REPRODUCIBILITY AND APPLICABILITY OF ENSEMBLE AVERAGED SURFACE NORMAL IMPEDANCE OF MATERIALS USING AN *IN-SITU* TECHNIQUE

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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 various sound fields. 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. A series of measurement in different sound fields was 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. The general tendencies and discrepancies of ten materials in the various reverberation rooms are discussed. In the second stage, the method was applied with four types of selected materials to examine material's absorption characteristics at different sound fields such as in architectural spaces. This paper revealed the reliability, applicability and robustness of the method despite the room's geometrical differences throughout the *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 standards. 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 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 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 the measurement result to give an appropriate expected value of the surface normal impedance of the glass wool. Also, a series of measurements by proposed method using pu-sensor (Microflown, [14], [15]) is presented to investigate the considerable geometrical configurations e.g. the sensor height, and the sample size, in measuring the acoustics behavior of absorptive material [16].

Method reliability is one of the factors that needs to be taken into consideration while aiming toward an efficient *in-situ*

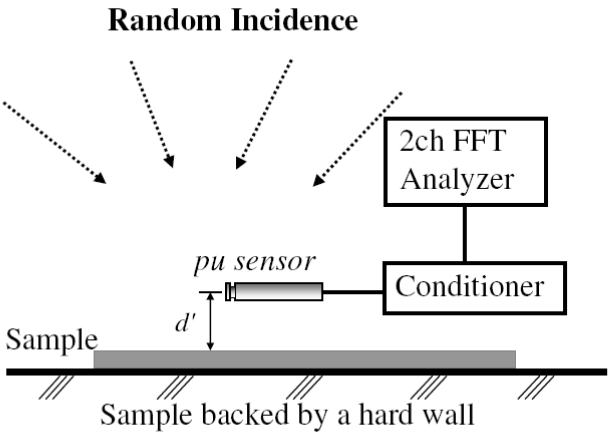

Figure 1. Schematic diagram of the measurement setup with a pu sensor

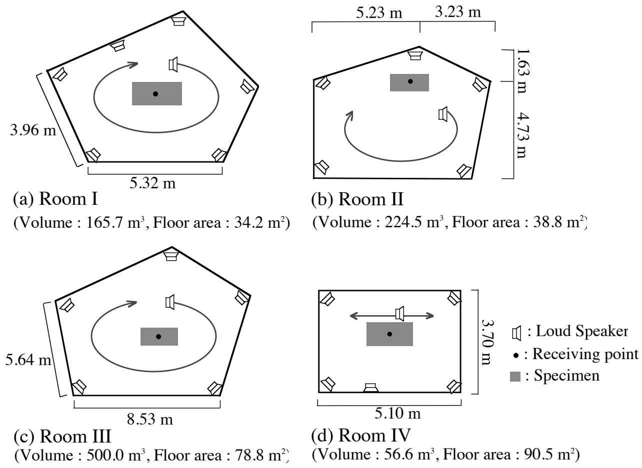

Figure 2. Location of sound sources, receiving points and specimens: (a) Room I; (b) Room II; (c) Room III; (d) Room IV

measurement technique. There is a lack of data on the method reliability of the method that uses pu-sensor. The objectives of 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

In this section, we summarize the explanation given in our previous papers [10], [16]. The authors proposed an ensemble averaged impedance, $\langle Z_n \rangle$, as

$$\langle Z_n \rangle = \frac{\langle p_{\mathrm{surf}} \rangle}{\langle u_{n,\mathrm{surf}} \rangle} \tag{1}$$

where $\langle \cdot \rangle$ denotes the ensemble average.

In a practical measurement using digital techniques with a fast Fourier transform (FFT), the process of ensemble averaging is assumed that $p(t,\theta_i)$ and $u_n(t,\theta_i)$ denote, respectively, the sound pressure and particle velocity normal to the surface of sound incidence angle, θ_i close to the surface at time t.

The ensemble averaging of the sound pressures and particle velocities $\langle p(t) \rangle$ and $\langle u_n(t) \rangle$, respectively, in incident event number, M, can be written as

$$\langle p(t) \rangle = \frac{1}{M}\sum_{i=1}^{M} p(t,\theta_i) \times W(t), \tag{2a}$$

$$\langle u_n(t) \rangle = \frac{1}{M}\sum_{i=1}^{M} u_n(t,\theta_i) \times W(t), \tag{2b}$$

where $W(t)$ is a window function with length, T_w. Applying the Fourier transform, we have

$$\langle p(\omega) \rangle = \int_{-T_w/2}^{T_w/2} \langle p(t) \rangle \, e^{-j\omega t} dt, \tag{3a}$$

$$\langle u_n(\omega) \rangle = \int_{-T_w/2}^{T_w/2} \langle u_n(t) \rangle \, e^{-j\omega t} dt, \tag{3b}$$

where ω is the angular frequency of sound and j denotes the imaginary number $\sqrt{-1}$.

Next, the transfer function $H_{up}(\omega)$ between the velocity output to the pressure response for averaged sound pressures and averaged particle velocities in the frequency domain becomes $H_{up}(\omega) = \langle p(\omega) \rangle / \langle u_n(\omega) \rangle$.

Here, with the linear averaging number, N, on FFT, we express the ensemble averaged impedance as

$$\langle Z_n \rangle = \frac{1}{N}\sum^{N} H_{up}(\omega). \tag{4}$$

The corresponding absorption coefficient, $\langle \alpha \rangle$, is given by:

$$\langle \alpha \rangle = 1 - \left| \frac{\langle Z_n \rangle - \rho c}{\langle Z_n \rangle + \rho c} \right|^2. \tag{5}$$

Here, ρ and c are the density of air and the speed of sound, respectively.

Measurement outline

Figure 1 shows schematics of the apparatus used in the measurement. The pu-sensor was located at the middle of the specimen with the height of 10 mm above from specimen surface ($d' = 10$ mm) to measure p and u_n. The pu-sensor was calibrated using an acoustic tube with 10 cm 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, $W(t)$, of duration 0.8 s with the averaging number, N, of 150 was employed to measure the transfer function.

In the original method [17], 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

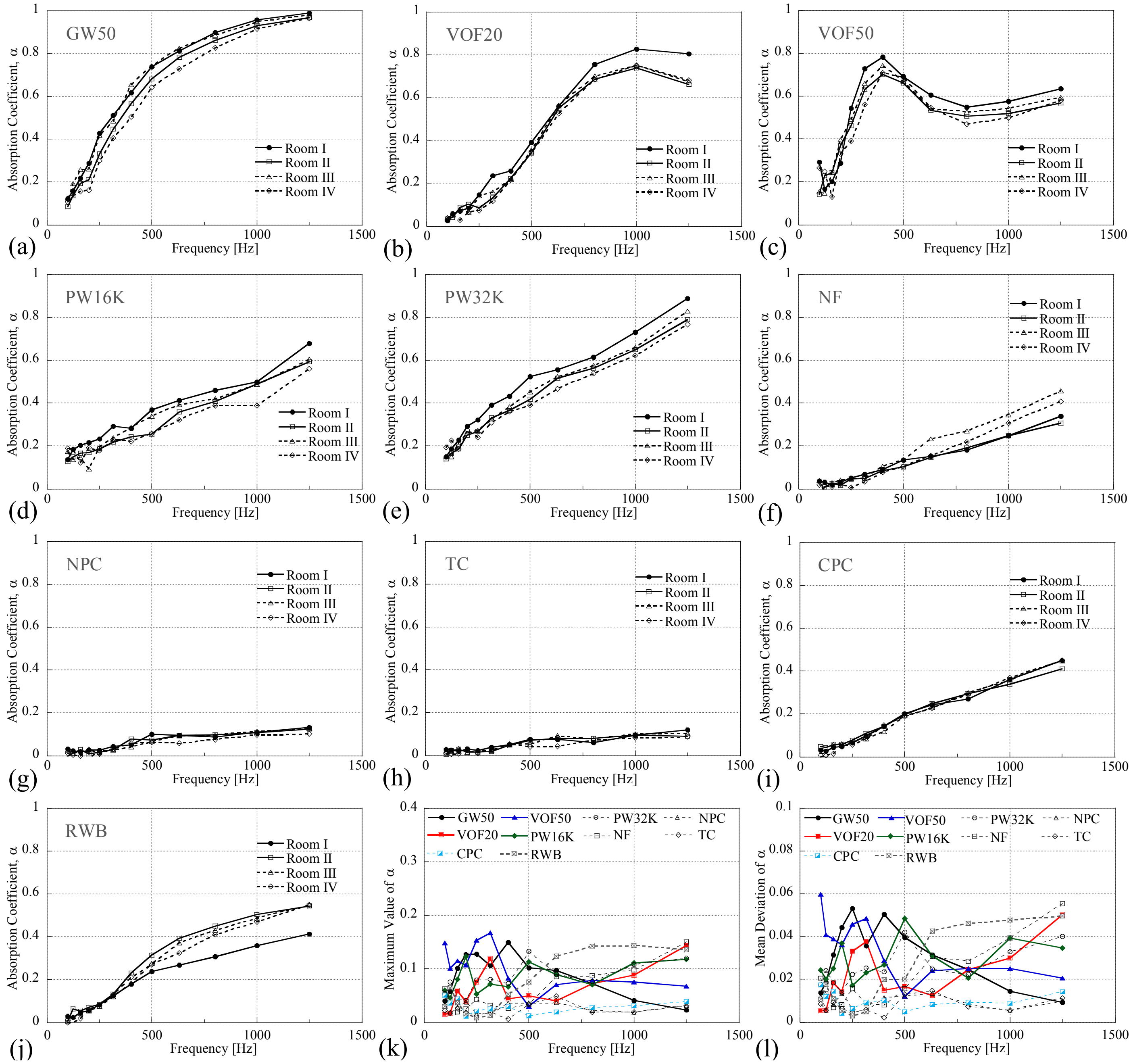

Figure 3. Comparisons of (a) - (j) measured absorption coefficients of ten types of specimens obtained by proposed method in four reverberation rooms; (k) maximum differences value of absorption coefficients; (l) mean deviation of absorption coefficients

to radiate incoherent pink noises and focused to examine the 100 Hz to 1500 Hz in 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.

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 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. Suspended diffuser panels are installed in Room II and the reverberation time in Room IV is compensated as suggested in ISO 354 and JIS A 1409. Figure 2 also indicates the location of sound sources, receiving point and specimen under test. Table 1 shows the details of dimension and volume of each type of reverberation rooms.

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

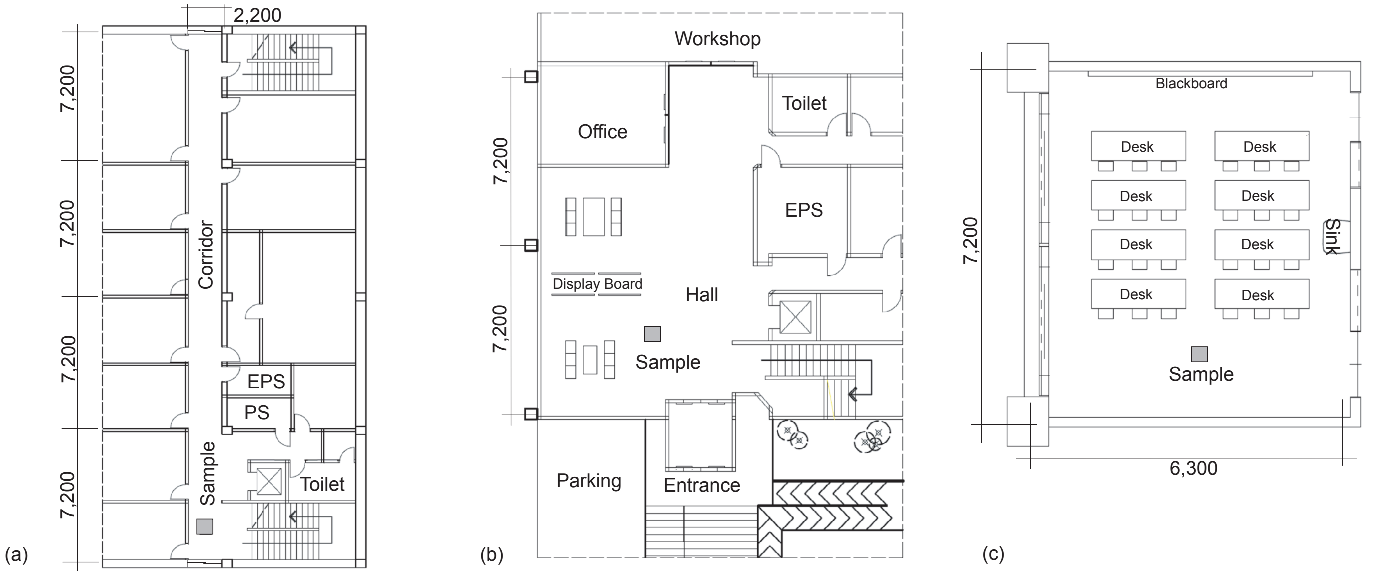

Figure 4. Plan views of furniture layouts and material locations: (a) a corridor; (b) an entrance hall; (c) a seminar room

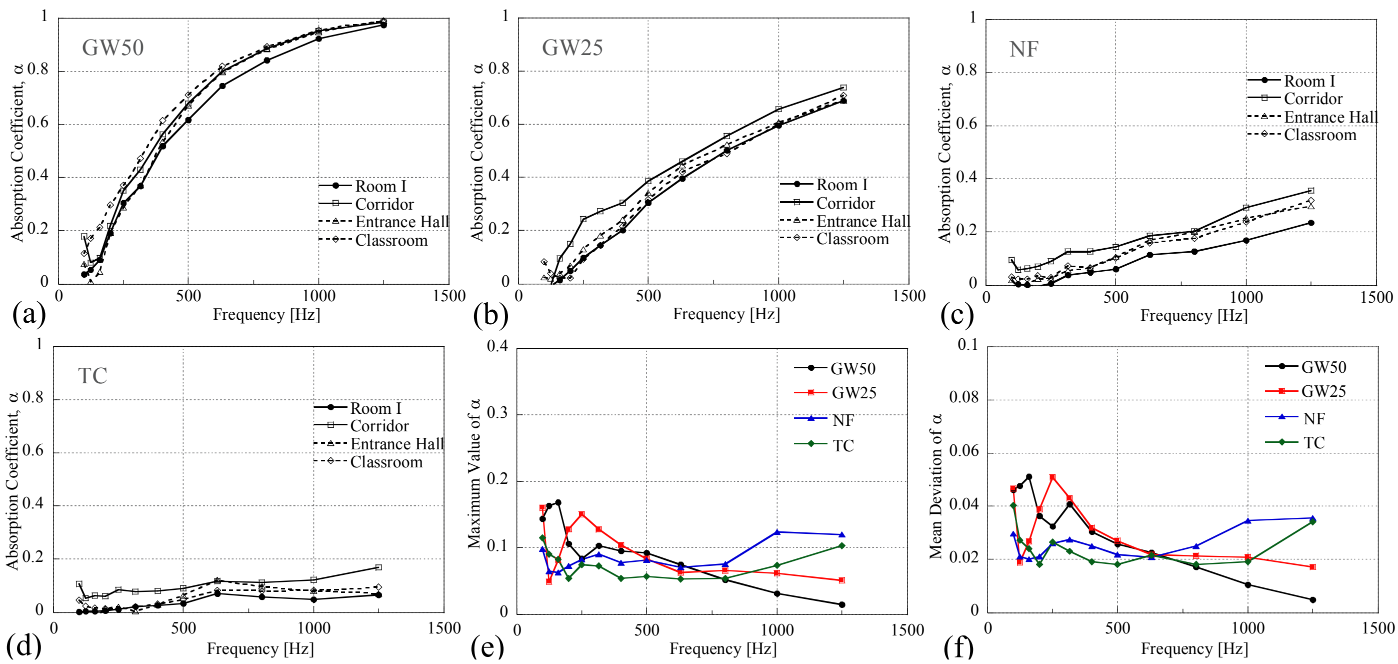

Figure 5. Comparisons of; (a) - (d) measured absorption coefficients of four types of specimens obtained by proposed method in the corridor, the entrance hall and the seminar room; (e) maximum differences value of absorption coefficients; (f) mean deviation of absorption coefficients

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.

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 in value relatively independent on the frequency. From these results, the good agreements for the measured absorption coefficients obtained in the four reverberation rooms are observed in 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

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

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

below 0.17. Even though the high dispersion values are observed in the measured absorption coefficients, they can be considered as acceptable discrepancies based on 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, it can be concluded 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 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. 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 sufficient validity can be expected for the discussion as described in Ref. 11. 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 a comprehensive comparison, the measurements of similar specimens are conducted in Room I using six fixed loudspeakers to radiate incoherent pink noises.

Figures 5(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. 5(e) - (f), respectively.

The same basic tendencies can be observed for all specimens in Figs. 5(a) - (d) but there are noticeable differences in the dispersion. The result of measured absorption coefficients of Room I is lower than the results measured in three other environments. There can be complementary aspects that 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. The dispersion of measured absorption coefficients can be considered plausible agreements to support the applicability of the proposed method in various sound fields.

CONCLUSIONS

In this study, an extensive measurement of "ensemble averaged" surface normal impedance at random incidences in different sound fields using the pu-sensor has been performed onto various selected materials. A series of measurement in different types of reverberation rooms revealed that the material's absorption coefficients yield relatively small measured maximum mean deviation to confirm the reproducibility of the method. The *in-situ* measurements using pu-sensor offers good applicability of the method to apply onto various practical measurements. Further numerical and experimental investigations are now being pursued intensively.

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