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A DIAGNOSTIC SYSTEM MEASURING ORTHOGONAL FACTORS OF SOUND FIELDS IN A SCALE MODEL OF AUDITORIUM

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Based on the model of auditory–brain system which consists of the autocorrelation mechanism, the interaural cross-correlation mechanism between both the auditory pathways, and the specialization of human cerebral hemispheres (Y. Ando 1998 *Architectural Acoustics, Blending Sound Sources, Sound Fields, and Listeners* New York: AIP Press/Springer-Verlag), a new diagnostic system was developed. After obtaining the binaural impulse response, four orthogonal factors including the *SPL*, the initial time-delay gap between the direct sound and the first reflection, the subsequent reverberation time and the *IACC* can be analyzed for the calculation of the scale values of both global and individual subjective preferences. In addition, two more factors extracted from the interaural cross-correlation function τ_{IACC} and W_{IACC}, can be figured out. Also, the sound energy, $\Phi(0)$, the effective duration, τ_e, and fine structures of autocorrelation function of sound signals including the magnitude of first maximum, ϕ_1, and its delay time, τ_1, can be analyzed. As an example of the measurement, effects of reflectors' array above the stage in a 1/10 scale model of auditorium at each seat are discussed here.

1. INTRODUCTION

In order to measure orthogonal factors, *SPL*, ΔT_1, T_{sub}, *IACC*, τ_{IACC}, and W_{IACC} [1–6], and also the running *ACF* of sound field at each seat in a scale model as well as in a real auditorium, a diagnostic system is developed. Based on the model of

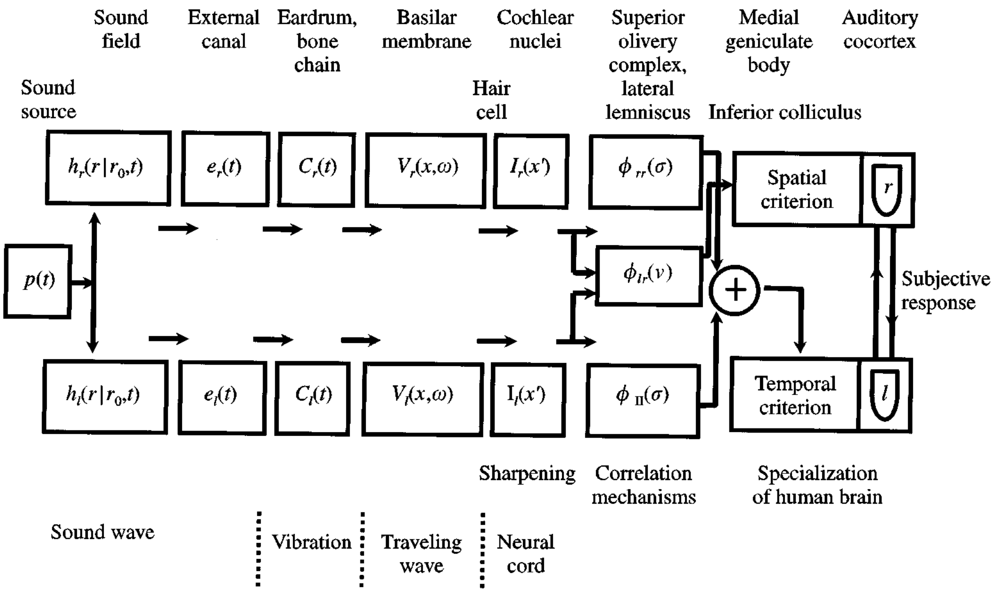

Figure 1. A model of auditory–brain system.

auditory–brain system which consists of the autocorrelation mechanism, the interaural cross-correlation mechanism between both the auditory pathways, and the specialization of human cerebral hemispheres as shown in Figure 1 [1], a diagnostic system was designed. The system works on PC for Windows with AD&DA converters; there is no need for special additional devices. After obtaining the binaural impulse responses, four orthogonal factors including the *SPL*, the initial time-delay gap between the direct sound and the first reflection, the subsequent reverberation time and the *IACC* are analyzed. These factors are used for the calculation of the scale values of both the global and individual subjective preferences. In addition to the four factors, two more factors, τ_{IACC} and W_{IACC} as defined in Figure 2, extracted from the interaural cross-correlation function can be figured out for evaluating the image shift of sound source and the apparent source width [6] respectively. Also, the averaged sound energy, $\Phi(0)$, the effective duration, τ_e, defined by the delay at which the envelope of normalized *ACF* becomes 0·1 (see Figure 3), and fine structures of autocorrelation function of sound signals including the magnitude of first maximum, ϕ_1, and its delay time, τ_1, of source signals are analyzed. In order to examine effects of the reflectors' array above the stage in a $\frac{1}{10}$ scale model of auditorium, the *IACC* measurements are demonstrated here.

2. OUTLINE OF A DIAGNOSTIC SYSTEM

Because the complex requirements made the system difficult to evaluate, an advanced diagnostic system and a high-power computer was used. The measuring system was utilized to obtain the binaural impulse response at each listening

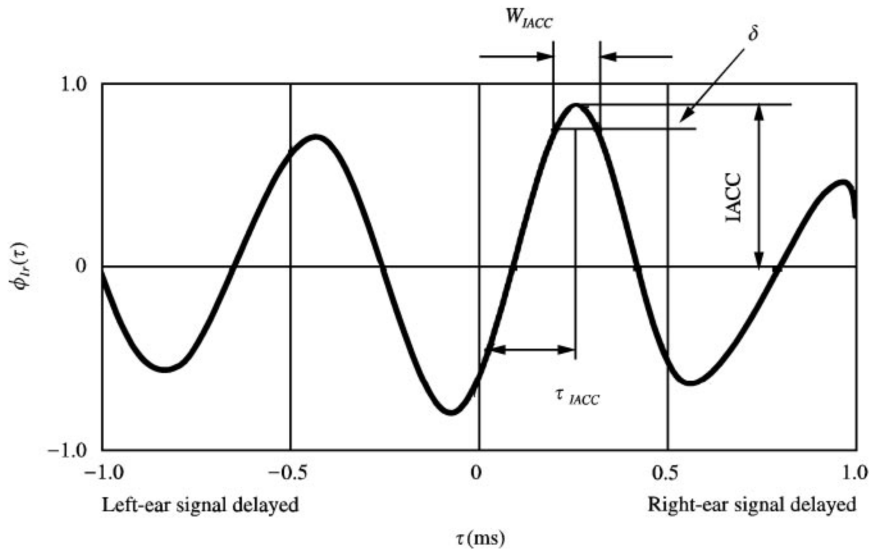

Figure 2. Definitions of the $IACC$, τ_{IACC} and W_{IACC} in the interaural cross-correlation function.

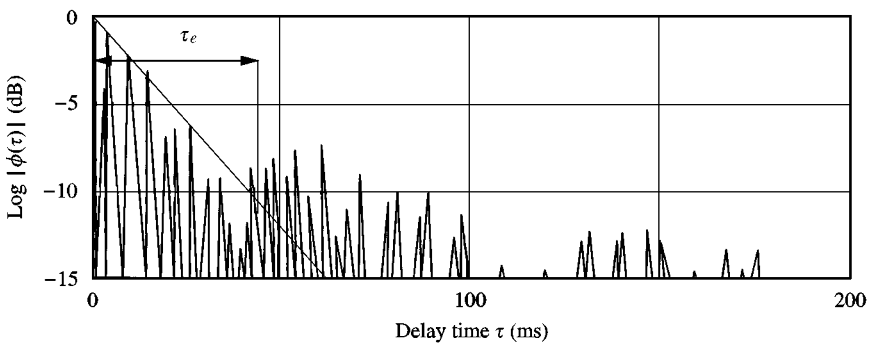

Figure 3. A practical example of determining effective duration of ACF defined by the ten-percentile delay, with the straight line-fitting envelope of ACF from 0 to -5 dB.

position. The sound was created by using an omni-directional loudspeaker fed with a maximum length signal produced by a diagnostic system in a notebook PC. The period of the maximum length signal (MLS) was between 1024 and 524 288 samples, and the sampling rate can be changed between 8 and 48 kHz. The acoustic signal amplified from the two microphones placed at the entrances of ears of a $\frac{1}{10}$ scale model of dummy head (a sphere with a diameter of 25 mm) was sampled after passing through a low-pass filter (see Figure 4). The binaural-impulse-response measurement may be performed by a summation of the output data from the linear system, without any multiplication operation [7, 8]. The measurement was done automatically within only a few seconds by pushing a single button. It took another few seconds for the analysis of the orthogonal acoustic factors and the scale value of the subjective preference. And at the same time this program can take the result to compute the acoustic parameters and prepare the reports.

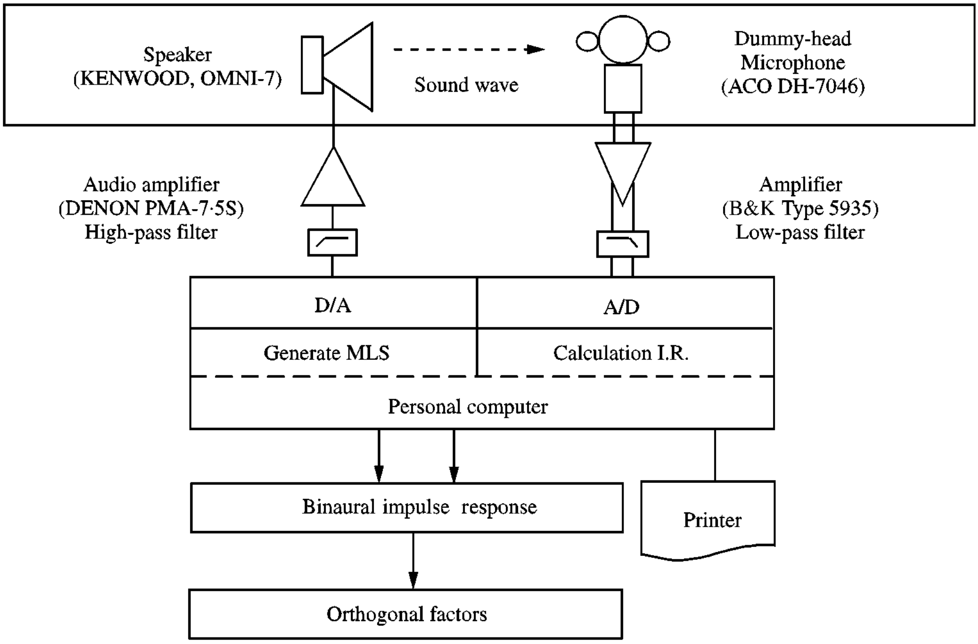

Figure 4. A block diagram of the measurement system.

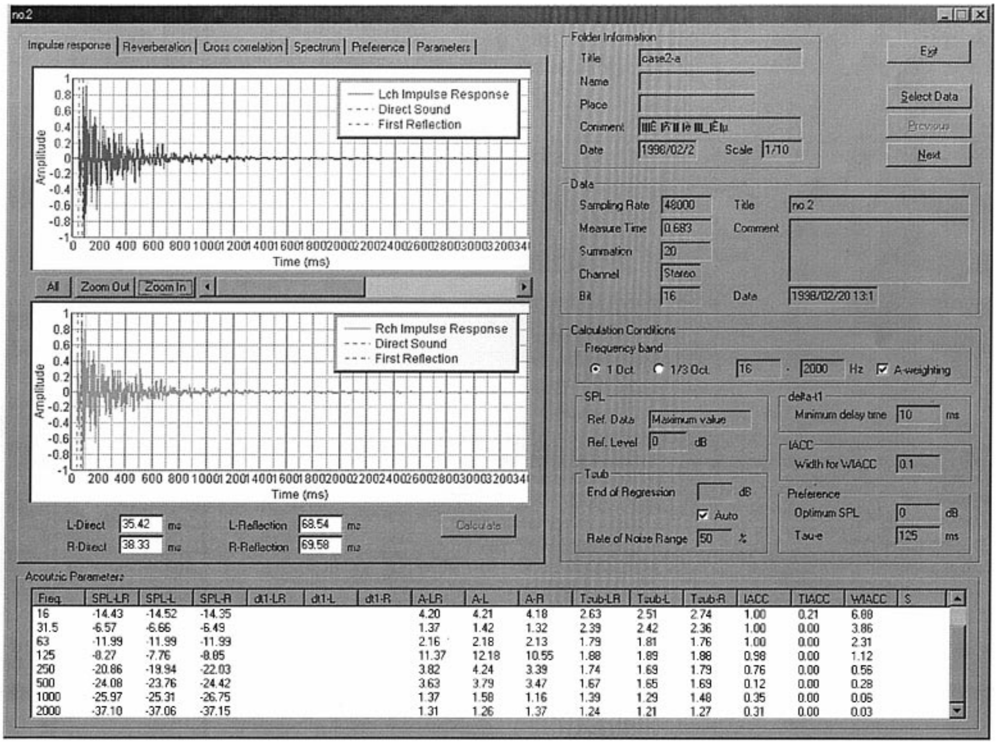

Figure 5. An example of display window of the diagnostic system, with binaural impulse responses.

3. MEASUREMENT OF ORTHOGONAL ACOUSTIC FACTORS

3.1. PROCEDURE

The diagnostic system developed may examine effects of scattered reflections of complex boundary conditions of the room. The reflectors above the stage are designed mainly for the performer obtaining the preferred reflections according to the program sources. We measured the *IACC* of the sound field at each seat to find the effects of the reflectors' array above the stage [9]. The effective direction of reflections to listeners for the 2000 Hz range is centered on $\pm 18^{\circ}$ from the median plane, which might be realized by a reflectors above the stage [1]. Therefore, the *IACC* of the 2000 Hz frequency band is selected here to be examined.

In order to obtain reliable results, measurements were repeated several times until the same results for the binaural impulse responses were obtained. The sound is produced by using an omni-directional loudspeaker fed with the MLS produced by the diagnostic system in a notebook PC. Figure 5 shows the window on PC of actual diagnostic system with the data obtained from the impulse responses. In the measurement, special attention should be paid to maintain a suitable value of the signal-to-noise ratio adjusting the power level of the loudspeaker.

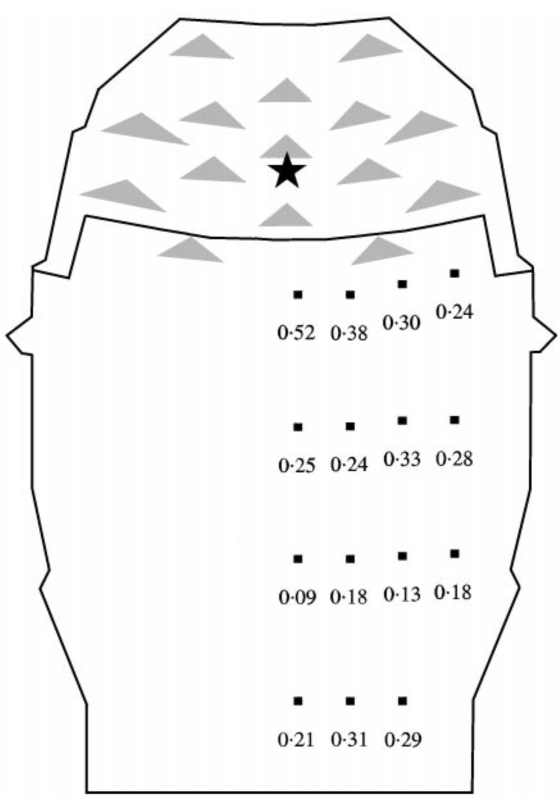

Figure 6. Measured *IACC* for the 2000 Hz frequency band with reflectors above the stage.

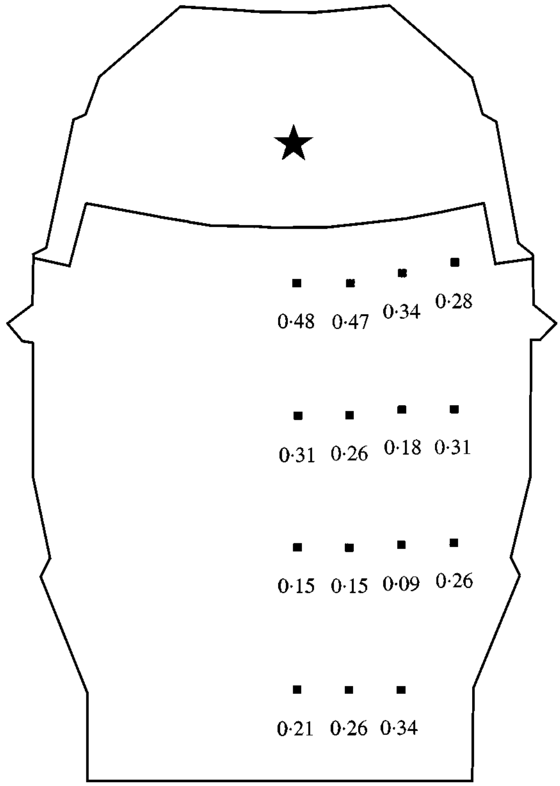

Figure 7. Measured *IACC* for the 2000 Hz frequency band without reflectors above the stage.

3.2. RESULTS

As mentioned above, in order to examine effects of reflectors' array on the *IACC* for the 2000 Hz range at 15 seating positions shown in Figure 6, measurements were performed with and without reflectors above the stage. As indicated in this figure, the location of the sound source is marked by a star, and the triangular reflectors' arrays [9] are installed above the stage. Figure 7 shows the measured results of the *IACC* without reflectors, and Figure 6 shows those with the reflectors' array. The *IACC* values of the 2 kHz frequency band for a real room were measured at the 20 kHz frequency band in the $\frac{1}{10}$ scale model. As shown in these figures, the reflectors decrease the results for the *IACC* at the 9 measuring points, so that acoustic quality is much improved. Especially, the decrement of *IACC* values was remarkable in the frontal area close to the stage in audience floor except for the centre, due to the reflections from above the stage to the listeners.

4. REMARKS

It has been shown that measurements in the $\frac{1}{10}$ scale model for acoustic parameters by the diagnostic system may prove the effects of the reflectors' array and other scattering elements [10] which may not be available by calculation at the design stage. In order to examine the sound fields after the construction of the auditorium, the diagnostic system measuring orthogonal factors may be applied. Also, keeping the subjectively optimal conditions, this system may be applied for the automatic control of sound fields by the use of electro-acoustic systems.

REFERENCES

1. Y. Ando 1998 *Architectural Acoustics—Blending Sound Sources, Sound Fields, and Listeners*. New York: AIP Press/Springer-Verlag.
2. H. Sakai and Y. Ando 1997 *Music and Concert Hall Acoustics* (Y. Ando and D. Noson editors) London: Academic Press, chapter 13. Inter-individual differences in subjective preference judgements of sound fields.
3. Y. Ando *et al*. 1997 *Music and Concert Hall Acoustics* (Y. Ando and D. Noson editors) London: Academic Press, chapter 4. Global subjective evaluations for design of sound fields and individual subjective preference for seat selection.
4. M. Sakurai *et al*. 1997 *Music and Concert Hall Acoustics* (Y. Ando and D. Noson editors). London: Academic Press, chapter 6. A sound simulation system for seat selection.
5. S. Sato, Y. Mori and Y. Ando 1997 *Music and Concert Hall Acoustics* (Y. Ando and D. Noson editors). London: Academic Press, chapter 12. The subjective evaluation of source locations on the stage by listeners.
6. S. Sato and Y. Ando 1997 *Proceedings of the* 134*th Meeting of the Acoustical Society of America*, *San Diego*. The apparent source width (ASW) for music source in related to the IACC and the width of the interaural crosscorrelation function (W_{IACC}).
7. H. Alrutz 1981 *Fortschritte der Akustik DAGA* 81, *Berlin*, 525–528. Ein Neuer Algorithmus zur Auswertung von Messungen mit Pseudo-Rausch Signalen.
8. Y. Ando 1985 *Concert Hall Acoustics*. Heidelberg: Springer-Verlag. see appendix E.
9. T. Nakajima, Y. Ando and K. Fujita 1992 *Journal of the Academical Society of America* **92**, 1443–1451. Lateral low-frequency components of reflected sound from a canopy complex comprising triangular plates in concert halls.
10. Y. Suzumura, Y. Ando, M. Sakurai, M. Oowaki, T. Iizuka and I. Yamamoto 1999 *Proceedings of the* 137*th Meeting of the Acoustical Society of America and the* 2*nd Convention of the European Acoustics Association*: *FORUM ACOUSTICUM* 1999—*integrating the* 25*th German Acoustics PAGA Conference*, *Berlin*. An Evaluation of Scattered Reflections in Sound Fields (Unpublished).