Method of acoustical estimation of an auditorium

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The impulse response calculation of the early reflection in an auditorium has been established, accordingly its transfer function. A rectangular pulse of 0.05ms from a loudspeaker was obtained to give it an inverse filter. The linear response of human hearing system was measured in the form of impulse response. When a positive and a negative pulse were given from the opposite direction, they were heard on loudness as if two positive pulses were given. It means that they are absolutized after the linear response. The discrimination angle of the 0.05ms rectangular pulse was measured, and it happened with the cross-correlation 0.98 on the head related transfer function (HRTF). Acoustical information can be smoothed spatially and temporally in that region, being convolved with the impulse response of our hearing system which is modified by the directivity. To find the loudness of a sound, it must be integrated in a time window. The above information can be expressed using the stereo-scopes. It is called visual sound field. One of the authors got the acoustic measurement of world famous concert halls to relate such information of the early reflections of them and their reputations.

Keywords; Discrimination angle, cross-correlation, visual sound field.

Introduction

The impulse response calculation of the early reflection in an auditorium has been established as well as its transfer function [1]. A rectangular pulse of 0.05ms from a loudspeaker was obtained after giving it an inverse filter. The linear response of human hearing system was measured in the form of impulse response [2]. When a positive and a negative pulse were given from the opposite direction, they were heard on loudness as if two positive pulses were given. It shows that they are absolutized after the linear response [3].

The discrimination angle for the 0.05ms rectangular pulse was measured, and it happened with the cross-correlation 0.98 on the head related transfer function (HRTF) [4]. Acoustical information can be smoothed spatially and temporally in that region, after the impulse response is convolved with the impulse response of our hearing system which is modified by the directivity. To find its loudness, it must be integrated in a time window [5] after the convolution is absolutized.

The above information can be expressed using the stereo-scopes. It is called visual sound field [6]. One of the authors got the acoustic measurement of world famous concert halls and it is planned to find the relationship between their sound field and their reputations with the methodology given in this paper.

1). Spatial discrimination angle for sound field estimation

A rectangular pulse of 0.05ms was generated every second in the anechoic chamber at Kansai Univ. A test person was on a rotary chair and asked when he felt that the coming direction was changed. Seven center angles were chosen from 0 degree to 180 degrees at every 30degrees to start with. The chair was rotated clockwise and anticlockwise. The median plane was at 0 degree and the loud speaker was rotated at 1.2 meters away from a test person as shown in Fig.1.

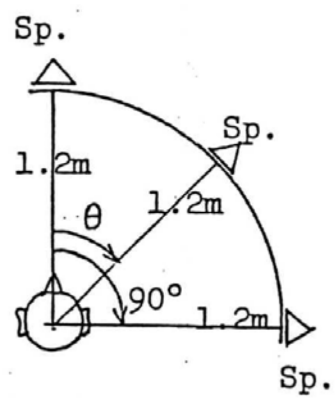

Fig.1 Incident center angle for a rectangular pulse wave

Eight male students were tested twice for each and its average was obtained. A discrimination angle in Fig.2 is for the clockwise and anticlockwise. Threshold angle of discrimination for monaural hearing is given for each center angle in Fig.2 (i), and that for binaural hearing in Fig.2 (ii).

It is very interesting that the binaural hearing shows much more sensitive. The cross talk between both ears should be possible to explain it.

The monaural discrimination threshold is supposed to be given by the change of head-related transfer function (HRTF). Namely, it was caused by the cross-correlation function between the HRTF at the center angle and the discriminated angle.

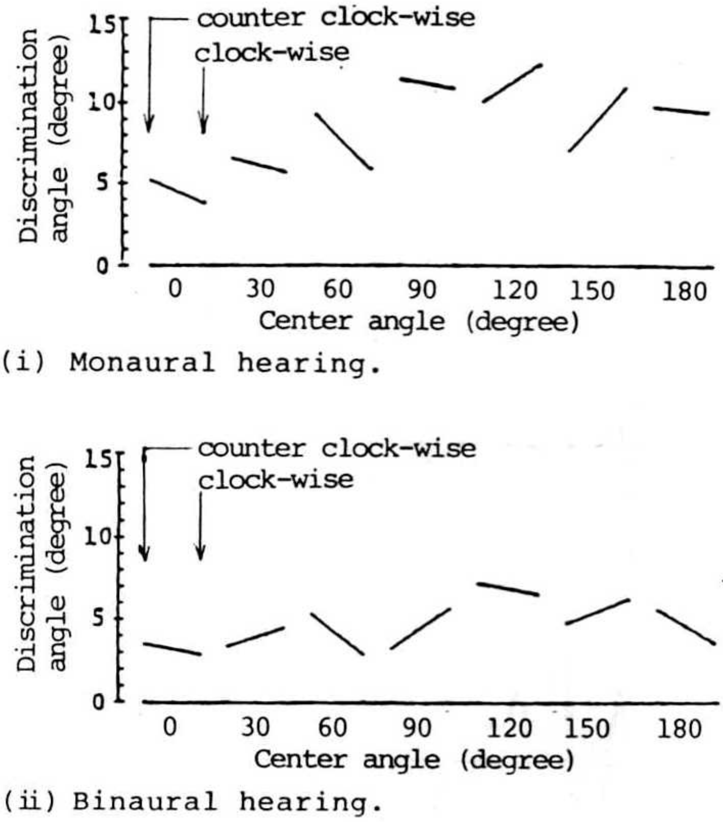

Fig.2 Threshold angle of direction discrimination to a rectangular pulse of 0.05ms

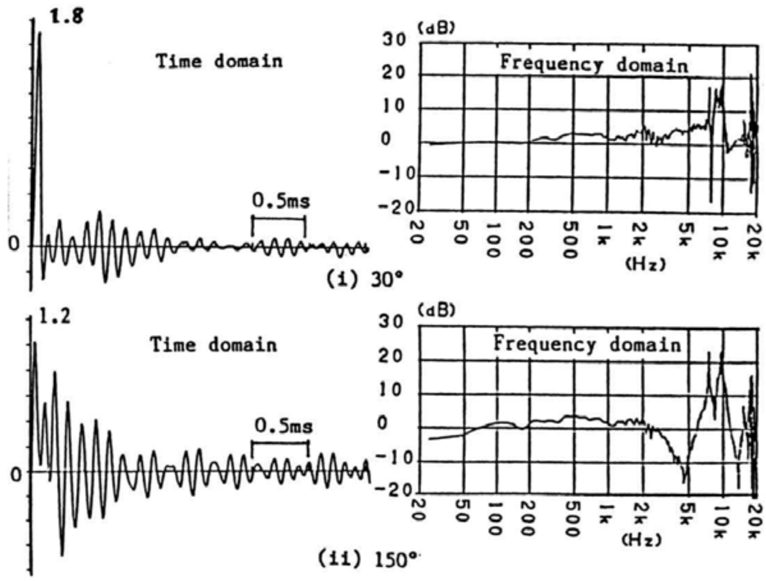

Fig.3 Directivity of head-related transfer function normalized by the one at the normal incidence for the incident angle 30 degrees above and 150 degrees below.

HRTF was measured at the eardrum of a dummy head at a different incident angle with the rectangular pulse of 0.05ms width. The directivity of the HRTF at 30 degrees and 150 degrees is shown in Fig.3 as examples after it was de-convolved or normalized with the one at the front incidence. They are shown for the time domain in the left and the frequency domain in the right.

The transient response of our hearing system, usually written by R (t), was measured at the front. If R (t) is convolved with the directivity at an incident angle, the transient response of our hearing system of the angle is obtained. When directivity is expressed in the time domain being de-convolved with the front one, it can be clearer to understand its feature and it is the information enough for the direction.

As the angle discrimination was supposed to be caused by the directivity of HRTF, it is discussed how the maximum value of the cross correlation function $\psi_{12}(\tau)$ between the directivity at a center angle $f_1(t)$ and the one at the angle $f_2(t)$ when it was felt changed. It was normalized by the auto-correlation of $f_1(t)$, which is expressed by $\varphi_1(0)$ and that of $f_2(t)$, by $\varphi_2(0)$, as shown in the following equation,

$$\psi_{12}(\tau) = \int f_1(t)\ f_2(t+\tau)\ dt \Big/ [\varphi_1(0)\,\varphi_2(0)]^{1/2}$$

where $\varphi_1(0)$ is obtained at $\tau=0$ in the next equation, and the same for $\varphi_2(0)$,

$$\varphi_1(\tau)=\int f_1(t)\, f_1(t+\tau)\, dt$$

The maximum cross correlation for each center angle is shown in Fig.4 for clockwise with ○ and counter clockwise with x. It deviates around 0.98.

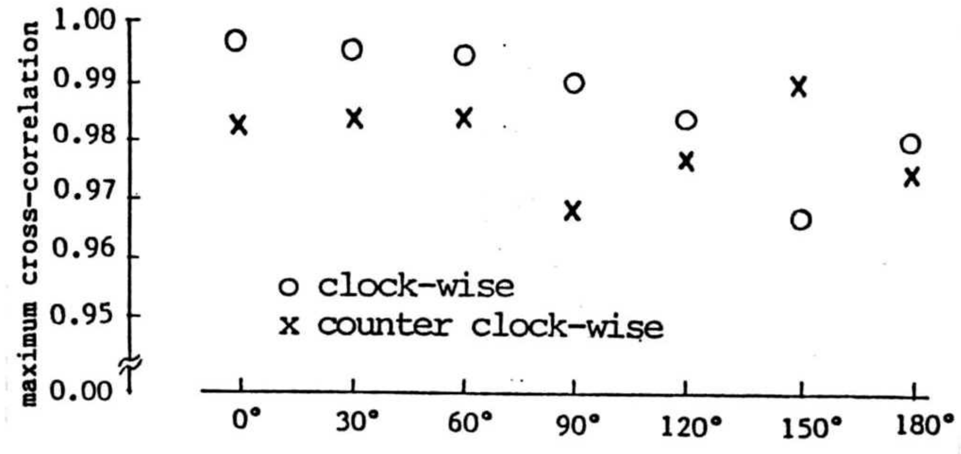

Fig.4 Relation between the threshold of angle discrimination with the maximum cross correlation of head-related transfer function

The result in Fig.4 was obtained from the experiment in the horizontal level. It is evident that the discrimination is strongly depending on the directivity of the HRTF. If the directivity of a dummy head for a different angle is obtained and the space is divided with angles where cross correlation is 0.98, the spatial discrimination angle will be found.
The sound field information on the impulse response is separated in the angle and then the transient response of hearing system modified to the angle is convolved to it. After then it is absolutized and integrated in a time window. The acoustic information is smoothed and easier to discuss with.

2). Visual sound fields

It is not enough to have the information only in the time domain for the evaluation of an auditorium. It must be discussed with the spatial information. Here is a try to do so and it is called a visual sound field.

Reflection of a boundary accompanies edge waves and they give time and spatial information. When we discuss auditorium acoustics, a sound field must be well explained to be with. It is tried to see a sound field in the stereoscopic expression. Using the parallax, an impulse response of a sound field is observed in the space.

Some examples of boundary reflection with edge waves are given in Fig.5. They are a large and small plane panel [7], a convex panel, concaved panel [8] and a panel with reflection coefficient [9]. Amplitude is expressed wave is expressed with ○ and a negative with ●. Edge waves are negative when a panel has specular reflection and different with each other.

An example in Fig.6 is a sound field of a scale model auditorium whose reflections are up to the second. There are two pairs at two different receiving points. Here, not only many specular reflections but also a lot of edge waves are emerged. The second reflections of the edge waves are given only their specular reflections.

It was shown only for an impulse response of a sound field. It must be convolved with the transient response of hearing system and integrated in a time window after absolutization for the discrimination space.

An actual concert hall has complex boundaries. For the sound field calculation, it must be efficiently abbreviated. Here in Fig.7 is a preparation example of Boston Symphony Hall for the first reflection calculation.

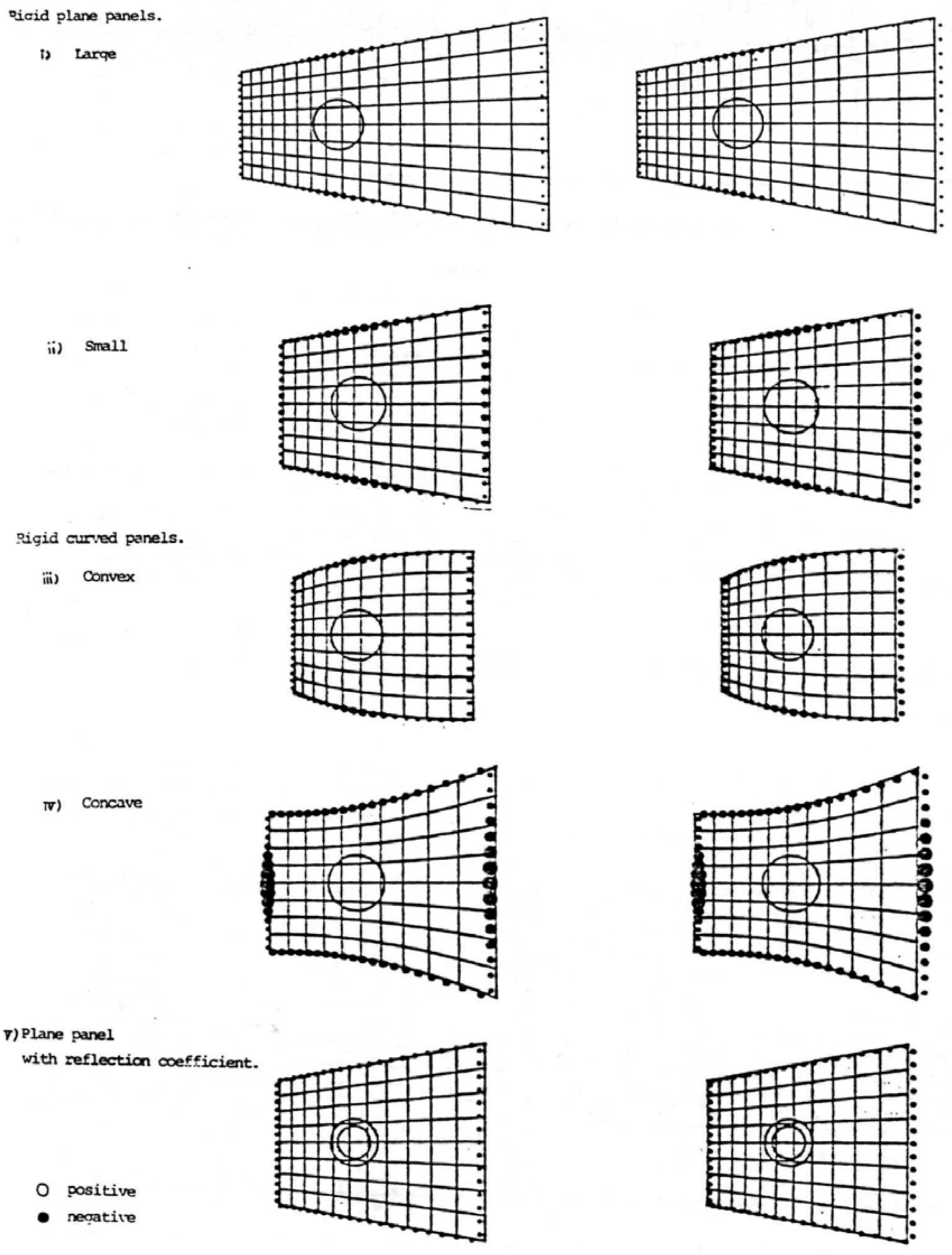

Fig.5 Stereoscopic expressions of the first reflections for a variety of boundaries

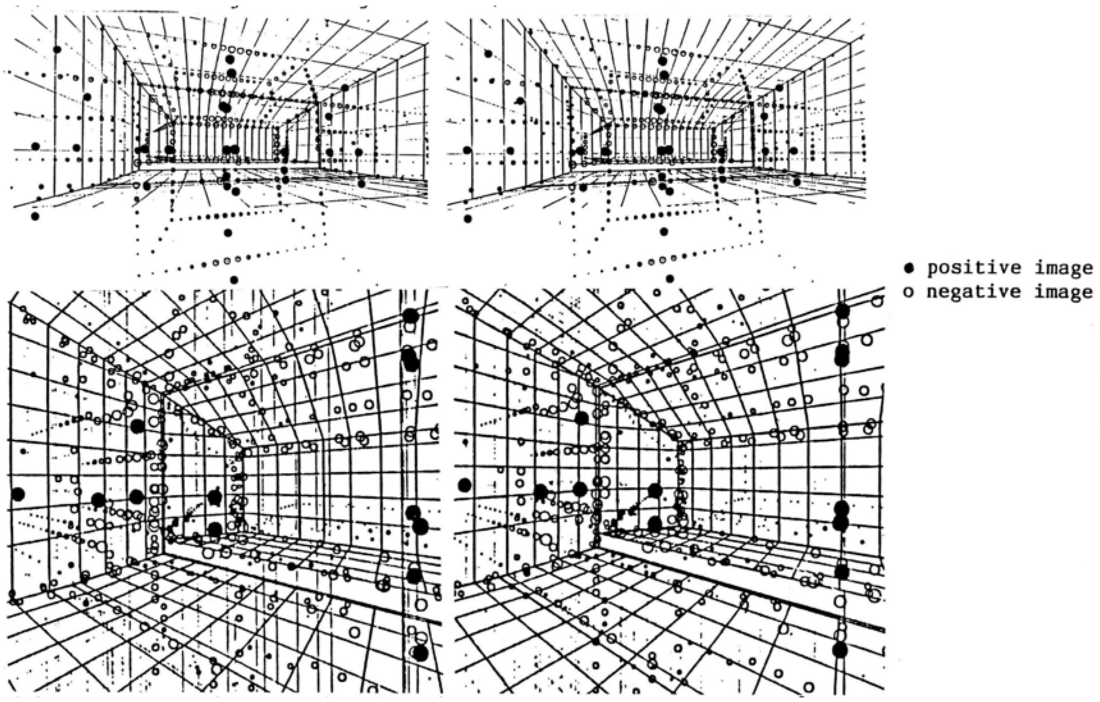

Fig.6 Visual sound field in a scale model auditorium with the reflections up to the second

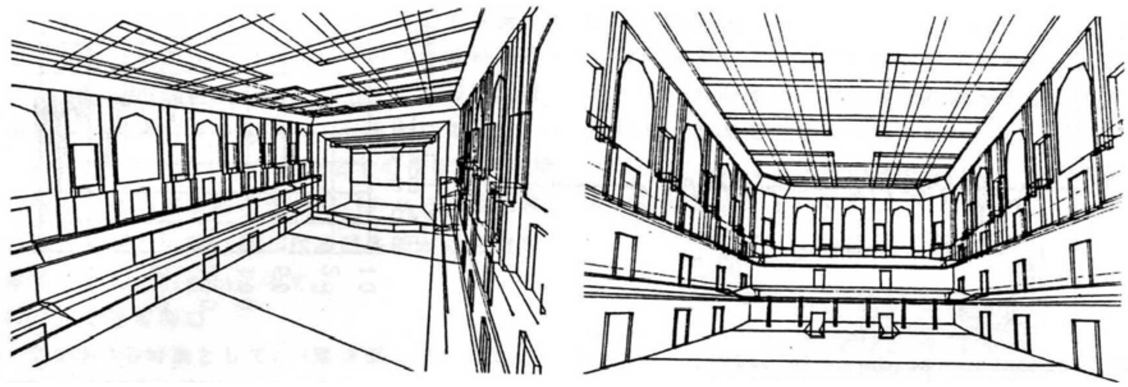

Fig.7 Boston Symphony Hall for the first reflection calculation

3). Summary for the method of acoustical estimation of an auditorium

○ Calculation of the impulse response of an auditorium to see the spatial information as well as in the time domain.

○ Convolution of the transient response in a discrimination angle with the directivity-modified HRTF: the space of the discrimination angle must have 0.98 on the cross correlation.

○ Integration of its absolute value in a time window for loudness; for instance, 40ms of a time window is for an impulsive sound [10].

○ The loudness in each discrimination angle is calculated in one after another time window.

The loudness for reflections is expressed in the time sequence through the auditorium space.

○ Using visual sound field to see the reflections in loudness, its change can be observed from one seat to another. Reputation of each seat is referred to the visual sound field and finds common character of reflections.

When one of the authors got a sabbatical leave in 1985 to 1986, he visited world famous concert halls for acoustical measurements. It was done with omni-directional impulsive sound source on the stage and received at a several audience seats. Reflection coefficient measurements were also done with the sound source for absorptive boundaries at each concert hall. The impulse response of early reflections will be calculated and the special and time sequence of reflections will be found following the above section's procedures.

The concert halls he visited for the purpose were as follows. They are arranged in visiting order:

Bynjanei Haoma (Israel)
Stadt Casino (Switzerland)
Grosser Music Vereinssaal (Austria)
Concert Gebau (Holland)
Boston symphony Hall (USA)
Tanglewood Music Shed (USA)
Central University Auditorium Caracas (Venezuela)
Teatro Colon (Argentine)
Christchurch Town hall (NZ)
Michel Fowler (NZ)

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