Qualification of the combined insulation and absorption properties of a multilayer material for the automotive industry

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Abstract:

In automotive industries, acoustic comfort is mainly governed by the ability of the soundproofing material to both insulate the car cabin from outside noise and absorb noise inside compartment. The requirements of mass reduction and the reduction of absorbent area led a supplier to develop a new multilayer material formed with only textile materials (felt) with both insulation and absorption properties. To understand the behaviour of the system, a complete study is performed by the CTTM, in collaboration with the automotive supplier, in the following steps: measurements of intrinsic parameters of each layer of the system, measurements of acoustic performances of the system for absorption and insulation, numerical simulations with MAINE3A and analysis of acoustic behaviour of the system. The definition of a combined indicator is then proposed: it takes into account the two acoustic properties allowing easier comparisons. Finally, a fast and easy testing method using a small reverberant chamber is presented to determine this indicator.

Keywords: Insulation, absorption, fibrous material, reverberant chamber

1 Introduction

The resulting Sound Pressure Level (SPL) inside a cavity, and particularly inside a car cabin, is a function of the insulation and of the absorption of the panels constituting the cavity.

Usually the two phenomenons are considered separately. The insulation from the three main noise sources – i.e. the engine noise, the road noise and the aerodynamic noise - is usually obtained by using two sheets (steel and viscoelastic mass) separated by a porous material. This principle allows good performances for insulation but not for absorption except for the low frequencies, near the specific mass-spring resonance. In this case, to improve the acoustic comfort in the passenger compartment, it is necessary to add absorbent materials and as a result the weight of acoustic treatments increases.

Hence, the separated optimization of each function leads to a strong mass and cost increase of the soundproofing layers.

Moreover, the usual insulation devices use raw materials from petrochemical industries with, nowadays, waste recycling difficulties and prices variability. Also, the reduction of the absorbent area in the passenger compartment (with increase of glass area for example) and the requirements for mass reduction impose the automotive industry to define new insulating concepts which provide also good performances in absorption.

These critical issues were solved by a tier 1 – automotive supplier which has developed an innovative 2-layers material based on textile structure. This new acoustic system exhibits dual acoustic performances as well as an environmentally friendly behaviour thanks to the major use of recycled raw materials.

By controlling the characteristics of each layer, the global acoustic behaviour of the system tends to an ideal compromise between absorption and insulation.

Figure 1 shows the new fibrous system with dual acoustic performances which competes effectively with EPDM mass/spring system (mainly insulating) and common fibrous system (mainly absorbing).

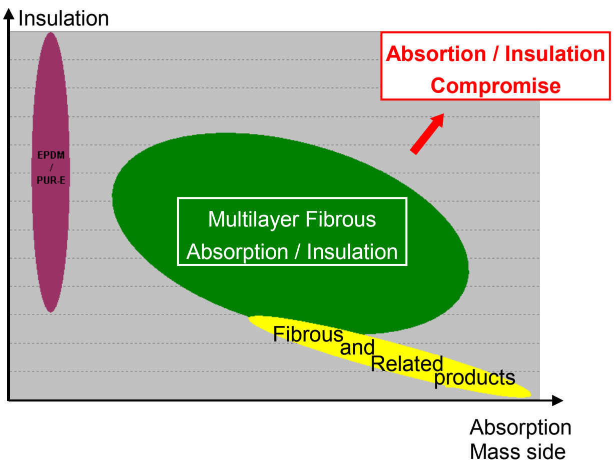

Figure 1 : Dual acoustic performances

Figure 2 focuses on the ecological features of the fibrous system: the life-cycle answers to the current environmental requirements from the raw material supplying to the end-life of the product.

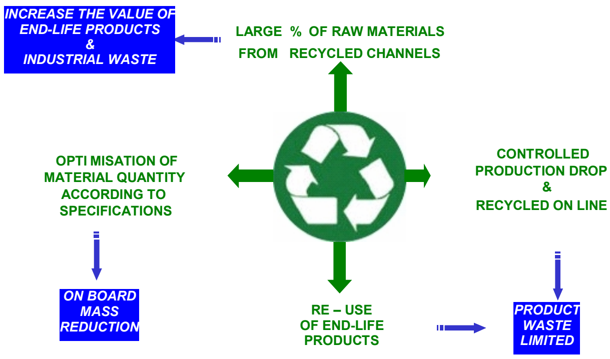

Figure 2 : Ecological features of the fibrous system

2 Full Study of the multilayer felt

2.1 Introduction

The multilayer material we studied (Figure 3) is constituted with only fibrous materials and based on the mass-spring principle. The mass layer has a high density obtained with solid inserts and high compression. This layer keeps good absorption properties and the system takes the advantages of both concepts (mass spring and usual absorption - Figure 4) and is therefore efficient in a broad frequency range.

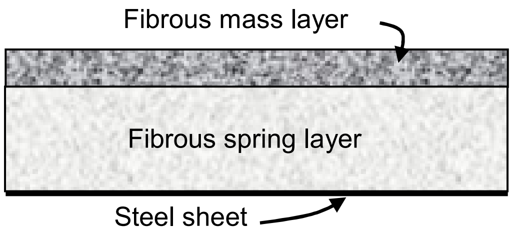

Figure 3 : Fibrous multilayer concept

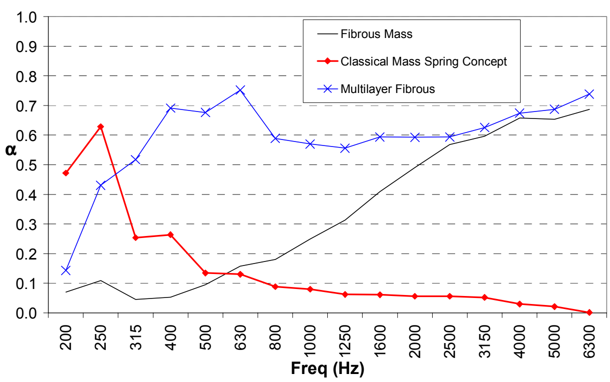

Figure 4 : Absorption coefficients of different concepts

To understand the behaviour of this system, we have made a study of the multilayer material according to the following steps:

- Measurements of the intrinsic parameters of each layer;
- Numerical simulation with MAINE3A of acoustical performance in absorption and insulation of each layer and of the global system;
- Measurements of acoustic performances of each layer and of the global system and validation of the numerical model;
- Analysis of the acoustic behaviour of the fibrous multilayer material.

2.2 Numerical simulation and measurement of intrinsic parameters

The software MAINE3A is used to simulate the acoustic behaviour of each single layer and the global system. At first, only the main intrinsic parameters - air flow resistance, material Young modulus, thickness, specific weight - were measured. The others parameters - porosity, tortuosity and characteristic dimensions - were estimated with successive adjustments (inverse method) by comparing with the acoustic performances measured for each single layer (absorption and insulation). This method yielded plenty of possible solutions, mainly because of the particularity of the mass layer: a bi-composed layer (fibrous and solid inserts) with high flow resistance and low porosity in comparison with usual fibrous materials. In consequence, these parameters were measured on the CTTM and LAUM specific test-benches.

2.3 Acoustic performances measurements

Each layer of the system (steel sheet / fibrous spring layer / fibrous mass layer) was measured separately to estimate its insulation (transmission loss) and its absorption (Alpha Sabine) properties. The same measurements were conducted with the multilayer material.

The insulation measurements were performed with the usual intensimetric method between the reverberation room (350 m^3) and the coupled semi-anechoic room (1000 m^3) of the CTTM. The dimensions of the measurement window are 0,8 m x 0,6 m.

The absorption measurements were conducted with the CTTM small reverberation chamber validated a few years ago [1].

2.4 Building and validation of the numerical model

To build the numerical model of the system, each layer is validated by comparing the numerical simulations to the measurements of the acoustic absorption and insulation properties. Figure 5 and Figure 6 show the results of simulations compared with measurements in two cases: the single fibrous mass layer and the multilayer material (with steel sheet for insulation).

All the measured intrinsic parameters are used in the MAINE3A simulation. Only small adjustments of the air flow resistance and the specific weight have been performed in accordance with the uncertainties on the measured parameters to improve the accuracy of the model.

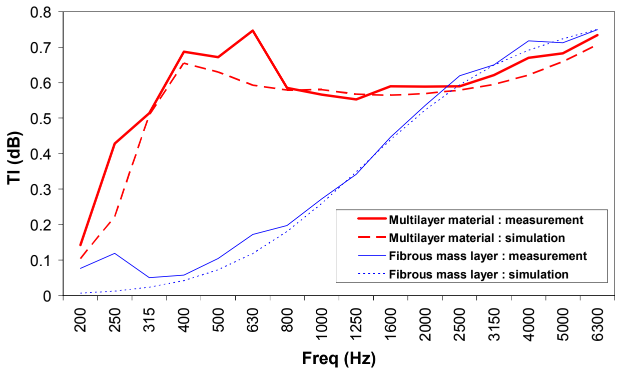

Figure 5 : Absorption properties measured / simulated of the multilayer material and of the single fibrous mass layer

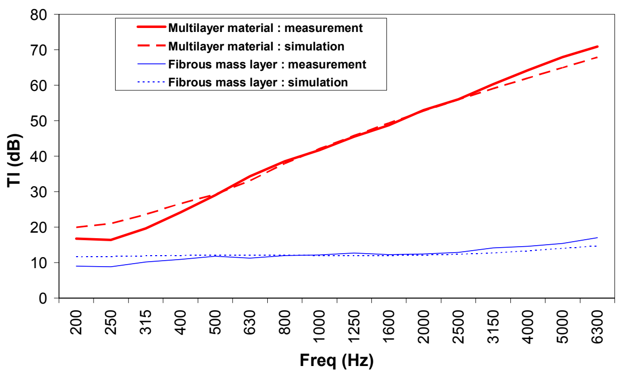

Figure 6 : Insulation properties measured / simulated of the multilayer material and of the single fibrous mass layer

2.5 Acoustic behaviour analysis of the fibrous multilayer material.

With the numerical MAINE3A model validated above, it is easy to study the influence of each parameter on the acoustic behaviour of the fibrous multilayer system. Three different behaviours clearly appear corresponding to three frequency domains:

- In the low frequency range, the absorption performances are determined by the specific frequency of the mass-spring system. The main influential parameters are the Young modulus, the thickness of the fibrous spring and the specific weight of the fibrous mass. The resonance frequency of the mass-spring system corresponds to the minimum of the insulation performances.
- In the medium frequency range, the multilayer absorption is determined by the fibrous spring thickness and the fibrous mass parameters (mainly the flow resistance). To illustrate this effect, Figure 7 shows simulations in which the fibrous spring is replaced by an air layer of the same thickness and by an air layer of a double thickness. For the same thickness, between 1 and 2 kHz, the absorption does not change, whereas for the double thickness, the absorption is shifted towards the low frequencies. This effect can be explained by the increase of the acoustic velocity (according to the wavelength) with the elevation of the upper layer.
- In the high frequency range, the multilayer absorption is determined by the fibrous mass absorption only. As shown on the Figure 7, the performances of the multilayer material and the single fibrous mass are the same above 2000 Hz.

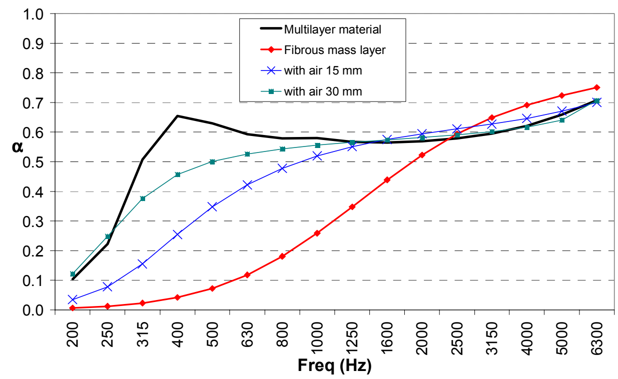

Figure 7 : Acoustics behaviours in three frequency domains : low, medium and high frequencies

3 Combined Indicator for multilayer comparison

3.1 Introduction

To compare the acoustic performances of two multilayer systems both in absorption and in insulation, a single combined indicator is proposed.

3.2 Noise reduction between enclosures

Considering a simple case of two reverberant cavities separated by a partition wall, the Noise Reduction (NR) – i.e. the difference between the noise levels in the two cavities – is defined as follows [2] :

$$NR = 10\log_{10}\left(1 + \frac{1}{\tau}\frac{S\alpha}{S_w}\right) \qquad (1)$$

Where:

- τ is the transmission coefficient of the partition
- S_w is the surface area of the partition ;
- S the total surface area of the receiving cavity ;
- α is the average absorption coefficient in the receiving cavity

Generally the second term of equation (1) is greater than unity, so the previous equation becomes the well-known equation of coupled reverberation chambers [3] :

$$NR = TL + 10\log_{10}\left(\frac{S\alpha}{S_w}\right) \qquad (2)$$

Where TL is called the Transmission Loss of the partition in dB :

$$TL = 10\log_{10}\left(\frac{1}{\tau}\right) \qquad (3)$$

The expression (2) shows that the decrease of the noise inside the receiving cavity is due to the transmission loss of the partition and also to the global absorption of the receiving cavity.

3.3 Absorption contributions

In the receiving reverberant cavity, the total absorption area can be decomposed as followed:

$$S\alpha = (S - S_w)\alpha_0 + S_w\alpha_w \qquad (4)$$

Where α_0 and α_w are respectively the absorption coefficients of the empty cavity and of the partition on the receiving side.

The two parts of equation (4) represent the contribution of the absorption of the cavity walls and the contribution of the absorption of the partition alone.

For example, if we consider a partition of 1.2 m² tested on a reverberant cabin of 6.44 m^3 volume and of 22 m² developed surface, the equivalent absorption area of the empty cabin is of the same order as the absorption area of the partition. Thus the contribution of the cavity is often equivalent to that of the partition alone.

3.4 Combined Indicator

To consider both absorption and insulation of a partition, Duval [4] proposed a SEA model of two coupled cavities separated by the test panel. The Noise Reduction (equation 2) is directly computed, taking into account the total absorption of the receiving cavity (walls and partition).

In this article, we consider only the partition contribution to the Noise Reduction.

Combining equations (1) and (4), the Noise Reduction becomes:

$$NR = 10\log_{10}\left(\frac{\alpha_w}{\tau} + \frac{S - S_w}{S_w}\frac{\alpha_0}{\tau}\right) \qquad (5)$$

The first term of this equation is representative of the contribution of the partition alone: it is defined as the ratio of the absorption coefficient of the partition over the transmission coefficient. This term is called the Combined Indicator Q:

$$Q = \frac{\alpha_w}{\tau} \qquad (6)$$

Expressed in dB:

$$LQ = TL + 10\log_{10}(\alpha_w) \qquad (7)$$

In the context of a reverberant cavity, the absorption of the partition is added (negative term) to its insulation performance and this combined parameter is interpretable as a Noise Reduction NR. Regarding equation (7), the maximum value of the Combined Indicator reaches the transmission loss when the absorption is maximum.

Therefore this indicator is well-suited for qualifying a soundproofing layer for both its insulation and absorption performances.

4 Testing method

4.1 Description

The information on the insulation and on the absorption of the partition is required. Thus the two separated measurements are performed and then the combined indicator Q is deduced. The testing method described next lies on a single experimental set-up used for the two measurements: no additional manipulation is required.

Insulation

The measurement of insulation is performed with the small reverberant chamber of CTTM and the partition is fixed on a test window (Figure 8). Incident sound is generated inside the cabin and the incidence intensity is evaluated by usual pressure measurements. For the receiving intensity a p-p probe is used with a manually operated sweeping. The main advantage of this technique is that the receiving media is not specific (it must be simply quiet and slightly reverberant).

The Transmission Loss is then the ratio of the incident power to the receiving power.

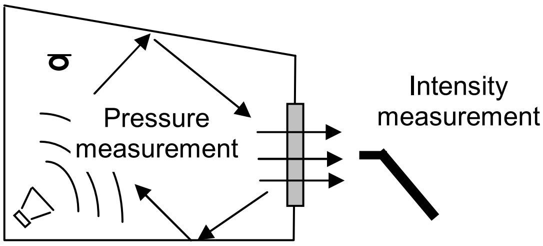

Figure 8 : Insulation set-up

Absorption

The measurement of absorption is performed with the same experimental set-up (Figure 9): the partition still mounted on the window, with the absorption side inside the cabin. The advantage of this configuration is that it can be more representative of the real case.

The absorption coefficient is obtained by the usual Alpha Sabine technique for diffuse field conditions.

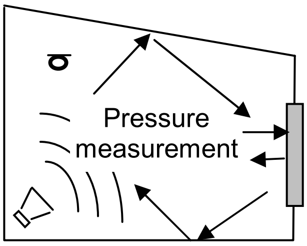

Figure 9 : Absorption set-up

Preliminary validations on insulation and absorption in small reverberation chamber are next presented.

4.2 Insulation validation for the cabin

To validate the measurement of insulation with the CTTM cabin, several arrangements of materials have been tested both with the cabin and with the large coupled reverberant and anechoïc chambers of CTTM. The Figure 10 shows an example of comparison between the two different apparatus on a multilayer felt. A good agreement is obtained with the cabin even with a high level of the multilayer insulation in high frequencies.

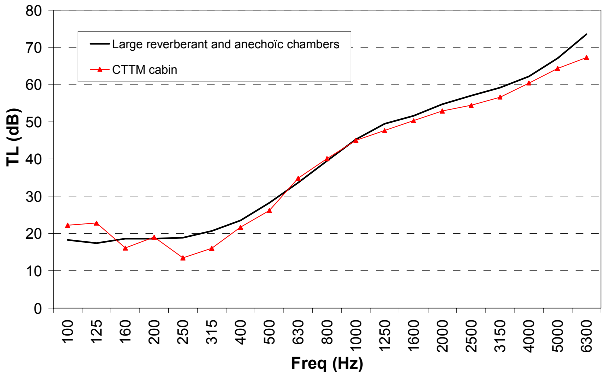

Figure 10: Transmission Loss for a multilayer felt

4.3 Absorption validation for the cabin

A few years ago, the CTTM developed its own small reverberant chamber and validated it estimating the confidence intervals (based on the GUM [5]) of the absorption coefficients of a large panel of materials measured both in the large and the small chambers of the CTTM [1]. The measurements in the large reverberant room were performed according to the standard ISO 354 [6] .The statistical study presented in the previous paper and the evaluation of the absorption coefficient uncertainties have allowed the validation of the small reverberation chamber of the CTTM. The use of a weighting correction, depending on frequency, to the cabin results allows for reliable measurements from 200 Hz, far below the conventional limits. An illustration is shown on Figure 11.

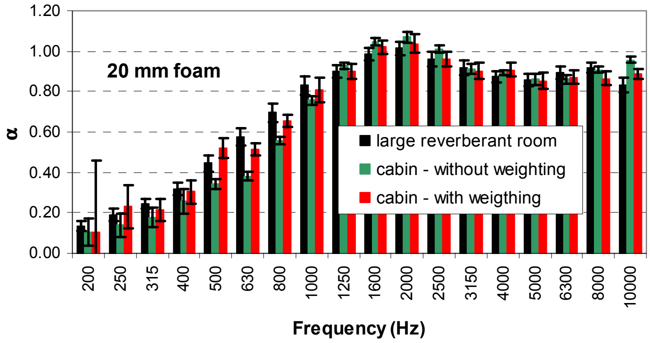

Figure 11: Absorption coefficient for a 20 mm foam

4.4 Absorption in vertical conditions

The previous validation of the absorption was conducted in usual condition, i.e. with the absorbent layer on the floor. In the present study, the absorption measurement is performed with an upright set-up used for insulation measurements, i.e. with the absorbent layer bound to the steel sheet.

For mass-spring systems, differences are expected because of the arrangement of the heavy felt layer on the light felt layer when the panel is placed vertically: due to the gravity the fibrous layer is compressed when the system is on the floor whereas, for an upright setup, the fibrous layer is free. Thus the resonance frequency can shift between these two configurations (this effect can not be predicted with Maine3A).

From an acoustic point of view, another difference between these two configurations lies on the strong difference on the surface impedance of the metal layer. For the floor case, a thick plate of 5 mm is used whereas for the window case a thin steel sheet of 1.2 mm is used.

On Figure 12, simulated absorption coefficients for the multilayer material are performed with Maine3A in two cases: with the rigid hard wall condition (no displacement allowed at this limit) and with a 1.2 mm steel sheet (with displacement allowed). The difference is clear in very low frequencies: a greater absorption is observed between 100 and 160 Hz due to the transit through the steel sheet and the resonance is shifted from the third octave band 400 Hz to the third octave band 500 Hz.

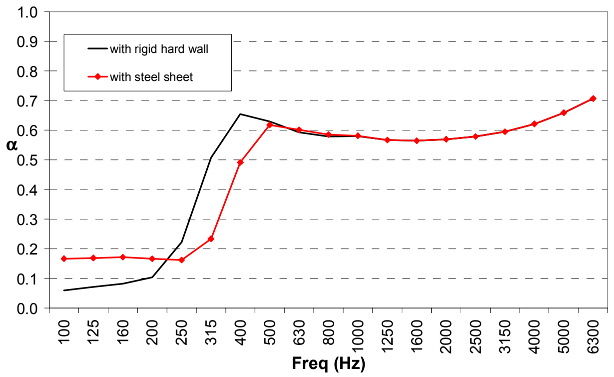

Figure 12: Simulated absorption for the multilayer material

On Figure 13, absorption coefficients for a 20 mm polyurethane foam are presented. The two first results correspond to the measurement on the floor with the same panel but with different areas: 1.2 m² for the first case and 0.55 m² for the second case (this small surface is that used for the measurement on the window). We can observe a strong over estimation of the absorption with the small panel over 1 kHz: this is due to the diffraction effect increasing with the ratio perimeter to area [7]. The third result is obtained with the foam bound to the steel sheet: for the same test area, no significant difference is observed even for the low frequencies.

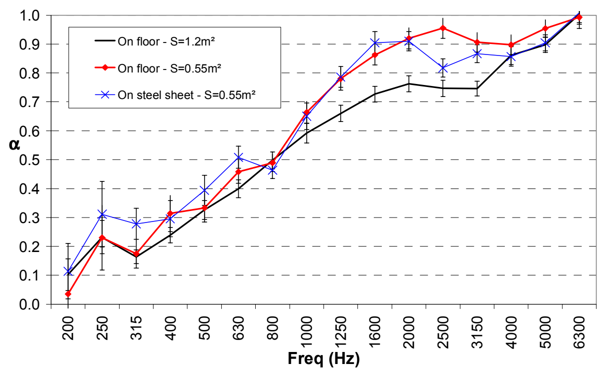

Figure 13: Absorption for a 20 mm polyurethane foam

The same experiments were conducted on the multilayer felt (Figure 14) and the same effect on the diffraction is observed with small areas of material.

However, any effect is observed on the resonance of the multilayer due to the gravity.

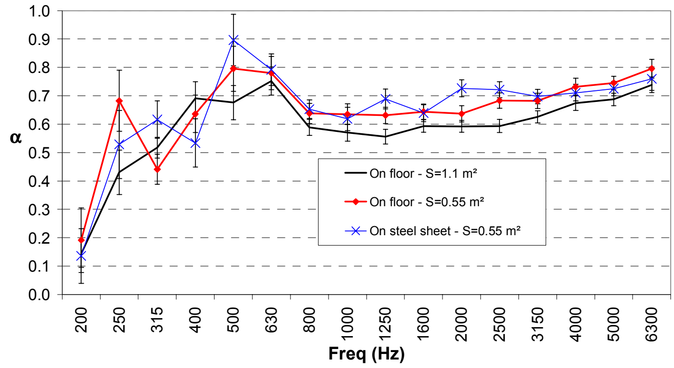

Figure 14: Absorption for the multilayer felt

The main conclusions for this part are:

- The absorption measured with the small reverberant chamber is not dependant of the position of the material (vertical or on the floor). This result should be verified in the large chambers because of the discrepancies that exist with the small reverberant chamber in the frequency range considered (below 800 Hz).
- The important effect of diffraction when small area of material are tested must be corrected by using, for example, a correction function of the frequency and the surface area tested. This correction function can be obtained by comparing measurements between the cabin and a large reverberation chamber, and by using two different surface areas of the same material. The diffraction effect is then linear with the aspect ratio [7].

4.5 Measured Combined Indicator

This part is dedicated to illustrate the use of the Combined Indicator Q for comparing the acoustical performances (insulation and absorption) between soundproofing layers.

Three configurations are tested in the CTTM Cabin with three different materials:

- The usual absorbent : a fibrous layer of 15mm of thickness ;
- The usual arrangement for insulation : a heavy layer of EPDM on the previous fibrous layer ;
- The multilayer felt: a heavy layer of compressed felt on the previous fibrous layer.

In this comparison the EPDM layer is 10% heavier than the heavy layer of compressed felt.

Figure 15 shows the absorption coefficients of the three configurations:

- the fibrous layer presents a usual absorption response, i.e. a strong absorption in the medium and high frequencies ;

- the configuration with EPDM has the usual behaviour of a mass-spring arrangement, i.e. a maximum of absorption at the resonance and a null absorption elsewhere ;
- the multilayer felt presents a broadband absorption.

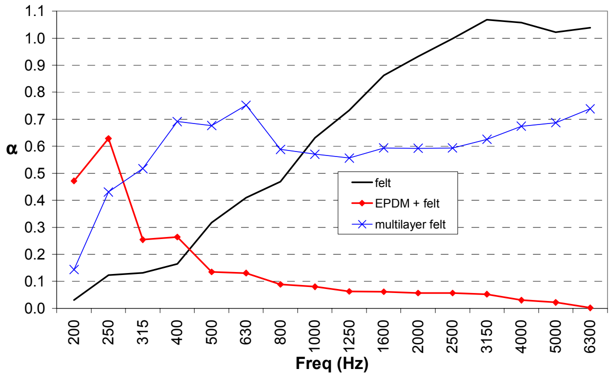

Figure 15: Absorption

Figure 16 shows the transmission loss of the two mass spring configurations obtained with a thin steel sheet. The usual configuration with EPDM and the multilayer felt present a similar transmission loss below 1000 Hz, and the EPDM arrangement is better above.

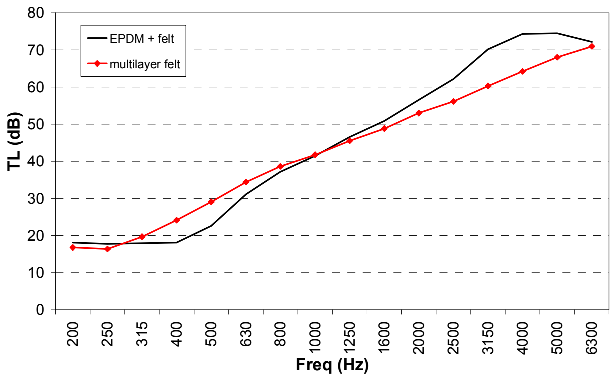

Figure 16: Insulation

Considering separately the absorption and the insulation, the classification of these configurations according to their acoustical performances is impossible. On the contrary, if we compute the Combined Indicator Q (Figure 17), the classification in terms on Noise Reduction becomes easier. In this case, the multilayer felt is the best arrangement above the third octave band 315 Hz.

These results show that despite a strong transmission loss (Figure 16), if the absorption is very low (as for the usual configuration with EPDM - Figure 15) the resulting noise inside a cavity closed with this partition will be higher than with the use of the multilayer felt tested in this study.

Hence, for this particular case, the acoustic performances for the multilayer felt are better than those for the usual configuration with EPDM and with a mass reduction of about 10%.

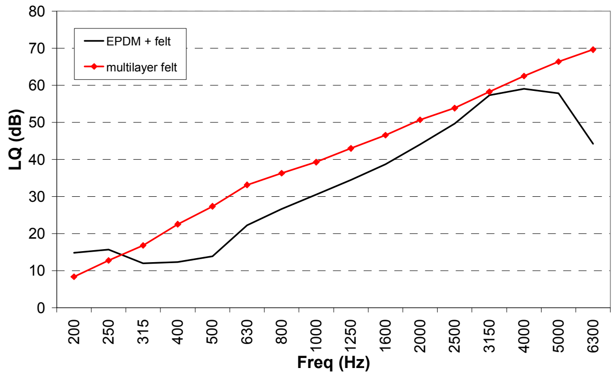

Figure 17: Combined Indicator

5 Conclusion

This paper deals with an innovative multilayer material based on textile structure and developed by an automotive supplier. The new fibrous system shows dual acoustic performances and competes effectively with the usual EPDM mass-spring system (for insulation) and common fibrous system (for absorption).

A numerical study performed with MAINE3A allowed the absorption behaviour understanding of the multilayer material. The broadband absorption performances are due to three phenomenons: the mass-spring response for low frequencies, the flow resistance effect of the thin layer with the back space for the medium frequency range and the common absorption of the upper porous material for high frequencies.

In order to compare systems with dual acoustic performances, a new criterion is proposed to take into account their absorption and insulation performances: the Combined Indicator Q. This Indicator is homogeneous to the Noise reduction between two enclosures. Its level is given by the Transmission Loss but weighted by the absorption characteristics of the material. The application of this criterion on the new fibrous system and on the common mass-spring system emphasizes the acoustical performances of the new concept compared to the usual concept to reduce noise inside a car cabin for example.

Finally, a testing method is presented with the use of a small reverberant chamber developed by the CTTM. With one single experimental set-up the two measurements of absorption and then of insulation are performed and, finally, the Combined Indicator is deduced.

6 Acknowledgement

The authors acknowledge Sandra Gaonac'h, Engineering Student of ENSIM, to her contribution to this work.

7 References

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8 Glossary

CTTM : Centre de Transfert de Technologie du Mans

ENSIM : Ecole Nationale Supérieure d'Ingénieurs du Mans

SEA : Statistical Energy Analysis

EPDM : Ethylene Propylene Diene Monomer

NR : Noise Reduction

TL : Transmission Loss