REPRODUCIBILITY OF SOUND ABSORPTION AND SURFACE IMPEDANCE OF MATERIALS MEASURED IN A REVERBERATION ROOM BY ENSEMBLE AVERAGING TECHNIQUE USING A PRESSURE-VELOCITY SENSOR

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In earlier papers, the developments of measurement method with a pressure-velocity sensor (pu-sensor) for measuring absorption coefficient and surface normal impedance of materials using ensemble averaging: EA method have been researched. The present study proposes a reproducibility of sound absorption and surface impedance of materials measured in a reverberation room by ensemble averaging technique using a pressure-velocity sensor. A round robin test measurements by experimenting the sound absorption characteristics in three reverberation rooms is conducted. The target frequency range is 200 - 2500 (Hz). The measurement results of two materials are reported here. In an early stage, EA method was targeted mainly at constructing impedance boundary conditions of sound fields that used in numerical methods such as finite element method. Therefore, its frequency range was set as 100-1500 Hz. Takin into account the recent progress of computational resources, absorption characteristics in a rather higher frequency region are required. Herein, to raise the measurable frequency upper limit of EA method with a pu-sensor up to 3000 Hz, geometrical improvements are applied to an acoustic tube. The effectiveness of the improvement was confirmed using a series of EA method measurements conducted in three reverberation rooms. In all measurements, relative humidity was monitored carefully based on earlier findings by some of the authors. Using the improved acoustic tube, a series of EA method measurements of the glass-wool panel and a needle felt sheet were conducted in three reverberation rooms at different places with the improved calibration including relative humidity consideration. Those of sound absorption coefficient values are satisfactory in the entire frequency region from 100-3000 Hz, although agreement of impedance values among three different reverberation rooms are fair for frequencies below 200 Hz. The results presented here confirm the reproducibility of EA method using improved pu-sensor calibration with consideration of relative humidity.

Keywords: ensemble averaging, pressure-velocity sensor, impedance, reproducibility, reverberation room,
1. Introduction

Aiming at construction of appropriate boundary conditions used in wave-based room acoustics simulations, with numerical methods such as finite element method and boundary element method, we have been developing a measurement method for the surface normal impedance of materials using ensemble averaging: EA method.

First, Takahashi et al. [1] showed the repeatability and wide applicability of EA method with two-channel-microphone (pp-sensor) at both laboratory and in-situ conditions. After a pressure-velocity sensor (pu-sensor) was newly developed and put on the market by Microflown Technologies [2, 3], we use the sensors of both types. Here, we denote the measurements using the sensors respectively as “EA_{pp}” and "EA_{pu}”. Otsuru et al. [4] applied boundary element method to clarify the measurement mechanism of EA_{pu} method and demonstrated that ensemble averaging using random incidence incoherent noises decreases interference effects efficiently and that considerably stable values can be measured both of surface normal impedance and of the corresponding absorption coefficient at a pseudo-random incidence condition that is less affected by sample size. Din et al. [5, 6] showed the geometrical configurations for EA method and investigated the reproducibility and applicability of EA_{pu} method with round robin tests. To assess the deviations and differences, Asniawaty et al. [7] conducted numerous measurements including preliminary trials. They found a humidity effect for measured values in EA_{pu} method. Furthermore, as an application of the humidity effect issue, the uncertainties included in the results of EA_{pu} method with humidity consideration are examined in the literature [8], revealing that the measured absorption coefficient satisfies the tentative requirement from the room acoustical simulation side raised by Vołänder [9]. Recently, Otsuru et al. [10] took precise measurements and inferred a guideline how to calibrate a pu-sensor to eliminate humidity effects on application measurements.

Hereinafter, we continue to use an acoustic tube for pu-sensor calibration because of the portability and feasibility for practical applications. Considering the progress of computers, we reset the target frequency upper limit of EA_{pu} method from 1500 Hz to 3000 Hz. To raise the upper limit up to 3000 Hz, several geometrical changes are performed and examined for their effectiveness in the following section. To prove the reproducibility of EA_{pu} measurements with improved calibration, round robin tests were conducted in three reverberation rooms at different places.

2. Improvement of pu-sensor calibration with acoustic tube

All conventional tubes are designed for the use of the frequency region below 1500 Hz as presented in Fig. 1. There, the \((x, y)\) coordinate system is given; the pu-sensor measuring position \(MP(X, Y_{MP})\) is shown as a black circle. We assume that both signals of sound pressure and particle velocity are measured at MP. Our conventional tubes have almost similar geometries, with dimensions of \(D = 50\) mm and \((L - X) = 50\) mm. Sound pressure minima because of length \((L - X)\) occur at 1700 Hz and its integer-multiples. Then the measurable frequency upper limit is expected to be 1700 Hz. As a conservative estimate, we consider that calibrations can be conducted properly at frequencies below 1500 Hz.

To raise the frequency upper limit up to 3000 Hz, We shorten \((L - X)\) to 25 mm in the geometries of the improved tube. Accordingly, both lengths \(D\) and \((L - X)\) have the same restricting frequency at 3400 Hz. One can anticipate a upper limit of measurable frequency to be 3000 Hz conservatively.

3. Reproducibility examination with three reverberation rooms

3.1 Overview of EA_{pu} method measurement in this study

To evaluate the reproducibility of EA_{pu} method measurement with the improved acoustic tube as well as relative humidity consideration, we conducted a series of sound absorption measurements.
Figure 1: Geometrical configurations of acoustic tube in the \((x, y)\) coordinate system. MP indicates a measurement point located at \((X, Y_{MP})\); \(D\) and \(L\) respectively denote the tube width and length.

Figure 2: Location of specimens, sound sources and receiving points: (a) Room I, (b) Room II, and (c) Room III.

Table 1: Measurement configuration of three reverberation rooms (Room I, Room II, and room III).

<table>
<thead>
<tr>
<th>room number</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
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<tbody>
<tr>
<td>temperature (^{\circ})C</td>
<td>27.4 – 28.2</td>
<td>26.4 – 26.9</td>
<td>26.5 – 27.0</td>
</tr>
<tr>
<td>relative humidity (%)</td>
<td>43 – 50</td>
<td>62 – 64</td>
<td>62 – 67</td>
</tr>
<tr>
<td>volume ((m^3))</td>
<td>168</td>
<td>197</td>
<td>179</td>
</tr>
<tr>
<td>surface area ((m^2))</td>
<td>180</td>
<td>257</td>
<td>188</td>
</tr>
</tbody>
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Table 2: Abbreviations and dimensions of measured specimens.

<table>
<thead>
<tr>
<th>material of specimen</th>
<th>abbrev.</th>
<th>dimensions ([mm \times mm \times mm])</th>
</tr>
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<tbody>
<tr>
<td>Glass-wool ((32 \text{ kg/m}^3))</td>
<td>GW</td>
<td>500 × 500 × 50</td>
</tr>
<tr>
<td>Needle felt</td>
<td>NF</td>
<td>500 × 500 × 10</td>
</tr>
</tbody>
</table>
in three reverberation rooms as shown in Fig. 2. Room I is located at the Information Center of Oita University. The other two rooms belong to other institutes of different prefectures in Japan. Dimensions and atmospheric environments related to the measurements are presented in Table 1. In the list, the temperature and relative humidity respectively portray the fluctuation ranges at the measurement in each room.

Regarding FFT setting, linear averaging in the time domain was performed 150 times using a Hanning window with about 1 s time length. All pu-sensor calibrations with the improved acoustic tube were conducted on-site immediately before and/or after each series of EApu measurement in a day. The relative humidity differences between at EApu measurement and at calibration were maintained to satisfy the requirements described in earlier reports [7, 10], i.e. less than 8 %.

Fundamentally, all the EApu method measurements were taken following the procedures presented in our earlier reports [4, 5, 6]. Because the measurement frequency upper limit is raised to 3000 Hz in this study, we used loudspeakers and sub-woofers to radiate incoherent pink noises of roughly 50-5000 Hz. The sound source locations are shown respectively in Fig. 2. Loudspeakers and sub-woofers were set on the floor.

Two measured specimens (Table 2) having the same sizes and similar materials to those of previous study of the EA method reproducibility were selected [6]. In each reverberation room, EApu method measurements were conducted on each specimen at three positions each three times within a single day. That repetition was implemented to decrease the effect of the specimens’ subtle point-by-point fluctuations in density, surface shape, and so on. Therefore, to ascertain a specimen’s sound absorption appropriately, we conducted thus-repeated measurements for which the averaging number equals nine.

3.2 Results and discussion

The obtained mean values, accompanied by standard deviation ranges, are shown respectively in Figs. 3 and 4. In Fig. 3, agreements among $Z_{EA}$ mean values measured in three reverberation rooms are good for both the specimens in the frequency region above 200 Hz. Below 163 Hz, the agreement worsens, especially for NF. Nonetheless, in Fig. 4, no significant discrepancy was found in the $\alpha_{EA}$ values of either specimen throughout the frequency range of 125-2500 Hz. Some discrepancies of impedance values remain in the lower frequency region below 163 Hz, but both $Z_{EA}$ and $\alpha_{EA}$ values show satisfactory agreement among the three reverberation rooms. For evaluating the agreements, Pearson’s correlation coefficient $r$ was calculated among the three rooms. The last two minima of the values were 0.892 of the real part of $Z_{EA}$ of GW and 0.922 of the imaginary part of $Z_{EA}$ of GW. Those of the others were greater than 0.979, which confirms the effectiveness of the improvements. To clarify the deviations found in $\alpha_{EA}$ values, the standard deviations of nine-times measurements at each reverberation room are depicted in Fig. 5. All values remain at less than 0.04 for GW; and at less than 0.06 for NF. Although it is not easy to evaluate the values, we regard them tentatively as satisfactory small compared to those of the ordinary reverberation room method.

4. Conclusions

To raise the measurement upper limit of EApu method from 1500 Hz to 3000 Hz, we improved the geometries of the acoustic tube used for pu-sensor calibration. Because of the portability and feasibility, using an acoustic tube for pu-sensor calibration is advantageous especially for in-situ measurements and for observing relative humidity fluctuations both at measurement and at calibration. Effectiveness of the calibration using an improved acoustic tube is confirmed from a series of EApu method measurements of a glass-wool panel in three reverberation rooms. Agreement between resulting surface impedances of the three rooms are good, but excellent agreement was found for sound absorption coefficients throughout the frequency region of 100-3000 Hz. In this study, all measurements were conducted in reverberation rooms, In EA method measurements, however, sample size...
Figure 3: Comparisons of mean values with standard deviation ranges of surface normalized impedance of GW (left) and NF (right) measured in three reverberation rooms using $EA_{pu}$ method.

Figure 4: Comparisons of mean values with standard deviation ranges of $\alpha_{EA}$ of GW (left) and NF (right) measured in three reverberation rooms using $EA_{pu}$ method.

Figure 5: Comparisons of standard deviations of $\alpha_{EA}$ of GW (left) and NF (right) measured in three reverberation rooms using $EA_{pu}$ method.
effect is not distinct and practical measurements at various sound field are executable without special
equipments. but the issues presented above are important for various applications at practical sound
fields. Further studies are now underway to clarify improvements in a low-frequency region, in-situ
measurements, and so on.

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