Development of acoustically effective foams: a new micro-macro optimization method

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Entwicklung von akustisch wirksamen Schäumen: Eine neue Mikro-Makro Optimierungsmethode

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Abstract

Using numerical homogenization techniques at microstructure scale, one can simulate the acoustic macro-behavior of open-cell or partially closed-cell polymeric foams, typically their absorption coefficient or Transmission Loss. This link is realized through the scaling of an idealized 3D Periodic Unit Cell (PUC), which represents statistically the pores shape as regular arrays of polyhedra. Based on two non-acoustic standard measurements, namely the porosity and the static viscous permeability (airflow resistance measurement), plus a microstructure ligament length measurement, the 3D PUC is scaled including membranes interconnecting the pores in the actual foam morphology. The opening of these membranes, constituting partially closed windows or throats between pores, proves to be an essential microstructure optimization parameter for sound absorption.

On this 3D PUC, Finite Element computations are carried out in order to determine the intrinsic Biot-Allard parameters of the foam (transport and elastic parameters, pure geometric ones being known), by solving asymptotically the viscous Navier-Stokes flow at low frequencies, the inertial Laplace potential flow (identical to electric conduction) at high frequencies and the thermal conduction (similar to diffusion-controlled reactions) at low frequencies. This micro-macro procedure proves to give very good correlation with complete non-acoustic and acoustic characterization measurements, like impedance tube, building a new reliable optimization scheme for foams, which will be illustrated on a PUR injected soft foam H1 (spring of insulators) and on a slab stiff PUR foam H2 (pure absorber).

1. Introduction

Optimizing sound absorbing materials is of the utmost importance for the transportation industry in general and for the automotive industry in particular. Indeed, new CO_2 emissions reglementations (95 g/km CO_2 emission instead of 130 g/km) coming very soon in 2020 have put a high pressure on one of its key lever: weight reduction. The acoustic package of a car can represent up to 60 kg and has to play its role in the overall weight reduction effort that lies between – 200 kg to – 300 kg globally, meaning a minimum of – 25 % on the global NVH perimeter: absorbers, insulators, deadeners, carpets etc... One has to distinguish two classes of noise treatment problems: the absorption ones quantified by sound absorption coefficients (energy dissipation) and the insulation ones quantified by Transmission Losses (energy reflection). The authors have developed a wide range of lightweight insulator technologies mixing optimal absorption and insulation properties depending on the environment (pass-throughs, intermediate cavities like Instrument Panels etc…) ([1], [2], [3]). The application of these multi-layers concepts combining foams, felts, controlled airflow resistive non-wovens, airtight barriers like foils or heavy layers, stiff foil backed “fiber septums” (etc…), are reaching progressively the limits of a pure “concept based” weight reduction strategy ([4],[5]). Felts and foams themselves have to be drastically optimized as well in order to achieve such a weight reduction target at iso-acoustic performance. Indeed, acoustic comfort remains an important issue for the end consumer and is often a way to differentiate between brands…

Classical trial-error experimental optimization methods combined with a good understanding of the macro-acoustic Biot-Allard parameters physical role have led to efficient optimization works for fiber porous materials mainly [6]. Indeed, for absorption properties, microfibers having diameters between 10 µm down to an ideal 1 µm (approximately 1 dtex down to 0,1 dtex for PET fibers) have been more and more used in the transportation industry since 20 years for performance increase or weight reduction purposes. For insulator springs applications behind heavy layers typically, these microfiber felts are too soft and decouple badly in the middle frequency range. In this latter case, spring crimped or helicoïdal hollow fibers have to be mixed with the microfibers for improving the elastic properties [7]. The reason why a micro-macro approach is not so necessary for fibers here, even if powerful for explanation purposes and automatized optimization tools [8], is that one controls in fact quite easily the average microstructure through the mixing of noble “sized controlled” fibers (diameter) and through the compression rate (throat size), especially when the fibers are laid horizontally (which one gets easily with carding/napping/thermofixing felt production processes, like PET felts). On top of this, when using bi-component fiber bonding technology in low density cases, the resulting felt presents almost no tortuosity and very high porosities (typically above 0,98). Typical fibers where one can control the diameter size are synthetic or mineral fibers like PET, PP, acrylic, glass fibers etc… All recycled felts, using cotton waste for example also called “shoddy”, have to be analysed in a statistical fiber distribution sense on the contrary and present classically randomly oriented fibers [9].

Unlike fiber felts classically, the determination of relationships between 3D microstructure and acoustical macro-behavior of porous media is compulsory for foam optimization purposes, especially when dealing with membranes or solid films interconnecting the pores ([10], [11]). Indeed, any microstructure realistic morphology change will impact at least two intrinsic Biot-Allard parameters (geometrical and transport) at a time [12]. This means that looking for an optimal macro-acoustic parameters set, with Transfer Matrix Method for example ([6], [13]), will most likely lead to non-physical and/or unfeasible porous materials (impossible to manufacture in other words), with no existing corresponding microstructure. In the hypothesis, that there would be one matching microstructure, this does not mean that the corresponding porous material could be manufactured physically anyway. Finally, this is really what is at stake: linking the chemistry, the process, the corresponding microstructure and the resulting acoustic macro-parameters upwards and downwards (cf. Figure 1). This is a ten years multi-physics research program! This paper will focus on the two last steps of Figure 1, showing the reliability of the presented 3D optimization method on two industrial cases: a PUR injected soft foam H1 (spring of insulators) and on a slab stiff PUR foam H2 (pure absorber).

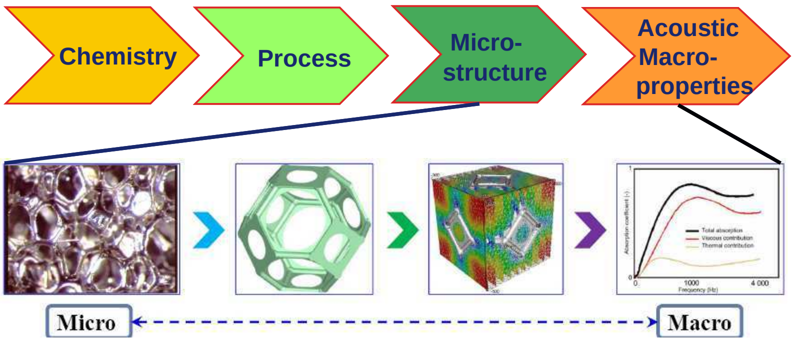

Figure 1: Focus of the presented bottom-up approach: *micro-macro link*

2. Biot-Allard parameters target setting

		Standard Foam	Resistivity σ x2	Tortuosity α_∞ x2	Young's Modulus E /3
Geometrical	Thickness (mm)	20	20	20	20
	Porosity ϕ	0,95	0,95	0,95	0,95
	Thermal Characteristic Length Λ' (μm)	150	150	150	150
Transport	Airflow Resistivity σ (N.m^{-4}.s)	20000	**40000**	20000	20000
	Tortuosity α_∞	1,3	1,3	**2,6**	1,3
	Viscous Characteristic Length Λ (μm)	50	50	50	50
Elastic	Density ρ (kg/m3)	55	55	55	55
	Young's Modulus E (Pa)	40000	40000	40000	**13333**
	Loss Factor η	0,22	0,22	0,22	0,22
	Poisson Ratio ν	0,3	0,3	0,3	0,3

Figure 2: Standard soft foam Johnson-Champoux-Allard (JCA) Biot parameters [6]

- Absorption problem

Using the classical Johnson-Champoux-Allard (JCA) 5 geometrical and transport Biot parameters of a standard soft foam implemented in a Finite Transfer Matrix Method code (FTMM), one can run optimization numerical experiences, where only one Biot-Allard parameter moves at a time: multiply by 2 the airflow resistivity and the tortuosity and divide by 3 the Young's modulus ([14], [15]).

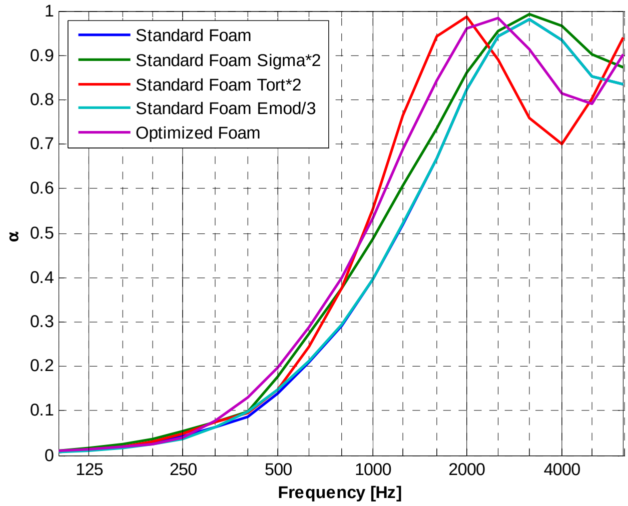

Figure 3: Absorption problem (FTMM normal incidence): *Biot parameters target setting*

The results shown Figure 3 emphasize the importance of both airflow resistivity and tortuosity for improving the absorption in the middle frequency range particularly, even if the tortuosity should not exceed α_∞=2 in order to avoid too much absorption losses in the high frequency range. On the contrary, the Young's modulus divided by 3 decrease does not bring anything in this already soft foam absorption case (the frame is not excited here anyway).

- Insulation problem

For the insulation problem, a mass-spring system is considered, namely a heavy layer and the same standard soft foam, in order to excite both interstitial fluid and frame solid phases of this spring foam.

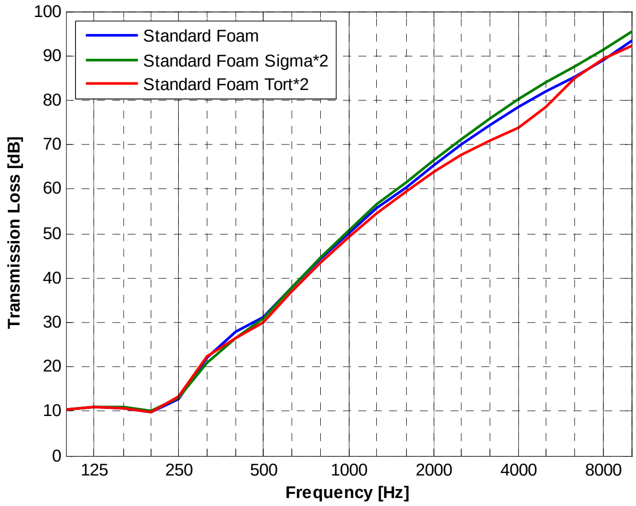

Figure 4: Insulation problem (FTMM diffuse field): *Biot parameters target setting*

The same FTMM numerical experiences are launched as for the pure absorption case (more refined systematic optimization analysis can be carried out with poroelastic finite elements like in [16]). Figure 4 shows the results for the geometrical and transport Biot-Allard parameters, showing once again the importance of good airflow resistivity for improving the Transmission Loss by 1 dB to 2 dB above 1 kHz up to 10 kHz. On the contrary, the tortuosity has a negative impact in the same high frequency area (without any gain in the middle frequency), which is directly linked to the drop in dissipation observed on its absorption coefficient of Figure 3 at 4 kHz as well.

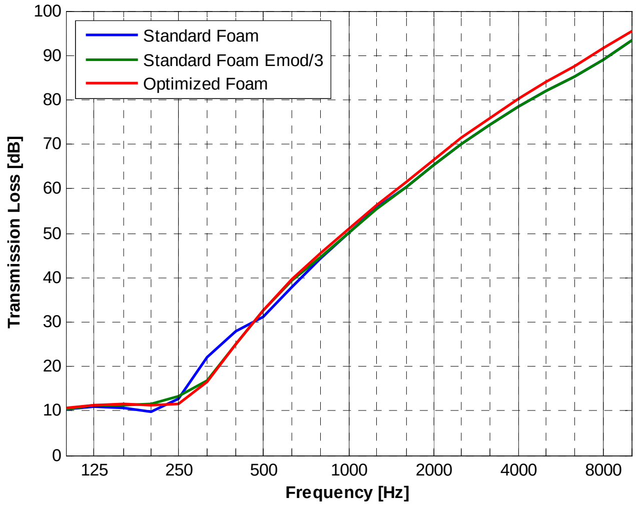

Figure 5: Insulation problem (FTMM diffuse field): *Biot parameters target setting*

Reducing drastically the Young's modulus alone brings a 1 dB improvement in the middle frequency range for the Transmission Loss between 500 Hz and 1 kHz (cf. Figure 5). The observed loss between 250 Hz and 500 Hz is linked to the quarter wave resonance of the first frame-borne Biot wave for the standard foam, which is often not observed with this magnitude experimentally [17].

Anyway, dividing by 3 the Young's Modulus makes this resonance disappear, like we observe for very soft porous materials like felts. In the latter case, the complete poroelastic Biot-Allard model is not necessary anymore and the limp model is then sufficient [6]. The best optimized foam is then a combination of a doubled airflow resistivity and of a divided by 3 Young's modulus very soft spring foam, showing a 1,5 dB to 2 dB improvement in Transmission Loss from 500 Hz up to 10 kHz. The question is now how to materialize this into an actual foam and go downwards from ideal poroelastic macro-parameters down to a feasible corresponding microstructure?

3. Translation of the targeted poroelastic Biot-Allard macro-parameters into a feasible microstructure

The presented study gives an approximate answer to the last question, in the sense that the downwards path has not been neither established nor used here. Many bottom-up micro-macro computations have been used instead, in order to identify classes of microstructures that could fulfill the previously set targets for both absorbing and insulating foams knowing chemical and process morphology influent adjustable parameters.

For absorbing foams, the defined targets are double the airflow resistivity and increase the tortuosity up to α_∞=2 maximum, compared to our standard soft foam reference (H2 foam afterwards) without any specific constraint on Young's modulus. For insulating foams, the defined targets are double the airflow resistivity and divide by 3 the Young's modulus (H1 foam afterwards), without changing the low tortuosity values of the standard soft foam reference, if possible (cf. Figure 3 to 5).

For the absorption problem, the various computations ([10], [11], [12], [18]), as well as PUR foam systematic microstructure characterization and empirical modeling [19], show that including and controlling membranes seems to be the best morphological way, in order to increase both airflow resistivities and tortuosities (and consequently reduce Λ, which follows the throat size, as well as increase the ratio Λ'/Λ [18]).

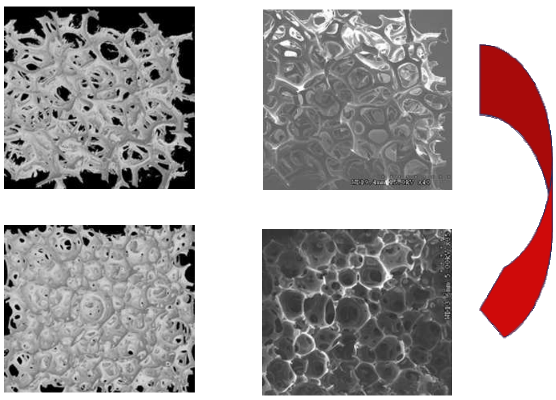

Figure 6: Microstructure morphology improvement: introducing membranes (H1 lower foam) with X-Ray tomography pictures on the left and Scanning Electron Micrography on the right.

For the insulation problem, the bottom-up computations ([12], [18]) and empirical modeling [19] show that a „commonly observed" homothetic reduction of the size of the pores D and corresponding ligaments length L and diameter 2r (cf. Figure 7a) would answer to the airflow resistivity increase target without any introduction of partially closed membranes. These fully open-cell microstructures without membranes, sometimes called „fully reticulated", are rather easy to get with melamine slab foams (genuine stiff 3D microfiber „felt"!) or even with PUR slab foams, which are produced with a free expansion. For the considered injected „standard“ foam, it is another story and it is much easier to both reduce the size of the pores and introduce membranes, by playing with the PUR formulation and the additives (cell opener, catalysts, surfactant etc...), in order to reach the rather high resistivity targets. Of course, the tortuosity will increase consequently, which is not particularly sought for insulation purposes here (cf. Figure 4).

On the contrary, the skeleton’s Young’s modulus reduction problem is an “easy to solve” issue from a PUR chemistry point of view. Regarding a specific PUR foam index situation, which depends on the mixing of diols and triols and therefore on the resulting available –OH radicals, as well as on MDI isocyanate molecule type with corresponding available N=C=O radicals, and while taking into account stoechiometric mixing ratios and water H_2O content, one can predict the number of “urethane” chemical bonds, which are directly linked to the stiffness of the foam (with “urea” secondary products bonds also). From this standpoint, it is then possible to scan above and below this stoechiometric value and get various soft Young’s modulus values here, with a certain chemically feasible delta (collapse etc…). Figure 6 illustrates this switch from a typical open-cell rather coarse foam microstructure (above) to our optimized very soft H1 injected foam, with smaller pores and the presence of partially closed membranes (below).

4. Micro-Macro approach: linking microstructure with acoustic macro-parameters

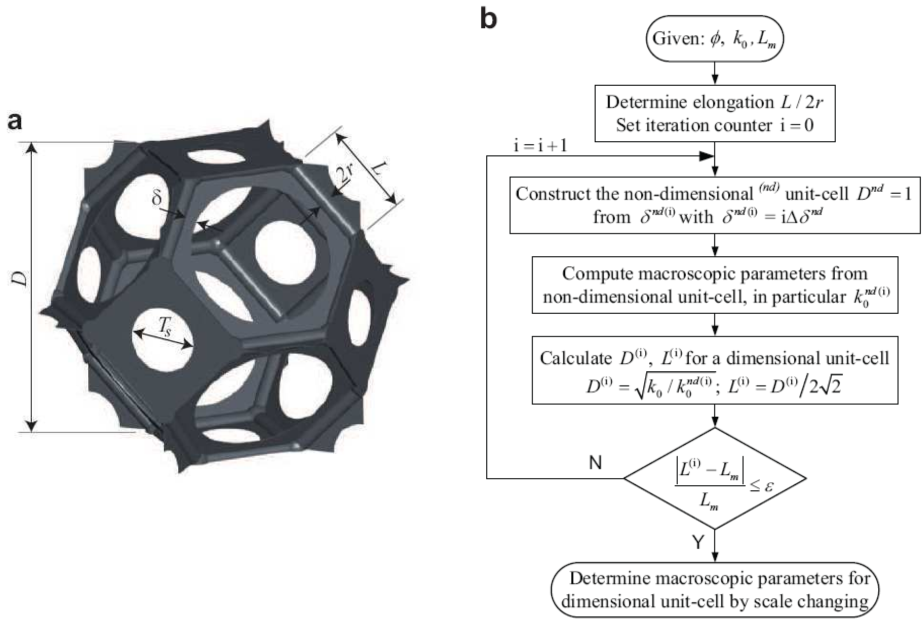

Figure 7: Microstructure tetrakaidecahedron morphology with membranes (left) and unit-cell local characteristic lengths identification algorithm (right)

Using numerical homogenization techniques at microstructure scale, one can simulate the acoustic macro-behavior of open-cell or partially closed-cell polymeric foams, typically their absorption coefficient or Transmission Loss ([8], [10], [20]). This link is realized through the scaling of an idealized 3D Periodic Unit Cell (PUC), which represents statistically the pores shape as regular arrays of polyhedra (tetrakaidecahedron shape cf. Figure 7a). Based on two non-acoustic standard measurements, namely the porosity and the static viscous permeability (airflow resistivity measurement), plus a microstructure ligament length measurement, the 3D PUC is scaled including membranes interconnecting the pores with a good representativity of the actual rather inhomogeneous foam morphology (cf. Figure 7b for a description of the detailed procedure from [12]).

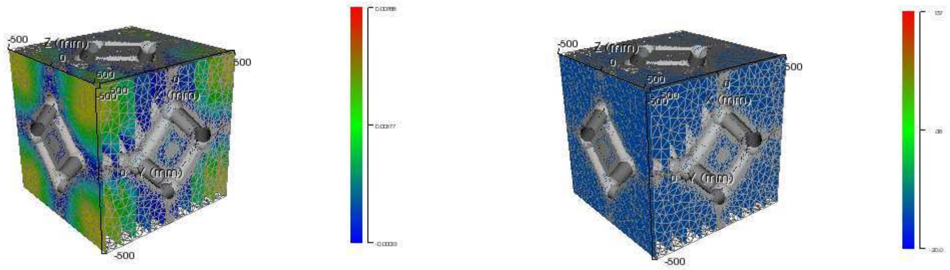

Figure 8: Velocity fields in asymptotic low (left) and high (right) frequency behaviors.

On this 3D PUC, Finite Element computations are carried out in order to determine the intrinsic Biot-Allard parameters of the foam (transport and elastic parameters, pure geometric ones being known), by solving asymptotically the viscous Navier-Stokes flow at low frequencies (cf. Figure 8), the inertial Laplace potential flow (identical to electric conduction) at high frequencies and the thermal conduction (similar to diffusion-controlled reactions) at low frequencies. The determination of elastic parameters is discussed in the conclusion.

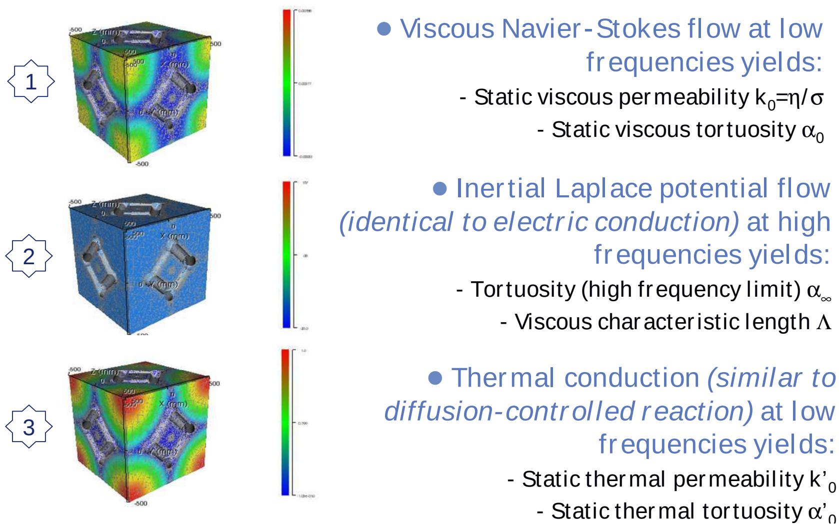

Figure 9: Macroscopic transport parameters are computed from three asymptotic calculations

Figure 9 describes the hybrid “asymptotic FEM calculations” based procedure for simulating the acoustic macro-properties from a representative 3D PUC by using semi-phenomenological porous material models with thus identified Biot-Allard parameters for the computation of the dynamic equivalent density and the dynamic bulk modulus of the foams. The great advantage of this hybrid method is the computational efficiency, by avoiding a computation at each frequency and by solving classical non-acoustic boundary value problems. There are three most commonly used models with an increasing complexity and precision: the well-known Johnson-Champoux-Allard model (JCA) with the 5 geometrical and transport parameters of Figure 2 ([14], [15]), the Johnson-Champoux-Allard-Lafarge model (JCAL) with 6 geometrical and transport parameters (introduction of the thermal permeability k'_0) [21], the Johnson-Champoux-Allard-Pride-Lafarge model (JCAPL) with 8 geometrical and transport parameters (introduction of the static viscous tortuosity α_0 and of the static thermal tortuosity α'_0) ([22], [23]).

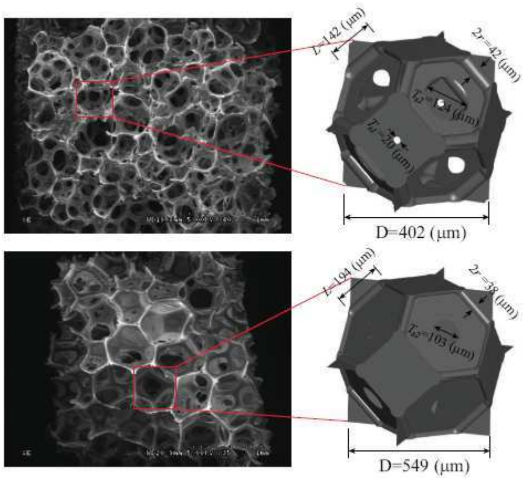

Figure 10: H1 (above) and H2 (below) foams resulting idealized PUC microstructures

Figure 10 illustrates the resulting Periodic Unit Cells identified applying the procedure of the Figure 7b for the two optimized insulating H1 foam and absorbing H2 foam. One can see very easily the important presence and significant closure rate of membranes, especially for the H2 foam, which was definitely the optimization lever for absorption. H1 foam is as a consequence less tortuous than the H2 foam, which was also at stake for the insulating properties. The opening of these membranes, constituting partially closed windows or throats between pores, proved to be an essential microstructure optimization parameter here. Indeed, it allows PUR foams, optimized this way, to compete against melamine and microfiber felts for their excellent absorption properties in the middle frequency range especially.

5. Micro-Macro approach: correlation results

The intrinsic Biot-Allard parameters characterization has been carried out using direct and inverse methods. The porosities Φ, static viscous permeabilities k_0, Young's modulus E, loss factors η and poisson ratios ν were measured directly with the standard „missing mass method", the „laminar flow element" method and the „Mariez-Langlois quasi-static" method respectively [6]. For the other parameters, namely thermal permeability k'_0, high frequency tortuosity α_∞, viscous and thermal characteristic length Λ and Λ', an expert manual JCA (Faurecia) or automatized JCAL inverse method (Foam-X software developed by the University of Sherbrooke) was used.

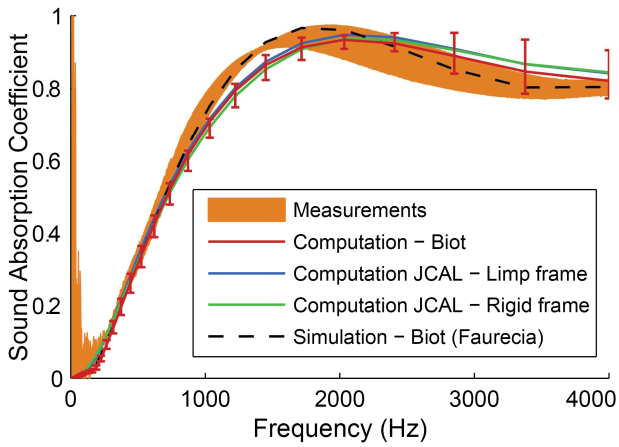

Figure 11: Normal incidence absorption coefficient 3D unit-cell TMM correlation: H1 foam

Despite common difficulties linked to the potential mechanical Biot waves perturbation inherent to the impedance tube measurement technique used as reference (sample boundary condition problem occuring for H2 typically) [24], the Panneton-Olny indirect method (analytical inversion knowing Φ and k_0) remains much better than any „curve fitting" inverse numerical technique ([25], [26]). This latter indirect technique was unfortunately not used here and is not yet implemented at Faurecia.

Nevertheless, the micro-macro 3D unit-cell based computations can be correlated directly to the impedance tube absorption coefficient measurements (or Transmission Loss afterwards), as shown Figure 11 for the H1 foam with good results whatever the frame stiffness hypothesis may be (rigid, limp or elastic for the Biot-Allard model). As expected for such a soft H1 foam [24], taking into account potential „bonded" boundary conditions with an axisymmetric poroelastic FEM code (FEMspire from the Sherbrooke University) for the side of the sample doesn't change anything in the correlation quality Figure 12.

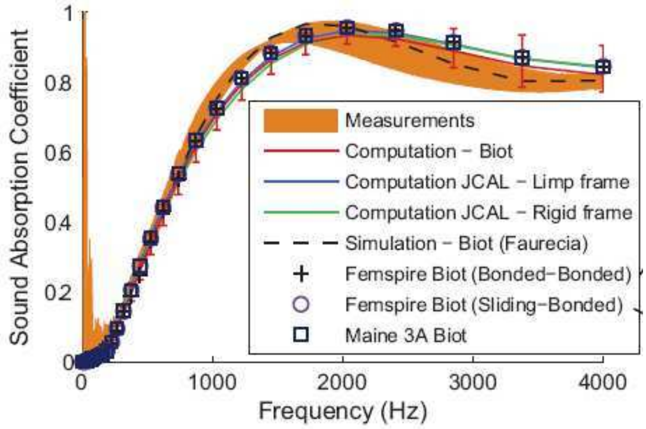

Figure 12: Normal incidence absorption coefficient 3D unit-cell poroelastic FEM correlation: H1 foam

On the contrary, the application of the „Frame Acoustical Excitability" criterion defined by Pilon et al. [24] leads to the prediction of a difficult measurement for the H2 foam, which is very resistive, very stiff and light (25 kg/m^3). Figure 13 shows clearly a disturbed measurement result (poroelastic Biot waves modes influence). The rigid model is not working here due to the low density of H2, whereas the limp model is giving a good approximation Figure 13.

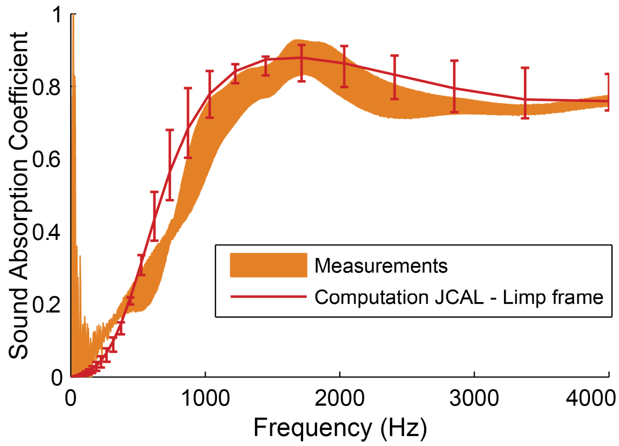

Figure 13: Normal incidence absorption coefficient 3D unit-cell TMM correlation: H2 foam

Only a complete poroelastic FEM model like the FEMspire code can catch the boundary condition issue [27]. Indeed, a TMM Biot-Allard simulation makes the hypothesis of a laterally infinite elastic flat sample. Solely a poroelastic FEM simulation with „sliding boundary condition" for the sample sides (sliding-bonded case) can give the same „ideal" results. The good as well as better correlations for the „bonded-bonded" case Figure 14 with a 2% pre-constraint for the Young's modulus measurement value demonstrates the strong influence of the elastic properties of the H2 foam on its absorption properties here and consequent attention to be paid to the mounting conditions of samples in the impedance tube. A way to circumvent the difficulty could have been to drive nails randomly in the foam like suggested by Panneton et al. in many publications in order to block the poroelastic Biot waves modes.

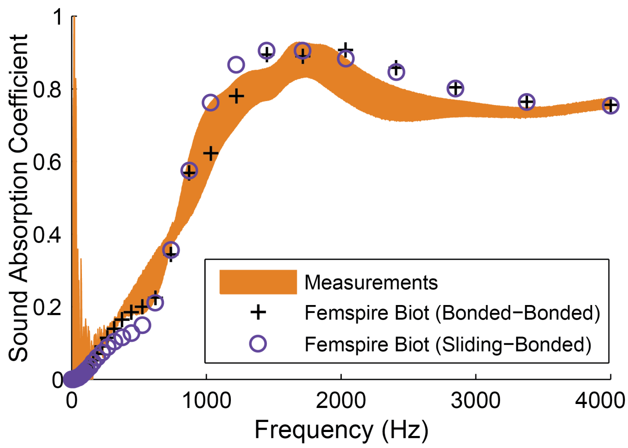

Figure 14: Normal incidence absorption coefficient 3D unit-cell poroelastic FEM correlation: H2 foam

Figure 15 shows the coupled reverberant rooms Transmission Loss (TL) measurement and FTMM simulation very good correlation results of the H1 injected „spring“ foam with a 3,5 kg/m² heavy layer on top, laid on a 0,8 mm steel plate in the middle and high frequency range. The less good correlation in the low frequency range before the respiration frequency is due to an overestimation of the spatial windowing technique [6]. A full BEM/FEM poroelastic simulation would correct the issue very well ([17], [27]).

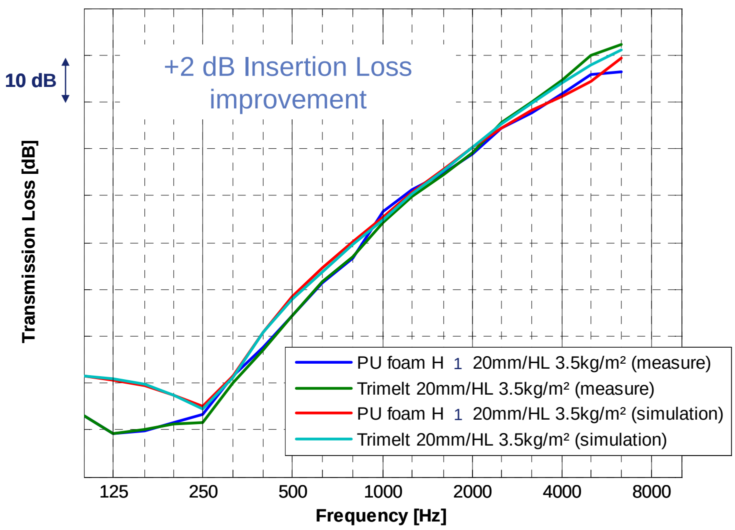

Figure 15: Diffuse field Transmission Loss 3D unit-cell FTMM correlation: H1 foam

The airflow resistivity (permeability) and Young's modulus optimizations have led to a + 2 dB Insertion Loss improvement of the soft H1 foam as predicted Figure 5 and allow reaching the same TL performance as thermoplastic very soft felts with better damping properties. Nevertheless, a slight difference occurs between the H1 foam and the thermoplastic felt (called Trimelt by Faurecia) as poroelastic decoupler in the high frequency. The relatively high tortuosity of the foam leads to this slight TL decrease above 2,5 kHz compared to the thermoplastic felt, phenomenon which is perfectly caught by the FTMM simulation.

6. Conclusion and perspectives

The three-dimensional idealized unit-cell based method for computing acoustic properties of low-density reticulated foams presented here proves to be efficient and reliable. The computed macro-acoustic properties of the foams were found to be in good agreement with multi-scale experimental data, showing the importance of membrane closing control at pore microstructure scale in acoustic foam optimization. The resulting increase of both airflow resistivities and tortuosities improves drastically the middle frequency performance of absorptive PUR foams. Another direct application to the insulation properties of PUR injected soft foams leads to a + 2 dB Insertion Loss improvement combined with Young's modulus reduction.

The microstructure based Finite Element mechanical simulation (Young's modulus E and Poisson ratio ν for isotropic and isotropic transverse cases) is fully validated now. This new methodology and results, including membranes, will be published soon, closing the complete loop for the Biot-Allard poroelastic parameters determination [28]. This 3D idealized unit-cell based method is now ready for extensive optimization studies of microstructures regarding specific acoustic targets for both absorption and insulation problems. The full link between product (foam chemical formulation with additives), process (injection parameters like mass flow, pressure, temperature of the mold, degassing points etc…) and the resulting microstructure remains the final goal, combined with the presented micro-macro approach. A PhD running now at Faurecia for the simulation of foam injection is a first step in this direction.

7. Acknowledgments

The authors would like to thank Jean-François Rondeau from Faurecia for the fruitful discussions during this work, as well as Fabien Chevillotte from Matelys for developing the software used in this study.

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9. Glossary

PUC: Periodic Unit Cell

PUR foam: Polyurethane foam

NVH: Noise Vibration and Harshness

PET: Polyethylene theraphthalate (polyester)

TL: Transmission Loss

HL: Heavy Layer

TMM: Transfer Matrix Method

FTMM: Finite Transfer Matrix Method

FEM: Finite Element Method

BEM: Boundary Element Method

dtex: Decitex, textile unit in g/10km of fiber