Diversity of materials with miscellaneous fluctuations are generally installed to sound fields in practical buildings, which make the rooms’ acoustical simulations harder because of the unpredictable complexity of the boundary condition. The complexity of the boundary condition is roughly classified into two categories: shape and absorption. In our former papers, the authors have been proposing a new measurement method for surface normal impedance of materials at pseudo-random incidence utilizing the ensemble averaging technique. The method enable us to obtain practical expected values of a materials surface normal impedances that suit especially for the mathematica-physical treatment of acoustical energy in the finite element method. Herein, outline of EA method is summarized, first. Then, the ensemble averaging technique is introduced in relation to FEM as well as the impedance measurement with two-microphone or with a pressure-velocity sensor (Microflown). Several example measurements at six sound fields including in-situ conditions show the reliability and applicability of the measurement method. The simplicity of the method and the robustness of the results show that the ensemble averaging technique provides a way to overcome the diversity of the materials used in practical sound fields in built environments.

Keywords: Random-incidence-impedance, Room-acoustics-simulation, Wave-based-method, Boundary-condition, Ensemble-averaging

1. Introduction

Room acoustics simulations based on the wave-based-acoustics such as finite differential method, finite element method, boundary element method and so on have become important tools for scientific researches as well as practical applications. [1, 2, 3] Although high accuracy can be expected in the results of such simulations, the validity of the results depend strongly on the boundary conditions assigned. Considering about the boundary conditions of sound fields in ordinary rooms at practical situations, shapes and absorptions on the walls, ceilings and floors are not simple enough to be modeled as a summation of smooth and homogeneous plains.
To construct an appropriate surface impedance database of materials mainly for the room acoustics simulations, the authors have been developing a measurement method using ensemble averaging, namely EA method. [4, 5, 6, 7, 8] Ensemble averaging used here can be expected to decrease above-mentioned difficulty caused by the complexity and/or diverseness of sound fields in architectural environments. On occasion, however, the averaging might decrease the high accuracy of numerical simulations; and enough attention should be paid for keeping the balance between accuracy and applicability.

There are two types of EA method: one utilizes two-microphone and the other uses pressure-velocity sensor (pu-sensor, Microflown Technologies). We designate them as "EA<sub>pp</sub>" and as "EA<sub>pu</sub>," respectively. Generally speaking, EA<sub>pp</sub> is advantageous in obtaining robust results because of the robustness of conventional microphones, while, EA<sub>pu</sub> is disadvantageous in geometrical restriction to approximate particle velocity by the differential of two microphones’ locations. Conversely, EA<sub>pu</sub> is more advantageous in geometrical configuration, while, EA<sub>pu</sub> is less reliable mainly because of less accumulated know-hows due to the particle velocity sensor’s short history. To make EA<sub>pu</sub> measurement results more robust and reliable, we proposed a calibration procedure using acoustic tube taking care of relative humidity difference between calibration and the measurement. [8]

Because of the simplicity of required instruments, EA method is applicable at various sound fields including in-situ conditions and the results are less affected by the specimen’s size. [4, 6] The measurement mechanism of EA method was examined by boundary element simulation to result that ensemble averaging with pseudo-random incidence incoherent random noises can decrease interference effect efficiently. [5] Based on the studies, EA method is expected to have certain potential to overcome the complexity of sound fields in built environments.

Herein, outline of EA method is summarized, first; and advantage of the method in various applications of the room acoustics simulations is described. Then, example results of EA<sub>pu</sub> measurement is given to show the validity of the modeling.

2. EA method outline

2.1 Definition of impedance and absorption coefficient

In our former study [5], surface normal impedance of a material was defined as Eq. (1) considering an ensemble of multiple sound incidences (Fig. 1).

\[
Z_{EA} = \frac{\langle p \rangle}{\langle u_n \rangle}.
\]  

(1)

In Eq. (1), \(\langle \cdot \rangle\) and \(u_n\) respectively denote the ensemble average and particle velocity with respect to the normal direction at the material surface. The impedance is designated as the "ensemble averaged impedance". To check and evaluate the results, the "corresponding sound absorption coefficient" is defined as follows:

\[
\alpha_{EA} = 1 - \left( \frac{Z_{EA} - \rho c}{Z_{EA} + \rho c} \right)^2.
\]  

(2)

In a practical measurements using incoherent pseudo-random noises, averaging is performed using a fast Fourier transform (FFT) as

\[
Z_{EA} = \frac{1}{N} \sum_{N} H_{up},
\]  

(3)

where \(H_{up}\) is the transfer function between \(u_n\) and \(p\), and where \(N\) is the averaging number of FFT.
2.2 Dissipation matrix in finite element method [9, 11, 12, 13]

Following the standard procedure of finite element method (FEM), the sound field of a room with dissipative walls is governed by the discretized matrix equation of motion as:

\[
[K] \{p\} + i\omega [C] \{p\} - \omega^2 [M] \{p\} = i\omega \rho v_0 \{W\}.
\]

Where, \([M]\), \([C]\) and \([K]\) denote acoustic mass, dissipation and stiffness matrices respectively; and \(\{p\}, \rho, \omega, u\) and \(\{W\}\) are sound pressure vector, air density, angular frequency, displacement and distribution vector respectively. Assuming that \(\cdot\) and \(\cdot\) to be first and second order derivative with respect to time respectively, the equation in the time domain can be:

\[
[M]\{\dot{p}\} + [C]\{\ddot{p}\} + [K]\{p\} = \rho \omega^2 u \{W\}(= \{f\}).
\]

With an interpolation function, \(\{N\}\), the acoustic element matrices that construct global matrices in the Eq.(4) are given by

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

\[
[M]_e = \frac{1}{c^2} \int_e \left\{ N \right\} \left\{ N \right\}^T dV;
\]

\[
[C]_e = \frac{1}{c} \int_\Gamma \frac{1}{Z_n/\rho c} \left\{ N \right\} \left\{ N \right\}^T dS.
\]

Where \(c\), \(Z_n\) and \(\rho\) are sound speed, surface normal impedance and air density respectively, and \(\Gamma\) denotes the surface area to be integrated. (Fig. 2)

Note that \(Z_{EA}\) is measurable at a point on a specimen’s surface as the average value of the specimen’s sound absorption over incident sounds with multiple incident angles as well as the incident angle dependency of the specimen’s sound absorption. In FEM, the area \(\Gamma\) is divided into some amount of finite elements with certain nodal points. A nodal point needs to represent both geometrical and sound absorptive nature of surrounding area of the point. Then, we expect that \(Z_{EA}\) has the basic potential to overcome the specimen’s ununiformity in sound absorption as well as subtle shape fluctuations.

3. EA_{EA} method example measurements at different points and places

3.1 Measurement set up

All the EA_{pu} method measurements conducted in this paper follow the procedure given in our former studies. A pu-sensor (PU-Regular P-900782, Microflown Technologies) was employed and
the output from the pressure and particle velocity sensors were plugged into 2ch FFT analyzer (Pulse, B & K Co.). The frequency resolution of FFT was set to 3.125 Hz and linear averaging was performed 150 times in the time domain using Hanning window. Calibration of pu-sensor was conducted in a standing-wave-tube with 50 mm diameter once a day paying attention to keep the relative humidity difference between at calibration and at measurement less than 8 % [8].

Randomly located six small loudspeakers were employed to radiate incoherent pink noises. In in-situ measurements, loudspeakers were moved around randomly by human-hands apart roughly 1.5 ~ 2 m from the specimen’s center. On the other hand, loudspeakers were placed on the floor in a reverberation room.

A series of EA\textsubscript{pu} method measurements were conducted in five rooms and at a terrace (Fig. 3). The rooms are reverberation room at Oita University Information Center (RR), cafeteria of Oita University (Caf), corridor in a concrete building (Cor), room for environmental experiment (R-E) and room in a reinforced-concrete house (RC). As a trial case, the same measurements were carried out at outside-terrace of a concrete building. Figure 3 infers the complexity of boundary conditions of sound fields in practical built environments.

Absorption coefficients of two specimens, glass-wool (GW: 32 kg/m\textsuperscript{3}, 50 mm thick) and needle felt (NF: 10 mm thick), were measured by the EA\textsubscript{pu} method. Figures 4, 5 show the outlook of two specimens and three measurement points MP1, MP2 and MP3, respectively. The pu-sensor was placed at a point 1 cm above the measurement points one by one and sound pressure and particle velocity were measured by the pu-sensor with the FFT instrument. A single measurement at a point on each specimen finishes within about 33 seconds. In a "set", three measurements were conducted continuously at the three points from MP1 to MP3, in turn. For each specimen, three sets of measurement were conducted in a day and three sets were performed paying attention to keep relative humidity difference between at calibration and at measurement less than 8 %.

3.2 Results and discussion

3.2.1 Sound absorption difference among measurement points

Practical building materials like glass-wool and needle felt shown in Fig. 4 are not uniform and sound absorptions frequently differ point by point. To observe the difference, sound absorption coefficient values \(\alpha_{EA}\) at three measurement points are compared in Fig. 6. In the figure, one-third octave band mean values of \(\alpha_{EA}\) are depicted to make comparison clearer. Because of the frequency restriction governed by the acoustical tube’s diameter, results in the frequency region above 3200 Hz are meaningless.

On the whole for both specimens, the differences among the measurement points are not distinct. In the frequency region above 800 Hz of NF, certain discrepancies are observable. Here, considering the physical size of an acoustical sensor, e.g. pu-sensor and microphone, a certain distance between a material’s surface and the sensor is inevitable. Moreover, particle-velocity sensor (\(\mu\)-flown)
Figure 3: Diversity of boundary conditions of practical sound fields. Photographies of reverberation room (RR), cafeteria (Caf), corridor (Cor), laboratory for environmental engineering (R-E), room in a concrete house (RC) and outside-terrace (Tr).

Figure 4: Outlook of specimens; (a): glass-wool (GW) and (b): needle felt (NF).

Figure 5: Three measurement points MP1, MP2 and MP3 on the specimen’s surface.
consists of 1 mm long two wires and half-inch microphone has about half-inch diameter membrane. Such physical sizes bring certain averaging over measurement surface area. Therefore, point-by-point measurement in a mathematical sense is not easy for EA method measurement, but certain averaged characteristics are obtainable as are given in Fig. 6. Nonetheless, "point impedance" of material with far more accurate sense is measurable by EA method than those by reverberation method or by impedance tube method.

### 3.2.2 Sound absorption difference among measurement places

Figure 7 shows comparisons of sound absorption coefficient values $\alpha_{EA}$ among measurement places RR, Caf, Cr, Tr, R-E and Tr for each specimen. Mean values of $\alpha_{EA}$ of all the results measured at three points three times in a day for three days are plotted as to represent the sound absorption characteristics of the specimen. Except for $\alpha_{EA}$ values of NF measured at R-E, agreements of sound absorption coefficients are good. Although $\alpha_{EA}$ values of GW measured at the six places show certain discrepancies each other in the frequency regions below 125 Hz and above 2500 Hz, agreements in the other frequency regions are excellent. Similar excellent agreements are observable for $\alpha_{EA}$ values of NF measured at the places except R-E in all frequency regions from 100 Hz to 3000 Hz.

The discrepancy found in $\alpha_{EA}$ values of NF measured at R-E from the values measured at the other places is attributable to absorptive carpet on the floor under the specimen. For the measurement of GW, the absorption of carpet has indistinct effect because of GW’s high absorption. Note that the floors of the other rooms are hard made by concrete, vinyl-tile and bricks.

Even if the effect of the absorption of carpet is included, standard deviation $\sigma$ values of $\alpha_{EA}$ of NF stay less than 0.041 throughout the frequency regions from 100 Hz to 3000 Hz. Standard deviation values of GW stay less than 0.025 throughout the frequency range. According to the tentative uncertainty criterion for sound absorption measurement targeted at applications for room acoustics simulations [14], standard deviation less than 0.040 is acceptable. Though example applications of surface normal impedance values measured by EA$_{pu}$ method to FEM room acoustics simulations are omitted here because of space limitation, satisfactory results are obtained, so far (e.g. refer to our previous paper [15]).

### 4. Conclusions

Accurate results can be expected by room acoustics simulations based on the wave-based-acoustics provided the boundary modeling is appropriate. One of the bottlenecks of modeling sound fields in practical built environments is caused by the complexity and/or diversity of shapes and absorptions of the rooms’ boundaries. EA method is expected to overcome the difficulty. Note that all EA method measurements presented here except one in a reverberation room (RR) are conducted in-situ con-
Figure 7: Comparisons of one-third octave band mean values of sound absorption coefficients of GW (left) and NF (right) among measurement places RR, Caf, Cr, Tr, R-E and Tr. Standard deviation $\sigma$ is plotted together with vertical-axis on right-hand-side.

...conditions including outdoor-terrace with different as well as complicated environments. Nonetheless, uncertainties of absorption coefficient caused by the difference of measurement place stay satisfactory small values.

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