Simulation Based Optimization of Layered Non-wovens as Acoustic Trims

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Overview

Background and motivation

Virtual acoustic material design in a nutshell

Non-wovens as absorbers – effective material models

Layered structures

Compression simulation

Acoustic properties of compressed non-wovens

Summary and outlook
Physical and mathematical formulation of multiscale problems

Material: Parts:
Nano- and micrometers

System:
Centimeter

Meter

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<table>
<thead>
<tr>
<th>Empirical process</th>
<th>Virtual material design</th>
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</thead>
</table>
| Material production and testing  
(acoustic measurement in impedance tube or alpha cabin) | • The microstructure (e.g. Non-woven) is generated entirely on the computer |
| **Disadvantages:** | • Determination of effective material parameters by numerical simulation |
| - Prototyping is time consuming and expensive! | **Advantages:** |
| - Measurements are demanding | - No prototyping required |
| - Instead of an optimisation only small improvements are possible | - Extensive parameter studies can be done with moderate efforts |
| | - Potential for computer aided optimisation |
ITWM-Softwaretool GeoDict (Geometry generation and prediction)

Interactive microstructure generator

www.geodict.com

80% PET fibers, 7dtex
20% PP fibers, 2.2 dtex
Area weight: 200 g/m²

50% PET fibers, 60dtex, elliptic cross section
50% PP fibers, 8 dtex, circular cross section
95% porosity, with and without binder

Carbon paper, used as gas diffusion layer in a fuel cell
70% porosity

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Parameter prediction: GeoDict modules

FlowDict: Permeability/Flow resistivity and relative permeability

SatuDict: Capillary pressure-saturation curves

DiffuDict: Gas diffusivity

ThermoDict: Heat conductivity

ElastoDict: Elasticity tensor

FilterDict: Filtration efficiency

AcoustoDict: Acoustic properties

www.geodict.com
## Effective acoustic models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model and type of absorber</th>
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</thead>
<tbody>
<tr>
<td>Flow resistivity $\sigma$ [kg/m³s]</td>
<td>Delany/Bazley, Mechel</td>
</tr>
<tr>
<td></td>
<td>Highly porous absorbers</td>
</tr>
<tr>
<td>Porosity, $\Phi$</td>
<td>Allard/Johnson</td>
</tr>
<tr>
<td>Tortuosity, $\tau$</td>
<td>Pride/Lafarge</td>
</tr>
<tr>
<td>Viscous charact. length $\Lambda$</td>
<td>Porous with rigid frame</td>
</tr>
<tr>
<td>[µm]</td>
<td></td>
</tr>
<tr>
<td>Thermal charact. length, $\Lambda'$</td>
<td></td>
</tr>
<tr>
<td>[µ]</td>
<td></td>
</tr>
<tr>
<td>Density, $\rho$ [kg/m³]</td>
<td>Biot</td>
</tr>
<tr>
<td>Young’s modulus $E$ [GPa]</td>
<td>Porous with (visco-)elastic frame</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td></td>
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<tr>
<td>Damping loss, $\eta$</td>
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</tbody>
</table>
Numerical determination of the Allard-Johnson parameters

**Porosity:** Given as input parameter for non-woven generation

**Flow resistivity:** From the flow field as the solution of the Stokes equation

**Tortuosity:** Evaluation of the path length of the streamlines

\[ \tau = \frac{\langle |\vec{v}| \rangle}{\langle \vec{v}_x \rangle} \]

**Thermal characteristic length:**

\[ \Lambda' = \frac{2 \cdot \text{pore volume}}{\text{fibersurface}} \]

**Viscous characteristic length:**

\[ \Lambda \approx 0.5 \cdot \Lambda' \]
How good is our prediction?

Result of the virtual material design and numerical parameter prediction

No fit to data!

Measured data
(Impedance tube)

Layer 1, d=12 cm
Modeled as "Delany&Bazley"
- 97% Porosity
- Flow resistivity: 15 000 kg/m²s
- Tortuosity factor: 1.26
- Viscous length: 105 μm
- Thermal length: 208 μm

Layer 2, d=0.33 cm
Modeled as "Allard-Johnson"
- 88% Porosity
- Flow resistivity: 95 000 kg/m²s

*Courtesy of Sandler AG

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Compression study

Compression of the non-woven can be used to modify the material properties in a controlled way.

Example: non-woven PET fibers, 12.15 dtex
Initial thickness 13.13 mm
Area weight 900 g/m²

How does the microstructure change when it is compressed?

How do the material properties change under compression?
Allard-Johnson parameters versus thickness und compression

Each flow simulation takes several hours cpu time

Compression, thickness [mm]

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Parameterisation

Allard-Johnson parameters as a function of the porosity $\Phi$

$Aw$: Area weight
$\rho$: Material density
$d$: Thickness

$$\Phi = 1 - \frac{A_w}{\rho \cdot d}$$

Flow resistivity
$$\sigma(\Phi) = \alpha \Phi^{-\beta}$$

Tortuosity
$$\tau(\Phi) = \gamma (1 - \Phi) + 1$$

Characteristic lengths
$$\Lambda'(\Phi) = \frac{1}{\delta (1 - \Phi)}$$

$$\Lambda(\Phi) = 0.5 \cdot \Lambda'(\Phi)$$

Poroacoustic material parameters, different for each non-woven
Example: 12.15 dtex PET non-woven under compression

Allard-Johnson parameters versus thickness/porosity

Flow resistivity

\[ \sigma(\Phi) = 12,834 \cdot \Phi^{-8.3548} \text{ kg/m}^3\text{s} \]

Tortuosity

\[ \tau(\Phi) = 0.521 \cdot (1 - \Phi) + 1 \]

Characteristic lengths

\[ \Lambda'(\Phi) = 0.0673^{-1} \cdot (1 - \Phi)^{-1} \mu\text{m} \]

\[ \Lambda(\Phi) = 0.5 \cdot \Lambda'(\Phi) \mu\text{m} \]

Porocoustic material parameters:
Complete description of the acoustic properties of the compressed non-woven
Acoustic absorption

12.15 dtex PET

Area weight 900 g/m²
**AdOpt: Acoustic database and optimization tool**

GeoDict+AcoustoDict \* AdOpt

- Material database
  - Fiber parameters
  - Poroacoustic material parameters

Prediction of acoustic
- Impedance
- Transmission Loss
- Absorption
  for **layered** materials

Optimal material selection

Export to acoustic simulation software:
- AutoSEA2, Ansys, SysNoise, ...

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Summary

Without prototyping we predict the acoustic properties of uncompressed and compressed layered non-wovens

Step 1: GeoDict
Microstructure generation based on
• Fiber diameters
• Area weight
• Anisotropy
• …

⇒ Poroacoustic material parameters

Step 2: AcoustoDict
Numerical determination:
• Flow resistivity
• Tortuosity
• Characteristic lengths

⇒ Poroacoustic material parameters

Step 3: AdOpt
Prediction of acoustic absorption, transmission loss, etc. for layered structures
Arbitrary parameter variation possible (number of layers, thickness, compression)
Outlook

Extended validation of the method is on the way

Numerical determination of the viscous characteristic length (instead of $\Lambda \approx 0.5 \Lambda'$)

Application to other porous absorbers such as wovens or metal foams

Extension to porous absorbers with (visco-)elastic frame ('foams')
  $\Rightarrow$ numerical determination of the Biot parameters

Ongoing software development
AcoustoDict and AdOpt will be available Fall 2007

Material database

Layered trim

Acoustic absorption

AdOpt: Screenshot of the developer version
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