ACOUSTICAL LETTER

Uncertainty examination of ensemble averaging method for sound absorption of materials in a reverberation room

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1. Introduction

To construct appropriate boundary conditions for wave-based room acoustics simulations, the authors have proposed a method for measuring sound absorption of materials using the ensemble averaging technique [1,2]. We have also shown several applications of the method (EA method, hereafter) both conditions in the laboratory and in situ [3,4].

Based on several example calculations conducted for a music hall with volume of $11,000 \, \mathrm{m}^3$, Vorländer pointed out that the uncertainty of the absorption coefficient must remain less than 0.04 to keep the uncertainty of calculated reverberation time below its just noticeable difference (JND) [5]. There followed the statement that such a small uncertainty cannot be obtained from the reverberation room method following ISO 354. Although Vorländer made no statement related to the tube method, the mounting problem [6] of the method has not been solved yet. It is likely to affect the resulting uncertainty as expressed by Stanley [7] that "an impedance tube system to measure the acoustic absorption is not an extremely precise and repeatable process because of unavoidable variations of specimen cutting and cell fit."

Herein, as an alternative method, the uncertainty of EA method is discussed. First, theoretical basis of EA method is described briefly, proposing a mathematical-physical model of ensemble averaging to clarify the definition of measured absorption with respect to sound incident events. The knowhow is described to measure the absorptions of reflective materials with a pressure-velocity sensor (Microflown [8], or pu-sensor). Then, a series of repeated measurements are conducted to assess the uncertainty of EA method on both absorptive and reflective materials in the frequency region of $100 \, \mathrm{Hz}$ to $1,500 \, \mathrm{Hz}$. To examine the validity of the mathematical-physical model described above and knowhow, tube methods of two kinds, at a laboratory and in situ, are conducted on the parts of the same materials. Then the agreement between methods is observed.

2. EA method formulation

2.1. Mathematical-physical model of ensemble averaging

In our previous paper [2], the following equations for ensemble averaged surface normal impedance $\langle Z_\mathrm{n} \rangle$ and corresponding absorption coefficient $\langle \alpha \rangle$ were proposed.

$$\langle Z_\mathrm{n} \rangle = \frac{\langle P_\mathrm{surf} \rangle}{\langle U_\mathrm{n,surf} \rangle}, \tag{1}$$

$$\langle \alpha \rangle = 1 - \left| \frac{\langle Z_\mathrm{n} \rangle - 1}{\langle Z_\mathrm{n} \rangle + 1} \right|^2. \tag{2}$$

In those equations, $\langle \cdot \rangle$ denotes the ensemble averaging; P_surf and $U_\mathrm{n,surf}$ respectively denote the sound pressure and particle velocity normal to the specimen surface at the surface in the frequency domain.

In the time domain, we respectively express the sound pressure and particle velocity normal to the surface at the surface by p_surf and $u_\mathrm{n,surf}$. That is, P_surf and $U_\mathrm{n,surf}$ in Eq. (2) are the Fourier-transform of p_surf and $u_\mathrm{n,surf}$, respectively. In a practical EA method measurement, we use a two channel digital signal analyzer with the function of Fast-Fourier-Transformation (FFT) to measure the values both in the time and frequency domains. In the FFT function, we also use the time-window and linear-time-averaging.

At each sample time i in a time-window (Hanning window) shown in Fig. 1, the measurement of $p_{\mathrm{surf},i}$ and $u_{\mathrm{n,surf},i}$ can be regarded as the measurements of ensemble of incident events $\{E_{i,j}\}$. That is:

$$p_{\mathrm{surf},i} = \sum_{j}^{M_i} p_{\mathrm{surf},i,j} W_i, \tag{3}$$

$$u_{\mathrm{n,surf},i} = \sum_{j}^{M_i} u_{\mathrm{n,surf},i,j} W_i. \tag{4}$$

Here, M_i and W_i respectively denote the cardinality of $\{E_{i,j}\}$ and the coefficient of window-weighting at a sample time i.

The ensemble averages of $p_{\mathrm{surf},i}$ and $u_{\mathrm{n,surf},i}$ over j are expressed respectively as

$$\langle p_{\mathrm{surf},i} \rangle_j = \frac{1}{M_i} \sum_{j}^{M_i} p_{\mathrm{surf},i,j} W_i, \tag{5}$$

$$\langle u_{\mathrm{n,surf},i} \rangle_j = \frac{1}{M_i} \sum_{j}^{M_i} u_{\mathrm{n,surf},i,j} W_i. \tag{6}$$

Then, at every instance i,
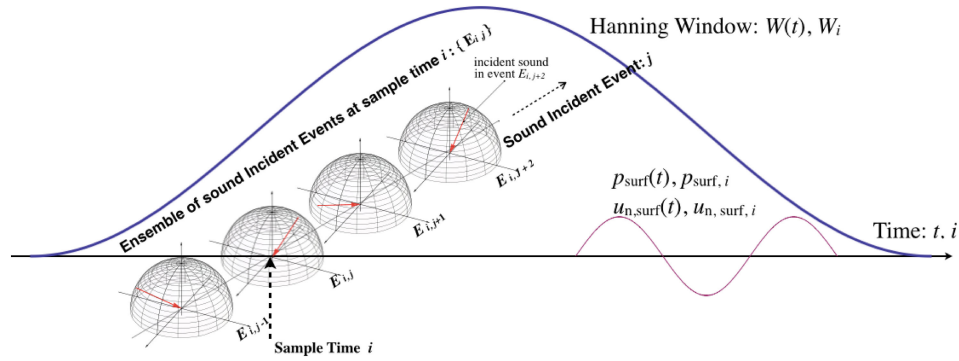
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Fig. 1 Mathematical-physical model of sound incident events within a Hanning window with EA method measurement. The sound pressure and particle velocity observed at each sample time *i* consist of the ensemble of sound incident events $\{E_{i,j}\}$.

$$\frac{\langle p_{\mathrm{surf},i}\rangle_j}{\langle u_{\mathrm{n,surf},i}\rangle_j} = \frac{p_{\mathrm{surf},i}}{u_{\mathrm{n,surf},i}}, \qquad (7)$$

stands. On the assumption of the ergodicity, we can reduce $\langle P_{\mathrm{surf}}\rangle$ and $\langle U_{\mathrm{n,surf}}\rangle$ in the Eq. (1), respectively applying FFT to measured p_{surf} and $u_{\mathrm{n,surf}}$ within the time window. As a general measurement with a FFT instrument, linear averaging is performed over multiple windows.

2.2. Note for reflective material measurement

In practical measurements of absorptive materials such as glass-wool and rock wool, $\langle P_{\mathrm{surf}}\rangle$ and $\langle U_{\mathrm{n,surf}}\rangle$ are obtained on a FFT instrument with a Hanning window of around 1.0 s time-length and with linear averaging of 150 times [2–4]. When a reflective material is to be measured, Eq. (1) might be likely to encounter the difficulty of "division by zero." In such cases, admittance $\langle\beta\rangle = 1/\langle Z_{\mathrm{n}}\rangle$ calculation readily eliminates the difficulty.

Consequently, provided that impedance or admittance is calculated selectively, EA method is applicable not only to absorptive materials but to reflective materials. Because the incident angle dependency of sound absorption characteristics of an ordinary reflective material might be negligible, we expect that measured values of $\langle\alpha\rangle$ using EA method approach the value of a normal absorption coefficient α_0 obtained using the tube method.

3. Uncertainty examination of EA method measurement

3.1. Measurement setup

Actually, EA method used here follows the configuration given in our earlier papers [1–3]: a pu-sensor (Microflown; PR-900782) is placed 1 cm above the material's surface and is plugged into a 2ch-FFT (B&K; Type 3160-A-042) instrument. All measurements are conducted in the reverberation room having volume of 168 m³ at Oita University. Incoherent filtered pink noise of 100–1,500 Hz was emitted from six loudspeakers (Fostex; FE-103E) mounted in wooden box and a sub-woofer (Victor; SX-DW77). All loudspeakers and a subwoofer are distributed on the floor close to the walls of the reverberation room.

For comparison, the tube method following JIS A1405-2 [9] (ISO 10534-2 [10]) is applied to measure the normal incidence sound absorption coefficients α_0 of sample cuts of

Table 1 Abbreviations and dimensions of measured materials.

Material	Abbrev.	Dimensions [mm³]
Glass wool (32 kg/m³)	GW	$500 \times 500 \times 50$
Needle felt	NF	$500 \times 500 \times 10$
Concrete floor	CF	Room's floor

glass wool (GW) and needle felt (NF). A tube with 10 cm diameter (Nihon Onkyo Engineering Co., Ltd.) was used. For measurement of the concrete floor of the reverberation room (CF), an in situ method following ISO 13472-2 [11] was applied using a handmade acrylic tube of 10 cm diameter.

Table 1 shows the abbreviations and dimensions of measured materials. We tentatively regard such a material with the absorption coefficient less than 0.1 as "reflective." Hereinafter, all measurements follow the knowhow presented above. To examine the uncertainty of EA method, each measurement setup is repeated three times for three straight days while maintaining the relative humidity differences in a day less than 5%. The pu-sensor calibration is conducted using a tube (Microflown; Short standing wave tube) every day, once a day immediately before the EA method measurements. The humidity range is set to keep the effect of humidity acceptably small [12].

In the setup, three receiving points are chosen for placing the pu-sensor at 1 cm above the point: for GW and NF, one is set at the center of the material area. The other two are at 5 cm away from the center to the opposite directions on one diagonal line: for CF, the center point is set at almost the center of the reverberation room and the other two are similar to GW and NF.

Herein, considering the uniformity of the materials, we assume that the sound absorption characteristics at the three points are selected from the same population. We also consider that the assumption is sufficiently appropriate for measurements of practical materials used in architectural and environmental acoustics. Even if the sound absorption characteristics of the material differ by position, the following results can be regarded as conservative. Then, taking account of the three times of repetition, the statistical sample size of
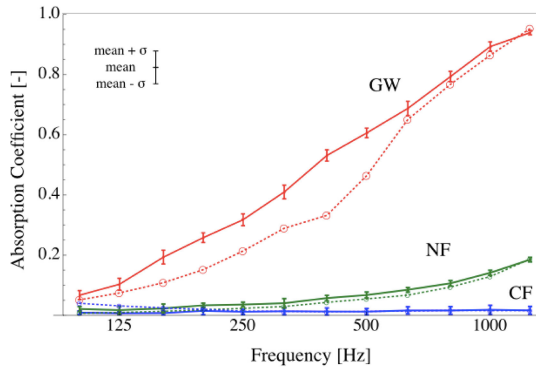
Fig. 2 Absorption coefficients $\langle\alpha\rangle$ of glass-wool (GW), needle felt (NF) and concrete floor (CF) measured using EA method (solid lines with error bars) compared with α_0 values obtained using the tube method (dotted lines with ◯).

Fig. 3 Uncertainties σ of absorption coefficients of glass-wool (GW), needle felt (NF), and concrete floor (CF) measured using EA method. Mean values of the standard deviations over the entire frequency region of 100–1,500 Hz are shown for comparison.

each examination of a material is nine. To keep consistency with Vorländer's uncertainty issue, all the examinations are made on the mean values in one-third-octave bands.

3.2. Results and discussion

Measured results of sound absorption coefficient values $\langle\alpha\rangle$ of GW, NF, and CF are mutually compared in Fig. 2. The sound absorption coefficient values shown here are mean values averaged over the repetitions and frequencies within a one-third-octave band. To assess the uncertainty of EA method measurement, standard deviation σ of the absorption coefficient values are calculated. They are given as error bars in the figure. Together with the mean values of $\langle\alpha\rangle$ by EA method, the values of α_0 measured using tube methods are shown.

Because the incidence conditions of EA method and the tube methods differ, the results cannot be expected to agree mutually in a straightforward manner [1–3]. The mounting problem might be included into the results of the tube methods. Nonetheless, frequency characteristics of sound absorption coefficients show similar trends between EA method and the tube methods. Moreover, in the cases of NF and CF, considerably good agreement is observed: the maximum and mean differences of absorption coefficients of NF are, respectively, 0.018 and 0.012, and of CF, 0.030 and 0.007.

Agreement of GW between EA method and the tube method is not very good. Actually, large discrepancies are observed especially at frequencies around 400 Hz. The maximum and mean values of differences are, respectively, 0.200 and 0.075. The difference, however, is explainable by the incidence-angle-dependence of the material's sound absorption characteristics [2]. Good agreement between EA method and tube method of NF and CF are attributable, based on the mathematical-physical model, to an assumption that their incidence-angle-dependence is not distinct.

The standard deviations σ of absorption coefficients with respect to the frequency are depicted in Fig. 3, together with the mean averages of the values over all frequency region of 100 Hz to 1,500 Hz. The mean and maximum values of the standard deviations are presented in Table 2.
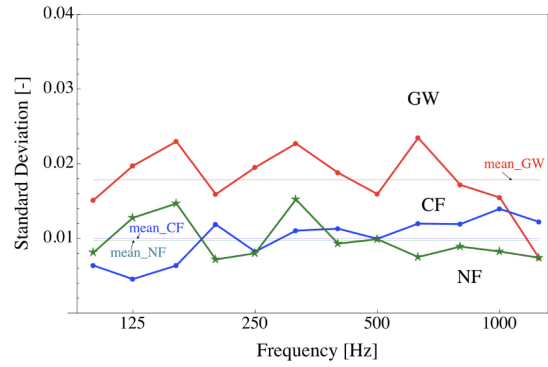
Table 2 Mean and maximum values of the uncertainties σ shown in Fig. 3, and the frequencies at which the maximum occurs.

Material	mean	max.	freq. [Hz]
GW	0.018	0.023	630
NF	0.010	0.015	315
CF	0.010	0.014	1,000

The mean and maximum values of the standard deviations of GW are 0.018 and 0.023, respectively. The maximum values of NF and CF are less than 0.015. No distinct difficulty was found in measuring the reflective materials using EA method. Within the limited scope of this paper, all the uncertainty values were found to satisfy the requirement of "less than 0.04" [5]. Although the sample numbers and repetitions are not large, the authors infer that the fundamental applicability of EA method is confirmed including the measurements of reflective materials, and that the uncertainties of EA method remain with the range of expected values.

4. Conclusions

The uncertainty of EA method measurement is discussed to ascertain whether the EA method satisfies the requirement raised by Vorländer for the computational room acoustics simulations. Results of repeated measurements both on absorptive and on reflective materials revealed that the uncertainties of EA method remain less than 0.03. The required value of 0.04, however, is given as a tentative number. Less uncertainty might be necessary. However, because the treatment of measurement points causes the results to fall to a safer side, more improvement can be expected. Further examinations must be undertaken to increase the number of cases and to achieve sufficient precision to satisfy the requirements from various aspects of acoustics, especially from computational room acoustics simulations.

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