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Improvement of efficiency in reverberation time measurement method using constant signal-to-noise ratio swept sine signal

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1. Introduction

The reverberation time is a typical quantity for evaluating room acoustics and is generally calculated using the impulse response of the room. The conditions of the measurement of the reverberation time are specified in International Standard ISO 3382 [1], and the measurement sometimes requires a high signal-to-noise (SN) ratio. To address this problem, we have proposed an efficient measurement method using a constant-SN-ratio swept sine (CSN-SS) signal [2,3]. In this method, smoothing of the frequency characteristics of a measured noise spectrum is required to estimate the true noise spectrum. We previously confirmed this method by simulation. However, it was found that smoothing of the noise spectrum sometimes does not work well in a real situation. In this study, we examined a new method for smoothing the frequency characteristics required to synthesize a CSN-SS signal and confirmed the effectiveness of the method.

2. Measurement method for reverberation time using CSN-SS signal

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. Here, k is the discrete frequency number and is omitted in the figure. When the output signal is filtered through an inverse filter of the measurement signal, 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 $N(k)/S(k)$ as

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

Here, the environmental noise is assumed to be stationary and $P_{\mathrm{N}}(k)$ represents its power spectrum.

In the calculation of the reverberation time, the noise level for each frequency band of interest should be at least 45 dB lower than the peak level of the impulse response of the band (ISO 3382). The SN ratio required for each frequency to meet this requirement [3] is denoted as $D_{\mathrm{SN}}(k)$. Then, $SN(k)$ in Eq. (1) is replaced by $D_{\mathrm{SN}}(k)$, and the power spectrum of the CSN-SS signal, $|S(k)|^2$, is given by

$$|S(k)|^2 = D_{\mathrm{SN}}(k) \cdot \frac{P_{\mathrm{N}}(k)}{|H(k)|^2}. \tag{2}$$

A swept sine signal with the power spectrum of $|S(k)|^2$ is synthesized [2] and the impulse response is measured using this measurement signal. The measurement result has the desired SN ratio, $D_{\mathrm{SN}}(k)$. Here, $P_{\mathrm{N}}(k)$ and $H(k)$ are unknown in advance and should be estimated from a preliminary measurement.

Figure 2 shows a model diagram of the noise level of the measurement for different frequencies obtained using a conventional signal and a CSN-SS signal. For the conventional signal, the noise level is lower than −45 dB at high frequencies but higher than −45 dB at low frequencies. In the proposed method, however, a constant noise level of −45 dB, which is the minimum requirement, can be realized over the entire target band.

3. Problems of measurement in an actual environment

Previously, the validity of the proposed method was verified by simulation [3]. In an actual environment, however, the noise level of the measurement sometimes increased near the lowest frequency of the target band, as shown in Fig. 3. We examined the cause of this and found that the noise in the measurement environment had highly periodic peaks at low frequencies, as indicated by the green line in Fig. 4. In our previous work, noise spectra $P_{\mathrm{N}}(k)$ were smoothed by extracting a short-time section of the autocorrelation function of the noise to estimate the noise spectrum. This was considered to result in the underestimation of the intrinsic noise peaks, as shown by the blue line in Fig. 4, and failure to control the noise level.

4. Proposed method for smoothing spectra

Our proposed method for smoothing spectra combines two smoothing techniques.

The reverberation time is measured by either a one or one-third octave band. Hence, the frequency band is narrow at low frequencies and the band energy is easily affected by peaks and dips in the noise. For low frequencies, we adopted a linear prediction, which can be used to accurately estimate the peaks of periodic noise and determine the spectral envelope.

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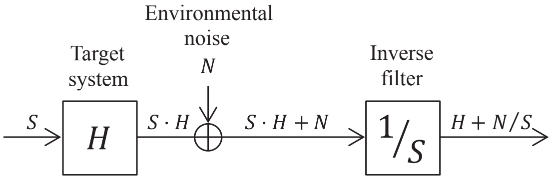

Fig. 1 Principle of impulse response measurement.

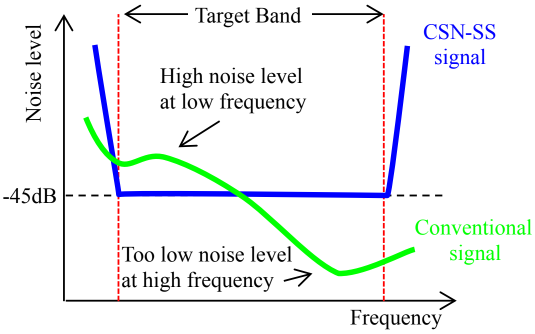

Fig. 2 Model diagram of measured noise levels for different frequency bands.

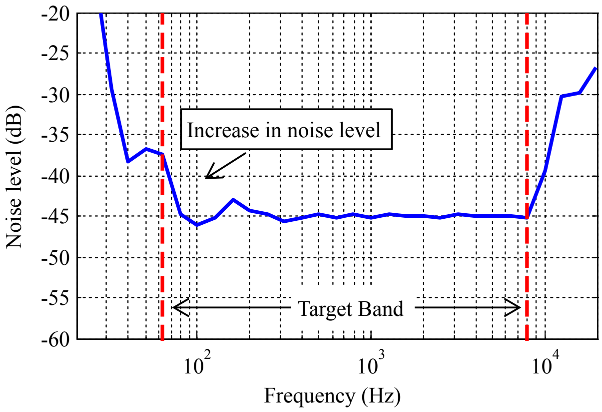

Fig. 3 Increase in noise level at low frequencies measured in an actual environment.

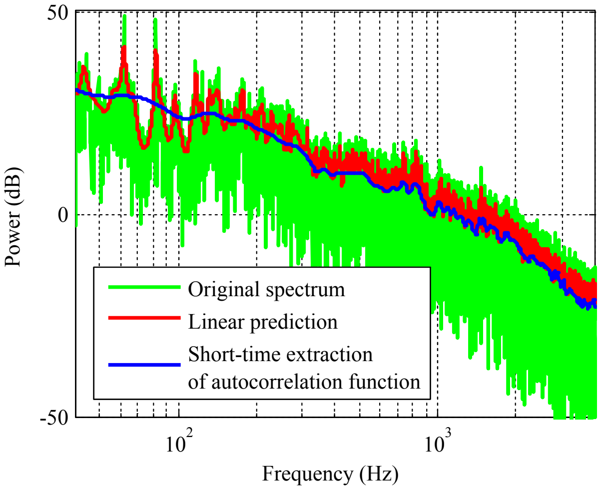

Fig. 4 Result of smoothing noise spectra.

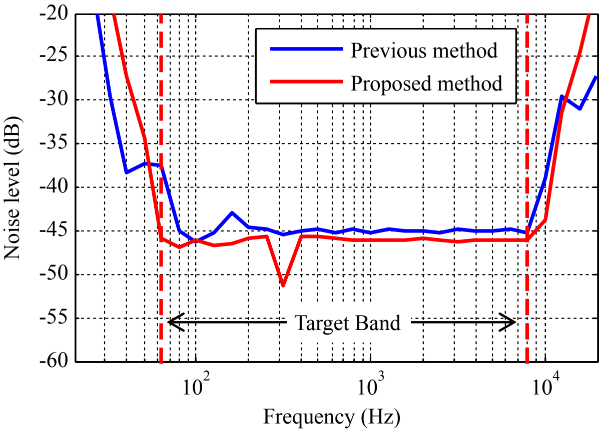

Fig. 5 Noise level in measurement obtained by the proposed smoothing method and previous method.

For high frequencies, the noise spectra were smoothed by extracting a short-time section of the autocorrelation function of the noise. Octave bands are wide at high frequencies. The adverse effect of the randomness of noise can be suppressed by this smoothing method rather than by accurately expressing the individual peaks and dips in the band.

In Fig. 4, the blue and red lines represent the results obtained by short-time extraction of the autocorrelation function and linear prediction, respectively. The two smoothed results intersected in the frequency range of 150–650 Hz and were taken to be the final estimated noise spectra.

5. Noise level and measured reverberation time

The reverberation time was measured in a room to confirm the validity of the proposed method. The room had dimensions of $6.3 \times 9.1 \times 2.8\,\mathrm{m}^3$ and a volume of $161\,\mathrm{m}^3$. A full-range speaker (Bose Corporation, MM-101) and a woofer (Yamaha Corporation, NS-SW300) were used for the measurement.

Figure 5 shows the noise level of the measurement. The noise level was essentially maintained at −45 dB over the target band (63 Hz–8 kHz, 1/3 octave band). Figure 6 shows the reverberation time for different bands calculated from the measurement. The true values in the figure were obtained from a long-time (signal time length, 43 s) measurement using a Log-SS signal [4]. It was confirmed that the reverberation times obtained using the CSN-SS signal were in good agreement with the true values.

6. Conclusions

In this report, we proposed an effective method of smoothing the spectra of environmental noise required to synthesize a CSN-SS signal. In the proposed method, different techniques are used to smooth the spectra at low and high frequencies. Using this method, the increase in the noise level at low frequencies that occurs in the conventional method was successfully prevented.

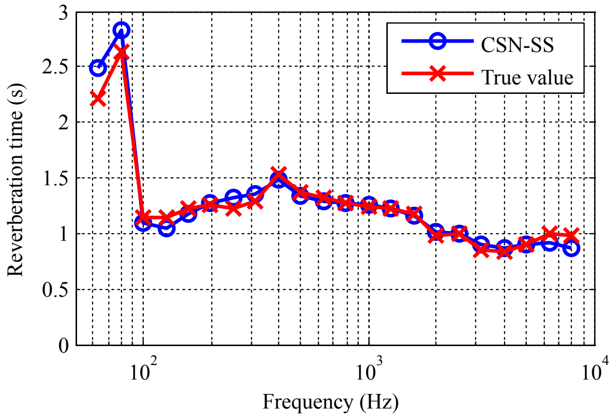

Fig. 6 Measured reverberation time.

Acknowledgement

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