A study of the flow resistance of triaxial woven fabrics under medium to high sound pressure levels

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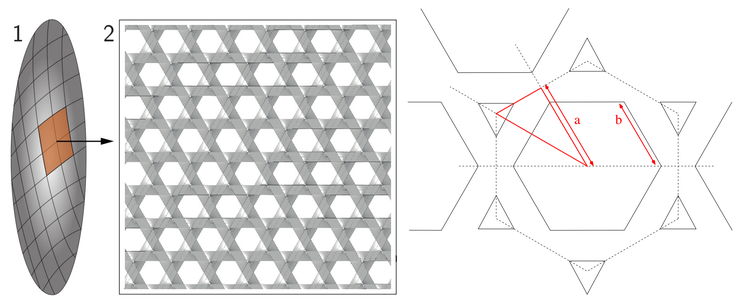
Introduction

Motivations:

- Limit acoustic loading on satellite antenna reflector during launching
- Investigate the meso-scale geometrical properties of the triaxial woven fabrics used in their design
- Establish tradeoff conclusions with electromagnetic constraints and aim at acoustic-electromagnetic micro/meso-scale recommendations

Objectives:

- Parametric study of the flow resistance of triaxial woven fabrics
- Identify a Forchheimer's law: link between acoustic loading, geometry, and acoustic excitation level

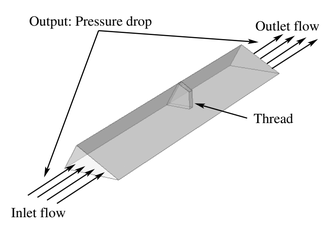


Assumptions:

- Flow resistance from steady-state FE simulations
- **Hexagonal unit cell**, downsized to $\frac{1}{12}^{\text{th}}$ triangular cell (geometry and presumably physics symetries)
- **Influential independent parameters**: a, b (linked by porosity ϕ, or $\frac{b}{a}$), thickness h
- **Dimensional assumptions**:
  - ◇ $\frac{b}{a} = 0.7$ (practical design constraint),
  - ◇ $a \sim 1$mm, or $a \sim 0.1$mm
  - ◇ a most influential,
  - ◇ $h \sim 0.1$mm, initially fixed

Forchheimer's law – linear term identification

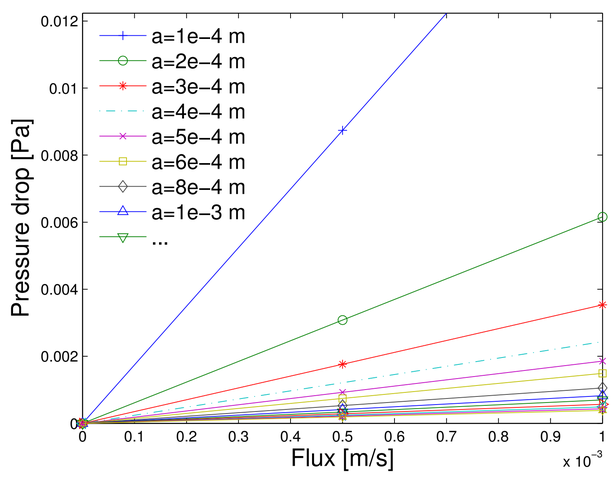
Flow resistance assumptions:



- **Flow resistance:**
  Pressure drop (Loading) vs. flow velocity (Excitation level)
- **Viscous regime:** $Re \ll 1$, Stokes flow
  $$-\nabla P + \nabla \cdot \mathbf{T} = \mathbf{0}$$
  Phenomenologically – Darcy's law:
  $$\Delta P = k_1 v$$
- **Inertia regime:** $Re \sim 1$
  $$\rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla P + \nabla \cdot \mathbf{T}$$
  Phenomenologically – Forchheimer's generalization:
  $$\Delta P = k_1 v + k_2 v^2$$

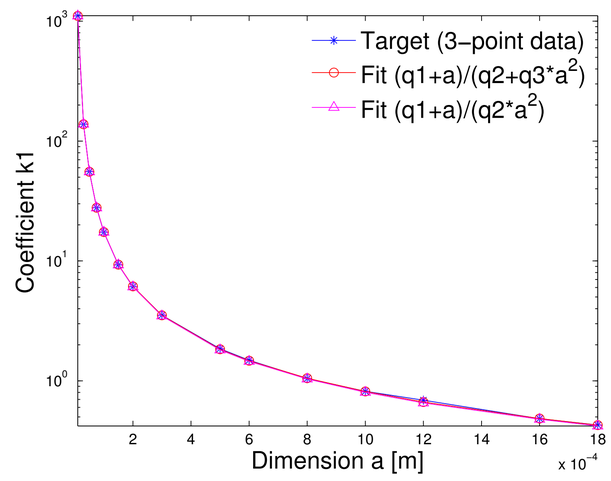
The viscous flow regime – Darcy's linear law

- Multiple apertures analyses:



$\Rightarrow$ **Assumption:** $\Delta P = k_1(a) V$

- 3-point identification of Forchheimer coeff. $\Rightarrow k_1(a)$:

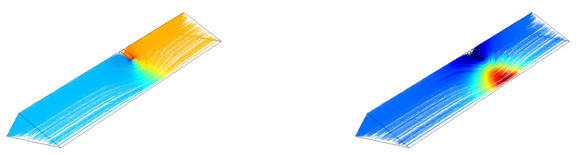


$\Rightarrow$ **Power law fit:** $k_1(a) = \dfrac{q_1 + a}{q_2 a^2}$

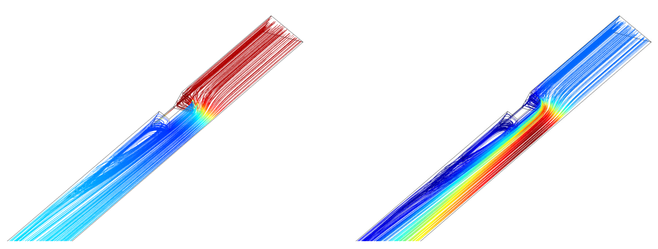
Forchheimer's law – quadratic term identification

Viscous vs. inertia flow regime:

- **Viscous flow regime:**
  Pressure field **Velocity** streamlines

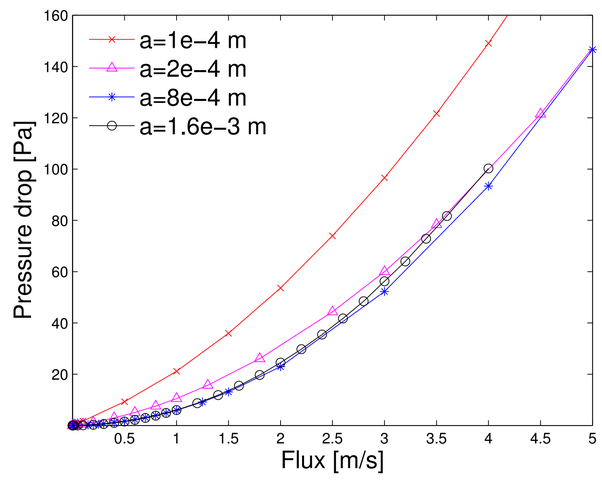


- **Inertia flow regime:**
  Pressure field **Velocity** streamlines



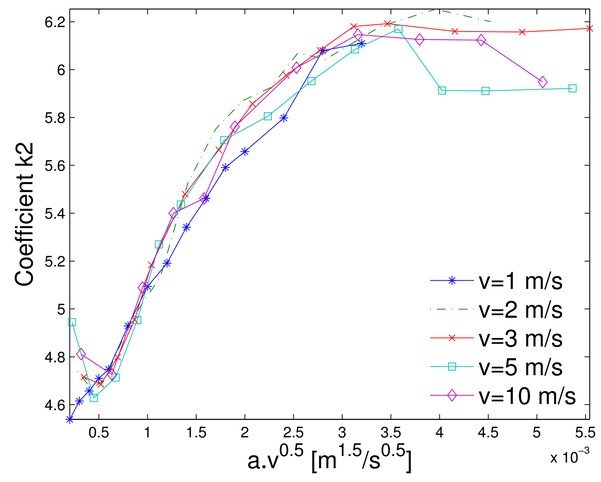
The inertia flow regime – Forchheimer's generalized law

- Multiple apertures analyses:



$\Delta P = k_1(a) V + k_2(a) V^2 ? \Rightarrow k_2(a)?$

- Fit for $k_2(a, v)$:



$\Rightarrow$ **Power law with exponential cutoff and offset:**

$$k_2(a\sqrt{v}) = q_3 (a\sqrt{v})^{-q_4} e^{-\frac{(a\sqrt{v})}{q_5}} + q_6$$

Full Forchheimer-like law

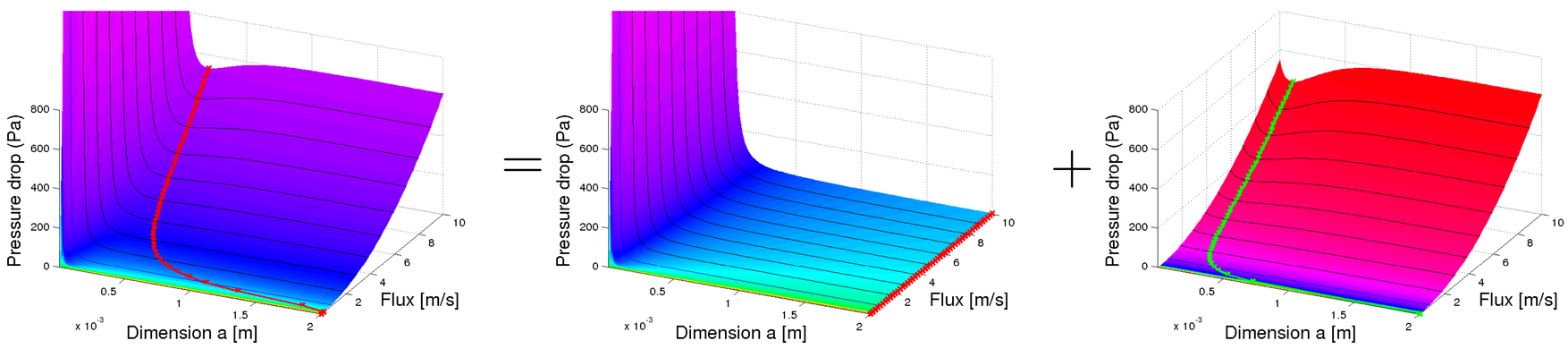
Analytical fit for Forchheimer's law:

$$\boxed{\Delta P = k_1(a) v + k_2(a, \sqrt{v}) v^2}$$

where:

- $k_1(a) = \dfrac{q_1 + a}{q_2 a^2}$
- $k_2(a, \sqrt{v}) = q_3 (a\sqrt{v})^{-q_4} e^{-\frac{(a\sqrt{v})}{q_5}} + q_6$
- $q_1 \cdots q_6$: Coefficients from numerical experiments

Complete Forchheimer law = **Viscous contribution** + **Inertia contribution**



Conclusions

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- Surface fit of a Forchheimer-like law: relation between weave geometry (cell size), acoustic loading (pressure drop), and acoustic excitation level (velocity)
- 6-coefficient law whose coefficients can be identified from simple numerical experiments
- Validity with multiple cell interactions validated on a 7-cell model
- Constraint for avoiding the viscous-driven flow resistance: Unit cell typical dimension greater than 0.5mm

Perspectives

- Extend the study to propose a Biot-like model
- Use of the model for the analysis of multi-porosity, multilayer arrangements
- Combine the analysis with the electromagnetic models (Lund University) in order to derive optimal tradeoffs