ForumAcusticum 2005

A new definition of boundary point between early reflections and late reverberation in room impulse response

Takayuki Hidaka, Yoshinari Yamada and Takehiko Nakagawa

Takenaka R&D Institute, 1-5-1, Otsuka, Inzai, Chiba 270-1395, Japan, **hidaka.takayuki@takenaka.co.jp**

The early reflections in the room impulse response (RIR) are usually defined as those observed within the initial 80 ms after the arrival of the direct sound, after which time the sound field is called reverberant. This number was apparently arbitrarily chosen from measurements of other functions in a limited number of halls. In order to give an objective foundation to this time separation and to establish a physical indicator for it, a new method is proposed that defines a "transition time, t_L" which is the time at which the energy correlation between the direct plus initial sound and the subsequent decaying sound first achieves a specified low value. For various halls this number is shown and its relevance as a new parameter is discussed.

1 Introduction

In room acoustics a wave-related method and a statistical method are utilized in the characterization of sound fields in halls for the performance of music. It appears that there is no single physical measure for determining the range of these two parameters. Beranek (1992, Figs. 10 and 33) [1] infers from two measured parameters that 80 ms is an approximate time separation between early reflections and late reverberation time. Barron (1993) [2] writes that individual reflections (in large halls) arriving after 100 ms are no longer distinguishable. Hidaka *et al.*, (1995) [3] state "…the time that separates the early reflections from the late reflections exists in the range from 50 to 200 ms." A more meaningful separation time is needed for electronic reverberators, auralisation, and other sound field simulations.

This paper addresses the need by focusing on the room impulse response (RIR) measured in actual concert and chamber music halls and determining the times t where the correlation between the direct plus initial sound and the subsequent sound first achieves a specified low value.

2 Definition and Analysis

2.1 Transition time, t_L

By applying Levin distribution to evaluate a transient signal, the time-frequency distribution of the acoustic energy $E(t,\omega)$ is given [4] by

$$E(t,\omega)=\left|\int_t^{\infty} p(\tau)\exp(i\omega\tau)d\tau\right|^2 . \qquad (1)$$

Where, $p(t)$ is room impulse response RIR between a sound source and a receiving position in the hall.

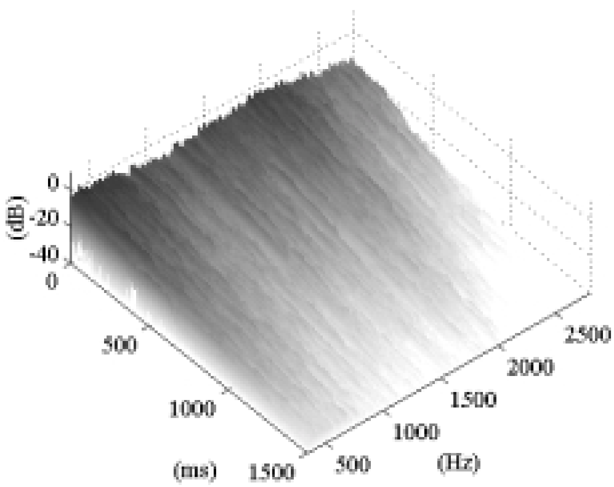

Fig.1 Numerical example of Eq.(1)

Figure 1 is a numerical example of Eq. (1) for a large concert hall which shows the reverberant decay curves at each sampling frequency as well as the temporal variation of the amplitude of RIR, i.e., the instantaneous sound pressure.

The correlation function

$$\rho(t) = \langle E(0,\omega)E(t,\omega) \rangle_{\omega} \qquad (2)$$

gives the correlation between the energy of the initial state (t = 0 sec) and the energy of state at any time t later, for a particular frequency range. The "transition time t_L" is defined as the boundary point on the RIR, where the correlation function first becomes sufficiently low, i.e., $\rho(t)$ = 1/e = 0.367 (Fig. 2).

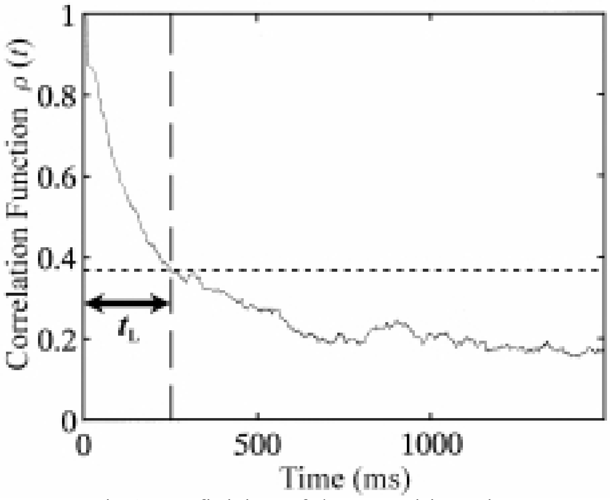

Fig.2 Definision of the Transition Time t_L

Considering the definition of a reverberation decay curve which assumes a diffuse sound field, t_L is the time when the total sound field (early reflections plus late reverberation) of a hall becomes a sound field that is dominated by the energy of the reverberant sound alone. Previously, *Nachhalleinsatzeit* ($t_{st} = 2V^{½}$) (literal translation, "time of onset of reverberation"), which is based on a psycho-acoustical premise [5], has been used for this purpose. Because t_L is derived from a measured sound field and not a generalized architectural dimension, it is vastly more meaningful.

2.2 Measurement procedure

The RIR was measured at a receiving position near the center of a hall, but off the centerline, with an omnidirectional source located on the centerline of the stage, usually located 3 meter from the lip. The sampling time of the RIR was 44.1 kHz and the frequency range for determining the Levin distribution of Eq. (1) covered the limits of 3 mid-frequency octave bands, i.e., 353 to 2.8k Hz [6].

3 Results of analysis

Transitions times t_L derived from measurements of RIR are plotted in Fig. 3 (a) against room volume V for both concert halls [7] and chamber music halls [8]. The two kinds of halls are divided into shoebox (rectangular) and non-shoebox (other) shapes. From Sabine's theory it is known that the number of reflections per unit time in a rectangular room with uniform but not large absorption, is $4\pi c^3 t^2/V$. Hence t_L should be proportional to $V^{½}$. There is a general increase as indicated in Fig. 3 (a) for shoebox halls, 150 to 400 ms, but for the others the distribution is random and spreads only from 120 to 280 ms.

If it is assumed that the horizontal seating area is highly absorptive and doesn't reflect sound, then, in the space above, mainly tangential waves will exist so that the number of reflections per unit time will be $8\pi c^2 t/S_A$, where S_A is the audience area [7]. Thus, for this case, t_L should be directly proportional to S_A. When the t_L's are plotted against S_A, shown in Fig 3 (b), the results are inconclusive—only for the four rectangular halls, Zurich, Vienna (2 halls) and Amsterdam, covering a limited range of S_A, does t_L appreciably increase with S_A. The fact that t_L is longer for these four halls than for the others happens because there are larger, non-absorbent, spaces above their top balconies.

When the correlation coefficients between t_L and other architectural parameters or other objective acoustical parameters are calculated, no significant correlations have been found. For t_L plotted against reverberation time RT (average for three octave bands—500/1k/2k Hz), as seen in Fig. 4, there is a definite increase, but with a wide scatter of data. When t_L is plotted against Binaural Quality Index BQI (= 1 – $IACC_{E3}$), shown in Fig. 5, there is no discernible trend.

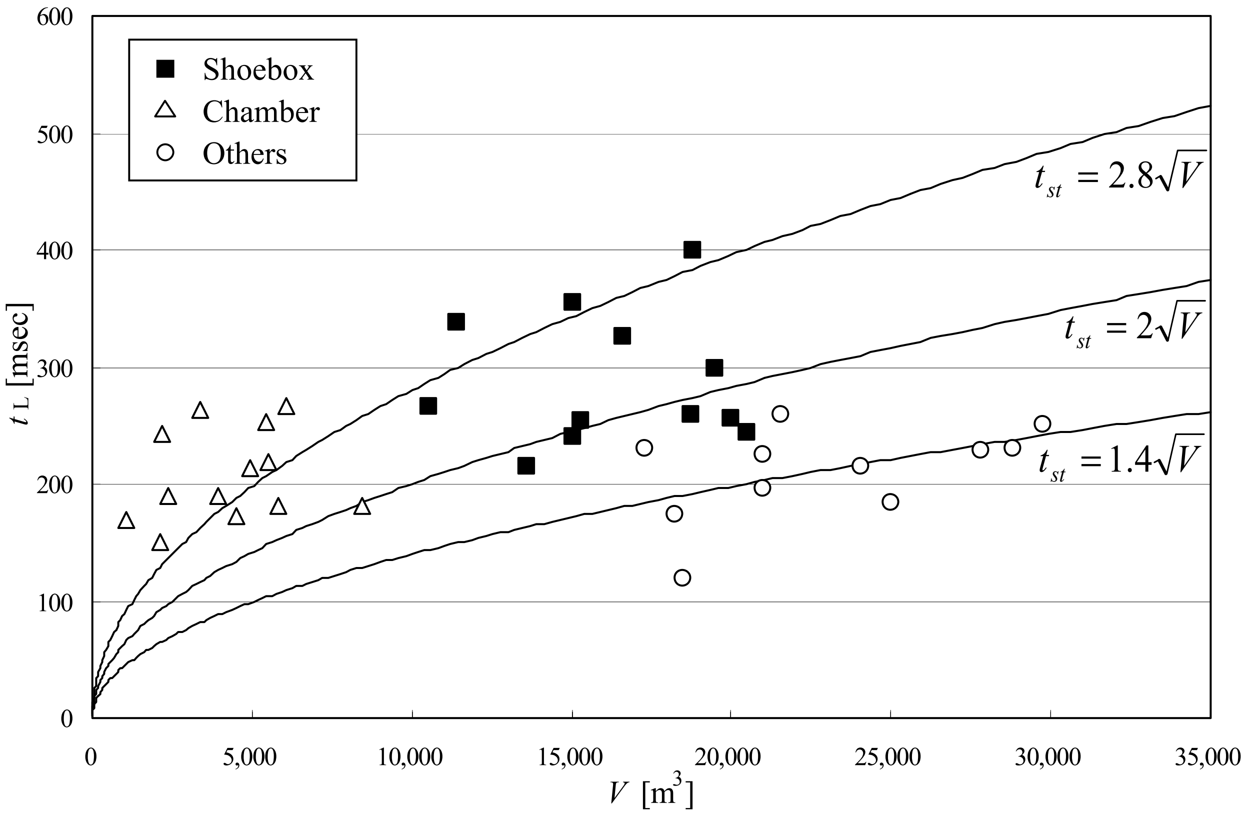

Fig.3(a) t_L vs. Volume V

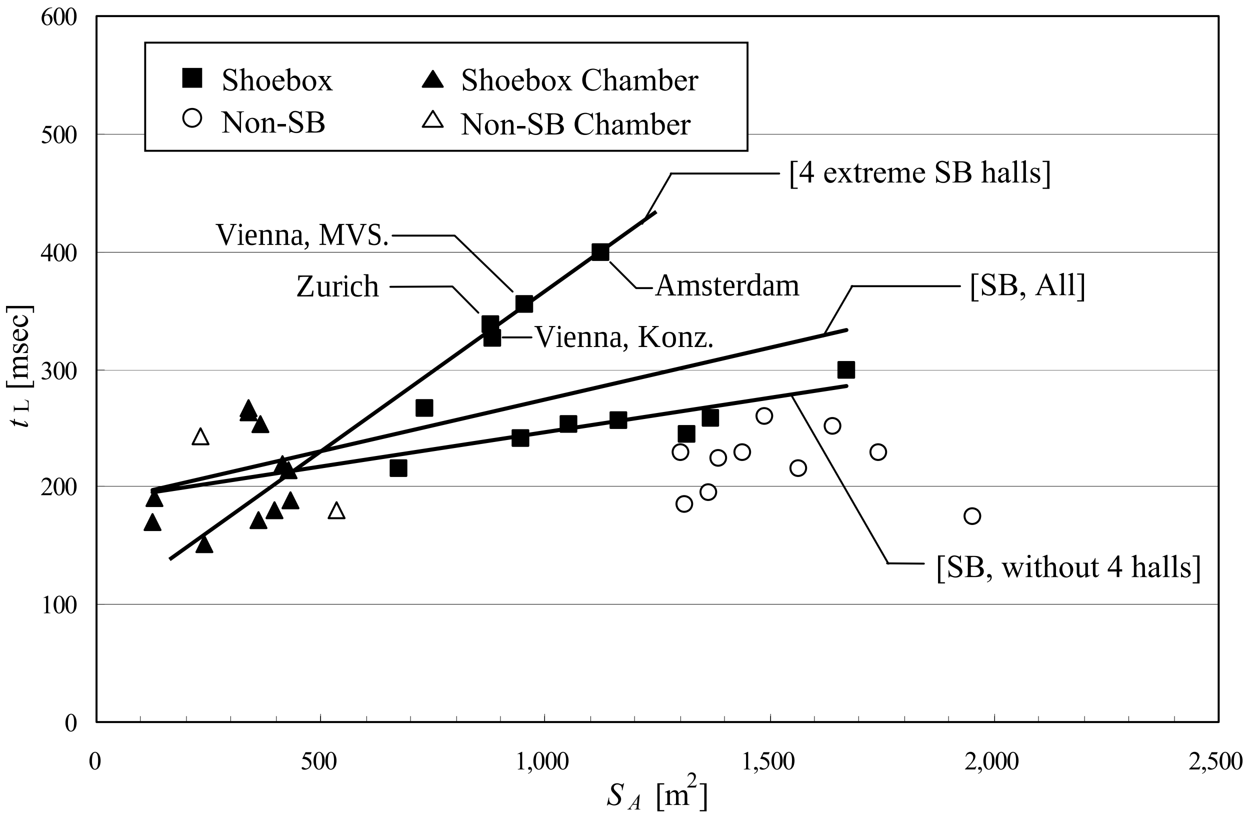

Fig.3(b) t_L vs. Audience Area S_A

Further, the number of early reflections (with amplitudes greater than -20 db relative to the direct sound) was counted for each hall. The results are shown Fig. 6. This number does not contribute to t_L.

No attention was paid to the phase component of RIR because it should be randomized by propagation in the room [7].

4 Conclusion

The objective parameter t_L, proposed in this paper, is a definite means for separating the room impulse response RIR into two parts, that part which correlates meaningfully with the initial sound and that part which has low correlation ($\rho \leq 0.4$). For 35 actual halls for music performance t_L varies from 100 to 400 ms. If the classical separation of about 80 ms were used, ρ would equal about 0.65, indicating a substantial presence of early reflections in the later physical state. The values of t_L shown in Fig. 3 are about one-half to twice the *Nachhalleinsatzeit* indicating that that older measurement does not accomplish what its name implies. The plot of Fig. 3 also shows that t_L is related to room shape, which indicates that in a rectangular room, with only one surface highly absorbent (audience area), the early sound can persist longer in the upper space.

Acknowledgement

The authors wish to thank Dr. Leo Beranek for his kind editorial assistance.

References

[1] Beranek, L. L. (1992). "Concert hall acoustics—1992", JASA. **82**, 1-39.

[2] Barron, M. (1993). *Auditorium acoustics and architectural design* (E. & FN Spon), p.17.

[3] Hidaka, T., Beranek, L. L. and Okano, T. (1995), "Interaural cross-correlation, lateral fraction, and low- and high-frequency sound levels as measures of acoustical quality in concert halls" JASA. **98**, 988-1007.

[4] Yamada, Y. and Hidaka, T. (2001). "Application of Page-Levin distribution for the evaluation of transient responses in rooms", Proc. of 17th ICA.

[5] Cremer, L. and Müller, H. A. (1982). *Principles and applications of room acoustics* (Applied Science), Chap.III.2.1

[6] Hidaka, T. and Nishihara, N. (2002). "On the objective parameter of texture", Proc. of Forum Acusticum Sevilla.

[7] Beranek, L. L. (2003). *Concert halls and opera houses – Music, Acoustics, and Architecture* (Springer, N.Y.), Chap.4.

[8] Hidaka, T. and Nishihara, N. (2004). "Objective evaluation of chamber-music halls in Europe and Japan", JASA **116**, 357-372.

[9] Kuttruff, H., (2000). *Room Acoustics* (E. & FN Spon), Chap. 9.

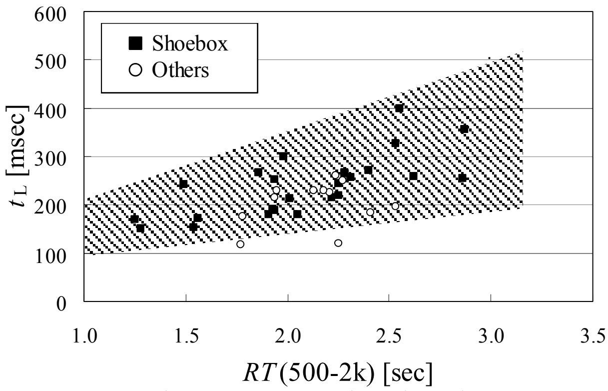

Fig.4 t_L vs. Reverberation Time

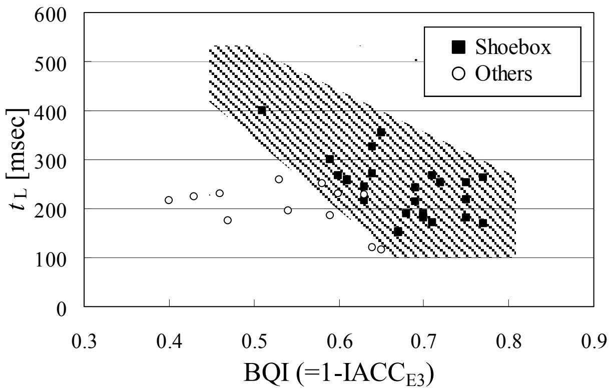

Fig.5 t_L vs. Binaural Quality Index

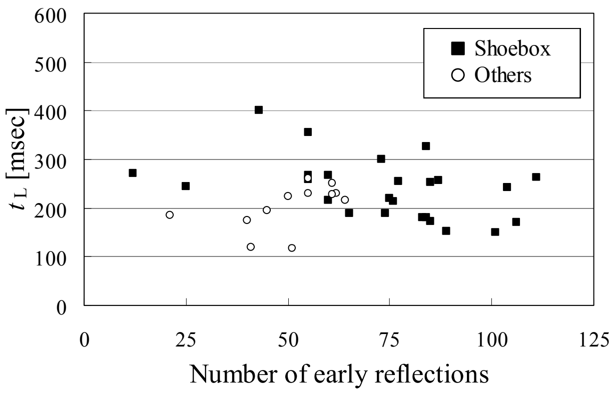

Fig.6 t_L vs. the Number of early reflections