COMSOL API based Toolbox for the Mixed-Level Modeling of Squeeze-Film Damping in MEMS: Simulation and Experimental Validation

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1. Problem Description and Modeling Approach
2. COMSOL Implementation
3. Evaluation
4. Conclusion

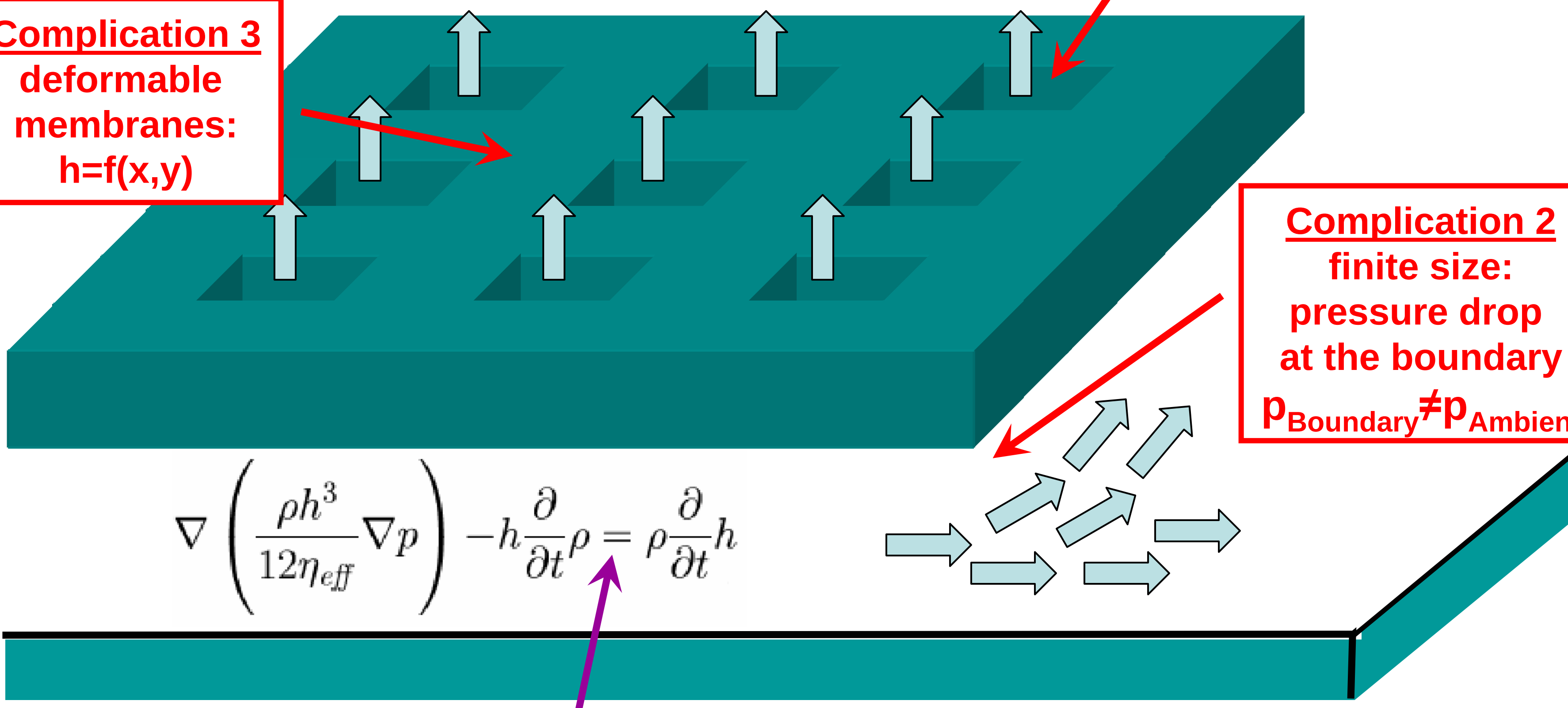
Problem Description

Problem description:
1. calculate pressure underneath moving plate
2. calculate damping from pressure

Complication 1
perforations: loss of fluid

Complication 3
deformable membranes: $h=f(x,y)$

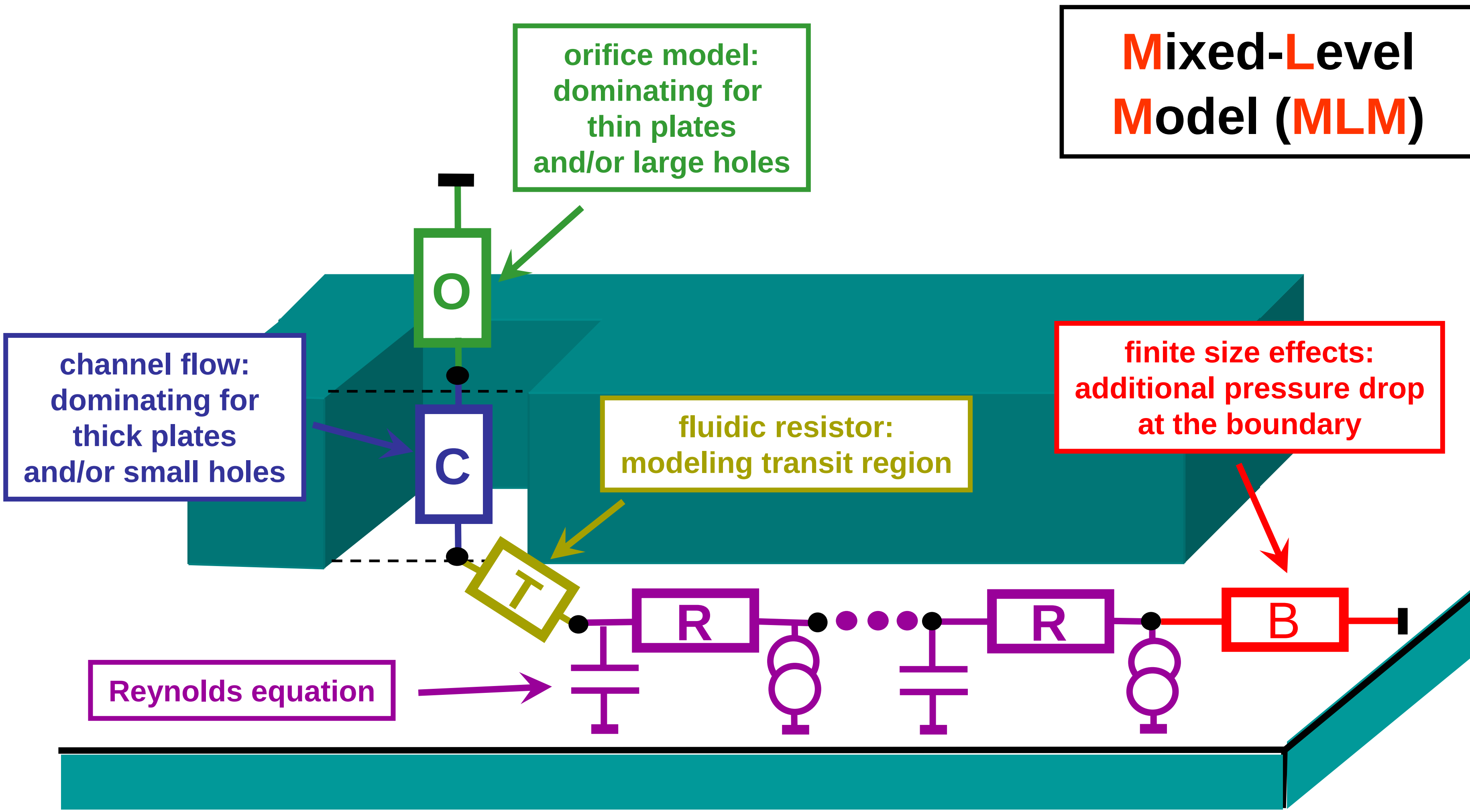
Complication 2
finite size: pressure drop at the boundary $p_{Boundary} \neq p_{Ambient}$



$$\nabla\left(\frac{\rho h^3}{12\eta_{eff}}\nabla p\right) - h\frac{\partial}{\partial t}\rho = \rho\frac{\partial}{\partial t}h$$

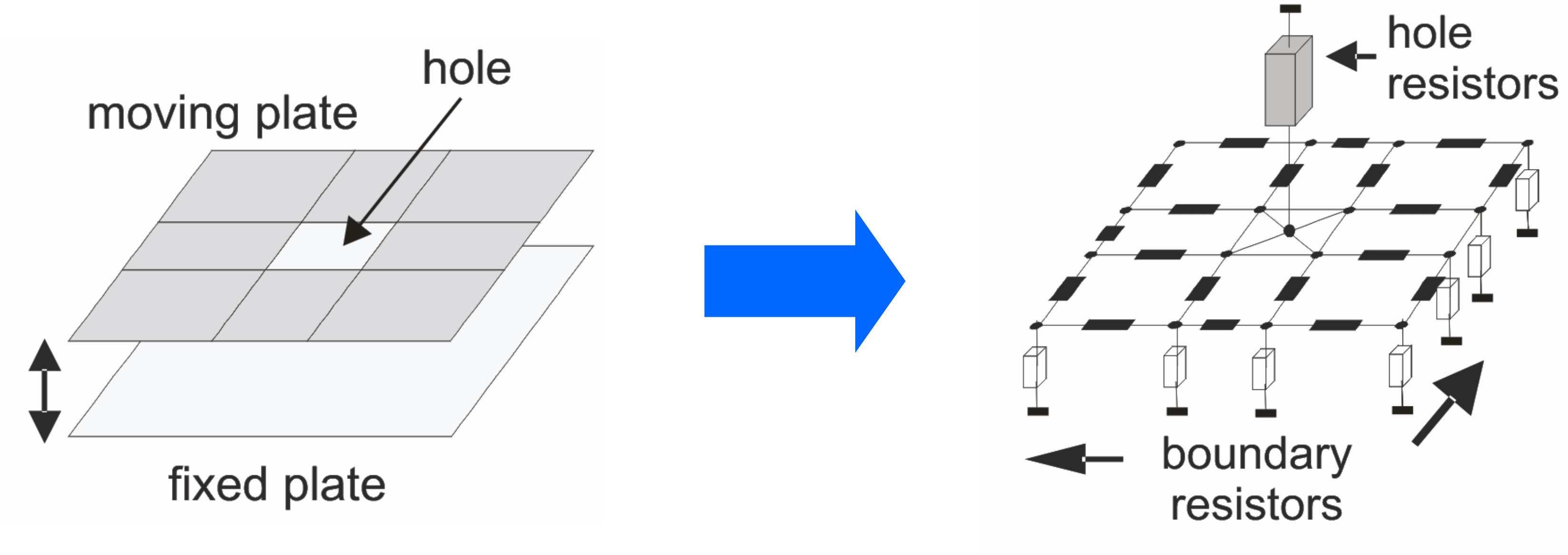
Simplification Reynolds equation is employed: valid for $l \gg h_{gap}$

C1 & C2: Mixed-level Damping Model (1/2)



Framework for the model: **Generalized Kirchhoffian network theory**

C1 & C2: Mixed-level Damping Model (2/2)



Features:

- **Discretized system-level model**
- **Physics-based**

Boundary resistance:

$$R_B = 0.84 \cdot \frac{3\pi\eta}{h_i{}^2 l_i} \cdot \Psi_B^{-1}$$

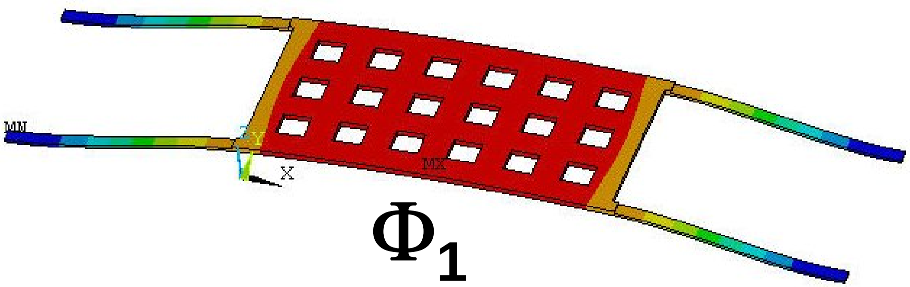
geometry and material parameters only

Correction for rarefied gas effects

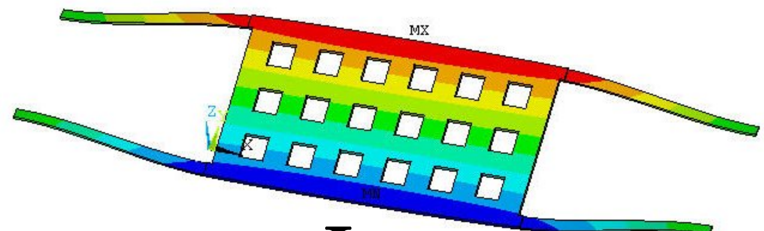
Deformable membranes are modeled by

a superposition of mechanical eigenmodes:

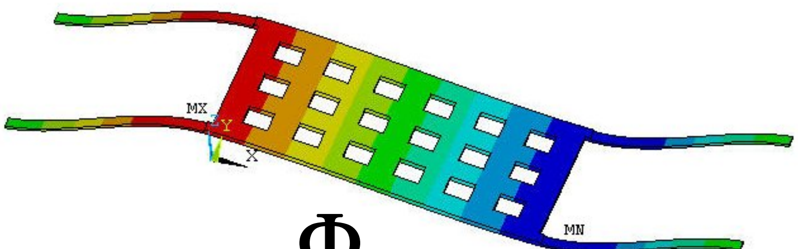
$$\mathbf{h}(t) \approx \mathbf{h}_0 + \sum_{i=1}^{m} q_i(t)\,\mathbf{\Phi}_i$$



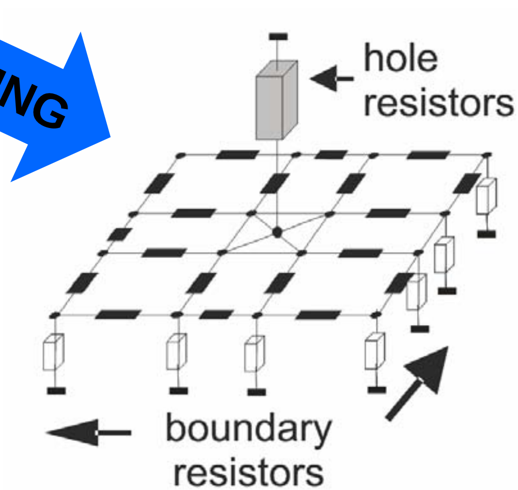
Φ_1



Φ_2



Φ_3



. . . Φ_m

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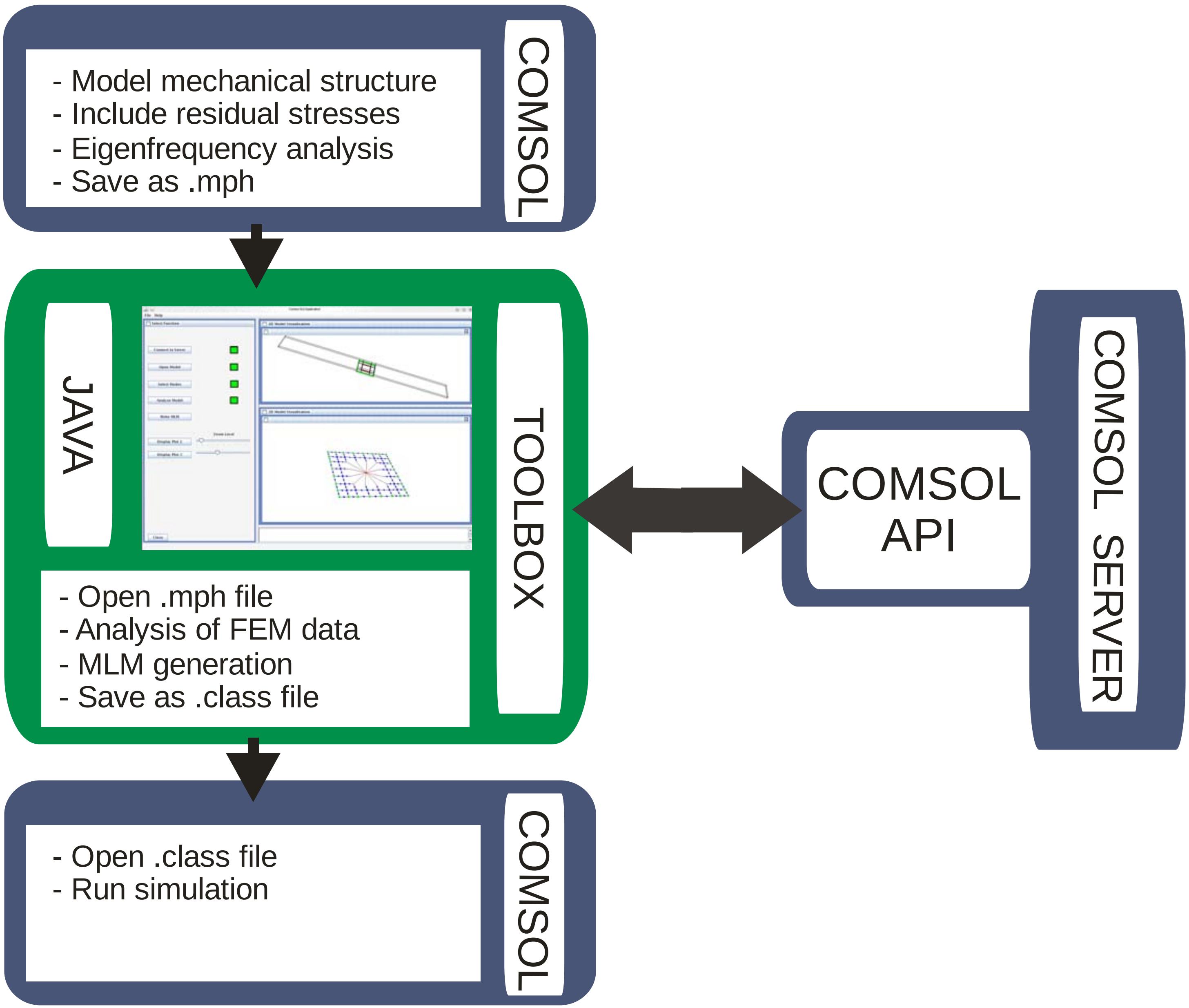
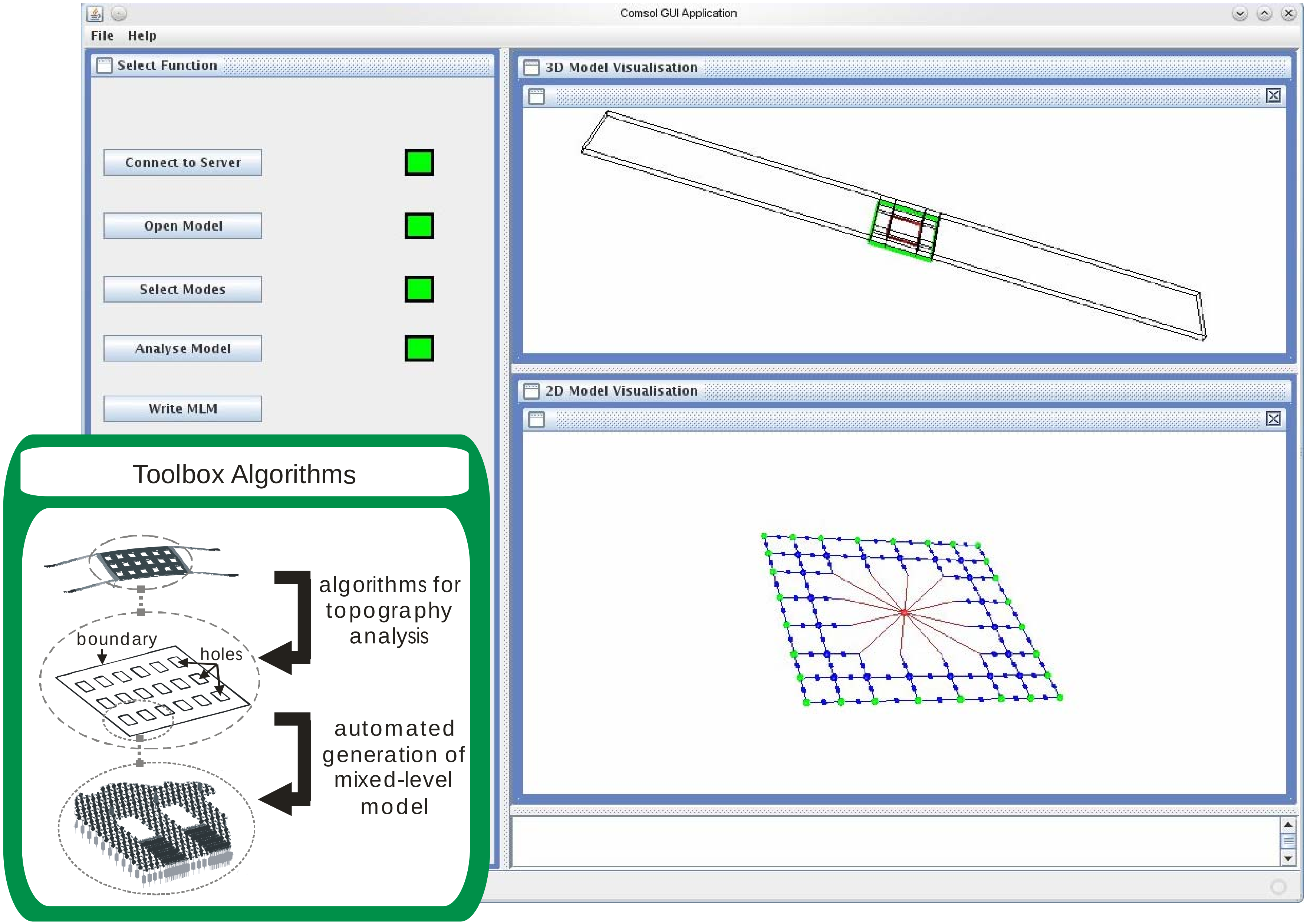
General Workflow



Toolbox: GUI & Algorithms



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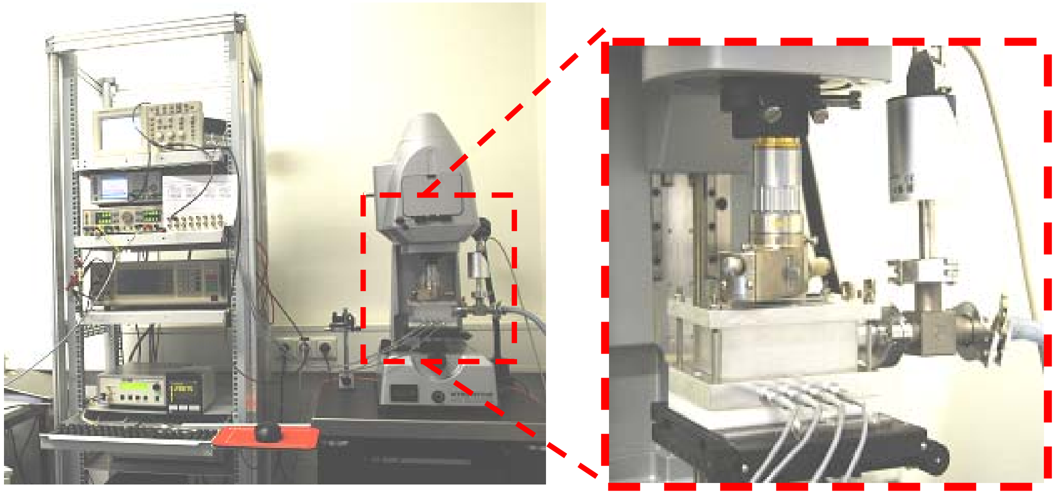
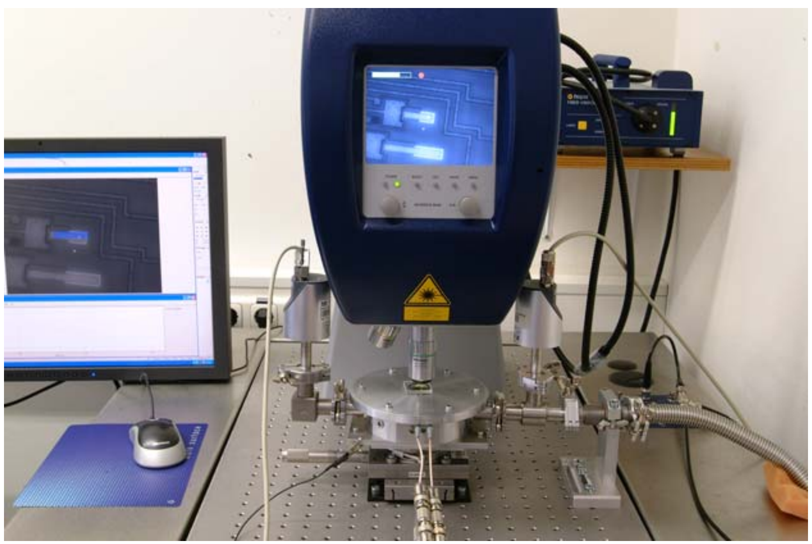
Experimental Setups



white light interferometer
(Veeco WYKO NT1100 DMEMS)
- static measurements

Verification of device dimensions



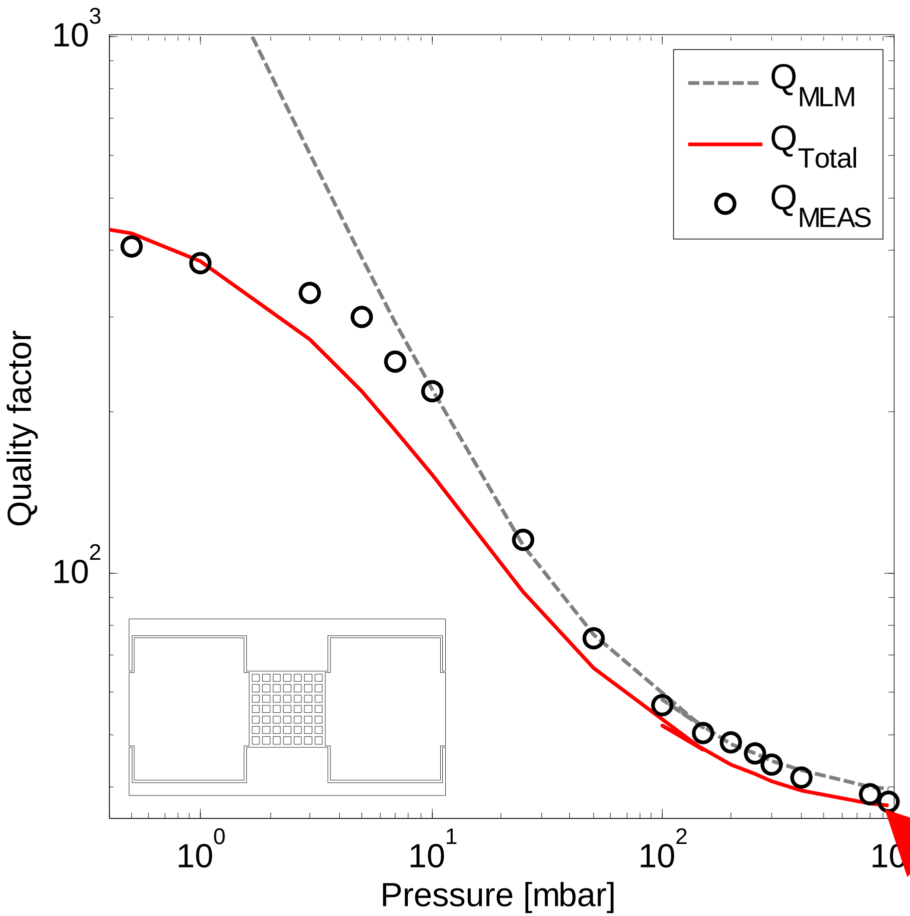
laser scanning vibrometer
(Polytec MSA-500 [customized])
- dynamic measurements
- pressure chamber

Q is calculated from frequency domain (3dB-bw)

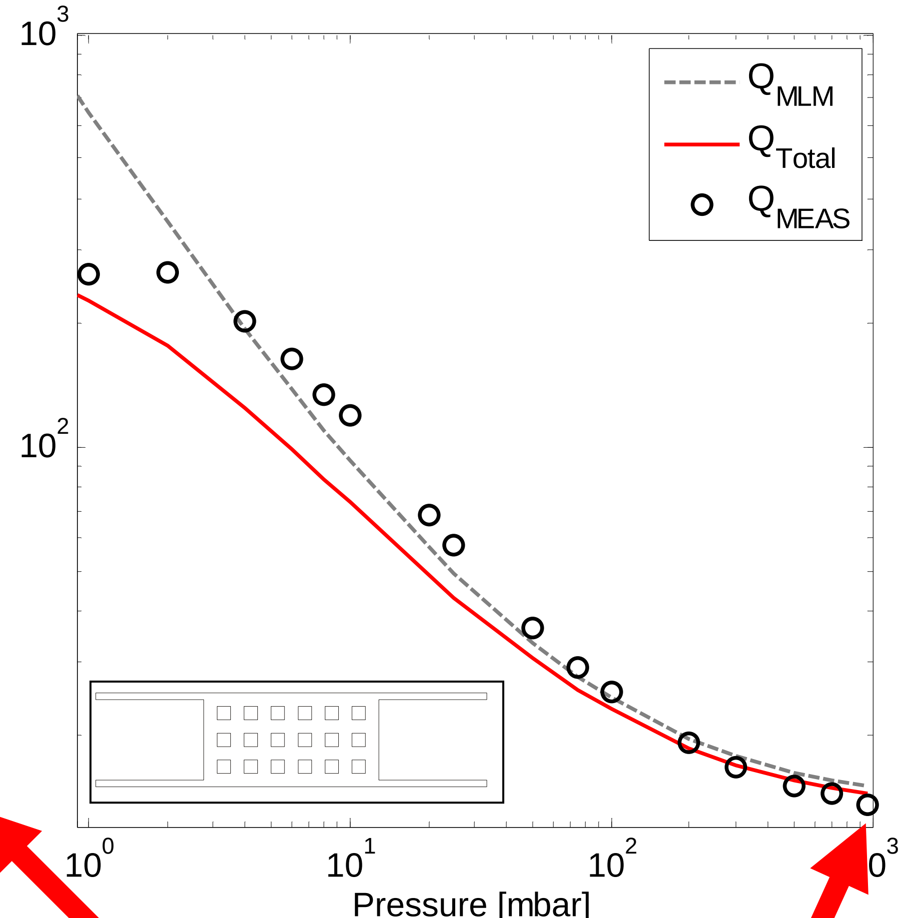
→ Allows for dynamic measurements at varying ambient pressure conditions

Experimental Data vs. Simulation

Microresonator



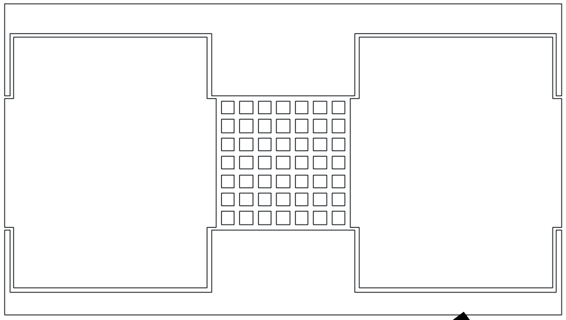
RF-MEMS switch

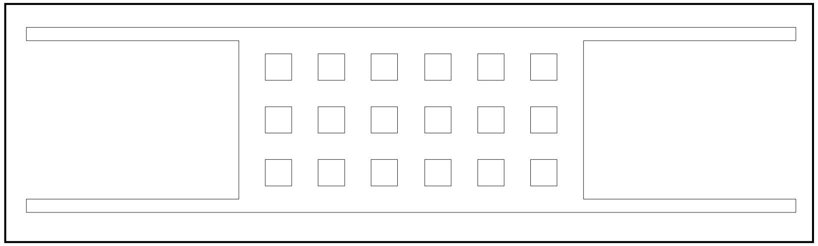


$$\frac{1}{Q_{TOTAL}} = \frac{1}{Q_{MLM}} + \frac{1}{Q_{LIMIT}}$$

Maximum error at normal pressure: 7%

Benchmark vs. Alternative Models





	Microresonator	RF switch
Q_{MEAS}	37.47	13.58
$Q_{TOTAL,MLM}$	36.72 (+2%)	14.49 (-6.7%)
$Q_{TOTAL,BAO}$ [2]	23.77 (+36.6%)	6.84 (+49.6%)
$Q_{TOTAL,VEIJOLA}$ [3]	22.32 (+40.4%)	17.16 (-26.3%)

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Conclusion

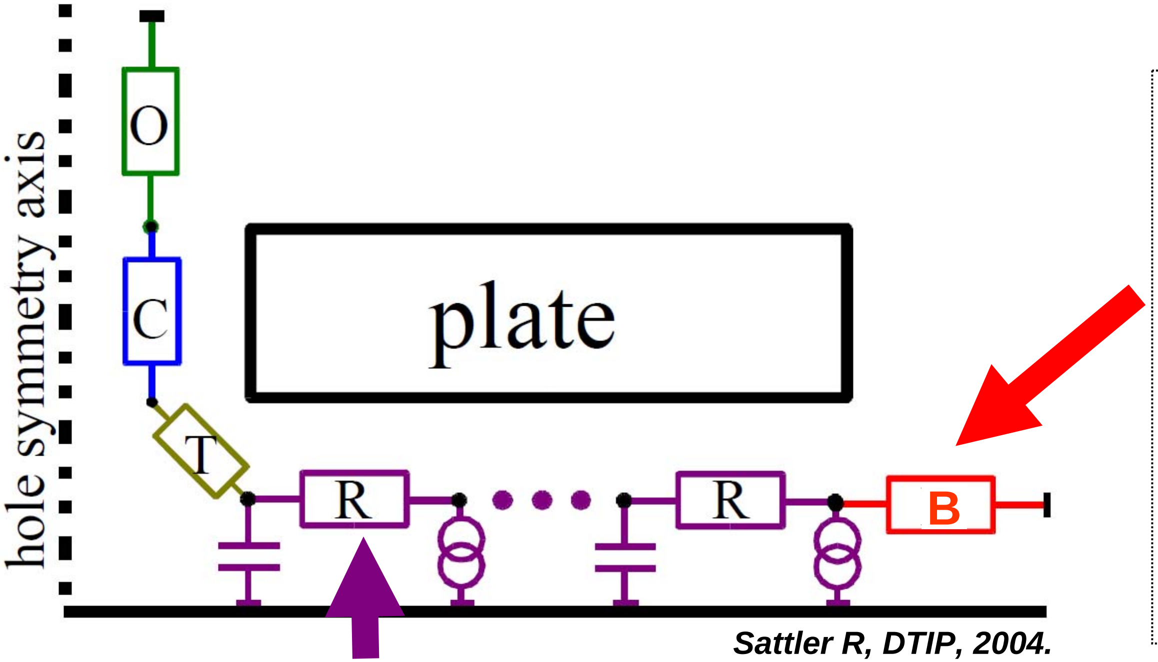
- **Toolbox for the modeling of SQFD in MEMS:**
  - Based on **Generalized Kirchhoffian network theory**
  - Uses the **mixed-level modeling approach**
  - Employs **physics-based** models
  - Is **extendible**
  - Exploits the functionality of the **COMSOL API**
  - Allows **easy-to-use automated model generation**

- **Experimental evaluation:**
  - Two devices were investigated
  - Excellent agreement with measurements:
    - **Maximum error** of **7%** at normal pressure

- **Benchmark:**
  - Two alternative compact models were investigated
  - **Minimum error** of alternative models is **26%** at normal pressure
  - Automatically generated **mixed-level model** performs **better**

Thank you for your attention!

MLM: Details



Sattler R, DTIP, 2004.

Boundary resistance:

$$R_B = 0.84 \cdot \frac{3\pi\eta}{h_i^{\,2} l_i} \cdot \Psi_B^{-1}$$

with

$$\Psi_B = \Psi_R \cdot \frac{1 + 0.5D^{-0.5} \cdot 30^{-0.238}}{1 + 2.471 D^{-0.659}}$$

Sattler R, PhD thesis, 2007.

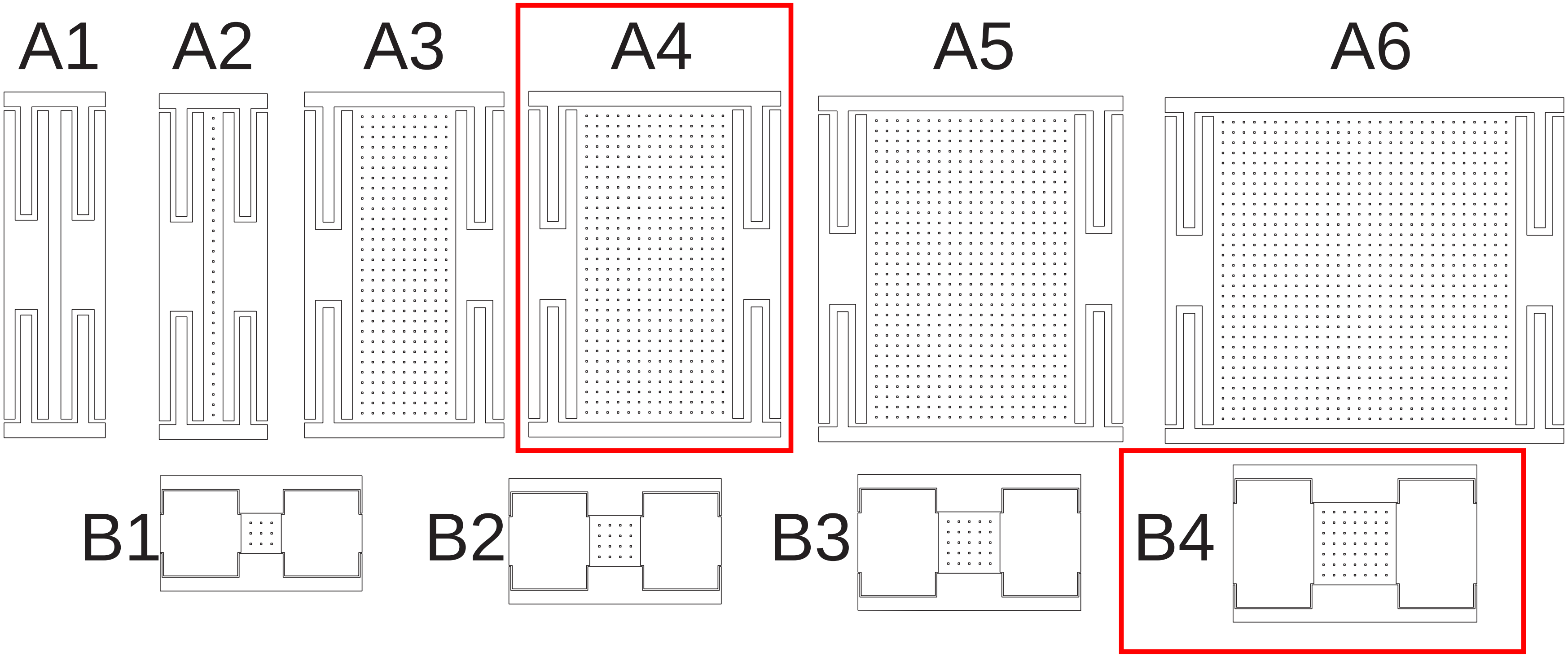
Reynolds regime resistance:

$$R_R = \frac{12\eta r_{ik}}{b_{ik} h_{ik}^3} \cdot \Psi_R^{-1} \quad \text{with} \quad \Psi_R = 1 + 9.638 Kn^{1.159}$$

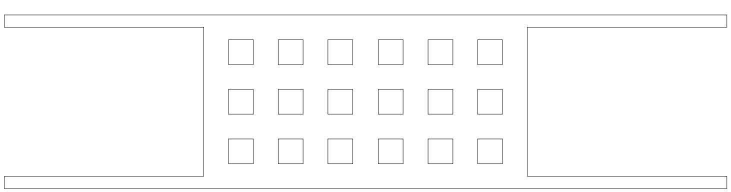
Sattler R, PhD thesis, 2007 and Veijola T, S&A, 1998.

- → Models are physics-based
- → Models have geometry-based and material parameters only (no fit!)
- → Corrections factors account for rarefied gas effects (is fit!)

Teststructures



RFS



Summary of geometrical parameters:

- number of holes: **18 .. 903**
- hole size: **13 µm .. 20 µm**
- plate thickness: **5 µm .. 15 µm**
- perforation level: **23% .. 47%**
- gap: **2 µm .. 3 µm**
- frequency: **14 kHz .. 44 kHz**

	MLM Toolbox	**Implementation of Veijola's mixed-mode model of SQFD for perforated plates in COMSOL 3.5a**
Formulation	Flux-conserving	FEM-based -> Potential
Modeling	Physics-based	Heuristic
Autom. Model Gen.	Yes	No
Condensation	Possible	No
Number of DOFS	~2300	>> 2300