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In situ measurement methods for characterising sound diffusion

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ABSTRACT

With the aim of defining a new in situ method of diffusion measurement, two methods have been investigated. The first one is based on the measurement of a mono-dimensional reverberation time between two parallel plates and gives an evaluation of a scattering coefficient. This field method has been tested through computer simulation and shows high sensitivity to experimental conditions. The experimental set-up has been realized and laboratory measurements conducted. The second method is focused at the scale of a concert hall and proposes new parameters which could lead to a new global diffusivity index. It has been simulated with a computer model with various diffuser arrangements.

These two methods are complementary and if further developed could lead to efficient tools for evaluating and optimizing diffusion in real concert halls.

INTRODUCTION

The ISO standard 17479 part 1 concerning the laboratory measurement of the scattering coefficient has been published in 2004. The in-laboratory measured scattering coefficient can now be used in prediction tools such as simulation software.

Unfortunately today no standardized method exists to measure the scattering coefficient or even to characterize the diffusion in an existing hall. The development of a measurement method for the scattering coefficient which is applicable in already constructed halls would permit the enrichment of existing reference tables of scattering coefficient values with existing and also non-academic shapes of diffusers. These new values could be used for acoustic simulation models.

An in situ measurement method that characterizes diffusion would be very useful for the analysis and study of appropriate acoustic solutions for already existing halls.

RINDEL METHOD

Jens Holger Rindel proposed an in situ measurement method for the scattering coefficient [1].

Theoretical principle

The theoretical principle of the method is based on the measurement of two "monodimensional" reverberation times [1]. The measurement protocol needs the use of a mobile surface with a low normal incidence absorption coefficient α1 and a rigid plane reference surface with a normal incidence absorption coefficient $\alpha_0 \approx 0$. Both surfaces are placed parallel to each other at a distance l.

A first reference measurement is done in laboratory with the rigid and plane surface which permits the characterization the mobile surface.

The same measurement is done in situ between the diffuser surface and the earlier characterized mobile surface. The distance between the diffuser surfaces and the mobile surface is identical to the one used for the reference measurement (see **Figure 1**).

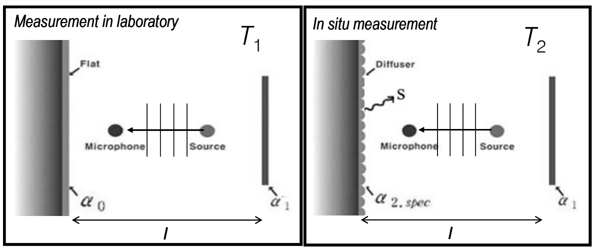

Figure 1. Principle of the reference and in situ measurement

The reverberation time of the reference measurement corresponds to :

$$T_1 = \frac{13.8l}{c(-\ln\sqrt{(1-\alpha_0)(1-\alpha_1)} + m_1 l)} \quad (1)$$

Scattering is considered to be an energy loss which adds up to the loss of energy due to the absorption of the surface. The in situ measured reverberation time therefore contains the information of the scattering coefficient:

$$T_2 = \frac{13.8l}{c(-\ln\sqrt{(1-\alpha_1)(1-\alpha_{2,0})(1-s)} + m_2 l)} \quad (2)$$

where the final equation obtains the scattering coefficient :

$$s = 1 - \frac{1-\alpha_0}{1-\alpha_{2,0}} \exp\left(\frac{2\cdot 13{,}8l}{c}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) + 2l(m_2 - m_1)\right) \quad (3)$$

with :
T_1 : reverberation time measured in laboratory for the reference surface
T_2: reverberation time measured in situ
$\alpha_{2,0}$: absorption coefficient in normal incidence
m_1, m_2 air absorption factor

The definition of the scattering coefficient in this presented Rindel method is not directly equivalent to the definition of the scattering coefficient in the ISO-17497-1 standard [2] because it is measured in random incidence and the Rindel method is measured only in normal incidence. This could reduce the interest of this method [3] because it would give a scattering coefficient depending only from the scattering qualities of the surface close to the normal incidence and it would not be possible to differentiate diffusers which have different polar responses for higher angles (Figure 2).

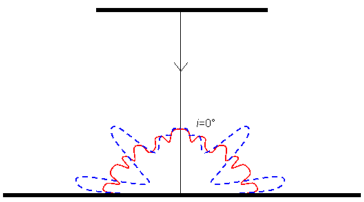

Figure 2. Polar responses of diffusers relative to the measurement set-up of the Rindel method.

Study of the theory

Equation 1 is based on very restrictive hypotheses. First, the description of the sound field through rays supposes that the dimension of the measurement set-up is large compared to the studied wave length.

Furthermore, the precision of the result depends on the assessment of the absorption coefficient of the diffuser. If the absorption of the diffuser is underestimated, the scattering coefficient will be overestimated because the energy decrease between the two surfaces takes into account the normal incidence absorption and the scattering.

On the other hand, a plane wave is considered between the two surfaces, but the reality is closer to a spherical point source with an amplitude attenuation depending of the distance. In the case of a spherical point source the sound pressure level decreases during the propagation. To illustrate this effect, the case of two surfaces separated by a distance of 1 m is considered (Figure 3).

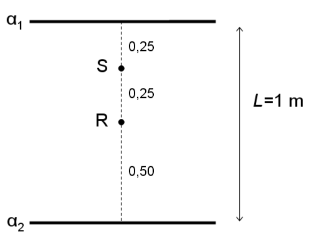

Figure 3. Example case for the study of the difference between the plane wave and the spherical wave. R : receiver position; S : source position; α_1 et α_2 normal incidence absorption coefficients of the two surfaces.

In this case, the amplitude and the arrival time of each reflection are mathematically known: the theoretical energy decay can be calculated depending on the source characteristics. Three cases will be considered: the case based on Rindels formula, which means a plane wave between both surfaces with the same averaged absorption coefficient α_m.; the same case but each surface having its own absorption coefficient to show that it is equivalent to the first case and finally the case of the spherical wave between both surfaces each having its own absorption coefficient with a decrease of the sound pressure level of 1/r trough propagation time. The results for $\alpha_1 = 0{,}5$, $\alpha_2 = 0{,}2$ and an unitary source are shown in Figure 4.

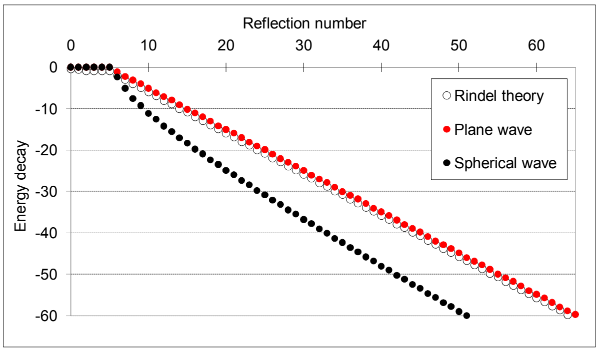

Figure 4. Decay curve of the energy for the case shown in Figure 3.

The energy decrease of the spherical wave depending on the propagation time is no longer exponential which means that the decay curve is not longer linear and the definition of an RT60 more difficult.

BEM 2D simulations

The numerical study has been done with the 2D-BEM simulation tool MICADO developed by CSTB [4]. The influence of different measurement set-up parameters on the obtained reverberation time using an omnidirectional source has been tested.

A simple set-up has been considered with a totally reflective finite mobile surface and an infinite totally reflective plane surface separated by the distance L = 1 m (Figure 5), using an omnidirectional point source S1 and an omnidirectional receiver R1. Source and receiver were placed outside of first modes nodes.

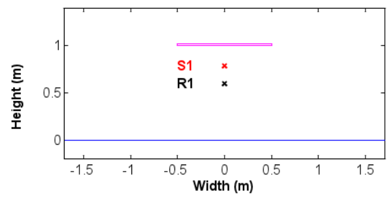

Figure 5. Configuration for the parametric study.

Resonance Modes

The results in Figure 6 show resonance peaks corresponding to the modes due to the distance between the surfaces $f_n = \frac{n}{2}.\frac{c}{L}$. With diffusive surfaces one can observe the diminution of these spectral peaks.

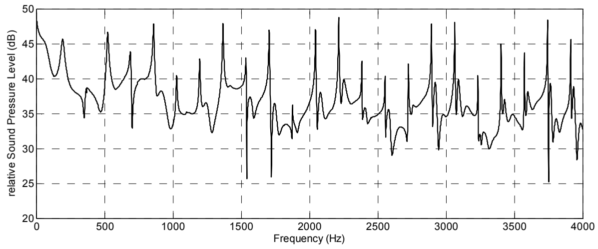

Figure 6. Frequency response (dB) for the totally reflective mobile surface and an infinite totally reflective plane surface.

Because the surfaces are considered totally reflective the observed decay curves are in this case only due to the loss of energy by edge effects and radiation.

Size of the mobile surface

The decay curves for the size of the mobile surface from 1 m to 2.20 m are represented in Figure 7. The larger the mobile surface the more the energy is confined between the two surfaces and the decay curve is slower. In particular, the size of the mobile surface should be large compared to the studied wave length.

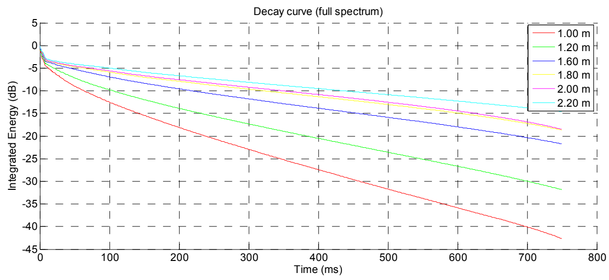

Figure 7. Full spectrum decay curves depending on the size of the mobile surface.

Size of the rigid plane surface

In Figure 8 it can be seen that the decay curves for the third octave frequency bands 1000 and 2000 Hz are similar to the infinite rigid plane surface (red curve) if the size of the rigid plane surface is approximately 2.20 m. It can be concluded that the larger the diffuser size is the closer it is to the ideal infinite case.

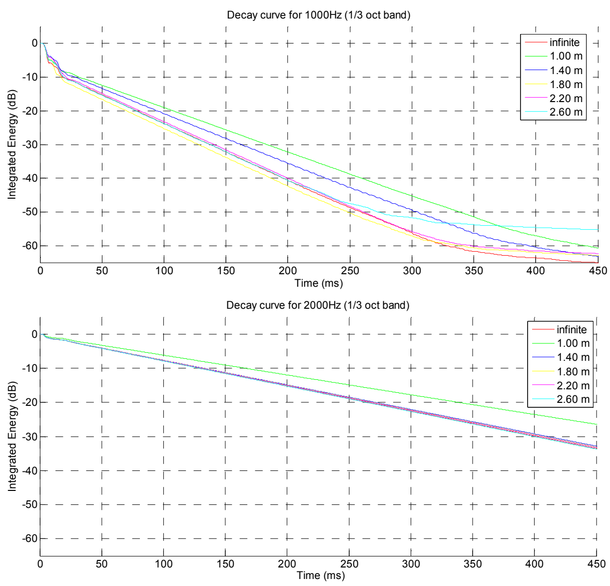

Figure 8. Decay curves in third octave bands for different sizes of the rigid plane surface (1000 and 2000 Hz respectively).

Parallelism of the surfaces

In case of a parallelism defect between the mobile plate and the surface to be measured the ideal conditions for a flutter echo are no longer present. The simple case of a rotation around the centre of the mobile plate relative to the plane rigid surface in the totally reflective case has been studied.

The echograms in Figure 9 correspond to rotations of 0°, 0.5°, 1°, 2°, 5° et 10°. The non-parallel results reach the background level in under 500 ms. Already at 10 ms the reflection peaks of the impulse response are strongly attenuated caused by the redirection of the energy even for only 0.5° rotation.

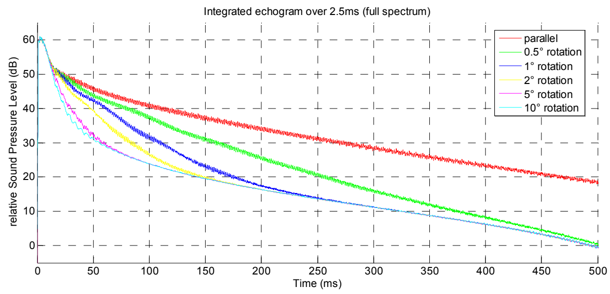

Figure 9. Integrated echogram (2.5 ms) for different rotation of the reference surface.

Consequently, the decay curve of the echogram is strongly altered and the calculated reverberation times can change by up to 100%. This condition is a strong constraint for the in situ measurement set-up because perfect parallelism is difficult to assure.

The reverberation time increases with the frequency. This effect can be explained by the missing absorption in our models and by the confinement effect of the high frequencies between the two surfaces. This confinement effect disappears for rotation angles of the mobile surface above 1°.

The energy decrease of non-parallel set-ups is steeper than for the parallel set-up. This is even more important if the mobile surface is large because of the increase of the difference between the parallel (which keeps more energy) and the non-parallel cases (cf. Figure 10). The sensitivity of the measurement method disappears with a diffuser instead of the rigid plane surface.

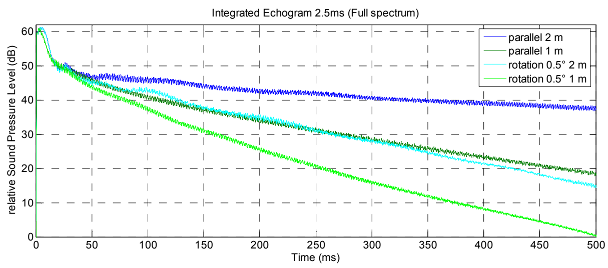

Figure 10. Integrated echogram (2.5 ms) for parallel and non-parallel cases with a mobile surface of 1 and 2 m.

Source position

To study the sensitivity of the measurement set-up concerning the source positioning a parametric study with vertical and horizontal source shifts from 1to 20 cm has been done.

Figure 11 shows the effect of a horizontal shift of the source from the median axis. The modal peaks are preserved with more differences on the spectrum when the source shift is larger especially because of the border effects. But for all third octave bands the slope of the decays curves are identical.

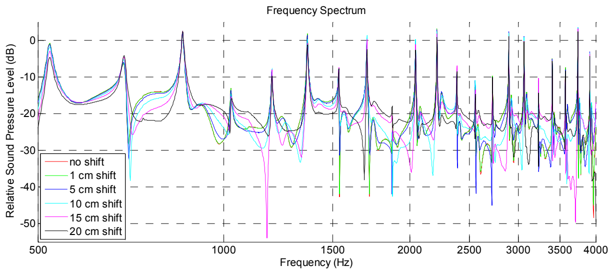

Figure 11. Frequency spectrum (dB) for different source shift.

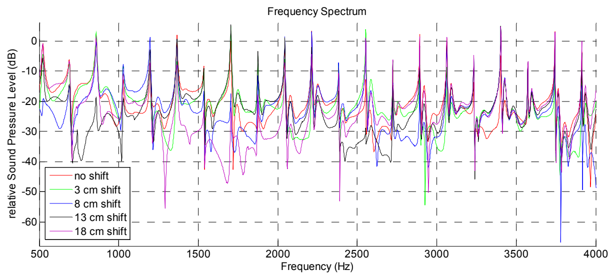

Figure 12. Frequency spectrum (dB) for different vertical source shift.

Figure 12 shows the effect of a vertical shift of the source towards the mobile surface. Note that the modal peaks are more or less attenuated depending on the source proximity to a node.

Depending on the source position at a mode resonance node or at an antinode, shift effects on the energy decay can be observed but generally the principal decay slopes stay parallel.

2D MLS diffuser

The considered 2D MLS diffuser is composed of a N=15 order sequence with 8 cm large and 10.5 cm deep wells. It is totally reflective and positioned on an infinite rigid surface as shown in Figure 13.

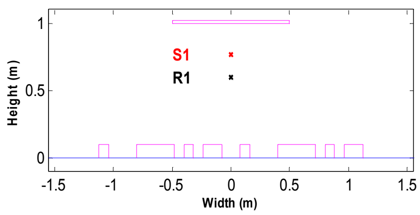

Figure 13. General configuration for the 2D MLS diffuser.

Two different well depths have been considered: MLS1 with 10.5 cm and MLS2 with 5.25 cm. Both simulation results have been compared with the reference situation of an infinite plane surface (REF). On Figure 14 one can visually detect that the frequency range of efficiency is different for both diffusers. Between 1000 and 3000 Hz the resonance modes are clearly attenuated (up to -10 dB) through the use of a diffuser.

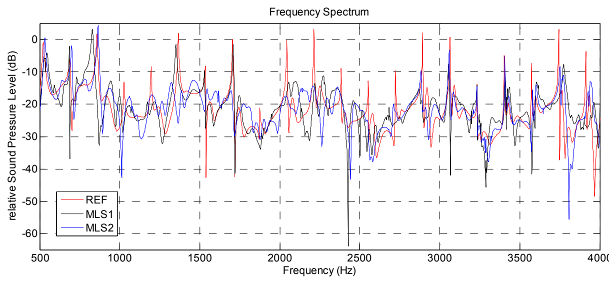

Figure 14. Frequency spectrum (dB) with and without MLS diffusers.

The observed decay curves are steeper with diffuser: the diffuser redirects the sound in all directions and induces a loss of energy of the flutter echo between the two surfaces. The analysis of the decay curves in third octave bands permits to deduce for which frequency range the studied diffusers are effective. The attenuation of the modal peaks could be emphasized with the calculation of the following criteria M :

$$M = \frac{\int_{1000}^{4000} |H(f)|^2 .df}{\left(\int_{1000}^{4000} |H(f)| .df \right)^2} \quad (4)$$

where $H(f)$ represents the frequency spectrum which quantifies the energetic importance of the modal peaks relative to the mean energy for the frequency range [1000 Hz ; 4000 Hz].

Figure 15 shows a comparison between the CSTB measured scattering coefficient [5] and the coefficient calculated through BEM 2D simulations for the order 15 MLS1 diffuser. The scattering coefficient according to the ISO-17497-1 standard is obtained in random incidence contrary to the Rindel method which concerns a normal incidence. In addition the simulations did not take the absorption coefficient of the surfaces into account. Therefore identical results are not expected.

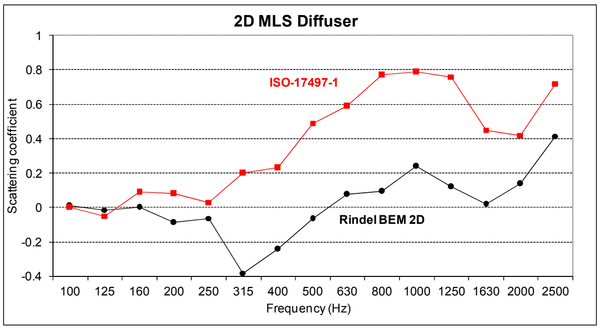

Figure 15. Comparison of the scattering coefficients obtained through simulation and measurements [5].

Considering the third octave band results above 500 Hz a similar shape of the curve can be observed for the two coefficients with a maximum around 1000 Hz and a local minimum around 1600 Hz.

BEM 3D simulations

Calculations have been done with the BEM3D simulation tool MICADO 3D for semi-spherical diffusers. The diffuser surface has a size of 2.56 m × 2.56 m on an infinite rigid surface, with a mobile surface of 1 m × 1 m placed at a distance of 1 m. The diffuser is composed of 41 semi-spheres with a diameter of 25 cm randomly distributed on the surface with a coverage rate of 31 %. All materials have been considered totally reflective. The simulations have been done up to 1600 Hz. The results are shown in Figure 19.

Experimental set-up

The measurements have been done in a dry room with a very short reverberation time of approximately 0.2 s at mid frequencies.

The measurement set-up (see Figure 16) uses a spark source, a microphone and a mobile surface of pressed wood supported by four wooden legs and a rigid plane surface of hard plastic. The distance between the two surfaces is 1.3 m.

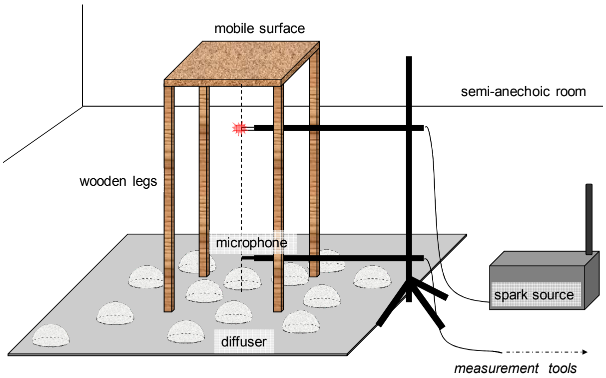

Figure 16. Set-up for the in situ measurement of the scattering coefficient

The spark source has been chosen because of its size: the source and receiver need to be placed on the vertical axis of the flutter echo without disturbing it.

In sort to obtain the smoothest possible energy decay curve, the microphone is positioned halfway between the surfaces and the source halfway between the microphone and the mobile surface so that the echoes arrive at regular intervals.

The influence of the positioning of the semi-spheres on the scattering coefficient, three different arrangements for a single coverage rate of 31 % have been done (cf. Figure 17).

Figure 17. View of different 25 cm diameter semi-sphere diffuser arrangements (Diff 1, Diff 2, Diff 3) for a coverage rate of 31 %.

Experimental results

The measured reverberation times (cf. Figure 18) for the reference case (without diffuser) show good reproducibility. The results are more fluctuating for the three different diffuser arrangements, especially for the 2nd case where large differences appear below 315 Hz. It should be emphasized that in our measurement set-up the Rindel theory is not really valid below 500 Hz.

The sensivity to the arrangement of the semi-spheres could also be due to only the differences in the positioning of the semi-spheres close to the microphone. Tests show that this sensitivity does not appear below a distance of 20 cm which almost corresponds to the size of a semi-sphere.

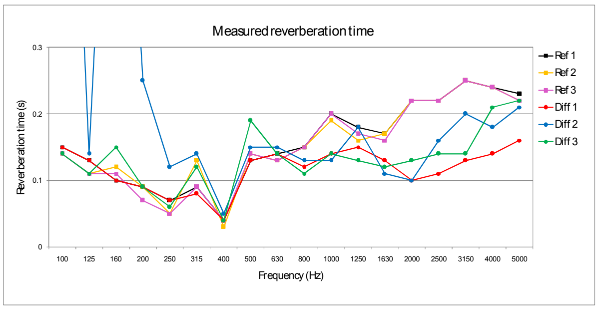

Figure 18. Measured reverberation time in third octave bands for three reference measurements and the configurations of Figure 17.

The scattering coefficient for a coverage rate of 31 % according to the standard ISO-17497-1 has been obtained by interpolation between the measured values for the coverage rate of 28 and 37 % [5].

The cut-off frequency of the semi-spherical diffuser which has been experimentally observed at 315 Hz for semi-spheres of a diameter of 25 cm [5] can be again observed with the Rindel method (see Figure 19).

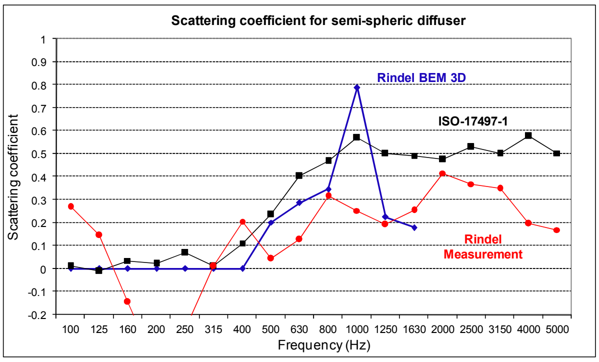

Figure 19. Scattering coefficients obtained through ISO 17497-1 and Rindel method measurements and 3D BEM simulation 3D for a semi-spherical diffuser of diameter 25 cm and a coverage rate of 31 %.

JEON METHOD

Another approach has been more recently proposed by Jin Yong Jeon [6] who proposes to define criteria which permit the characterization of the diffusivity of a hall.

Theoretical principle

The proposed criteria are based on the principle that through the presence of the diffuser new sound paths are created reducing at the same time the energy of the first specular reflections.

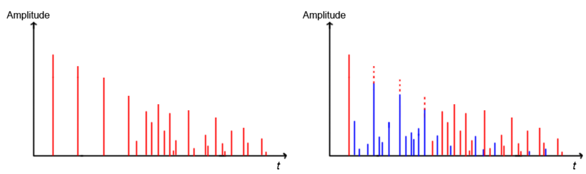

Figure 20. Theoretical echogram without (left) and with (right) diffuser.

Two parameters are studied:

- RN (t): the number of reflections whose level is contained in the range of [0, –30 dB] relative to the direct sound for the time between 0 and t.

- RE (t): The sum of the energy of the reflection whose level is contained in the range of [0, –30 dB] for the time between 0 and t.

The impact of the diffusion is especially noticeable between the first specular reflections and the diffuse field of the echogram. Jeon defines therefore two time intervals E (early) from 0 to 80 ms and L (late) from 80 to 200 ms, for which the parameter RN(E), RN(L), RE(E) and RE(L) will be calculated.

Numerical simulations

Numerical simulations have been done with the particle tracing method of the simulation tool ICARE developed by CSTB [7] for a simplified model of the Boston Symphony hall with a source on stage and four receiver distributed in the hall (see Figure 21).

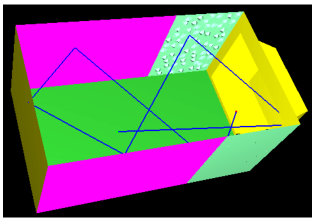

Figure 21. View of the Boston symphony hall model in ICARE

The diffusion from 0% to 100% coverage of the side walls has been studied. For this a semi-spherical diffuser has been used.

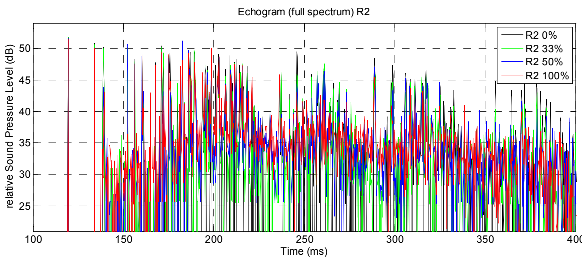

Figure 22. Echogram for receiver R2 for different coverage of the side walls.

Figure 22 shows that the presence of a diffuser creates many new paths between the specular reflections (in black). Most from the diffuser created paths in the time range of [0 ; 200 ms] are contained between −30 and −15 dB below the direct sound.

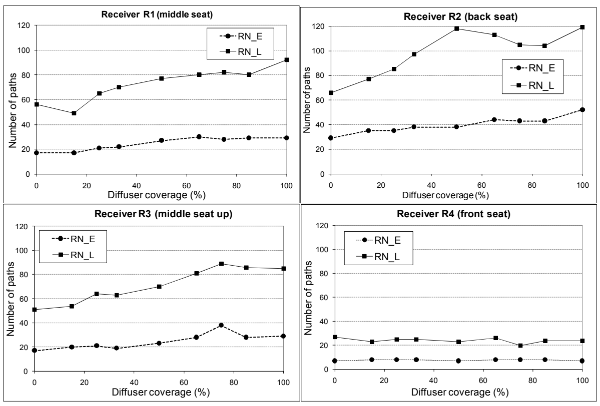

Figure 23. Variation of RN depending of the coverage rate of a pyramidal diffuser

In Figure 23 one can observe a diminution of RN_L depending of the coverage rate for receiver R1 and R3. This effect can be explained by the fact that the diffuser destroys the very energetic specular paths and replaces them with paths of higher order of lower energy and therefore below the criteria of counting the RN. In the back of the hall (R2) the RN is much higher because the SPL of the direct sound is lower. To be able to equally compare between different RN, the dynamic range of the energy for counting the paths should not be calculated as a difference from the level of the direct sound but as a difference from the background level.

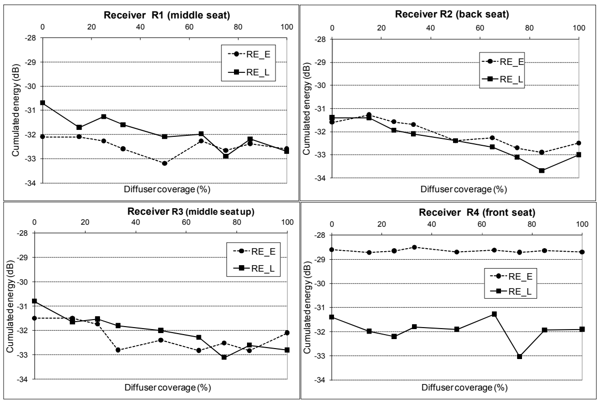

Figure 24. RE variation depending on the diffuser coverage

In Figure 24 for the receivers far enough from the source (R1, R2 and R3) the energy has a tendency to diminish with the increase of the diffuser coverage rate: the semi-spheres break the very energetic specular paths and replace them with more paths with less energy, which sometimes are not counted with the dynamic criteria of – 20 dB from the direct sound.

This effect has been studied by increasing the coverage rate between 0 and 49% of the semi-spheres on only a part of the side walls. (see Figure 25).

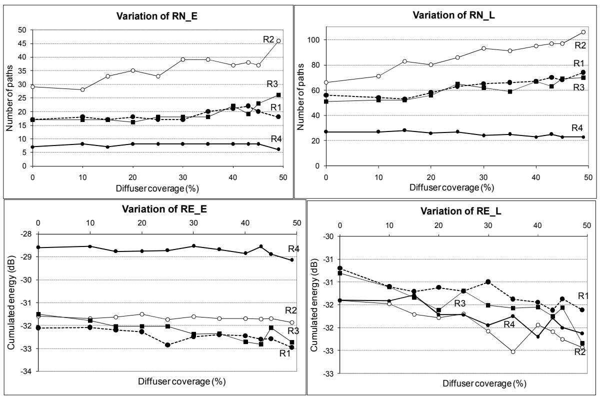

Figure 25. Comparison of RN and RE for different coverage rate of the diffuser.

Receiver R4 which is close to the source does not benefit from the diffusive wall. The number of paths stays approximately constant independent from the diffuser coverage. For receivers R1, R2 and R3 the number of paths for the early and late parts increases with the coverage rate. The diffuser seems ineffective for a coverage less than 15 %.

Concerning the energy, RE_E decreases with the increase of the coverage rate. The variations of RE_L are less coherent but seem to have the same tendency.

CONCLUSION

With the intention to develop a new in situ measurement method of acoustic diffusion two possibilities have been explored: one based on a material approach which proposed a measurement of a scattering coefficient and one other based on a global point of view of the hall giving two new diffusivity criteria.

The study of the Rindel method which is based on the measurement of a mono-dimensional reverberation time between two parallel surfaces showed the difficulties of a practical implementation. The parametric study showed the importance of the parallelism of the surfaces on the speed of sound energy decrease, even if this sensitivity of the method is attenuated by the presence of a diffuser.

BEM simulations on 2D MLS and 3D semi-spherical diffusers has given encouraging results but have not been done to enough high frequencies for a conclusion to be possible.

In practice the measurements of the reverberation time has shown good reproducibility above 600 Hz. The measured scattering coefficient showed large variations depending on the positioning of the semi-spheres with a constant coverage rate. This leads to believe that it is more a local scattering coefficient than a global one. Important research work still needs to be done so to clarify the physical mean given by the method and the real possibilities of implementation.

The proposed method gives a scattering coefficient in normal incidence, contrary to the standard ISO-17497-1 which gives a scattering coefficient in random incidence. Acoustic simulation software uses the scattering coefficient in random incidence but some methods exist through certain hypothesis to deduct on from the other [8].

The study of the second method proposed by Jeon which is based on the counting of the number of high energy reflections of the echogram has been done through computer simulations with a semi-spherical diffuser. The calculation of the new proposed criteria has been done on a simplified model through particle tracing. The theoretic concept of a "reflection peak" on which the calculation of the RN and RE is based, is still to be investigated. In this study local maximums have been counted, but two paths can arrive at the same time and create one single peak whose energy is more important. In this case even if the diffuser created two paths only one will be counted. For this reason RN and RE cannot be dissociated. A clarification of the relation between these criteria and other hall parameters is still to be done before normalized diffusivity criteria can be proposed.

The two methods are complementary and would permit once developed to obtain practical optimization tools of the diffusion in halls.

In the future it would be valuable to find a relationship between the in laboratory condition measured scattering coefficient and an in situ measured coefficient which would permit the calculation of the diffusivity criteria of a hall for comparison with the in situ measured diffusivity criteria (see Figure 26).

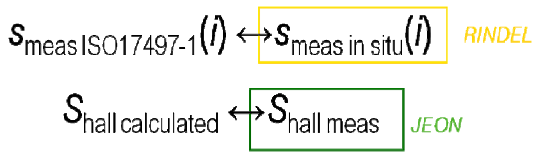

Figure 26. Relationship between the different scattering and diffusivity criteria.

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