3P2-10

Measurement Error of Temperature Distribution Using Acoustic Probe and Matrix Method

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1. Introduction

The measurement of temperature distribution is an important technique in various fields like meteorology[1] and architecture[2]. An acoustic probe, which emits sound waves and measures the time-of-flight (ToF) of sound waves to reach a microphone, can measure the average temperature along the sound propagation path. By placing multiple acoustic probes around the measurement space, it is possible to measure the temperature distribution in the space with fewer sensors compared to point-type sensors like thermocouples or resistance thermometers[3].

The accuracy of measuring temperature with acoustic probe depends on the accuracy of ToF measurement. The measurement error of ToF depends on the signal-to-noise ratio (SNR) of the signal received by the microphone. However, the error propagation from the ToF to the temperature distribution has not been studied well.

In this study, we investigate the effect of measurement error in the ToF of sound waves on the measurement of temperature distribution using acoustic probes.

2. Principle of Temperature Measurement

2.1. Overview of acoustic probe

The acoustic probe consists of a speaker (SP) and a microphone (MIC) is shown in **Fig. 1.** The speed of sound in air c (m/s) is calculated as

$$c = 331.45 + 0.607T, \tag{1}$$

where T (°C) represents the air temperature. The average sound velocity $\overline{c}$ (m/s) between speaker and microphone can be calculated as

$$\overline{c} = L/t\,, \tag{2}$$

where t (s) and L (m) represent the ToF of the sound wave and the length of the acoustic path, respectively. Then, transforming Eq. (1), we can obtain the average temperature between SP and MIC as,

$$T = (\overline{c} - 331.45)/0.607\,. \tag{3}$$

2.2. Measurement of Temperature Distribution Using Matrix Method

By placing multiple acoustic probes, the temperature distribution in a space can be measured. **Figure 2** shows the measurement of the temperature distribution in an space divided by $m \times n$ cells. The ToF of the sound wave t_i can be calculated as

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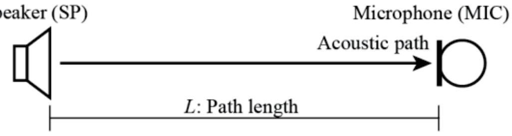

Fig. 1 Acoustic probe

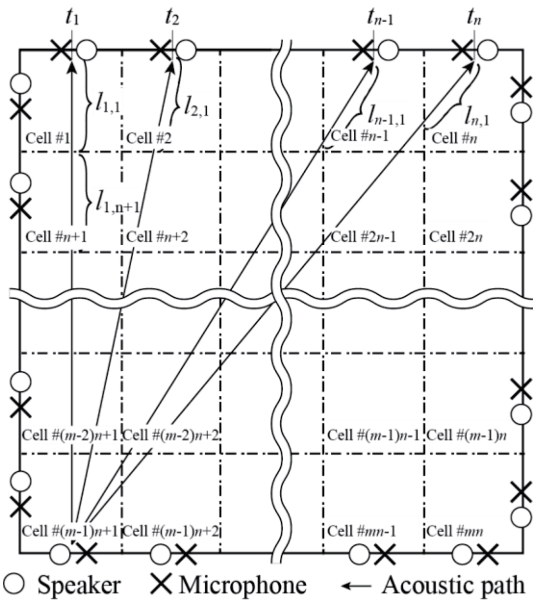

Fig. 2 Measurement of temperature distribution using acoustic probe.

$$\begin{pmatrix} l_{1,1} & \cdots & l_{1,N} \\ \vdots & \ddots & \vdots \\ l_{M,1} & \cdots & l_{M,N} \end{pmatrix} \begin{pmatrix} 1/c_1 \\ \vdots \\ 1/c_N \end{pmatrix} = \begin{pmatrix} t_1 \\ \vdots \\ t_M \end{pmatrix}, \tag{4}$$

where the number of acoustic paths is M and the number of cells is N, the distance that path i passes through cell j is $l_{i,j}$, and the sound velocity of the sound wave in cell j is c_j. By solving the inverse problem for c_j in Eq. (4), the sound speed distribution and the temperature distribution can be calculated.

3. Simulation of Measurement Error in Temperature Distribution

The measurement error of the ToF due to noise was verified. White Gaussian noise at various SNRs was added to an up-chirp signal with a center frequency of 5.5 kHz, bandwidth of 9 kHz, and signal length of 1 ms. **Fig. 3** shows a histogram of the ToF measurement error when SNR equals -5 dB, and **Fig. 4** shows the mean and the standard deviation of ToF measurement error under noise at various

SNRs. The measurement error approximately follows a normal distribution, whose mean is constant regardless of SNR, whereas standard deviation decreases with increasing SNR.

Assuming the measurement of the temperature distribution shown in **Fig. 5**, we verified the effect of ToF measurement error due to noise on the measurement error of the temperature distribution. While varying the SNR, the measurement error following a normal distribution of the corresponding mean and standard deviation based on the results showed in Fig. 4 is added to the ToF for each path. The temperature distribution is then calculated using Eq. (4) based on the ToF of each path to which the error has been added. The mean absolute error between the calculated temperature distribution and the temperature distribution given in Fig. 5 is calculated to evaluate the measurement error of the temperature distribution. m and n are set to 5, and the cells on each side are set to 0.8 m.

Figure 6 shows the measurement error of the temperature distribution. The average temperature measurement error for each path is constant regardless of the number of paths, while the measurement error of the temperature distribution increases with decreasing the number of paths. For example, when the number of paths is 31 and the SNR is -5 dB, the average error in the temperature measurement for each path is 0.06°C, but the error in the measurement of the temperature distribution increases to 1.07°C. Generally, temperature measurement for air conditioning control requires accuracy within 0.5°C. This result implies that even if each probe has sufficient accuracy for air quality control, the accuracy of temperature distribution measurements may not meet requirements.

4. Conclusion

In this study, the error propagation from the measurement of ToF to the measurement of temperature distribution was investigated. The results show that when the number of paths is 31 and the temperature error due to ToF measurement error is 0.06°C, the temperature distribution measurement error increases to 1.07°C.

Ackowledgement

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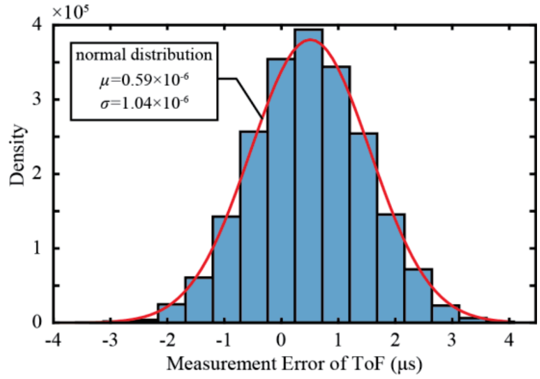

Fig. 3 Measurement error of ToF when SNR equals -5 dB.

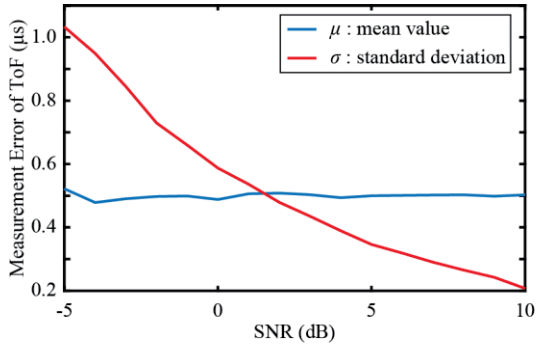

Fig. 4 Mean and standard deviation of ToF measurement error under noise at various SNRs.

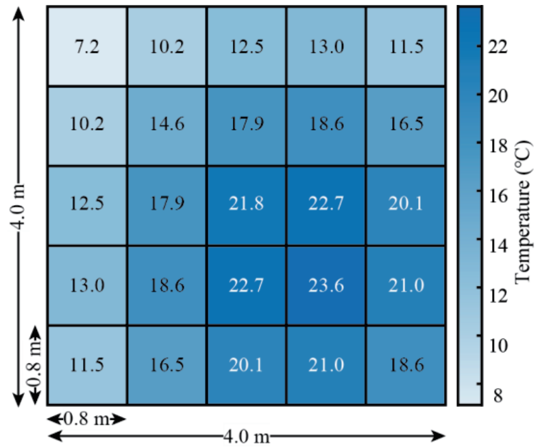

Fig. 5 Virtual temperature distribution used for simulation.

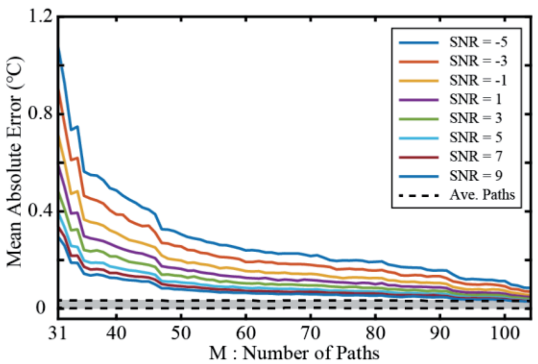

Fig. 6 Measurement error of temperature distribution.