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ROOM ACOUSTICS.
MUSICAL ACOUSTICS

Effect of Diffusive and Nondiffusive Surfaces Combinations on Sound Diffusion[1]

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Abstract—One of room acoustic goals, especially in small to medium rooms, is sound diffusion in low frequencies, which have been the subject of lots of researches. Sound diffusion is a very important consideration in acoustics because it minimizes the coherent reflections that cause problems. It also tends to make an enclosed space sound larger than it is. Diffusion is an excellent alternative or complement to sound absorption in acoustic treatment because it doesn't really remove much energy, which means it can be used to effectively reduce reflections while still leaving an ambient or live sounding space. Distribution of diffusive and nondiffusive surfaces on room walls affect sound diffusion in room, but the amount, combination, and location of these surfaces are still the matter of question. This paper investigates effects of these issues on room acoustic frequency response in different parts of the room with different source-receiver locations. Room acoustic model based on wave method is used (implemented) which is very accurate and convenient for low frequencies in such rooms. Different distributions of acoustic surfaces on room walls have been introduced to the model and room frequency response results are calculated. For the purpose of comparison, some measurements results are presented. Finally for more smooth frequency response in small and medium rooms, some suggestions are made.

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1. INTRODUCTION

Sound propagation in a room is combination of direct and reflected sound from surfaces and boundaries in the room. Since reflected sound waves have significant effect on what we hear and perceive, so knowing how to treat and manipulate these reflections is one of the main subjects in room acoustics.

Diffuse reflections have an important role to play in the acoustics of rooms as they can improve the uniformity of a reverberant field and reduce the risk of areas of poor acoustics within a room [1]. They also create a softer sound [2] and reduce the risk of undesirable echoes by improving the smoothness of the reverberant decay. Several researches signify the importance of accounting for surface diffusion in the modeling of enclosures [3–5]. Since Sabine founded architectural acoustics, most of room acoustic researches have been devoted to studying how absorption affects sound. In contrast, significant scientific knowledge on the role of diffusive surfaces has only been developed much more recently [6]. Over these years significant research on methods to design, predict, measure, and quantify sound diffusive surfaces has resulted in a growing body of information on this topic [7, 8].

Acoustic aberrations such as image shift and colouration can be removed by using diffusers; however, they are still in their formative years [9]. There is enough evidence to show that diffusers can be effective in treating these defects, and a few scientific studies have demonstrated this [10–12]. So why not just cover the whole space with diffusive surfaces? Proper amounts of the right diffusion are credited with contributing to spectacular acoustics; too much of the "wrong" diffusion is blamed for ruining one space, while the lack of scattering in another is held responsible for a poor acoustic. Data about the effect of large scale diffusion on the acoustic is very little. There is a fear among some that this would remove spatial cues that are present in early reflections, leading to an imprecise sound, but no one has measured such effects [13]. Consequently, there is a need for more studies to investigate how much diffusion is needed and where it should be applied.

In this paper surface diffusion effects on room frequency response are studied. To investigate the optimum amount of diffusors used in a room to have more flat frequency response, various combinations of diffusive and non-diffusive surfaces are considered. Since the location of source and receiver have direct impact on the result, this paper try to take that into consideration by applying different source-receiver locations to the model. This paper studies the subject on two different rooms, a pretty small and a medium sized room. Room acoustics have been modeled using Boundary Element Method, which is a very accurate wave based

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model. For validation of the results some measurements have been done.

The paper content is organized as following. At the beginning some definitions about modeling technique and how diffusive surfaces are implemented in the model is explained; then different cases which are applied to the model are presented, including room dimensions, source-receiver locations, and kind of surfaces and their positions. Finally modeling and measurement results are presented.

2. THEORY

Computer models of room acoustics have an advantage over other design methods in that they are cost effective. They also allow considerable flexibility in the design process, where changes in materials or geometry can be tried and tested relatively quickly compared to, for instance, scale modeling techniques.

This paper implemented Boundary Element Method (BEM) to solve interior acoustics of rooms. The BEM only requires the discretisation of the boundary walls and hence requires much less elements than the FEM. The Helmholtz-Kirchhoff integral equation forms the core of many of the prediction models used, including BEM. This integral equation formulates the pressure at a point, as a combination of the pressure direct from the sources, and a surface integral of the pressure and its derivative over the reflecting surfaces. The single frequency form of the integral could be found in [14–16]. The boundary integral formulation is theoretically exact and it has been proved to be a highly accurate method in many acoustic problems. However the application of these numerical methods is only advisable in practice at frequencies up to a few hundred Hz for a typical size listening room. They are generally too computationally demanding to use routinely in practice for room acoustics [17].

2.1. Diffusive Surface Modeling

Since sound can be described by its phase and amplitude, it is possible to modify the directionality of scattered sound by modifying the phase and amplitude of the scattered wavelets. Change of phase and angle of reflected wave causes diffuse reflection and that's directly related to surface admittance value and its variations. Therefore to apply the diffusive surface on any part of room's wall in the model, the changes of surface admittance can be considered, when sound is scattered from a surface. So the model applies constant values for normalized admittance value for nondiffusive parts, while changing values are considered for diffusive parts. Since the BEM model uses boundary elements to less than 1/6 wavelength, it assumes a different value for normalized admittance value of that element which differs from neighboring elements. The admittance value assignment for each element on any diffusive surface is stochastic. Since admittance of a diffusive surface is a complex number, to apply diffusive surface to the model, its admittance values are randomized between 0.007 and (0.2, 0.2j); 0.007 approximately corresponds to a random incidence absorption coefficient of 0.056 and (0.2, 0.2j) corresponds to an estimated random incidence absorption coefficient of about 0.7. This approach might be prone to error, but the results could lead us to a better understanding and perception of the questions mentioned in introduction. Admittance values of all reflecting, pretty rigid, or nondiffusive surfaces are real and assumed to be 0.009 corresponds to an estimated random incidence absorption coefficient of about 0.07. In whole text, all mentioned admittance values are normalized. Omitting these assumptions and modelling real diffusors is the next phase of this study. Another important matter which must be pointed out is change of diffusivity behavior of surfaces at different frequencies. Hodgson [18] noted that diffusion coefficients of surfaces should be frequency dependent. By repeating calculations with different assigned admittance values in BEM model the effect of changes at different frequencies could be assessed.

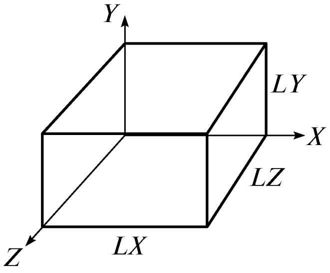

Fig. 1. 3D of rooms modeled according to *xyz* coordinates.

3. ROOM ACOUSTIC MODELING

In this study BEM has been used to model acoustic of the room. Element dimension is set below $\lambda/6$, where λ is the wavelength of the acoustic wave, to keep the numerical errors small, at corners elements are considered smaller. Two rectangular rooms with different combinations of surfaces were modeled. The 3D vision of the rooms is shown in Fig. 1. It is obvious from the figure and *xyz* coordination, that the *xz* planes located at $y = 0$ and $y = LY$ are floor and roof of the room, respectively.

Two different rooms have been used for the modeling. In Room 1 the dimensions are (4 m × 2.8 m × 3 m), according to *xyz* coordination, and three different source-receiver locations are considered (see Table 1).

For better understanding of the obtained result and to study the effect of the suggested combination of diffusive and nondiffusive surfaces for a medium to large room frequency response, room 2 is considered. Room 2's dimensions are (6.9 m × 2.8 m × 4.6 m)

Table 1. Source-receiver locations for room

Source-receiver	Source location	Receiver location
First	(0.2, 1, 0.2)	(1, 1.5, 1)
Second	(2, 1, 0.5)	(2, 1.5, 2.5)
Third	(2, 1, 0.5)	(0.2, 1.5, 2.8)

Table 2. Source-receiver locations for room

Source-receiver	Source location	Receiver location
First	(0.3, 1, 0.3)	(3, 1.5, 2)
Second	(3.4, 1, 0.5)	(3.4, 1.5, 3.5)
Third	(3.4, 1, 0.5)	(0.3, 1.5, 4.3)

according to *xyz* coordination. Again three different source-receiver locations are assumed as seen on Table 2. In all cases in two rooms, source is omnidirectional with the same power.

3.1. The Structure of the Research

To study the effects of different combination of diffusive and reflective surfaces, first of all two categorized cases are considered. In these two categories, different kinds of surfaces are used just on side walls and just on roof. Predicted results for different cases of these categories for various source-receiver positions (according to Tables 1 and 2) are shown and discussed. After discussion of the results and according to them, hybrid category which is combinations of best cases in two categories is introduced to the model. To show the flatness of the frequency response, the results in all cases are presented as mean and standard deviation in assigned tables, whenever is needed results are shown as figures. In both rooms, the simple room case is considered. In this case all room's surfaces are assumed to be reflecting and their admittance value is 0.009. Since room has several close spacing modes below 100 Hz, frequency response behavior in this range would be a good reference. Therefore both categories and simple rooms are simulated for 20–100 Hz frequency band at 1 Hz interval.

3.1.1. First category. This category is about combinations of diffusive and nondiffusive surfaces only on side walls; roof and floor remain completely nondiffusive. So each side wall is divided to three or five parts either vertical or horizontal, with different combination of surfaces on them; then the room frequency response for different source-receiver positions are calculated (using the model). Descriptions of different cases are shown in Fig. 2. Since in each case, all four side walls are similar, the pattern of one wall is shown. In the first category eight different cases are considered, figures (a) to (h) in Fig. 2 show cases one to eight, respectively.

Result of applying all these cases to the model is shown on Table 3. In all following tables M stands for mean of sound pressure levels, and SD refers to standard deviations (in percent) of sound pressure levels.

It is obvious from Table 3 that case two, has best results among all, which is a more flat frequency response for different source-receiver positions.

3.1.2. Second category. In the second category only roof is considered to have diffusive and nondiffusive surfaces while other walls remain pretty rigid. The roof is divided to three, five or twelve parts in different directions; various combinations of mentioned surfaces are considered, and like the former category, room responses for different source-receiver locations are calculated. In this category nine different cases are considered. Descriptions of different cases (roof patterns) are shown in Fig. 2, figures (a) to (i) show cases one to nine, respectively.

The results of second category are shown on Table 4. It is obvious from Table 4 that case one, has the best results among all.

3.1.3. Hybrid case. According to the two former categories' results, this case is concluded. Now the

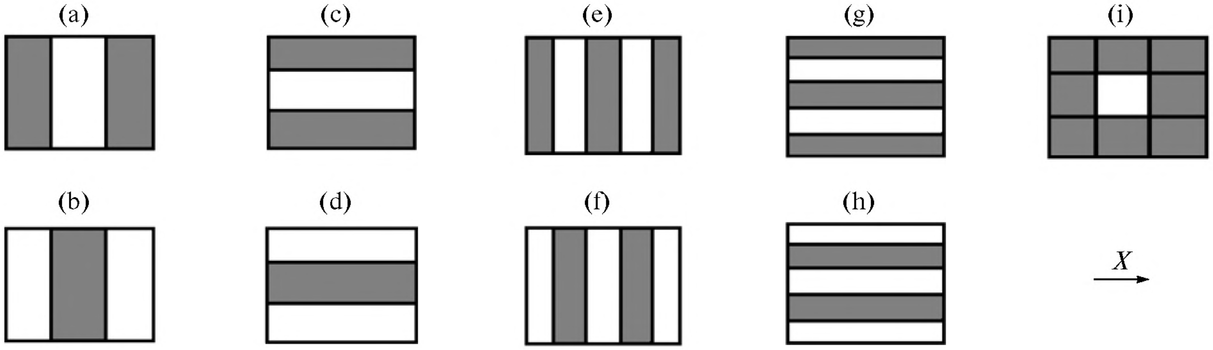

Fig. 2. Different cases for first and second categories; (a)–(i) figures have shown cases one to nine, respectively. Divisions in all patterns are according to *x* axis. Dark and white segments are representing non-diffusive and reflecting surfaces, respectively. The *x* direction is shown for reference.

Table 3. Comparison of results for different cases of first category for three source-receiver locations in room 1

	First source-receiver		Second source-receiver		Third source-receiver	
	M	SD	M	SD	M	SD
Case one	75.2	10.0	79.6	3.9	80.9	5.1
Case two	80.3	5.4	80.6	4.6	81.7	5.1
Case three	75.2	9.9	81.2	5.2	79.9	6.3
Case four	75.5	10.2	81.5	5.7	79.7	7.3
Case five	81.3	8.3	81.6	6.0	80.6	7.6
Case six	81.3	8.9	82.0	6.5	80.4	8.5
Case seven	75.2	10.0	80.9	5.2	79.8	6.2
Case eight	75.5	10.2	81.5	5.7	79.7	7.3
Simple room	81.2	9.2	79.4	10.5	82.9	7.4

Table 4. Comparison of the results for different cases of second category for three source-receiver locations in room 1

	First source-receiver		Second source-receiver		Third source-receiver	
	M	SD	M	SD	M	SD
Case one	79.3	8.3	82.1	6.5	82.5	6.3
Case two	79.4	8.4	82.2	6.6	82.9	6.4
Case three	78.9	10.0	82.7	7.0	81.3	8.6
Case four	79.1	10.2	82.9	7.2	81.2	9.1
Case five	78.8	9.6	82.0	6.7	80.5	8.8
Case six	78.8	9.8	82.2	7.0	80.7	9.1
Case seven	78.6	10.4	81.8	6.8	81.2	8.4
Case eight	78.6	10.2	81.8	6.8	81.2	8.3
Case nine	79.6	9.4	82.4	6.9	81.0	8.3

Table 5. Comparison of the results for hybrid and fully diffusive case for three source-receiver locations in room 1

	First source-receiver		Second source-receiver		Third source-receiver	
	M	SD	M	SD	M	SD
Hybrid case (20–100 Hz)	80.2	4.9	79.4	4.2	81.1	5.0
Hybrid case (1/3 octave)	83.8	7.7	81.3	4.9	82.9	5.0
Fully diffusive (20–100 Hz)	78.8	7.2	80.4	5.1	80.4	6.1
Fully diffusive (1/3 octave)	78.4	8.4	80.0	4.6	80.5	5.1

combination of best results (case two of first category and case one of second category) is introduced to the model. The results for 20–100 Hz band at 1 Hz interval are shown in first row of Table 5; second row contains results for 1/3 octave band for the range of 12.5–315 Hz.

For the purpose of comparison, another case has been considered. In this case all side walls and roof of the room are covered with diffusive surfaces. This case is the first solution come cross the mind having no concern about cost and appearance to make frequency response flat. Third and forth rows of Table 5 show the results.

As can be easily seen, the hybrid case is much better than fully diffusive one. In this case some parts of side walls and roof are covering with diffusive surfaces; side walls are covered according to case 2 of first category and roof is covered according to case 1 of second category. Hybrid case will result more flat frequency response than covering whole side walls and roof with such surfaces. It completely confirms the cost and appearance issues as well.

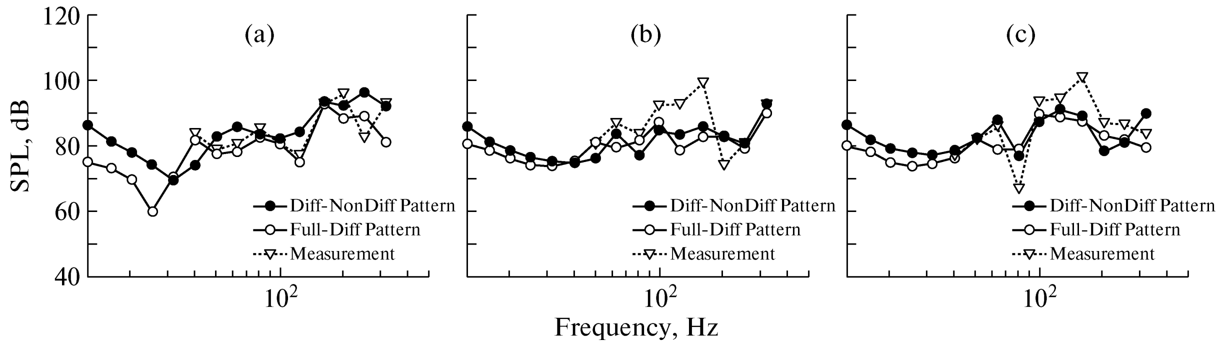

Fig. 3. Comparison of hybrid case, fully diffusive case, and measurement for three source-receiver positions in room 1, (a), (b), and (c) respectively.

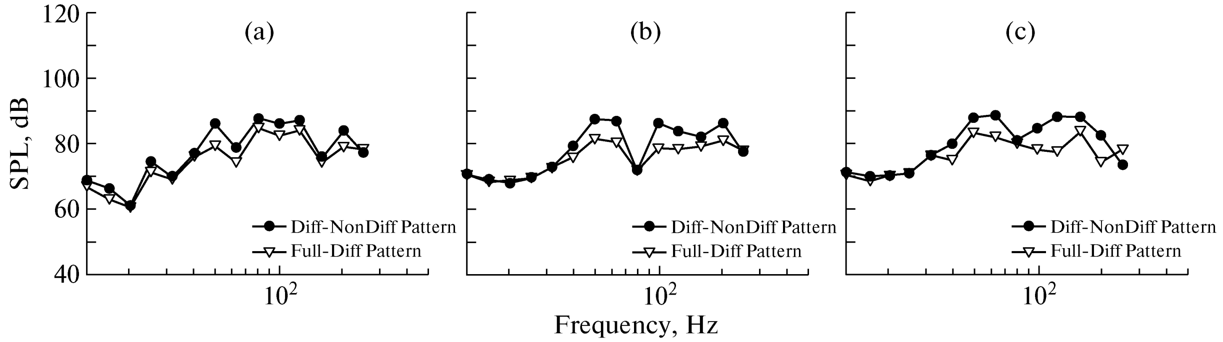

Fig. 4. Comparison of hybrid case and fully diffusive case for three source-receiver positions in room 2, (a), (b), and (c) respectively.

To provide some basic validation of the accuracy of the numerical models, sound field measurements were carried out in room 1 with pretty rigid walls for 1/3 octave band which is shown in Fig. 3. The sound source is a loudspeaker. The sound pressure levels were calculated to a source strength that gives a free field sound pressure amplitude of $1/4\pi$ at 1 m from the source. Because of the discrepancy at frequencies below 40 Hz is due to measurement errors caused by the low signal strength of the loudspeaker at such low frequencies, the measurement results are shown above that frequency. For room acoustics at high frequencies one may not be interested in the details at single frequency but the level in 1/3 or full octave bands. In Fig. 2, the 1/3 octave band results for the hybrid case, the case of fully diffusive side walls and roof, and the measurement are shown; the privilege of hybrid case is obvious.

To investigate the validation of the obtained result for other rooms, room 2 is considered. The result of hybrid and fully diffusive case for 1/3 octave band predicted by the BEM model are shown on Table 6 and Fig. 4.

As one could anticipate, the hybrid case for room 2 does not result more flat frequency response than fully diffusive one. But we can not cover all surfaces with diffuser, it's not nor economic neither beautiful. So we have to find the optimum amount of diffusors needed to obtain a more flat and acceptable response for this room; this issue is the subject of more research.

The results would definitely improve if other walls get absorptive but that would weaken important parts

Table 6. Comparison of the results for hybrid and fully diffusive case for three source-receiver locations in room 2

	First source-receiver		Second source-receiver		Third source-receiver	
	M	SD	M	SD	M	SD
Simple room	78.3	13.3	78.4	10.0	82.5	9.5
Hybrid case (1/3 octave)	76.8	8.3	78.2	7.4	79.5	7.4
Fully diffusive (1/3 octave)	74.3	7.4	75.4	4.9	76.3	5.0

of the sound especially in low frequencies, however it is not considered in this research.

4. CONCLUSIONS

The role of diffuse reflection in room acoustics has been of interest for many years. If the absorption is not desired, diffusor designs and arrangements can be altered to minimize absorption and make a significant improvement in reducing the unevenness in frequency response produced by the modes. The research was about surface diffusivity and its influence on sound field in small to medium rooms. In these rooms at low frequencies, the existence of wave induced room modes is well known and wave based computer models are necessary for the prediction of the sound field. For room acoustic modeling a wave based method which its accuracy is well known—Boundary Element method—was chosen. Two different rooms (pretty small and medium) were modeled. To model surface diffusion, stochastic admittance values for surfaces were implemented. Different cases of surface diffusion and admittance value distributions have been studied. However, considerable research remains. BEM simulations have explored how diffusive surfaces might behave when arranged in particular order. The simulations have confirmed the good performance of some combinations of diffusive and nondiffusive surfaces in room 1, but have shown weaknesses in their performance for another room, that indicate avenues for further research. There are also some challenges regarding the use of some absorption in combination of diffusive surfaces, which require further research. Another important issue, which significantly enhances the accuracy of the results is simulation of different kind of diffusers and apply them to our model. Using BEM model and taking advantage of its high accuracy need, in particular, overcoming the computation burden of the program especially when room dimensions and frequency increase.

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