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Sound absorption measurement method using ensemble averaging technique: A robust method for surface impedance including *in-situ* applications

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Abstract

Sound absorption characteristics of materials are of importance for controlling the quality of sound fields as well as of materials. In the authors' previous papers, we proposed the concept and measurement method for surface normal impedance and sound absorption coefficient at random incidence condition, namely, ensemble averaged surface normal impedance and sound absorption coefficient. We named the measurement method as EA method, for short. We also showed the theoretical validation using boundary element method and experimental confirmations on the effectiveness of EA method in successive several papers. In this paper, outline of EA method is summarized, first. Then, reproducibility of the results are examined on measurements conducted both in a reverberation room as well as in five *in-situ* sound fields. All the measurements were conducted by EA method with a pressure-velocity sensor (Microflown PU-sensor) which was calibrated on-site using an acoustic tube. The results reveal that robust absorption coefficient values with the uncertainties less than 0.03 $\sim$ 0.04 were obtained regardless of sound fields.

Keywords: Sound Absorption Coefficient, Surface Impedance, Ensemble Averaging, Measurement

1 INTRODUCTION

Since the early days of architectural acoustics established by W. C. Sabine, sound absorption characteristics of materials play crucial roles for predicting as well as controlling sound fields in built environments. To measure the values, various methods have been proposed; and some of them were standardized internationally. Not a small number of people, however, frequently encounter difficulties at their practical measurement stages for materials' sound absorption characteristics. Sometimes, the difficulty depends on the material's property itself: *i.e.* mounting issues are pesky enough for certain materials to measure sound absorption characteristics properly in the tube method, an expensive reverberation room is indispensable for the reverberation room method, results of the reverberation room method depend on the room's characteristics, standard area size required for the reverberation room method might cost a lot for certain materials under development, and so on.

The ensemble averaging technique was proposed to overcome such difficulties. First, Takahashi et al. [1] proposed an *in-situ* measurement method utilizing the transfer function method with two-microphone, namely EA_{pp} method, for short. Then, Otsuru et al. [2] presented an improved method utilizing a pressure-velocity sensor (PU-sensor, Microflown), EA_{pu} method; and they also revealed, using boundary element method, that the ensemble averaging efficiently cancels the disturbing interference effects caused by the specimen's edge diffractions. Comparisons of measurement results between EA method and tube method were presented by Nazli et al. [3] along with detailed discussions on the effects of sample size and receiver-to-sample distance. They also examined the reproducibility and applicability of EA_{pu} method method with round robin tests conducted at four reverberation rooms and three ordinary environments: a classroom, lobby and corridor.

On the other hand, Asniawaty et al.[5, 6] reported a humidity effect on measurement values by EA_{pu} method. Then, Sakamoto et al. [7] proposed a refined on-site calibration method; and, with the method, EA_{pu}'s reproducibility in three reverberation rooms located at different cities were presented.

In this paper, EA_{pu} method outline is summarized, first; and detailed information required for practical applica-

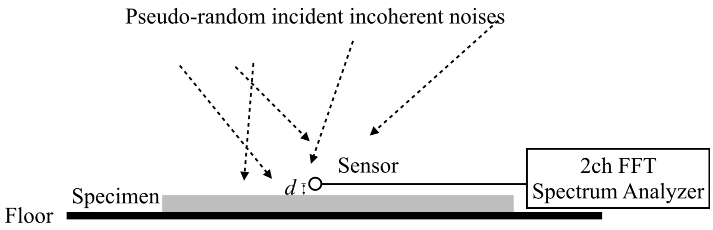


Figure 1. Measurement setup of the EA method. At the sensor position, $\mathrm{EA_{pu}}$ method sets PU-sensor; and $\mathrm{EA_{pp}}$ method sets two-microphone. Sensor is located d m above the specimen surface.

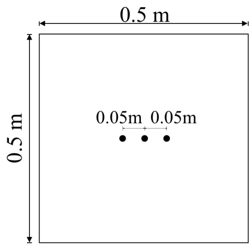


Figure 2. Specimen size and receiving points.

tions is exhibited. Then, to show $\mathrm{EA_{pu}}$ method's applicability, results of $\mathrm{EA_{pu}}$ method measurement conducted at sound fields including *in-situ* conditions, when on-site calibration is performed, are demonstrated.

2 EA METHOD OUTLINE

Standard setup for EA method is illustrated in figure 1. At the sensor position, $\mathrm{EA_{pu}}$ method sets PU-sensor; and $\mathrm{EA_{pp}}$ method utilizes two-microphone. In this paper, $\mathrm{EA_{pu}}$ method is focused on because of the theoretical simplicity based on their geometrical allignment.

2.1 Geometrical configurations

Theoretically, the less is the distance d between PU-sensor and specimen surface, the better the values of absorption characteristics become, which was supported by BEM simulation presented in literature [3]. While, in a practical measurement, certain distance is inevitable because of physical sensor-sizes as well as roughness of specimens' surfaces. Based on many trial-and-error measurements using PU-sensor (Microflown, PU regular), the authors have employed $d = 0.01$ m since the studies focused on the measurement within the frequency range from 200 Hz to 1500 Hz [4]. Considering that the PU-sensor sensor diameter is half-inch, the distance is a safer compromise. However, when a precise measurement in higher frequency range is to be conducted, some improvements be required.

Sample specimen's size effect is also discussed in one of our former papers [3] and, when EA method is conducted, specimens made of the same material with the dimensions larger than 0.5 m $\times$ 0.5 m result almost identical sound absorption characteristics: ensemble averaged surface normal impedance $Z_{\mathrm{n,EA}}$ and absorption coefficient α_{EA}. In case non-uniform materials are to be measured in rather high frequency regions, selection of proper receiving points shall be an important issue. The issue, however, will be discussed in another paper, and hereinafter, PU-sensor is located at three points on a specimen to average(figure 2). A measurement on a specimen with the same setting at one of the three points is repeated three times to examine repeatability, *i.e.* the total number of a single measurement equals nine.

2.2 Sound source

EA method at early stage [1] utilized environmental pseudo-random noise as sound source for measurement; and, in case it is insufficient, loudspeakers radiating incoherent pseudo-random noises were employed. In such measurements, two-microphone of IEC 61672 class 1 quality was employed and signal to noise ratios (SNR) at measurements were considerably satisfactory.

On the other hand, it is known that SNR of particle velocity sensor in rather lower frequency region is less satisfactory comparing to those of microphones for precise measurements. Then, up to until now, in EA_{pu} method measurements conducted *in-situ*, we have employed four to eight portable loudspeakers to radiate incoherent pink noises which were moved around randomly by human-hands at the speed about 0.8 $\sim$ 1.0 m/s on an ideal sphere with the radius about 1.5 m away from the specimen's center receiving point. At the measurements conducted in reverberation rooms, four to six loudspeakers and one or two sub-woofers were set on the floor which radiate incoherent pink noises, as well [7].

2.3 Signal processing [2]

As is illustrated in figure 1, sound pressure P and particle velocity U_{n} normal to specimen surface are respectively measured by PU-sensor through a Hanning window with a time length of 0.64 s $\sim$ 1.00 s on a 2-channel fast Fourier Transform (FFT) instrument. Then, ensemble averaged surface normal impedance $Z_{\mathrm{n,EA}}$ and corresponding absorption coefficient α_{EA} are defined and calculated by the following equations:

$$Z_{\mathrm{n,EA}} = \frac{P}{U_{\mathrm{n}}}, \tag{1}$$

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

On the FFT, $Z_{\mathrm{n,EA}}$ is measurable as the transfer function $H_{\mathrm{U,P}}$ between U_{n} and P with linear averaging 150 times in the time domain; and ensemble averaging is, thus, performed automatically.

2.4 On-site PU-sensor calibration

Generally speaking, sensor calibration is essential for a precise measurement. In EA_{pp} method, the authors employ the "changing sensor position" method. While, in EA_{pu} method, we recommend on-site calibration using an acoustic tube, the details of which is discussed in literature[7]. A brief summary is given, below.

When an *in-situ* measurement of some kinds for sound absorption is conducted, environmental conditions, *e.g.* atmospheric temperature and humidity, frequently fluctuate. To avoid contamination of the atmospheric fluctuations from measured results by PU-sensor, on-site calibration is preferable[5, 6, 7]. Figure 3 illustrates an overview of an acoustic tube for PU-sensor calibration. The acuostic tube with the dimensions of $D = L - X =$ 0.05 m is designed to cover the frequency range from 100 Hz to 3000 Hz, or, from 125 Hz to 2500 Hz in 1/3 octave band[7]. Whenever a measurement is conducted by EA_{pu} method, it is desirable to perform a calibration using such an acoustic tube. The authors' former studies[5, 6] have revealed that relative humidity difference within 8% is acceptable between relative humidities at a sound absorption measurement and at a PU-sensor calibration.

Although wind speed is another important issue on environmental conditions, it will be discussed near future. All the measurements in this study are conducted when wind speed is slow enough to neglect the effect. From the view point of wind speed, closed tube is advantageous in eliminating the effect. Influence of environmental noise is easy to eliminate, too.

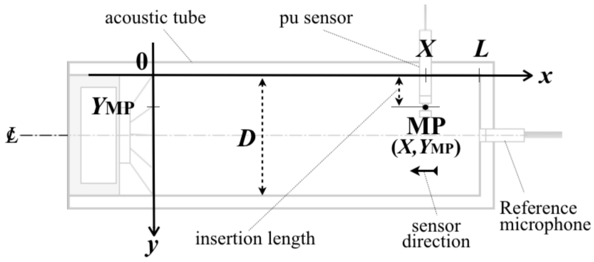


Figure 3. Acoustic tube for PU-sensor calibration. End walls are openable for the purpose of ventilation.[7]

Table 1. Abbreviations and dimensions of measured specimens.

Material	Abbrev.	Dimensions [m×m×m]
Glass-wool (32 kg/m^3)	GW	0.5 × 0.5 × 0.05
Needle felt	NF	0.5 × 0.5 × 0.01

3 MEASUREMENT SETUPS FOR REPRODUCIBILITY EXAMINATION

3.1 FFT setting

Following above mentioned configurations and procedure, $\mathrm{EA_{pu}}$ method measurements were conducted using 2ch-FFT (B& K, Pulse) and PU-sensor (Microflown, PU regular). The time length of Hanning window was set to 0.64 s to shorten measurement time especially for *in-situ* measurement.

3.2 Specimens and on-site PU-sensor calibration

Sound absorption characteristics, $Z_{\mathrm{n,EA}}$ and α_{EA}, of two specimens listed in table 1 were measured. The two specimens were brought to each sound field to measure their absorption characteristics *in-situ*. As mentioned above, each measurement of a specimen was conducted at three receiving points (figure 2) on the specimen surface and the measurement was repeated three times on different days to investigate the repeatability.

Here, on-site PU-sensor calibration using the acoustic tube was performed just before/after a series of measurement in a day at one of the following sound field. At every on-site PU-sensor calibration, both end walls were opened for ventilation to make atmospheric conditions similar to each other between in and out of the acoustic tube.

3.3 Sound fields

Measurements were conducted in five *in-situ* sound fields and in Oita university reverberation room. Details of the sound fields are listed in table 2. As to show an example overview, photographies of Caf are shown in figure 4. All the *in-situ* measurements were performed at ordinary furniture conditions with desks, tables, chairs, and so on. Only extraordinary impulsive noise like door-bangs were eliminated manually but ordinary environmental noise like air-conditioner noise existed during the measurements.

3.4 Sound source systems at measurements

As mentioned in section 2.2, all measurements conducted in Oita university reverberation room employed the sound source system consists of both a sub-woofer (YAMAHA, NS-SW700) and six full-range loudspeakers (Fostex, FE-103En mounted in wooden box) located on the floor. While, the other measurements conducted *in-situ* employed a system that consists of six portable loudspeakers (JBL, Micro wireless) moved by human-hand. Incoherent pink noises were emitted from the loudspeakers as well as from the sub-woofer. Figure 5 shows frequency characteristics of $L_{eq,\mathrm{20s}}$ measured by sound level meter during the three-day $\mathrm{EA_{pu}}$ method

Table 2. Sound fields used for the measurements.

Abbrev.	Name	Volume [m^3]	Interior surface materials (ceiling, walls, floor)
RR	Oita univ. reverberation room	168	Concrete, Concrete, Concrete
Caf	Cafeteria	2389	Wood, Wood & Glass, Stone
Cr	Corridor in a building	177	Gypsum board, Mortar, Vinyl tile
Tr	Terrace (semi-outdoor)	-	-, - & Glass, Brick-tile
R-E	Room for environmental simulation	70	Rock wool board, Wall cloth & Glass, Tile-Carpet
RC	Reinforced concrete house	34	Concrete, Concrete, Concrete

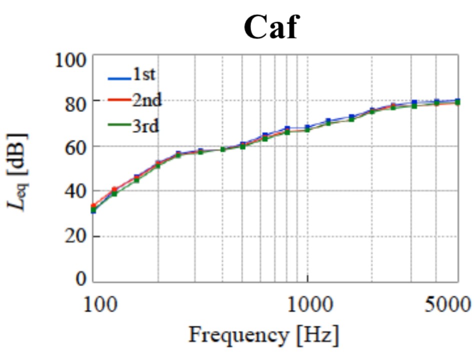
Figure 4. Snapshots of sound field at Oita university cafeteria "Caf" where *in-situ* $\mathrm{EA_{pu}}$ method measurements were conducted. (Left): overview, (Right): scenery at $\mathrm{EA_{pu}}$ method measurement of GW.

measurements at the specimen's center point in Caf. Microphone position of the sound level meter is set close to the location of sensor of PU-sensor.

4 RESULTS AND DISCUSSION

4.1 Comparison between six sound fields

Figure 6 shows sound absorption characteristics measured by $\mathrm{EA_{pu}}$ method at the six sound fields. Both $Z_{\mathrm{n,EA}}$ and α_{EA} are averaged over nine-time repetitions; and mean values of them are compared between sound fields. As for GW, agreements of $Z_{\mathrm{n,EA}}$ values between sound fields are excellent in the frequency region from 500



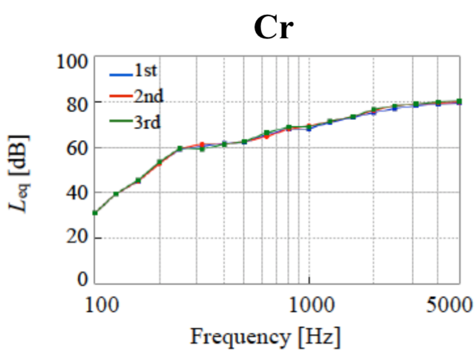


Figure 5. Frequency characteristics of $L_{eq,20\mathrm{s}}$ measured by sound level meter during the three-day (1st, 2nd and 3rd) $\mathrm{EA_{pu}}$ method measurements. Microphone of the sound level meter was placed at the specimen's center point close to PU-sensor. The measurements were conducted in the sound fields Caf (Left) and Cr (Right).

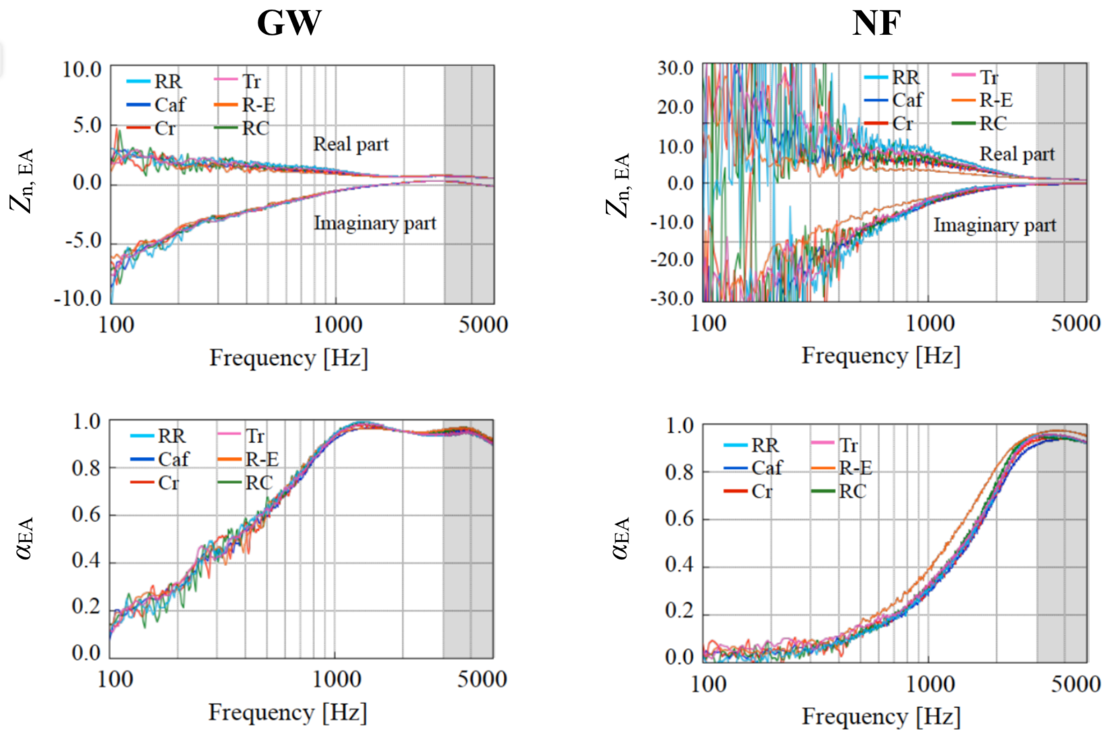


Figure 6. Sound absorption characteristics of GW (left column) and NF (right column) measured by EApu method at six sound fields (RR, Caf, Cr, Tr, R-E, RC). Mean values over nine-times repetition in each sound field are plotted. (upper row): surface normal impedance; and (lower row): absorption coefficient.

Hz to 3000 Hz. Although, in the lower frequency region below 500 Hz, certain discrepancies caused by zig-zag shape fluctuations are observable, overall tendencies agree well each other.

Likewise, agreements of α_{EA} values between six sound fields are excellent in the frequency region from 500 Hz to 3000 Hz; and similar tendencies to those of Z_{EA} values are observable.

On the other hand, as for NF, agreements of both $Z_{n,EA}$ and α_{EA} values are rather worse comparing to those of GW; and $Z_{n,EA}$ values in the frequency region below 500 Hz show certain large deviations.

Here, it is noteworthy that both $Z_{n,EA}$ and α_{EA} values measured in R-E show distinct differences from those measured in the other five sound fields. The differences are considered to be caused by flooring materials behind NF listed in table 2. In R-E, floor material is tile carpet; while, in the other five rooms, floor materials are concrete, stone, vinyl tile, brick tile, and concrete. Thus, higher absorption coefficient obtained in R-E is considered to result from the absorptive tile carpet behind NF. The effect is not obvious for GW because of the specimen's higher absorption.

4.2 Reproducibility examination

To examine the reproducibility of measurements by EA_{pu} method over sound field difference, 1/3 octave band values of α_{EA} and their standard deviation σ values are plotted in figure 7. As for both GW and NF, agreements of 1/3 octave band mean values of α_{EA} between six sound fields are excellent in all the frequency region from 100 Hz to 3000 Hz except those of NF measured in R-F. The reason why the exception occurs is resulted from the existence of the absorptive tile carpet behind the specimen, as stated above.

Due to the disagreement caused by the measurement of NF in R-E, standard deviation σ values of NF become

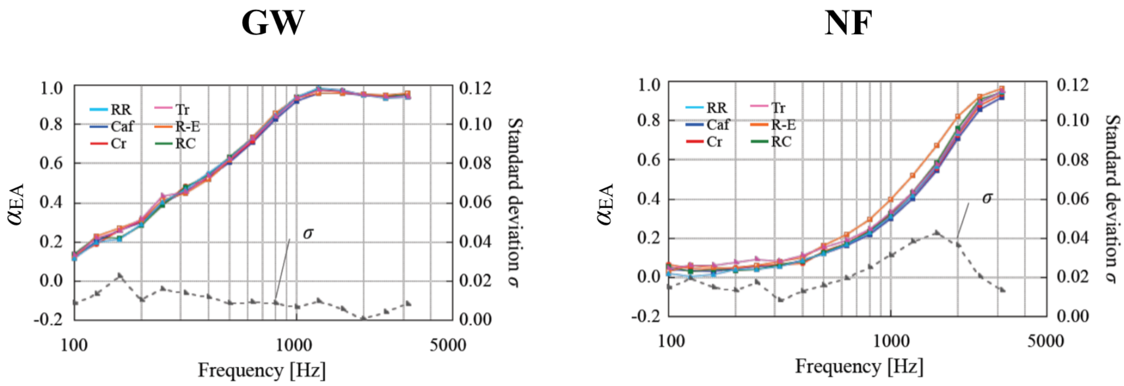


Figure 7. Comparisons of 1/3 octave band mean values of α_{EA} of GW and NF between six sound fields (RR, Caf, Cr, Tr, R-E, RC). Standard deviation σ values are plotted together with right axis.

larger than 0.03 in the frequency region from 1000 Hz to 2000 Hz. Nonetheless, the other σ values stay around or less than 0.02, which shows the reproducibility of EA_{pu} method applied to sound fields including *in-situ*. Note that, though all the *in-situ* measurements at five sound fields were conducted with six portable loudspeakers moved around by human-hands, α_{EA} values were obtained with such small deviations.

Thus, EA_{pu} method following above mentioned configurations and procedure results robust results with $\sigma \leq 0.03 \sim 0.04$ regardless of sound field difference provided on-site PU-sensor calibration is performed.

5 CONCLUSIONS

As a measurement method for sound absorption characteristics of materials, EA method is robust and advantageous in: (1) short measurement time about 1 min (for 150 times linear averaging in time domain on FFT); (2) *in-situ* measurements give almost similar results to those measured in a reverberation room; (3) reproducibility on sound field difference is as exhibited above: standard deviation $\sigma \leq 0.03 \sim 0.04$ for 1/3 octave band mean values of α_{EA}; and (4) edge effect of material is insignificant: *i.e.* flexible for specimens in shapes and sizes (larger than 0.5 m $\times$ 0.5 m area is recommended). A disadvantage might be that PU-sensor calibration takes some additional time. Meanwhile, material's non-uniformity issue is needed to be discussed and various applications including the issue are undertaken, as well.

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