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Improvement of the acoustics under the balcony in auditoria using the electro-acoustic method—A study with a full-scale model

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ABSTRACT

In auditoria, the acoustical properties of audience areas located under balconies are regarded as inferior to the main area. This is caused by the reduction of direct and reflected sound energy due to the smaller open area and the reduction of diffusive energy due to the limited acoustical space. In this paper, a new electro-acoustic system is proposed to compensate for this acoustical condition. The proposed system is a non-regenerative system and consists of directional microphones, head amps, a convolver, a matrix processor, amplifiers, and ceiling loudspeakers located under the balcony. The loudspeakers, located at positions corresponding to measurement points across the balcony, recreate the reflecting sound from above the balcony area, which otherwise fail to reach to the listeners under the balcony. The authors have examined the proposed system's performance via two methods: acoustical measurement using a full-scale model and a corresponding psycho-acoustical experiment. The results showed that the energy of the reflections from above the system was the same or more than that without the balcony, and the decay curve with the system was almost the same as that without the balcony. The MUSHRA method was used in the psycho-acoustical experiment, which focused on the evaluation of apparent source width (ASW) and listener envelopment (LEV). The results of the experiment show that the system is significantly better for all tests to the use of no system and that the system is superior to a standard PA (delay system).

1. INTRODUCTION

In the middle of the orchestra floor in the “shoe-box” concert halls, we can enjoy the rich acoustics consisting of sufficient early reflections and reverberation. However, in larger auditoriums, balconies are installed to increase the number of the seats and improve the visibility from the seats to the stage. These balconies disturb the unified acoustics of the hall by dividing the seating area space, creating an acoustically undesirable shape. The effect is strongest on the seats beneath the balcony. These seats are considered to be acoustically inferior. They are often said to "have dull sound at low frequencies," "make the listener feel as if the sound is coming through a window," and "have diminished reverberation." We can assume that the reasons for the inferior acoustics of the seating area below the balcony include the reduction of direct and reflective sound energies caused by the narrower opening to the main area and the reduced diffusive energy caused by the limited acoustical space.

The research of Furuya and others indicates that the experience of "dull sounds at low frequencies" is caused in part by distortions in the direct sound resulting from diffraction waves from the edge of the balcony overhang [1]. Also, measurements from several auditoriums indicate that the feeling that the "sound is coming through a window" is a result of the reduced reverberation energy compared to the main seating area and the remarkably small amount of early reflection energy from above [2]. Furthermore, psycho-acoustical experiments have shown the difference limens of vertical component ratio to total early reflection energy ER_v on auditory envelopment when the ratio of lateral component arriving within 100 ms is constant. Therefore, ER_v can be used effectively as an objective parameter when the peculiarity of directional distribution of early reflections, for example, the lack of early reflections arriving from above under overhangs, should be considered for auditory envelopment [3]. The results of another psycho-acoustical experiments clarified that not only the late lateral sound, but also the late sound from other directions, such as overhead and back, contributes to the sense of listener envelopment (LEV) [4].

At a theater for traditional Japanese performing arts, Ishii and others have successfully used electro-acoustic supplementation of direct sound to improve the acoustics of the area below the balcony. They successfully increased the SPL by 3 dB by installing eight hyper cardioid microphones at the edge of a balcony and feeding them to eight ceiling speakers under the balcony [5].

This paper focuses on improving the acoustics of the area beneath the balcony during musical performances in concert halls. We produced an electro-acoustic system whose purpose is to faithfully reproduce the reflected sounds from above that are blocked by the balcony, thus simulating an acoustic space without a balcony. We created a full scale model of the under-balcony seats with the system, measured its quantitative effects, and tested its efficacy through psycho-acoustical experiments.

2. UBR (UNDER BALCONY REMEDY) SYSTEM

2.1 Concept of UBR system

By faithfully reproducing the reflected sounds from above that are blocked by the balcony, it is assumed that we can supply the early reflection and reverberation energy while masking the distortion of the direct sound and the too early reflection from the ceiling of the balcony, thus realizing an acoustic space equivalent to one without a balcony. Inspired by this conclusion, we created a system that acquires direct sound components from the sound source on the stage and convolves them with revised impulse responses (IR) captured in advance from above the auditorium's balcony to produce sound from distributed loudspeakers on the ceiling beneath the balcony. Figure 1 shows the conceptual image of the system.

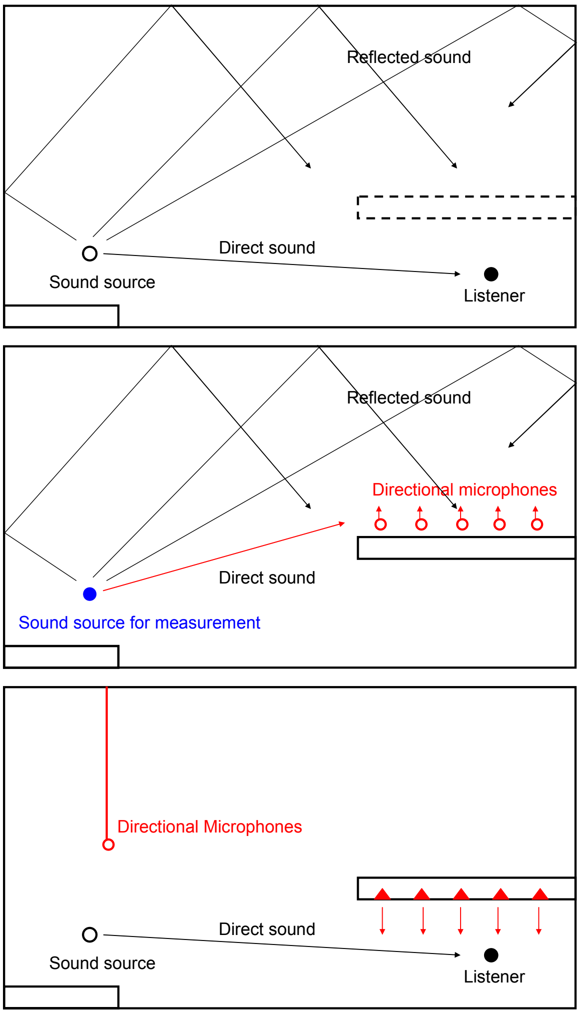

Figure 1. Conceptual image of UBR system

2.2 Design method for the system

This section explains the methods that were used to produce a system based on the concepts above. We used the non-regenerative method, in which the level of feedback from the speakers to the microphone is extremely low [6]. Figure 2 is a simple block diagram of the system. The methods are proceeded as follows.

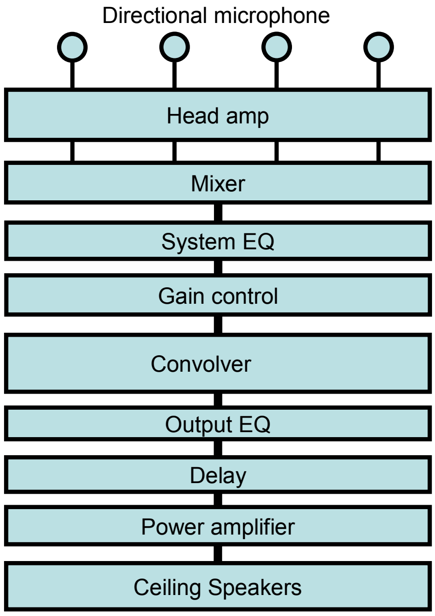

Figure 2. Block diagram of UBR system

1. Locate the sound source for IR measurement in any location on the stage (at the position of a soloist for example).

2. Acquire "upside IRs" stands for IRs arriving from above, used later for convolution in the balcony seats. In practice, this means that cardioid microphones must be located facing upwards at H = 1,200 in positions that correspond to the locations of the speakers beneath the balcony and used to acquire sound from above.

3. Edit the acquired upside IR to eliminate the direct sound, which is called DCU-IR (direct cut upside IR).

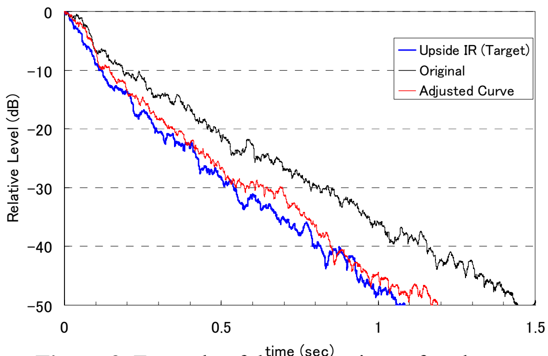

Figure 3. Example of the comparison of each rms curve

4. Calibrate the installation conditions for each speaker beneath the balcony, and adjust and set the delay from the sound source to each speaker location.

5. Use an open loop to acquire the IR between the sound source on the stage and the hung directional microphone installed near the sound source, and convolve it with a representative DCU-IR. When convolving the acquired IR and the DCU-IR, apply an exponential window to the DCU-IR so that the decay is almost the same as that of the upside IR. Diterming how adjust the DCU-IR, use values for the target rms curve that conform to the following equation. Figure 3 is an example of what each of the curves look like. The adjusted DCU-IR will be used for the convolution in the system.

$$Min_{value} = 10\log\sum_{t=0}^{t\max}(X_t - X_{0t})^2$$

X_t: Each level of the adjusted rms curve based on the convolution data with DCU-IR at t (sec)

X_{0t}: Each level of the rms curve of upside IR measuring above the balcony at t (sec)

6. Measure the open loop gain, and adjust the system, so that the total system loop gain is -6 dB or less.

7. Use the gain control to make minor adjustments to the gain so that it matches the sound pressure level in the balcony seats.

3. MEASUREMENTS

3.1 Method of physical experiments

To gain a quantitative grasp of the improvements that result from a system based on the design method explained above, we used a full-scale model. Figure 4 and picture 1 show the configuration of the model. Figure 5 is a block diagram of the system that was used. We used a movable balcony so that we could test the conditions with and without a balcony. To absorb sound, in the area below the balcony, we laid carpet on the floor and used fiberglass (25 mm, 32 kg/m^3) on the back and side walls.

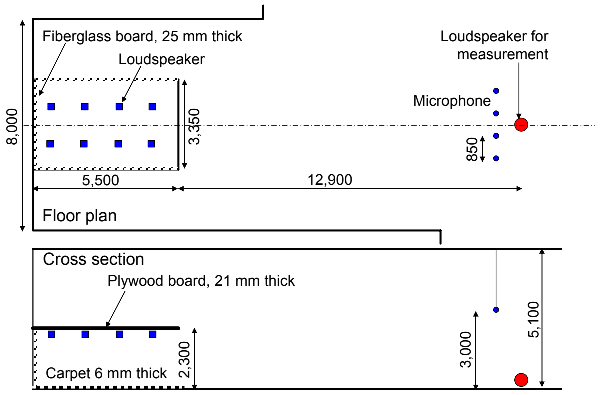

Figure 4. An experimental balcony model

Picture 1. An experimental balcony model

The experiment tested four conditions: the conditions (1) without the balcony, (2) with the balcony but with the system turned off, (3) with the balcony when the delay system is used, and (4) with the balcony when the UBR system is used. The delay system is thought of as a common method for using a PA system to improve the acoustics in the area below the balcony which uses the delay to each loudspeaker to make the reproduced sound arriving later than the direct sound. The total gain of the delay system levels was adjusted with the aim of keeping the total system loop gain at or below -6 dB while making sure that the overall SPL at the measured points were approximately the same as those of the UBR system.

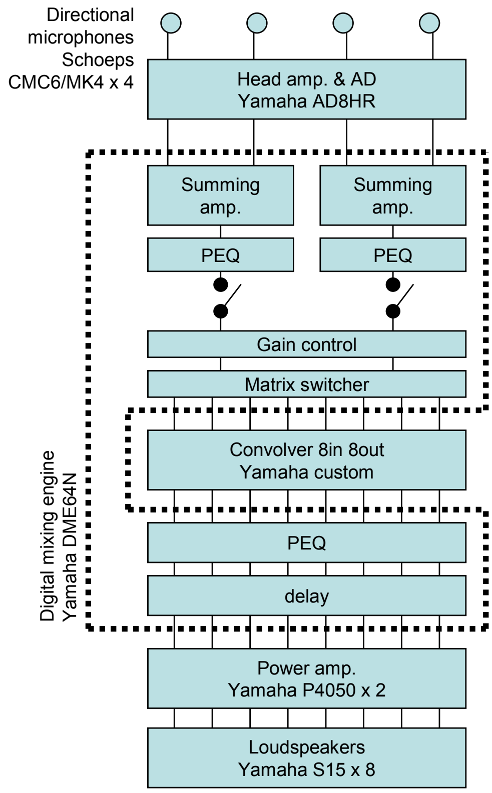

Figure 5. Block diagram of experimental system

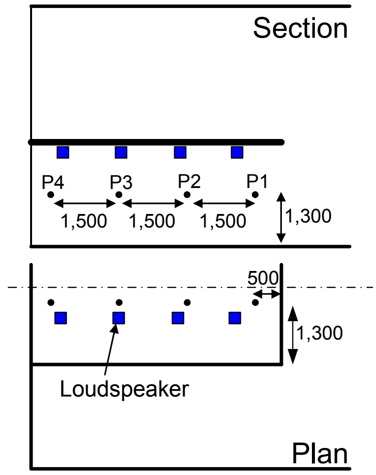

Figure 6. Floor plan and measuring points of the model

Two loudspeakers (Yamaha NS-1000M) facing outward from each other at an angle and tilted backward were placed in the position of the sound source indicated in figure 4, a time-stretched pulse (TSP) signal was reproduced, and the cross spectrum method was used to measure the impulse response at the four points below the balcony indicated in figure 6. The sound was recorded using an omni-directional microphone, a directional microphone pointing up and a dummy head.

From the measured impulse responses, we computed typical indices of room acoustics, such as RT (reverberation time), EDT (early decay time), C_{80} (clarity), Ts (center time) and $IACC_{E3}$ [7]. Next, in order to determine the early reflection energy and the decay curve of reflections arriving from above, we analyzed the early reflected sound levels and rms curve.

3.2 Results and discussion

For each of the tested conditions, table 1 shows the measured results of the typical indices for room acoustics that we used. Compared to the measurements made with no balcony, in the measurements made with a balcony, EDT and Ts are small and C_{80} is larger by approximately 2 dB. The measured values for the delay system are close to the values of the measurements made with a balcony. On the other hand, the measured values for the UBR system are close to the values of the measurements made without a balcony. This is because the delay system is adding direct sound only, whereas the UBR system is also adding early and late reflections. The measured value of RT is 0.13 s longer with the UBR system than it is without a balcony because of the influence of DCU-IR in the 250 Hz band. From these results, we can assume that the UBR system compensates for the loss of reverberation energy caused by the balcony. Regarding the values of $IACC_{E3}$, the values of both systems are close to the value of the measurements made without a balcony, but there is not clear difference between both systems.

Table 1. Acoustical indices measured in the experimental model (Average for 250 Hz to 2 kHz except $IACC_{E3}$).

Condition	RT(s)	EDT(s)	C_{80}(dB)	Ts(ms)	$IACC_{E3}$
Without balcony	1.44	1.24	1.7	95	0.40
With balcony system off	1.44	1.06	3.8	76	0.58
Delay system	1.46	1.02	3.6	81	0.45
UBR system	1.57	1.22	1.5	98	0.46

Figure 7 shows the early reflection energy from above for each of the tested conditions. Both the delay system and the UBR system achieve approximately the same amount of energy as when there is no balcony.

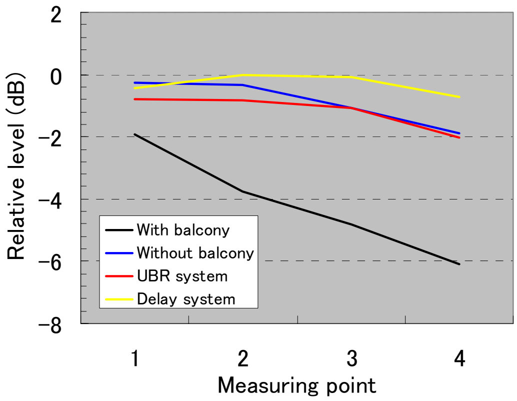

Figure 7. Comparison of early reflection energy from above (0- 100 ms)

Figure 8 shows the rms curves for each of the tested conditions. The decay curve for the UBR system is approximately the same as the curve of the measurements made without a balcony. Also, when compared to the curve for the delay system, the curve for the UBR system shows that the system can control early reflections. These findings match the results of the analysis of the indices of room acoustics. Figure 8 is for P3, but the same tendencies were observed at the other measurement points.

The above results indicate that to create acoustic conditions equivalent to those that exist when there is no balcony, in addition to the supplementation of the direct sound energy from above, early and late reflections from above of the original space is necessary.

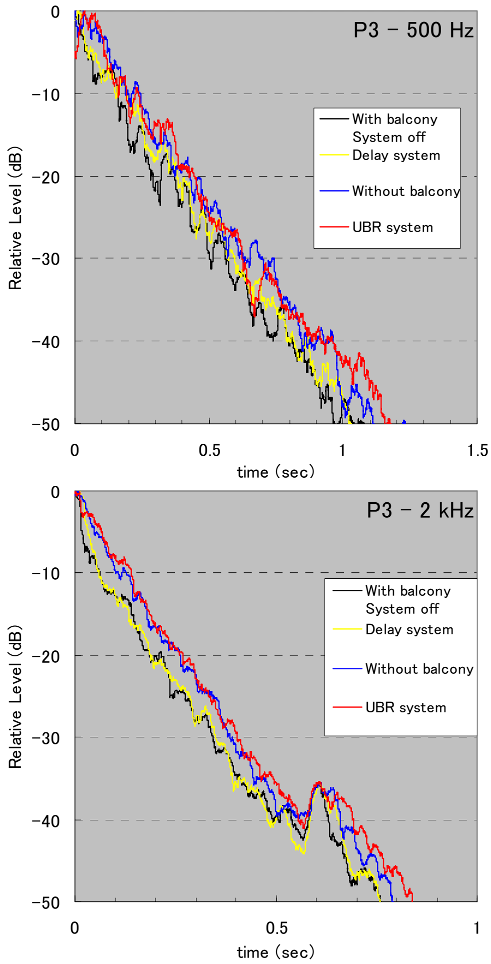

Figure 8. Example of comparison of rms curve captured by cardioid microphone (time const. =25 ms)

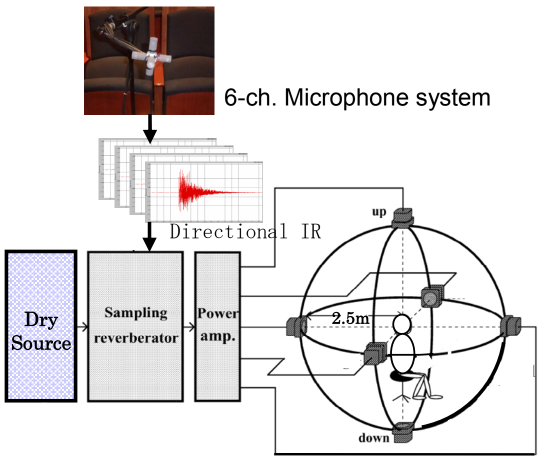

Figure 9. Outline of the 6-channel recording/reproduction system

4. SUBJECTIVE EXPERIMENT

4.1 Method of psycho-acoustical experiment

We performed psycho-acoustical experiments to determine the impact of the system on the listening experience. For each of the tested conditions, at the measurement points in the actual acoustic area (see figure 6), we used groups of six cardioid microphones pointing in the directions of the x, y, and z axes to measure the impulse responses for each direction. We convolved a piano solo as a dry source (Yamaha Original: Prologue) and reproduced each sound field using 6-channel recording/reproduction system for 3-dimensional auralization of sound fields [8]. The testing system is shown in figure 9.

The method that we used in the experiment was the MUSHRA (multi stimulus test with hidden reference and anchor) subjective test method, which is recommended an appropriate method for evaluations of intermediate audio quality in International Telecommunication Union [9]. Subjects rate multiple stimuli on a 101-step scale from 0 (poor) to 100 (excellent) at the same time. We chose to use this method because it is very useful for comparing relationships between different conditions. The subjects were nine male spatial acoustic engineers ranging from 20 to 50 years of age. We used the four tested conditions at each measurement point as stimuli. To determine how the reflected sounds from above affect the spaciousness during a musical performance, we had the subjects evaluate the apparent source width (ASW) and LEV.

4.2 Results and discussion

Figure 10 and 11 are shown the mean and 95% confidence interval of the statistical distribution of the assessment grades. If the confidence intervals of two tested conditions overlap at all, it means that there is a 95% chance that there is no meaningful difference between the two conditions. The results show that for both ASW and LEV, the conditions when the UBR system is used are meaningfully different from the conditions when there is a balcony and the system is off. While the conditions without a balcony received a rating of "Excellent," the conditions when the UBR system was used were rated as "Good."

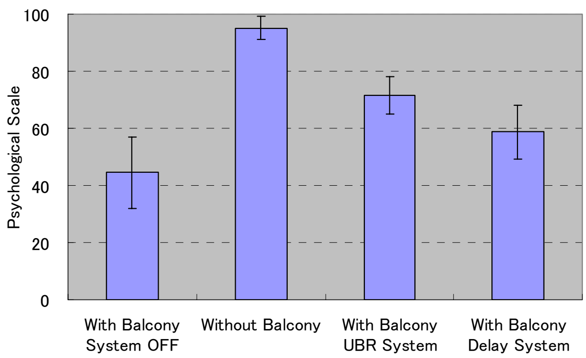

Figure 10. Listening test result of each condition on ASW

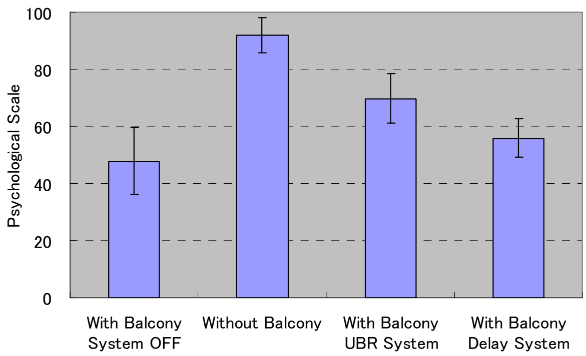

Figure 11. Listening test result of each condition on LEV

The above psycho-acoustical results also indicate that to create acoustic conditions equivalent to those that exist when there is no balcony, in addition to the supplementation of the direct sound energy from above, early and late reflections from above of the original space is necessary.

5. CONCLUSION

With the goal of improving the acoustics of the area beneath the balcony during musical performances in concert halls, we used an electro-acoustic system (UBR system) for simulating an acoustic space without a balcony. The goal of the system was to faithfully reproduce the reflected sounds from above that are blocked by the balcony. After creating a full scale model of the system, we measured the system's quantitative effects—and also measured the results of using a common PA system to improve the acoustics (delay system)—and tested the system's efficiency through psycho-acoustical experiments.

The main indices of room acoustics show that the physical characteristics achieved using the UBR system are close to those achieved without a balcony. This serves as a quantitative indication that the system compensates for the loss of reverberation energy caused by the balcony. Also, the IR analysis results show that the UBR system achieves approximately the same amount of early reflection energy from above as when there is no balcony, while also achieving a decay curve that is equivalent to that achieved when there is no balcony. Comparison with the delay system indicates that to create acoustic conditions equivalent to those that exist when there is no balcony, in addition to the supplementation of the direct sound energy from above, early and late reflections from above of the original space is necessary.

The MUSHRA method was used in the psycho-acoustical experiment, which focused on the evaluation of ASW and LEV. The results of the experiment show that the UBR system is meaningfully superior for all measures to the use of no system at all and that the UBR system is superior to the delay system.

ACKNOWLEDGEMENT

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