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On the influence of sound scattering in room acoustic modelling

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ABSTRACT

In general, the sound field inside a closed space is influenced by several parameters, such as the room shape, volume, amount and location of sound absorption, and the scattering of the surfaces. In geometrical room acoustic computer models, the scattering coefficient (s) is usually employed to considerer the diffusivity of surfaces. It is therefore important to understand how the introduction of dispersion can affect acoustic parameters of a room.

This paper focus on addressing the impact of the introduction of sound dispersion in room acoustic modelling. In this theoretical study, an auditorium with a shoe-box shape is modelled using ray tracing approach. This geometric configuration is recognized by the parallel side walls, which play a key role in the generation of multiple reflections. Different factors, such as the average sound absorption of the space and volume changes in the geometry are addressed. The amount of diffuse reflections at each room boundary is defined by assigning a value s to the surface. Changes in the room sound field, in particular, in the reverberation time, are analyzed.

Keywords: *room acoustics, scattering, modeling, shoe box,*

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1. INTRODUCTION

When a sound source emits a sound inside a room, part of the energy is absorbed, and the remaining is reflected by the different surfaces, giving rise to multiple reflections. Understanding these interaction processes between the sound and the environment is essential for a detailed analysis of sound dispersion and for the development of effective acoustic conditioning strategies [1,2,3].

Several researchers have analyzed the contribution of dispersion in the acoustic behavior of a closed environment. According to the study by Lam [4], the dispersion coefficient has a direct impact on the reverberation time, especially at low frequencies and in larger auditoriums. The study by Torres et al. [5] explored the perception of changes in dispersion at different frequencies and position of listeners, having verified, through auditory tests, that listeners close to the diffuser surfaces are more sensitive to changes in diffusion.

In the analysis conducted by Wang and Rathsam [6], the sensitivity of the acoustic models, carried out by means of computer simulation, with regards to the variations in the dispersion coefficients was quantified using the concept of JND (Just Noticeable Difference), in relation to some acoustic parameters, which were the initial decay time (EDT), reverberation time (RT), clarity (C80) and initial lateral energy fraction (LF). The authors found that the parameter most affected by the variation of the dispersion coefficient of the surfaces is the space reverberation time. Another point perceived in this analysis is that receivers located closer to the wall are more sensitive to changes in this coefficient.

Taking into account the above, it is important to understand the influence that the introduction of sound dispersion can have on the acoustic parameters of a room, aiming to find more insight on the insertion of solutions that provide scattering. In this work, it is intended to evaluate the impact of the introduction of sound scattering on surfaces by means of numerical modeling, using the ray tracing method.

For this purpose, an auditorium with a shoe-box shape is used, since this geometry is characterized by parallel surfaces that have a preponderant role in the generation of multiple reflections, leading to flutter echoes. The diffusivity generated by each surface is considered by allocating different scattering coefficients (SC). Changes in the sound field are analyzed by evaluating the reverberation time. Two scenarios of average sound absorption of the environment are analyzed, one assumed more reverberant and one more absorbent. The influence of the volume of the space is also evaluated.

2. DESCRIPTION OF THE SHOE-BOX AUDITORIUM

The geometry of the reference auditorium used in all analyses has the following dimensions (see Figure 1): width of 14 meters, length of 23 meters and height of 12 meters, leading to a volume of 3864 m^3. This closed environment is composed of six main surfaces and, in certain cases, the side walls will be divided in half, to enable the introduction of absorption. For each case study, these surfaces will present specific values of sound absorption and dispersion, adapted to the conditions analyzed.

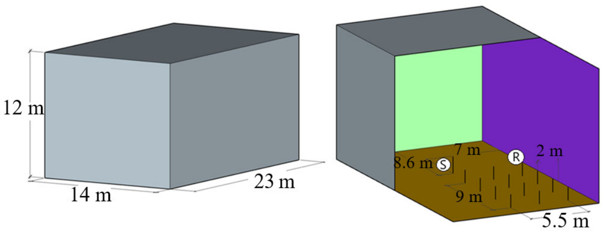

Figure 1 Dimensions of the shoe-box closed space considered as reference, with S being the location of the sound source and R corresponding to the receivers.

All the configurations analyzed have in common the fact that they are based on the volume and stage/audience ratio of a generic auditorium. Related to the analysis of the results, sound dispersion coefficients of specific surfaces are considered constant in frequency and vary in amplitude, ranging from 0.1 to 0.99, for a better understanding of their impact on the reverberation time. As for the sound absorption coefficients they were kept constant in frequency and in the following sections the corresponding amplitudes are defined according to each scenario.

3. METHODOLOGY

The numerical simulations were performed using a ray tracing code developed in Matlab, which used around 25000 rays during the calculation and an Impulse Response (IR) maximum length of 4.5 s. This method uses a large number of particles (rays) emitted by an omnidirectional sound source. The rays travel through the room, losing energy in each reflection according to the absorption coefficient of the surfaces [7]. Using this computational method, it is possible to calculate, at different locations in the room, several objective acoustic parameters, such as, reverberation time (RT), sound pressure level (SPL), Definition (D50), Clarity (C80), Speech Transmission Index (STI), and Strength (G). In this paper, focus will be given to the analysis of the reverberation time (T_{30}) and on the corresponding Just Noticeable Differences (JND).

4. REVERBERANT SCENARIO

In the first analysed setup, two situations are considered, as illustrated in Figure 2. Case A has a single sound absorbent surface, with an absorption coefficient of 0.7, located on the floor, whereas, case B has all reflective surfaces with an absorption coefficient corresponding to 0.1. The values of the sound absorption coefficient were kept constant at all frequencies, and the sound dispersion coefficients of all surfaces varied, with seven simulations conducted for each case, with increasing values of s, from 0.1 to 0.99. Case A has an average absorption coefficient of 0.23, while case B has a value of 0.1.

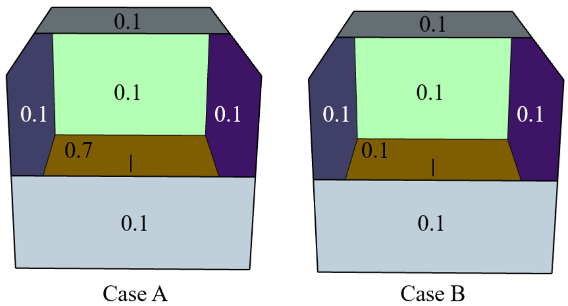

Figure 2 Reverberant setup, where the sound absorption coefficients of the different surfaces are defined.

The values obtained for the reverberation time (T_{30}) in both cases are shown in Figure 3 a). It is observed that, in case A, the increase in the dispersion coefficient (s) allows the progressive reduction of the reverberation time until it stabilizes at lower values for s equal to 0.7. This case A, with large vertical reflective and parallel surfaces, combined with a single absorbent surface on the floor, creates an environment in which sound energy is predominantly reflected between the walls and ceiling, some of which are directed to the floor. In these conditions, the introduction of sound diffusion on the reflective surfaces allow for reflected sound to be oriented towards the absorbent floor, therefore allowing for a reduction on T_{30}. This result demonstrates the significant impact of sound dispersion on the acoustic control of closed environments with mirrored reflective surfaces, where there is some absorption. This behavior is in line with the conclusion of Wang and Rathsam [6], who identified that the presence of large mirrored reflecting areas increases the sensitivity of the sound field to changes in dispersion coefficients, if there is any absorption.

In case B, with all reflective surfaces and a uniform sound absorption coefficient of only 0.1, the reverberation time remains high, even with the increase in the sound dispersion coefficient. This is because the absence of absorbent surfaces limits the efficiency of sound dispersion in the redistribution of sound energy. Although the sound dispersion coefficient increases the amount of diffuse reflections, the sound field is still dominated by specular reflections and the energy is not redirected to surfaces that could dissipate it. This result suggests that, in closed environments dominated by parallel reflective surfaces, the introduction of sound diffusers needs to be combined with absorbent surfaces so as to be able to adjust T_{30} parameter.

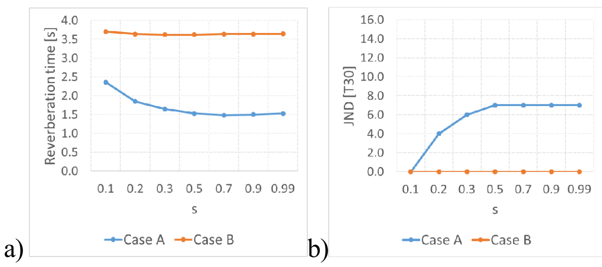

Figure 3 Graphs corresponding to the simulation of the reverberant scenario, where a) corresponds to the reverberation time and b) to #JND [T_{30}].

Regarding the analysis of #JND [T_{30}], displayed in Figure 3 b), the result for case A, where the floor is absorbent, shows the impact of scattering on the reverberation time and the just noticeable differences are high. However, in case B, where all surfaces are reflective, the change in sound diffusion has no perceptible influence on reverberation time, with a small #JND evolution.

5. ABSORBING SCENARIO

In the sound absorbent scenario, different configurations were considered (see Figure 4), in order to evaluate the impact of the location of the sound absorbent surfaces on the reverberation time (T_{30}).

Table 1 shows the average sound absorption coefficients of all the cases analyzed. Case A represents the most absorbent configuration, with a constant sound absorption coefficient of 0.7 on all surfaces. Case B, with an average sound absorption value of 0.44, considers the side walls and the floor as absorbent surfaces. Cases C and D have intermediate mean absorption values, respectively of 0.40 and 0.33, in which the lateral wall was divided into sections with different sound absorption coefficients. Finally, case E has the lowest average sound absorption of 0.29, where only the floor and the back wall are absorbent, while the other surfaces remain reflective. These variations between the cases allow a comparative analysis of the influence of the location and distribution of the sound absorbent surfaces on the acoustic performance of the closed environment.

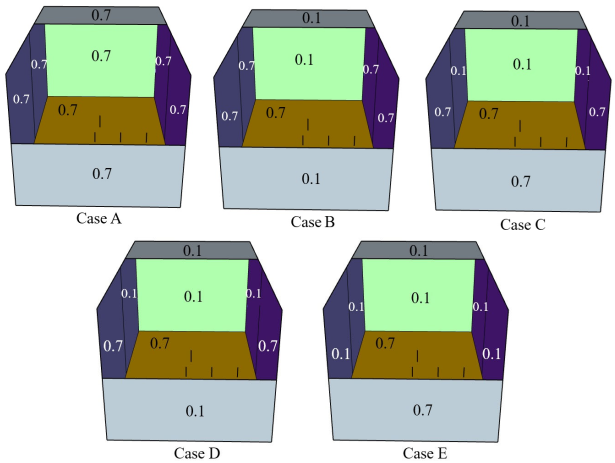

Figure 4 Absorbing scenario and sound absorbent surfaces configuration.

Table 1 Average sound absorption coefficients of the different settings.

Configurations	Case A	Case B	Case C	Case D	Case E
Average absorption (αmed)	0.70	0.44	0.40	0.33	0.29

Regarding the five cases analyzed, Figure 5 a) presents the reverberation times as a function of the different values of the dispersion coefficient. Notice that this coefficient was allocated with the same value on all surfaces (increasing from 0.1 to 0.99).

Case A, with all surfaces having a high absorption coefficient (0.7), exhibits the shortest reverberation time of all the scenarios analyzed and is not affected by the increase in diffusion. This behavior can be explained by the high average sound absorption coefficient, which allows for the first reflections to be immediately absorbed. In spaces with higher average sound absorption, as in this case, the effects of dispersion will therefore not be perceived, as most of the reflected sound energy is immediately absorbed.

In the remaining cases, the reverberation time progressively decreases as the s-coefficient increases. This is because the average sound absorption coefficient of these cases is lower than in Case A, allowing for the reflected energy to remain in the closed environment for a longer time and, therefore, to be more sensitive to sound diffusion. If we compare Cases B and C, with an approximate average sound absorption coefficient, we notice that, for the primer, there is a more significant reduction in the T_{30} with the increase of the scattering coefficient. In this case (B), the front and back walls are both reflective generating floating reflections that increase the reverberation time. With the introduction of higher sound diffusion in the surfaces, the reflections are redirected to the absorbent surfaces, generating a decrease in reverberation time. However, in case C, the presence of sound absorption on the back wall, allows for the flutter echoes to be avoided, therefore a low influence on T_{30} is provided by sound diffusion.

Case D, although with less sound absorption, also shows a significant reduction in T_{30} with the increase of the scattering coefficient. Here, also, the front and back walls are reflective and parallel, thus generating floating reflections, and therefore the introduction of diffusion redirects the sound to the absorbent surfaces.

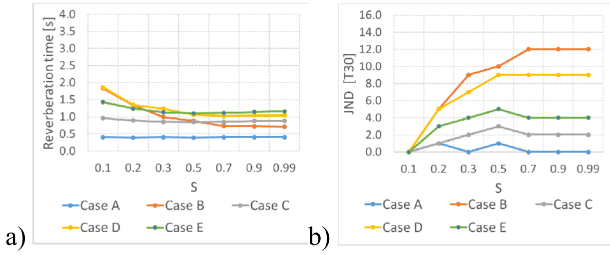

Figure 5 Graphs corresponding to the simulation of the absorbing scenario, where a) corresponds to the reverberation time, and b) to the #JND [T_{30}] analysis.

Case E, with the lowest average sound absorption, provides a reduction in T_{30} with the increase of diffusion because still displays reflective lateral walls in the area where the receivers are located, providing therefore floating echoes which are removed with insertion of diffusion.

From the analysis of the #JND for these scenarios, case A presents the lowest #JND values, remaining practically constant and with values less than or equal to 1 for all scattering coefficients. In cases C and E, the #JND reaches the highest value at s=0.5 and stabilizes above 0.7. This suggests that increased diffusion initially brings noticeable variation in T_{30}, but this perception stabilizes with additional diffusion. On the other hand, in cases B and D, providing parallel reflective walls, the #JND values reach the highest levels, especially for case B. These high values indicate that the introduction of sound diffusion generates a change in the reverberation time which will be strongly perceived. In cases with sound absorption properly distributed (cases A, E and cases C), sound diffusion generates lower noticeable changes in T_{30}.

6. SCENARIO WITH VOLUMETRIC CHANGE

Analyzing scenarios related to parallelepiped rooms, with volumetric changes, makes it possible to investigate the interaction between the volume of the space and the sound dispersion coefficients. When the volume of the space increases and the average sound absorption coefficient is kept constant, it is expected that T_{30} will increase, however, the impact of the sound dispersion coefficient on this parameter is not clear.

For this investigation, only the absorbing scenario will be considered. The analyzed configurations are shown in Figure 6 and the respective values of the average sound absorption coefficients and volumes are presented in

Table 2. Regarding the dimensional proportions considered, the V.A case, with a volume of 3862 m^3, is the reference case. The V.B case, with a volume of 2252 m^3, was obtained from case V. A, by reducing only the ceiling height by 5 m. This dimension was chosen because it has the shortest length among all. The V.C geometry corresponds to considering half the dimensions of the V.A case, providing a volume of 482 m^3. And, finally, the V.D case was analyzed, with a volume of 13036 m^3, which corresponds to considering 1.5 times the dimensions of the V.A case. In all scenarios, the average absorption coefficient and their distribution along the surfaces remained practically constant.

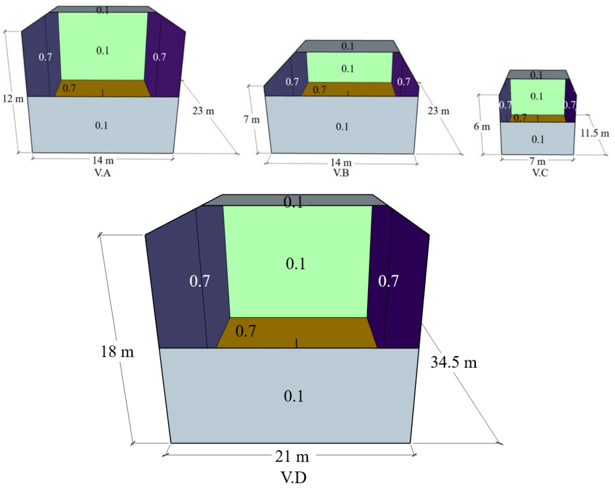

Figure 6 Scenario with volumetric change.

Table 2 Average sound absorption coefficient and volume of the scenario with volumetric change.

Configurations	Case V.A	Case V.B	Case V.C	Case V.D
Average absorption (αmed)	0.44	0.43	0.44	0.44
Volume (m^3)	3862	2252	482	13036

As shown in Figure 7 a), the reverberation time graph shows a trend towards the reduction of this indicator, as the sound dispersion coefficient increases, and this trend is similar in all cases. Cases V.A and V.B have intermediate reverberation times, however, V.B case has a slightly smaller T_{30} than V.A, probably due to the decrease in volume. The V.C case exhibits the lowest volume, which promotes a fast dissipation of sound energy, resulting in the lowest T_{30}. According to the study by Shtrepi et. al. [8], the effect of sound dispersion becomes more evident as the volume of the room increases, since the sound energy travels longer trajectories before being absorbed, however this behavior is not here completely perceived in case V.D.

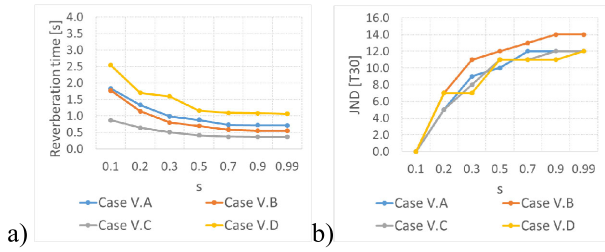

Figure 7 Graphs corresponding to the simulation of the scenario with volumetric change, where a) corresponds to the reverberation time, and b) to the #JND [T_{30}].

As for #JND results (Figure 7 b), they increase in a similar way for cases in which there is proportional change in the volume, as a function of the dispersion coefficient. The V.B case is the one that stands out with the highest #JND values, showing that this configuration is the most sensitive to the perception of changes in reverberation time. Probably the reduction of the ceiling height generates a greater intensification of flutter echoes and if coefficient dispersion is introduced, it will generate a more effective decrease on T_{30}.

7. CONCLUSIONS

The results of this preliminary analysis emphasize the complex interaction between sound dispersion, sound absorption and volume of the room in the configuration of the acoustic environment. The investigation covered different scenarios and sought to demonstrate how each variable contributes in a unique way to the control of reverberation time (T_{30}) and to the uniformity of the sound field of a shoe-box room.

The introduction of sound scattering proved to be fundamental in the redistribution of sound energy, enabling changes in the reverberation time, especially in scenarios with parallel surfaces that generate floating reflections. However, its effectiveness is limited in closed environments that do not have absorbent surfaces, as observed in the reverberant scenarios. The distribution of sound absorption in the room proved to be equally important when it is intended to introduce sound diffusing solutions.

The analysis carried out in relation to dimensional changes proportional to the volume of the space suggests that the perception of variations in reverberation time in relation to sound dispersion remains almost unchanged. However, changing the relative shape of the closed environment has been shown to have a more significant impact on the perception of reverberation. When only one specific room dimension was changed, generating a significantly larger dimension than the others that remained constant, a distinct behavior has been observed, showing that disproportionate changes in the structure of the space affect the way dispersion influences the acoustics of the closed environment.

8. ACKNOWLEDGMENTS

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