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Measurement of Humidity Based on Sound Attenuation
音響波の減衰に基づく湿度計測

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1. Introduction

In a museum, the cultural assets with historical value are preserved. The temperature and humidity management is necessary so that these cultural assets may be damaged because of insects, mold, or decomposition. Therefore, the temperature and humidity measurement system are requested to prevent these damages. However, compared with the temperature, the humidity changes greatly by a little change of environment. It is difficult to observe spatial average humidity in a room because a conventional sensor such as a wet-dry hygrometer measures the local humidity at a measurement point that depends on the setup.

In this paper, an acoustic technique is proposed, for measuring the spatial average humidity. In previous work, the ultrasonic sensor that utilizes influences of humidity to sound velocity is proposed [1]. The sensor measures average humidity on the line between sensors. Our proposed technique is based on the room acoustics, and uses sound attenuation in audible frequency for spatial average measurement in a room. The damping phenomenon of sound used in the technique is expressed by the parameter called attenuation coefficient, which depends on the temperature and humidity [2,3]. The attenuation coefficient is determined by the measurement under the condition of a constant temperature, and humidity is calculated in order to verify the results.

2. Principle of Measurement

When the sound wave propagates in a room, the intensity of sound attenuates by damping in air and surface absorption. The intensity of sound, I, after the propagation via path length, L, is expressed by

$$I = I_0 e^{-\left(\frac{a}{4V}+m\right)L}. \qquad (1)$$

Where I_0, a, V, and m are initial intensity, total surface absorption, volume of a room, and attenuation coefficient of sound, respectively. The total surface absorption that depends on experimental environment is constant, and can be measured beforehand. The attenuation coefficient is a function of temperature, T, and relative humidity, H_R.

$$m(T, H_R) = (33 + 0.2T) f^2 \times 10^{-12} + \frac{Mf}{\frac{k}{2\pi f} + \frac{2\pi f}{k}} \quad (\mathrm{m}^{-1}). \qquad (2)$$

Where f, $M(T)$, and k are frequency of sound source, function of temperature given by the reference [2], and angular relaxation frequency of oxygen molecules in air, respectively. The angular relaxation frequency is given by the absolute humidity, H_A, which is given by saturation vapor pressure, $E(T)$, total pressure, A, and relative humidity, H_R.

$$k = 1.92 H_A^{1.30} \times 10^5 \quad (\mathrm{s}^{-1}). \qquad (3)$$

$$H_A = \frac{E(T) H_R}{A}. \qquad (4)$$

The relation between relative humidity and attenuation coefficient is expressed by a solid line in **Fig. 1**, when the frequency of sound source is 10 kHz and temperature is 20 °C. Thus, it is understood that the attenuation coefficient becomes maximum within the range of low humidity, near 20 %. In general, it does not become such low humidity in an indoor condition. Therefore, low humidity is not an object of the measurement and management. In this paper, the range of high humidity since the peak is targeted. The relative humidity and attenuation coefficient correspond uniquely with each other because attenuation coefficient decreases monotonously within the range of high humidity. Relative humidity can be determined by the measured attenuation coefficient.

To determine the attenuation coefficient, m, reverberation time is utilized. The measurement based on the attenuation of intensity by eq.(1) is difficult since the change of intensity by the humidity is smaller than the surrounding noise in audible frequency. In this paper, the reverberation time is defined as the time for attenuation in sound pressure level, ΔL_p, achieves -60 dB from its maximum value in a room. The reverberation time is given by

$$t = -\frac{4}{10\log_{10} e} \frac{\Delta L_p V}{c(a + 4mV)}. \qquad (5)$$

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Where the sound velocity, c, is depending on temperature. Therefore, the attenuation coefficient is determined by reverberation time, and the relative humidity is obtained.

3. Experimental Procedure and Results

We measured the relative humidity in the room whose volume is 300×300×250 (mm^3) as shown in **Fig. 2**. The room is thermostat and humidistat chamber (SH241, Espec) that can keep the inside temperature and relative humidity constant. The humidity variation in this chamber is within ±3 %. In this chamber, the loudspeaker (ND20FB-4, DAYTON) and microphone (WM-61A, Panasonic) are set up as shown in Fig. 2 for the acoustic measurement. The environment in this chamber is the temperature 20 °C constant, and change the relative humidity, 50, 60, 70, 80 %. In each condition, reverberation time is repeatedly measured 100 times. As the measurement signal, a sine burst pulse at 10 kHz of 10 cycles is used. The sampling frequency is 250 kHz. A signal generation and processing are carried out by a personal computer (PC). The loudspeaker and microphone are connected to the PC via an A-D/D-A converter (USB-6212, National Instruments) and an amplifier. The PC processes the received signal from the microphone, and extracts the reverberation time. Based on the reverberation time, the attenuation coefficient is calculated, and the relative humidity, H_{Rmes}, is finally obtained. The reference of humidity, H_{Rref}, is measured by the wet-dry hygrometer that set in this chamber.

The measurement results of the attenuation coefficient are shown in Fig. 1. The calculated humidity from averaged reverberation time is plotted as circle on this figure. The error bars indicate their standard deviations. According to Fig.1, by the proposed technique based on the reverberation time, the attenuation coefficient can be measured in the same order as the theoretical value and previous work. Therefore, the results of humidity obtained by the attenuation coefficients shown in **Table 1** have good agreements with the reference values.

4. Conclusion

In this paper, the humidity measurement technique based on sound attenuation was proposed. As a practical examination of this technique, the attenuation coefficients in the thermostat and humidistat chamber were measured, and compared with the theoretical values. According to the results, the possibility of humidity measurement by the proposed technique was suggested.

References

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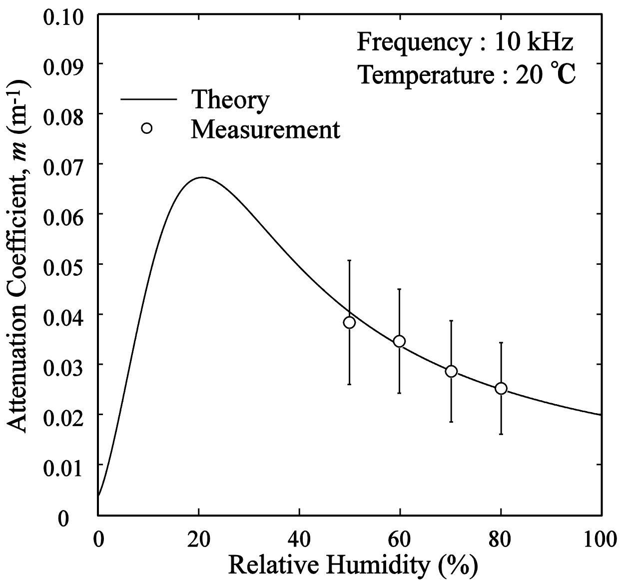

Fig. 1 Relation between relative humidity and attenuation coefficient with experimental results.

Table 1 Experimental results of relative humidity.

H_{Rref} (%)	50	60	70	80
H_{Rmes} (%)	52.8	58.5	70.3	79.5

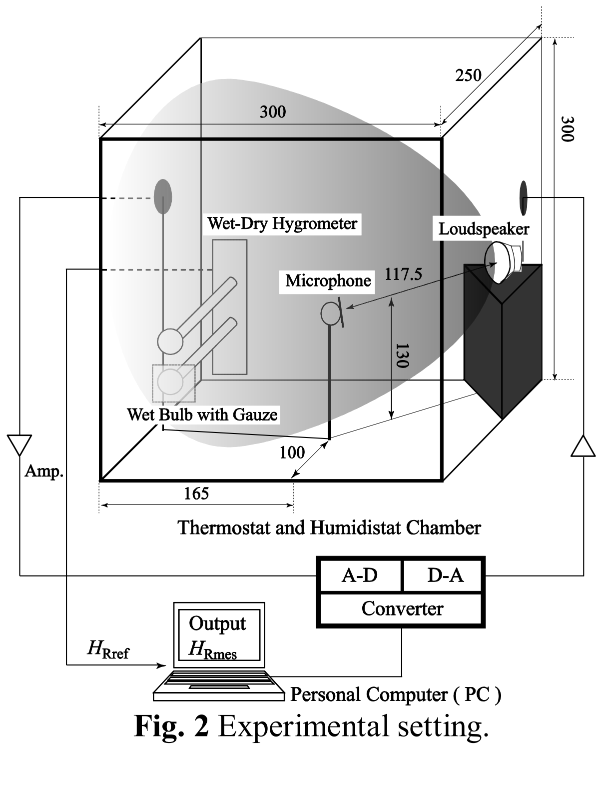

Fig. 2 Experimental setting.