Humidity effect onto measurement of ensemble averaged surface normal impedance of materials using combination of microphone and particle velocity sensor

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ABSTRACT
In our former papers, we presented the concept and sample results of a method (EA-method, for short) to measure ensemble averaged surface normal impedance of materials using a sound probe combining sound pressure and particle velocity sensors (pu-sensor). Recently, pu-sensors have been widely used in acoustical measurements, especially in measurements on architectural acoustics. However, insufficient information is available on sensors stability or accuracy in its practical use. Herein, we conducted a series of measurements following the EA-method to examine the effect of relative humidity onto pu-sensor’s sensitivity. Two sets of pu-sensor were calibrated in an impedance tube to obtain the correction values. Then, with combinations of pu-sensor and correction values, ensemble averaged surface normal impedance of glass wool were measured. All measurements were conducted in a reverberation room under controlled humidity from 30\% to 60\%. Stability of the pu-sensors were investigated by observing fluctuations of their correction values and by observing the fluctuations' effect onto the corrected absorption characteristics of the material. Finally, the relationships among relative humidity, correction values and differences of absorption characteristics were clarified.

Keywords: Relative humidity; pu-sensor; measurement method

1. INTRODUCTION

For the purpose of measuring sound absorption characteristics of materials, various methods have been proposed\textsuperscript{[1-3]}, including some of the recent studies utilized a pressure-velocity probe (pu-sensor, in short)\textsuperscript{[4-5]}. Utilizing this pu-sensor, authors also proposed one method (namely EA-method) to measure the surface normal impedance of material applying an ensemble-averaging technique\textsuperscript{[6-7]}. On the application of pu-sensor, Jacobsen et. al. had conducted both sound absorption and intensity measurements and pointed out that there remain some uncertainties arisen from the calibration methods\textsuperscript{[8]} recommended on the production manual\textsuperscript{[9]}. The authors also employed one of the recommended methods as summarized below and conducted a series of EA-method measurements for the preceding papers. In the measurements, stability of transfer function between sound pressure and particle velocity which is measured in the prior calibration procedure was monitored to assure the accuracy.

Yet, authors encountered another uncertainty due to instability of the monitored transfer function. Though all the result that is considered to consist of uncertainties had been eliminated from the former studies, the authors hypothesized that sensor instability is affected by the surrounding humidity of the pu-sensor.

The purpose of this paper is to verify the hypothesis in relation with the EA-method measurement and to present a guideline for further usages of pu-sensor. The guideline will be useful not only for EA-method

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measurement but also for various measurement methods on acoustics.

2. METHOD OUTLINE

Generally, in a measurement, a sensor requires prerequisite calibration. The authors use the following calibration for EA-method measurement.

2.1 Calibration method in impedance tube

The authors employ the following method using an impedance tube to calibrate pu-sensors. As is illustrated in Figure 1, the tube has the length of \( L \) and its end is terminated with a hard wall. A reference microphone preliminary calibrated using a piston phone, or by some other way, is set on the hard wall.

Hereafter, the time factor \( \exp(i\omega t) \) is omitted, \( i \) is the imaginary number \( \sqrt{-1} \), and \( \omega \) is angular frequency. Then, at an arbitrary point \( x \) in the tube, sound pressure \( p(x) \) and particle velocity \( u(x) \) are respectively obtained by

\[
p(x) = \cos[k(L-x)] \cdot p_{\text{ref}}, \quad (1)
\]

\[
u(x) = \frac{i}{\rho c} \sin[k(L-x)] \cdot p_{\text{ref}}. \quad (2)
\]

Here, \( k \) is wave number, \( \rho \) is density of air, \( c \) is speed of sound, and \( p_{\text{ref}} \) is sound pressure measured by the reference microphone.

In the measurement with a pu-sensor, the true sound pressure \( p_t(x) \) and the measured sound pressure \( p_m(x) \) are linked by assuming correction value \( C_p \) as:

\[
p_t(x) = p_m(x) \cdot C_p. \quad (3)
\]

Likewise, for true and measured particle velocities, \( u_t(x) \) and \( u_m(x) \), we assume:

\[
u_t(x) = u_m(x) \cdot C_u. \quad (4)
\]

where \( C_u \) is the correction value for particle velocity.

Then, both \( p_m(x) \) and \( u_m(x) \) are measured by a pu-sensor located at point \( X \). Meanwhile, \( p_{\text{ref}} \) is measured by the reference microphone at \( x=L \). Assuming that \( p_t(x) \) in Eq. (3) equals \( p(X) \) in Eq. (1) and that \( u_t(X) \) in Eq. (4) equals \( u(X) \) in Eq. (2), one can derive \( C_p \) and \( C_u \) to correct or calibrate measured values by the pu-sensor.

For the calculation of true transfer function \( H_{up,m}(\omega) \) between particle velocity and sound pressure measured by a pu-sensor, \( u \) and \( p \) respectively, another correction value \( C_H \) can be defined as:

\[
H_{up,m}(\omega) = H_{up,m}(\omega) \cdot C_H. \quad (5)
\]

\[
C_H = \frac{\rho c \cos[k(L-X)] \cdot u_m(X)}{i \cdot \sin[k(L-X)] \cdot p_m(X)}. \quad (6)
\]

where \( H_{up,m}(\omega) \) denotes measured transfer function.

2.2 Short description of EA-method and corresponding absorption coefficient

In the previous papers[6-7], the authors introduced an impedance as:

\[
\langle Z_n \rangle = \frac{\langle p \rangle}{\langle u_n \rangle}. \quad (7)
\]

where \( p \) and \( u_n \) denote sound pressure and particle velocity with respect to the normal direction at the material surface, and \( \langle \cdot \rangle \) denotes ensemble averaging at random incidence. Tentatively, the resulting impedance, \( \langle Z_n \rangle \), was named as “Ensemble Averaged” impedance and the authors defined “corresponding absorption coefficient”, \( \langle \alpha \rangle \), by:

\[
\langle \alpha \rangle = 1 - \frac{(\langle Z_n \rangle - \rho c)^2}{Z_0 + \rho c}. \quad (8)
\]

In the practical measurement, the averaging can be performed using a fast-Fourier-Transform (FFT) like,

\[
\langle Z_n \rangle = \frac{1}{N} \sum_{\omega=1}^{N} H_{up}(\omega) = \frac{1}{N} \sum_{\omega=1}^{N} \frac{\langle p \rangle}{\langle u_n \rangle}. \quad (9)
\]

where, \( N \) is the averaging number used in FFT. In the case of system is ergodic and assuming sufficient averaging, Eqs. (7) and (9) become identical, hence we can measure averaged surface normal impedance at random incidence.
3. MEASUREMENT OUTLINE

3.1 Calibration Outline

In the practical calibration of the following measurements sections, we used an impedance tube with the inner dimensions of 10 cm x 10 cm and with $L = 70$ cm, and the pu-sensor positioned at point $X = 68$ cm. Pink noise was emitted by a loudspeaker at the opening edge of the tube ($x=0$). The resolution of the two-channel FFT (RION SA-78) unit is set to 1.25 Hz and a Hanning window of duration 0.8 s is employed. Linear averaging in the frequency domain is performed $N = 150$ times.

Two sets of pu-sensors named pu-1 and pu-2 were calibrated through the procedure described in Section 2.1 to compare the results each other. Examination of humidity effects onto each of pu-sensor calibration were conditioned in six relative humidity, $\varphi$, levels ranging from 35% to 60% with 5% step. The calibration is conducted in a reverberation room of 168 m$^2$ with non-parallel walls, located at Information Center of Oita University. In the room, we also conducted the measurement by EA-method. Temperature and relative humidity are controlled and measured by thermo-hygrometer (A&D AD-5640A).

3.2 EA-Method Measurement Outline

Figure 2 shows a schematic diagram of the measurement set up of EA-method with pu-sensor. The pu-sensor is positioned at the centre of 0.9 m x 0.9 m material. The distance, $d$, is 1 cm above material surface. Glass wool (GW50) with 32 kg/m$^3$ density and 50 mm thickness is used. The same settings of two-channel FFT in the Section 3.1 are applied. Here, the thermo-hygrometer is positioned 1m away from the sensor.

To produce the incidence condition close to random incidence, six loudspeakers (Fostex FE-103) mounted in small boxes that radiate incoherent pink noise were placed in the reverberation room. Following the former papers [6-7], the pink noise is filtered to focus the frequency range from 100 Hz to 1200 Hz. A sub-woofer (JVC SX-DW77) is also installed to increase the low frequency energy, roughly below 200 Hz.

4. RESULTS AND DISCUSSIONS

4.1 Effect of Humidity onto Sensors Calibration

Figure 3(a) portray the comparison of frequency characteristics of correction value, $C_{IR}$, of pu-1 at different relative humidity levels from 35% to 60%. In the figure, the six relative humidity levels represent as the parameter. The frequency characteristics of real parts for the six correction values from humidity 35% to 60% vary in the frequency range from 100 Hz to 1200 Hz. A slight upward shift of frequency characteristics can be found when the humidity changed from 35% to 40% by maximum value 0.03 at frequency 1200 Hz. From humidity 40% to 45% and from 50% to 55% the frequency characteristics shift

Figure 3 - Correction value, $C_{IR}$, at different relative humidity from 35% to 60% (a) pu-1 and (b) pu-2
downward with maximum value 0.18. A slight downward shift occurred when the humidity changed from 45% to 50% by maximum 0.07. Downward shift also occurred in the frequency characteristics when the humidity changed from 55% to 60% by maximum 0.19. The figure also shows that imaginary parts of $C_H$ have similar order to those of the real parts, i.e. when the humidity changed from 45% to 60% the order shifts downward in sequence while shifts upward when the humidity changed from 35% to 40%.

Similarly, Figure 3(b) shows the comparison of frequency characteristics of correction value, $C_H$, of pu-2 at different relative humidity from 35% to 60%. In the figure, frequency characteristics of real parts, $C_H$, at relative humidity from 35% to 40% shift upward by maximum value 0.06. Meanwhile, from relative humidity 40% to 60% (with 5% step), the frequency characteristics of real parts shift downward in sequence. Likewise, the imaginary parts have the same order to the real parts sequentially.

In general, the shift that found in Figures 3(a) and 3(b) on frequency characteristics of correction values both in real and imaginary parts are affected by the difference of relative humidity. To some extent, the significance of the effect is discussed below.

### 4.2 Effect of Humidity onto EA-Method Measurement

To evaluate the significance, combination of sensor calibration and impedance measurement of material (GW50) by EA-method measurement with six relative humidity levels are investigated.

Firstly, we compare normalized surface normal impedance ($<Z_n>/\rho c$) and $\alpha'$ measured by EA-method for the case with the same relative humidity both in calibration and measurement. Then, we compare $<Z_n>/\rho c$ and $\alpha'$ for the case with different relative humidities in calibration and in measurement.

<table>
<thead>
<tr>
<th>Group</th>
<th>The difference of relative humidity, $\Delta \rho$</th>
<th>Combination</th>
<th>Calibration (c) and Measurement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td></td>
<td>c35m40; c40m45; c45m50; c50m55; c55m60; c40m35; c45m40; c50m45; c55m50; c60m55</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td></td>
<td>c35m45; c40m50; c45m55; c50m60; c45m35; c50m40; c55m45; c60m50.</td>
<td></td>
</tr>
<tr>
<td>15%</td>
<td></td>
<td>c35m50; c40m55; c45m60; c50m35; c55m40; c60m45.</td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td>c35m55; c40m60; c55m35; c60m40.</td>
<td></td>
</tr>
<tr>
<td>25%</td>
<td></td>
<td>c35m60; c60m35.</td>
<td></td>
</tr>
</tbody>
</table>

#### 4.2.1 Comparisons of impedance and absorption coefficient for the case with same relative humidity

We compared six "combinations", which are c35m35, c40m40, c45m45, c50m50, c55m55 and c60m60. Here, symbols "c" and "m" represent calibration and measurement and two digit number mean relative humidity during calibration and measurement.

To compare the $<Z_n>$ or $\alpha'$ obtained for six combinations each other, firstly, the $<Z_n>$ and $\alpha'$ are moving averaged with 50 Hz step and we denote the values as $Z'_n$ and $\alpha'$. Secondly, we also calculate mean averaged impedance and and absorption coefficient over combinations, that are denoted as $\bar{Z}'_n$ and $\bar{\alpha}'$ respectively. The two values are used as reference. Furthermore, for quantitative comparison, we define a measure as

$$\Delta \alpha'_{comb} = \left| \alpha' - \alpha'_{comb} \right|,$$

where $\alpha'_{comb}$ is $\alpha'$ for each combination, c35m35–c60m60.

Figure 4(a.1) and (a.2) respectively show the comparison of ($<Z_n>/\rho c$), $\alpha'$ obtained by EA-method using pu-1. We also plot mean averaged impedance and absorption coefficient, $Z'_n$ and $\alpha'$.

On these figures, overall outlines of both impedances and absorption coefficients are in good agreements with respect to the six cases. However, distinct fluctuations observed in the real parts of measured impedances, $<Z_n>$, in frequency below 200 Hz.
From frequency 775 Hz and above, the averaged absorption coefficients, $\alpha'$, are in good agreement with the reference value, $\bar{\alpha}'$, by considering the maximum differences is below 0.01. However, in Figure 4(a.3) absolute difference, $\Delta\alpha_{\text{comb}}$, in the frequency less than 800 Hz are slightly higher, with maximum value 0.07 at 225 Hz.

Similar procedure to pu-1, Figures 4(b.1) and 4(b.2) portray the comparisons of measured normalized impedances and absorption coefficients for pu-2. In the figures, similar tendencies of pu-1 also occurred in all the six cases, and no distinct differences are found on the impedances or on the absorption coefficients. Yet, in Figure 4(b.3), the value of $\Delta\alpha_{\text{comb}}$ are slightly higher than those of pu-1 whereby the maximum value 0.09 at 125 Hz.

At this stage authors confirm that to provide absorption coefficient by EA-method, the absolute difference, $\Delta\alpha_{\text{comb}}$, among values of averaged absorption coefficients, $\alpha'_{\text{comb}}$, and its mean averaged value, $\bar{\alpha}'$, for both sensors pu-1 and pu-2, are relatively small with maximum difference is less than 0.09.

### 4.2.2 Comparison of absorption coefficient for the case with different relative humidity

The absorption coefficients $<\alpha>$ obtained for the cases with different relative humidities between calibration and measurement are compared with averaged absorption coefficient $\bar{\alpha}'$ obtained for the case with same relative humidity. Table 1 shows all the combinations considered here. We considered five relative humidity difference group, and, for each group, all possible combinations are investigated.

Firstly, for quantitative comparison we define a measure as

$$\Delta\alpha_{\Delta\phi} = \left| \bar{\alpha}' - \bar{\alpha}'_{\Delta\phi} \right|$$

Figure 4 - Absorption characteristic of GW50 obtained by same humidity of calibration and measurement and the differences of $\alpha$ ranged from 35% to 60% : pu-1 and pu-2

Figure 5 - Comparison of differences among mean averaged from 5% difference group to 25% difference group of relative humidity obtained by pu-1.

Figure 6 - Comparison of differences among mean averaged from 5% difference group to 25% difference group of relative humidity obtained by pu-2.

Figure 7 - Standard deviation of absorption coefficient with respect to mean averaged from 5% difference group to 25% difference group obtained by pu-1 and pu-2
where, $\bar{\alpha}_{\Delta \phi}$ represents mean averaged absorption coefficient over combinations for $\Delta \phi = 5, 10, 15, 20, 25 \%$ group.

Figure 5 illustrates the absolute difference, $\Delta \alpha_{\Delta \phi}$. The reference value is the mean averaged values, $\bar{\alpha}$', taken from the same relative humidity. Humidity difference distributed from 5% to 25% by 5% intervals. In the figure, the reference values are the lowest comparing to other $\Delta \phi$ cases. The absolute difference, $\Delta \alpha_{\Delta \phi}$, of 5% humidity difference has a smaller difference than the absolute difference, $\Delta \alpha_{\Delta \phi}$ of 10% humidity difference. Generally, the absolute differences, $\Delta \alpha_{\Delta \phi}$, continue to increase along with the increasing $\Delta \phi$ in all the frequencies. Yet, instability occurred in frequency below 225 Hz.

Similar to pu-1, Figure 6 also shows the absolute difference, $\Delta \alpha_{\Delta \phi}$. This figure also shows the similar tendency of pu-1 where $\Delta \alpha_{\Delta \phi}$ increase along with the increasing humidity difference $\Delta \phi$. However, instability results are found in the frequency lower than 275 Hz.

Up to this stage, authors assume that, by pu-sensor utilization, the smaller humidity difference between calibration and measurement will provide the better result of absorption characteristics measured by EA-method. In this case, it occurs at 0% humidity difference with maximum difference value of 0.06.

Finally, Figure 7 portrays the average of $\Delta \alpha_{\Delta \phi}$ over frequency with respect to the difference of relative humidity from 0% to 25% by pu-1 and pu-2. Distinct tendency can be observed that $\Delta \alpha_{\Delta \phi}$ increases as the $\Delta \phi$ increases.

5. CONCLUSIONS

The effect of relative humidity onto pu-sensor and the absorption characteristics have been examined experimentally. From the results, humidity effect can be regarded as a not negligable in obtaining absorption characteristics through EA-method with pu-sensor. Further studies to confirm and overcome the factor are undergoing.

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