Mechanism of the sweep sounds perceived in a regular-shaped reverberation room

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1. Introduction

Two of the authors reported that sweep sounds are perceived when a pulse sound is generated in a rectangular parallelepiped reverberation room.^{1,2)} The sweep sounds are related to the reflected pulse series, whose interval is inversely proportional to time. We have now analyzed the mechanism of the sweep sounds. To simplify the analysis, the reverberation room was assumed to be cubic, and both the source and the receiver were located at the center of the room. The simulation was rerun with all other assumptions the same.

2. Reflected pulse intervals in a cubic room

We first show that the regularity of the reflected pulses in a cubic room. Figure 1 shows the mirror-image sources for a cubic room whose sides are L where origin O is located at the center of the room. The image sources are located at coordinates $(n_x L, n_y L, n_z L)$, where n_x, n_y , and n_z take plus and minus integers. Under these conditions, consider arrival time t of a pulse sound at the origin, that is, the receiver position. The arrival time of a pulse sound from the image source located at $(n_x L, n_y L, n_z L)$ is represented as

$$t = \frac{\sqrt{(n_x^2 + n_y^2 + n_z^2)L^2}}{c}, \quad (1)$$

where c represents the sound velocity.

The squared time is represented by

$$t^2 = M(L/c)^2, \quad (2)$$

where

$$M = n_x^2 + n_y^2 + n_z^2. \quad (3)$$

Equation (2) represents the location of the reflected pulses on the squared-time axis. It is M times the constant $(L/c)^2$. Because n_x, n_y , and n_z are integers, number theory³⁾ can be used to prove that $M (=n_x^2 + n_y^2 + n_z^2)$ takes all integers except the following forbidden numbers,

$$M \neq 4^k(8m+7) \quad (k, m=0, 1, 2, \dots). \quad (4)$$

The forbidden numbers comprise 1/6 of all integers. Therefore, M covers almost all integers, so the reflected pulses are located at equal intervals of $(L/c)^2$ on the

squared-time axis.

3. Pulse interval on the squared-time and time axes

Consider the n -th and $(n+1)$ -th reflected pulses at time t_n and t_{n+1} , respectively; the interval of these pulses on the t^2 axis is $(L/c)^2$, so

$$t_{n+1}^2 - t_n^2 = \frac{L^2}{c^2}. \quad (5)$$

The mean time of the two pulses t_m is defined by $(t_n + t_{n+1})/2$. By factorizing and rearranging Eq. (5), the pulse interval on the time axis, $t_{n+1} - t_n$, can be represented as

$$t_{n+1} - t_n = \left(\frac{L^2}{2c^2} \right) \frac{1}{t_m}. \quad (6)$$

From this equation, the interval between the pulses is inversely proportional to mean time t_m . Thus, the interval of the pulses, which is equal on the squared-time axis, becomes inversely proportional to time on the time axis. Assuming that on the time axis the perceived frequency is a reciprocal of the pulse interval, frequency $f(t_m)$ at time t_m can be represented by the function of the meantime (t_m) :

$$f(t_m) = \frac{1}{t_{n+1} - t_n} = \left(\frac{2c^2}{L^2} \right) t_m. \quad (7)$$

This indicates that the perceived frequency increases proportionally with time; that is, sweep sound is perceived.

4. Results of simulation

4.1 Equal-interval pulses on squared-time axis

Equal-amplitude pulses, whose intervals are equal on the squared-time axis, are shown in Fig. 2(a). The interval is $L^2/(2c^2)$, where $L=10$ [m] and $c=340$ [m/s]. Figure 2(b) shows the same pulse series on the time axis, and Fig. 2(c) shows the short-time FFT of the pulse series. Line (A) in Fig. 2(c) is consistent with the result of Eq. (7) for $L=10$ [m] and $c=340$ [m/s], and corresponds to perception. Lines (B) and (C) are harmonics of line (A).

4.2 Reflected-pulse series in cubic room

Actual reflected pulses do not have completely equal intervals because M does not include all integers.

Fig. 1 Mirror image sources of cubic reverberation room.

Fig. 3 Short-time FFT of simulated reflected pulse series by mirror-image source method.

Because the source and reception points are located at the center of the room, the amplitudes of the pulses are also not completely equal because some of the reflected pulses arrive at the same time due to degeneracy of the mirror sources. The reflected-pulse series generated by the mirror image method was analyzed using short-time FFT. As shown in Fig. 3, the most dominant line (A) has the same slope as line (A) in Fig. 2(c) and matches the time-frequency-variant characteristics reflected in Eq. (7). In addition, this line component is perceived as the main sweep sound. These results show that the theoretical analysis in the previous sections explains the generation mechanism of sweep sound in a reverberation room.

The lower frequency sweep components (the lines

(a) Pulse series whose intervals are equal on squared-time axis.

(b) Pulse series whose intervals are equal on squared-time axis represented on time axis.

(c) Short-time FFT of pulse series.

Fig. 2 Pulse series whose intervals are equal on squared-time axis.

lower than line (A)) seem to have been caused by the lack of pulses due to forbidden numbers, in other words, the addition of pulses with antiphase amplitude at the forbidden numbers. Investigation of this is left for future study.

5. Conclusion

When a pulse sound, such as that of a hand-clap, is generated in a rectangular parallelepiped reverberation room, sweep sounds are perceived. In this paper we showed that most of reflected pulses from image sources

have the same interval on the squared-time axis, and this regularity causes the sweep sounds.

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References

- 1) K. Kiyohara and Y. Kaneda, "Sweep sounds perceived in a rectangular parallelepiped reverberation room," *J. Acoust. Soc. Jpn.* **21**, 25-27 (2000).
- 2) K. Kiyohara and Y. Kaneda, "Sweep sound perceived in a rectangular parallelepiped reverberation room," *Proc. Spring Meet. Acoust. Soc. Jpn.*, 503-504 (1997) (in Japanese).
- 3) M. R. Schroeder, *Number Theory in Science and Communication* (Springer-Verlag, Berlin, 1984), pp. 111-112.

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