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A PRACTICAL APPLICATION OF ENSEMBLE AVERAGED SURFACE NORMAL IMPEDANCE MEASURED *IN SITU*

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ABSTRACT

This paper presents the application of an *in situ* measurement technique of sound absorption characteristics, namely the “Ensemble Averaged Method”. Previously, a measurement technique of material surface normal impedance by using a two-microphone (p-p) technique and ambient noise was proposed by some of the authors. This includes the concept of “ensemble averaged” surface normal impedance to extend the usage of the obtained values to various applications, such as architectural acoustics and computational simulations. With the development of a particle velocity (p-u) sensor, the practicality of techniques for the direct measurement of impedance becomes feasible. A concept of the ensemble averaged surface normal impedance is addressed, including a basic technique to measure it by using p-p and p-u sensors. Then, the agreements between p-p and p-u sensors are discussed and the discrepancies of absorption coefficients are shown to be small. The paper reveals the reliability, applicability and feasibility of the method throughout the investigation as an *in situ* measurement technique.

Keywords: *In situ* technique; ensemble average; normal impedance; absorption coefficient.

INTRODUCTION

Numerous *in situ* measurement techniques have been proposed to measure sound absorption characteristics. There are two well-known methods of laboratory measurement of absorption, which have been described as international standards (ISO 105034, 1996; ISO 10534, 1998; ISO 354, 2003) in providing important databases regarding test materials, i.e., the reverberation room, and the tube method. A number of studies (Kosten, 1960; Makita et al., 1968a; Makita et al., 1968b; Cummings, 1991; Iwase and Izumi, 1995; Horoshenkov et al., 2007) have been conducted in order to check the effectiveness of the standard. Nevertheless, there are still issues that remain unresolved, e.g., the difficulty of measurements *in situ* because similar mounting conditions are difficult to reproduce.

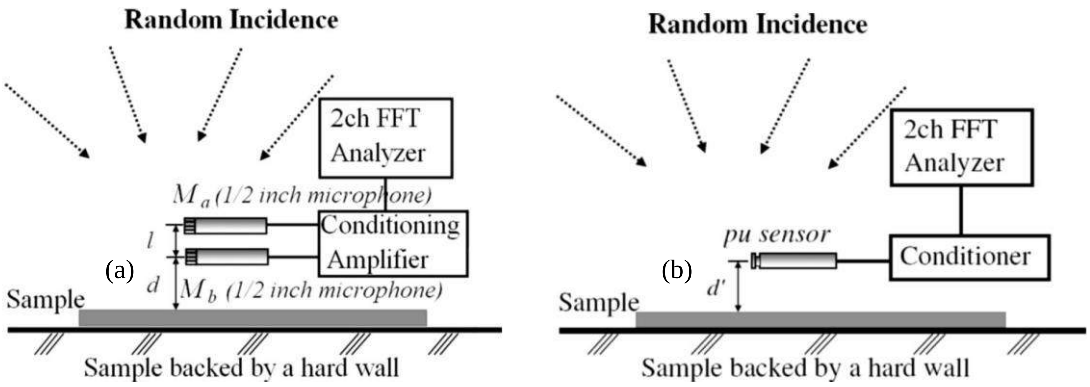


Figure 1. Schematic diagram of the measurement setup by using: (a) p-p sensor, and (b) p-u sensor.

On the other hand, numerous methods have been proposed to measure the absorption characteristics of material *in situ*. One of most popular methods it the "reflection method", which has been used to derive the sound absorption coefficient *in situ*. Among the works in the literature on the reflection method, Garai (1993) applied the maximum length sequential (MLS) technique as a test signal to improve the immunity to background noise and to measure the absorption coefficient *in situ*. However, there are restrictions of the method at low frequencies because the assumption of the plane wave is unachievable. Thus, the method proposed by Allard and Champoux (1989) is popular and efficient among the reflection methods. Their method focuses on a transfer function method using two microphones (p-p) located near the surface and this enables *in situ* measurements of a sample area. Nevertheless, the required sample size increases as the frequency decreases. To overcome this situation, some authors have proposed a method using a two microphones technique with Environmental Anonymous Noise as the sound source; known as "the EA method" (Takahashi et al., 2005). Initially, the sound source was intended for use only with diffuse ambient noise that exists around the specimen to be measured. However, in cases where this is insufficient, a supplemental noise source(s) can be added to improve the result.

Meanwhile, with the development of a particle velocity sensor, i.e., Microflown™, alternative measurement techniques have become possible for direct related particle velocities quantities (de Bree et al., 2006). Aiming towards a simple and efficient *in situ* measurement technique, the authors make use of the combination of a microphone and a particle velocity (p-u), instead of a two microphones technique, in order to determine the acoustic behavior of absorption material in the EA method. This paper is structured as follows: Section 2 presents the description of the EA method for each type of sensor. Section 3 discusses the results obtained by practical measurement with different types of sensor. Section 4 presents the preliminary results for the absorption coefficient of *in situ* measurements, i.e., in architectural spaces and in car cabins. Section 5 shows that the method is applicable for absorption characteristics of perforated-type panels, and Section 6 concludes the paper.

ENSEMBLE AVERAGE METHOD

Outline of the Method using p-p Sensor

The technique described below is based on the measurement of the pressure transfer function between two microphones. As shown in Figure 1(a), two ½ inch microphones are located at M_a and M_b. The distance *d* from the material surface is about 10 mm; the space *l* between the two microphones is 13 mm. The transfer function H_{ab} (ω) between $p_a(\omega)$ and $p_b(\omega)$ at M_a and M_b is measured by means of a Fast Fourier Transform (FFT) analyzer. When ambient noise is utilized as the sound source with the sound pressure $p_{aEA}(\omega)$ and $p_{bEA}(\omega)$ under the plane wave assumption, the normal impedance ratio of material to air $Z_{EA}(\omega)$ is given as (here, time dependence $e^{j\omega t}$ is omitted):

$$Z_{EA}(\omega) = \rho c \frac{H_{abEA}(\omega)(1-e^{2jk(l+d)}) - e^{jkl}(1-e^{2jkd})}{H_{abEA}(\omega)(1+e^{2jk(l+d)}) - e^{jkl}(1+e^{2jkd})}, \quad (1)$$

where *k* is the wavelength constant, and *j* is an imaginary unit. If the ambient noise is insufficient, a supplemental sound source can be added to improve the signal-to-noise ratio.

Outline of the Method using p-u Sensor

If a p-u sensor is applied to the EA method (Figure 1(b)) instead of a p-p sensor, it can be located at the same position of M_b in Figure 1(a). Surface normal impedance of a material is simply defined as:

$$Z_n = \frac{p_{surf}}{u_{n,surf}} \quad (2)$$

where *u* and *p* are normal particle velocity and sound pressure at the material surface, respectively.

Our previous paper (Otsuru et al., 2009) introduced impedance $\langle Z_n \rangle$ that is an ensemble averaged impedance over a sufficient number of incoherent sound sources such as to expect random incidence. Consequently, the following equations are expected to yield a statistically good approximation of the surface normal impedance and corresponding absorption coefficient of a specimen.

$$\langle Z_n \rangle = \frac{\langle p_{surf} \rangle}{\langle u_{n,surf} \rangle} \quad (3)$$

$$\langle \alpha \rangle = 1 - \left| \frac{\langle Z_n \rangle - \rho c}{\langle Z_n \rangle + \rho c} \right|^2 \quad (4)$$

In a practical measurement, to achieve sufficient averaging, the authors propose the following:

$$\langle Z_n \rangle = \frac{1}{N} \sum_N \frac{\langle \tilde{p} \rangle}{\langle \tilde{u}_n \rangle} \quad (5)$$

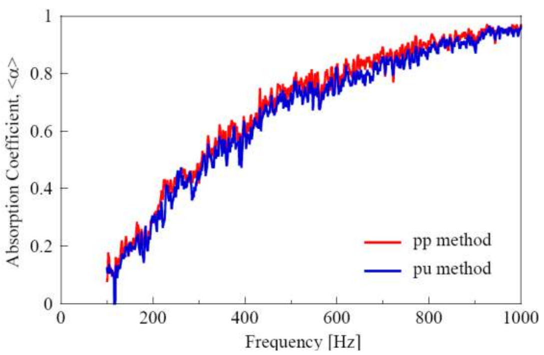
COMPARISON OF TWO DIFFERENT MEASUREMENT PRINCIPLES

Measurement Framework

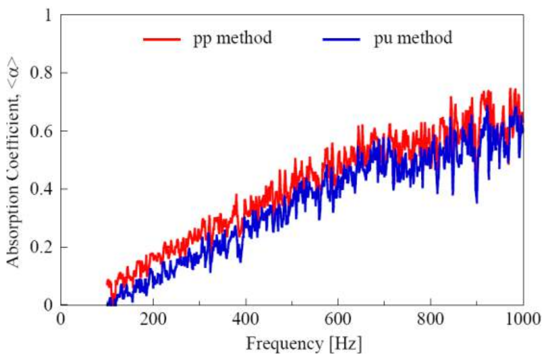
A series of absorption characteristic measurements was conducted by use of the EA method with both p-p and p-u sensors, as shown in the schematic diagram of the measurement setup (Figure 1). The measurement of the p-p sensor, the transfer function $H_{ab}(\omega)$ between the sound pressures at the two microphones p_a and p_b, was measured. Then, if a p-u sensor is applied to the measurement instead of the p-p sensor, it can be located 10 mm above the surface to measure p and u_n. Prior to detailed investigations, a refinement of the calibration system by use of an impedance tube of 10-cm diameter was conducted and the basic characteristics of the p-u sensor were measured. The resolution of two channels FFT (RION SA-78) is set to 1.25 Hz and a Hanning window with a 0.8 s time length is employed to measure the transfer function. Linear averaging in the frequency domain is performed N = 150 times. The measurements were conducted in a reverberation room (Room I) at the Information Center of Oita University. For the random incidence condition, six loudspeakers (Fostex FE-103) mounted in small boxes were used to radiate incoherent pink noise. The pink noise is filtered to eliminate unnecessary frequency components and to focus on 100 to 1000 Hz. A sub-woofer (JVC SX-DW77) is also added to increase the low frequency energy roughly below 200 Hz.

Results of Absorption Coefficients

In Room I, the absorption characteristics of two specimens of glass wool: GW50, 50-mm thick, and GW25, 25-mm thick, were measured with different types of sensors. The sensor position was fixed at the center of 0.9 × 1.8 m specimen. The corresponding absorption coefficients of GW50 obtained using measurements are compared in Figure 2(a). The agreements of absorption coefficients are good. Similarly, those for GW25 are compared in Figure 2(b). Slight discrepancies of about 0.05 are observed in the absorption coefficients. The discrepancies between the two methods can be regarded as resulting mainly from differences in the measuring mechanism of the particle velocity between the sensor types. The method using the p-u sensor is expected to give better results because the configuration is simpler. At this point, the authors conclude that, our method offers satisfactorily equivalent absorption coefficient for the specimens tested with either type of sensor.

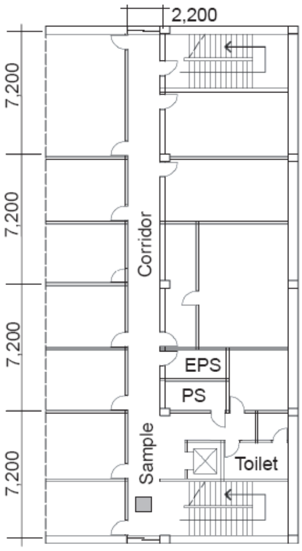


(a)



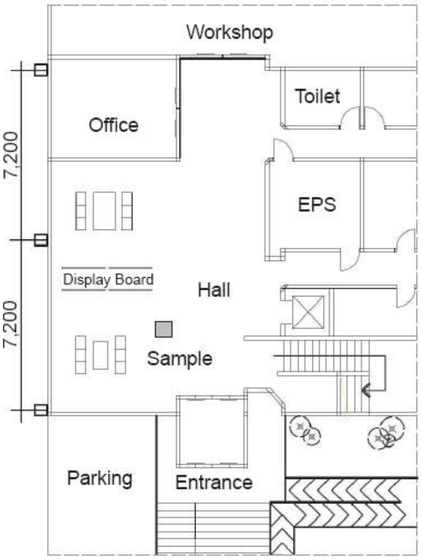
(b)

Figure 2. Comparison of absorption coefficients obtained by p-p and p-u sensor: (a) GW50, and (b) GW25.



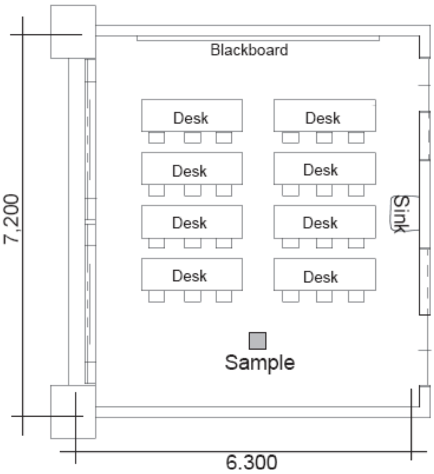
a (i)

a (ii)



b (i)

b (ii)



c (i)

c (ii)

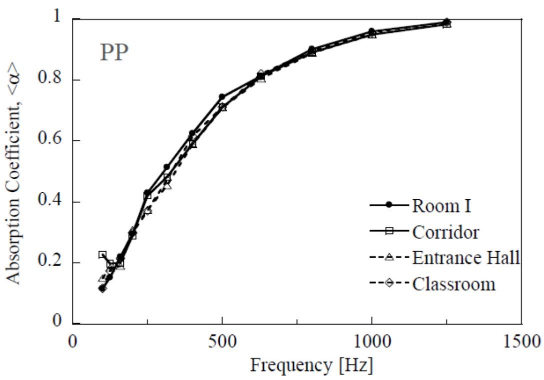
Figure 3. Plan views and photos of field measurement in architectural spaces: (a) a corridor, (b) an entrance hall, and (c) a seminar room

APPLICATION ON *IN SITU* MEASUREMENT

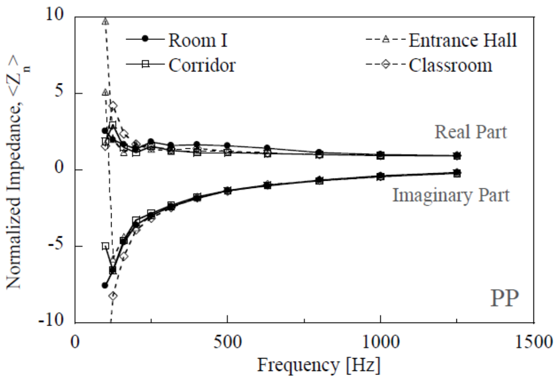
Architectural Spaces

To investigate the general applicability of the proposed method, a series of preliminary measurements of the two different measurement principles was carried out in three architectural space environments (a corridor, an entrance hall, and a seminar room). Photos and plan views of the furniture layouts with material locations in the field measurements are shown in Figure 3. The specimen investigated is GW50. The specimen is laid on a 0.02-m acrylic plate and has the same square area of 0.6 m^2. The specimen's sizes are not exactly identical to that of the investigation in the previous section, but we expected to have sufficient validity for the discussion, as described by Nazli et al. (2012). Six portable sound speakers with incoherent pink noise are employed and manually moved randomly by three people to realize the random noise conditions because of insufficient noise within all three environmental conditions. For comprehensible comparisons, the measurements of similar specimens are conducted in Room I using six fixed loudspeakers to radiate incoherent pink noise.

Figures 4 and 5 present the combined results of the corresponding absorption coefficients and normalized impedances obtained by both the p-p and p-u methods in three other environments for GW50, respectively. All the measured absorption characteristics in the three other environments are compared with the measured absorption coefficients obtained in Room I. The maximum differences and mean deviation of the measured absorption coefficients are provided in Figure 6(a) and 6(b), respectively. The similar basic tendencies of absorption characteristics can be observed for GW50 in Figures 4 and 5, but there are noticeable differences in the dispersion that can be observed below 250 Hz in the impedance results. There can be complementary aspects, which can explain this phenomenon: (i) influences of room modes, and (ii) the dissimilarity of the measurement setting of sound sources where the fixed loudspeakers are employed in Room I. Moreover, both methods can be considered as having fair agreement based on the maximum dispersion being below 0.17 and the maximum mean deviation being lower than 0.06. The authors consider the dispersion of measured absorption coefficients yield plausible agreements that support the applicability of the proposed method in various sound fields.

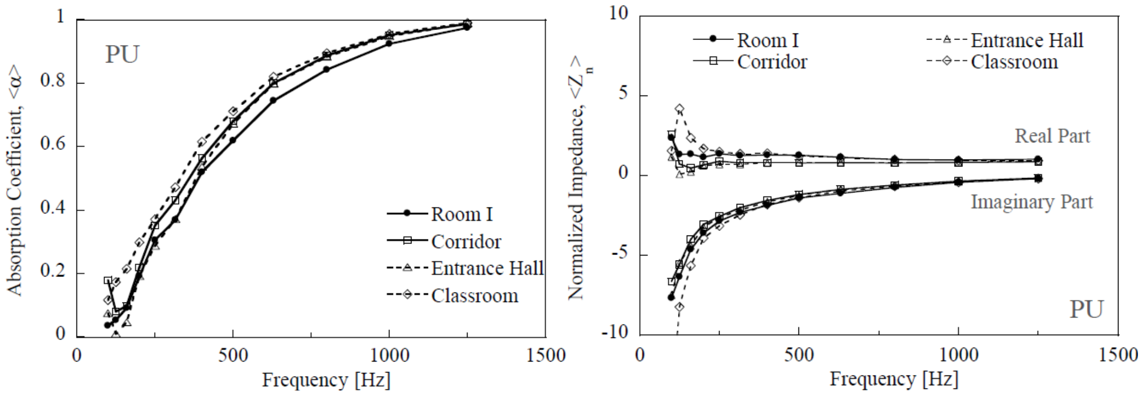


(a)



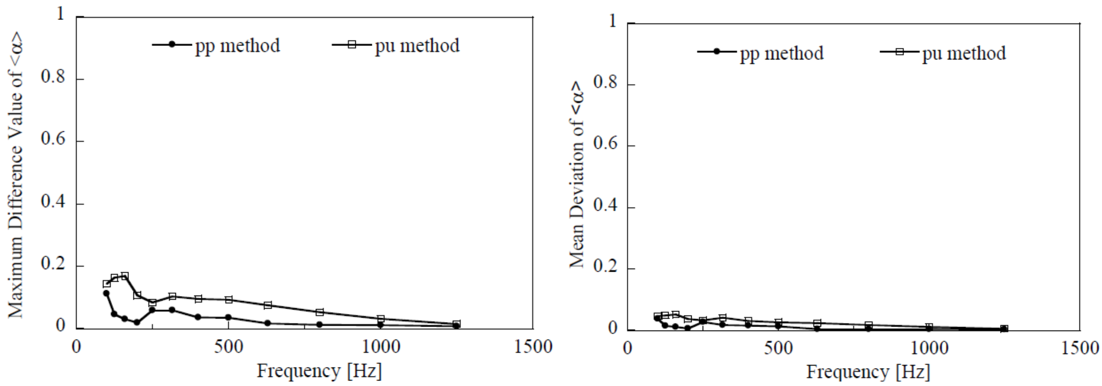
(b)

Figure 4. Comparison of measured absorption characteristics of GW50 obtained by p-p sensor in the reverberation room (Room I), the corridor, the entrance hall, and the seminar room.



(a) (b)

Figure 5. Comparison of measured absorption characteristics of GW50 obtained by p-u sensor in the reverberation room (Room I), the corridor, the entrance hall, and the seminar room.



(a) (b)

Figure 6. Comparison of: (a) maximum differences value of absorption coefficients, (b) mean deviation of absorption coefficients of GW50, obtained by proposed method in the corridor, the entrance hall, and the seminar room.

Car Cabin

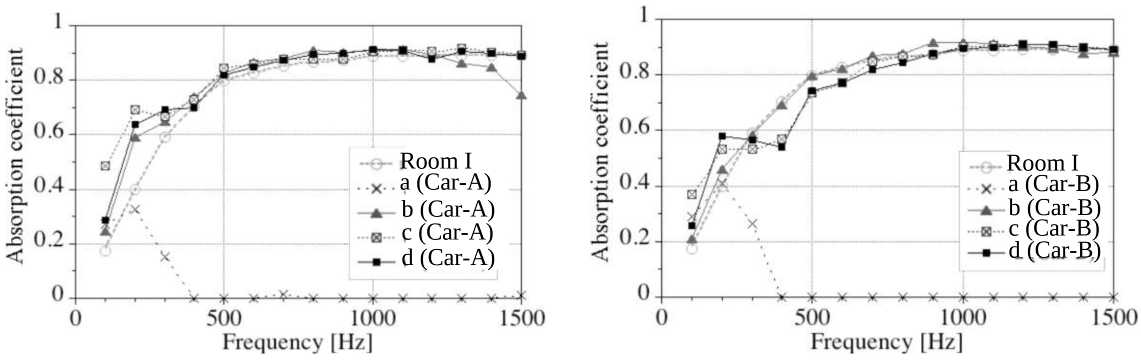
In this study, a preliminary measurement using the p-p sensor is conducted in a car cabin to measure the normal surface impedance of carry test sample. Two types of cars are used for the experiment: Car-A; 5-door, 7-passenger minivan with dimensions of 2825 × 1470 × 1355 mm^3, and Car-B; 5-door, 4-passenger tail wagon with dimensions of 1795 × 1255 × 1255 mm^3, as shown in Figure 7. The specimen to be investigated is GW50. The specimen is laid on an acrylic plate and it has dimensions of 0.6 × 0.3 m. Five conditions were set for the sound source as follows:

a. all doors are closed with ambient noise surrounding the car
b. all doors are open with ambient noise surrounding the car
c. one portable sound source added onto condition a
d. one portable sound source added onto condition b
e. three portable sound sources added onto condition b.

For comparison purpose, the measurement of a similar sample of GW50 is conducted in Room I using six fixed loudspeakers to radiate incoherent pink noise. The sound absorption coefficients of GW50 measured in Car-A are compared in Figure 8. The corresponding absorption coefficients agree well with the results measured in Room I within the frequencies of 400 to 1200 Hz, except for sound source condition of *a* and *b*. Moreover, the measurement in Car-B reveals the same basic tendencies of the measured corresponding absorption coefficients as for GW50 (Figure 8(b)), but there are non-negligible differences below 500 Hz. Clearly, the GW50 measured results show distinct fluctuations for sound source conditions *a* and *b*, which suggests that there is insufficient noise when all doors of Car-A and Car-B are closed. The authors consider that the good agreement shows the plausibility of the method for measuring absorption, because the absorbent tendencies were captured in accordance with the results of Room I when sufficient noise was achieved in the measurement. However, different types of material need to be investigated to support the general applicability and repeatability of our method.

(a) (b)

Figure 7. Two types of car used for experimental purposes: (a) Car-A, and (b) Car-B.



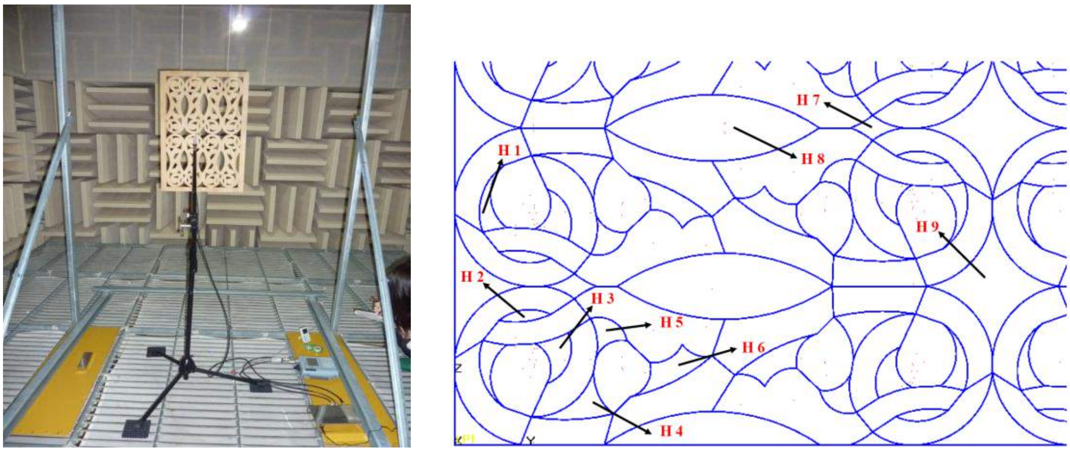
(a) (b)

Figure 8. Comparisons of absorption coefficients of GW50: (a) in Car-A, and (b) in Car-B.

TRIAL APPLICATION ON DIFFERENT TYPE OF MATERIAL

Perforated-type Panel

Direct piercing carved wood panels (DPCWPs) with floral patterns have been used as exterior walls in Masjid Abidin located in Kuala Terengganu, Terengganu, from as early as 1900. The DPCWP with floral pattern is among the most complex forms of DPCWP (Nordin, 2009). Most common DPCWPs with floral patterns are installed with the *Daun Sireh* motif (DSM). The same procedure of measurement using the p-u sensor, as mentioned above, was applied, but the measurements were conducted in an anechoic room with a volume of 58 m^3 at Oita University. There are nine types of aperture available for measurement. Figure 9(a) shows the measurement condition for the front view of the DPCWP with DSM. An aluminum frame was used in the measurement to hold the sample in the middle of the room. The dimensions of the sample are 0.37 × 0.63 m. The foliage of this sample is repeated eight times from a single unit, which comprises nine different types and shapes of aperture, as shown in Figure 9(b).



(a) (b)

Figure 9. Measurement condition: (a) DPCWP with DSM inside the anechoic room, and (b) nine types of aperture of the DPCWP.

The measurement of sound absorption characteristics was applied to the DPCWP with 30% and 40% perforation ratios. The measurement results for both perforation ratios for the individual apertures are presented in Figure 10. For 30% perforation ratio, three larger apertures with area of 455 mm^2 (H9), 1808 mm^2 (H4), and 3278 mm^2 (H8) have higher absorption coefficients within 750 Hz and above. The other six smaller apertures with areas in the region of 139 mm^2 to 386 mm^2 show similar basic tendencies for absorption coefficient values. However, for 40% perforation ratio, the measured absorption coefficients for all apertures are almost similar from 100 to 800 Hz. The measured absorption coefficients of both perforation ratios are higher when the apertures become larger. For simplicity, all individual aperture results are averaged and presented for both 30% and 40% perforation ratios from 100 to 1500 Hz in Figure 11. The averaged absorption coefficients for both 30% and 40% perforation ratios show a significant decrement from 100 to 1500 Hz. It might be readily apparent in the results that the absorption coefficients become higher when the perforation ratio becomes larger. The authors consider that the measured absorption coefficients of the DPCWP yield a plausible tendency that supports the feasibility of the proposed method for measuring different types of material.

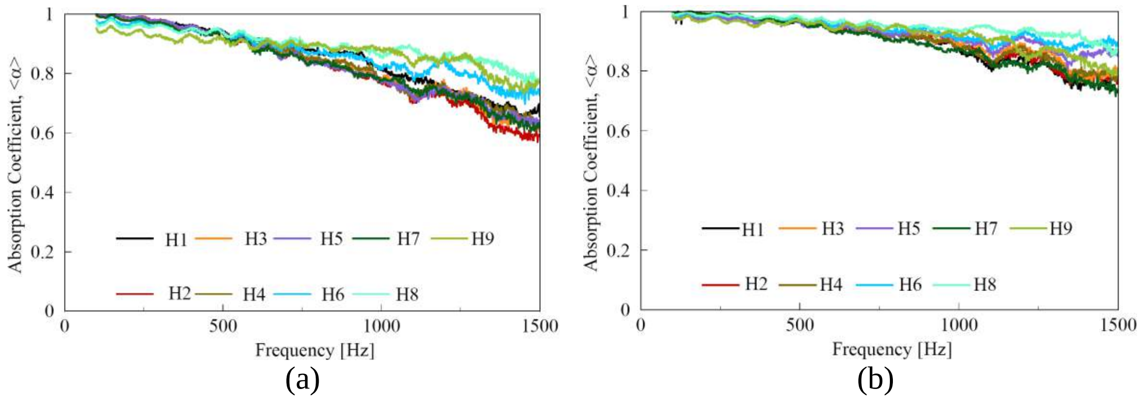


Figure 10. Sound absorption coefficients of each aperture: (a) 30% perforation ratio, and (b) 40% perforation ratio.

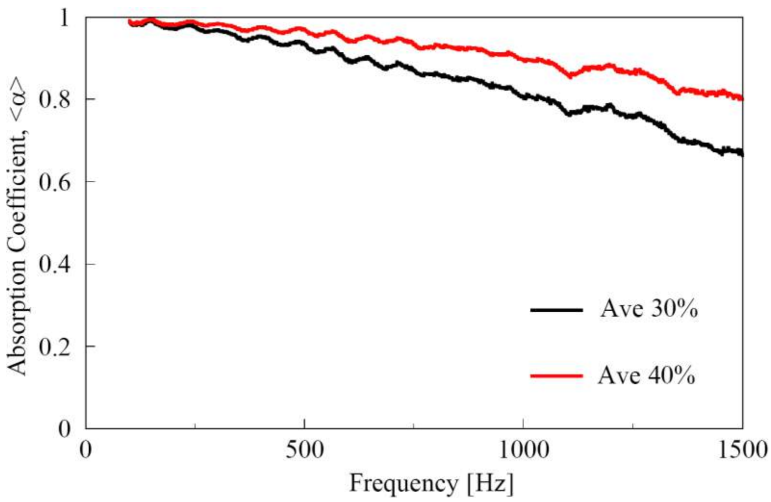


Figure 11. Averaged absorption coefficients obtained using p-u sensor for 30% and 40% perforation ratios.

CONCLUSIONS

Several measurements obtained using methods with p-p and p-u sensors revealed that discrepancies of absorption coefficients attributable to the sensors are small. In this study, the measurements of "ensemble averaged" surface normal impedance at random incidences in different sound fields have been performed. *In situ* measurements using p-p and p-u sensors suggest good applicability of both methods for various practical measurements. Then, we found good agreement between the results obtained by using the p-p method and the values measured in a reverberation room to represent the specimen's sound absorption characteristics in a car cabin. The investigation of DPCWP with DSM showed that larger apertures yielded higher absorption coefficients when a larger perforation ratio was applied. However, both perforation ratios demonstrate an identical decrement of absorption coefficients from lower frequency to higher frequency. Further experimental investigations are now being pursued actively.

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