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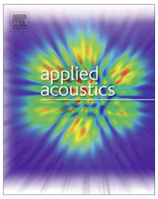

Reproducibility of sound absorption and surface impedance of materials measured in a reverberation room using ensemble averaging technique with a pressure-velocity sensor and improved calibration

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ABSTRACT

The authors have been developing a method using pressure-velocity sensors (pu-sensors) to measure the absorption coefficient and surface normal impedance of materials using ensemble averaging: $\mathrm{EA}_{\mathrm{pu}}$ method. The improvement of geometrical configurations for pu-sensor calibration using an acoustic tube is presented first. Because no clear guideline for pu-sensor positioning in acoustic tube has been reported to date, such improvement is important. Moreover, it enables $\mathrm{EA}_{\mathrm{pu}}$ method measurement to be conducted properly at frequencies region up to 3000 Hz. The tube has two openable hard end-walls that help us to make inside humidity conditions similar to those of the outside room and to realizing a one-dimensional sound field at calibration. With such improvements and with consideration of humidity, a round robin test using $\mathrm{EA}_{\mathrm{pu}}$ method was conducted in three reverberation rooms to prove the reproducibility of measurements of absorption characteristics of glass-wool and needle felt. Results revealed excellent agreement of absorption coefficient values for reverberation rooms at frequencies of 100–3000 Hz. Results also demonstrated that the maximum difference of absorption coefficient values is less (almost equal or less than half) of those found in the authors' earlier study of the 125–1250 Hz frequency region.

1. Introduction

Aiming at construction of appropriate boundary conditions used in wave-based room acoustics simulations, using numerical methods such as finite element method and boundary element method, we have been developing a method to measure the surface normal impedance of materials using ensemble averaging: EA method. Because the numerical methods described above require higher computational costs for higher frequencies [1,2], our primary target frequency range of measurement was set as 100–1500 Hz.

Takahashi et al. [3] demonstrated the repeatability and wide applicability of EA method with a two-channel-microphone (pp-sensor) in both laboratory and *in situ* conditions. After a pressure-velocity sensor (pu-sensor) was newly developed and put on the market by Microflown Technologies [4,5], we began to use sensors of both types. For this study, we respectively designate measurements using the sensors as $\mathrm{EA}_{\mathrm{pp}}$ and $\mathrm{EA}_{\mathrm{pu}}$.

Otsuru et al. [6] applied boundary element method to clarify the mechanisms of $\mathrm{EA}_{\mathrm{pu}}$ method measurement. They demonstrated that ensemble averaging using random-incidence incoherent noises decreases interference effects efficiently. Moreover, they showed 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. demonstrated geometrical configurations for EA method and investigated the reproducibility and applicability of $\mathrm{EA}_{\mathrm{pu}}$ method using round robin tests conducted in four reverberation rooms and in three ordinary environments [7,8]. The measured absorption coefficients reported in the literature [8] yield considerably small deviations to confirm the reproducibility and applicability of $\mathrm{EA}_{\mathrm{pu}}$ method.

Nevertheless, certain deviations also exist between the measured values at different places. Certain differences are also observable between the measured values of $\mathrm{EA}_{\mathrm{pp}}$ and $\mathrm{EA}_{\mathrm{pu}}$. To assess the deviations and differences, Asniawaty et al. [9] took numerous measurements including preliminary trials. They found a humidity effect for values measured using in $\mathrm{EA}_{\mathrm{pu}}$ method. As an application of the humidity effect issue, uncertainties included in the results obtained using $\mathrm{EA}_{\mathrm{pu}}$ method with humidity consideration were

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examined in one study [10], revealing that the measured absorption coefficient satisfies the tentative requirement from the room acoustical simulation side raised by Voländer [11]. Recently, Otsuru et al. [12] took precise measurements and inferred a guideline for pu-sensor calibration to eliminate humidity effects on application measurements.

All pu-sensor calibrations conducted in our earlier studies were done using several acoustic tubes such as a short standing wave tube (SWT; Microflown Technologies) [13], and acoustic tubes created with lengths of less than 1 m because of their portability and suitability especially use in obtaining *in situ* measurements. Both ends of the acoustic tubes we used are hard and openable at default setting. Immediately before pu-sensor calibration, we assembled the calibration apparatus.

Regarding pu-sensor calibration, the manufacturer provides detailed information [13]. Several notable reports have proposed and discussed free field method, standing wave tube method (STM), piston on a sphere method, and a method using a long wave guide [11,14–16].

We continue to use an acoustic tube for pu-sensor calibration because of its portability and feasibility for practical applications because closure of a tube is beneficial for eliminating the effects of outside room conditions. Such a tube is also beneficial for making the humidity roughly equivalent to that of the outside room when opened. Considering the progress of computers, we reset the target frequency upper limit of $\mathrm{EA_{pu}}$ method from 1500 Hz to 3000 Hz. To raise the upper limit to 3000 Hz, several geometrical changes were performed and examined for their effectiveness, as described in the following section. In general, applications of acoustic tubes for microphones are known to have geometrical restrictions related to the measurable frequency range for wavelengths such as a tube's diameter and a sensor's distances from the inner walls [17]. The improvement described below includes both. Here, a newly found important point is the pu-sensor insertion length. Considering all of those prospective improvements collectively, we propose an improved acoustic tube that provides feasible measurements reliably up to 3000 Hz. The effectiveness of the improvement can be demonstrated through a series of $\mathrm{EA_{pu}}$ method measurements of a glass-wool panel conducted in a reverberation room.

To prove the reproducibility of $\mathrm{EA_{pu}}$ method measurements with improved calibration, round-robin tests were conducted in three reverberation rooms at different places following the procedures used by Din et al. for an earlier study [8]. The effectiveness of the improvements including humidity considerations was examined by comparing deviations of the sound absorption coefficients measured in round robin tests of an earlier study and of the present study. That comparison reveals that, although further improvement is necessary for frequencies lower than 400 Hz, most deviations can be decreased by more than half by using calibration with the improved acoustic tube and by considering humidity, which ensures the robustness of $\mathrm{EA_{pu}}$ method with the thus-calibrated pu-sensor.

2. Outlines of $\mathrm{EA_{pu}}$ method measurements and pu-sensor calibration

The measurement setup of $\mathrm{EA_{pu}}$ method used for our earlier studies is presented in Fig. 1. A pu-sensor is placed at a point close to the sample surface. The output signals are plugged into a two-channel fast Fourier transform (FFT) analyzer. In the FFT analyzer, transfer function $H_{\mathrm{P,U}}(=1/H_{\mathrm{U,P}})$ between the sound pressure and particle velocity sensors is calculated in the frequency domain. In reports of earlier studies [6–8], we presented definitions of ensemble averaged surface normal impedance Z_{EA} and the corresponding absorption coefficient α_{EA} respectively as

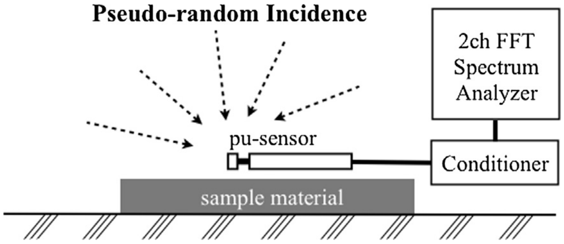

Fig. 1. Schematic diagram of the $\mathrm{EA_{pu}}$ method measurement setup.

$$Z_{\mathrm{EA}} = \frac{1}{N}\sum^{N} H_{\mathrm{U,P}} = \frac{1}{N}\sum^{N} 1/H_{\mathrm{P,U}}, \tag{1}$$

$$\alpha_{\mathrm{EA}} = 1 - \left|\frac{Z_{\mathrm{EA}} - \rho c}{Z_{\mathrm{EA}} + \rho c}\right|^2, \tag{2}$$

where, N, ρ and c respectively denote the averaging number, air density, and speed of sound. In our studies, linear averaging in the time domain was performed 150 times using a Hanning window with about 1 s time length. A single measurement is completed in about 90 s using time-window overlapping. Ensemble averaging is performed under a pseudo-random incidence condition that is realized using 4–6 loudspeakers that respectively radiate incoherent pink noises.

In practical measurements, the measured raw value $\widetilde{H}_{\mathrm{P,U}}$ usually includes measurement errors that must be eliminated. The error caused by sensors can be minimized using pu-sensor calibration [13] to obtain the true value of Z_{EA}. Then, we use the correction value C_{pu} as

$$C_{\mathrm{pu}} = H^{\mathrm{theory}}_{\mathrm{P,U}} / H^{\mathrm{meas}}_{\mathrm{P,U}}. \tag{3}$$

Here, $H^{\mathrm{theory}}_{\mathrm{P,U}}$ and $H^{\mathrm{meas}}_{\mathrm{P,U}}$ respectively denote the theoretical and measured transfer functions between sound pressure and particle velocity at the pu-sensor to be calibrated which is placed in a sound field where the theoretical values of sound pressure and particle velocity at the pu-sensor position are known in advance. With C_{pu}, transfer function correction is done as

$$H_{\mathrm{P,U}} = \widetilde{H}_{\mathrm{P,U}} C_{\mathrm{pu}}. \tag{4}$$

In the $\mathrm{EA_{pu}}$ method, transfer function correction performed using Eq. (4) plays a role of calibrating the pu-sensor, although the pu-senosr calibration in an original sense is done to obtain the true values of sound pressure and particle velocity. For pu-sensor calibration in practical sound absorption measurements taken in field conditions, we used acoustic tubes, actually an SWT (Microflown Technologies) [13] and several self-made tubes, because of their portability and simplicity. Considering the targeted frequency range, all the tubes (SWT and self-made tubes) were designed for use at frequencies lower than 1500 Hz. Geometrical configurations of the tube and the (x, y, z) coordinate system is given in Fig. 2. The pu-sensor measuring position $\mathrm{MP}(X_{\mathrm{MP}}, Y_{\mathrm{MP}}, Z_{\mathrm{MP}})$ is shown as a black circle. We assume that both sound pressure and particle velocity signals are measured at MP. Details of the position and apparatus of MP are presented in Fig. 3, although the detailed position of Y_{MP} was not discussed in an earlier report [13]. We have been using half-inch PU-regulars (Microflown Technologies). We use one in the following investigations as well.

Self-made tubes described above have similar geometries with dimensions of $D = 50$ mm, and $(L - X_{\mathrm{MP}}) = 50$ mm of SWT with $D = 47$ mm, and $(L - X_{\mathrm{MP}}) = 55$ mm. For air temperature of about