Absorption modeling with ensemble averaged impedance for wave-based room acoustics simulations

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ABSTRACT

With the rapid progress of computers, wave-based room acoustics simulations like finite element method have come to be applicable onto many practical problems on acoustics. Generally, such methods can calculate sound fields quite accurately provided their boundary modelings are given appropriately. Although the absorption on the boundary can be modeled efficiently by using surface impedance, the impedance database is not accumulated yet. It is due to the difficulty in the practical measurement of surface impedance of materials at field conditions. To overcome the difficulty, the authors proposed a way to measure surface impedance by using ensemble averaging technique. In this paper, the basic concept of the authors' measurement method of surface impedance is summarized first. Then, an application of the measurement technique onto a realistic sound field in a cafe-restaurant is shown, and comparisons with the other methods are given to prove the effectiveness of the technique.

Keywords: Room acoustics simulation, Boundary condition, Finite element method, Absorption modeling, Surface impedance I-INCE Classification of Subjects Number(s): 75.3, 51.1

1. INTRODUCTION

Various kinds of computational simulations have come to be available to analyze and/or design the sound fields in built environments scientifically. Fundamental tactics of the simulations can be roughly classified into two approaches: the geometrical approaches and the wave-based approaches. The authors presented a simulation method based on the wave-based approach, or finite element method (FEM), and revealed the accuracy and applicability of the method. (1, 2, 3, 4, 5, 6) To model the absorption on the boundary, geometrical approaches need absorption coefficient α of the boundary surface, while wave-based approaches require complex impedance Z_{n}. However, one can find only insufficient impedance databases especially those of practical rooms.

Recently, quantitative investigations on the uncertainties in all the acoustic prediction and simulation tools quantitatively were published, and the notation was given that "input data of absorption coefficients are not accurate enough to obtain simulation results with an uncertainty below the JND of reverberation time."(7) Measured absorption coefficients by tube method also varies to some extent because of the difference of mounting conditions and so on(8). While, as Alvarez and Jacobsen described "it is surprisingly difficult to measure the impedance of materials in situ,"(9) absorption measurements in "field conditions" are not easy problem still now.

In order to provide some more practical and reliable boundary conditions for room acoustics simulations, the authors proposed a concept of ensemble averaging technique for measuring sound absorption of materials in-situ. At first, we employed two-microphone technique based on the studies of Allard et al. (10) and proposed a method using environmental noise that suites for in-situ measurements of sound absorption of materials(11). Meanwhile, particle velocity sensor (Microflown) was developed(12) and has come to be used widely in sound absorption measurements along with the manufacturing of pressure-velocity sensor (pu-sensor). The authors also improved the measurement method by employing a pu-sensor instead of two-microphone and denoted the method as "ensemble averaging technique," or EA-method for short(13).

In this paper, the outline of the authors' finite element sound field analysis is summarized first and dissipation modeling using in the FE-procedure is explained breifly. Next, the definition of our ensemble averaged

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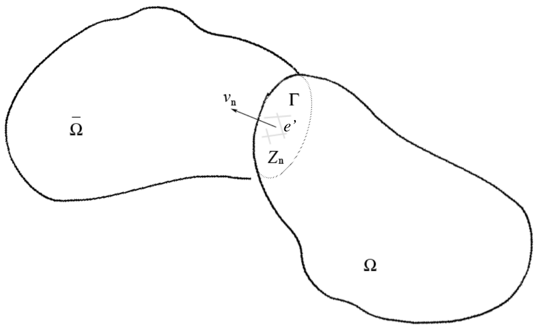

Figure 1 – Sound field Ω and its adjoint system $\bar{\Omega}$ coupled together through a dissipative boundary Γ with normal impedance Z_{n}.

surface normal impedance is explained. Then, a practical application of the technique onto an acoustic improvement of a cafe restaurant is given to show the effectiveness of the technique.

2. FINITE ELEMENT ANALYSIS OF SOUND FIELD WITH DISSPATION

2.1 FEM Formulation

Applying the energy principle onto the three-dimensional sound field with the time factor $e^{i\omega t}$, the discretized matrix equation of motion in the frequency domain can be obtained:

$$[K]\{p\} + i\omega[C]\{p\} - \omega^2[M]\{p\} = i\omega\rho v_{\text{n}}\{W\}, \tag{1}$$

where, $[M]$, $[C]$ and $[K]$ denote acoustic mass, dissipation and stiffness matrices respectively; and $\{p\}$, ρ, ω, v_{n} and $\{W\}$ are sound pressure vector, air density, angular frequency, vibration velocity and distribution vector respectively. Assuming that $\dot{x}$ and $\ddot{x}$ to be first and second order derivative of x with respect to time respectively, the equation in the time domain can be:

$$[M]\{\ddot{p}\} + [C]\{\dot{p}\} + [K]\{p\} = \rho\dot{v_{\text{n}}}\{W\}(=\{f\}). \tag{2}$$

With a shape function, $\{N\}$, the acoustic element matrices that construct global matrices in the Eq.(1) are given by

$$[K]_e = \int_e \left(\{\frac{\partial N}{\partial x}\}\{\frac{\partial N}{\partial x}\}^T + \{\frac{\partial N}{\partial y}\}\{\frac{\partial N}{\partial y}\}^T + \{\frac{\partial N}{\partial z}\}\{\frac{\partial N}{\partial z}\}^T \right) dV, \tag{3}$$

$$[M]_e = \frac{1}{c^2}\int_e \{N\}\{N\}^T dV, \tag{4}$$

$$[C]_e = \frac{1}{c}\int_{e'} \frac{1}{(Z_{\text{n}}/\rho c)}\{N\}\{N\}^T dS. \tag{5}$$

Therein, c and Z_n are sound speed and surface normal impedance respectively, and e' denotes the surface area to be integrated. The detailed treatment of the dissipation is given in the next subsection.

2.2 Dissipation Modeling

When a dissipative area exists in the system Ω, one needs to take both dissipation energy J and adjoint system $\bar{\Omega}$ into account (Fig. 1). Since the adjoint system works to represent the increasing energy which corresponds to the dissipating energy in the original system, the principle of minimum potential energy comes to be applicable and eq.(5) for dissipative boundary modeling can be reduced (14).

Although different kinds of modeling like one employing absorbent finite element are available, the modeling with eq.(5) makes the finite element sound field analysis of rooms simpler and more efficient in many cases. Impedance Z_{n} is the ratio of p to u_{n} and practical impedance values of material surfaces are generally obtained by tube method measurements which follow standards(15). While, it is well known that tube method measurements are not always easy to be conducted because of the mounting problems, e.t.c. Moreover, the standard tube method does not suit for in-situ measurements of realistic walls, ceilings and floors in practical rooms. Then, to extend the applicability of such a method as with the simple modeling by eq. (5), the authors proposed a concept and measurement method of ensemble averaged surface normal impedance of materials (13, 16).

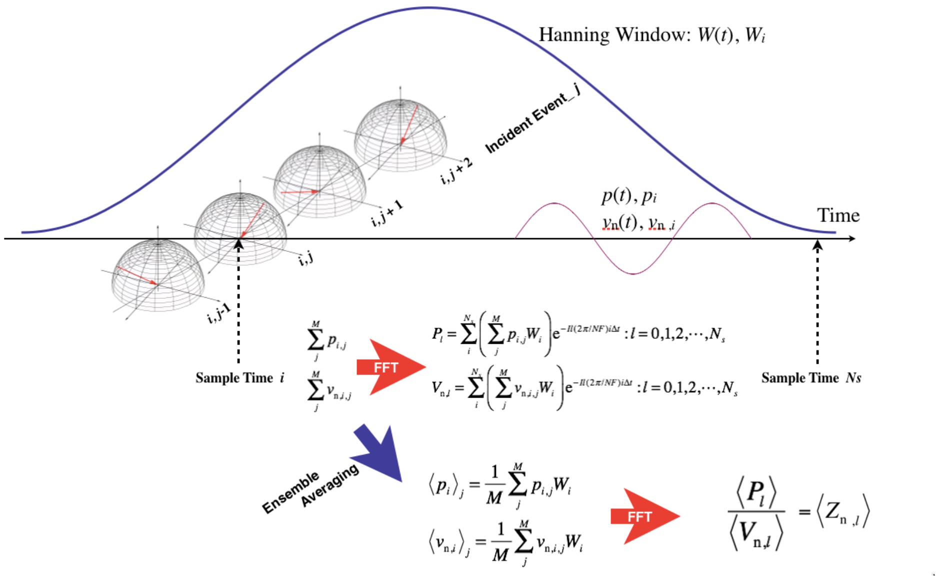

Figure 2 – Schematic of ensemble averaging technique: analogous and discretized models.

3. ABSORPTION MEASUREMENT BY ENSEMBLE AVERAGING TECHNIQUE

3.1 Ensemble averaged surface normal impedance(13)

Ensemble averaged surface normal impedance $\langle Z_\mathrm{n} \rangle$ is defined in frequency domain by

$$\langle Z_\mathrm{n} \rangle = \frac{\langle P_\mathrm{surf} \rangle}{\langle V_\mathrm{n,surf} \rangle}, \tag{6}$$

and corresponding absorption coefficient is given as

$$\alpha_\mathrm{EA} = \langle \alpha \rangle = 1 - \left| \frac{\langle Z_\mathrm{n} \rangle - \rho c}{\langle Z_\mathrm{n} \rangle + \rho c} \right|^2, \tag{7}$$

where, $\langle\,\rangle, P_\mathrm{surf}$ and $V_\mathrm{n,surf}$ denote ensemble average, sound pressure at material surface, and particle velocity normal to the surface, respectively. In our previous papers, the authors have proposed to apply $\langle Z_\mathrm{n} \rangle$ as Z_n in eq. (5).(17)

As is illustrated in Fig. 2, sound pressure $p(t)$ and particle velocity normal to surface $v_\mathrm{n}(t)$, which are measured at a material's surface in time domain, are preliminarily time-windowed by a Hanning window with the length of 1.0 s or similar; and the signals are discretized as p_i and $u_{n,i}$, repectively. Then, $P(\omega)$ and $V_\mathrm{n}(\omega)$, or P_l and $V_{\mathrm{n},l}$, are respectively calculated by performing Fourier transform, or by discrete Fourier transform. Herein, enough number M of incident events with random and incoherent noise each other are assumed to incident randomly on the material surface. If the system is ergodic and averaging number is sufficient, the ensemble averaging is expected to give general property of the system. The authors tentatively named the procedure as ensemble averaging method or EA method, for short. (13)

Figure 3 illustrates a practical setup of EA method. A pu-sensor is placed close to a material surface. The output signals of the pu-sensor is plugged to a 2ch fast-Fourier-transform instrument and $\langle Z_\mathrm{n} \rangle = \langle P_l \rangle / \langle V_{\mathrm{n},l} \rangle$ is calculated as a transfer function. Linear averaging of N times is performed to eliminate unnecessary noises. Furthermore, in such rather practical situations as of general measurements, because of the non-negligible sensors' sizes or of specimens' finite sizes, and due to the finite windowing sizes of the FFT utilized or insufficient windowing lengths comparing to the sounds' wavelengths, $\langle Z_\mathrm{n} \rangle$ can be expected to represent time- and space- averaged impedance property of the material's surface with a certain area around a target point.

3.2 Example application onto acoustical improvement of cafe restaurant

To examine the effectiveness of the technique in a practical situation, EA-method measurement is applied onto an acoustical improvement project of a cafe-restaurant in Oita-city, Japan. The volume and total-surface-area of the room are 201 m^3 and 270 m^2, respectively; and the plan view is plotted in Fig. 4. The building is

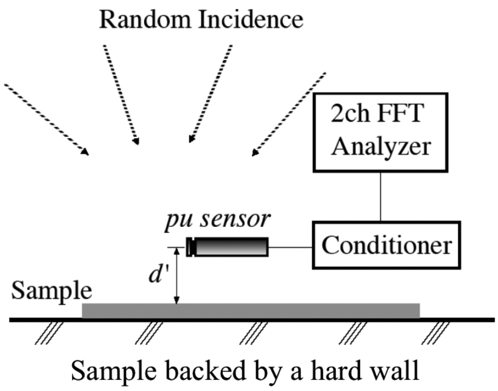

Figure 3 – EA-method measurement setting.

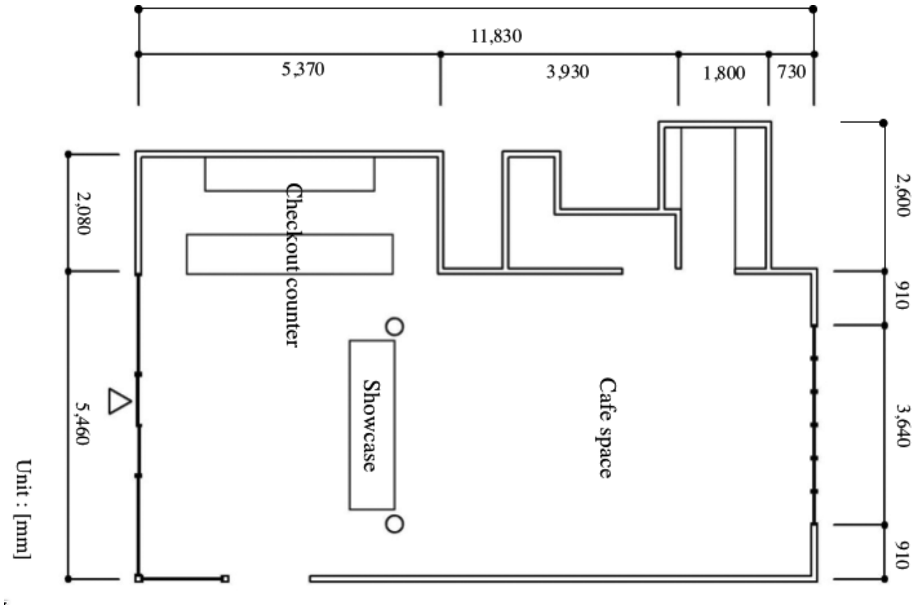

Figure 4 – Plan view of cafe-restaurant.

constructed of reinforced concrete and major interior materials at original conditions are plasterboard (ceiling, wall) and concrete mortar (floor). Windows with double glazings are installed on both side-ends of the room. Soon after the opening of the cafe-restaurant, guests and workers including the owner started complaining about the acoustics of the room. Then, an acoustics improvement project has commenced.

In the project, measurements on acoustics were conducted at two different terms separated about a year: before and after the renovation. In each term, impulse response (ISO 3382, TSP method) measurements and sound absorption (EA-method) measurements were conducted. Reverberation times RT measured at equally distributed eleven points in the cafe-space before the renovation are averaged and compared in Fig.5 with RT of the room after renovation. In the original condition, rather reverberant acoustics with $RT \approx 1.0$ s is revealed in the frequency region from 250 Hz to 2000 Hz. In Fig. 6, absorption coefficients of plasterboards on wall and ceiling measured in-situ by EA-method were compared. Since the wall and ceiling are made of similar plasterboards, there is no distinct difference between the absorption coefficients and they are less than 0.1 except that of wall at the frequency region between 200 Hz and 316 Hz. It is notable that absorption coefficients of both positions are less than 0.1 in the frequency region above 400 Hz, which correspond to the short reverberation times at the frequency region shown in Fig. 5.

In order to reduce the reverberation time of the room based on the measurement results, appending rock-wool-board (RWB) to the existing ceiling made of plasterboard was proposed and executed as the first trial of the project. According to the RWB manufacturer's catalogue, more absorption could be expected because a backside air-space with 300 mm is presumed. While, in the renovated ceiling, RWB is glued directly to the existing plasterboard stiffly with no air-space installed. Therefore, in any scientific discussion on the project,

Table 1 – Configurations of four types of sound absorption measurements of RWB.

No.	method	place	sound source	sample size (mm × mm)	RWB bonding
1)	*in-situ* EA-method	cafe-restaurant	4 portable loudspeakers	11830 × 5460	glued
2)	*lab.* EA-method	reverberation room	6 loudspeakers, 1 sub-woofer	910 × 605	glued
3)	*lab.* EA-method	reverberation room	6 loudspeakers, 1 sub-woofer	910 × 605	double-face taped
4)	*lab.* tube method	100 mm radius tube	1 loudspeaker	r = 100 mm circle	double-face taped

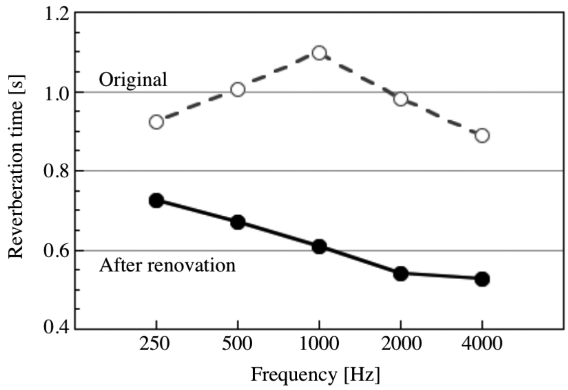

Figure 5 – Comparison of mean reverberation times between original (dotted line) and after the renovation (solid line).

in-situ measurement results of the absorption of the new ceiling is indispensable.

Then, after finishing the renovation of the ceiling, in-situ measurements of RWB by EA-method were conducted. Additionally, two kinds of EA-method measurements were conducted in the reverberation room at Information Center of Oita University for the absorption characteristics of RWB with the area of 910 mm × 605 mm: glued to plasterboard; and double-face taped to RC floor. Furthermore, RWB with the radius 100 mm double-face taped to backside-hard-wall was measured by tube method. All the measurement configurations are listed in Table 1.

In Fig.7, the results of the four measurements are compared and good agreements between the measurements can be observed except that of in-situ EA-method measurement below 200 Hz. The discrepancy of in-situ measurement from the other methods in the lower frequency region below 200 Hz is due to the insufficient incident sound energy of the portable loudspeakers. In the frequency region from 250 Hz to 1600 Hz, the higher the frequency is, the more the absorption coefficient becomes. The frequency characteristics of the absorption are consistent with the improvement of the reverberation time shown in Fig. 5.

Moreover, good agreement between the results between EA-method and tube method can be explained by the fact that the absorption characteristics of RWB do not have distinct dependency on incident angle. In the case of RWB, sample size effect is not obvious and EA-method measurements give almost similar results to that of tube method. Since RWB is not easy to be glued to hard-wall in the tube method measurement, double-face tape is tried to examine the effect to absorption; and good agreement between glued and taped RWBs can be confirmed on EA-method measurements conducted in the reverberation room. Therefore, the comparisons in Fig. 7 make sense and the effectiveness of EA-method measurement is exhibited.

4. CONCLUSIONS

The authors have proposed the concept and practical applications of ensemble averaging technique for measuring surface normal impedance and absorption characteristics of rooms' boundaries in previous papers. The main and original target of the technique is constructing the dissipation matrix in FEM room acoustics simulations. The technique is applicable to in-situ measurements as well as those conducted in reverberation rooms. In this paper, an example application of the technique to an acoustical improvement project of a room in a cafe-restaurant is exhibited to show the effectiveness of the technique as: (i) in-situ measurement of absorption by EA-method provides quantities effective enough to estimate the room's acoustics; (ii) in case the absorption of a material has no incident-angle-dependency, e.g. rock wool board, absorption coefficient measured by EA-method measurement agrees with that of tube method; (iii) sample size effect is not obvious.

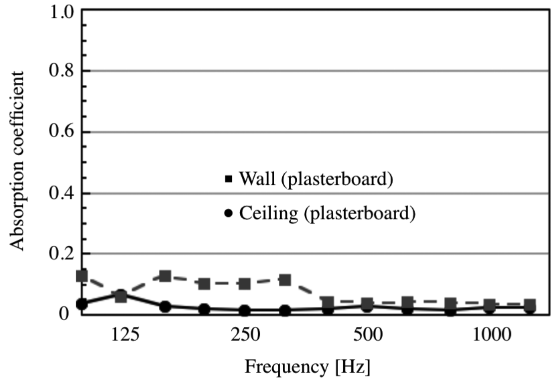

Figure 6 – Absorption coefficients of wall and ceiling measured in-situ by EA-method.

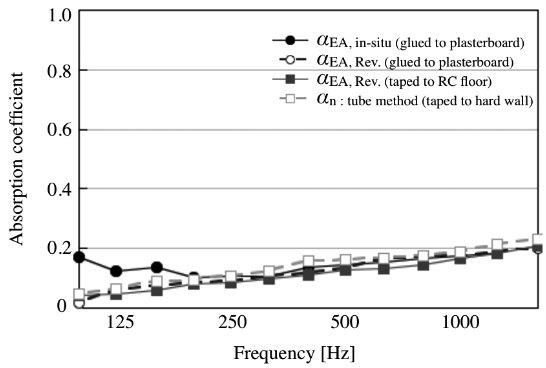

Figure 7 – Comparison of absorption coefficients of RWB measured by EA-method (in-situ), EA-method (glued to plasterboard, in Reverberation room), EA-method (double-face taped to RC floor, in Reverberation room) and tube method.

Further improvements of measurement method, e.g. examination on the uncertainty issue and enforcement of low frequency sound energy e.t.c., as well as the application in the FEM simulation are undergoing.

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