A system-theoretical evaluation method for the reverberation time of an acoustically coupled room system

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A reverberation time is very important for evaluating the reverberation characteristics of a room and the sound power of an acoustic source. The definition of reverberation time is given originally for an acoustically isolated single room. On the other hand, in an acoustically coupled room, respective reverberation times of individual rooms are fairly different from independently measured reverberation times without mutual power flow interactions through apertures or acoustic insulation walls. In this paper, first, a general type characteristic expression of acoustically coupled rooms is established as a power flow system consisting of several subsystems, in close connection with a Statistical Energy Analysis method, corresponding to a kind of system equation in a state estimation theory. On the basis of a solution of this system equation, new type six different methods are proposed on trial by introducing various type evaluation criteria so as to evaluate the reverberation time of the acoustically coupled room system, especially from various type system-theoretical viewpoints. Finally, the effectiveness of the proposed theory is experimentally confirmed by applying it to the actual coupled acoustic rooms and the above six evaluation methods are compared with each other.

Keywords: Reverberation time, Coupled room, Matrix norm, Matrix measure, System-theoretical viewpoint

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1. INTRODUCTION

Not to say, a reverberation time is very important for evaluating the reverberation characteristics of a room and the sound power of an acoustic source. In general, as is well-known, a reverberation time of room is defined as the time interval in which the reverberation level drops down by 60 dB and experimentally measured from the actual decay curve. As is well-known, this definition is given, however, originally for an acoustically isolated single room.

On the other hand, an acoustically coupled room^{1,2)} is functionally given as a system composed

of virtually separated rooms, connected by relatively small apertures or by acoustically transparent walls. Owing to power flow interactions between arbitrary two rooms through the apertures or acoustic walls, a respective reverberation time of individual room in such a coupled room system is fairly different from independently measured reverberation times without mutual power flow interactions. But, until now, a considerable much researches for evaluating the reverberation characteristics of a coupled room were reported only in an extension form of the standard evaluation method for a single room.³⁻⁸⁾

In this paper, first, a general type characteristic

expression of acoustically coupled rooms is established as a power flow system consisting of several subsystems, in close connection with a well-known Statistical Energy Analysis method, corresponding to a kind of system equation in a state estimation theory. On the basis of a solution of this system equation, new type six different methods are proposed on trial by introducing various type evaluation criteria so as to evaluate the reverberation time of the acoustically coupled room system, especially from various type system-theoretical viewpoints. Thus, not only an extended method of conventional standard evaluation but also various type synthetic evaluation methods can be found. Finally, the effectiveness of the proposed theory is experimentally confirmed by applying it to the actual coupled acoustic rooms and the above six evaluation methods are compared with each other under various type different conditions of acoustical coupling.

2. THEORETICAL CONSIDERATIONS

2.1 Matrix Equation of Power Flow for Acoustically Coupled Rooms

Let us consider an acoustically coupled room consisting of n individual rooms in the form of total power flow system with n subsystems as shown in Fig. 1. It is assumed that each room R_i has a sound source with an output power W_i and an external noise is transmitted into only room R_1 through the window or the aperture for simplicity.

According to Statistical Energy Analysis (abr. SEA) method,⁹⁾ simultaneous equations of power balance among n rooms are expressed as follows:

$$V_1 \frac{dE_1}{dt} = W_0 - \pi_{1,0} - \pi_1 - \pi_{1,2} + \pi_{2,1} + W_1, \quad (1a)$$

$$V_i \frac{dE_i}{dt} = \pi_{i-1,i} - \pi_{i,i-1} - \pi_i - \pi_{i,i+1} + \pi_{i+1,i} + W_i, \quad (i=2, 3, \dots, n-1) \quad (1b)$$

$$V_n \frac{dE_n}{dt} = \pi_{n-1,n} - \pi_{n,n-1} - \pi_n + W_n, \quad (1c)$$

where

- V_i : air volume of room R_i [m^3],
- $E_i (\equiv E_i(t))$: sound energy density in room R_i [J/m^3],
- $\pi_i (\equiv \pi_i(t))$: sound energy lost through walls in room R_i per second [J/s],
- $\pi_{i,j} (\equiv \pi_{i,j}(t))$: sound energy transmitted from room R_i to room R_j per second [J/s].

Fig. 1 Acoustically coupled series rooms.

For establishing a basic theory to evaluate the acoustic characteristics of this coupled room system, let us assume that the sound field in each room is a diffuse sound field and that the sound energy of each room is transmitted into the adjoining rooms only through its apertures or connecting walls. At this time, considering that sound energy incidents to a unit area of space in a unit time is given by $cE_i(t)/4$ in a perfect diffuse field, where c is the sound velocity, Eqs. (1a)–(1c) can be organized into a matrix equation as follows:

$$\frac{d\mathbf{E}(t)}{dt} = \mathbf{A}\mathbf{E}(t) + \mathbf{B}\mathbf{u}(t), \quad (2)$$

where

$$\mathbf{E}(t) = [E_1(t), E_2(t), \dots, E_n(t)]^T,$$

$$\mathbf{u}(t) = [W_0(t) + W_1(t), W_2(t), \dots, W_n(t)]^T,$$

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 & \dots & 0 \\ a_{21} & a_{22} & a_{23} & 0 & 0 & \dots & 0 \\ 0 & a_{32} & a_{33} & a_{34} & 0 & \dots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \dots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \dots & a_{n-1,n} \\ 0 & 0 & 0 & 0 & 0 & \dots & a_{n,n} \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{V_1} & 0 & 0 & \dots & 0 \\ 0 & \frac{1}{V_2} & 0 & \dots & 0 \\ \cdot & \cdot & \cdot & \dots & 0 \\ 0 & 0 & 0 & \dots & \frac{1}{V_n} \end{bmatrix}, \quad (3)$$

$$a_{ij} = \frac{cS_{ji}\tau_{ji}}{4V_i} \quad (i \neq j, i, j=1, 2, \dots, n), \quad (4a)$$

$$a_{ii} = -\frac{c}{4V_i} \{ S_i \alpha_i + S_{i,i-1} (\alpha_{i,i-1} + \tau_{i,i-1}) + S_{i,i+1} (\alpha_{i,i+1} + \tau_{i,i+1}) \} \quad (i=1, 2, \dots, n-1), \quad (4b)$$

$$a_{nn} = -\frac{c}{4V_n} \{ S_n \alpha_n + S_{n,n-1} (\alpha_{n,n-1} + \tau_{n,n-1}) \} \quad (4c)$$

with

- S_{ij} : area of partition between R_i and R_j ($S_{ij} = S_{ji}$),
- α_{ij} : sound absorption coefficient of the surface of partition between R_i and R_j ,
- S_i : inner surface area of room R_i excepting $S_{i,i-1}$ and $S_{i,i+1}$,
- α_i : mean sound absorption coefficient of the inner surface S_i ,
- τ_{ij} : transmission coefficient of the surface of partition between R_i and R_j ($\tau_{ij} = \tau_{ji}$).

Hereupon, the following points must be noticed:

- (1) The n -dimensional state vector $E(t)$ denotes an n set of sound energy density in each room.
- (2) The n -dimensional vector $u(t)$ denotes an n set of output power of sound source in each room.
- (3) The coefficient matrix A is a tridiagonal matrix and the matrix B is a diagonal matrix.

In the actual living situation, it is difficult to measure the accurate values of each sound absorption coefficient α_i and the transmission coefficient τ_{ij} . Accordingly, it is difficult to calculate the accurate values of element a_{ij} in matrix A from Eq. (4) on the basis of the internal mechanism of a coupled room. Therefore, we have proposed a new trial of parameter identification for a_{ij} in the above matrix state equation.

2.2 Solution of Matrix Type Reverberation Equation

As mentioned in the previous section, such a coupled room can be considered as a power flow system. In this section, the solution of the matrix system equation, Eq. (1), is discussed especially from a system-theoretical viewpoint.

Following to the well-known solution of a time-invariant linear type differential equation in the state space method, a solution of Eq. (1) is given directly as follows:

$$E(t) = \Phi(t)E_0 + \int_0^t \Phi(t-\tau)Bu(\tau)d\tau, \quad (5)$$

where

$$E(t) = [E_1(t), E_2(t), \dots, E_n(t)]^T,$$

$$E_0 = E(0) = [E_1(0), E_2(0), \dots, E_n(0)]^T$$

and

$$\Phi(t) = e^{At}.$$

Because $a_{i-1,i}$ and $a_{i,i-1}$ are positive from Eq. (4),

matrix A has n different real eigenvalues of negative value. Let n real eigenvalues be $-\lambda_1, -\lambda_2, \dots, -\lambda_n$, where these are classified as $0 < \lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_n$. After employing a well-known Sylvester's expansion theorem, the transition matrix $\Phi(t)$ can be easily expressed as follows:

$$\Phi(t) = \sum_{i=1}^n e^{-\lambda_i t} \prod_{j=1, j \neq i}^n \frac{A + \lambda_j I}{-\lambda_i + \lambda_j}. \quad (6)$$

Next, the stationary response E_0 of this system for a stationary input $u_0 \equiv u(0)$ is given by setting $dE(t)/dt = 0$ in Eq. (2) as follows:

$$E_0 = -A^{-1}Bu_0. \quad (7)$$

Let all of the sources stop at the same time when the sound field in each coupled room reaches at a stationary state. After that, $E(t)$ decays exponentially as follows:

$$E(t) = \Phi(t)E_0 = -e^{At}A^{-1}Bu_0. \quad (8)$$

It is easily shown from Eq. (6) that every element $E_i(t)$ of vector $E(t)$ consists of n different damping components. Hereupon, we must notice that a matrix $e^{At}A^{-1}B$ shows a symmetry.

2.3 New Evaluation Methods for Reverberation Time of Coupled Room System

In this section, six different type methods are newly proposed on trial for evaluating the reverberation time of a coupled room system especially from various type system-theoretical viewpoints.¹¹⁻¹⁴⁾

(Method 1) A synthetic evaluation method

By regarding many coupled rooms as a total system consisting of several subsystems, the following synthetic evaluation method of reverberation time can be proposed.

When all of sound sources into the coupled rooms stop at $t=0$, the vector $E(t)$ of reverberation process, is given as mentioned in the previous section:

$$E(t) = \Phi(t)E_0. \quad (9)$$

A time T satisfying the following equation can be synthetically employed as a reverberation time of a coupled room system with the sound power flow interactions:

$$10 \log_{10} \frac{\|E(T)\|}{\|E_0\|} = -60, \quad (10)$$

where $\|\cdot\|$ denotes a vector norm. It is noteworthy that T satisfying Eq. (10) especially for one dimensional state variable $E(T)$ agrees with the conventional definition of a reverberation time due to Sabine.

There are various ways on how to choose the vector norm according to the engineering needs. For example, every room should be treated with an equal weight, or each room should be reasonably treated with a particular weight. At this time, of course, T 's obtained in the different ways of selecting vector norm are different from one another and from a reverberation time obtained by the traditional way. Once after a vector norm is selected in advance, the following relationship can be set by newly introducing a matrix norm and a measure of matrix determined by the vector norm:

$$\begin{aligned} & \max\{-\mu(-\Phi(T)), -\mu(\Phi(T))\} \\ & \leq \frac{\|E(T)\|}{\|E_0\|} \leq \|\Phi(T)\|, \end{aligned} \quad (11)$$

where $\mu(A)$ is a measure of matrix A and $\|A\|$ is a matrix norm of matrix A .

In other words, it can be expected that Eq. (11) gives a certain measure of allowance for the estimation of T . In particular, when an Euclidean norm:

$$\|x\|_2 = \sqrt{\sum_{i=1}^n |x_i|^2}$$

is selected for the vector norm in Eq. (10) and matrix A is a real symmetric matrix, the corresponding measure of matrix and matrix norm for this matrix A can be given as follows:

$$\mu_2(A) = \max_i \left\{ \lambda_i \left(\frac{A^* + A}{2} \right) \right\}, \quad (12a)$$

$$\|A\|_2 = \sqrt{\max_i \{\lambda_i(A^*A)\}}, \quad (12b)$$

where $\lambda_i(A)$ denotes the i -th eigenvalue of matrix A and A^* denotes a conjugate transpose matrix of A .

Finally, Eq. (11) can be rewritten in a more concrete forms as follows:

$$e^{-\lambda_n T} \leq \frac{\|E(T)\|_2}{\|E_0\|_2} \leq e^{-\lambda_1 T}, \quad (13)$$

where it is assumed that those eigenvalues are classified as $\lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_n$.

(Method 2) A conventional evaluation method

In this method, though there are acoustically power flow interactions among the rooms, the reverberation time of each room is separately and conventionally measured as a time to decay 60 dB from an initial level based on a measured reverberation curve.

(Method 3) An evaluation method with a safety factor

Equations (5) and (6) show that n kinds of reverberation processes in n rooms have respectively the proper pattern of exponentially decay curve.

In this method, as one of six evaluation methods for a whole coupled room system, a reverberation time of a coupled room is evaluated with a safety factor by use of the most slowly decaying curve among n exponentially decaying curves as follows:

$$T = \frac{6 \ln 10}{\min_i \lambda_i}. \quad (14)$$

Note that this method gives a representative reverberation time for a coupled room system.

(Method 4) An approximated evaluation method of locally exponential type

Based on the above consideration, a reverberation process in the i -th room R_i can be obviously approximated by an exponentially damping function, $E_{i0}e^{-\mu_i t}$. Let the approximated reverberation process be $\hat{E}(t)$. Then, $\hat{E}(t)$ can be expressed as follows:

$$\hat{E}(t) = \text{diag}[e^{-\mu_1 t}, e^{-\mu_2 t}, \dots, e^{-\mu_n t}]E_0. \quad (15)$$

Hereupon, the constant μ_i is determined so as to make the inclination of $e^{-\mu_i t}$ equal approximately to the inclination of $E_i(t)$ at $t=0$. That is, a reverberation time of the room R_i is approximately given as follows:

$$T_i = \frac{6 \ln 10}{\mu_i}. \quad (16)$$

(Method 5) An approximated evaluation method of integrated exponential type

As another evaluation method, a constant μ_i can be determined so as to make the integrated value of $E_{i0}e^{-\mu_i t}$ equal to the integrated value of $E_i(t)$ in a whole time domain $[0, \infty)$, as follows:

$$\int_0^\infty E(t)dt = \int_0^\infty \text{diag}[e^{-\mu_1 t}, e^{-\mu_2 t}, \dots, e^{-\mu_n t}]E_0 dt. \quad (17)$$

That is, a reverberation time of the room R_i can be given as follows:

$$\begin{aligned} & [T_1, T_2, \dots, T_n]^T \\ & = -6 \ln 10 \{ \text{diag}[E_{10}, E_{20}, \dots, E_{n0}] \}^{-1} A^{-1} E_0. \end{aligned} \quad (18)$$

(Method 6) Ziegler-Nichols' type approximated evaluation method

On the other hand, a reverberation time T_i in the room R_i can be determined based on the inclination at the inflection point on the decay curve drawn by Eq. (6). This evaluation method is the same as the well-known Ziegler-Nichols' approximation in the field of automatic control system (see Fig. 2).

Fig. 2 Ziegler-Nichols' approximation method.

3. EXPERIMENTAL CONSIDERATIONS

3.1 Experimental Method

In the experimental study, the measurement of a reverberation time has been carried out especially in a coupled room system with two kind of individual reverberant rooms as shown in Fig. 3. A room R_1 has an air volume of 50.2 m^3 and a room R_2 has an air volume of 24.6 m^3 . The aperture of the wall between R_1 and R_2 has an area of $1.74 \text{ m} \times 0.84 \text{ m}$.

The following three cases for this aperture have been considered for measuring quantitatively the acoustic influences of strength of mutual coupling:

- (Case 1) fully opened,
- (Case 2) 1/8 opened,
- (Case 3) closed with a lauan board of 3 mm thickness.

The sound source signal has been an octave band white noise with a center frequency 500 Hz. Each room can be regarded respectively as a complete diffuse sound field (See Appendix for the experimental verification of complete diffuseness of each room). The sampling interval of the measurement has been $1/6 \text{ s}$ and 500 data have been used and then averaged to obtain individually the stationary energy densities in two rooms. Moreover, the experimental data have been observed for several locations of the sound source and the microphones in each room, and have been spatially averaged for finding successfully a complete diffuseness in our experiment.

3.2 Results of Parameter Estimation

The method of measuring an output power of source can be first briefly explained as follows.

Let us assume that the sound source to be measured emits a power W in a reverberant room. At this time, an energy density in the room can be ex-

Fig. 3 Block diagram experiment.

pressed as follows:

$$V \frac{dE(t)}{dt} = W - KE(t), \quad (19)$$

$$K = \frac{c\alpha S}{4}, \quad (20)$$

where

- V : air volume of the room,
- c : sound velocity,
- α : mean sound absorption coefficient,
- S : inner surface area of the room.

After stopping the sound source emission when the energy density in the room reaches at a stationary state, $E_0 = W/K$, the following solution of the above reverberation equation can be derived:

$$E(t) = E_0 e^{-(K/V)t}. \quad (21)$$

As is well-known, from this equation, a reverberation time of the room is given as follows:

$$T = 6 \ln 10 \cdot \frac{V}{K}. \quad (22)$$

Finally, from Eqs. (20) and (22), the output power of sound source can be estimated as follows:

$$W = 6 \ln 10 \cdot \frac{V}{T} E_0. \quad (23)$$

That is to say, the sound output power W can be measured by measuring a reverberation time and the stationary energy density E_0 . The estimation of W has been carried out in a room R_1 in a typical case where absolutely isolated from a room R_2 and the

estimated value of W has been 0.466 watt.

From our another related research¹⁰⁾ for estimating the parameter matrix A in the system Eq. (2), an estimated parameter matrix A is given by a deterministic estimation method as follows:

$$A = -\text{diag} \left[\frac{u_1}{V_1}, \frac{u_2}{V_2} \right] \cdot [E_1, E_2]^{-1}, \quad (24)$$

where E_i denotes a vector of stationary energy densities of rooms R_1 and R_2 when a sound source with an input u_i is placed in a room R_i . Substituting the value of W for u_1 or u_2 in Eq. (24) (cf. Eqs. (2) and (3) when $dE/dt=0$ (stationary)) and observing the actual data of E_i , the parameter matrix A has been concretely estimated. The values of E_1 , E_2 , A and the eigenvalues (λ_1 , λ_2) of A are shown in the previous three cases as follows:

(Case 1)

$$E_1 = \begin{bmatrix} 2.04 \times 10^{-3} \\ 1.26 \times 10^{-3} \end{bmatrix}, \quad E_2 = \begin{bmatrix} 8.71 \times 10^{-3} \\ 3.02 \times 10^{-3} \end{bmatrix},$$

$$A = \begin{bmatrix} -5.52 & 1.59 \\ 4.70 & -7.62 \end{bmatrix}, \quad \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} -3.64 \\ -9.50 \end{bmatrix},$$

(Case 2)

$$E_1 = \begin{bmatrix} 2.34 \times 10^{-3} \\ 3.16 \times 10^{-4} \end{bmatrix}, \quad E_2 = \begin{bmatrix} 3.16 \times 10^{-4} \\ 4.17 \times 10^{-3} \end{bmatrix},$$

$$A = \begin{bmatrix} -4.00 & 0.303 \\ 0.618 & -4.59 \end{bmatrix}, \quad \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} -3.77 \\ -4.81 \end{bmatrix},$$

Fig. 4 Comparison between experimentally sampled points and theoretically estimated curves for decay curves of reverberation in the acoustically coupled room in Case 1.

(Case 3)

$$E_1 = \begin{bmatrix} 2.40 \times 10^{-3} \\ 9.12 \times 10^{-5} \end{bmatrix}, \quad E_2 = \begin{bmatrix} 9.12 \times 10^{-5} \\ 4.26 \times 10^{-3} \end{bmatrix},$$

$$A = \begin{bmatrix} -3.87 & 0.083 \\ 0.169 & -4.44 \end{bmatrix}, \quad \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} -3.84 \\ -4.46 \end{bmatrix}.$$

In order to confirm the effectiveness of the proposed method, the comparisons are given for the above cases in Figs. 4, 5 and 6 between experimentally sampled points and theoretically estimated curves.

Fig. 5 Comparison between experimentally sampled points and theoretically estimated curves for decay curves of reverberation in the acoustically coupled room in Case 2.

Fig. 6 Comparison between experimentally sampled points and theoretically estimated curves for decay curves of reverberation in the acoustically coupled room in Case 3.

All of theoretically estimated curves fairly agree with the corresponding experimentally sampled points. Furthermore, it is found that the looser acoustical power flow interaction between two rooms R_1 and R_2 becomes, the larger the differences between the curves of R_1 and R_2 become.

3.3 Evaluation Result on Reverberation Time

The evaluation result of reverberation time by using the above six different methods are shown in Tables 1, 2 and 3 for the above three cases. Here, T_1 and T_2 denote two reverberation times of room R_1 and room R_2 respectively. That is, we get experimentally two observed values $T_1 = 4.1$ s and $T_2 = 2.8$ s by evaluating the slope of respective decay curve when the rooms are absolutely isolated from each other. Blanks in these tables denote that reverberation times are not computable.

The following characteristic points can be found from the above results:

- (1) In the room having the speaker, the results by six different methods make to remarkable difference. But in the other room, the results show a relatively great difference.
- (2) Results based on two Methods 2 and 6 agree with each other in all cases.

Table 1 Reverberation times in Case 1.

	(s)			
	Speaker in R_1		Speaker in R_2	
	T_1	T_2	T_1	T_2
Method 1	3.83	3.83	3.69	3.69
Method 2	3.78	3.93	3.93	3.62
Method 3	3.79	3.79	3.79	3.79
Method 4	3.04			2.21
Method 5	3.44	5.25	3.93	3.62
Method 6	3.78	3.93	3.93	3.62

Table 2 Reverberation times in Case 2.

	(s)			
	Speaker in R_1		Speaker in R_2	
	T_1	T_2	T_1	T_2
Method 1	3.68	3.68	3.46	3.46
Method 2	3.63	4.07	4.07	3.34
Method 3	3.67	3.67	3.67	3.67
Method 4	3.49			3.04
Method 5	3.53	6.54	6.54	3.08
Method 6	3.63	4.07	4.07	3.34

Table 3 Reverberation times in Case 3.

	(s)			
	Speaker in R_1		Speaker in R_2	
	T_1	T_2	T_1	T_2
Method 1	3.59	3.59	3.21	3.21
Method 2	3.59	4.11	4.11	3.15
Method 3	3.59	3.59	3.59	3.59
Method 4	3.57			3.12
Method 5	3.58	6.70	6.70	3.12
Method 6	3.59	4.11	4.11	3.15

- (3) In the room having the speaker, the resultant values from all methods in Case 3 are smallest.
- (4) In the room having the speaker, the resultant values from all methods for R_1 in Case 1 are closest to 4.1 s of single room with no mutual power flow interaction. On the other hand, the resultant values from all methods for R_2 in Case 3 are closest to 2.8 s of a single room R_2 with no mutual power flow interaction.

4. CONCLUSION

In this paper, the evaluation methods of reverberation time for a coupled room system have been newly proposed on trial from various type system-theoretical viewpoints. More concretely, first after introducing the system equation for this coupled room system, six different evaluation methods of reverberation times for this coupled room system have been proposed under the introduction of various type evaluation criteria.

Finally, the measurement of reverberation times in the actual acoustic system with two reverberant rooms coupled acoustically each other has been carried out to clarify the effectiveness of the proposed evaluation methods.

Since such system-theoretical trials in this paper for evaluating the reverberation time of a coupled room system are at early stage of study especially in the field of room acoustics, the chief purpose of this paper has been focused on principally finding how to evaluate a coupled room system-theoretically.

There still remain our future researches for applying these evaluation methods to many of the actual coupled rooms and determining which method is most effective to explain the actual reverberation characteristics of a coupled room in close connection with variety of the actual engineering needs.

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APPENDIX: EXPERIMENTAL VERIFICATION OF COMPLETE DIFFUSENESS OF ROOMS

The complete diffuseness of rooms R_1 and R_2 can be experimentally verified as follows.

Let us employ Eq. (4a) as a kind of indices for evaluating the complete diffuseness of rooms R_1 and R_2 . In Case 2, the theoretically calculated values of a_{12} and a_{21} by using Eq. (4a) are 0.307 and 0.627, respectively. On the other hand, the experimentally estimated values $\hat{a}_{12}$ and $\hat{a}_{21}$ from the actually observed data are 0.303 and 0.618, respectively, as mentioned before. These values are very close each other. In Case 3, the estimated values of the transmission loss of the lauan board of 3 mm thickness are 14 dB from Eq. (4a) by using both of estimated values $\hat{a}_{12}=0.083$ and $\hat{a}_{21}=0.169$. On the other hand, the experimental transmission loss of the lauan board of 3 mm thickness from the reference 15 is the same 14 dB for a center frequency 500 Hz. These results suggest that two rooms R_1 and R_2 can be respectively regarded as completely diffuse sound

fields.

Moreover, it is noteworthy that the same rooms had been already employed and then verified very often their complete diffuseness in our other previous researches.¹⁶⁻²⁰⁾

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