Compensation of Temperature Fluctuation in Inverse System of Sound Field Reproduction by Linear Warping Processing

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This paper describes a compensation method for temperature fluctuation by linear-time-warping processing which is applied to the impulse responses of room transfer functions (RTFs) to achieve the high-quality sound field reproduction system. At first, RTFs were measured before and after temperature fluctuation, and the former were transformed into the latter by the proposed processing. Next, we design inverse filters for the reproduction system, and evaluate the improvement of the reproduction accuracy. By using an adequate warping ratio, we can improve the reproduction accuracy of about 10 dB in average.

INTRODUCTION

To achieve a sound field reproduction system by loudspeaker, it is important to design multichannel inverse filters which cancel the effects of room transfer functions (RTFs). We often consider the RTFs as a time-invariant system. However, the time invariance of the RTFs cannot be guaranteed in a real acoustic environment. The temperature fluctuation is the most important factor which modifies a propagation time of sound because the sound speed is a function of temperature. From the above-mentioned reason, we should rescale (or "warp" in other words) the time axis of the impulse responses of RTFs to compensate the room temperature fluctuation.

Hikichi and Itakura have been examined how the RTFs change under various temperature conditions, and proposed a time axis scaling technique to compensate the time varying characteristics of the RTFs [1]. In this paper, we apply the time-warping method to the inverse system of multichannel sound field reproduction system.

LINEAR-WARPING PROCESSING

Consider to warp N-point-length impulse response of RTF, \( g(n) \), into \( g'(m) \) with a warping ratio \( C_{th} \). First, \( g(n) \) is transformed into a frequency domain by DFT, this can be given by

\[
G(k) = \sum_{n=0}^{N-1} g(n)e^{-j\frac{2\pi kn}{N}} \quad (0 \leq k \leq N - 1), \tag{1}
\]

where \( G(k) \) is a frequency-domain representation of \( g(n) \).

Next, we find \( g'(m) \) at every sampled point \( m \) \((0 \leq m \leq M - 1)\), where \( M \) is a maximum integer which does not exceed \( C_{th} \cdot N \). If \( C_{th} \geq 1 \), \( g'(m) \) can be given by

\[
g'(m) = \begin{cases} 
\frac{1}{N} \sum_{k=0}^{M-1} G(k)e^{-j\frac{2\pi km}{C_{th}N}} & \text{otherwise} \\
\sum_{k=0}^{M-1} G(k)e^{-j\frac{2\pi km}{C_{th}N}} + \sum_{k=N-M}^{N-1} G(k)e^{-j\frac{2\pi km}{C_{th}N}} & \end{cases} \tag{2}
\]

otherwise \( g'(m) \) can be given by

\[
g'(m) = \frac{1}{M} \sum_{k=0}^{M-1} G(k)e^{-j\frac{2\pi km}{C_{th}N}} + \sum_{k=N-M}^{N-1} G(k)e^{-j\frac{2\pi km}{C_{th}N}} \tag{3}
\]

Theoretical value of the warping ratio is defined as a ratio of two sound speeds as shown below:

\[
C_{th} = (331.5 + 0.6T_0)/(331.5 + 0.6T_i), \tag{4}
\]

where \( T_0 \) is an original room temperature, and \( T_i \) is a room temperature after fluctuation in time \( t \).

MEASUREMENT OF RTFS

The impulse responses used in this study are measured in an acoustic experiment room. The arrangement of apparatus is shown in Fig. 1. Time stretched pulse (TSP) is used as the sound source signal for measuring, where TSP signal length is 131072-point, sampling frequency is 48000 Hz, and addition for averaging is 4 times. The impulse responses were measured before and after temperature fluctuation, where the room temperature of \( T_0 \) is 27.6 °C in average, and that of \( T_i \) is 26.2 °C in average.

COMPENSATION OF RTFS

We try to warp the impulse responses of RTF, \( TF_0 \), which were measured at \( T_0 \) to those of RTF, \( TF_i \), which were measured at \( T_i \). Hereafter, we define that \( TF'_0 \) is the warped \( TF_0 \) by the theoretical warping ratio 1.0024 which is obtained by Eq. (4), and \( TF''_0 \) is the warped \( TF_0 \) by the adequate warping ratio 1.00195 which is obtained by a preliminary experiment.
EVALUATION OF SDRS

16384-point-length inverse filters in which the pass-band range is 150–4000 Hz are designed from 4096-point-length TF₀, TF₁, TF₂, and TF₃, respectively, for multichannel sound field reproduction system [2]. The filters are designed based on least-norm solution method [3]. Each filter is convolved with TF₁, and the reproduction accuracy for original source is evaluated with the signal-to-deviation ratio (SDR) at each control point.

Table 1 shows the result of the SDRs in which C₁–C₆ indicate control points. The SDRs reproduced by TF₀ degrade by 48.5 dB in average in comparison with those by TF₁. In the case of TF₂ which is warped by the theoretical warping ratio, the degradation of SDRs is 43.6 dB in average. In the case of TF₃ which is warped by adequate warping ratio, the degradation of SDRs is 38.5 dB in average, i.e., we can improve the SDR by about 10 dB by using the proposed compensation method. Also, although the difference between warping ratios is very small, the difference of SDRs is not so small.

Figure 2 shows the expanded waveform which is obtained by the convolution of inverse filters with impulse responses at C₂. These results reveal that the error can be reduced, and in particular, the error after the peak is remarkably decreased. From this, we confirm that the proposed compensation method is effective and indispensable for the realization of the accurate sound reproduction system in a real acoustic environment.

CONCLUSIONS

We described a compensation method for temperature fluctuation by linear-time-warping processing for a sound field reproduction system. In the numerical simulation, we can improve the reproduction accuracies by about 10 dB using the proposed method with an adequate warping ratio. Therefore, in future, we must obtain the fluctuation of sound speed without measuring the temperature precisely to innovate the warping method to the sound field reproduction system.

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