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An *in-situ* technique for extensive field measurements of absorption characteristics of materials by using ensemble averaging

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ABSTRACT

This paper investigates by experiment the absorption characteristics of several materials associated with the proposed acoustics impedance method using the combination of sound pressure and particle velocity sensors in a various sound field. This method is based on the concept of "ensemble averaged" surface normal impedance that extends the usage of obtained values to various applications such as architectural acoustics and computational simulations. The measurement technique itself is an improvement of the method using two-microphone technique and diffused ambient noise, as proposed by Takahashi, Otsuru et al. A series of measurement in different sound fields were conducted to expand the relevant applicability of *in-situ* measurement using pu-sensor. The first part of the experiment aimed to confirm the reproducibility of the measured values of the method. Here, comparative round robin measurements in four reverberation rooms were conducted to ensure that the results could be obtained with reasonable accuracy. An accompaniment discussion on general tendencies and discrepancies of ten materials between the various reverberation rooms are provided. In the second stage, a trial application with four types of selected materials with reliable specimen size was carried out to impress the ubiquitous examination of material's absorption characteristics at different sound fields such as in architectural spaces. This paper revealed the reliability, applicability and robustness of the method throughout the investigation as *in-situ* measurement.

INTRODUCTION

There are two well-known methods of laboratory measurement of absorption which have been described as international standards [1]−[3] in providing important information about the test material (i.e. reverberation room and tube method). A number of studies [4]−[9] have been conducted in order to check the effectiveness of the standard. In Europe, a set of round robin test was carried out in the past decade to investigate the accuracy of the measurement of the reverberant sound absorption coefficient [4]. Nevertheless, there still remain unresolved issues e.g. diffusivity in the reverberation room, edge effect of specimen, etc. Another series of round robin tests were carried out in Japan [5]−[6] to look into the some of the aforementioned problems. Differences of measurement values due to the room volume, measurement instruments, etc. were kept central to the investigation to maintain a satisfactory level of accuracy.

Meanwhile, the accuracy of the performance of the tube method has also been reported [7]−[9]. Horoshenkov et al. [9] presented the dispersion of measured normal incident results of inter laboratory reproducibility experiments of the acoustical properties in Europe and North America. They are highlighted the importance of the boundary conditions, homogeneity of the porous material structure and stability of the adopted signal processing method. However, similar mounting conditions are difficult to reproduce and this may affect the measured results.

In our previous paper [10], the theoretical development and concept of ensemble averaged surface normal impedance at random incidences were given. Several boundary element method (BEM) simulations of glass wool both at normal and at random incidences showed that ensemble averaging decreases the interference effect caused mainly by the specimen's edges. The BEM simulation with anisotropy consideration [11]−[13] is compared with those by the measurement result and gives an appropriate expected values of the surface normal impedance of the glass wool. Also, a series of measurements by proposed method using pu-sensor (Microflown [14]) are presented to investigate the considerable geometrical configurations e.g. the sensor height, and the sample size, in measuring the acoustics behavior of absorptive material [15].

Method reliability is one of the factors that needs to be taken into consideration while aiming toward an efficient *in-situ* measurement technique. There is lack of data on the method reliability of our method which uses pu-sensor. As a preliminary study, our objectives in this paper are: (i) to investigate whether the proposed method can offer plausible agreements of reproducibility for selected materials between different reverberation rooms; and (ii) to expand the relevant applicability of *in-situ* measurement using pu-sensor outside laboratory rooms.

SHORT DESCRIPTION OF THE METHOD

Ensemble Averaged Surface Normal Impedance [10]

The authors proposed an impedance as:

$$< Z_n >= \frac{< p_{\mathrm{surf}} >}{< u_{n,\mathrm{surf}} >}, \tag{1}$$

where, $< p_{\mathrm{surf}} >$ and $< u_{\mathrm{n,surf}} >$ denote averaged sound pressure and particle velocity with respect to normal direction at the material surface. Tentatively, the resulting impedance, $< Z_n >$, was named the "Ensemble Averaged" surface normal impedance. The corresponding absorption coefficient, $< \alpha >$, is given by:

$$< \alpha >= 1 - \left| \frac{< Z_n > -\rho c}{< Z_n > +\rho c} \right|^2. \tag{2}$$

Here, ρ and c are the density of air and the speed of sound, respectively. The averaging can be performed using a fast-Fourier-transform (FFT) like,

$$< Z_n >= \frac{1}{N} \sum_N H_{up}(\omega) = \frac{1}{N} \sum_N \frac{< \tilde{p} >}{< \tilde{u}_n >}. \tag{3}$$

where $H_{up}(\omega)$ denotes the transfer function that links p and u_n. N is an averaging, used in the FFT. In the case where the system is ergodic and assuming sufficient averaging, Eqs. 1 and 3 become identical.

Measurement outline

Figure 1 shows schematics of the apparatus used in the measurement. The pu-sensor was located 10 mm above the specimen surface ($d' = 10$ mm) to measure p and u_n. The pu-sensor was calibrated using an acoustic tube with 10 mm diameter for the usage within the frequency from 100 Hz to 1500 Hz. The resolution of the two-channel FFT (RION SA-78) unit was set to 1.25 Hz and a Hanning window of duration 0.8 s was employed to measure the transfer function.

In the original method [16], the sound source was intended for use only with diffuse ambient noise that exists around the specimen to be measured. However, in the case where the noise is insufficient, a supplemental noise source(s) can be added to improve the result. Generally, the loudspeakers were employed to radiate incoherent pink noises. The pink noise was filtered to eliminate unnecessary frequency components for the measurements, which are focused tentatively within the 100 Hz to 1500 Hz range.

So as to provide a compact presentation and ensure convenience for the reader, all the results are averaged in 1/3 octave band and presented as absorption coefficients base.

Table 1: Dimensions of the reverberation rooms.

Room	Geometry	Volume [m^3]	Floor Area [m^2]
I	irregular	165.7	34.2
II	irregular	224.5	38.8
III	irregular	500.0	78.8
IV	regular	56.6	90.5

METHOD REPRODUCIBILITY

The main purpose of the measurements in this section is to investigate whether the proposed method can offer reproducibility of measured absorption characteristics on various materials

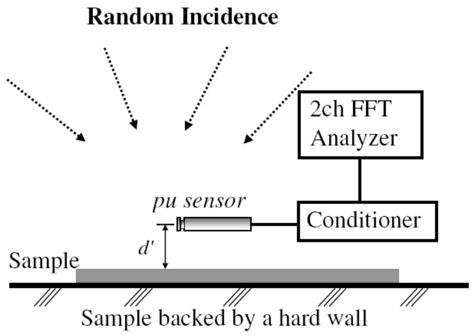

Figure 1: Schematic diagram of the measurement setup with a pu sensor.

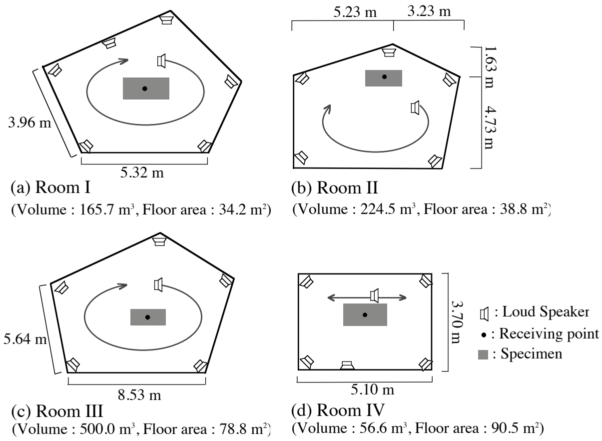

Figure 2: Location of sound sources, receiving points and specimens: (a) Room I; (b) Room II; (c) Room III; (d) Room IV.

in different reverberation rooms. A series of measurement is conducted in four reverberation rooms with kind permission from the participating institutes in Japan as depicted in Fig. 2. In addition, suspended diffuser panel are installed in Room II and the reverberation time in Room IV was compensated as suggested in ISO 354 and JIS A 1409. Table 1 shows the details of dimension and volume of each type of reverberation rooms. In Fig. 2, the location of sound sources, receiving point and specimen under test are illustrated.

Five fixed loudspeakers are employed to radiate incoherent pink noises except in Room I where six fixed loudspeakers are employed. Also, an additional movable loudspeaker are used in all reverberation rooms. Ten types of materials with specific dimensions are investigated as listed in Table 2. All of specimens are laid on a 0.02 m acrylic plate. The resolution of FFT settings is set to be 2.5 Hz in all reverberation rooms except in Room I where the resolution is set to be 1.25 Hz.

Table 2: Materials to be measured.

Material	Abbrev.	Size [mm^3]
Glass wool (32kg/m^3)	GW50	1820x910x50
Flexible urethane foam	VOF20	1820x910x20
Flexible urethane foam	VOF50	1820x910x50
Polyester nonwoven (16kg/m^3)	PW16K	1820x910x50
Polyester nonwoven (32kg/m^3)	PW32K	1800x900x50
Needlefelt	NF	1800x900x10
Needle punched carpet	NPC	1800x900x3
Tile Carpet	TC	(500x500x6)x6.5
Cut pile carpet	CPC	1820x910x15
Rock wool board	RWB	(600x300x12)x9

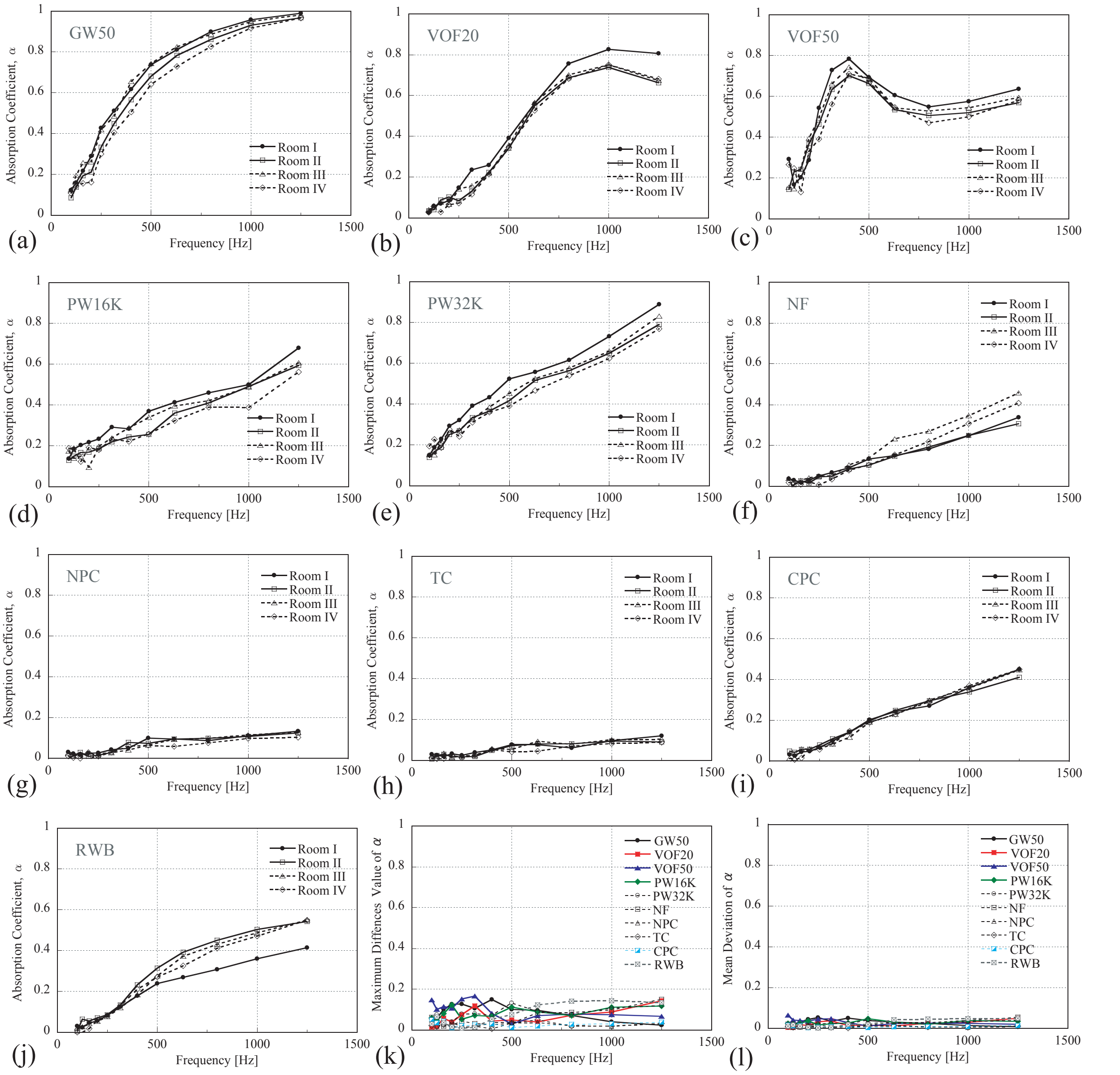

Figure 3: Comparisons of; (a) - (j) measured absorption coefficients of ten types of specimens obtained by proposed method in four reverberation rooms; (k) maximum differences value of absorption coefficients; (l) mean deviation of absorption coefficients.

Figures 3(a) - (j) shows the comparisons of measured absorption coefficients of each type of specimens in four types of reverberation rooms. The maximum differences values and the mean deviation of absorption coefficients for each specimens also provided by Figs. 3(k) and 3(l), respectively. In general, the measured absorption coefficients show the same basic tendency for their respective specimens with some differences value relatively independent on the frequency. From these results, the good agreements for the measured absorption coefficients obtained in the four reverberation rooms as observed in the Figs. 3(g) - (i), whereby the maximum dispersion in the measured absorption coefficients is 0.05 for CPC.

Furthermore, the other specimens can be considered having fair agreements based on the maximum dispersion being below 0.17. Even though the high dispersion values are observed in the measured absorption coefficients, they can be considered as acceptable discrepancies according comparison with other results related to acoustics impedances round robin tests [5],[6],[9]. In Fig. 3(l), on the whole, the maximum mean deviation of absorption coefficients is lower than 0.06. At this stage, we conclude that the reproducibility of the proposed method is satisfactory, and that the method gives appropriate absorption coefficients despite the geometrical differences of the reverberation rooms.

METHOD APPLICABILITY

To investigate the general applicability of the proposed method, a series of preliminary measurements of the four materials has been carried out in three other environments of architectural spaces [a corridor, an entrance hall and a seminar room]. Plan views of furniture layouts and material locations in the field measurements are shown in Fig. 4. Figure 5 shows the conditions of field measurements in the corridor, the entrance hall and the seminar room. Specimens to be investigated are GW50, NF, TC and additional of glass wool 25 mm thick (GW25). All the specimens are laid on a 0.02 m acrylic plate and have the same square areas with 0.6 x 0.6 m^2 except for TC where the area is 0.5 x 0.5 m^2. The specimen's sizes are not exactly identical to that of the investigation in previous section, but

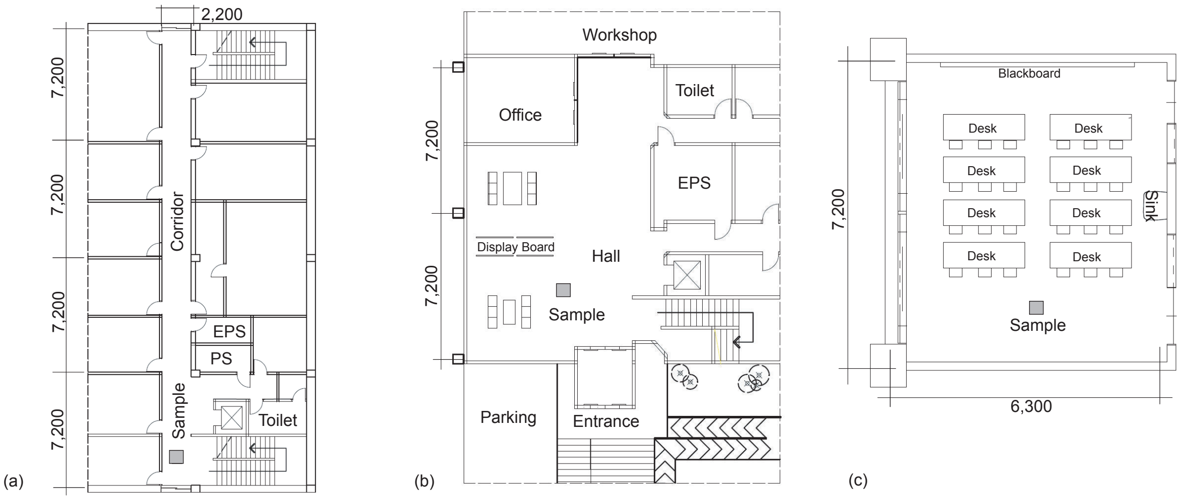

Figure 4: Plan views of furniture layouts and material locations: (a) a corridor; (b) an entrance hall; (c) a seminar room.

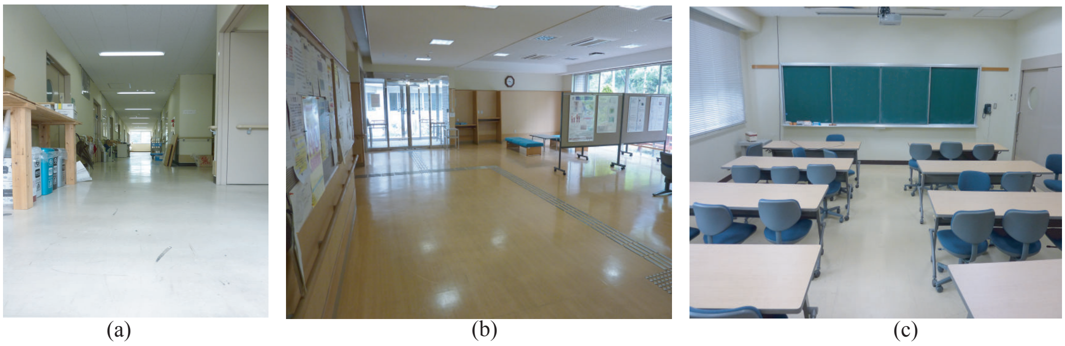

Figure 5: Photo of field measurements in architectural spaces: (a) a corridor; (b) an entrance hall; (c) a seminar room.

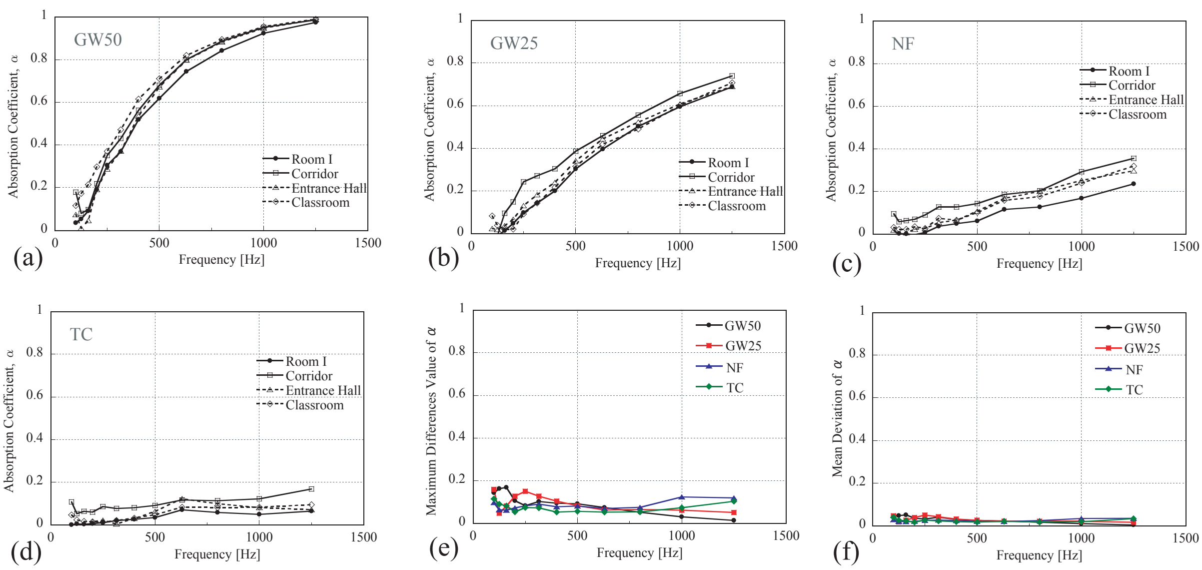

Figure 6: Comparisons of; (a) - (d) measured absorption coefficients of four types of specimens obtained by proposed method in the corridor, the entrance hall and the seminar room; (e) maximum differences value of absorption coefficients; (f) mean deviation of absorption coefficients.

we expected to have sufficient validity for the discussion as described in Ref.15. The six portable sound speakers with incoherent pink noises are employed and manual-moved randomly by three people to realize the random noises condition because of insufficient noises in all environments conditions. For comprehensibly comparisons, the measurements of similar specimens are conducted in Room I using six fixed loudspeakers to radiate incoherent pink noises.

Figures 6(a) - (d) present the combined results measured in three other environments for all the specimens GW50, GW25, NF and TC, respectively. All the measured absorption coefficients in three other environments are compared with the measured absorption coefficients obtained in Room I. Same as previous section, the maximum differences and mean deviation of measured absorption coefficients are provided in Figs. 6(e) - (f), respectively.

The same basic tendencies can be observed for all specimens in Figs. 6(a) - (d) but there are noticeable differences in the dispersion. The results of measured absorption coefficients of Room I is lower than the results measured in three other environments. There can be complementary aspect which can explain this phenomenon: (i) the result of sound reflections coming from the specimen's surrounding; (ii) the dissimilarity of measurement setting of sound sources where the fixed loudspeakers are employed in Room I. Moreover, all specimens can be considered as having fair agreements based on the maximum dispersion being below 0.17 and maximum mean deviation being lower than 0.06, similar as found in the previous section. We consider the dispersion of measured absorption coefficients yield plausible agreements to support the applicability of the proposed method in various sound fields.

CONCLUSIONS

In this study, an extensive measurements of "ensemble averaged" surface normal impedance at random incidences in different sound fields have been performed onto various selected materials. A series of measurement in different types of reverberation rooms revealed that the discrepancies in absorption coefficients brought by the pu-sensor gives reasonable accuracy measured values to confirmed the reproducibility of the method. The preliminary of *in-situ* measurements using pu-sensor offers good applicability for our method to apply onto various practical measurements. Further numerical and experimental investigations are now being pursued intensively.

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