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Prediction of Room Acoustics Using Image Method

(영상 음원법을 이용한 실내 음향 특성의 예측)

Hee-Won Lee,* Byung-Ho, Lee**

이 희 원,* 이 병 호**

ABSTRACT

A computer simulation technique using image method is developed for the prediction of the acoustical characteristics of a room. Also a mehtod of compensating simulation error is proposed because the simulated impulse response is truncated to the finite time duration. The results of simulation are the sound ray paths from source to receiver, the impulse response obtained from the ray paths, the reverberant sound energy decay, and the early / late sound energy ratio at the audience area.

요 약

본 연구에서는 건축물이 갖게될 음향학적 특성을 미리 예측함으로써 그 건축물의 음향학적 요구에 맞는 설계를 수행할 수 있도록 하기 위해 computer simulation 방법을 개발하였다. 본 연구에서 사용된 simulation 방법은 영상음원법을 기초로 하였으며, simulation에 의한 임펄스 응답이 유한한 시간 내로 제한되어 발생되어 오차를 줄이기위한 방법이 제시되었다. 개발된 simulation 방법으로 실내에서의 임펄스 응답, 잔향 곡선, early / rate energy ratio 등을 예측하고 실험 결과와 비교 하였으며, 실용적인 응용 가능성도 검토하였다.

I. INTRODUCTION

A concert hall needs good acoustical quality for musical performance and a lecture room or a conference room needs a good acoustical quality for speech transmission. The major problem to construct a hall with good acoustical quality, is how to predict the acoustical properties of the hall at the design stage prior to its completion .

Computer simulation based on the geometrical acoustics is one of these techniques that make it possible to predict room acoustical parameters, such as impulse responses and reverberant sound energy decays.

Two different algorithms for the calculation of transient sound propagation in rooms on the com-

*Department of Mechanical Design, Seoul National Polytechnic University.

**Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology.

puter are known. The first is based on the image method[1, 2], where as the second one is ray tracing[3]. In the image method, the major drawback is to truncate the length of impulse response because the computation time increases exponentially with legth. On the other hands, relatively short computation time is specific advantages of the ray tracing method, but the temporal resolution is limited.

In this study, a simulation technique using image method is developed for the prediction of several room acoustical parameters. Developed simulation technique includes a method of compensating simulation error occurred from the truncation of the length of impulse responses. Simulated room acoustical parameters are the sound ray paths from source to receiver, impulse responses obtained from the ray paths, reverberant sound energy decays, and early / late sound energy ratios.

Also an experimental investigation is performed to evaluate the simulation accuracy, by comparing the simulated results with the measured data. With the developed simulation method, an example of the practical application is tried. In the next sections, developed simulation method is briefly described, and then the experimental results and application example will be dicussed.

II. CALCULATION OF SOUND RAY PATHS

In the image method sound ray paths are calculated from all possibie combinations of reflecting walls through the following procedure. First, positions of image sources are calculated from the geometrical relationship with the original source position. Second, sound ray paths are obtained by connecting the image source to the receiver and calculating the intersection points on the reflecting walls.

In this study, the positions of image sources are calculated by using the coordinate transformantion. If a surface in a room is assumed to be mirror plane, there exist an image of the original room in the image space. From the geometrical relationship between the image room and the original room, we can develope a coordinates transformation matrix between the original coordinates system and its image coordinates system. We can calculate the positions of image sources using this transformation matrix. More complicated procedure is necessary for the computation of sound ray paths using the coordiantes transformation method: computation of transformation matrix, discrimination of invalid ray paths, etc. Advantages using coordinates transformation methods are the reduction of computation time and the reduction of required core memory size, especially for the case of multiple sound sources. Details are appeared in the reference[1].

III. PREDICTION OF ROOM ACOUSTICAL PARAMETERS

From the calculated sound ray paths, we can predict room acoustical parameters such as impulse response, reverberant sound energy decay, and early / late sound energy ratio. Impulse response is easily computed by considering the delay times and energy losses along the obtained ray paths. Other parameters can be computed as follows.

(1) Reverberant Sound Energy Decays

Reverberant sound energy decay can be computed by using the modificaton of Shroeder integration method[4]:

$$E_d(t) = \int_t^{\infty} p^2(\tau)\, d\tau \qquad (1)$$

where $E_d(t)$ is the reverberant sound energy decay and $p(\tau)$ is an impulse response at the receiver. We can not compute the infinite integration of the above equation because the simulation of impulse response is limited to the finite time duration. In this study, we modified the above equation and approximately compute the above integration.

$$\begin{aligned} E_d(t) &= \int_t^{\infty} p^2(\tau)\, d\tau \\ &= \int_0^{\infty} p^2(\tau)\, d\tau - \int_0^{t} p^2(\tau)\, d\tau \\ &= \int_0^{t_l} p^2(\tau)\, d\tau + \int_{t_l}^{\infty} p^2(\tau)\, d\tau - \int_0^{t} p^2(\tau)\, d\tau \end{aligned} \quad (2)$$

where t_l is the time length of the impulse response obtained from the simulation by image method. Let the first term in the eqn.(2) be E_1 and the second term E_2, i.e.,

$$E_1 = \int_0^{t_l} p^2(\tau)\, d\tau \text{ and } E_2 = \int_{t_l}^{\infty} p^2(\tau)\, d\tau \quad (3)$$

In the above equation E_1 can be obtained from the simulated impulse response but E_2 can not. In this study, E_2 is calculated from Eyring's reverberation formula:

$$E_e(t) = E_0 \exp\left(\frac{cS}{4V}\ t\ \ln(1-\bar{\alpha})\right) \quad (4)$$

Where, c is the speed of sound, S is the total surface area of the room, V is the total volum of the room, and $\bar{\alpha}$ is the average absorption coefficient. From eqn. (3) and (4) we can obtain the relation between E_1 and E_2:

$$E_2 = E_1\left[\exp\frac{cS}{4V} t_l\ \ln(1-\alpha)\right] / \left[1 - \exp\frac{cS}{4V} t_l \ln(1-\alpha)\right] \quad (5)$$

(2) Early / late Sound Energy Ratio

From the simulated impulse response, we can compute the early / late sound energy ratio, which is an index representing the speech intelligibility. The early / late sound energy ratios are defined by the various time limit as follows[5]:

$$\begin{aligned} C_{35} &= 10 \log\left[\int_0^{0.035} p^2(t)\, dt \Big/ \int_{0.035}^{\infty} p^2(t)\, dt \right] \\ C_{50} &= 10 \log\left[\int_0^{0.05} p^2(t)\, dt \Big/ \int_{0.05}^{\infty} p^2(t)\, dt \right] \\ C_{80} &= 10 \log\left[\int_0^{0.08} p^2(t)\, dt \Big/ \int_{0.08}^{\infty} p^2(t)\, dt \right] \\ C_{95} &= 10 \log\left[\int_0^{0.095} \alpha\, p^2(t)\, dt \Big/ \int_{0.095}^{\infty} p^2(t)\, dt \right] \end{aligned} \quad (6)$$

Ⅳ. EXPERIMENTAL INVESTIGATION

In this section, the evaluation of the simulation accuracy is performed by comparing the simulaltion results with the measured data. In this study, reverberant energy decay curves and speech intelligibility factors(C80), which can be computed from the impulse response, are compared with the measured ones.

Experimental measurement of impulse response was performed in the reverberation room at KSRI, because the acoustical properties of the room was accurately obtainable. Measurement procedures were as much as a practical compromise, incorporating common acoustical equipment where possible. These included tape recording of pistol shots and the recorded data were converted to the digital form and finally processed by the computer. Fig.(1) represents the block diagram of the measurement set up, Isometric view of th room and the source and microphone locations are appeared in the Fig.(2). Three selected microphone positions were at the center(R1), at the side(R2), and at the corner (R3) and the source position was fixed at S0 throughout the measurements. Measurement of impulse response was performed in the two different environments, the one was in the empty room (case-1) and the other was in the room with seventeen chairs on the floor(case-2). Each measurement at each microphone position was repeated for three pistol shots. Absorption coefficients of the each wall was determined from the measured reverberation time, which were 0.0339 for each

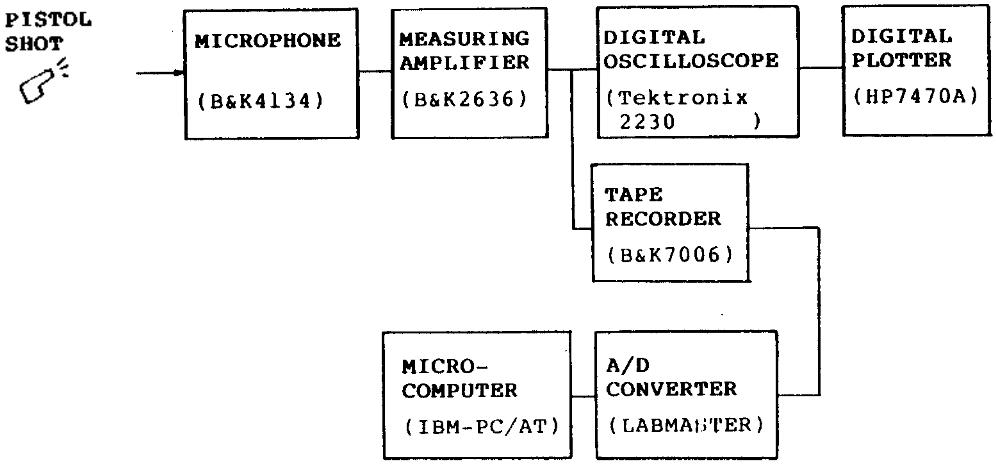
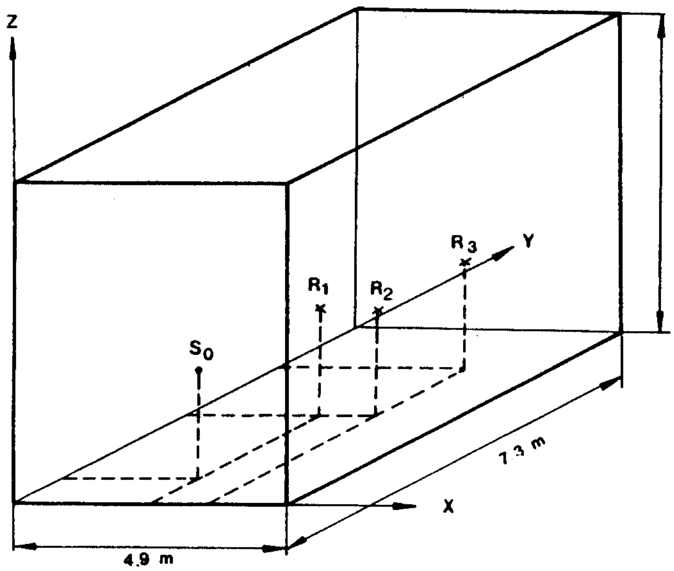


Fig. 1. Block diagram of the Experimental Measurement Set-up



Locations

	x	y	z
S_0	2.45	1.00	2.10
R_1	2.45	3.65	1.53
R_2	3.90	3.65	1.53
R_3	3.40	5.80	1.53

Fig. 2. Isometric view of the room for the experimental measurement

surfaces in the empty room and 0.126 for the floor with chairs.

From the measured or the simulated impulse responses, we could obtain the reverberant energy decay curve at each microphone position, using the eqn.(1). Fig.(3) and (4) represent the comparison of the reverberant energy decay curves. Deviation of the calculated curve from the measured one is appeared more apparently for the case-2(with chairs on the floor).

Early / late ratios could be calculated for 0.035, 0.05, 0.080 and 0.095 sec early sound limits and are referred to as C35, C50, C80 and C95 as presented in the eqn.(6). All measures were calculated from the impulse responses obtained by the simulation and by the measurement. Table(1) shows

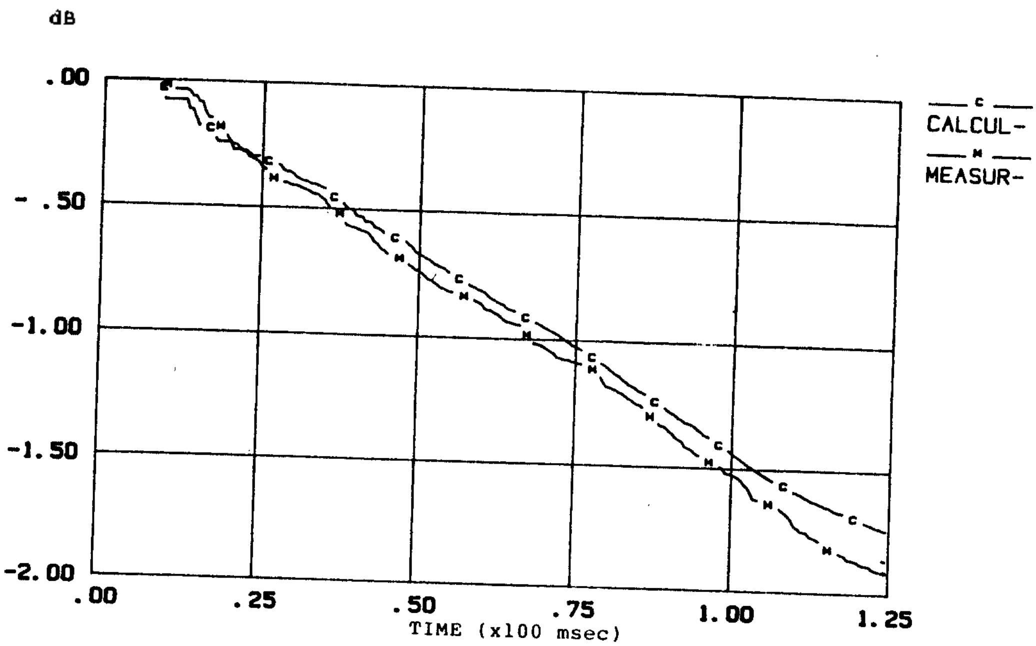


Fig. 3. Comparison of sound energy decay curve
(empty case, at reciver R_2)

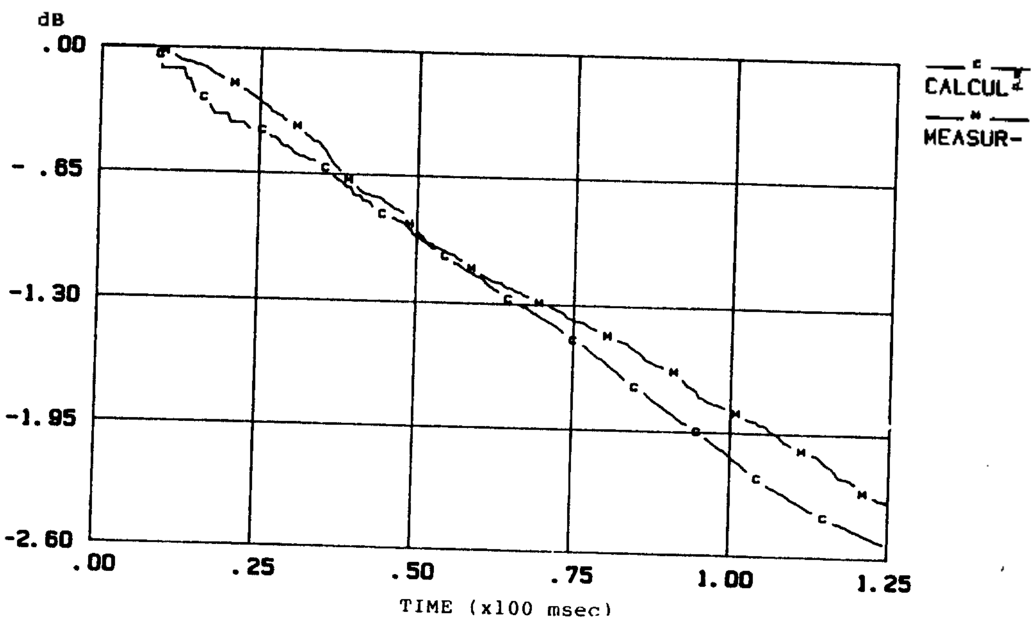


Fig. 4. Comparison of sound energy decay curve
(with chairs, at reciver R_2)

Table 1. Comparison of the Early / Late sound energy ratio.

			receiver positions R1	R2	R3	average	standard deviation
empty room	C 3 5	calculated	-9.31	-9.18	-9.30	-9.26	0.07
		measured	-9.09	-8.89	-9.29	-9.09	0.2
		difference	0.22	0.29	0.01	0.17	0.16
	C 5 0	calculated	-7.85	-7.68	-7.93	-7.82	0.13
		measured	-7.46	-7.63	-8.04	-7.71	0.30
		difference	0.39	0.05	0.11	0.18	0.18
	C 8 0	calculated	-5.54	-5.55	-5.54	-5.54	0.006
		measured	-5.29	-5.44	-5.63	-5.45	0.17
		difference	0.25	0.11	0.09	0.15	0.09
	C 9 5	calculated	-6.25	-6.20	-6.47	-6.31	0.14
		measured	-6.45	-6.21	-6.87	-6.15	0.33
		difference	0.20	0.01	0.40	0.20	0.20
			receiver positions R1	R2	R3	average	standard deviation
room with chairs	C 3 5	calculated	-7.58	-7.45	-7.56	-7.53	0.07
		measured	-8.71	-7.13	-7.58	-7.81	0.81
		difference	1.13	0.32	0.02	0.49	0.81
	C 5 0	calculated	-6.08	-5.91	-6.17	-6.05	0.13
		measured	-7.46	-7.63	-8.04	7.71	0.30
		difference	0.39	0.05	0.11	0.18	0.18
	C 8 0	calculated	-3.67	-3.68	-3.67	-3.67	0.006
		measured	-4.55	-3.46	-3.97	-3.99	0.55
		difference	0.858	0.22	0.30	0.47	0.36
	C 9 5	calculated	-4.23	-4.18	-4.44	-4.28	0.14
		measured	-5.01	-4.22	-5.14	-4.79	0.50
		difference	0.78	0.04	0.70	0.51	0.41

the comparison of the calcuated and measured Cte's. Maximum difference between the measured and the simulated speech intelligibility values was 1.13 dB (C35) at the R1 position in case-2. Average differences were 0.15 dB -0.20 dB for the case-1 and 0.47 dB -0.58 dB for the case-2. As shown in the results of comparison, the simulated values for the case-1 showed good correspondences to the measured data. Also, the correction of the simulation errors using the eqn. (5), could improve the simulation accuracy.

However, simulated results for the room with chairs(case-2) showed some differences from the measured data, because the developed simulation method did not consider the diffusive reflections by the chairs.

V. APPLICATION EXAMPLE

Although the more rigorous experimental investigations in the rooms of various size and shapes would be necessary for the evaluation of simulation accuracy, practical application is tried as follows.

With the developed simulation system, prediction of speech intelligibilities at the audience area in a practical hall was performed for investigating

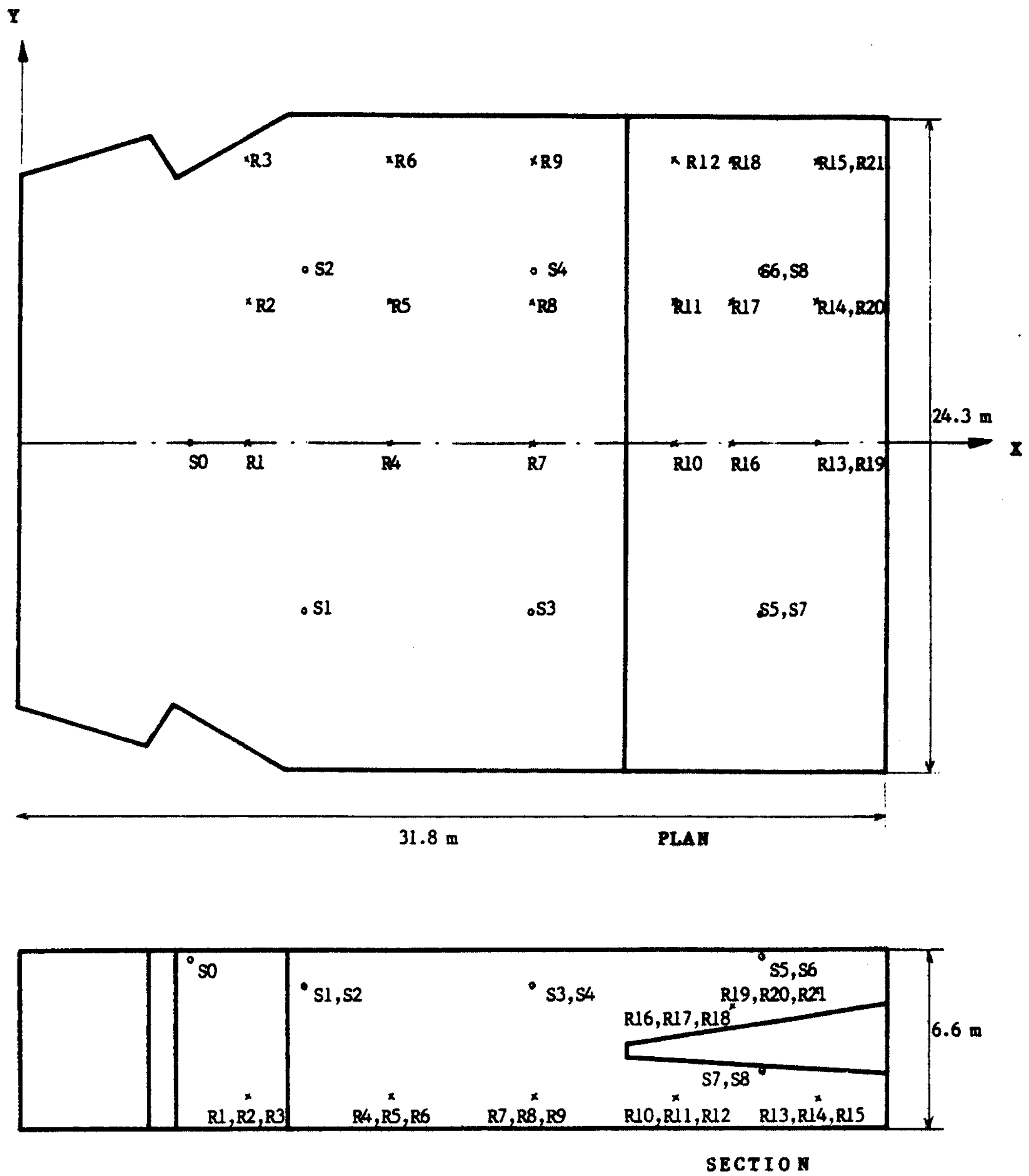


Fig. 5. Plan and sectional view of the model hall

the characteristics of the various type of sound reinforcement systems in a hall. Drawing of the model hall and selected positions of the loud speakers and receiver points are appeared in the Fig. (5). Speech intelligibility values (C80) at each receiver position were calculated using the image method with various changes of loudspeaker locations and directivities. Table(2) presents the calculated C80 values for four different cases, which are central type sound reinforcement system with omnidirectional and high directional loudspeakers, and distributed type sound reinforcement system with omnidirectional and high directional loudspeakers. Loudspeaker position for the central type sound reinforcement system was S0 in the Fig. (5) and the direction of main axis was assumed to be slanted 45° downward from X-axis. For the distributed sound reinforcement system the locations of eight loudspeakers were selected at S1-S8 in the Fig.(5) and the direction of main axis were assumed to be -Z-axis direction. As shown in Table(2), the central type sound reinforcement system has better speech intelligibility values(C80) than the distributed type, the average difference between the two systems was 2.42 dB. Also use of high directional loud-speakers can improve the speech intelligibility but the improvement was very small, about 0.61 dB for the central type and about 0.58 dB for the distributed type.

From the investigations of various sound reinforcement systems, we can conclude that the central type system gives the best speech intelligiblity values for the simulalted room model. This result corresponds to the general experience[6]. However, when using the central type sound reinforcement system, it is important to suppress the acoustical feedback instability which is not considerd in this study. In a common sense, the role of loudspeaker directivity is greatly related to the speech intelligibility in room, but in this study use of high directional loudspeakers does not improve the speech intelligibility values so much as the changes of the other acoustical parameters such as the arrangement of loudspearkers. Experimental investigations of K.D. Jacob[7] showed a similar result which indicated that the speech intelligibility and the loudspeaker directivity were not directly related.

Table 2. Predicted C80's of the example simulation (with the various changs of loudspeaker locations and directivities)

receiver location	central type		distributed type	
	omni directional	high directional	omni directional	high directional
R1	4.14	4.60	-0.27	0.46
R3	4.49	4.70	0.06	0.79
R7	2.44	3.77	1.59	2.23
R9	3.70	4.37	0.71	1.46
R13	3.39	3.43	1.76	2.30
R15	2.58	3.37	1.27	1.94
R19	3.45	4.02	1.74	1.96
R21	3.13	3.97	1.12	1.46
average	3.42	4.03	1.00	1.58
std.	0.71	0.50	0.77	0.67

Ⅵ. CONCLUSIONS

The proposed image method using coordinates transformation improves the efficiency of computing the sound ray paths in an arbitrary polyhedral room. From the calculated ray paths, reverberant sound energy decays and early / late sound energy ratios can be obtained. When the reverberant sound decays are simulated for a very reverberant room, they will be under-estimated because the impulse response obtained from the image method is limited to the finite time duration. Computation method presented in this study compensates the simulation errors by the approximate computation of the infinite integration. Simulated values of the reverberant sound energy decays and early / late sound energy ratios for a small reverberant room, show good correspondences to the measured values. Although the more advanced investigations would be needed for improving the accuracy of the simulation method, we could use the developed simulation method for the prediction of room acoustics.

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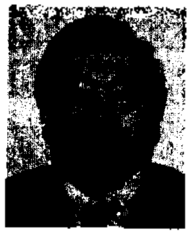
▲**Hee Won Lee** was born in Seoul, Korea, in 1956.

He received the B.S. degree in mechanical design from Seoul National University, in 1979, and M.S. degree and Ph.D. degree in mechanical engineering from the Korea Advanced Institute of Science and Technology (KAIST), in 1981 and 1988 respectively. Since 1984, he has been with the Seoul National Polytechnic University, Seoul, as an assistant professor of the department of mechanical design. His research interests include room acoustics, noise and vibration control of mechanical equipments, and application of computer technique to acoustics and machine design.

▲**Byung Ho Lee** He received the B.S. in mechanical



engineering from Seoul National University in 1950, M.S. in nuclear engineering from ISNSE operated by university of Chicago in 1958, Ph.D in physics from Imperial College of University of London in 1970. He was a professor in Seoul National University, from 1955 to 1971, and the Research Director in National Defence Research Institue (ADD) from 1971 to 1975. Since 1975, he has been a professor in the Korea Advanced Institute of Science and Technology (KAIST), delivering lectures on elasticity, vibration, acoustics, dynamics and nuclear reactor theories. He published more than 120 papers in many fields of acoustics, dynamics, material science, rocket Vibration, geo-science, nuclear science and engineering. He is now an emeritus professor of KAIST.