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Faster method of reverberation time measurement using signal realizing a constant noise level for each frequency band

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1. Introduction

The reverberation time is calculated using the impulse response of target systems. The measurement conditions for the reverberation time are specified in the International Standard ISO 3382 [1]. In our previous report, we proposed an effective method of measuring reverberation time using an impulse response measurement signal that can control the noise level in the measurement for each frequency band [2]. However, measurement time must be increased when a target system has a particularly small frequency response. In this report, we propose an improved measurement signal and the result obtained using the signal is explained.

2. Principle of impulse response measurement and signal-to-noise (SN) ratio

Figure 1 shows the principle of impulse response measurement in the frequency domain. First, a measurement signal, $S(k)$, such as a swept sine signal, is input to a target system. When the output signal is filtered through an inverse filter, $1/S(k)$, the frequency characteristic of the system, $H(k)$, is obtained as a quantity equivalent to the impulse response.

In this case, a noise component expressed as $N(k)/S(k)$ is included in the result. The SN ratio in the measurement result is given by the power ratio of $H(k)$ to $N(k)/S(k)$ by

$$SN(k) = \frac{|H(k)|^2}{P_N(k)/|S(k)|^2}. \tag{1}$$

Here, the environmental noise is assumed to be stationary and $P_N(k)$ represents its power spectrum.

3. Measurement method to realize a constant noise level for each frequency band [2]

In the measurement of reverberation time, the noise level for a one-third-octave (or a one-octave) band should be at least 45 dB lower than the maximum value of the impulse response of the band. To meet this requirement effectively, we considered that the noise level should be almost 45 dB lower than the maximum value of the impulse response over the entire target band and determined the required conditions of the SN ratio.

Figure 2 shows a diagram of the impulse response that satisfies the required condition. In Fig. 2, E_p represents the energy of the impulse response of the pth band and depends on the convergence characteristics of the impulse response of the frequency band. E_N represents the energy of stationary noise with a noise level 45 dB lower than the maximum value of the impulse response. To realize a noise level of −45 dB shown in the figure, we demonstrated that the SN ratio should be

$$D_{SN}(p) = \frac{E_p}{E_N} = \frac{E_p}{10^{-4.5} \cdot L}, \tag{2}$$

where the length of the signal (= duration of impulse response) is L.

We also demonstrated that the desired SN ratio $D_{SN}(p)$ for each frequency band is obtained when measurement is performed with a controllable-SN-ratio swept-sine (CSN-SS) signal with the power spectrum given by

$$|S(k)|^2 = D_{SN}(p) \cdot \frac{P_N(k)}{|H(k)|^2}. \tag{3}$$

Here, values estimated from a short-time preliminary measurement are used for E_P, $H(k)$, and $P_N(k)$ in Eqs. (2) and (3).

When measurement is carried out using conventional signals such as a time stretched pulse (TSP) signal or a log-swept sine (Log-SS) signal, the noise level in the measurement is either too large (not meeting requirements) or too small (requiring extra measurement time to sufficiently suppress the noise level) depending on the frequency band. In contrast, when a measurement is carried out using a CSN-SS signal, the quality of the measurement is guaranteed by maintaining a constant noise level of −45 dB for each frequency band, and a short measurement time compared with those using conventional signals is realized.

4. Proposal for a more efficient measurement signal

To realize the desired SN ratio $D_{SN}(p)$ for frequency band p, the CSN-SS signal is controlled so that the SN ratio is maintained at $D_{SN}(p)$ for any frequency k contained in frequency band p, as shown in Fig. 3. With this method, however, the amount of noise suppression for frequencies with small $|H(k)|^2$ must be increased, leading to a long sweeping time.

To solve this problem, controlling the SN ratio as the energy ratio over the entire target band, rather than the SN ratio at each frequency, was considered. Specifically, the

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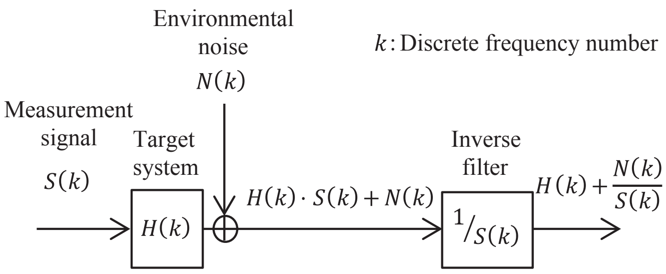

Fig. 1 Principle of impulse response measurement.

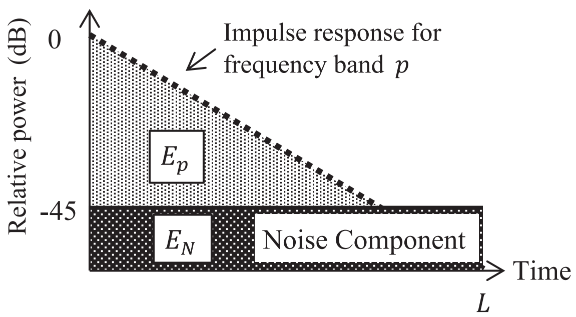

Fig. 2 Short-time power model of impulse response for each frequency band and noise component.

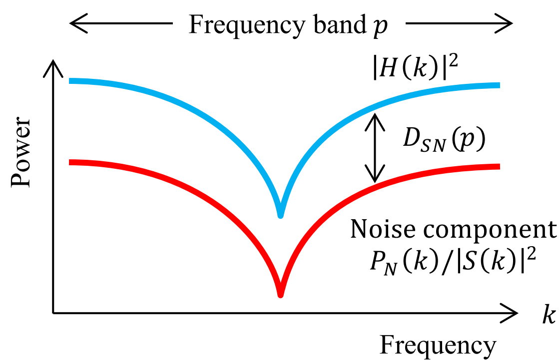

Fig. 3 Realization of $D_{SN}(p)$ using CSN-SS signal.

desired SN ratio $D_{SN}(p)$ is given as the ratio of the sum (energy) of $|H(k)|^2$ contained in the frequency band p to the sum of noise components $P_N(k)/|S(k)|^2$, i.e.,

$$D_{SN}(p) = \frac{\Sigma_p |H(k)|^2}{\Sigma_p P_N(k)/|S(k)|^2}, \tag{4}$$

where Σ_p represents the sum in the frequency band p. Then the measurement signal with the minimum energy (minimum duration) to satisfy the Eq. (4) is examined.

Here we focus on a minimum-noise swept sine (MN-SS) signal [3,4] that can minimize the energy of the noise component with a constant signal energy. MN-SS signal has the minimum energy (or signal length) among the signals that realize a certain amount of the noise component energy. Applying the idea of the MN-SS signal to the frequency band p, a signal with the shortest duration that gives the energy of the noise component satisfying Eq. (4) is obtained.

Concretely, the power spectrum of the MN-SS signal $|S(k)|^2$ for the frequency band p is given by $|S(k)|^2 = C_p \cdot \sqrt{P_N(k)}$, and the constant C_p is derived by substituting this equation into Eq. (4) as

$$C_p = D_{SN}(p) \cdot \frac{\Sigma_p \sqrt{P_N(k)}}{\Sigma_p |H(k)|^2}. \tag{5}$$

The signal realizes the desired SN ratio $D_{SN}(p)$ for each frequency band. As a result, the signal, called the bandwise minimum-noise swept-sine (BMN-SS) signal, can serve as the signal with the shortest duration used for impulse response measurement among the signals that can realize a noise level of -45 dB over the entire target band.

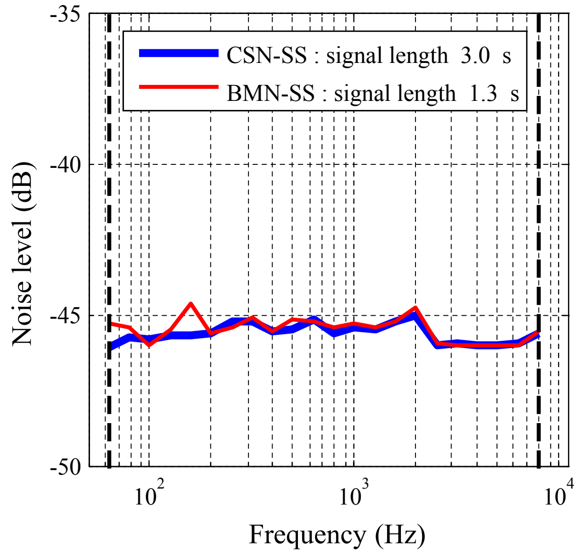

Fig. 4 Noise level for each frequency band obtained by simulation.

5. Simulation

The impulse response measurement was simulated using a conventional CSN-SS signal and a BMN-SS signal. The impulse response in a multipurpose hall (approximately 3,300 m^3) was measured and was subjected to convolution with measurement signals. Actual environmental recorded noise was added.

Figure 4 shows the noise level in the simulated results. From Fig. 4, we see that the noise level is essentially maintained at -45 dB over the target band (63–8,000 Hz) when a CSN-SS signal and a BMN-SS signal were used. The lengths of the signals required to maintain the noise level shown in Fig. 4 were approximately 3.0 and 1.3 s for the CSN-SS signal and the BMN-SS signal, respectively. From this result, the reverberation time can be measured in a shorter time using the BMN-SS signal than by using the conventional CSN-SS signal.

6. Conclusions

In this study, we determined the issues that must be solved to improve the performance of the measurement method of reverberation time using the CSN-SS signal proposed in our previous study. We proposed a BMS-SS signal to resolve the issues and demonstrated that the signal can further shorten the measurement time.

Acknowledgement

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