

Numerical Simulation of the Measurement of the Diffuse Field Absorption Coefficient in Small Reverberation Rooms

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ABSTRACT

The Diffuse Field Absorption Coefficient (DFAC) is a physical quantity very often used in the automotive industry to assess the performance of sound absorbing multilayers. From a theoretical standpoint, such quantity is defined under rather ideal conditions: the multilayer is assumed to be infinite in extent and the exciting acoustic field is assumed to be perfectly diffuse. From a practical standpoint, in the automotive industry the DFAC is generally measured on samples having a relatively small size (of the order of 1m²) and using relatively small cabins (in the order of 6-7m³). It is well known that both these factors (the finite size of the sample and the small volume of the cabin) can have an influence on the results of the measurements, generating deviations from the theoretical DFAC.

The widely used Transfer Matrix Method (TMM) allows the evaluation of the theoretical DFAC and can, in some implementations, approximately take into account the finite size of the sample by means of a suitable analytical correction. Within this method, though, the exciting acoustic field is always assumed to be ideally diffuse or, in any case, given by the superposition of a set of uncorrelated plane waves impinging on the sample with incident angles within a certain predefined range.

This paper intends to present numerical investigations that allow going beyond this modeling technique.

In a first part of the paper, this is done using an analytical model consisting of a rectangular cavity having the dimensions of a small cabin. The reverberation time of this cavity is evaluated with and without an absorbing sample

placed on its floor and, from these data, the corresponding DFAC is calculated using Sabine's law. Results from this model are presented and compared with results coming from testing. Using this analytical model, it is already possible not only to evaluate the effect of the finite size of the sample, but also the effect of its positioning on the cavity's floor and, more importantly, the effect of the limited volume of the measurement environment. Both these latter effects cannot be taken into account in any way by means of the TMM.

In the second part of the paper, a further degree of complexity is added: the same type of simulations are carried out by means of a finite element model of the widely used Alpha Cabin (whose volume is about 6.5m³), coupled to a finite element model of the absorbing sample. Also in this case, simulation results are compared to results coming from testing. The use of a finite element model allows taking into account also the effect of the diffraction around the sample's edges. Also this effect is known to have, in special cases, some influence on the results of DFAC measurements and, of course, cannot be taken into account within the analytical model based on a rectangular cavity.

1. INTRODUCTION

The Diffuse Field Absorption Coefficient (DFAC) is a physical quantity often used in the automotive industry to assess the performance of sound absorbing trim parts: this quantity is used to set targets, to compare parts' performance and also to set up vehicle models (typically, SEA models) on which design decisions are then based. In spite of the easiness of its well-known theoretical definition [1], the definition of a test methodology for evaluating the DFAC poses some challenges, in particular when such methodology has to be

tailored to the typical size and thickness of automotive trim parts.

The only two standards available in the field - namely, ASTM C423 [9] and ISO 354 [10] - define with a good precision the procedures that have to be followed for a proper evaluation of a material's sample DFAC and also the main features that the facilities that are used for such evaluation should have. In a way, these standards represent simply a set of prescriptions aimed at guaranteeing that the sound field exciting the test sample is "sufficiently diffuse", that undesired side effects related to the size and the shape of the sample are reduced to a minimum and that data acquisition and processing are carried out in such a way to guarantee a reasonable statistical reliability and accuracy of the final absorption result. A good review of these standards and the prescriptions they give can be found in [8]. Both the ASTM standard and the ISO standard are based on large reverberation rooms (200m³ or greater) and on large test sample areas: samples with an area of about 5-7m² are recommended by the ASTM standard, while samples with an area of 10-12m² are recommended by the ISO standard. These recommendations are related to the fact that both the ASTM and the ISO standards were developed for measurements on samples suitable for industrial and building applications, where absorbing panels are generally applied on big surfaces in more or less planar configurations and where the absorption of such panels can have a practical relevance also at low frequencies.

In the automotive industry the situation is quite different. First of all, it is generally considered important to have the possibility to conduct DFAC measurements not only on flat samples but also on molded parts, and typical parts used in the automotive industry (headliners, carpets, seats) have a size that is much smaller than the area of the samples as prescribed by the ASTM and ISO standards. Furthermore, even for measurements on flat samples, in the automotive industry it would be very impractical (if not impossible) to use samples with an area of 7m² or even 10m² for the daily activities. It has to be considered here that the development times in the automotive industry unavoidably call for a quick and efficient test procedure; given that for most materials it would be impossible to obtain single samples with an area of the order of 10m², it would be then necessary to assemble together many samples with a smaller surface and this, beyond being questionable for what concerns the effect of the "patching procedure" on the absorption results, it would be very impractical and it would also reduce strongly the efficiency of the measurement. To this it has to be added that in the automotive industry packaging space restrictions limit quite strongly the thickness of trim parts and then their absorption at low frequency. As a consequence, the evaluation of the absorption of trim parts below 300-400Hz is seldom relevant. For all these reasons, in the automotive

industrial practice it has become normal to perform DFAC measurements on relatively small samples and parts and this has led to consider small volume reverberation rooms for DFAC tests as a natural (or -at least- very practical) option [4]. The result is that, as a matter of fact, nowadays most vehicle manufacturers make use of small reverberation rooms for DFAC measurements and during the last years there has been also an important effort aimed at the development of a related SAE test standard ([5], [6], [7], [8]).

If it is true that the use of small reverberation rooms in the automotive field was originated by a practical engineering need (the size of the samples to be measured, the fact that measurements had to be quick), it is also maybe true that, in parallel, during the first years of use of such small reverberation rooms not enough attention was devoted to the issues related to their size and the consequences they could have on the absorption tests results. Nevertheless, this initial lack of attention was successively well compensated by the good number of articles on the topic that have been published during the last 5-10 years (see, e.g. [5], [6], [7], [8], [15]). Overall, these papers seem to indicate that the use of small reverberation rooms for the measurement of DFAC is a viable option, provided the fundamentals of the use of such rooms are well understood. In particular, [5], [6] and [8] report results of round robin tests where measurements were conducted in rooms of various sizes and with samples of different nature. These results indicated how, at least for samples with a thickness of 25mm or less, the absorption results obtained in "full size" reverberation rooms (volume 200m³ or higher) were on average similar to those obtained in "medium size" (volume ~25m³) or "small size" (volume ~6.5m³) reverberation rooms and that reproducibility and repeatability results were similar. Some more details on this will be recalled in the next section.

Among all the "small-size" reverberation rooms, one that is very commonly used by automotive OEMs and trim suppliers is a 6.5m³ room known as the "Alpha Cabin". This was originally developed as a dimensional scale reduction of 1:3 of a full size reverberation room existing at a Swiss public laboratory for material testing. To avoid recalling it too many times with its commercial name, hereafter we will refer to it simply as to the "Cabin". This article intends to focus on this small reverberation room, with the aim of reproducing a DFAC test (in the mid-low frequency range, i.e. below its Schroeder's frequency) by pure simulation, given that the limited size of the room makes this feasible. The possibility to get by simulation the same absorption results that are obtained by testing can be interesting in two main respects. First of all, it can help in limiting the amount of practical tests carried out during parts' development. Secondly, and this is maybe the most important point, it can help a better understanding of the physics of the room and of the factors and issues that are important for a proper measurement of the

DFAC. For example, using simulation it is in principle possible to better understand the issues related to the limited diffusivity of the room and how to set-up tests to analyze such issues experimentally. Other issues that can be -in a first approach, at least- analyzed by simulation are those related to the size of the sample, the type of excitation used and so on. Of course, it is clear that at the end of the day it will always be necessary to carry out extensive tests to properly validate a certain procedure. But simulation can be of some help to drive the definition of these tests in such a way to make them more focused on the objective they intend to achieve.

This article, of course, cannot cover in detail all the aspects and issues just mentioned. It represents, though, the first necessary step that must be taken to be able to use simulation as an analysis tool in this field, i.e. verify that it is actually possible to reproduce by pure simulation a DFAC test in the Cabin at least in the mid-low frequency range which is, on theoretical grounds at least, the most problematic one. Once the reliability of simulation methods is assessed (and the limitations of such methods are well understood) it will be possible to use them to go deeper into the physics of the Cabin. Further work for this is already planned and some results will be reported during the oral presentation. A simulation approach to the analysis of absorption tests in the Cabin was already tried in [23], but with limited success. The present article, apart from extending the analyses to more test-cases and substantially improving the correlation with test data, focuses explicitly on important aspects related to signal processing and proposes also a new analytical method for the simulation of the DFAC in the Cabin that was not considered in [23].

The article is organized as follows. Section 2 recalls the main features of the Cabin and discusses briefly the well-known issues related to absorption measurements in the Cabin itself. Section 3 reviews in detail the experimental procedure that leads to the evaluation of DFAC in the Cabin, with special focus on the aspects related to signal processing. Sections 4, 5 and 6 are concerned with the simulation of a DFAC in the Cabin. In section 4 the test cases used as a reference for the validation of the simulation methods subsequently presented are described. In section 5 an analytic approach is proposed based on a kind of “equivalent” rectangular cavity. In section 6 an approach based on FE is further proposed. Eventually, section 7 includes some final remarks and conclusions.

2. BRIEF REVIEW OF THE ISSUES RELATED TO ABSORPTION MEASUREMENTS IN THE CABIN

Figure 1 shows a view of the Cabin. To generate the excitation sound field, 3 loudspeakers are used, positioned close to 3 corners of the Cabin. In figure 1, the loudspeakers' positions are represented with red dots. The SPL is recorded

inside the Cabin at 5 positions, represented in figure 1 with yellow dots. For practical convenience, these 5 positions lie on a plane parallel to the Cabin's floor and are evenly spaced along a circle having a diameter of 1.2m. This allows the sequential measurement of the SPL at the 5 positions using a single rotating microphone

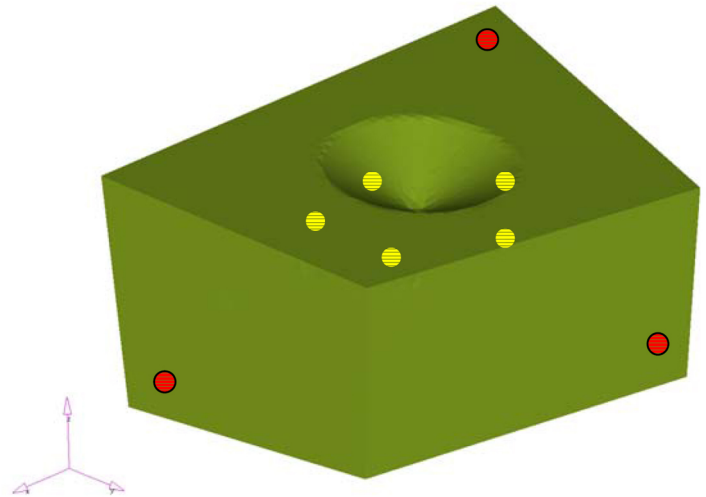


Figure 1. A view of the Cabin. Red dots indicate loudspeakers' positions. Yellow dots indicate response microphone positions.

The evaluation of the Cabin's average RT60 is carried out independently for each one of the 1/3-octave frequency bands from 400Hz to 10kHz. This of course reduces the efficiency of the procedure but considerably simplifies (and makes safer) all signal processing, avoiding the need to filter the microphone response signals. We will come back to this point in the next section.

As already mentioned in the introduction, the volume of the Cabin is about 6.5m³. Its cut-off frequency, evaluated using the well-known formula [8]

$$f_{\min} = \frac{c}{\left(\frac{V}{4}\right)^{\frac{1}{3}}} \quad (1)$$

is then about 300Hz. In (1), c is the speed of sound and V is the volume of the Cabin. This is the frequency limit above which the Cabin has -in principle- the potential of being diffuse. The low-frequency limit of 400Hz commonly used in absorption tests carried out in the Cabin is actually set taking into account (1).

Another important frequency limit commonly used to assess the diffusivity of a reverberation room is the so-called “Schroeder frequency”. This frequency is defined as the

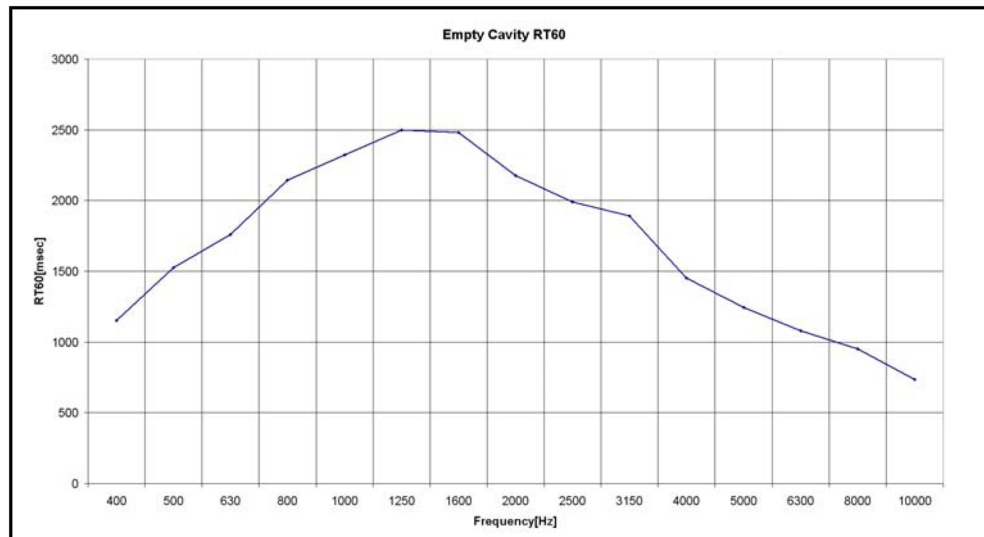


Figure 2. Typical average RT60 measured in the empty Cabin

frequency above which the average width of a mode's peak is such that at least another couple of mode peaks fall into it (i.e. the modal overlapping factor is at least 3). In other words above this frequency room modes are so close one to the other to be practically indistinguishable and the sound field can then be considered truly diffuse. This frequency depends on the geometry of the room and on its absorption area. An estimate can be calculated for the case of rectangular rooms, obtaining the formula:

$$f_{Sch} \approx 2000 \cdot \left(\frac{RT60}{V} \right)^{\frac{1}{2}} \quad (2)$$

In [formula \(2\)](#), RT60 represents the reverberation time of the Cabin that, of course, in turn depends on frequency. [Figure 2](#) shows the typical RT60 measured in the empty Cabin as a function of the frequency. Taking these values it is possible to see that the first frequency band for which the frequency calculated with [formula \(2\)](#) is lower than the center of the band itself is the band centered at 1.6kHz. This means that, for the Cabin, up to the 1.25kHz band the Schroeder's criterion for field diffusivity is not satisfied.

As it is explained in [8], [18] and [20], the fact that up to 1.25kHz the Schroeder criterion is not satisfied does not necessarily mean that it is not possible to carry out DFAC measurements in the Cabin with reasonable confidence. These authors actually report how in some cases, “reasonably smooth” sound fields could be obtained even in rectangular rooms with a modal overlapping as low as 0.2, being the shape of the room (i.e. the proportions between the edges of the room) responsible for that. As a matter of fact, to be above Schroeder's frequency is just a sufficient condition to have -with a proper excitation- inside the analyzed room a

diffuse sound field. But DFAC measurements appear to be anyway possible also for frequency bands between f_{min} and f_{Sch} provided the number of modes within the analyzed frequency bands is sufficiently high (in the above mentioned references, a mode number of 40 is mentioned as a reasonable minimum) and that the distribution of the modes within the same bands is sufficiently uniform. As already mentioned at the end of the introductory section, it is not the purpose of this paper to go deeper into this topic; some more details will be given in the oral presentation. The comments reported in this paragraph were just to remark how the assessment of the quality of a reverberation room is a rather complicated task and how it is not possible to carry it out simply on the basis of the evaluation of Schroeder's frequency.

From the practical engineering standpoint, it is of interest though to understand how the absorption measured in the Cabin compares with the one measured in a bigger reverberation room. [Figures 3a](#) and [3b](#) show a comparison between the absorption measured in the Cabin (on a small-size 1m × 1.2m sample) and the absorption independently measured in a full-size reverberation room at the University of Wiesbaden on a 12m² sample. The material analyzed here was a cotton felt with an area weight of 1000 gsm and two different thickness values, namely 7mm and 20mm. Similar comparisons were obtained also with independent measurements carried out in the full-size reverberation room of EMPA (the Swiss Federal Laboratories for Materials Science and Technology). Furthermore, analogous comparisons can be found in [6] and in [8]. Data reported in these latter references show that, at least for samples having a thickness below 25mm, absorption results in the Cabin compare reasonably well with those obtained in bigger reverberation rooms. On the other hand, [23] reports cases

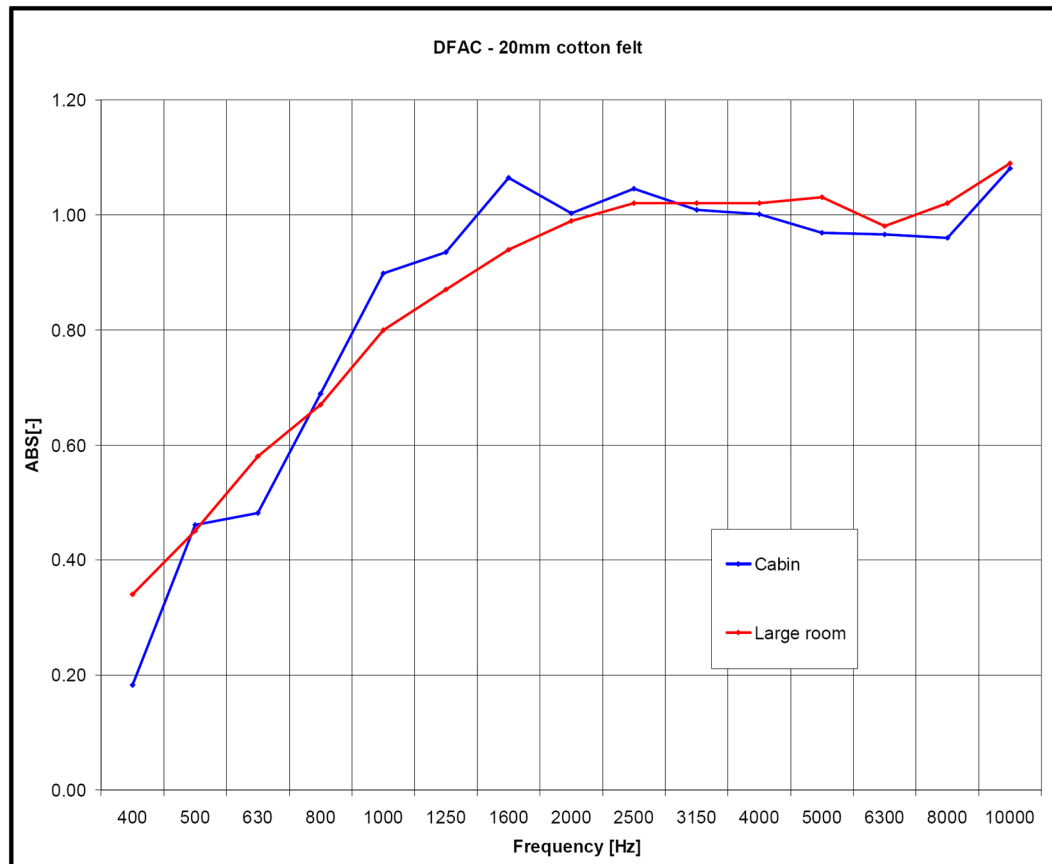


Figure 3a. Comparison between the DFAC measured in the Cabin and the DFAC measured in a large reverberation room for a cotton felt sample having a thickness of 20mm and an area weight of 1000gsm

where the absorption measured in a big reverberation room is much lower than that measured in the Cabin, being the discrepancies quite important, particularly in the mid-low frequency range. To the authors' knowledge, this is the only reference where such discrepancies are documented.

It is maybe fair to conclude that in most documented cases, the comparisons between the absorption results obtained in the Cabin and the absorption results obtained in a “full size” reverberation room show a rather good correlation but that, at the same time, the amount of data available in the technical literature is not enough to draw “safe” conclusions yet and that, on theoretical grounds, some doubts could remain even after looking at many good comparisons between results obtained in the Cabin and in big reverberation rooms.

In any case, the practical engineering needs that lie at the basis of the wide use of the Cabin and, more in general, of small reverberation rooms seem to indicate that the use of large reverberation rooms (and big material's samples) for the daily work is simply not a practical option. Also because, and this is an important point, even admitting that the absorption measured in a big reverberation room is the “real” diffuse field absorption, it is not clear at all whether this is a good

measure of the effect that the absorption of a part has on the acoustics of a vehicle passenger compartment (which has a rather small volume and where the sound field is in general not diffuse). A clear metric for quantitatively defining what this effect is has not been set yet. But, whatever it might be, it is this metric that should be used as a reference to assess whether the absorption data measured in a small reverberation room are representative or not, rather than the “ideal” diffuse field absorption coefficient.

3. BRIEF REVIEW OF THE EXPERIMENTAL PROCEDURE FOR THE EVALUATION OF THE CABIN'S AVERAGE RT60 AND EQUIVALENT ABSORPTION AREA

In this section the experimental procedure normally used for the evaluation of the Cabin's average RT60 is briefly reviewed. This is done in a purely descriptive way, just to facilitate the understanding of the rest of the article, where such procedure is often recalled.

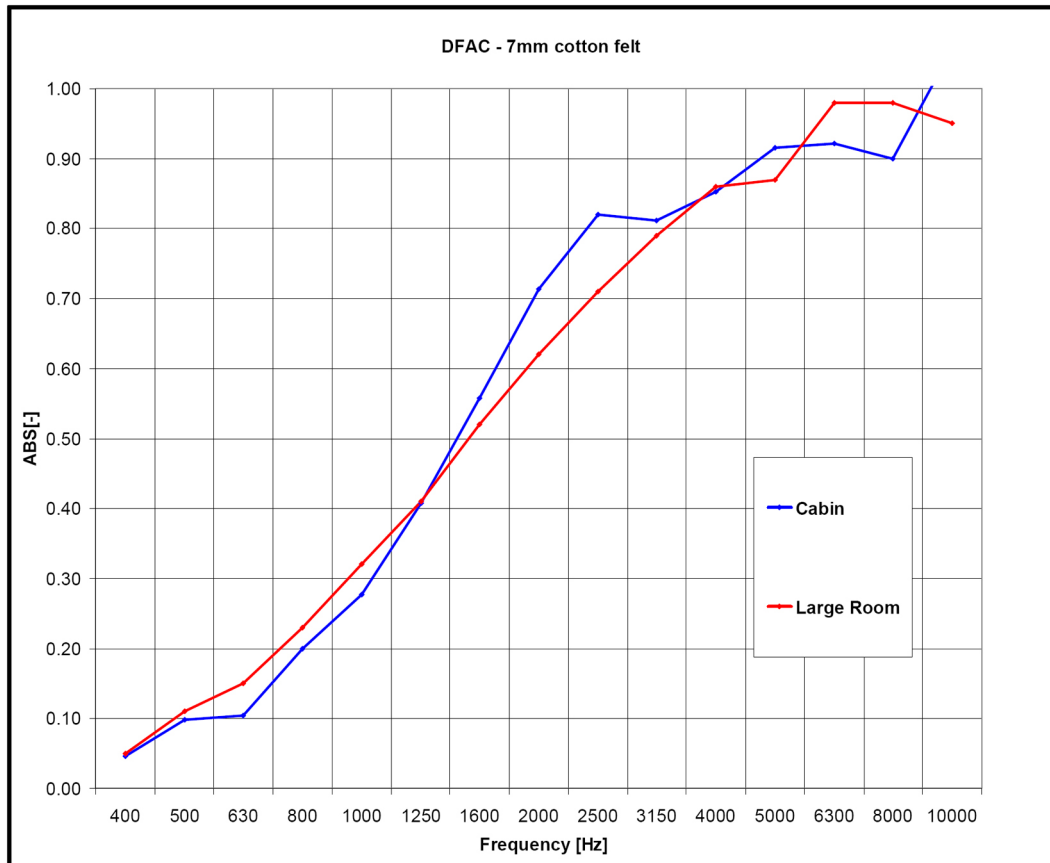


Figure 3b. Comparison between the DFAC measured in the Cabin and the DFAC measured in a large reverberation room for a cotton felt sample having a thickness of 7mm and an area weight of 1000gsm

So, for a given 1/3 octave frequency band and for a given microphone position, the experimental evaluation of the corresponding Cabin's RT60 is accomplished through the following steps:

1. The excitation signal relative to the given 1/3 octave band is generated and fed to the 3 loudspeakers. This signal is a frequency modulated tone burst. As an example, [figure 4](#) shows the excitation signal for the 800Hz band;
2. The time domain response of the Cabin at the microphone's position is recorded and its square magnitude is calculated. [Figure 5](#) shows an example of a microphone's time domain response.
3. On this function, the Schroeder back-integration process [21] is applied. In this way, a "smooth" SPL decay is obtained that is statistically equivalent to the ensemble average of an infinite number of independently repeated decays (all with the same source and receiver points, of course). An example of such a smooth decay is shown in [figure 6](#).
4. As a last step, a linear least-squares fit is performed on the section of the back-integrated smooth decay comprised between -5dB and -25dB (being these values referred to the

decay's initial SPL value). The desired RT60 is eventually calculated from the slope of the interpolating straight line so obtained. An example of interpolation line is shown in [figure 6](#).

All this measurement procedure for the evaluation of the RT60 fulfills the requirements of the ISO-354 standard. The cabin's absorption area is then evaluated from the RT60 using Sabine's law (as reported, again, in the ISO-354 standard):

$$A = \frac{55.3 \cdot V}{c \cdot RT_{60}} - 4 \cdot V \cdot m \quad (3)$$

where V is the Cabin's volume, c is the speed of sound and m is the power attenuation coefficient of the air in reciprocal meters. In the evaluation of c and m in (3), the effect of the variation of environmental parameters (temperature, humidity and atmospheric pressure) is taken into account, according to the procedure reported in the ISO standard 9613-1. At high frequencies, this can have a rather important impact on the evaluation of the Cabin's equivalent absorption area.

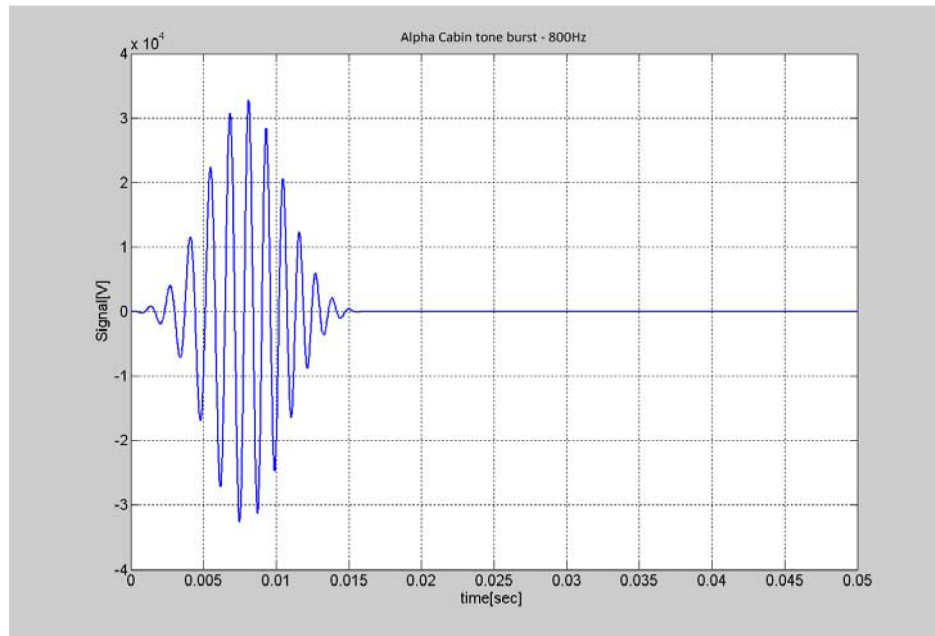


Figure 4. Excitation tone burst for 800Hz 1/3 octave band

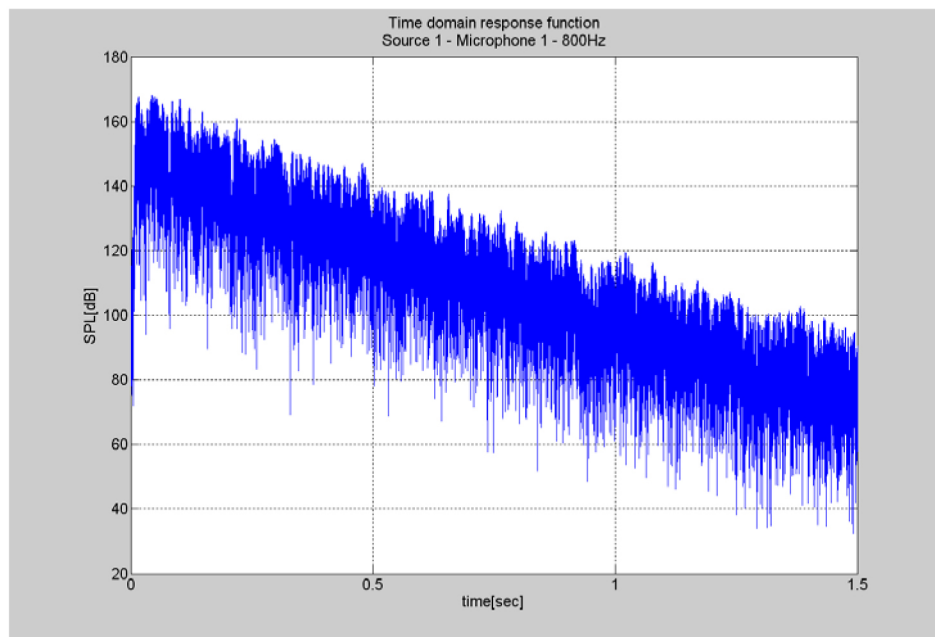


Figure 5. Example of microphone response function in the time domain Microphone position 1, 800Hz band

4. DESCRIPTION OF REFERENCE TEST-CASES

This paragraph introduces and describes 3 simple test-cases that will be used throughout the article as validation test-cases for the numerical procedures proposed for the evaluation of the Cabin's RT60. They all refer to the same type of felt (a felt typically used in the construction of porous

automotive carpets, hereafter genetically referred to as “Carpet Felt”), compressed to different thickness values, namely 7mm, 13mm and 20mm. [Figure 7](#) shows the DFAC measured in the Cabin on standard-size (i.e. 1m × 1.2m) samples, following the test procedure outlined in sections 2 and 3. Each curve in [figure 7](#) represents an average over 3 different samples.

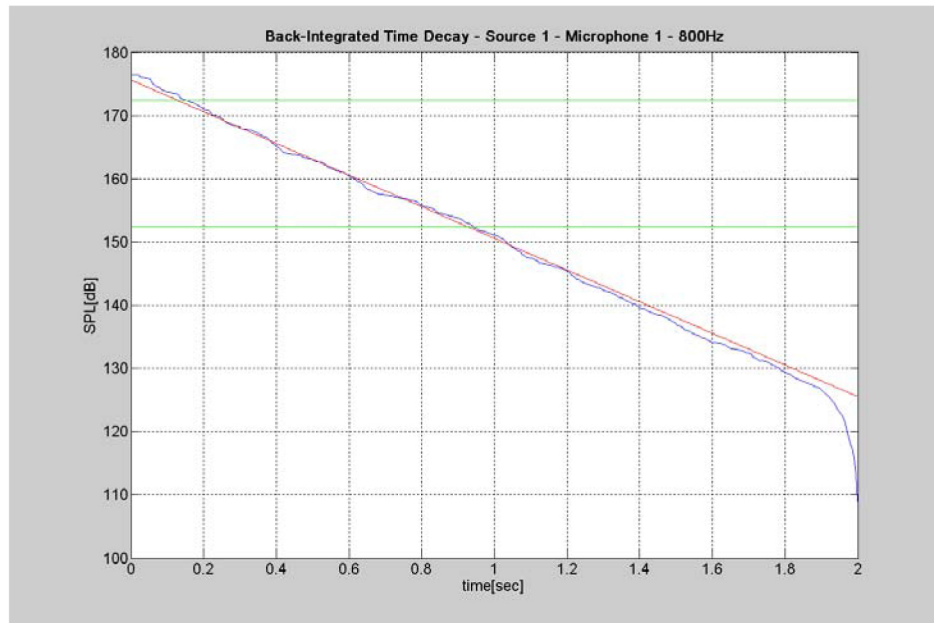


Figure 6. Back integrated time decay example -Microphoneposition 1, 800Hz band. The red line is the linear interpolation of the time decay section between -5dB and -25dB

Biot-Allard parameters [3] for the Carpet Felt at the different analyzed thickness values were measured with a combination of direct and indirect techniques: porosity and air-flow-resistivity were measured directly (see [27] and [28]), while for the other acoustical parameters (tortuosity and characteristic lengths) an inverse technique was applied [29]. As far as mechanical parameters are concerned, these were estimated from the transmissibility of Carpet Felt samples [30], assuming for the Carpet Felt itself a very low Poisson's ratio. Table 1 reports the Biot-Allard parameters obtained for the Carpet Felt for the 3 different thickness values of 7mm, 13 mm and 20mm.

The material parameters for the Carpet Felt were validated using Normal Incidence Absorption Coefficient (NIAC) measurements in a Kundt-Tube. As an example, the comparison between the measured NIAC for the 20mm Carpet Felt and the NIAC obtained by simulation using the well-known Transfer Matrix Method (TMM, see e.g. [24]) making use of the Biot-Allard parameters given in table 1 is shown in figure 8. As one can see (and as it is usual for this type of quantity), the correlation is quite good. It is worth remarking though that for a soft felt like the one considered here, this type of validation is actually relevant only for the acoustical Biot parameters. At the same time, it is also clear from the values reported in table 1 that the Carpet Felt considered here is very soft and that, as a consequence of this, the dynamical behavior of its skeleton plays a negligible role in the determination of its absorption (only the small oscillation appearing in the absorption curve after 500Hz could be due to some resonance of the material's skeleton). A

thorough validation of the structural parameters is then of little interest.

The comparison between the DFAC measured in the Cabin and the DFAC obtained by simulation with the TMM is shown in figures 9, 10 and 11 for the 3 different thicknesses of the Carpet Felt here under study. In the TMM, the exciting "diffuse field" is normally represented as a superposition of uncorrelated plane waves impinging on the surface of the material from all possible directions. Classically, when using the TMM, a maximum incidence angle is used, both to avoid numerical problems related with grazing incidence and to take into account the fact that, in most measurement environments (even in relatively big reverberation rooms) it is not very easy to obtain grazing incidence conditions. In the simulations with the TMM reported on figures 9, 10, 11, a maximum incidence angle of 80 degrees was used (this value is just one of the values classically used in the application of the TMM to diffuse field excitation). As one can see, relatively big discrepancies are found in the mid-low frequency range. These discrepancies are not a surprise, since they have been observed in several other cases (see, e.g. [11], [12], [13], [14], [15]), they are recalled by many other authors (e.g. [8] and [23]) and are known to be due to diffraction of sound at the edges of the sample (the so-called "edge effects"), as well as to a non-perfect diffusivity of the measurement environment.

To improve the correlation with DFAC test data and remaining within the framework of the TMM (that has the undeniable advantage of being extremely efficient from the

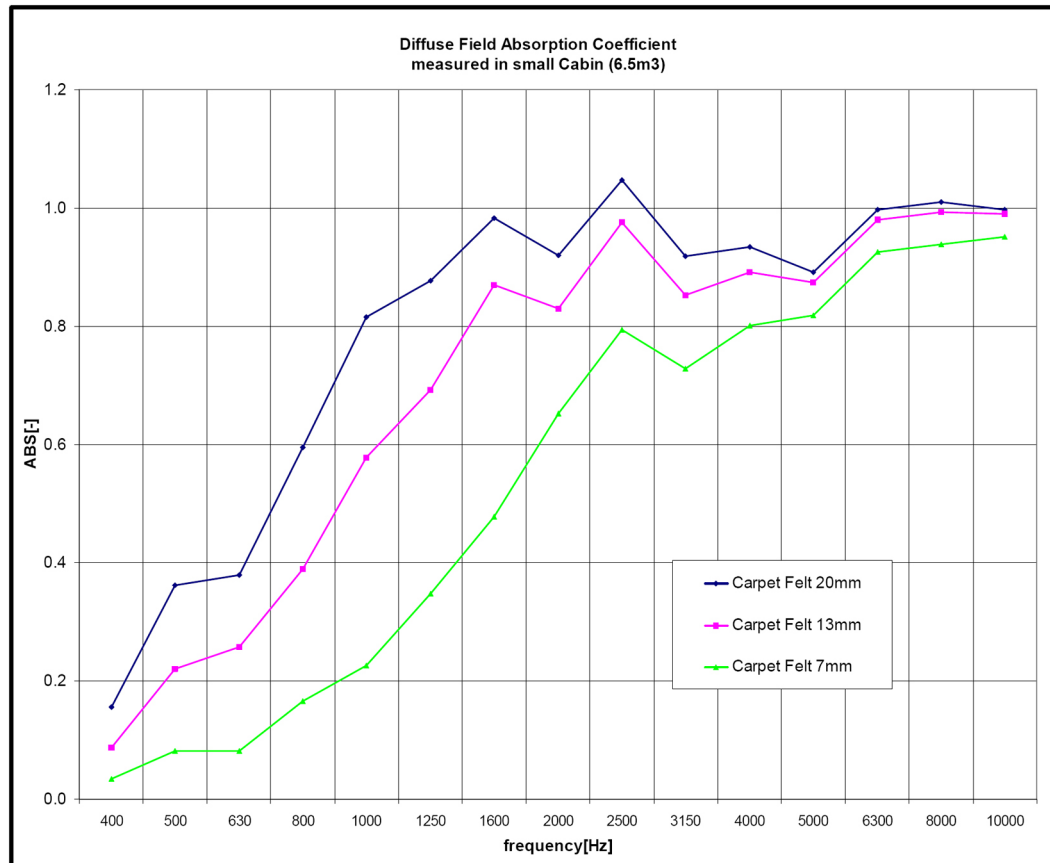


Figure 7. Diffuse Field Absorption Coefficient measured on flat samples of felt used for the construction of automotive carpets

Table 1. Biot Allard parameters for Carpet Felt at different thickness values

	Carpet Felt 7mm	Carpet Felt - 13mm	Carpet Felt - 20mm
structural density[kg/m3]	1423.7	1480	1471
porosity[-]	0.8927	0.944	0.9584
air-flow resistivity[Ns/m4]	161000	48600	27700
tortuosity[-]	1.4	1.16	1.14
viscous char. Length[μm]	24.3	37.7	51.7
thermal char. Length[μm]	80.3	134	168
skeleton Young's modulus[Pa]	44200	32700	22950
skeleton Poisson's ratio[-]	0.01	0.01	0.01
skeleton loss factor [-]	0.182	0.173	0.179

computational standpoint), in the available technical literature two techniques are proposed. The first one is very simple and consists in playing with the maximum incidence angle. For example, a slightly better correlation than the one shown in figures 9, 10, 11 could be obtained by reducing the maximum incidence angle from 80 degrees to 72 degrees. But the correlation improvement obtainable in this way is rather tiny (at least for the material analyzed here) and, furthermore, the change of the incidence angle has no clear justification from the physical point of view. A second (and much more

refined) procedure to improve the correlation between test results and TMM results consists in applying to the results of this latter method a “finite size correction” ([25]-[26]) mathematically represented by a spatial window (having the same size and shape of the measured sample) that is used to “truncate” the incident and reflected acoustic fields. The application of this spatial window determines a scattering of the wave-number spectrum of these fields towards wave numbers higher than the acoustical wave number and then an effective increase of the absorption. As it is well documented