting a subjective assessment experiment. Our study found that the acoustic characteristics of the three stage conditions could be reproduced and differentiated by physical characteristics as well as subjective auditory impression. Although the musicians were split with respect to their preferred condition, all musicians had the sense of acoustic reality of performing on a stage and enjoyed the acoustic effect during performance.

The size of the sound cask allows it to be installed in a normal-sized room. The participants of our subjective experiment showed great enthusiasm for future applications of the stage simulator with the sound cask. In addition, we are developing a sound simulation system for use with an ensemble by acoustically connecting two sound casks. Work will continue on the applicability of the system for musicians.

Acknowledgments

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References

[1] Ueno K.; Tachibana H. Experimental study on the evaluation of stage acoustics by musicians using a 6-channel sound simulation system. *Acoustical Science and Technology*, Vol 24, 2003, pp 130–138.

[2] Rokutanda M.; Kanamori T.; Ueno K.; Tachibana H. A sound field simulation system for the study of ensemble performance on a concert hall stage. *Acoustical Science and Technology*, Vol 25, 2004, pp 373–379.

[3] Ueno K.; Tachibana H. A consideration on acoustic properties on concert-hall stages. *Building Acoustics*, Vol 18(3 and 4), 2011, pp 221–236.

[4] Kato K.; Ueno K.; Kawai K. Effect of room acoustics on musicians' performance. Part II: Acoustic analysis on the variations in performed sound signals. *Acta Acustica united with Acustica*, Vol 101, 2015, pp 743-759.

[5] Omoto A.; Ise S.; Ikeda Y.; Ueno K.; Enomoto S.; Kobayashi M. Sound field reproduction and sharing system based on the boundary surface control principle. *Acoustical Science and Technology*, Vol 36(1), 2015, pp 1–11.

[6] Kobayashi M.; Ueno K.; Ise S. The effects of spatialized sounds on the sense of presence in auditory virtual environments: A psychological and physiological study. *Presence*, Vol 24(2), 2015, pp 163–174.

[7] Tsuchida K.; Ueno K.; Shimada S. Motor area activity for action-related and nonaction-related sounds in a three-dimensional sound field reproduction system. *NeuroReport*, Vol 26(5), 2015, pp 291–295.

[8] Ise, S. A principle of sound field control based on the Kirchhoff-Helmholtz integral equation and the theory of inverse systems. *Acustica*, Vol 85, 1999, pp 78–87.

[9] Watanabe Y.; Yoshida H.; Ikeda Y.; Ise S. Development of a sound-field simulation system based on boundary-surface control principle (in Japanese). *Journal of the Virtual Reality Society of Japan*, Vol 20(1), 2015, pp 45-53.

[10] Kohno S.; Yoshida H.; Ikeda Y.; Watanabe Y.; Ise S. Acoustic feedback canceller for the three-dimensional sound field simulator using a ‘Sound Cask'. *Proceedings of 7th Forum Acusticum* 2014, Krakow, Poland, September 2014, CD-ROM.