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Sound intensity-based indices for evaluating listener envelopment in concert halls

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ABSTRACT

Listener envelopment (LEV) is one of the most important factors for the overall impression of a concert hall. The author have proposed spatially balanced center time (SBTs) to predict LEV [T. Hanyu and S. Kimura, Appl. Acoust. 62, 155-184(2001)]. The SBTs is based on the center time (Ts) of impulse responses in each arrival direction. The SBTs have been proposed and validated first by using simulated sound fields that were reproduced by sixteen loudspeakers in a horizontal plane. However a method for measuring the SBTs in actual concert halls was not presented at that time. The purpose of this study is to investigate a method to measure the SBTs by using instantaneous sound intensity of a room impulse response. A sound intensity-based SBTs (iSBTs) is newly defined. Advantages of the iSBTs to the original SBTs are as follows: 1) Measuring the iSBTs has no problems of cross talk effect of directional microphones or microphone arrays. 2) The iSBTs becomes zero in a sound field in which reflections arrive only from a median plane. 3) The iSBTs becomes zero in a sound field in which left and right reflections arrive in completely the same time and level. In such sound fields, an inter-aural cross correlation becomes 1.0 theoretically, listeners should not feel LEV at all. The iSBTs can evaluate these phenomena.

Keywords: Listener envelopment, SBTs, iSBTs, Sound intensity

1. INTRODUCTION

Listener envelopment (LEV) is one of the most important factors for the overall impression of a concert hall. One of the authors have found that contribution of a reflection to LEV depends on the arrival directions of other reflections and that high LEV is achieved as the arrival directions and the levels of the reflections are balanced spatially. From these results, spatially balanced center time (SBTs) has been proposed to predict LEV [1]. The SBTs is based on the center time (Ts) of impulse responses in each arrival direction. The SBTs have been proposed and validated by using simulated sound fields that were reproduced by sixteen loudspeakers in a horizontal plane. However a method for measuring the SBTs in actual concert halls was not presented in the paper.

Suehiro and Onaga et.al reported that the SBTs can evaluate LEV in simulated sound fields which were used in their study [2]. Billon and Embrechts evaluated SBTs in some sound fields calculated by the ray tracing program [3]. In these studies, the SBTs were not measured in actual sound field. On the other hand, David and Vigeant investigated LEV in actual sound fields [4]. They calculated the SBTs using directional room impulse responses (IRs) derived by a spherical microphone array. However, the measured directional IRs have certain limits to temporal and spatial resolutions. Therefore a reasonable method other than the method using directional IRs is required for measuring SBTs.

The purpose of this study is to investigate a method to measure the SBTs by using instantaneous sound intensity of a room impulse response. In this paper, a sound intensity-based SBTs (iSBTs) is newly defined. Advantages of the iSBTs are also discussed.

2. ORIGINAL SBTs

The SBTs was proposed as a physical measure of LEV, based on results of subjective tests [1].

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The SBTs was defined using the center time Ts. First, Ts_i is defined in formula (1) below.

$$Ts_i = \frac{\int_0^\infty t \cdot p_i^2(t)dt}{\int_0^\infty p^2(t)dt} \tag{1}$$

where $p_i(t)$: omnidirectional impulse response, $p_i(t)$: reflections arriving from direction i.

As for time t, t=0 means time when a direct sound arrives to a receiving position. Ts_i means the contribution of individual reflections to Ts. Therefore a total of Ts_i becomes Ts, $Ts = \sum Ts_i$.

Next, Ts_i is directionally weighted as indicated in formula (2), taking the contribution of the direction of arrival to LEV into account.

$$a_i = Ts_i \frac{(1+\cos\theta_{Li})}{2} \tag{2}$$

where a_i: level, time and direction factors of reflections arriving from direction i, θ_{Li}: angle from binaural axis. In addition, the value of $(1+\cos\theta_{Li})/2$ of formula (2) reaches a maximum in the binaural axis direction and changes so that it does not become zero in the front/back direction.

The mutual effects of two reflections are quantified by multiplying their respective a_i values. The direction of arrival of the two reflections would contribute more to LEV as the angle between them increased. Furthermore, since the contribution of a certain reflection to LEV is influenced by all other reflections, all mutual effects of the other reflections are integrated. These are expressed by formula (3) below:

$$b_i = a_i \cdot \sum_{j=0}^{n} a_j \left|\sin\left(\theta_{ij}/2\right)\right| \tag{3}$$

where, b_i: contribution of reflection $p_i(t)$ to LEV, θ_{ij}: angle between directions of arrival i and j.

Finally, as indicated in formula (4) below, the b_i of all reflections are integrated. It is considered that to be the overall contribution SBTs (spatially balanced Ts) to LEV.

$$SBTs = \sqrt{\sum_{i=0}^{n} b_i} = \sqrt{\sum_{i=0}^{n}\sum_{j=0}^{n} a_i a_j \left|\sin\left(\theta_{ij}/2\right)\right|} \tag{4}$$

If impulse response is the same, SBTs increases when the direction of arriving reflections is in a broad range and the Ts_i of individual reflections has adequate spatial distribution.

Since the time structure and spatial structure of reflections are not independent of one another, each is not treated separately with SBTs but the time, level and direction of arrival of reflections as well as the mutual effects between reflections are treated comprehensively as indivisible elements. It is possible to consider SBTs to be an extension of the center time Ts taking into consideration the spatial balance of reflection energy.

To calculate SBTs in actual sound fields, it is necessary to measure Ts_i. It is possible to calculate SBTs by measuring directional responses including late arriving reverberant sound using a directional microphone or a microphone array. The ideal directivity of the microphone in this case would be $Ts = \sum Ts_i$, although it would be $Ts < \sum Ts_i$ in the case of ordinary directional microphones due to crosstalk generated between the directions of measurement. It is therefore usually possible to carry out approximate calculations of Ts_i by multiplying $Ts / \sum Ts_i$ by the Ts_i of each direction and correcting the effects of crosstalk. However, this correction is approximate approach. Error of the SBTs would be large if the effects of crosstalk is large. Therefore a reasonable method other than the method using directional microphones or microphone arrays is required for measuring SBTs.

3. SBTs USING SOUND INTENSITY

3.1 Intensity-based SBTs

In recent years, it has become easy to use various methods for measuring sound intensity. Here, we investigate a method to measure the SBTs by using a 3D instantaneous sound intensity vector $\mathbf{I}(t)$ of a room impulse response. Figure 1 shows Cartesian coordinates at a listener's position for the vector $\mathbf{I}(t)$ to calculate the intensity-based SBTs.

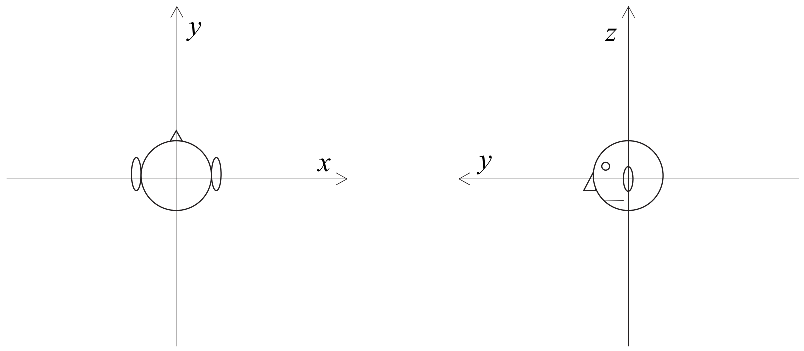

Figure 1 –Cartesian coordinates for the 3D sound intensity vector to calculate the intensity-based SBTs

$\mathbf{Ts}$ can be defined in formula (5) using the $\mathbf{I}(t)$ as a vector of the center time *Ts*.

$$\mathbf{Ts} = \frac{\int_0^\infty t \cdot \mathbf{I}(t)\,dt}{\int_0^\infty |\mathbf{I}(t)|\,dt} \tag{5}$$

Next, $\mathbf{Ts}(t)$ is defined instead of Ts_i in formula (6) below. Since the $\mathbf{Ts}(t)$ is calculated by the intensity vector $\mathbf{I}(t)$, the $\mathbf{Ts}(t)$ also becomes an instantaneous vector.

$$\mathbf{Ts}(t) = \frac{t \cdot \mathbf{I}(t)}{\int_0^\infty |\mathbf{I}(\tau)|\,d\tau} \tag{6}$$

The $\mathbf{Ts}(t)$ means the contribution of instantaneous sound intensity $\mathbf{I}(t)$ to the vector of the center time $\mathbf{Ts}$. Therefore an integration of $\mathbf{Ts}(t)$ becomes $\mathbf{Ts}$ as formula (7).

$$\mathbf{Ts} = \int_0^\infty \mathbf{Ts}(t)\,dt \tag{7}$$

In a similar way of the original SBTs, $\mathbf{Ts}(t)$ is directionally weighted as indicated in formula (8), taking the contribution of the direction of arrival to LEV into account.

$$\mathbf{a}(t) = \left(0.5 + 0.5\frac{|\mathrm{Ts}_x(t)|}{|\mathbf{Ts}(t)|}\right)\mathbf{Ts}(t) \tag{8}$$

where $\mathbf{a}(t)$: level, time and direction factors of the instantaneous intensity, $\mathrm{Ts}_x(\mathrm{t})$: a x-component of the vector $\mathbf{Ts}(t)$. Since $|\mathrm{Ts}_x(t)|/|\mathbf{Ts}(t)|$ becomes $\cos\theta_{Li}$, the directional weighting in formula (8) is the same as that in formula (2).

A vector subtraction between unit vectors of $\mathbf{a}(t)$ and $\mathbf{a}(\tau)$ becomes

$$\sin\frac{\theta_{t\_\tau}}{2} = \frac{1}{2}\left|\frac{\mathbf{a}(t)}{|\mathbf{a}(t)|} - \frac{\mathbf{a}(\tau)}{|\mathbf{a}(\tau)|}\right| \tag{9}$$

where θ_{t_τ}: angle between vectors of $\mathbf{a}(t)$ and $\mathbf{a}(\tau)$.

Multiplying $|\mathbf{a}(t)||\mathbf{a}(\tau)|$ to formula (9) yields

$$|\mathbf{a}(t)||\mathbf{a}(\tau)|\sin\frac{\theta_{t\_\tau}}{2} = \frac{1}{2}|\mathbf{a}(t)||\mathbf{a}(\tau)|\left|\frac{\mathbf{a}(t)}{|\mathbf{a}(t)|} - \frac{\mathbf{a}(\tau)}{|\mathbf{a}(\tau)|}\right| = \frac{1}{2}\big\||\mathbf{a}(t)|\mathbf{a}(\tau) - \mathbf{a}(t)|\mathbf{a}(\tau)|\big\|. \tag{10}$$

Therefore, the mutual effects of the instantaneous sound intensity in different times are quantified by vector subtraction between $\mathbf{a}(t)$ and $\mathbf{a}(\tau)$ in formula (11) below. The direction of $\mathbf{a}(t)$ and $\mathbf{a}(\tau)$ would contribute more to LEV as the angle between them increased.

$$b(t)=\frac{1}{2}\int_0^\infty \left\| |\mathbf{a}(t)|\mathbf{a}(\tau)-\mathbf{a}(t)|\mathbf{a}(\tau)| \right\| d\tau \tag{11}$$

where, $b(t)$: contribution of instantaneous intensity $\mathbf{I}(t)$ to LEV.

Finally, an intensity-based SBTs can be calculated as indicated in formula (12), by integrating the $b(t)$ as the overall contribution to LEV.

$$SBTs=\sqrt{\int_0^\infty b(t)dt}=\sqrt{\frac{1}{2}\int_0^\infty\int_0^\infty \left\| |\mathbf{a}(t)|\mathbf{a}(\tau)-\mathbf{a}(t)|\mathbf{a}(\tau)| \right\| d\tau dt} \tag{12}$$

As mentioned here, we can calculate the SBTs in actual sound fields by measuring the instantaneous sound intensity at listener's positions. As for the intensity-based SBTs, there is no problems of cross talk effect of directional microphones or microphone arrays in the original SBTs. This is one of the advantages of the intensity-based SBTs.

3.2 iSBTs

Figure 2 shows sound field in which reflections arrive only from a median plane. Because an inter-aural cross correlation becomes 1.0 theoretically in such a sound field, listeners should not feel LEV at all. However, the original SBTs and the intensity-based SBTs indicate some sort of values even in such a sound field. Although this phenomenon occurs only in an extreme condition, it implies that the SBTs has a certain limitation to evaluate LEV.

Therefore in order to remove the limitation of the original SBTs, another intensity-based SBTs (iSBTs) is newly defined here.

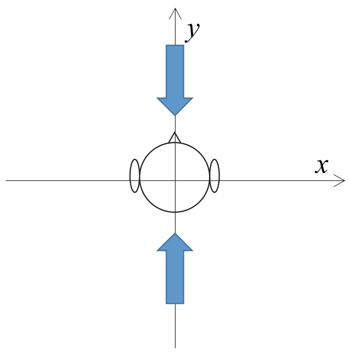

Figure 2 –Sound field in which reflections arrive only from a median plane

As for the iSBTs, $\mathbf{Ts}(t)$ is directionally weighted as indicated in formula (13). Since $|\mathrm{Ts}_x(t)|/|\mathbf{Ts}(t)|$ becomes $\cos\theta_{Li}$, the directional weighting in formula (13) is the same as that in conventional lateral energy measures such as Lf.

$$\mathbf{a}(t)=\frac{|\mathrm{Ts}_x(t)|}{|\mathbf{Ts}(t)|}\mathbf{Ts}(t) \tag{13}$$

Formula (13) means that a contribution of the $\mathbf{a}(t)$ becomes zero in the front/back direction. However, we had clarified that the influence of reflections arriving from the front a median plane is not zero [1]. This is reflected by calculating the mutual effects as indicated in formula (14). In formula (14), the mutual effects are quantified by vector subtraction between $\mathbf{a}(t)$ and $\mathbf{Ts}(\tau)$ in a different way from formula (11).

$$b(t)=\frac{1}{2}\int_0^\infty \left\| |\mathbf{a}(t)|\mathbf{Ts}(\tau)-\mathbf{a}(t)|\mathbf{Ts}(\tau)| \right\| d\tau \tag{14}$$

By using formula (14), the $b(t)$ becomes always zero in sound field in which reflections arrive only from a median plane, because the $\mathbf{a}(t)$ is always zero as shown in Figure 3. Figure 4 shows a sound field in which one of two reflections arrives from a median plane. In such a sound field, the $b(t)$ is not zero because the $\mathbf{a}(t)$ is not zero in one of the two situations in Figure 4.

Finally, in a similar way of the original SBTs, the iSBTs can be calculated by integrating the $b(t)$ as the overall contribution to LEV.

$$iSBTs = \sqrt{\int_0^\infty b(t)\,dt} = \sqrt{\frac{1}{2}\int_0^\infty \int_0^\infty \left\| \mathbf{a}(t)\left|\mathbf{Ts}(\tau)\right| - \mathbf{a}(t)\left|\mathbf{Ts}(\tau)\right| \right\| d\tau dt} \tag{15}$$

Significant differences between the iSBTs and the original SBTs are as follows:

1) The iSBTs becomes zero in the sound field in which reflections arrive only from a median plane as indicated in Figure 3.
2) The iSBTs becomes zero in a sound field in which left and right reflections arrive in completely the same time and level as indicated in Figure 5.

In such sound fields an inter-aural cross correlation becomes 1.0 theoretically, listeners should not feel LEV at all. The iSBTs can evaluate these phenomena.

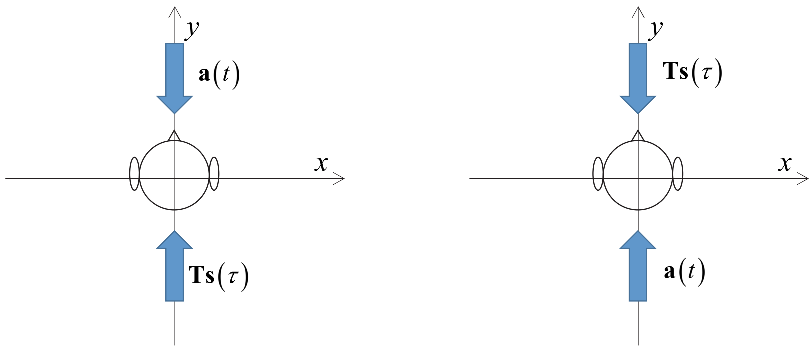

Figure 3 – $\mathbf{a}(t)$ and $\mathbf{Ts}(\tau)$ in sound field in which reflections arrive only from a median plane

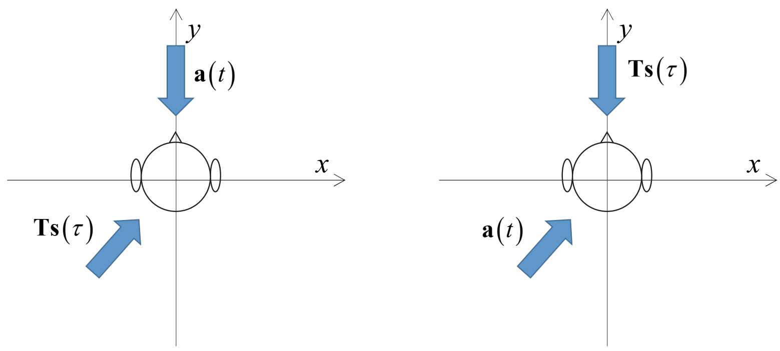

Figure 4 – $\mathbf{a}(t)$ and $\mathbf{Ts}(\tau)$ in sound field in which one of two reflections arrives from a median plane

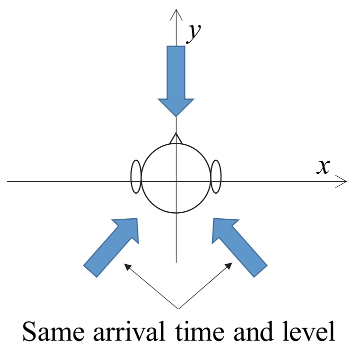

Figure 5 –Sound field in which left and right reflections arrive in completely the same time and level

4. CONCLUSIONS

In this study, we investigated a method to measure the SBTs by using a 3D instantaneous sound intensity vector of a room impulse response. An intensity-based SBTs, iSBTs, is newly defined. The iSBTs can measure in actual concert halls by using intensity probes. We can use any kinds of intensity probes which can measure the 3D sound intensity.

Advantages of the iSBTs to the original SBTs are as follows:

1) Measuring the iSBTs by the intensity probe has no problems of cross talk effect of directional microphones or microphone arrays.
2) The iSBTs becomes zero in a sound field in which reflections arrive only from a median plane.
3) The iSBTs becomes zero in a sound field in which left and right reflections arrive in completely the same time and level.

In such sound fields an inter-aural cross correlation becomes 1.0 theoretically, listeners should not feel LEV at all. The iSBTs can evaluate these phenomena.

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