Acoustic trim optimization

Volker Schulz[1], Heiko Andrä[1]

[1] *Institute for Industrial Mathematics, 67663 Kaiserslautern, Germany, Email: schulz@itwm.fhg.de*

Introduction

By its ongoing improvement the simulation of car acoustics reached the edge to be fully integrated at the design and prototyping stage. The acoustic properties of the materials therefore are becoming more and more important in the material selection process. Here, we present measurements and simulation data of PET materials on different scales building the basis of a software tool for an optimal material properties reaching a desired sound pressure level automatically. The effect of the acoustic trim is due to sound absorption and damping. In this work, we focus on the acoustic absorption.

Micro model

At first, we developed a model for the simulation of the non-woven PET fibers. The model included informations about the fiber diameters and their orientation which were obtained by different imaging techniques such as laser scanning microscopy [1]. Based on the data and a stochastic process, we generated different realizations of microscopic fiber geometries as shown in figure 1.

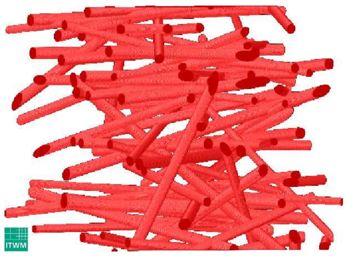

Figure 1: 3D visualization of simulated non-woven build from PET fibers. The fiber diameter is about 30μm and the porosity about 0.92 .

As it has been shown by Delany and Bazley [2] sound absorption of many non-woven fiber materials can be parameterized by their flow resistivity. This is also the case for PET fibers as we confirmed by simulations in comparison to impedance tube measurements. The simulations involved the determination of the flow resistivity by solving the Stokes' equation in the generated fiber geometry. As one can see from figure 2, the simulation and the measured values agree very well for different thicknesses and porosities. We extended that approach to modeling the acoustic properties of layered structures. Thus, the flow resistivity of each layer corresponds to an acoustic impedance and their serial connection determines the acoustic absorption of the entire system.

Macroscopic scale

Knowing the acoustic properties of the non-woven fiber material, the important question is: How does an acoustic

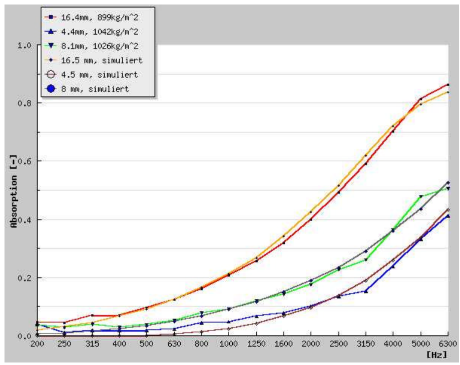

Figure 2: Simulated and measured acoustic absorption of non-woven PET fibers with different thicknesses.

trim made of that material influence the acoustics in the car passenger cabin? At higher frequencies, that behavior can be modeled by the method of Statistical Energy Analysis (SEA). For our purpose, we used the commercial software AutoSEA2© which is a standard tool in the automotive industry.

In a case study, we investigated the influence of a headliner made of PET fibers on the sound pressure level in the car interior. The Audi AG carried out the required measurements and also set up the corresponding AutoSEA2 model [3]. The AutoSEA2 model was calibrated by adjusting the input power spectrum to road measurements (at 140 km/h) without any headliner at all. Then, we applied the parameters of the prototypic

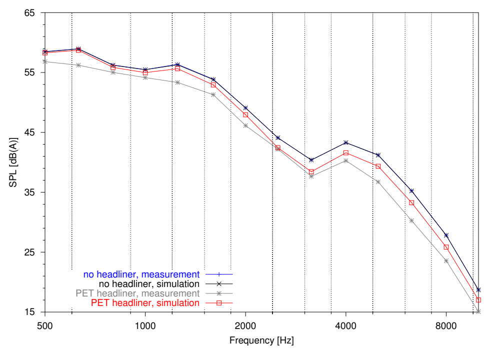

Figure 3: Simulated and measured sound pressure level at 140 km/h (back seat, left side). The simulation was calibrated to the case without headliner and shows the correct trend compared to the measured values.

headliner to the model and compared the results to the corresponding measurements. As one can see from figure 3, we could reproduce the measured trend in the sound reduction but only on a qualitative level. Therefore, an optimization based on that model as it will be given in the next section, can predict only the trend of the SPL while there might be an offset to corresponding measurements.

Optimization problem

In our case study, the objective of the optimization was to find the best fiber material for a two layer PET headliner in order to get a desired sound pressure level in the passenger cabin. In a more general way, we can formulate that problem as finding the minimum of the objective function

$$\min \sum_{f=500Hz}^{10kHz} \left(\mathrm{SPL}(f;\sigma_i,t_i) - \mathrm{SPL}_{\mathrm{desired}}(f)\right)^2 \quad (1)$$

where SPL is the sound pressure level which depends on the frequency f and the material properties of the trim such as the thicknesses t_i and the flow resistivities σ_i of each layer. Additionally, these variables have to fulfill some inequality constraints

$$t_i^{min} \leq t_i \leq t_i^{max} \quad \sigma_i^{min} \leq \sigma_i \leq \sigma_i^{max} \quad (2)$$

where $i = 1 \dots N$ and N is the number of layers. There exist several approaches for solving that optimization problem. We used a so-called pattern search since we have only a small number of variables. But we have to mention that a pattern search need not find the global but only the local optimum of the objective function. Therefore, a good choice of the initial conditions is mandatory.

Two examples

As initial conditions for the optimization algorithm we used the parameters of the prototypic PET headliner which are summarized in table 1.

	Base layer	Decoration	
Thickness t	3.5	3.0	mm
Flow resist. σ	$1.32{\cdot}10^5$	$4.8{\cdot}10^4$	$\frac{Ns}{m^4}$

Table 1: Thickness and flow resistivity for both layers of the investigated PET headliner.

In the following equation (2) is of great importance since at that point we introduce the information obtained by the micro model in the optimization procedure. Thus, we define the appropriate constraints.

In a first example we minimized the SPL over the entire frequency range between 500 Hz and 10 kHz where the maximum thickness of the headliner was restricted to 7 mm. Additionally, from our micro simulations we could specify the range of flow resistivities σ_i of the PET fiber material. For the given thickness around 3 mm (for each layer) the flow resistivity can be varied over a large range by changing the fiber diameter and the porosity. But it is bound to an upper value of about $10^7 \frac{Ns}{m^4}$.

Given these constraints, only a small reduction of the SPL could be found by the optimization routine. This is due to the fact that the maximum thickness of 7 mm is a strong constraint. Additionally, the prototypic PET headliner showed already a good absorption especially at higher frequencies.

In a second example we investigated the optimization when a higher thickness of the trim was allowed but at a fixed weight. In that case, the thickness of each layer can be varied by changing its compaction. The variation of the compaction ratio ensured that the weight keeps constant while the flow resistivity is now a function of the thickness. Again, from simulations on the micro scale we found the relations

$$\sigma_1 = 5945 \cdot \left(1 - \frac{1 - A_1}{\rho \cdot t_1}\right)^{-13.25} \quad (3)$$

and

$$\sigma_2 = 12202 \cdot \left(1 - \frac{1 - A_2}{\rho \cdot t_2}\right)^{-11.59} \quad (4)$$

for the base (3) and the decoration (4) layer where A_i is the area weight of each layer and $\rho = 1370 \frac{kg}{m^3}$ the density of PET. As a result, we found a configuration

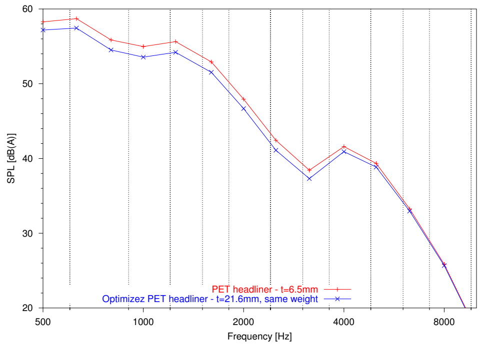

Figure 4: Sound pressure level for the prototypic PET headliner and the optimized configuration. Both trims have the same mass of about 2.2 kg but differ in their thicknesses.

($t_1 = 17.9$ mm, $t_2 = 3.7$ mm) where the SPL was up to 1.5 dB lower compared to the prototypic headliner as one can see in figure 4

Summary and outlook

All steps in our approach which had been used from the microscopic to the macroscopic level are highly flexible. Firstly, the determination of the effective properties by simulations on the microstructure can be extended to a wide class a materials such as visco-elastic foams. Secondly, instead of SEA other simulation methods such as FEM or BEM might be used in the low frequency range since the proposed optimization algorithm does not depend on the specific form of the objective function. Finally, the definition of constraints by the informations obtained on the microscopic level assures that the optimal configuration can be manufactured in reality.

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