10ème Congrès Français d'Acoustique

Lyon, 12-16 Avril 2010

Diffuse field absorption coefficient simulation of porous materials in small reverberant rooms: finite size and diffusivity issues

Arnaud Duval[1], Jean-François Rondeau[1], Ludovic Dejaeger[1], Franck Sgard[2], Noureddine Atalla[3]

[1] Faurecia, Centre R&D, Z.I François Sommer BP13, 08210 Mouzon, France, arnaud.duval@faurecia.com

[2] IRSST, 505 Boulevard de Maisonneuve Ouest, Montréal, QC, H3A 3C2, Canada, franck.sgard@irsst.qc.ca

[3] Université de Sherbrooke, GAUS, 2500 Boulevard Université, Sherbrooke, QC, J1K 2R1, Canada, noureddine.atalla@usherbrooke.ca

Small reverberant rooms are usually used in the automotive industry, like the well-known Alpha Cabin, for diffuse field absorption coefficient measurements of porous materials. The advantage is that rather small flat samples can be used here, typically $1,2\,m$ by $1\,m$. Real life parts can be measured as well, like engine hoods, in sufficient quantity close to the $1,2\,m^2$ area. With a Schroeder frequency of $1246\,Hz$, the simulation of the Alpha Cabin is rather problematic. There are diffusivity issues in the middle frequency range that are varying with the level of absorption of the sample. Moreover, critical diffractions due to the finite size effects of the $1,2\,m^2$ flat sample occur and must be taken into account. Different simulation approaches of small reverberant rooms are investigated in this paper and compared to the large reverberant rooms situation (with $12\,m^2$ material in that case). The first approach, for solving the diffraction issues, consists in applying recent spatial windowing techniques combined with the efficient Transfer Matrix Method (TMM) for porous materials, sometimes called Finite Transfer Matrix Method (FTMM). The second approach based on a simplified FEM-BEM model leads to a more accurate finite size effect modeling. The third approach, for solving the diffusivity issues, consists in modeling the Alpha Cabin with the Ray-Tracing method with statistical prolongations and comparing directly the reverberation times with measurements. In order to take into account both issues at the same time and potentially strong coupling between the porous domain and the fluid domain in the middle frequency range, a complete trim FEM model, as fourth approach, is built using poro-elastic finite elements with the (**u**,p) formulation. All simulation techniques will be compared with one another and correlated with measurements carried out in small and large reverberant rooms showing the advantages and limitations of each approach.

1 Introduction

The introduction of diffuse field absorption coefficients from multi-layers poroelastic materials in vibro-acoustic models has always been an issue in the transportation industry. As discrepancies occur between different measurements machines such as large reverberation rooms compared to small ones like the Alpha Cabin, pure diffuse field simulations using the Transfer Matrix Method (TMM) have been sometimes preferred for practical reasons [1]. Indeed, following the ISO 354 norm in large reverberant rooms requires large surfaces of material ($12\,m^2$), which is sometimes difficult to gather, even if this measurement technique remains the most accurate. Small reverberant rooms are therefore commonly used, the most famous one being the Alpha Cabin widespread in the automotive industry allowing to measure $1.2\,m^2$ flat samples or trim parts.

Two difficulties appear when dealing with the Alpha Cabin or small reverberant rooms in general : the lack of diffusivity on the acoustic field, especially in the middle frequency range, and the diffraction due to the finite size of the porous material (lateral size effects)([2],[3],[4],[5]). First, with a maximum reverberation time being $T = 2.5\,s$ and a volume being $V = 6.44\,m^3$, the Schroeder frequency limiting the beginning of the diffuse field $f_c = 2000\sqrt{\frac{T}{V}}$ yields $f_c = 1246\,Hz$. The Alpha Cabin absorption coefficient measurements, based on the Sabine law supposing a perfect diffusivity, are nevertheless usually considered as valid from $400\,Hz$ up to $10000\,Hz$... Second, another important issue is the diffraction effect due to the finite size of porous samples or parts particularly critical for small dimensions. The perimeter to surface ratio E of the sample has to be low in order to minimize these finite size effects. It is the case for large reverberant rooms following the ISO 354 norm ($E = 1.2\,m^{-1}$ for a $12\,m^2$ sample) but not for the Alpha Cabin ($E = 3.7\,m^{-1}$ for a $1.2\,m^2$ sample).

The investigations aiming at solving the finite size effects issue for porous materials were carried out for the Transmission Loss problem using spatial windowing combined with the Transfer Matrix Method (TMM), so called Finite Transfer Matrix Method (FTMM) ([6],[7],[8]). The application of this spatial windowing (FTMM) to absorption problems is more recent and turns out to be very efficient numerically ([9], [10]). Indeed, FEM-BEM numerical approaches including poroelastic finite elements implementing the (**u**,p) formulation have been developed in parallel for solving Transmission Loss and absorption problems baffled or not, including fluid loading effects ([9], [11]). This paper will concentrate on the diffuse field absorption coefficient simulation of porous materials measured in small or large reverberant rooms using the above described FTMM and FEM-BEM approaches as well as complete models of the Alpha Cabin using the Ray-Tracing method and a fully coupled trim FEM simulation [12]. All these simulation techniques will be compared with one another and correlated with measurements showing the advantages and limitations of each approach in the middle and high frequency range.

2 Diffuse field absorption coefficient simulation : finite size effects

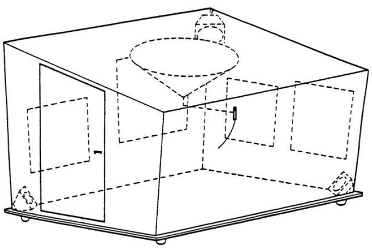

Figure 1 – Small reverberant room : Alpha Cabin

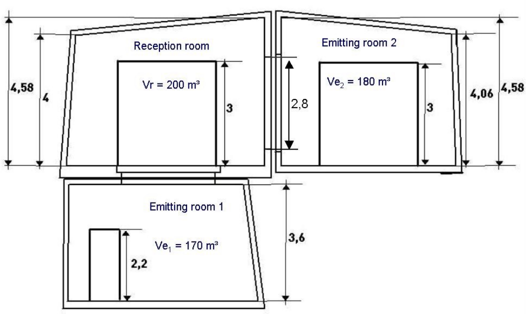

Figure 2 – Large coupled reverberant rooms

2.1 Finite Transfer Matrix Method

Three materials : a polyester carpet $550\,g/m^2$ $4\,mm$ with latex backing, a polyester felt $1000\,g/m^2$ $13\,mm$ and a thermoplastic cotton felt $1200\,g/m^2$ $20\,mm$ have been measured in the Alpha Cabin with a $1.2\,m^2$ flat sample and in the large reverberant emitting room 2 of the Faurecia's Center of Acoustic Technology with a $12\,m^2$ flat sample (cf. Figure 2). The Alpha Cabin is a small reverberant room having overall dimensions of $3.17\,m \times 2.29\,m \times 2.03\,m$, one-third of international standard large reverberant rooms, as presented Figure 1.

The Biot parameters of the above mentioned materials have been determined using an inverse technique based on impedance tube measurements, direct airflow resistivity, porosity and Complex Young modulus measurements. These last Complex Young modulus measurements show very low values as usual for felts, which tend to prove that a limp model (5 acoustical parameters and the skeleton density) is sufficient here [10].

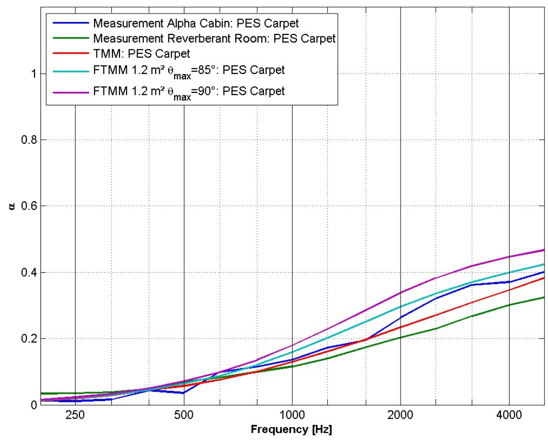

Figure 3 – Diffuse field absorption coefficient (FTMM) : PES carpet 550 g/m^2 4 mm

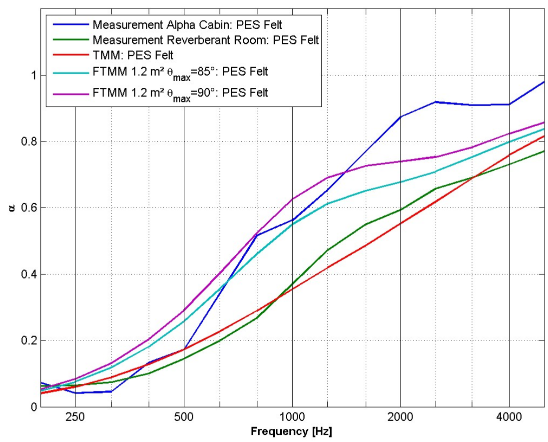

Figure 4 – Diffuse field absorption coefficient (FTMM) : PES Felt 1000 g/m^2 13 mm

The theory underlying the Finite Transfer Matrix Method based on a geometrical radiation impedance can be found in [9] and [10]. The measurements are compared with simulations obtained using the TMM for large samples and the FTMM for small samples integrating on the solid angle up to a certain $\theta_{max} = 85^\circ$ or 90°. Figures 3, 4 and 5 show discrepancies between the Alpha Cabin and the large reverberant room measurements. These discrepancies are mainly important at low frequencies and for the highly absorptive materials (as already stated in [2]). The FTMM diffuse field simulation applied to this absorption case catches the overall physics quite efficiently indeed, following the absorption performance effects, even if a slight overestimation in the low frequency range and an underestimation in the high frequency range can be observed. The optimum maximum angle of integration θ_{max} for the FTMM seems to lie here between 85° and 90°. The classical TMM diffuse field simulation shows an excellent correlation on the whole frequency range with the large reverberant room measurements and with all materials for this large $12\,m^2$

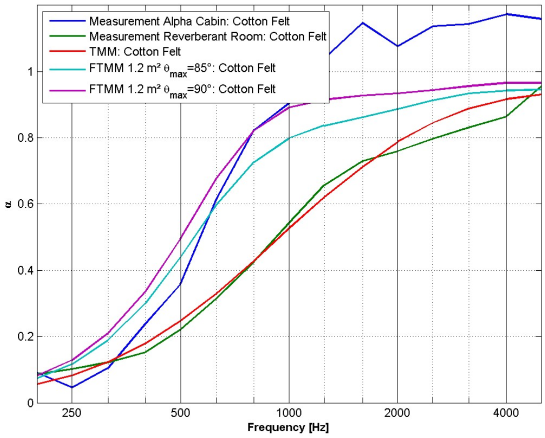

FIGURE 5 – Diffuse field absorption coefficient (FTMM) : Cotton Felt 1200 g/m^2 20 mm

sample case.

2.2 Finite Element Method - Boundary Element Method

The advantage of the FEM-BEM approach with poroelastic elements is that a simple surface mesh of the upper skin of the porous sample represents the fluid of the Alpha Cabin. Thus, the solid mesh of the porous materials without any additional meshing work is sufficient here. The three Biot wavelengths have been calculated in order to guarantee the convergence of the $40 \times 33 \times 37$ brick elements up to 2500 Hz while respecting a $\lambda/6$ mesh criterion for the shortest compressional wave, which is dominant in that flat case [13].

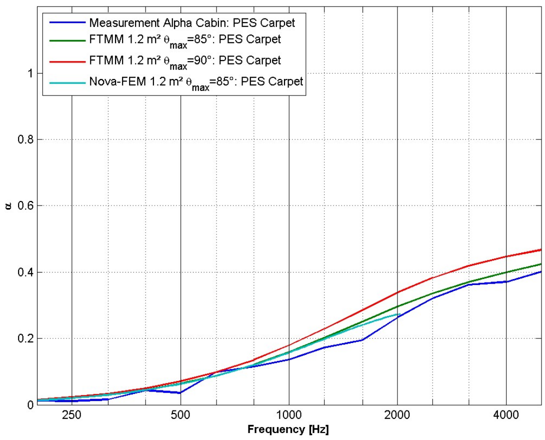

FIGURE 6 – Diffuse field absorption coefficient (FEM) : PES carpet 550 g/m^2 4 mm

Figures 6, 7 and 8 show quite good correlation with Alpha Cabin measurements of the FEM-BEM diffuse field absorption coefficient simulations using NOVA-FEM for these $1.2\,m^2$ small sample cases. These FEM-BEM simulation curves are lying between the two FTMM simulations with different θ_{max} taking the best of the two. All these simulations are limited to a maximum absorption coefficient of 1 here with $1.2\,m^2$ of material, even if the absorbed power is normalized to the incident power and not to the input power, in order to get the absorption coefficient. This means that the FTMM or FEM-BEM approaches may lead to diffuse field absorption coefficients of more than 1 [10].

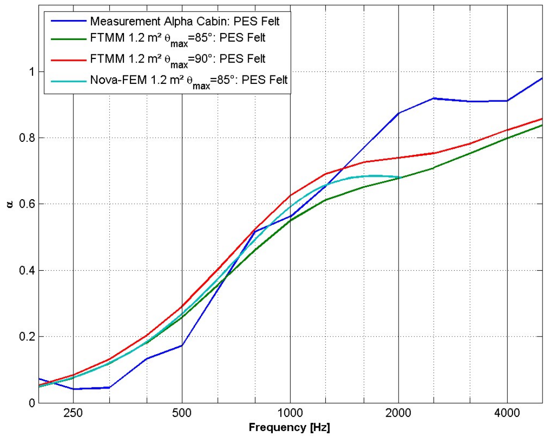

FIGURE 7 – Diffuse field absorption coefficient (FEM) : PES Felt 1000 g/m^2 13 mm

Nevertheless, the application of the Sabine law to small reverberant rooms leads classically to the unusual result of diffuse field absorption coefficients of more than 1 by far in the high frequency range. Thus, there may be also additional diffusivity issues to the finite size effects in the Alpha Cabin, we will try to address with Ray Tracing method models and full trim FEM models.

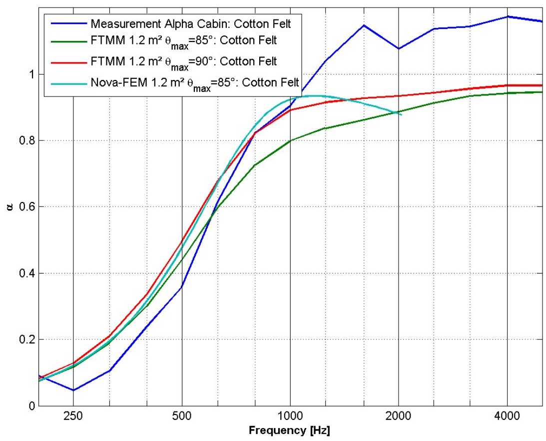

FIGURE 8 – Diffuse field absorption coefficient (FEM) : Cotton Felt 1200 g/m^2 20 mm

3 Diffuse field absorption coefficient simulation : diffusivity issues

3.1 Ray Tracing model

The Sabine absorption coefficient is defined by [14] :

$$\alpha_S = 0.163\,V\left[\frac{1}{S_0T_0} + \frac{1}{S_1T_1} - \frac{1}{S_1T_0}\right] \qquad (1)$$

where V is the room volume, S_0 is the enclosed room area, S_1 is the area of the sample to be characterized, T_0 is the reverberation time without sample and T_1 is the reverberation time with the sample.

The first hypothesis consists in neglecting the term $\frac{1}{S_0 T_0}$ which can be justified here by the influence of a strong reverberation time T_0 and a large area S_0.

After simplification, the new Sabine absorption coefficient is :

$$\alpha_S \simeq 0.163\, V \left[\frac{1}{S_1 T_1} - \frac{1}{S_1 T_0} \right] \qquad (2)$$

Figure 9 presents the Ray Tracing model (ICARE) built to simulate the Alpha Cabin [15]. A geometrical computation with 8 specular reflections is used then a statistical prolongation is carried out between 9 and 250 reflections to ensure a physical impulse response and therefore a good reverberation time computation. We have used spherical wave reflections.

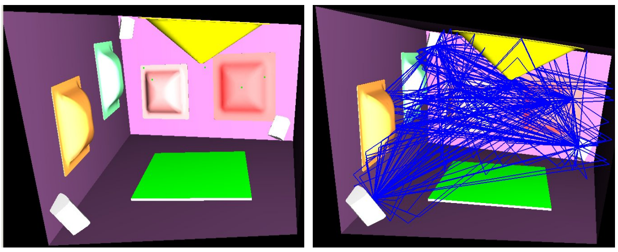

FIGURE 9 – Alpha Cabin Ray Tracing model

3.1.1 Bare Alpha Cabin T_0 correlation

The first step is to ensure that the reverberation time T_0 when the cabin is empty correlates well with the equivalent measured reverberation time. So the key question is to apply the correct diffuse field absorption coefficient or surface impedance on each faces of the model. First we apply an equivalent α coefficient. In order to apply a validated α coefficient on the ICARE model, an averaged measured reverberation time is introduced using the well known Sabine empirical equation :

$$\alpha = \frac{1}{S} \left[0.163 \frac{V}{T_0} \right] \qquad (3)$$

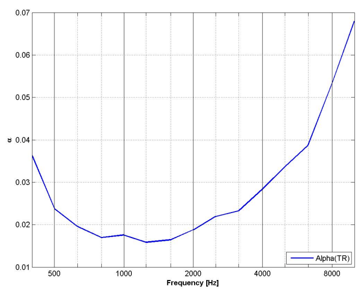

FIGURE 10 – Correlated α coming from measured Reverberation Time

This "bare" alpha coefficient is presented Figure 10, with surprisingly high values at 400 Hz and 500 Hz, which may be linked to vibro-acoustic coupling with potentially too soft walls at these frequencies.

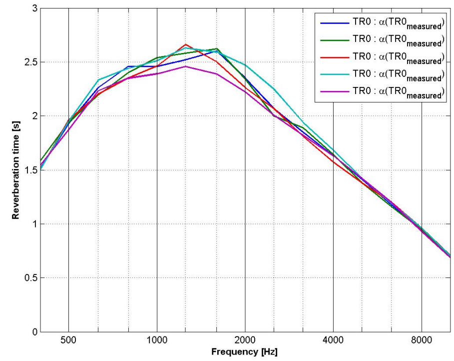

FIGURE 11 – Simulated Reverberation Times : 5 microphone positions

Figure 11 presents the reverberation time computed at the fives microphones in the cabin. Those reverberation times are simulated through the impulse responses of the resulting FRF from the three sources running simultaneously at each of the five reception points.

Figure 12 presents the correlation of the simulation with the direct measurement in Faurecia's Alpha Cabin. In this bare configuration, the correlation of the Ray Tracing model with measurements is quite good.

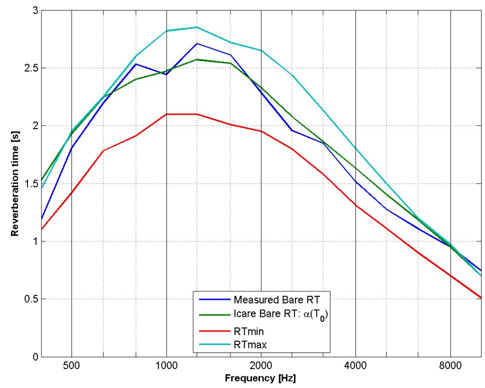

FIGURE 12 – Averaged simulated Reverberation Time with Icare vs. measurement

This protocol is nevertheless not so satisfying because of the strong link between the measurement and the "bare" diffuse α coefficient applied in the cabin. In consequence, an alternative absorption coefficient resulting from visco-thermal effects near the walls was also calculated as proposed by M. Bruneau [14]. Figure 13 presents this absorption coefficient compared to the $\alpha(T_0)$.

Unfortunately as shown Figure 14 this visco-thermal absorption coefficient does not provide a correct trend to simulate the T_0. As a first conclusion and as a general rule for the future discussions, we apply an $\alpha(T_0)$ on each surfaces except the sample to be characterized.

3.1.2 Trimmed Alpha Cabin T_1 correlation

The material considered in this section is a 20 mm flat sample 1200 g/m^2 epoxy-polyester felt 1 m × 1.2 m.

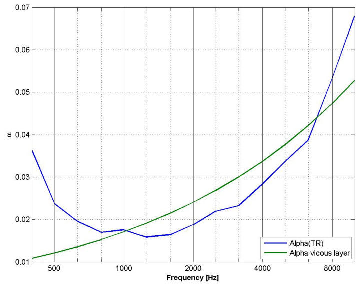

FIGURE 13 – Correlated α coming from measured reverberation time vs. visco-thermal boundary layer

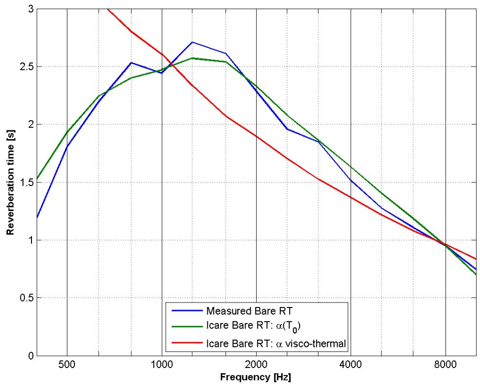

FIGURE 14 – Averaged simulated Reverberation Time with visco-thermal boundary layer

A correlated set of Biot's parameter is used as input data in the Ray Tracing model, either in the form of a surface impedance or in the form of a diffuse field absorption coefficient.

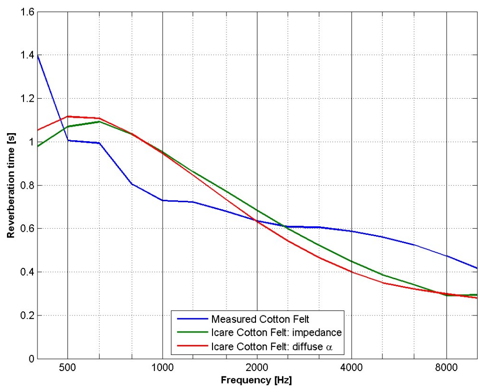

FIGURE 15 – T_1 measured in the Alpha Cabin vs. T_1 simulated with Icare

Figures 15 and 16 show the correlation between measurements and the predicted reverberation time and Sabine absorption coefficient, respectively. Some difficulties with the Ray Tracing model in the middle frequency range, and even more critical in the high frequency range, are observed. The problem lies very probably in the locally reacting impedance hypothesis made in the Ray Tracing model for the material simulation which we know as not realistic here.

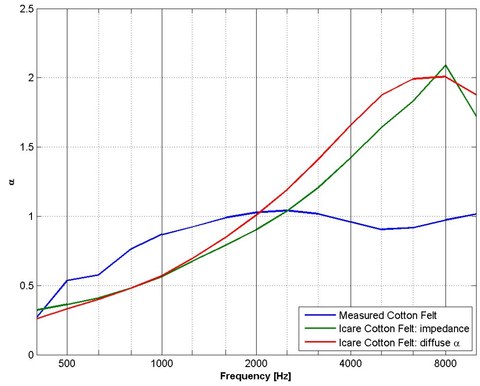

FIGURE 16 – α measured in the Alpha Cabin vs. α simulated with Icare

3.2 Trim FEM model

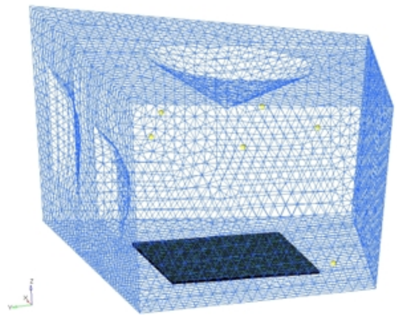

FIGURE 17 – Alpha Cabin trim FEM model

Due to the relatively high Schroeder frequency of 1246 Hz of the Alpha Cabin, one can think that a purely modal fully coupled trim FEM model may work well in the low and middle frequency range up to 1000 Hz. Indeed, strong coupling should occur in this modal area between the porous media and the fluid cavity, leading to a fully coupled trim FEM model.

Figure 17 shows this trim FEM model made using RAYON-VTM. The cavity is meshed using 92096 quadratic tetrahedral elements. The Cotton Felt 900 g/m^2 20 mm is meshed using $60 \times 50 \times 8$ hexahedral (brick) linear "limp" elements. A frequency dependent viscous fluid damping is introduced using the bare measured Reverberation Time of the Alpha Cabin. In order to avoid to solve a multi-source problem and to handle source directivity issues, a constant Volume Velocity source having a monopole directivity has been introduced in a corner of the Alpha Cabin where a hole was already existing (cf. Figure 18).

FIGURE 18 – Constant Volume Velocity source mounting : Monopole

The pure acoustic FRF response is computed up to 1000 Hz taking into account 1375 acoustic modes in the cavity up to 1200 Hz. Figure 19 and 20 show the very good FRF correlations point to point with measurements obtained with RAYON-VTM for the bare configuration for two different microphones points (out of five for the averaging post-processing of the Alpha Cabin), respectively. This good correlation remains for the other measurements points (not reproduced here), which confirms numerically the bad diffusivity of the Alpha Cabin below 1000 Hz (already remarkable on the two different points plotted).

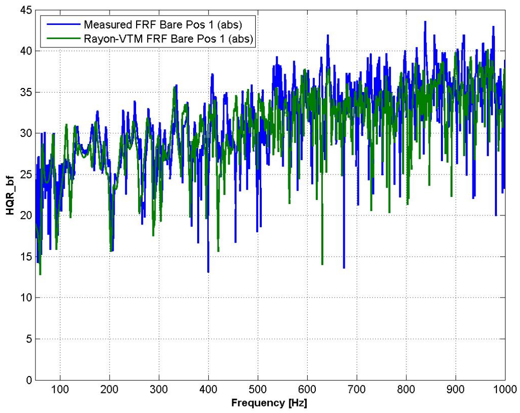

FIGURE 19 – Alpha Cabin $|P/Q|$ Rayon-VTM FRF (dB), micro pos. 1 : Bare

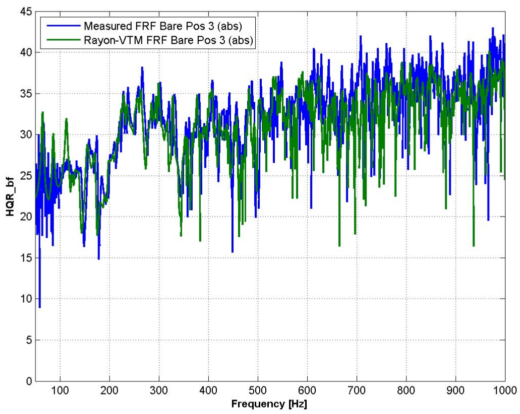

FIGURE 20 – Alpha Cabin $|P/Q|$ Rayon-VTM FRF (dB), micro pos. 3 : Bare

With the Cotton Felt 900 g/m^2 20 mm, the pure acoustic FRF response correlations presented in Figure 21 and 22 are even better, especially in the middle frequency range, where the porous material is clearly reducing the diffusivity. The trim FEM model is capturing very well the absorption effects of the Cotton Felt in the Alpha Cabin.

Figure 23 and 24 show the two Reverberation Times bare and with material necessary to compute the diffuse field absorption coefficient plotted in Figure 25. Different techniques have been used in order to get these Reverberation Times. The first classical one used for the standardized Alpha Cabin measurements consists

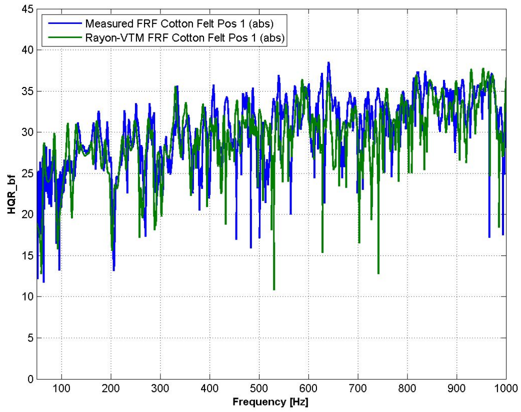

FIGURE 21 – Alpha Cabin $|P/Q|$ Rayon-VTM FRF (dB), micro pos. 1 : Cotton Felt 900 g/m^2 20 mm

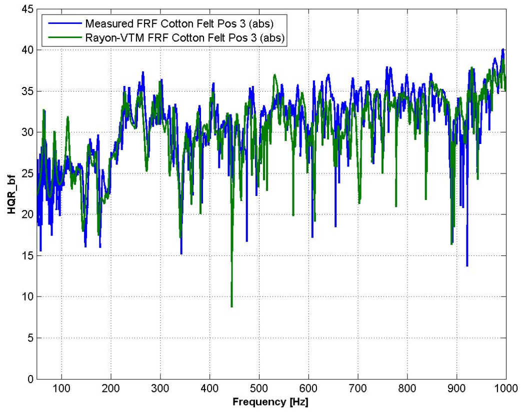

FIGURE 22 – Alpha Cabin $|P/Q|$ Rayon-VTM FRF (dB), micro pos. 3 : Cotton Felt 900 g/m^2 20 mm

in sending third octave chirps by the three loudspeakers positioned in the three upper corners and to analyse the decay of these already filtered time signals. The Reverberation Times are averaged on the five microphones positions.

Using our constant Volume Velocity source positioned in a lower corner, we have sent a white noise and measured the time decay. We have then used the post-treatments tools of ICARE called "postac" based on time third octaves filters of Tchebychev of order 7 and the time decay analysis of the filtered signals. The third and last technique consists in using the inverse FFT of the FRF signal either measured or simulated with the trim FEM model in order to compute the impulse response of the problem. The rest of the post-treatments remains then the same. This FRF based Reverberation Time technique is more complicated to apply due to the requirement of very fine and precise FRF in order to get a reliable impulse response.

On top of these signal processing issues, the position of the sources in the Alpha Cabin have a strong influence on the diffuse field absorption coefficient in the middle frequency range. All these effects lead to discrepancies in the post-treated Reverberation Times between the different techniques (cf. Figure 23). This is particularly critical at 250 Hz and 315 Hz with the FRF based technique. Globally, the Volume Velocity source based post-treatments lead to an overestimation of the Reverberation Time on the whole middle frequency up to 1000 Hz compared to the reference third octave chirps measurements. On the contrary, the simulated bare Reverberation Time based on the trim FEM FRF simulation correlates well in the low frequency up to 400 Hz but not at all above.

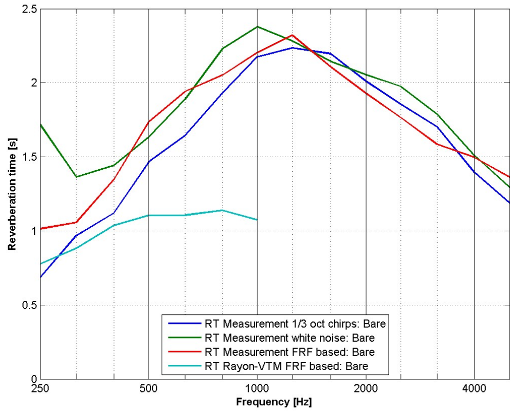

FIGURE 23 – Average Alpha Cabin Rayon-VTM Reverberation Time : Bare

Figure 24 presents on the contrary much better correlations not only between the different post-treatment techniques (and source position...), but also between the simulated Reverberation Time with porous material and the reference measurement with less than 0.1 s difference. In fact, the Cotton Felt 900 g/m^2 20 mm reduces the diffusivity drastically allowing a purely modal trim FEM simulation to better converge.

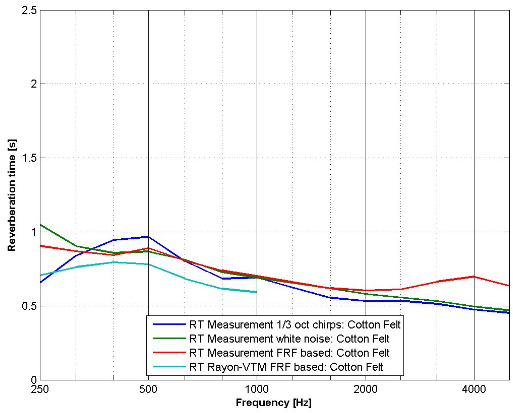

FIGURE 24 – Average Alpha Cabin Rayon-VTM Reverberation Time : Cotton Felt 900 g/m^2 20 mm

Globally, in the diffuse field absorption coefficient sense, Figure 25 shows rather good correlation between the trim FEM RAYON-VTM simulation and the reference measurement between 250 Hz and 800 Hz. The other measurement post-treatments overestimate in the low frequency the diffuse field absorption coefficient compared to the reference measurement, but agree all in the middle frequency, where the FTMM correlates well also.

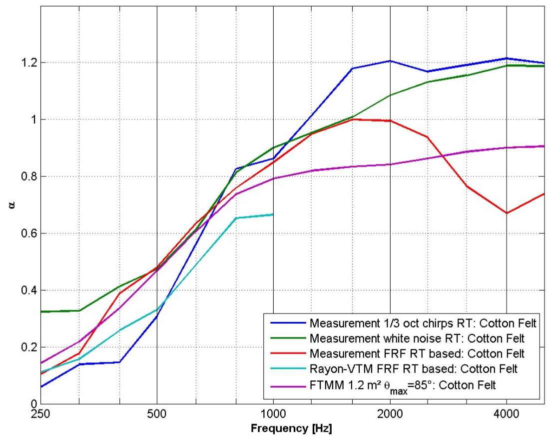

FIGURE 25 – Alpha Cabin Rayon-VTM diffuse field absorption coefficient : Cotton Felt 900 g/m^2 20 mm

4 Conclusion

All the investigations presented here have shown that simulating the diffuse field absorption coefficient as measured in a small reverberant room like the Alpha Cabin is not an easy task. Indeed, finite size effects are superposed to diffusivity issues leading to a rather complicated problem to solve. The classical Transfer Matrix Method proves to correlate very well with large reverberant rooms respecting the ISO 354 norm when using large porous samples (12 m^2 typically). Even in these large rooms, if the samples are much smaller the Finite Transfer Matrix Method leads to much better correlation and should be used. It is however the case in the Alpha Cabin with 1.2 m^2 samples, where the FTMM correlates well and is very efficient numerically. Simplified FEM-BEM models proves to correlate even better with a limited modeling effort but more computational time.

The Ray Tracing method captures the diffusivity effects quite well as long as the Alpha Cabin remains empty. Further work has to be done in order to introduce non-locally reacting porous materials in the models. The trim FEM model of the Alpha Cabin correlates very well in the low and middle frequency range up to 1000 Hz in the FRF sense, especially in the presence of a porous material. The correlation of the diffuse field absorption coefficient trim FEM simulation is very encouraging and seems to capture the physics in the middle frequency between 250 Hz and 800 Hz. Further work is planned on this trim FEM technique, in order to optimize the signal processing and the position of the sources in the Alpha Cabin.

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