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Modelling of Sound Fields with Different Surface Diffusivity of Rooms

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1. INTRODUCTION

In order to investigate the acoustic quality of rooms, many acoustical criteria have been developed and presented. Among acoustic parameters the importance of sound diffusion in a concert hall is widely acknowledged. In concert halls music is considered to sound better when to arrive at the listener from many different directions and the late sound reflections are diffuse. Although it is believed that sound diffusion is important for good acoustics in an auditorium, its role has been as difficult to prove as diffusion has been difficult to measure and the role of diffusing elements on room surfaces has been difficult to quantify. Diffusion can be defined as a measure of the directional distribution of sound energy arriving at a point. Several methods have been proposed for measuring diffusion and evaluating the degree of diffusion in reverberation rooms [1,2,3] but none appear to be satisfactory for assessing auditoria.

Before 20th century sound diffusion was provided by three-dimensional molded plaster or carved ornamentation on interior surfaces, as well as by niches and coffered ceilings [4]. Beranek [5] suggested a rating scale for sound diffusion based on the irregularities of walls and ceilings. He also gave two requirements for the diffusion of sound to be good. The first one was that the reverberation time must be fairly long, because the sound will have died out after relatively few reflections if the room is not reverberant. Since sound, to be diffuse, must undergo many reflections in a room, a long reverberation time contributes to diffusion. Beranek's second requirement was that the ceiling and walls of the hall must be irregular so that the sound waves are scattered when they reflect from these surfaces.

In earlier papers Haan and Fricke [6,7] demonstrated that surface diffusivity is an important measure of acoustic quality of halls. Geometrical and acoustical data were collected from a large number of concert halls and they tried to correlate these data with an Acoustic Quality Index (AQI) based on musicians average evaluation of each hall. 53 halls were used for the analysis and 17 different geometrical parameters were investigated. They also suggested a simple measure of the surface roughness, namely the Surface Diffusivity Index (SDI) according to the degree of irregularity of the walls and ceiling as determined by visual inspection. They found that Surface Diffusivity Index (SDI) has a much higher correlation than any of the other parameters. Though there is a need to develop a more systematic classification of the surface diffusivity, this simple and rough method for quantification of surface diffusivity was sufficient to demonstrate, that this parameter seems to be the most important single parameter for the acoustical quality of concert halls [8].

Beranek et.al.[9] showed a possibility that late interaural cross-correlation, ($1\text{-}IACC_L$) at 500, 1000 and 2000Hz could be used to indicate the effectiveness of the irregularities on the walls and ceilings of concert halls. They insisted that this parameter help to create good concert hall quality.

Recently, diffusion coefficient has been discussed as a measure to quantify the degree of diffuseness in room. However, there are still some problems in measuring method and the evaluation of directivity of scattered sound and the definition of 'ideal diffusivity' concerning the size and the shape of diffusing elements has not clearly answered yet [8].

Thus, the present study is aiming to express the possibility of an criterion to measure the surface diffusivity which could be easily applied to the design and the evaluation of halls using computer simulations or field measurements. As a pilot study on the measure of surface diffusivity the present paper deals with the findings from the computer modeling with different surface diffusivity of rooms.

2. METHOD OF EVALUATING SURFACE DIFFUSIVITY

Beranek [4] stated that fine-scale diffusion on wall or ceiling surfaces scatters well high frequency sound and reduce the high-frequency sound energy in the early specular reflections. This means that the risk of strong specular reflections is caused by large flat and smooth surfaces.

As Hodgson [10] pointed out, the limit of diffuse-field should be considered to predict the reverberation time and sound pressure level of room depend on the room acoustic parameters i.e. room shape, surface absorption and reflection and fittings. The sound field is diffuse under the following two conditions;

1) The reflected sounds are come from all directions with equal intensity at any position in the room
2) The reverberant sound field is the same at every position in the room

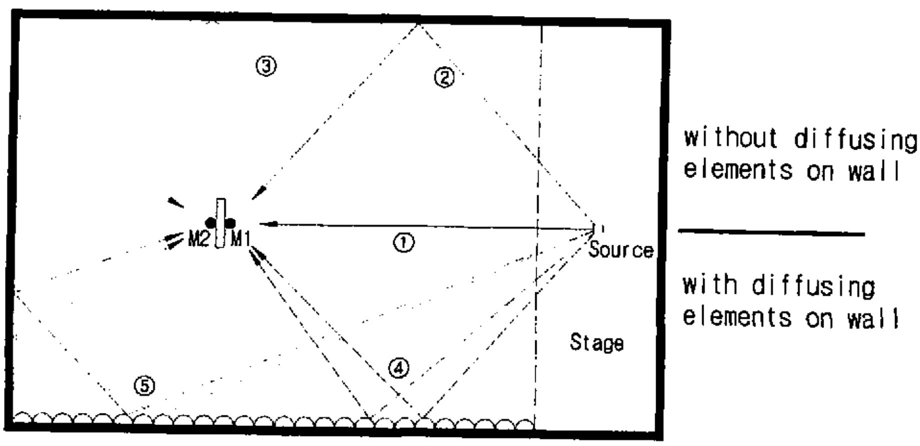
This implies that the value of any acoustic parameters can be more evenly distributed in irregular shaped rooms with non-specularly reflecting surfaces and non-uniform distribution of absorption which is normally due to the audience seated - that is the conditions of real concert hall we can easily imagine. In the room with rough surfaces and irregular walls or ceiling (i.e. high surface diffusivity) sound field gets closer to diffuse state.

The present study starts from the hypothesis that sound diffuses well in the room with high surface roughness so that reflected sound may come to the audience from more directions. It can eventually decrease the gap (difference in acoustic parameters) between seats or positions in the room.

If sound level at one position can be measured eliminating the direct sound from a sound source and early specular reflections, the amount of diffused sound could be predicted comparing it with the value of sound levels in normal condition. This could be applied to any other acoustic parameters so that we may know how much diffused sound affect the value of acoustic parameters. In this way, it can be verified that the difference of acoustic parameters at one position is depend on the surface condition of room.

The idea of measuring acoustic parameters under two different conditions was originally adopted from the Beranek' suggestion [9]. He stated that the differences in the values obtained from a cardioid microphone that is first pointed toward the forward part of the hall and then pointed toward the rear could be a useful additional measure of listener envelopment (LEV).

Furthermore, comparing value of late reflections, ignoring direct sound energy and early specular reflections, with the values which contain all the sound energy except late diffuse reflections can gives a clue to evaluate the surface diffusivity of rooms because the amount of diffuse reflection depends on the surface conditions of room. Fig.1 shows the configuration of two microphones used to capture the sound in computer simulations.



where, ① : direct sound, ② : early specular reflections, ③ : late specular reflections, ④ : early diffuse reflections, ⑤ : late diffuse reflections

Fig.1. configuration of two receiver microphones in one position.

In the hall of high surface diffusivity, microphone (M1) can captures the direct sound (i.e. most strong sound energy) and all the reflected sound including early specular reflections from stage walls and many early diffuse reflections from lateral walls while microphone (M2) can captures many late diffuse reflections from lateral and rear walls (refer to Fig. 1). In the hall of poor surface diffusivity (see upper part of Fig.1) microphone (M1) can captures the direct sound and early specular reflections while microphone (M2) can only captures few late specular reflections from rear walls.

The value of M1 is normally expected larger than the value of M2 in any cases since M2 can't capture the direct sound. If the difference of values from two microphones changes depending on the surface diffusivity, it is obvious that the diffusing elements on walls and ceiling make more diffuse sound so that M2 can get more sound energy than the energy obtained in the room with no diffusing elements.

Due to the increased diffuse condition, the value of acoustic parameters obtained from microphone (M2) can be raised. This eventually decrease the difference of values between two microphones. Meanwhile, in the halls of poor surface diffusivity, the difference between two microphones increase as the value obtained from microphone (M2) is low. Thus, it is expected that the difference of values between two microphones gets smaller depend on the surface diffusivity of room.

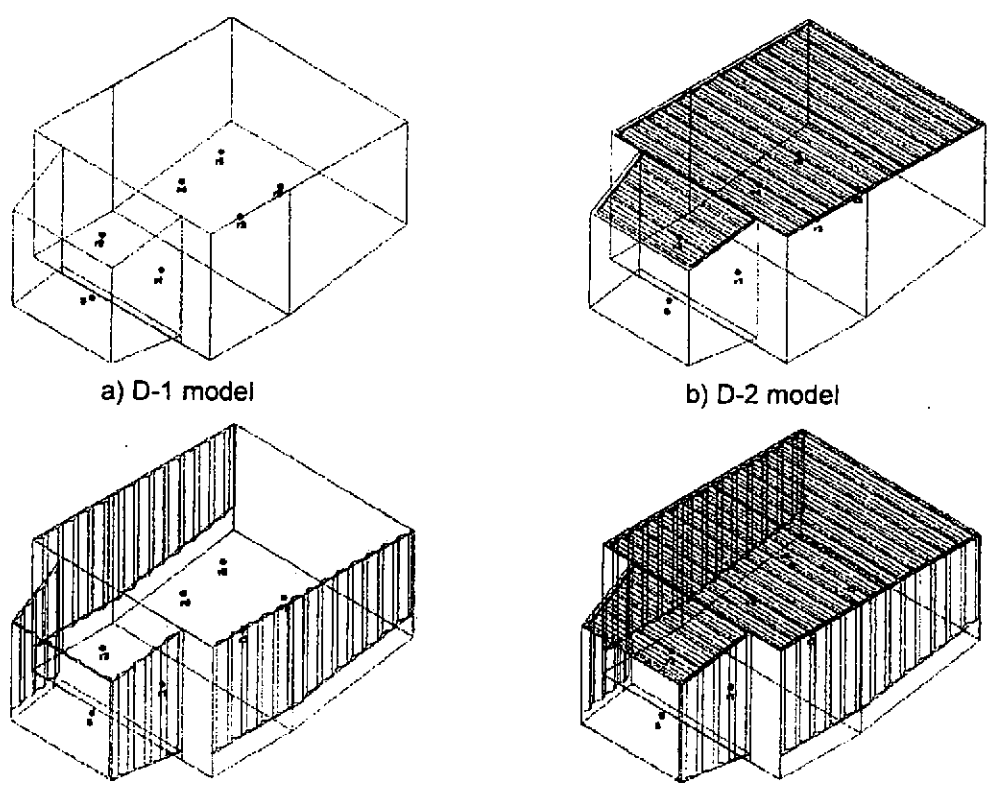
An evaluation criterion of surface diffusivity was suggested in the present work. The criterion, Δx, means the phase difference of the values of acoustic parameters between two microphones of which, the first microphone(M1) is pointed toward the stage of a hall while the other microphone(M2) is pointed toward the rear wall of the hall. The criterion, Δx, was defined as follows;

$$\Delta x = x(M1) - x(M2)$$

Where, x(M1) : value of acoustic parameters obtained from microphone facing the stage of hall.
x(M2) : value of acoustic parameters obtained from microphone facing the rear wall of hall.

3. COMPUTER MODELLING

In order to investigate the effect of surface diffusivity on the acoustics of halls computer predictions were carried out using four imaged models of a hall. The correlation between the diffusivity of interior surfaces and the acoustic measures of halls was investigated. These four imaged models have different condition of surface diffusivities. Architectural measures such as air volume, hall shape, materials used for each area of interior surfaces are same in all models except the surface diffusivity. All models have dimensions of 26 m length, 18m width and average height of 11 m. All these models were empty. At on end of the model there was a recessed stage 1.0m high from the auditorium floor. Four models used are illustrated in Fig. 2 showing three-dimensional perspective of each model.



a) D-1 model
b) D-2 model
c) D-3 model
d) D-4 model

Fig.2. Four imaged models with different surface diffusivity.

As shown in Fig. 2, each model has diffusing elements in different areas i.e. D-1 has large flat surfaces with no diffusing elements at all, and D-2 has diffusing elements on ceiling while D-3 has diffusers on lateral walls of both stage and auditorium. D-4 has most high surface diffusivity covering all the ceiling and lateral walls. D-4 model has most large area of diffused surface among four models and D-3 model has second large area of diffusing elements. Plastered board was applied to both flat surfaces and diffusing elements of ceiling and walls while floor was covered by carpet. Absorption coefficient of 0.5 was used for rear wall where absorptive materials are normally applied.

Ray-tracing program (ODEON) was used to investigate the change of acoustic parameters depending on different surface diffusivity of four imaged models. A sound source was treated as omni-directional and positioned in the center of the stage while six receiver positions were evenly distributed at a height of 1.2m above the floor (see Fig.2). Different scattering coefficients were applied to the surfaces of the model. According to the instruction of ODEON [11] scattering coefficient of 0.7 was applied to the diffused surfaces including diffusers on walls and ceiling, and scattering coefficient of 0.1 was applied to other areas including large flat surfaces without any diffusing elements or with highly absorptive materials. 2000 number of rays were traced calculating 100 reflections as the maximum limit. As the space of model is hypothetical, and the model is based on the geometric acoustics the frequency at which the prediction were made is irrelevant.

4. RESULTS

Predictions were made for acoustic measures such as reverberation time (T_{30}), early decay time (EDT), clarity index (C_{80}) at each receiver position. In order to verify the hypothesis of the present study, computer predictions were also undertaken to find how the acoustic values between two imaged receiver microphones are different depending on the surface diffusivity conditions.

Early decay time was plotted against frequency in Fig.3. It was found that D-4 model has longer early decay times at every frequency than those of any other models. This implies that strong early reflections stay longer in the hall of high surface diffusivity due to the many diffuse reflections.

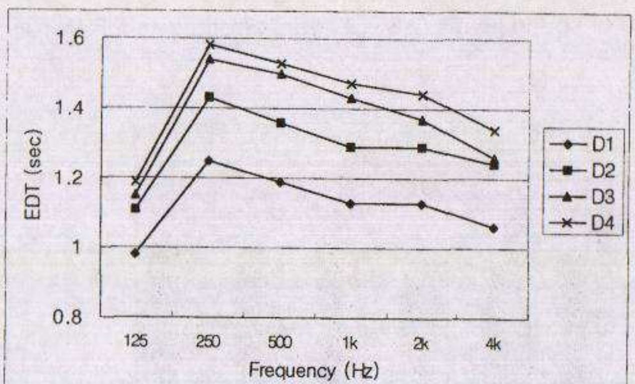


Fig.3. Comparison of early decay time versus frequency calculated for four models with the different surface diffusivity.

There is also significant difference between D-2 & D-3 models. It was shown that EDT of D-3 model is longer than that of D-2 model at most frequencies. This is because D-3 model has larger area of diffusing elements than D-2 model. It can be assumed that early decay time is influenced more effectively by the diffusing elements on lateral walls rather than by diffusers on ceiling.

The difference of sound pressure level (SPL), early decay time (EDT), clarity index (C_{80}) were calculated at each receiver position. In order to find the relation between surface diffusivity and the acoustic variation more clearly D-1 and D-4 models were only used for computer simulation. At each position of the model, two receiver points were set up around the microphone barrier (see Fig. 1). One was positioned 5 cm apart from the front of microphone barrier and the other was also positioned at 5 cm away from the back of microphone barrier facing the rear wall. The difference of acoustic measures values between two imaged receiver points was calculated averaging the values obtained from six receiver positions.

Fig. 4 shows the average difference of sound level (ΔSPL) obtained from two receiver microphones at each position of models. Fig. 4 represents that ΔSPL of D-4 is smaller than that of D-1 at most frequencies. This means that more sound reflections arrive at the receiving position, especially M2 receivers, in late sound field as well as in early sound field in the hall of high surface diffusivity.

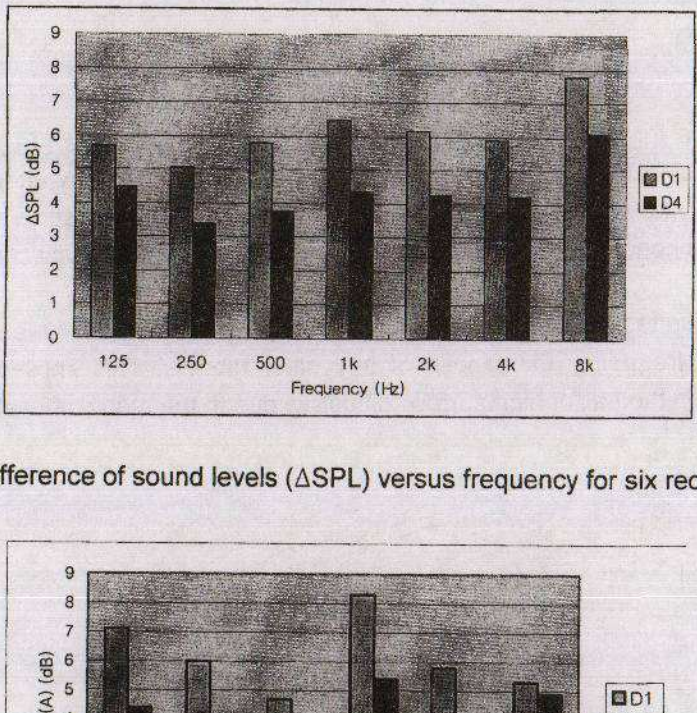


Fig.4. Average difference of sound levels (ΔSPL) versus frequency for six receiver positions.

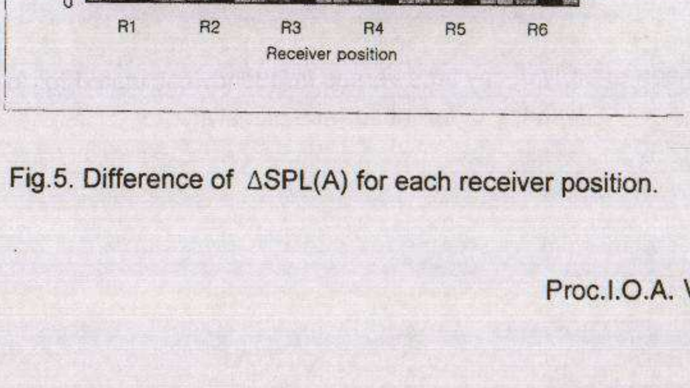


Fig.5. Difference of ΔSPL(A) for each receiver position.

Fig. 5 displays the difference of overall sound pressure level of each receiver position. It was found that ΔSPL(A) values of each position in D-1 model is larger than those in D-4. This demonstrates that low ΔSPL(A) is evenly distributed in the hall of high diffusivity regardless of the positions in the room as well as the frequency shown in Fig.4. It was also found that the deviation of ΔSPL(A) in D-4 model is much smaller than that of D-2 model.

Fig. 6 shows the average difference of clarity index (ΔC_{80}) between two microphones for each hall. The figure represents same result as shown in Fig. 4. The difference of ΔC_{80} of D-4 model is smaller than that of D-1 model.

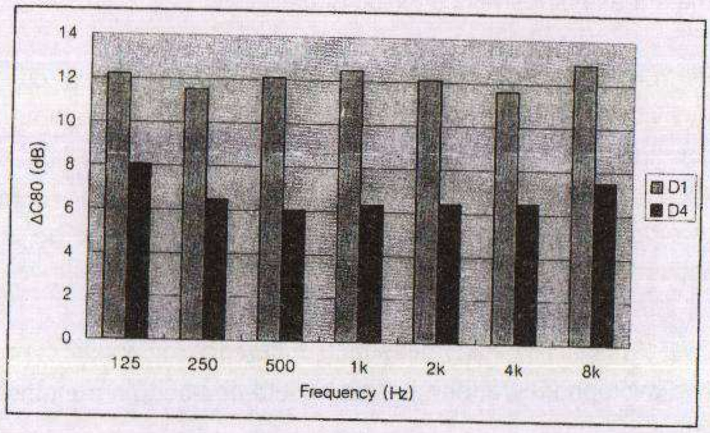


Fig.6. Average difference of clarity index (ΔC_{80}) versus frequency for six receiver positions.

Fig. 7 illustrates the average difference of early decay time (ΔEDT) between two receiver positions for each hall. On the contrary to the findings from the previous figures (Figs. 4 & 6). Fig. 7 displayed ΔEDT below 0 at all frequency bands. This means that early decay time captured at microphone (M2) is longer than that obtained from M1 in any cases. This is because microphone (M2) can only receives the late specular or diffuse reflections. The differences of EDT between two microphones in D-4 model is much smaller at most frequencies than that of D-1 model as shown in Figs. 4 & 6.

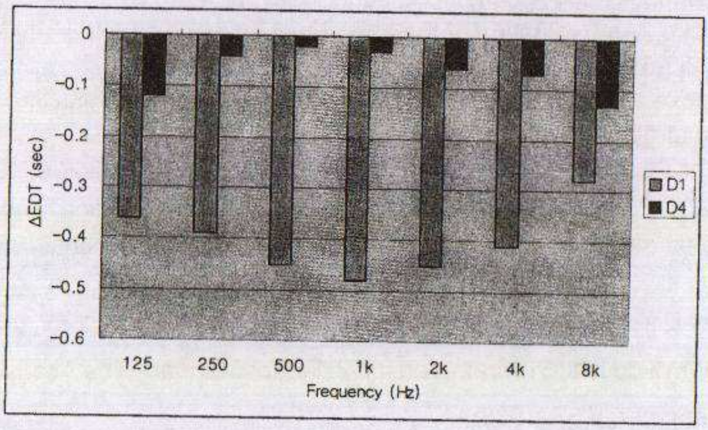


Fig.7. Average difference of early decay time (ΔEDT) versus frequency for six receiver positions.

5. DISCUSSIONS AND CONCLUSIONS

The results show that the difference of values of acoustic parameters decreases according to the increase of the interior surface diffusivity. It was found that, in the hall of high surface diffusivity i.e. halls with larger area of diffusing elements, ΔSPL, ΔC80, ΔEDT between two receiver microphones is smaller than those in the hall of low surface diffusivity. It was also found that smaller difference of acoustic values is evenly distributed in the hall of high diffusivity regardless of the positions in the room as well as the frequency. Thus, the present study demonstrates that the difference(Δx values) of acoustic parameters are low in the halls of high surface diffusivity and Δx values could be used as a criterion to measure the surface diffusivity condition of halls.

Even though the results from computer predictions have some problems in low frequencies, it is obvious that surface diffusivity makes even distribution of sound energy throughout the area of room. There is a need to confirm the validity of the application of Δx to other acoustic parameters and the knowledge on how much differences of acoustic values are required to obtain the sufficient diffuseness and surface diffusivity of room. Also, similar works are need to be undertaken in real halls which have different surface diffusivity.

Finally, this paper shows a possibility that measuring difference of acoustic parameters i.e. Δx values, obtained from two microphones at one position could be used as a method to evaluate the surface diffusivity of room.

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