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A study of non-linear effect on acoustic impulse response measurement

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1. Introduction

Impulse response is a fundamental characteristic of linear acoustical systems because such characteristics as frequency response and the reverberation curve can be calculated from the impulse response. However, there are error factors in the measurement of impulse response and the effects of these factors remain unclear. Dunn[1] and Vanderkooy[2] studied the effect of non-linearity on measurement using the maximum-length sequence (M-sequence), which is one of the most common measuring signal. While most of their studies were based on computer simulation, the present study is based on experimental results in practical situations.

This paper analyzes the errors in room impulse response measurement caused by the non-linearity of the loudspeakers and indicates what is needed to reduce measurement error.

2. Measurement errors caused by non-linearity

Figure 1 illustrates how room impulse response is measured using the M-sequence. M-sequence $m(k)$ is applied to a loudspeaker and emitted in a room. The impulse response (including the loudspeaker's response) is derived from the result of the circular convolution of signal $y(k)$ received by a microphone and the time-reversed M-sequence $m(-k)$.

The non-linear distortion of the loudspeaker causes measurement error. Figure 2(a) shows an example of a measured response with large non-linear distortion. The error caused by the non-linearity appears as pulses randomly excited but almost equally distributed over the measurement period. We call this non-linear error.

The non-linear distortion of a loudspeaker is reduced by reducing the output sound level. Figure 2(b) shows the result when the output is reduced by 36 dB compared to Fig. 2(a). The pulsive non-linear error is reduced. Too much reduction in the output sound level, however, reduces the signal-to-background noise ratio. This causes the increase of equally distributed random error, as shown in Fig. 2(c). The next section quantitatively demonstrates the relationships of this phenomena.

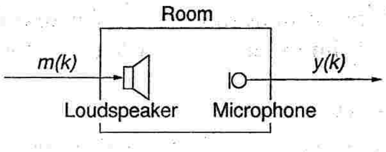

Fig. 1 Block diagram of room impulse response measurement using M-sequence $m(k)$.

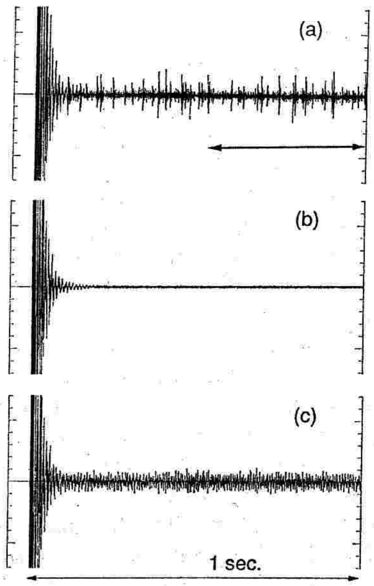

Fig. 2 Examples of measurement errors when the loudspeaker output is (a) too large, (b) moderate, and (c) too small. The vertical scales are magnified.

3. Measurement errors and output level of loudspeaker

Actual impulse response is well attenuated over the time period shown by the arrow in Fig. 2(a). In other words, only the error component is observed in this period. Error power P_T calculated in this period is the sum of non-linear error power P_D and error power P_N due to background noise. Assuming the background noise is stationary, the error signal due to background noise is derived by taking the convolution of the time-reversed M-sequence $m(-k)$ and the microphone output when the loudspeaker emits no sound. Error power P_N is calculated by taking the mean square of this error signal. Now the non-linear error power P_D can be calculated by

$$P_D = P_T - P_N \,. \qquad (1)$$

The experimental conditions were as follows. An M-sequence with a period of 16,383 was used for measurement. The frequency range of the measured impulse response was 100–3,500 Hz; the sampling frequency was 8 kHz. Measurements were conducted in a room with a reverberation time of 200 ms. Full-range loudspeakers with a diameter of around 10 cm were used. A microphone was set 0.5 m from the loudspeaker. Background noise level was 23 dB (equivalent sound level of the sum of acoustical and electrical noise in 100–3,500 Hz).

3.1 Optimal output sound level

Figure 3 shows experimental result. The horizontal axis represents the output sound level of the M-sequence from the loudspeaker at a distance of 0.5 m. The vertical axis represents the error level relative to the impulse response energy. Line ① shows the error power P_N due to background noise, line ② shows the non-linear error power P_D, and line ③ shows the total error power P_T.

The background noise power is constant. However, the error power due to the background noise decreases as the output sound level of the M-sequence increases as shown by line ①, because of the increase in the SNR. The non-linear error power P_D increases almost linearly as the output sound level increases. The total error P_T, the sum of P_N and P_D, has the minimum value as shown by line ③. This trade-off relationship between P_N and P_D was also pointed out by Dunn and Hawksford based on simulation.[1] The optimal sound level giving the minimum total error power is about 72 dB in this example.

3.2 Background noise level and optimal sound level

When the background noise level increases, line ① in Fig. 3 shifts upwards; the line for P_T also changes. Shifting the line ① upwards by 20 dB and 40 dB, therefore, gives the lines for noise levels of 43 dB and 63 dB, which are plotted by dotted lines in Fig. 4. The total error level P_T for each background noise level is shown by solid curves. These curves were derived by adding the dotted lines of P_N to the non-linear error level P_D shown by the dash-dot line.

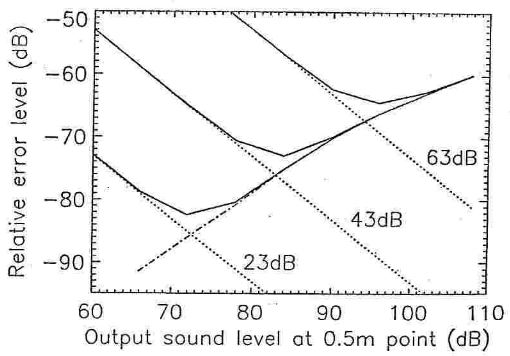

Fig. 4 Change in optimal sound level due to background noise level variation.

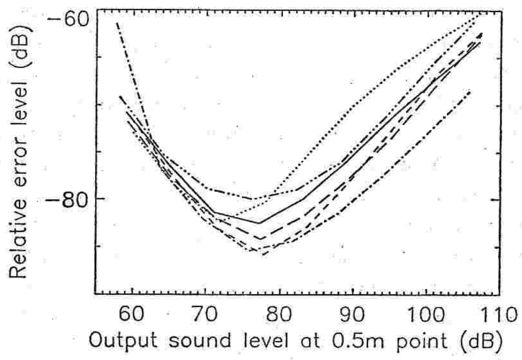

Fig. 5 Dependence of measurement error on type of loudspeaker.

Figure 4 indicates that the optimal sound level, which gives the minimum value of P_T, increases as the background noise level increases. Please note that the increase in the minimum value of P_T is less than the increase in the background noise. Figure 4 shows that the minimum value increases by about 12 dB for each 20 dB increase in background noise.

3.3 Dependence of measurement error on loudspeaker type

Impulse responses were measured using different types of full-range loudspeakers, all with a diameter of about 10 cm. The total error P_T for each loudspeaker was calculated and overplotted in Fig. 5. The maximum difference in the minimum values is about 6 dB. This result indicates that proper selection of the loudspeaker is important for accurate measurement.

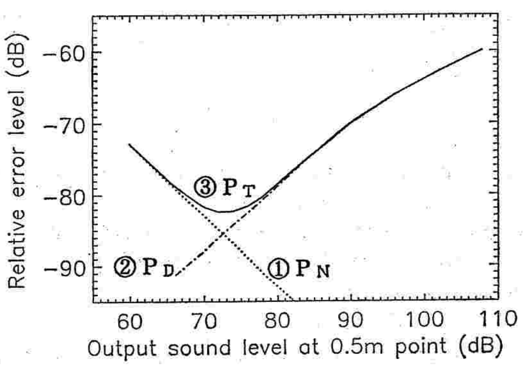

Fig. 3 Output sound level and measurement errors. ① P_N: error caused by background noise, ② P_D: error caused by non-linearity, ③ P_T: total error.

4. Conclusion

Non-linear errors in room impulse response measurement were studied experimentally. The results demonstrate that the measurement error caused by non-linearity increases as the output sound level from a loudspeaker increases, while the error caused by background noise decreases. It is concluded that the total measurement error should be minimized by selecting the optimal output sound level and the optimal loudspeaker.

Similar error features should also be observed for different measurement signals from the M-sequence, but this remains for future study.

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References

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2) J. Vanderkooy, "Aspects of MLS measuring systems," J. Audio Eng. Soc. **42**, 219–231 (1994).