

Ensemble averaged surface normal impedance measurement method in a reverberation room

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1. Introduction

While numerous methods have been proposed to measure material absorption characteristics [1–3], to date, the available impedance databases have generally been inadequate. In order to measure the surface normal impedance of a material, which may be used for absorption modeling in a numerical analysis of room acoustics on the basis of the wave equation, the authors previously proposed a method in which two microphones (a pp-sensor) and ambient noise [4] are used. Considering that the strong point of numerical analysis based on the wave equation is generally high accuracy in the lower frequency range, the target frequency range of the method was tentatively set to between 100 Hz and 1,500 Hz.

Several measurements were conducted in various environments (an office, a corridor, a cafeteria and a terrace) to measure the normal surface impedances of glass wool and rock wool. The results showed good repeatability and wide applicability. Moreover, preliminary investigations [5] using the boundary element method (BEM) proved that the measurement is based on the concept of ensemble averaging, and that such averaging makes the measurement efficient and appropriate for sound absorption measurements. However, there are only a limited number of experiments in which the results obtained by this method were compared with those obtained by conventional methods.

In the first section of this paper, we briefly review the new measurement approach in which a particle velocity sensor attached to a microphone (the pu-sensor) [5] is used. Although the original measurement method was designed for *in-situ* applications, the revised method described here is applied for use in a reverberation room to simplify measurement conditions and to make the system relevant for new applications. In the next section, a series of measurements made using both the original and revised methods are presented to clarify the agreement between the results obtained using the two sets of apparatus. Finally, the plausibility of the proposed method for the measurement of sound absorption characteristics as evidenced by comparing the output with the results obtained by two other conventional methods, namely the reverberation room method and the tube method, is discussed.

2. Outline of measurement method

2.1. Ensemble averaged impedance and corresponding absorption coefficient

In the previous paper [5], the authors proposed impedance as

$$\langle Z_n \rangle = \frac{\langle p \rangle}{\langle u_n \rangle}, \quad (1)$$

where p and u_n denote the sound pressure and particle velocity with respect to the normal direction at the material surface and $\langle \cdot \rangle$ denotes an ensemble average. Tentatively, the resulting impedance, $\langle Z \rangle$, was named the “ensemble averaged” impedance. The corresponding absorption coefficient, $\langle \alpha \rangle$, is given by

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

Here, ρ and c are the density of air and the speed of sound, respectively. Averaging can be performed using a fast Fourier transform (FFT), such as

$$\langle Z_n \rangle = \frac{1}{N} \sum H_{up}(\omega) = \frac{1}{N} \sum \frac{\langle p \rangle}{\langle u_n \rangle}, \quad (3)$$

where $H_{up}(\omega)$ denotes the transfer function that links p and u_n . N is the averaging used in the FFT. In the case where the system is ergodic and assuming sufficient averaging, Eqs. (1) and (3) become identical and we can measure the averaged surface normal impedance at random incidence.

2.2. Measurement framework

Figure 1 shows schematics of the apparatus used in the original method and in the revised method. The pu-sensor is located 1 cm above the surface ($d = 1$ cm) to measure p and u_n . The pu-sensor is calibrated using an acoustic tube of 10 cm diameter [6]. The resolution of the two-channel FFT (RION SA-78) unit is set at 1.25 Hz and a Hanning window of 0.8 s duration is employed to measure the transfer function. Linear averaging in the frequency domain is performed $N = 150$ times.

In the original method, shown in Fig. 1(a), the transfer function $H_{ab}(\omega)$ between the sound pressures is measured at the two microphones, p_a and p_b , with the same FFT and settings. The distance d is set to be 1 cm and the space l between the two microphones is 1.3 cm. Sound absorption

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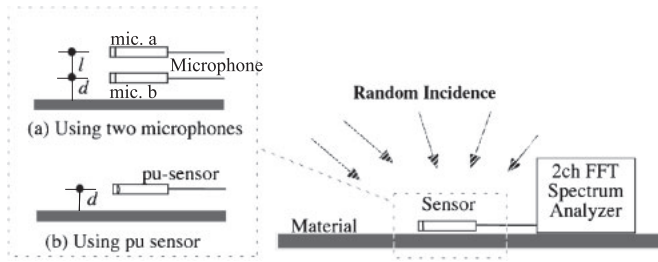


Fig. 1 Schematic diagram of measurement setup for the proposed method: (a) using a pp-sensor (original method); (b) using a pu-sensor (revised method).

characteristics are derived through the procedure described in the previous study [4]. The measurements are conducted in a reverberation room at the Information Center of Oita University. For the random incidence condition, six loudspeakers (Fostex FE-103) mounted in small boxes are employed to radiate incoherent pink noise. This pink noise is filtered to eliminate unnecessary frequency components of the measurements, which are focused within the 100 Hz to 1,500 Hz range. A subwoofer (JVC SX-DW77) is also added to increase the low-frequency energy below roughly 200 Hz.

3. Results and discussion

3.1. Comparison of absorption characteristics obtained by original method (pp-sensor) and revised method (pu-sensor)

In the reverberation room, the measurement of absorption characteristics are applied to three specimens, namely, 50 mm glass wool (GW50), 25 mm glass wool (GW25) and 10 mm needle felt (NF10), using the two methods and their respective sensor types. The sensor position is fixed at the center of the 0.9 m × 1.8 m specimens. The sound absorption characteristics of GW50, as measured by the two methods, are shown in Fig. 2. The real part of the impedances exhibits a slight discrepancy in the frequency range of 100 Hz to 800 Hz, but agreements are excellent between the imaginary parts of the impedances and the absorption coefficients. Similarly, Figs. 3 and 4 show the absorption characteristics of GW25 and NF10. Although additional discrepancies are apparent in both the real and imaginary parts of the impedances for these two specimens, a good agreement is evident in their absorption coefficients.

The discrepancies between the two methods can be regarded as resulting mainly from differences in the measuring mechanisms of the particle velocity between the sensor types. We tentatively assume that the discrepancies may result from the approximation technique using two microphones at different positions in the original method. The revised method with the pu-sensor is expected to give results with more consistency because the configuration becomes simpler. Furthermore, although certain discrepancies remain in terms of the impedance values, our method offers satisfactorily equivalent absorption coefficients for the specimens tested with either type of sensor.

3.2. Comparison of revised method with the reverberation room method and the tube method

The results of the revised method are compared, as

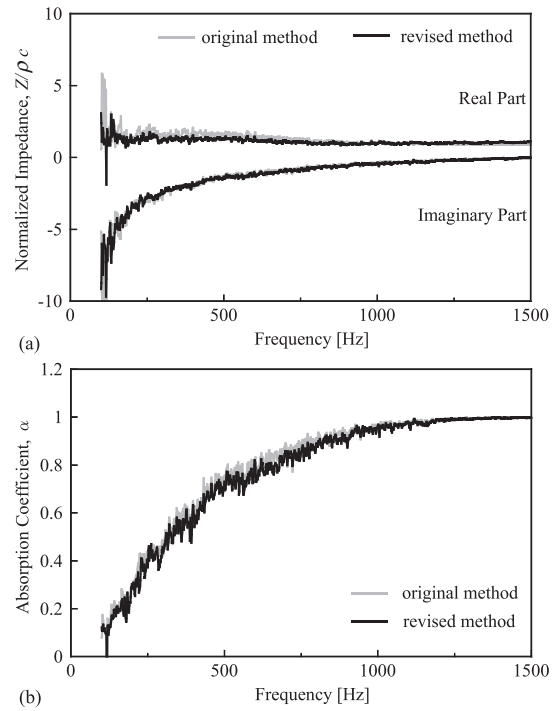


Fig. 2 GW50 absorption characteristics obtained by the proposed method with pp- (original method) and pu-sensors (revised method): (a) normalized impedance and (b) absorption coefficient.

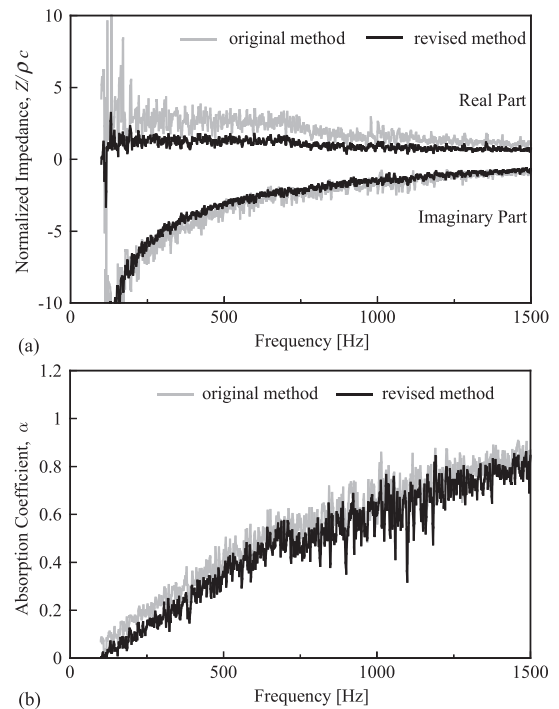


Fig. 3 GW25 absorption characteristics obtained by the proposed method with pp- (original method) and pu-sensors (revised method): (a) normalized impedance and (b) absorption coefficient.

discussed in Sect. 3.1, with those obtained by the reverberation room method and the tube method. Following ISO 354 (JIS A 1409), the absorption coefficients of GW50, GW25 and

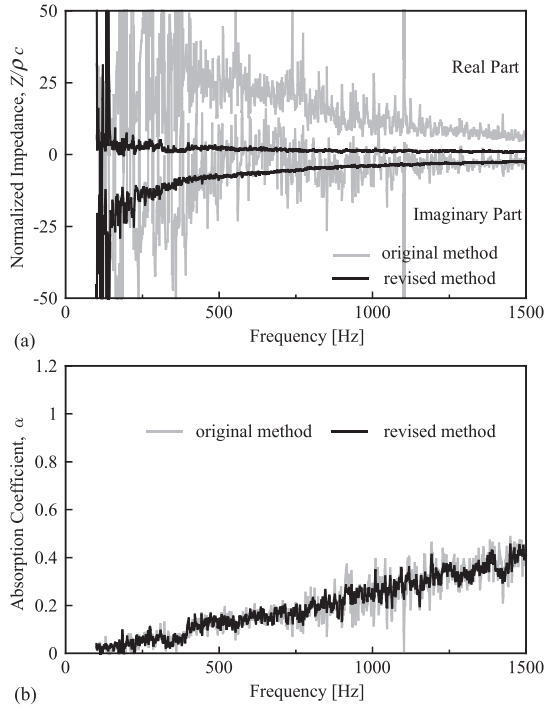


Fig. 4 NF10 absorption characteristics obtained by the proposed method with pp- (original method) and pu-sensors (revised method): (a) normalized impedance and (b) absorption coefficient.

NF10 are measured by the reverberation room method. The measurement of one-third octave-band absorption coefficients at the center frequencies, ranging from 125 Hz to 1,250 Hz, is conducted in the same reverberation room. Although the volume of the reverberation room, at 165.8 m³, without diffusers installed, and the specimen size (0.9 m × 1.8 m × 6 (pieces) = 9.72 m²) do not fully satisfy the ISO requirements, we nonetheless expect to observe meaningful trends from the results. Subsequently, the normal impedances are measured from a small part cut from the same specimens. For this purpose the tube method is used consistently with ISO 10534-2 (JIS A 1405).

Considering the differences in the measurement mechanisms of the three methods, including incidence conditions, a moderate agreement is expected in the output absorption characteristics. The main purpose of comparisons in this section is to investigate whether the proposed method can offer plausible absorption characteristics.

The GW50 results are shown in Fig. 5. There is good agreement between the imaginary parts of the impedances, as obtained by the revised method and the tube method, whereas a slight discrepancy is observed in the real parts of the impedances within the frequency range of 1,000 Hz and below. Although the general agreement between the absorption coefficients obtained by the three methods appears to be poor, the proposed method generates values that are close to the values measured by the tube method, except at around 550 Hz and below. At a frequency of 1000 Hz, the proposed method yields similar absorption coefficients to those determined by the reverberation room method, and are greater than those obtained by the tube method by about 0.03.

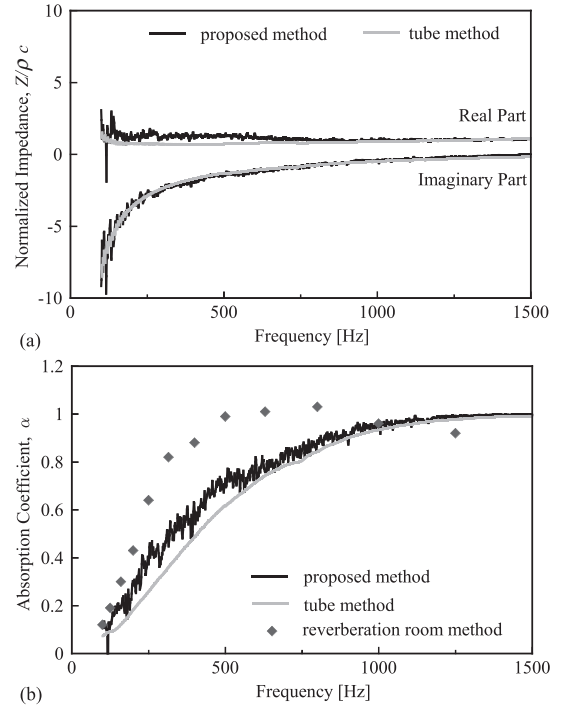


Fig. 5 GW50 absorption characteristics obtained by the proposed method with the pu-sensor (revised method), reverberation room method and tube method: (a) normalized impedance and (b) absorption coefficient.

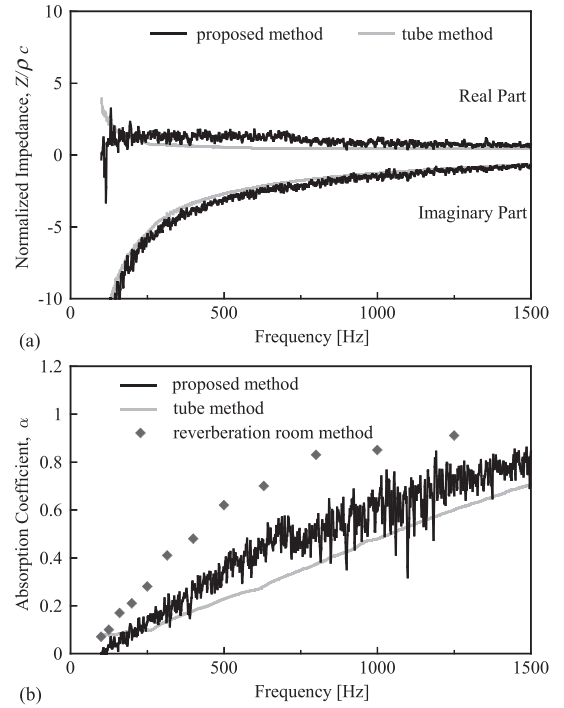


Fig. 6 GW25 absorption characteristics obtained by the proposed method with the pu-sensor (revised method), reverberation room method and tube method: (a) normalized impedance and (b) absorption coefficient.

Relevant GW25 data is illustrated in Fig. 6. In general, similar tendencies as for GW50 are observed. The absorption coefficients obtained by the proposed method fall in the

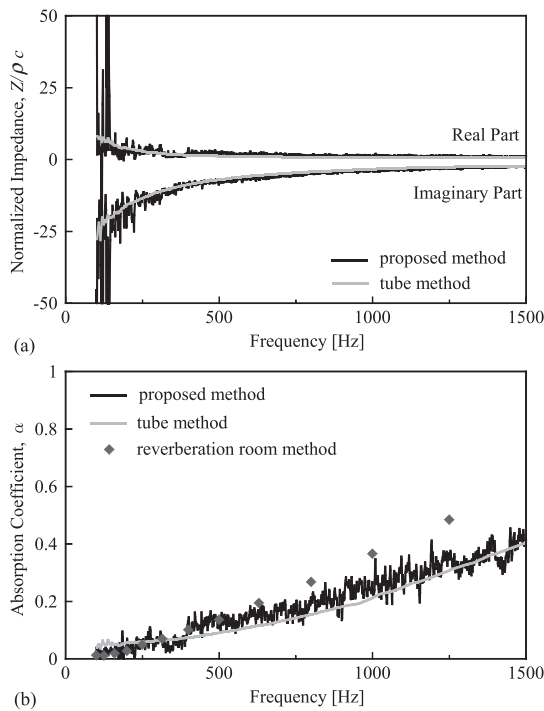


Fig. 7 NF10 absorption characteristics obtained by the proposed method with the pu-sensor (revised method), reverberation room method and tube method: (a) normalized impedance and (b) absorption coefficient.

intermediate range between those yield by the two conventional methods but are closer to those given by the tube method. Finally, the NF10 data is shown in Fig. 7. The impedance agreement is better than those for the aforementioned cases. Likewise, the consistency is considerably better between the absorption coefficients, as measured by the proposed method and the conventional methods. Since our previous study [5] revealed that the ensemble averaged impedance can take account of the anisotropy of a material, we consider that the results observed above show sufficient plausibility of the proposed method at this stage of study.

4. Conclusions

A revised method for measuring absorption characteristics

using a pu-sensor was presented. A series of measurements revealed that all sensor-induced discrepancies in the absorption coefficients were relatively small. Comparisons of the results obtained by the proposed method with those obtained by the conventional methods revealed that the proposed method can provide values closer to those obtained by the tube method for the specimen's sound absorption characteristics. The potential of our proposed method as a means of measuring sound absorption characteristics was confirmed. Further investigations of this method are now being undertaken.

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