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Improvement of Air Temperature Measurement Accuracy on Ultrasonic Probe Utilizing Sound Attenuation

音波減衰情報を活用する音響波プローブによる気温計測精度向上

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1. Introduction

Acoustic air temperature measurements based on the relationships between sound velocity and temperature have been proposed[1)]. In these techniques, an ultrasonic probe measures the sound velocity in air and temperature can be calculated from the measured sound velocity under the assumption that sound velocity only depends on temperature. The techniques have advantages that instantaneous temperature can be measured, and the measurements are not affected by thermal radiation because air is used as a sensor in the acoustic measurements. On the other hand, the conventional techniques have a problem that the sound velocity difference caused by humidity is ignored. The sound velocity in moist air is faster than that in dry air. Therefore, the temperature obtained by the sound velocity in moist air is higher than true temperature, and known as virtual temperature. The difference between virtual temperature and true temperature has been regarded as the temperature error.

To improve the air temperature measurement accuracy on ultrasonic probe, an acoustic technique is proposed in this paper. In previous work, sound velocity was corrected by using commercially available non-acoustic humidity sensors in addition to the probe[2)]. Instead of using additional humidity sensors, sound attenuation is measured as well as sound velocity by an ultrasonic probe in our proposed technique. Sound attenuation also depends on temperature and humidity. Therefore, air temperature and humidity can be calculated from the measured sound velocity and attenuation. Temperature is measured by the proposed technique, and compared with the virtual temperature to verify the improvement of air temperature measurement accuracy.

2. Principle of Measurement

The ultrasonic probe is composed of a pair of ultrasonic transducers, and the probe length, L, is known. As the measurement signal, a chirp signal and a sinusoidal burst signal are mixed and transmitted. First, the time-of-flight between the probe, t, is measured by cross-correlation method using a chirp signal, because the signal to noise (S/N) ratio is improved by using the pulse compression effect. Sound velocity can be calculated as, $c_{\mathrm{mes}} = L/t$. In dry air, the sound velocity, c'_{th}, only depends on temperature, T.

$$c'_{\mathrm{th}}(T) = \sqrt{c_0 (T / T_0)}. \tag{1}$$

Here, c_0 is the sound velocity at the temperature, T_0 = 273.15 K. The sound velocity in moist air, c_{th}, is

$$c_{\mathrm{th}}(T, H_R) = c'_{\mathrm{th}}(T) \Big/ \sqrt{1 - \frac{E(T) H_R}{A}\left(\frac{\gamma_w}{\gamma_a} - \varepsilon\right)}, \tag{2}$$

where $E(T)$, H_{R}, A, γ_{w}, γ_{a}, and ε are saturation vapor pressure, relative humidity, atmospheric pressure, specific heat ratio of water, specific heat ratio of air, and molecular weight ratio between water and dry air, respectively. When sound velocity is measured in moist air, virtual temperature is calculated by eq. (1) from the measured sound velocity in conventional techniques. Then, the difference between virtual temperature and true temperature, dT, is expressed by eq. (3), and shown in **Fig. 1**.

$$dT(T, H_{\mathrm{R}}) = T_0 \left[c_{\mathrm{th}}(T, H_{\mathrm{R}}) / c_0 \right]^2 - T. \tag{3}$$

To correct the temperature error, sound attenuation is utilized. Sound attenuation is measured by a sinusoidal burst signal at the center frequency of transducers for high S/N ratio, because sound attenuation measurement in air is easily affected by noises and transducer characteristics. The maximum value of the cross-correlation between received signal and sinusoidal burst signal is the energy at the single frequency which contains no noises at

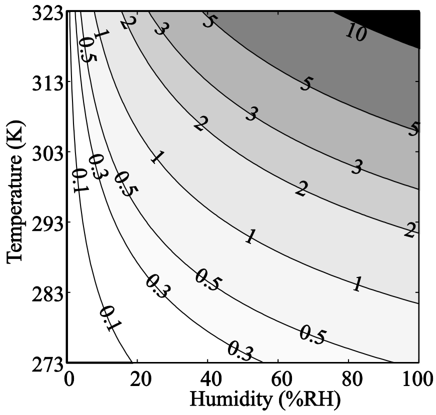

Fig. 1 Difference between virtual temperature and true temperature (K).

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other frequencies. Thus, the energy divided by signal length can be regarded as the root-mean-square (RMS) value of received signal, V_R. When the RMS value of transmitted signal, V_T, is known, attenuation coefficient in air can be calculated as, $\alpha_{mes} = 10\log_{10}(V_T/V_R)/L$. Then, the theoretical equations about attenuation coefficient, α_{th}, are suggested by ISO 9613-1[3]. It is regarded as that attenuation coefficient depends on temperature and humidity, $\alpha_{th}(T, H_R)$, when sound source frequency is known[4]. Therefore, temperature T and humidity H_R can be determined so as to satisfy eq. (4) using an optimization method from the measured sound velocity c_{mes} and attenuation coefficient α_{mes}.

$$\begin{cases} c_{th}(T, H_R) - c_{mes} = 0, \\ \alpha_{th}(T, H_R) - \alpha_{mes} = 0. \end{cases} \tag{4}$$

3. Experimental Procedure and Results

The temperature in moist air is measured in the thermostat and humidistat chamber (SH241, Espec) that keeps inside temperature and humidity uniformity. In this chamber, narrowband ultrasonic transducers (MA400A1, Murata) whose center frequency is 400 kHz are set up as shown in **Fig. 2** for ultrasonic probe. While keeping the humidity at 60%RH, temperature was varied at 293, 298, 303, 308 K in the chamber. In each condition, sound velocity and attenuation coefficient are measured 100 times. As the measurement signal, an up-chirp signal at 380-420 kHz and a sinusoidal burst signal at 400 kHz of 0.5 ms are mixed and transmitted. The applied voltage is 44.8 V peak to peak, and the standard sensitivity of transducers is 10 V/Pa. The sampling frequency is 1 MHz. The signals are generated and processed by a computer. The transducers are connected to the computer via A-D/D-A converter (USB-6259, National Instruments) and amplifiers. The computer processes received signals, and extracts sound velocity and attenuation coefficient. Temperature and humidity are finally obtained by optimization procedure. The reference of temperature and humidity are measured by the wet-dry hygrometer set in the chamber.

Experimental results of sound velocity and attenuation coefficient measurements are shown in **Fig. 3(a)** and **3(b)**, and the measured sound velocity and attenuation coefficient almost agree with the theoretical curves at 60%RH. Then, temperature errors are shown in Fig. 3(c). The differences of results between both techniques agree with the theoretical temperature error calculated by eq. (3), and measurement accuracy improvement by the proposed technique is confirmed. Moreover, the humidity is calculated as shown in Fig. 3(d).

4. Conclusion

In this paper, an acoustic technique focused on sound velocity and attenuation was proposed to improve the temperature measurement accuracy by ultrasonic probe in moist air. As a practical examination, temperature were measured, and compared with the conventional techniques. At the results, the improvement of temperature measurement accuracy by utilizing sound attenuation was confirmed.

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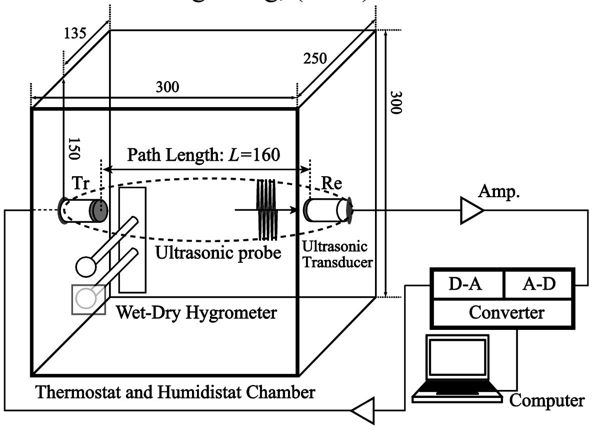

Fig. 2 Experimental setting.

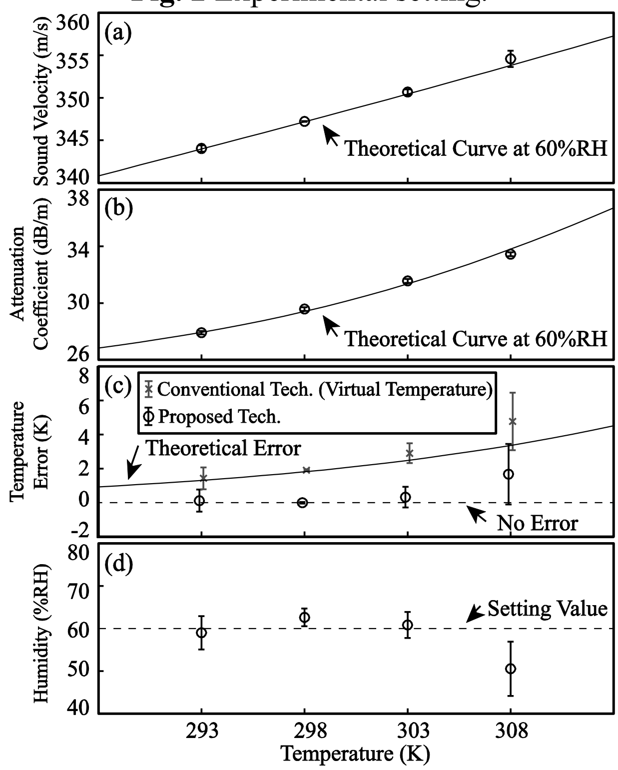

Fig. 3 Experimental results at 60%RH.