J. Acoust. Soc. Jpn. (*E*) **16**, 2 (1995)

Some further consideration on auralization of a sound field based on a binaural signal processing model

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(*Received 19 July 1994*)

The authors have indicated the possibility of auralization for a sound field consisting of only discrete reflections based on the running interaural cross-correlation (RCC) model, which is regarded as one of the mechanisms in binaural signal processing. In this paper, further experiments were performed to apply the RCC method to the auralization of a sound field which includes non-discrete reflections of 2 s long, such as a concert hall. The results show that the sound image perceived in the simulated sound field by the RCC method using 10 ms long temporal window with the inner ear mechanism is indistinguishable from the perceived one in the original sound field which is used in this paper. Moreover, all reflections of the impulse response must be reproduced for an auralization of a sound field which includes non-discrete (reverberant) reflections, though all reflections are not necessarily reproduced for the sound field which consists of only discrete reflections.

Keywords: Auralization, Sound field simulation, Running interaural cross correlation, Binaural signal processing, Concert hall acoustics

PACS number: 43. 55. Fw, 43. 55. Hy, 43. 55. Ka, 43. 66. Ba, 43. 66. Pn

1. INTRODUCTION

Auralization of a sound field is a useful technique in the acoustical design of conert halls. Auralization makes it possible to produce a sound image of an existing concert hall and a concert hall in the planning stage. Over the past few decades a lot of studies have been made on auralization. They can be divided into two types:

(1) auralization based on the simulation of room impulse response, and (2) auralization based on the simulation of binuaural impouse response.

The target of the first type is to simulate the transfer function from a sound source to a listening point in an original sound field.[1] Meyer *et al.*[2] reported an auralization system with 65 loudspeakers, which enclose the upper hemisphere of an anechoic chamber. Kleiner *et al.*[3] also reported a system with 50 loudspeakers. In this type of auralization, the time delay, the amplitude and the direction of each reflection of the simulated sound field must be physically equal to the original one, as a rule. It is possible to obtain these information of the early discrete reflections,[4] but not practicable to obtain in the subsequent reverberant part.

The target of the second type is to simulate the transfer functions from a sound source to both ear entrances of a listener.[5,6] TRADIS (True Reprodution of All Directional Information by Stereophony),[7] OSS (OrthoStereophonic System),[8] Partition-stereophony[9] and the binaural simulation[10] are well known examples of this type of auralization. However, the accuracy of these auralizations is not always enough. The difference in the head-related transfer function between a listener's head and a dummy-head often causes the

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inner-head localization and the incorrect sound localization in the median plane.[6)]

Here, let us consider the purpose of auralization. The purpose of auralization is to make a listener perceive the same characteristics of the sound image as those of a sound image which he perceives in an original sound field. Namely, the auralization is considered to be achieved if the characteristics of the sound image perceived in the simulated sound field are the same as those perceived in the original sound field, even if the simulated sound field is not physically equal to the original one.

The previous paper[11)] investigated the possibility of a new method of auralization of a sound field. The method simulates the output of the binaural signal processing mechanism, instead of simulating the room impulse response or the binaural impuse response. The method is based on the running interaural cross-correlation (RCC) model,[12-16)] which is regarded as a mechanism of spatial hearing, because the main target of auralization is to simulate the spatial attributes of sound images. Basic experiments of dissimilarity judgment and some subjective evaluation concerning sound image were carried out between an original sound field, which consists of only 67 discrete reflections of 200 ms long, and simulated ones with different durations of temporal window. The results infer the following. First, there is a possibility of simulating almost the same characteristics of sound image as those of perceived in an original sound field by the RCC method. Using the RCC method, the necessary reflections for the auralization is significantly less than reflections included in the original sound field. Secondly, there is an appropriate temporal window (shape, duration, and so on) for the auralization by the RCC method. An appropriate duration of the rectangular temporal window is 10 ms in calculating the RCC.

In this paper, some further consideration is made in order to apply the RCC method to the auralization of a sound field which includes non-discrete (reverberant) reflections of 2 s long, such as a concert hall.

2. PRINCIPLE OF AURALIZATION BASED ON RUNNING INTERAURAL CROSS-CORRELATION MODEL

It is necessary to determine the time delay, the amplitude, and the direction of each reflection in order to simulate a sound field. The RCC method is applied to determine the azimuth angle of the incident wave.

A lot of models of binaural signal processing have been reported. Jeffress,[12)] Licklider,[13)] and Sayers and Cherry[14)] built up a hypothesis that the hearing mechanism utilizes the running interaural cross correlation of incident sounds of the ears, and they suggested a binaural signal processing model. Blauert and Cobben[15)] developed the model further by adding the mechanism of the inner ear, which could explain the lateralization. Furthermore, Lindemann[16)] proposed an extension of the model with the mechanism of contralateral inhibition, which gave a good account of the law of the first wave front. In this paper, the auralization based on the running interaural cross-correlation (RCC) model that is composed of the outer ear model, the inner ear model, and the running interaural cross correlation mechanism, as shown in Fig. 1, is investigated.

The procedure of the RCC method is as follows. First, impulse responses from a sound source to both entrances of the ear canals in an original sound field, $h_l(\xi)$ and $h_r(\xi)$ are obtained by measurement with a dummy head or by calculation (for instance, the image method). Then, $h_l'(\xi)$ and $h_r'(\xi)$ which are affected by the inner ear signal processing are obtained.

Next, the normalized RCC function $\phi_{lr}(t, \tau)$ is calculated by Eq. (1).

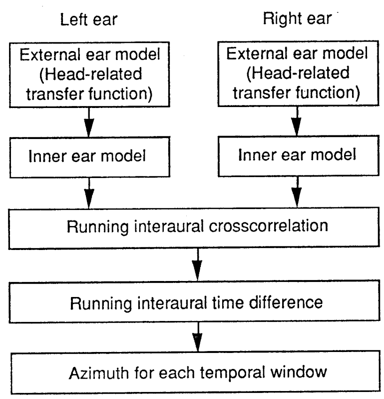

Fig. 1 Binaural signal processing model for auralization of a sound field by the RCC method.

$$\phi_{lr}(t,\tau) = \frac{\int_{-\infty}^{t} h_l'(\xi)h_r'(\xi-\tau)G(\xi)d\xi}{\left[\int_{-\infty}^{t} h_l'^2(\xi)d\xi \int_{-\infty}^{t} h_r'^2(\xi)d\xi\right]^{1/2}\left[\int_{-\infty}^{t} G^2(\xi)d\xi\right]^{1/2}} \tag{1}$$

where τ is a time lag between the left and right ear; $|\tau| \leq$ maximum interaural time difference; $G(\xi)$ is a temporal window.

Then, the interaural time difference for a temporal window at t, $RTD(t)$ is obtained by Eq. (2).

$$RTD(t)=\tau \quad \text{for} \quad |\phi_{lr}(t,\tau)|_{\max} \tag{2}$$

The running azimuth angle of the incident wave $\psi(t)$ is obtained from Eq. (3).[17]

$$\psi(t)+\sin\psi(t)=2C\times RTD(t)/D \tag{3}$$

where C is the speed of sound, and D is the distance between both ears.

3. TECHNICAL PROBLEMS TO BE SOLVED FOR PRACTICAL APPLICATION OF THE RCC METHOD

For putting the auralization by the RCC method to practical use in the acoustical design of concert halls, the following problems must be solved; the possibility of simplification of impulse response of the original sound field, the duration of the temporal window $G(\xi)$ in Eq. (1), and the effect of inner ear mechanism on the accuracy of the auralization.

In the previous paper,[11] it was clarified that the sound image of the original sound field which consists of only 67 discrete reflections of 200 ms long could almost be simulated by deriving only one reflection from each temporal window, that is named the impulse response simplified method, and that the proper duration of the temporal window was 10 ms in calculating the RCC.

In this paper, the three problems mentioned above are investigated for the original sound field which includes non-discrete reflections of 2 s long. In Experiment I, the difference in the accuracy of auralization between the impulse response simplified method and the impulse response not simplified method which reproduces all reflections in each temporal window is investigated. In Experiment II, the proper duration of the temporal window in calculating the RCC is investigated. Furthermore, in Experiment III, the effect of the mechanism of the inner ear in calculating the RCC on the accuracy of the auralization is investigated.

In this paper, the shape of temporal window $G(\xi)$ is set rectangular as shown in Eq. (4), and the adjacent temporal windows do not overlap each other but are in contact with each other, to first approximation.

$$G(\xi)=\begin{cases}1 & \text{for} \quad t-DTW\leq\xi\leq t\\ 0 & \text{otherwise}\end{cases} \tag{4}$$

where DTW is the duration of the temporal window.

4. PSYCHOLOGICAL EXPERIMENTS

Three psychological experiments were performed to clarify the problems mentioned above. The music motif used in the experiments was a 7 s section of Saint-Saens's Introduction et Rondo Capriccioso for violin, bars 4–6, recorded in an anechoic chamber. This motif is the same one as used in the previous paper.[11]

4.1 Experiment I

In the previous paper,[11] it was clarified that the sound image of the original sound field, which consists of only discrete reflections, could almost be simulated by deriving only one reflection from each temporal window (the impulse response simplified method). The purpose of Experiment I is to investigate the difference in the accuracy of auralization between the impulse response simplified method and the impulse response not simplified method which reproduces all reflections in each temporal window.

4.1.1 Method

The dissimilarity between the original sound field and the simulated one was investigated using Kruscal's multidimensional scaling.

A. Original sound field

There exists no standard original sound field which is enough to judge whether or not, a method can be applied for an arbitrary sound field. Anyone could not decide the standard original sound field

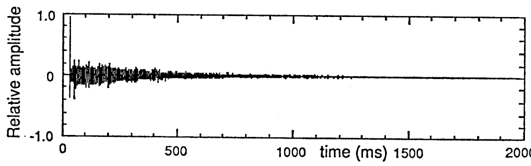

Fig. 2 Impulse response of an original sound field.

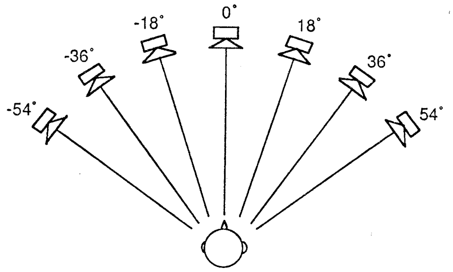

Fig. 3 Loudspeaker arrangement of an original sound field.

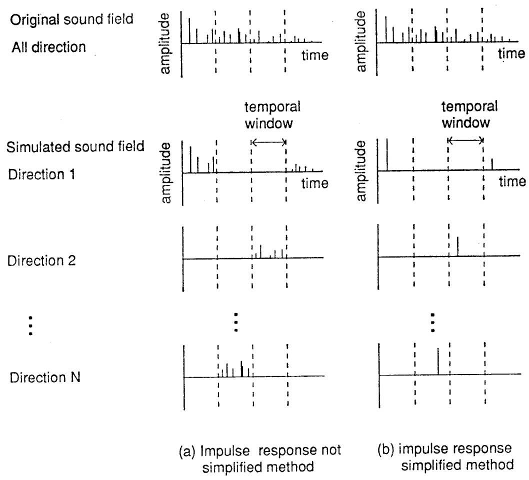

Fig. 4 Schematic diagram of two methods of creating directional impulse responses of simulated sound field. (a), the impulse response not simplified method; (b), the impulse response simplified method.

with scientific justification. In this paper, the impulse response measured in Vienna Musikvereinssaal was chosen as that of the original sound field. Figure 2 shows the impulse response of the original sound field. It includes non-discrete reflections of 2 s long. They were emitted from seven loudspeakers which were placed at the azimuth angles of 0°, ±18°, ±36°, ±54° from the median plane, as shown in Fig. 3. The incident azimuth of the direct sound was 0° from the median plane. Since the purpose of this paper is to clarify the possibility of the auralization of a diffused sound field, such as a concert hall, the incident waves should come from different directions at random. Therefore, each sample of the impulse response of the original sound field, which was sampled at the rate of 25 kHz and quantized with 16 bit resolution, was divided at random into seven directions.

B. Simulated sound fields

The impulse response of the original sound field was measured with a dummy-head (KEMAR) in an anechoic chamber, and then the running azimuth angle for each temporal window was calculated, as mentioned in chapter 2. The temporal window $G(\xi)$ was set rectangular, and the adjacent temporal windows did not overlap each other but were in contact with each other. In this experiment, the mechanism of the inner ear is practically approximated by a low-pass filter with a cut off frequency of 1,600 Hz.[18,19]

Figure 4 shows a schematic diagram of the two methods for creating directional impulse responses of a simulated sound field. In the impulse response simplified method, one reflection of the simulated sound field is derived from each temporal window. The incident azimuth of a reflection was decided by the RCC method. The time delay of the reflection is the time when the amplitude is maximum in the temporal window. The sound pressure level for a temporal window is obtained by the summation of energy within the temporal window. On the other hand, for the impulse response not simplified method, all reflections of the temporal window were derived for the simulated sound field. The incident angle for each temporal window was decided by the RCC method. Therefore, the incident azimuth of all reflections in a temporal window are identical.

Table 1 shows the eight kinds of simulated sound field used in this experiment. Four of the sound fields were created by the impulse response simplified

Table 1 Eight kinds of simulated sound field used in Experiment I.

Method	Not simplified				Simplified			
Name of simulated sound field	P2	P5	P10	P20	S2	S5	S10	S20
Duration of temporal window (ms)	2	5	10	20	2	5	10	20

Table 2 Categories for dissimilarity judgement.

Two sound images are
1: not different
2: a little different
3: different
4: fairly different
5: extremely different

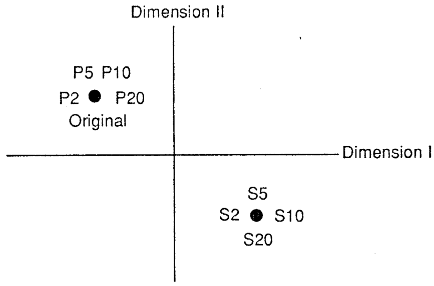

Fig. 5 Two dimensional configuration of an original sound field and eight simulated sound fields.

method. These sound fields were named S2, S5, S10, and S20. The other four sound fields were created by the impulse response not simplified method. They were named P2, P5, P10, and P20. The numeric represents the duration of the temporal window.

C. Procedure

Nine stimuli were created by convolution of the impulse responses of nine sound fields (an original sound field and eight simulated ones) and the music motif. The thirty-six pairs of nine stimuli and the additional nine pairs of the identical stimulus were presented to the subjects. In total, forty-five pairs were presented to the subjects. The task of the subjects was to judge the degree of dissimilarity of each pair, concerning sound images on a five-point scale as shown in Table 2. The interval between two stimuli was 1 s. All pairs of stimuli were arranged, followed by an interval of 4 s, in random order. The binaural sound pressure levels[20] of all sound fields were constant at 82.7 ± 0.3 dBA slow peak.

Each subject was tested individually, while seated, with his head fixed in an anechoic chamber. A spot light was used, such that it provided just enough lighting for the subjects to mark their judgment on the answer sheet. The subjects judged the dissimilarity of five particular pairs of sound fields (original-original, original-S10, original-P10, original-P20, and original-S20) as a practice before the experiment. Each subject judged the degree of dissimilarity twice for each pair.

D. Subject

Eleven persons, 21 to 28 years of age with normal hearing sensitivity acted as subjects in the experiment.

4.1.2 Results and discussion

The subjects' dissimilarity judgments which satified the following conditions were adopted in the analysis. (1) The average dissimilarity judgment on the pair of identical stimulus is less than 2 (a little different) on a five-point scale in Table 2. (2) The correlation coefficient between the first judgments and the second one for the identical pairs is more than 0.7.[21] (3) The correlation coefficient between the judgments of any two subjects is more than 0.7.[21] Since all subjects' dissimilarity judgments satisfied these conditions, they were averaged and analyzed by Kruskal's multidimensional scaling.[22,23] The stress for two-dimensional configuration was 0.0%. Figure 5 shows the two-dimensional configuration of the nine sound fields. The result shows that simulated sound fields fall into two clusters. This means a devoluted solution in Kruscal's analysis. After the experiment, the subjects reported that they perceived the difference between two clusters in tone color. The original sound field belongs to the cluter that includes the sound fields simulated by the impulse response not simplified method. In conclusion, the impulse response should not be simplified to simulate not only the spatial characteristics of the sound image but also the qualitative characteristics like the tone color which are perceived in the original sound field including non-discrete reflections.

4.2 Experiment II

In the previous paper,[11] it was clarified that the proper duration of the temporal window was 10 ms in calculating the RCC for the auralization of the sound field which consists of only discrete reflections. The purpose of Experiment II is to investigate the proper duration of the temporal window for the auralization of the sound field which includes non-discrete reflections.

4.2.1 Method

The dissimilarity between the original sound field and the simulated one was investigated using Kruscal's multidimensional scaling.

A. Original sound field

The same original sound field as Experiment I was used.

B. Simulated sound fields

Simulated sound fields were created by the impulse response not simplified method with the inner ear mechanism, according to the results of Experiment I. Table 3 shows four kinds of simulated sound field used in this experiment. These sound fields were named P2, P5, P10, and P20. The numeric represents the duration of the temporal window.

C. Procedure

Five stimuli were created by convolution of the impulse response of five sound fields (an original sound field and four simulated ones) and the music motif. Twenty pairs of the five stimuli, including reversals of stimuli, and the additional five pairs of the identical stimulus were presented to the subjects. In total, twenty-five pairs were presented to the subjects. The task of the subjects was to judge the degree of dissimilarity of each pair, concerning sound images on a five-point scale as shown in Table 2. The interval between two stimuli was 1 s. All pairs of stimuli were arranged, followed by an interval of 4 s, in random order. The binaural sound pressure levels[20] of all sound fields were constant at 82.7 ± 0.3 dBA slow peak.

Each subject was tested individually, while seated, with his head fixed in an anechoic chamber. A spot light was used, such that it provided just enough lighting for the subjects to mark their judgment on the answer sheet. The subjects judged the dissimilarity of three particular pairs of sound fields (original-original, original-P10, and original-P20) as a practice before the experiment. Each subject judged the degree of dissimilarity twice for each pair.

Table 3 Four kinds of simulated sound field used in Experiment II.

Method	Impulse response not simplified			
Name of simulated sound field	P2	P5	P10	P20
Duration of temporal window (ms)	2	5	10	20

D. Subject

Twenty-three students, 18 to 25 years of age with normal hearing sensitivity aceted as subjects in the experiment.

4.2.2 Results and discussion

No subjects' judgment satisfied the criteria (2) and (3) noted in Experiment I. However, three subjects' dissimilarity judgments satisfied the three criteria, under the condition that the correlation coefficient is more than 0.62 ($p < 0.05$) for criteria (2) and (3). Then, they were averaged and analyzed by Kruskal's multidimensional scaling. The stress for one-dimensional configuration was 0.0%.

Figure 6 shows the one-dimensional configuration of the five sound fields. It shows that the simulated sound fields using 2 ms and 10 ms long temporal windows are more similar to the original sound field than those using 5 ms and 20 ms long temporal windows. In the previous paper,[11] it was clarified that the simulated sound field using the 10 ms long temporal window is the most similar to the original sound field. Moreover, Moore *et al.*[24] proposed 8 ms as the duration of the rectangular temporal window, in regard to temporal masking. Therefore, it is reasonable to conclude that 10 ms is proper as the duration of temporal window, from the standpoint of the auditory mechanism.

4.3 Experiment III

The purpose of this experiment is to clarify the effect of the mechanism of the inner ear in calculating the RCC on the accuracy of the auralization.

4.3.1 Method

The psychological distance between the original sound field and the simulated one was investigated using the method of complete triads.[25]

A. Original sound field

The same original sound field as Experiment I was used.

B. Simulated sound fields

Simulated sound fields were created by the impulse response not simplified method, according to the results of Experiment I. Table 4 shows the two

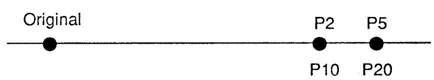

Fig. 6 Configuration of an original sound field and four simulated sound fields.

Table 4 Two kinds of simulated sound field used in Experiment III.

Method	with inner ear mechanism	without inner ear mechanism
Name of simulated sound field	P10	N10
Duration of temporal window (ms)	10	10
Simplification of impulse response	Not simplified	Not simplified

kinds of simulated sound field used in this experiment. These sound fields were named P10, and N10. P denotes the simulated sound field with the mechanism of the inner ear, which is practically approximated by a low-pass filter with a cut off frequency of 1,600 Hz. N indicates the simulated sound field not taking account of the mechanism of the inner ear in calculating the RCC. The numeric represents the duration of the temporal window.

C. Procedure

Three stimuli were created by convolution of the impulse responses of three sound fields (an original sound field and two simulated ones) and the music motif. Six triads of three different stimuli were presented to the subjects based on the method of complete triads.

The task of the subject was to choose which sound image most resembles that of the second stimulus, the first stimulus or the third one. The interval between stimuli in each triad was 1 s. All triads of stimuli were arranged, followed by an interval of 4 s, in random order. The binaural sound pressure levels[20] of all sound fields were constant at 82.7 ± 0.3 dBA slow peak.

Each subject was tested individually, while seated, with his head fixed in an anechoic chamber. Each subject judged forty times for each complete triad.

D. Subject

Five male students, 22 to 23 years of age with normal hearing sensitivity acted as subjects in the experiment.

4.3.2 Results and discussion

Table 5 indicates the psychological distance between three stimuli, which was obtained using the method of complete triads. After the experiment, the subjects reported the characteristics of the sound image which they noticed in their judgments. According to their reports, they can be divided into two groups. Namely, two subjects noticed the spatial characteristics (group I), while three subjects noticed the tone color (group II). It can be considered that the subjects of group I can discriminate between the original sound field and sound field N10 and between sound field P10 and N10, because these psychological distances exceed 0.68 which corresponds to the just noticeable difference. On the other hand, subjects of group II cannot discriminate between them because these distances do not exceed 0.68. These results conclude that the low pass filter is not necessary in calculating the RCC to simulate the qualitative characteristics of the sound image like tone color, but it is necessary to simulate the spatial characteristics, and that the RCC method using 10 ms long temporal window with the inner ear mechanism can simulate the sound image which is indistinguishable from the perceived one in the original sound field.

Table 5 Psychological distance between three sound fields.

	Between sound fields		
	Original-P10	Original-N10	P10-N10
Group I	0.05	0.87	0.82
Group II	0.51	0.42	0.09

5. CONCLUSIONS

The authors have proposed a method of auralization of a sound field based on the RCC. In the previous paper, it was clarified that the sound image of the original sound field which consists of only 67 discrete reflections of 200 ms long could almost be simulated by the RCC method. In this paper, three psychological experiments were carried out in order to clarify the technical problems for the auralization of a sound field which includes non-discrete (reverberant) reflections of 2 s long. The results shows:

(1) The impulse response should not be simplified. Therefore, all reflections of the impulse response must be reproduced. This differs from the result obtained for the original sound field consists of only discrete reflections.

(2) The proper duration of the temporal window calculating the RCC is 10 ms.

(3) The low-pass filter which approximates the mechanism of the inner ear should be considered in calculating the RCC.

(4) The sound image perceived in the simulated sound field by the RCC method using 10 ms long temporal window with the inner ear mechanism is indistinguishable from the perceived one in the original sound field which is used in this paper.

There, of course, still remain technical problems to be solved in practical application. In principle, for instance, though the RCC method can estimate the azimuth angle of the sound wave, it cannot distinguish between front and back directions of the sound wave nor can estimate its elevation angle.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. H. Iguchi for his cooperation in the experiments.

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