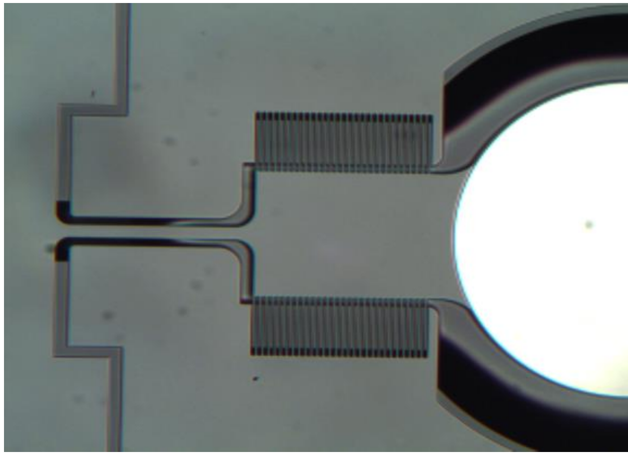
POLITECNICO DI MILANO

Modeling of Fluid Damping in Resonant Micro-mirrors with Out-of-plane Comb-drive Actuation

Ramin Mirzazadeh[1]

Stefano Mariani[1]

Marco De Fazio[2]



[1] Politecnico di Milano, Dipartimento di Ingegneria Civile e Ambientale, Italy

[2] STMicroelectronics, Advanced System Technology, Italy

Micro-Electro-Mechanical Systems (MEMS)

- MEMS*
  - MOEMS **
  - Accelerometers
  - Gyroscopes
  - Bio-chips
  - Microfluidics devices
  - Pressure sensors
- Micromirrors
  - Tunable lasers
  - Optical attenuators
  - Optical switching
  - Displays
  - Sensors

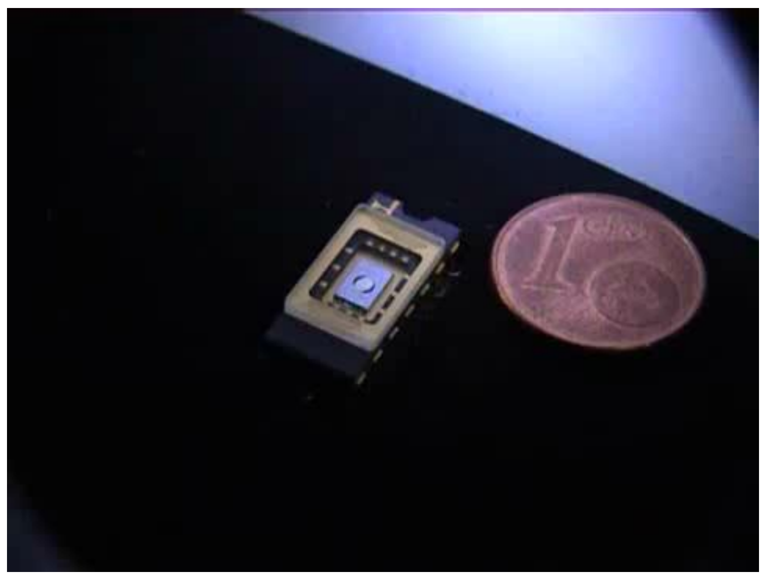


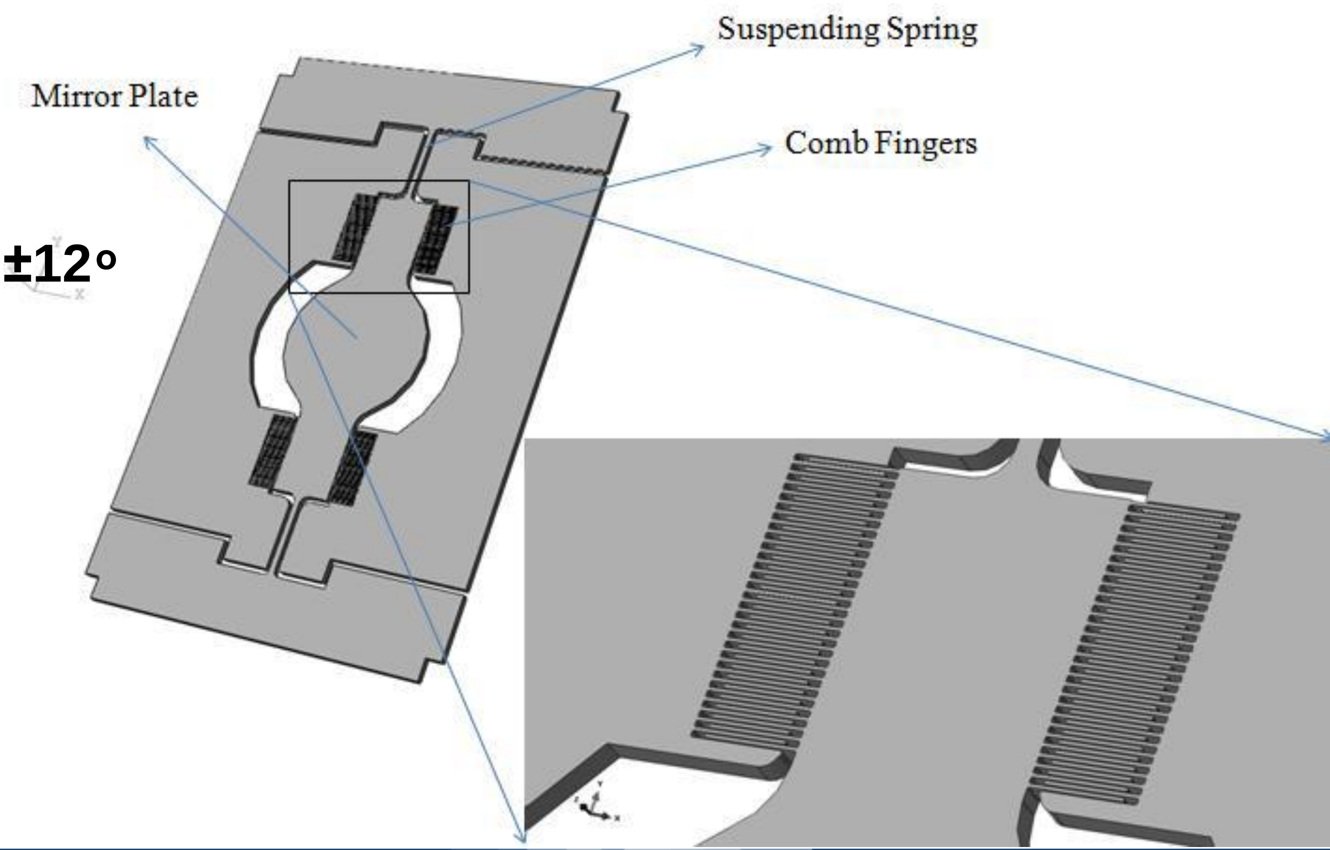
Image by Fraunhofer IPMS

* Micro-Electro-Mechanical Systems
** Micro-Opto-Electro-Mechanical Systems

Electrostatically comb-driven micromirrors

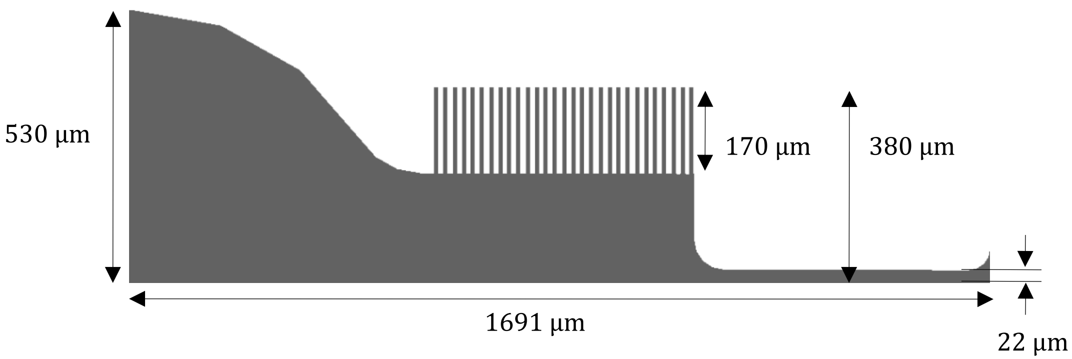
- Air-packaged
- Working frequency 19 343 Hz
- Made by *STMicroelectronics*

- **Large tilting angle ±12°**



Engineering motivation

- Out-of–plane oscillation of combfingers
- Large angle oscillation
- What happens to the fluid when the structure has complex geometry and motion?
- 3D CFD



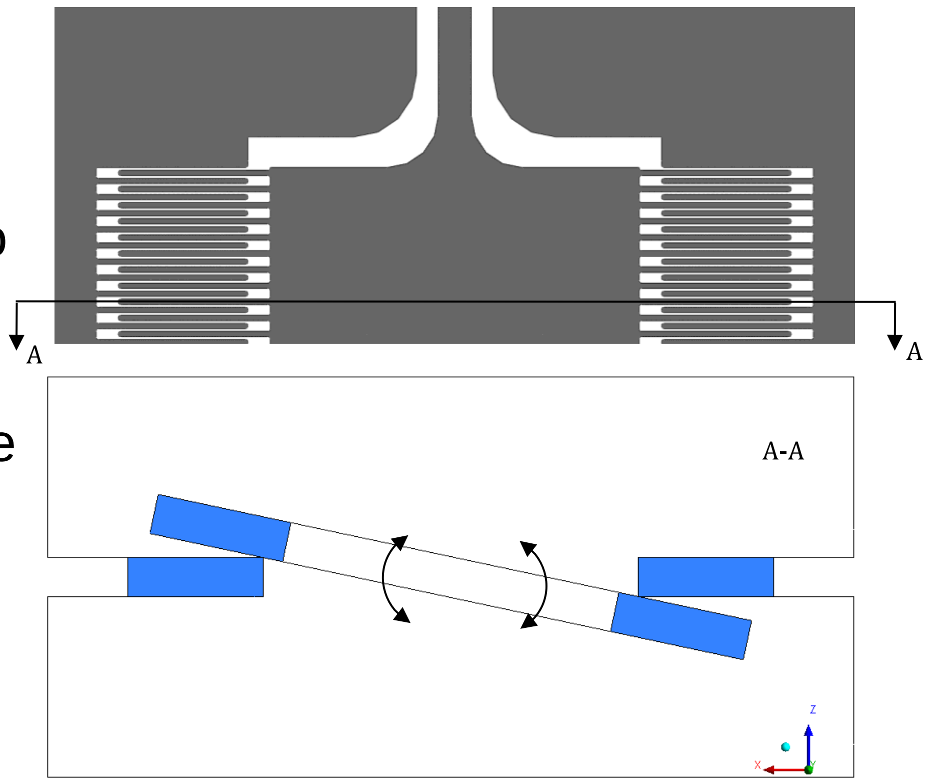
A quarter of model

Parameter	Value
Mirror diameter	1060 μm
Spring length	579.5 μm
Spring width	44 μm
Finger length	170 μm
Finger width	6 μm
Finger span	760 μm
Finger gap	3 μm
Number of fingers	29
Thickness of layout	50 μm
Substrate depth	450 μm

Engineering motivation

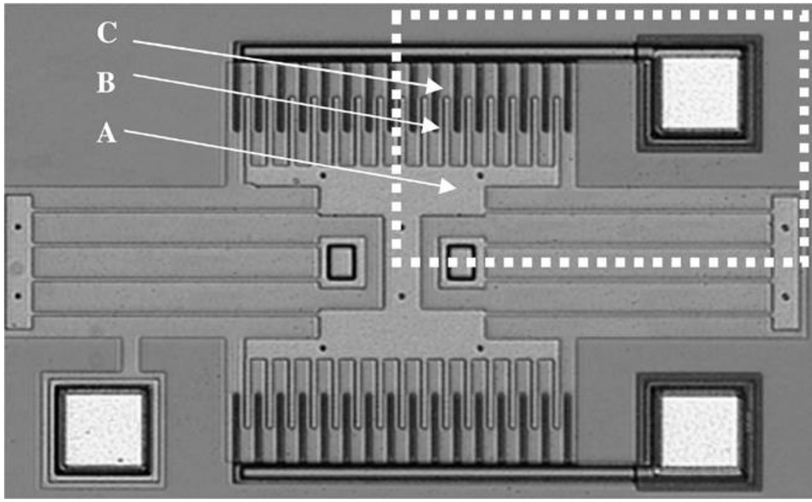
- Damping behavior is important in microscales (surface forces)
  - Mass=$1.81 \cdot 10^{-7}$ kg
  - Moment of inertia= $9.384 \cdot 10^{-14}$ kg m^2

- The energy dissipation is expected to be lower than the one for the small oscillation
- Experiments show no reduction in the energy dissipation



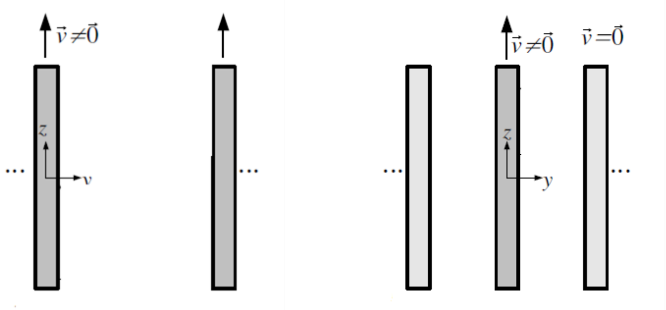
Previous works

- **Howe, Pisano et al** (JMEMS, 1993)
  - 1D Stokes flow
- **Zhang and Tang** (IEEE on MEMS, 1994)
  - The combfinger effect in experiments
- **Ye, Werner, White et al** (JMEMS, 2003)
  - 3D Stokes solver (3D BEM), Stick BC
- **Sudipto and Aluru** (JMM, 2006)
  - Coupled model, 2D compressible N_V

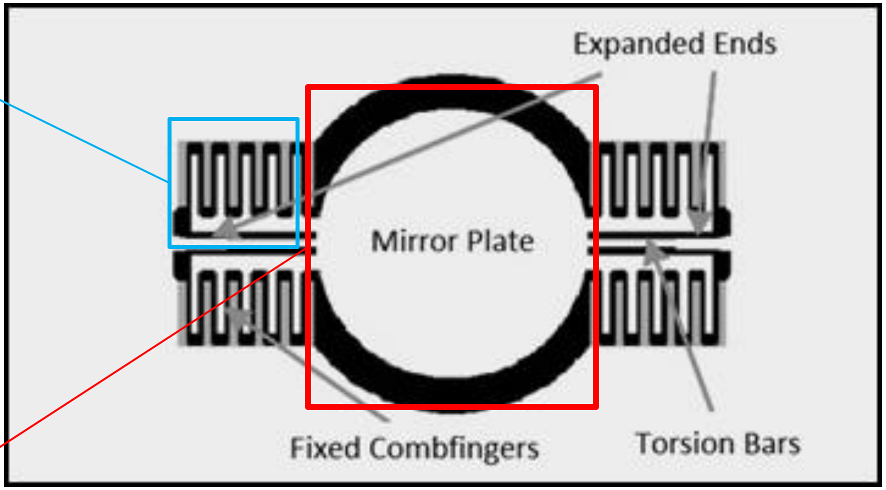


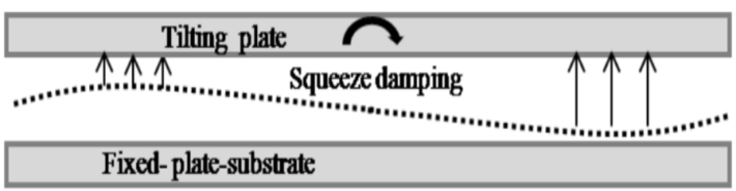
- **Frangi et al** (J. numerical methods Eng., 2006, Sensors and actuators A,2009)
  - Fast multipole boundary element, Slip BC
  - Boundary Integral Equation, Free molecule regime
- **Braghin et al** (NoD., 2008)
  - 3D Incompressible N_V, constant speed

Damping mechanisms in micromirrors



Shear damping





Drag damping
Squeeze film damping

Fluid-mechanical dissipation, Flow model

- Reynolds number $\ll 1$, — Laminar flow
- Mach number $\ll 1$, — Incompressible flow
- Knudsen number ≈ 0.01, — Continuum method

Mean free path of air molecules

$$Kn = \frac{\lambda}{L}$$

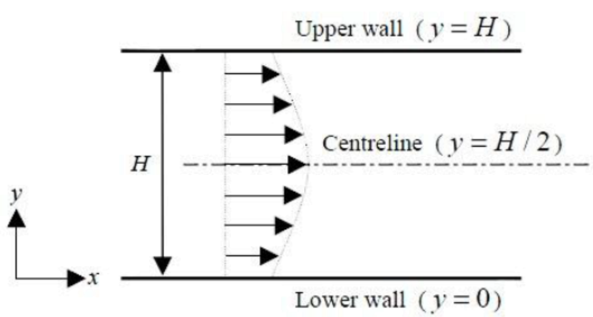
Characteristic length

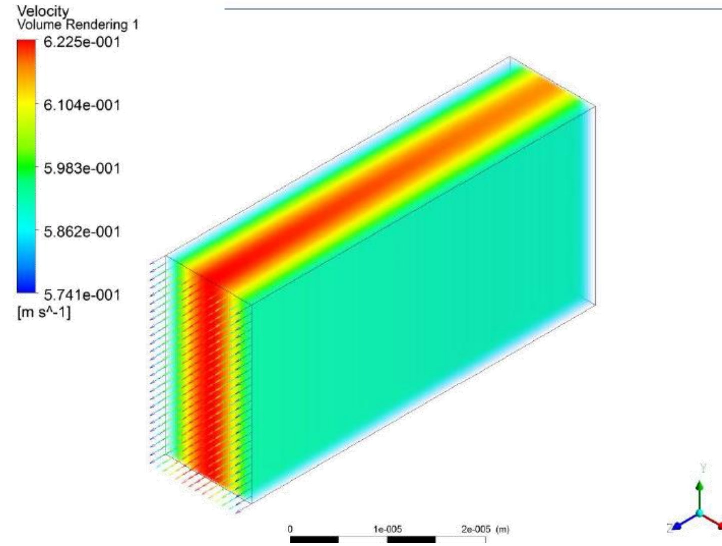
Kn	▶		0.01	0.1	10
Regime	▶	**Continuum**	**Slip**	**Transition**	**Free-molecule**

*G.E. Karniadakis, A. Beskok, Micro Flows, Fundamentals and Simulation, Springer, New York, 2002

Slip boundary condition- implementation in CFX

- ANSYS CFX
- User defined BC
- Error: 1.5%





TMAC

$$u_t = \frac{2-\sigma}{\sigma} Kn 2H \left.\frac{du}{dy}\right|_{y=0}$$

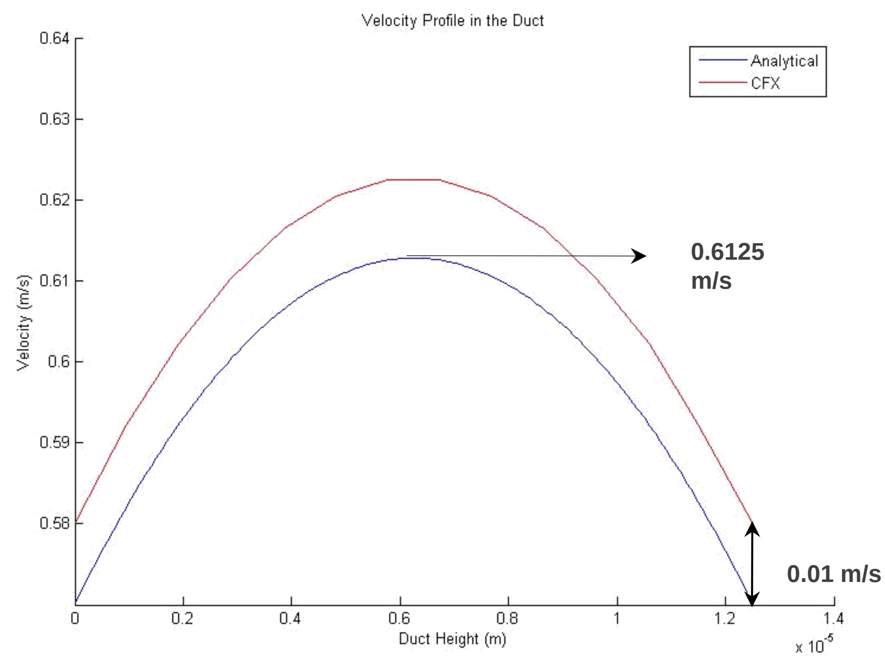
Knudsen number

Boltzmann's constant

$$\lambda = \frac{\mathfrak{R} T_K}{\sqrt{2}\pi p \mathfrak{D}^2}$$

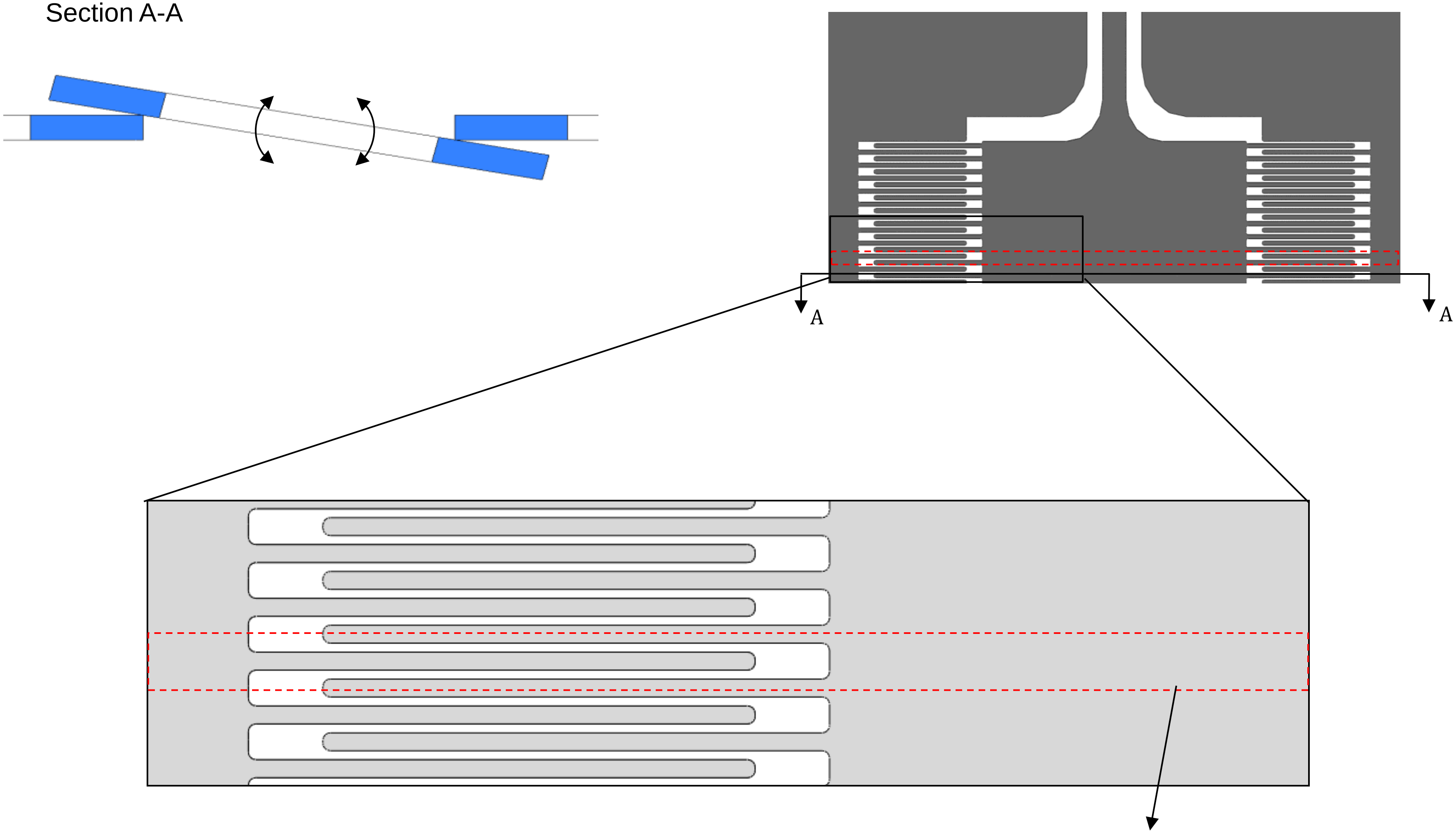
Averaged air molecule diameter

Mean free path of air molecules

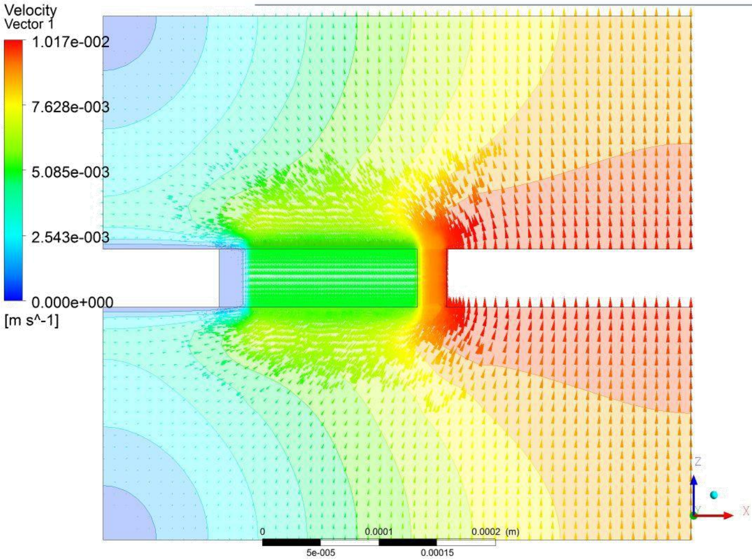


Shear Damping

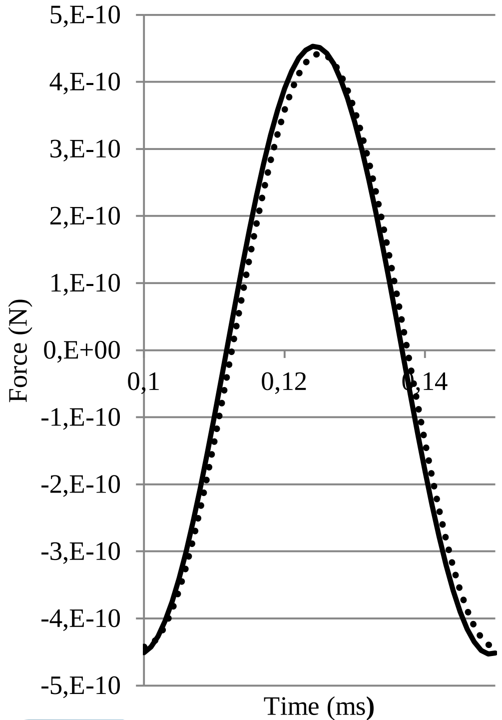
Section A-A

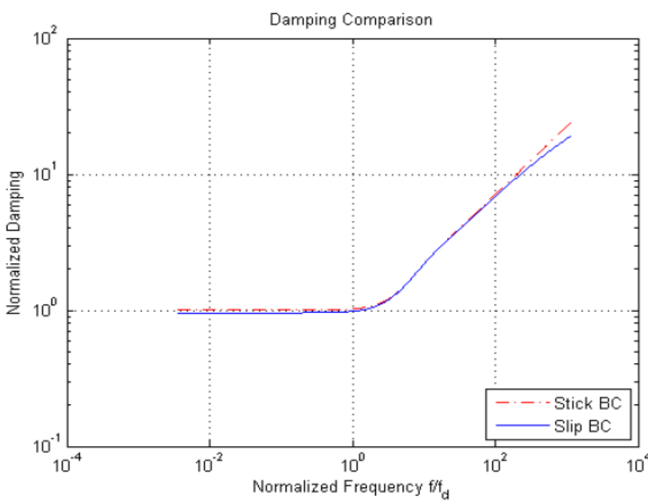


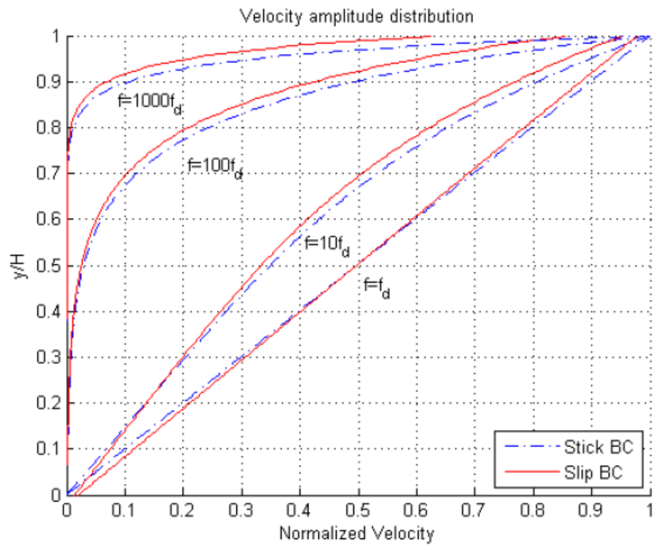
Validation for small displacements



- Shear damping, small oscillation
- Couette flow model $\{F_d\} \approx \{F_{Couette}\} = -\mu \dfrac{A_s}{g}\{u\}$
- 2% error





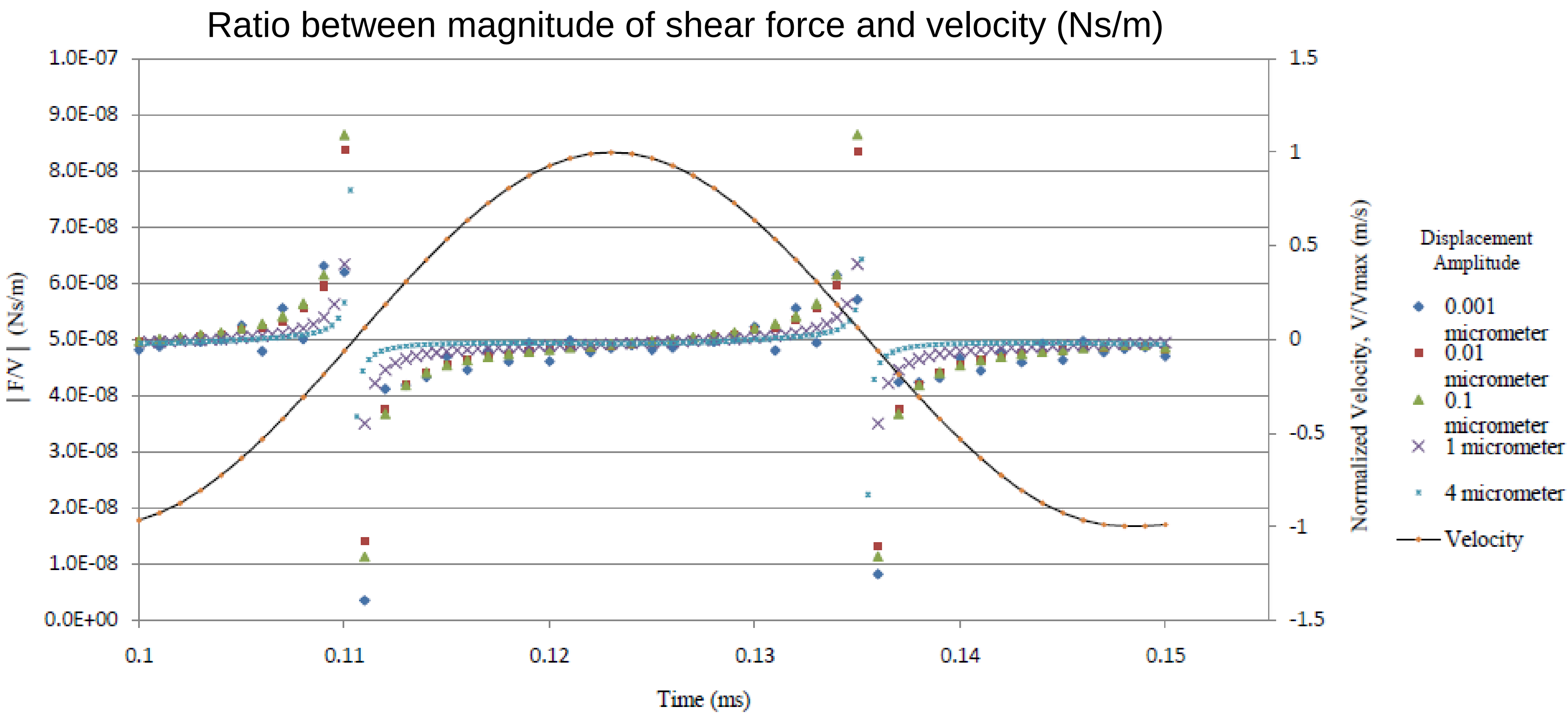


Numerical solution

Analytical solution

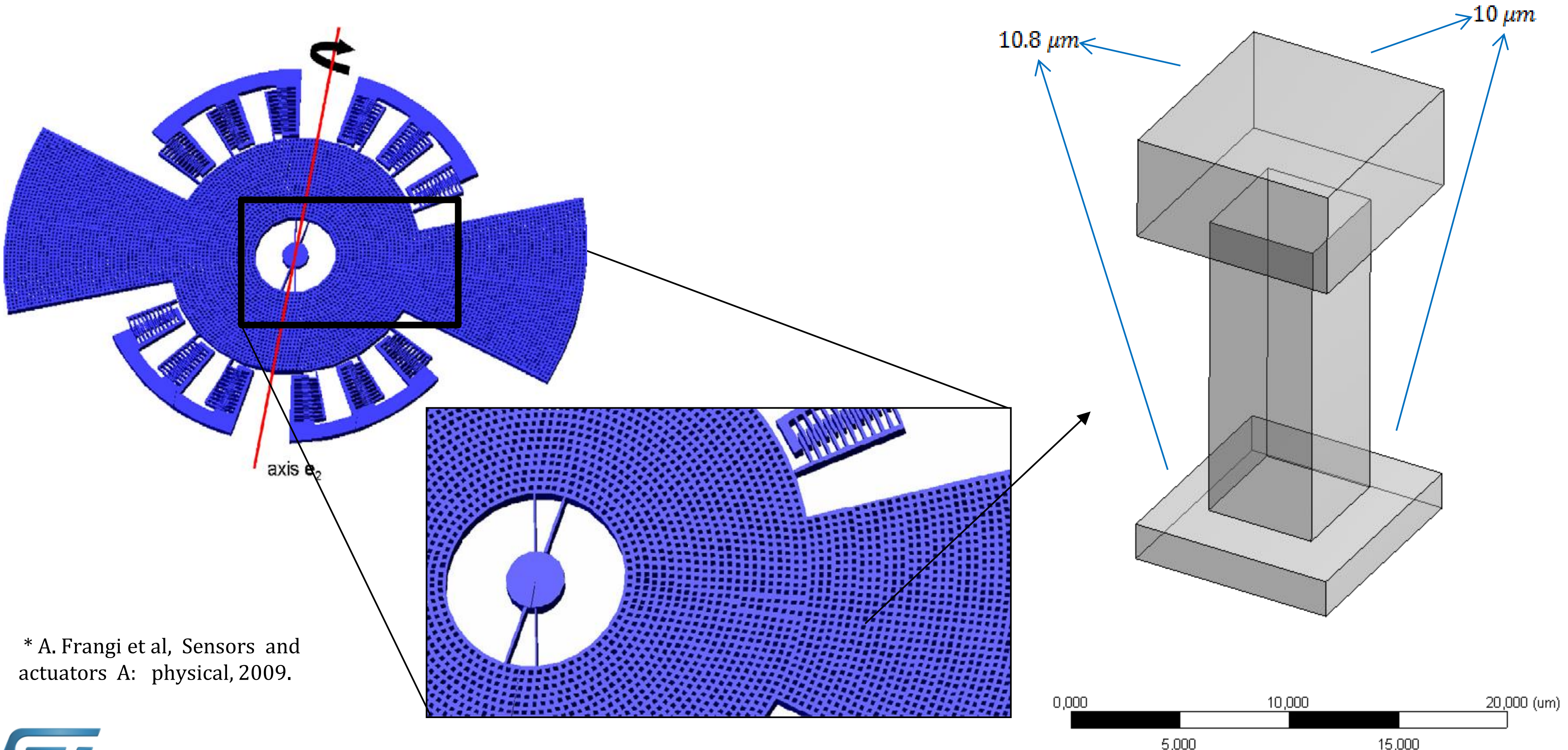
Linear behavior of flow in small oscillations

- Linear behavior
- Jumps when velocity is zero



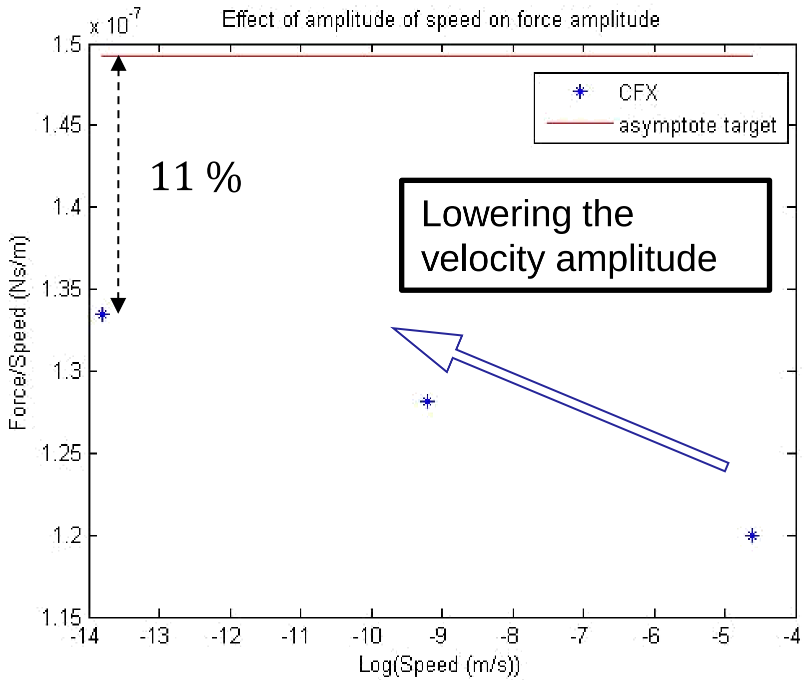
Validation for squeeze film damping-benchmark*

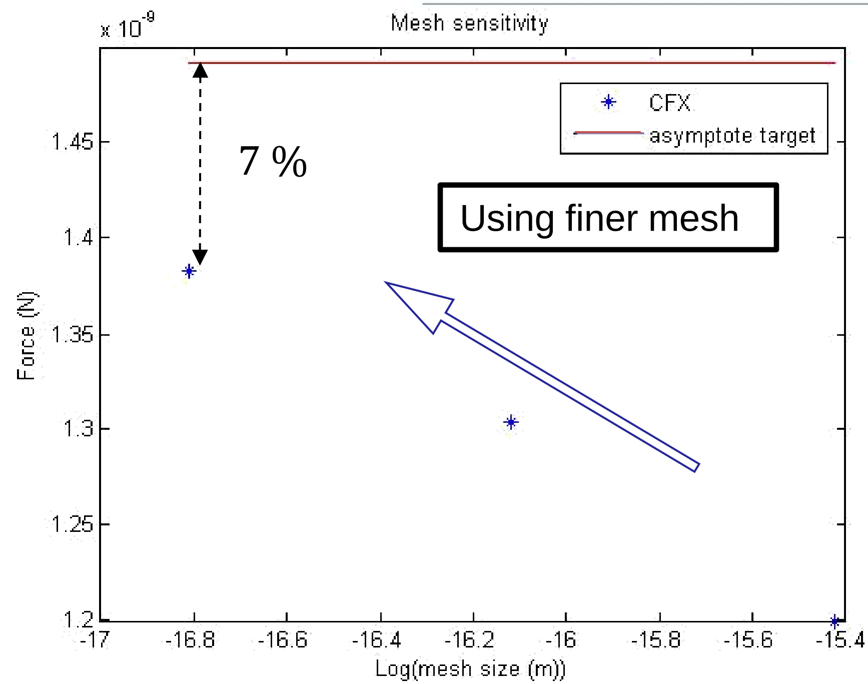
- Rotational resonator- perforation cell
- Resonance frequency: 4550 Hz
- Reported overall force on the unit cell for unit velocity: $1.492 \cdot 10^{-7}$ N

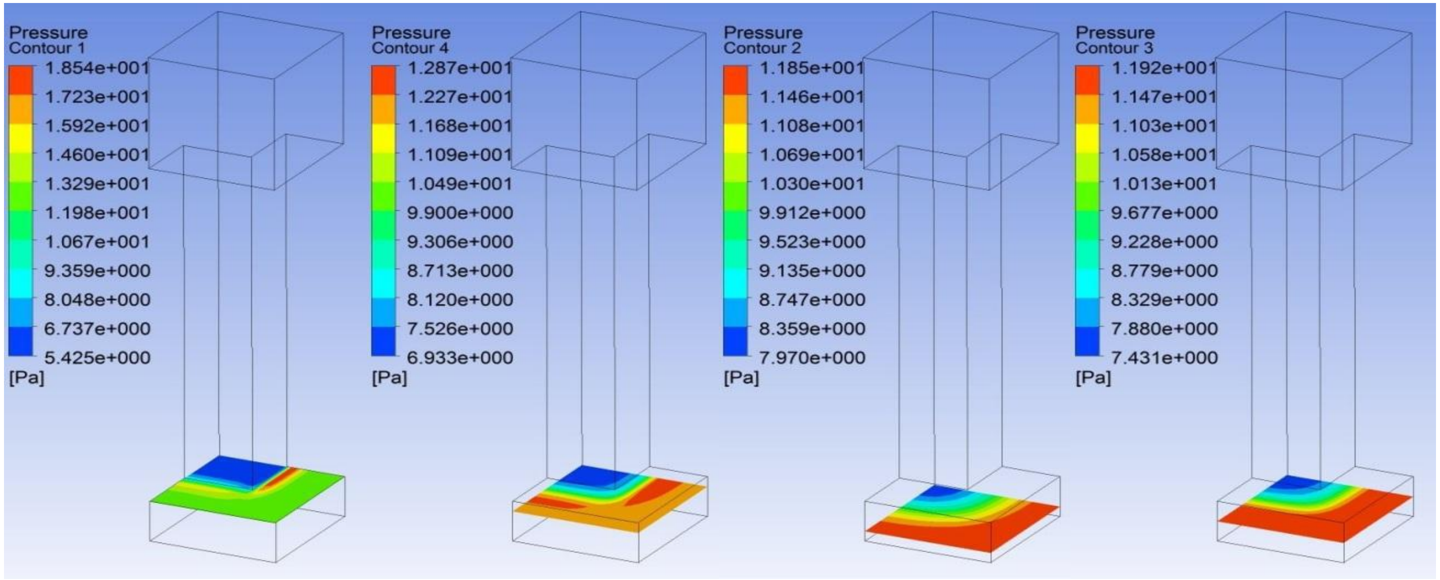


* A. Frangi et al, Sensors and actuators A: physical, 2009.

Mesh size and input velocity order effect





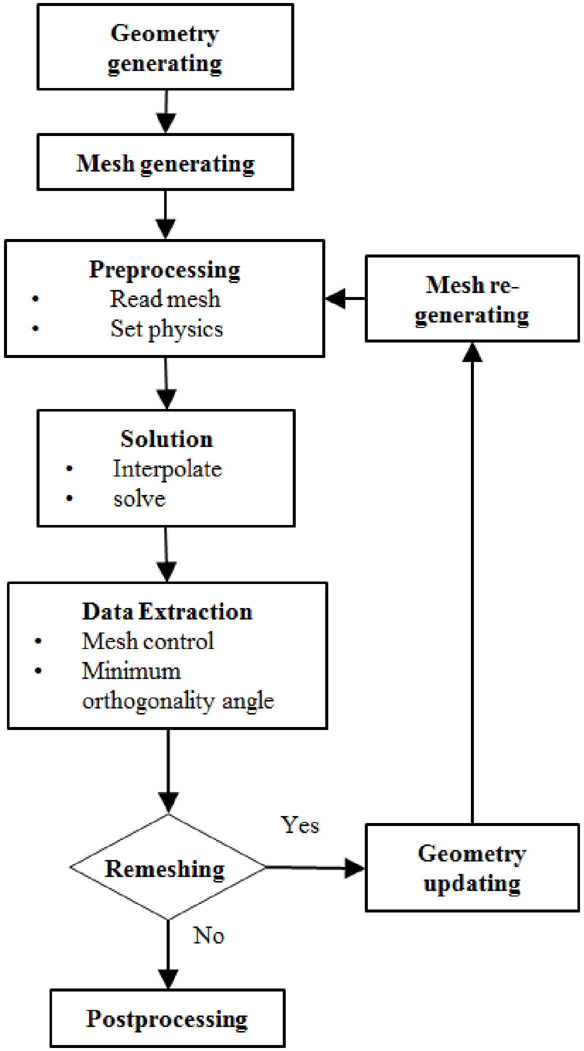


Remeshing

- Fortran subroutine
- Dynamic remeshing procedure
  - If mesh quality decays critically
  - Extracting the new geometry parameters
  - Update the geometry
  - Mesh the new geometry
  - Import the new mesh to the solver
  - Set the initial condition based on the previous solution step

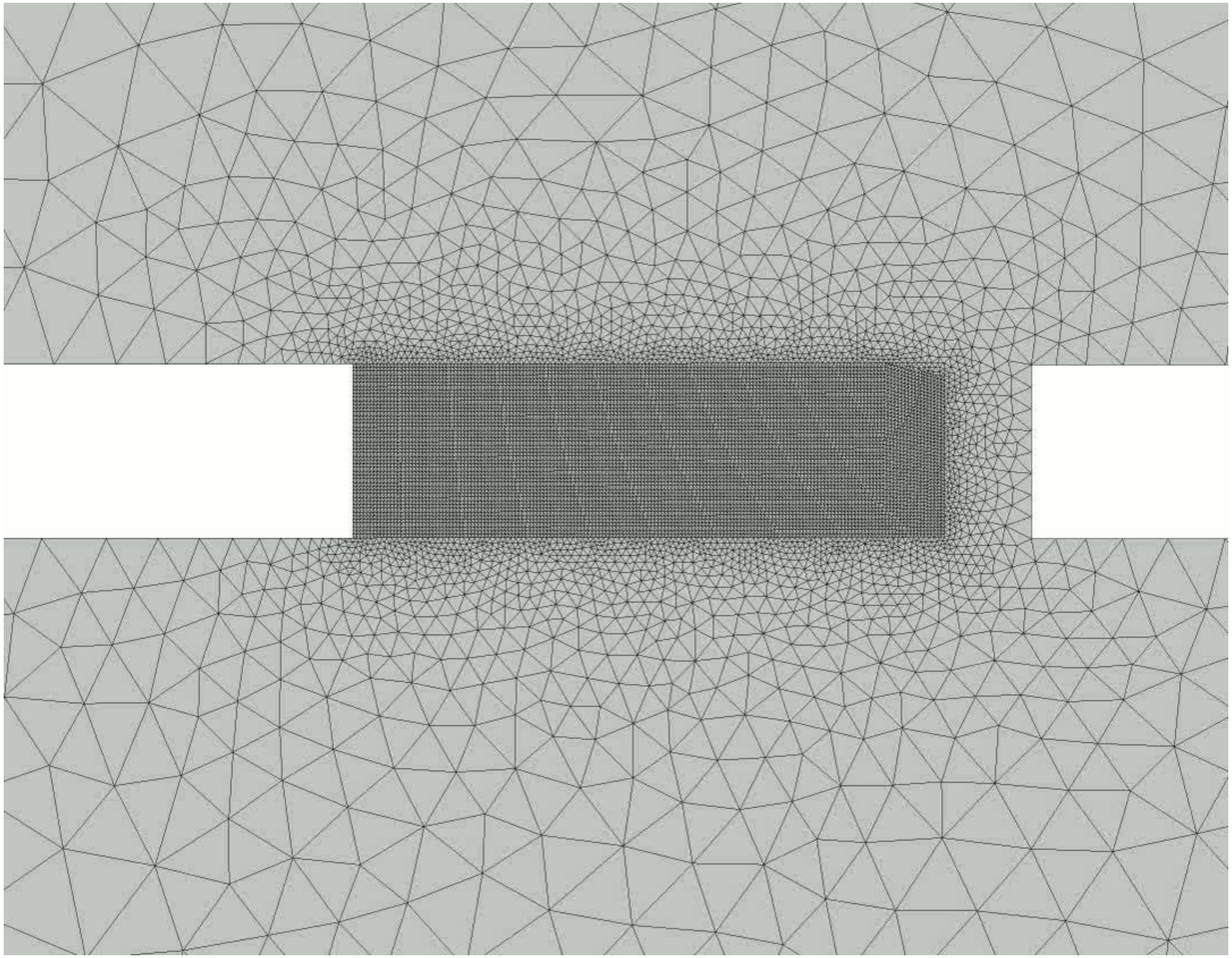
  - Mesh quality index:

    Minimum orthgonality angle



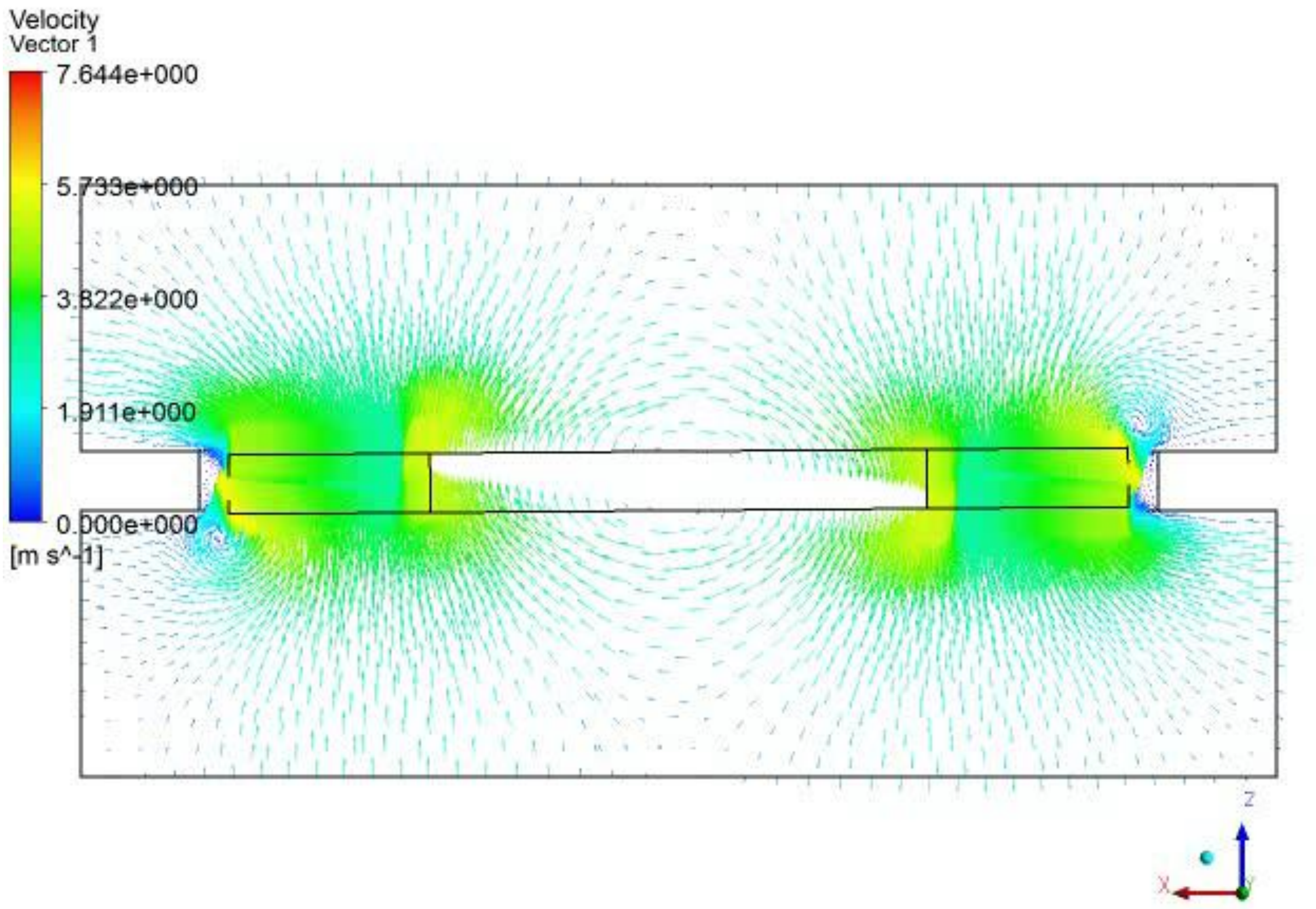
Rotational- large oscillation

- Mesh quality degradation and remeshing process occurs repeatedly



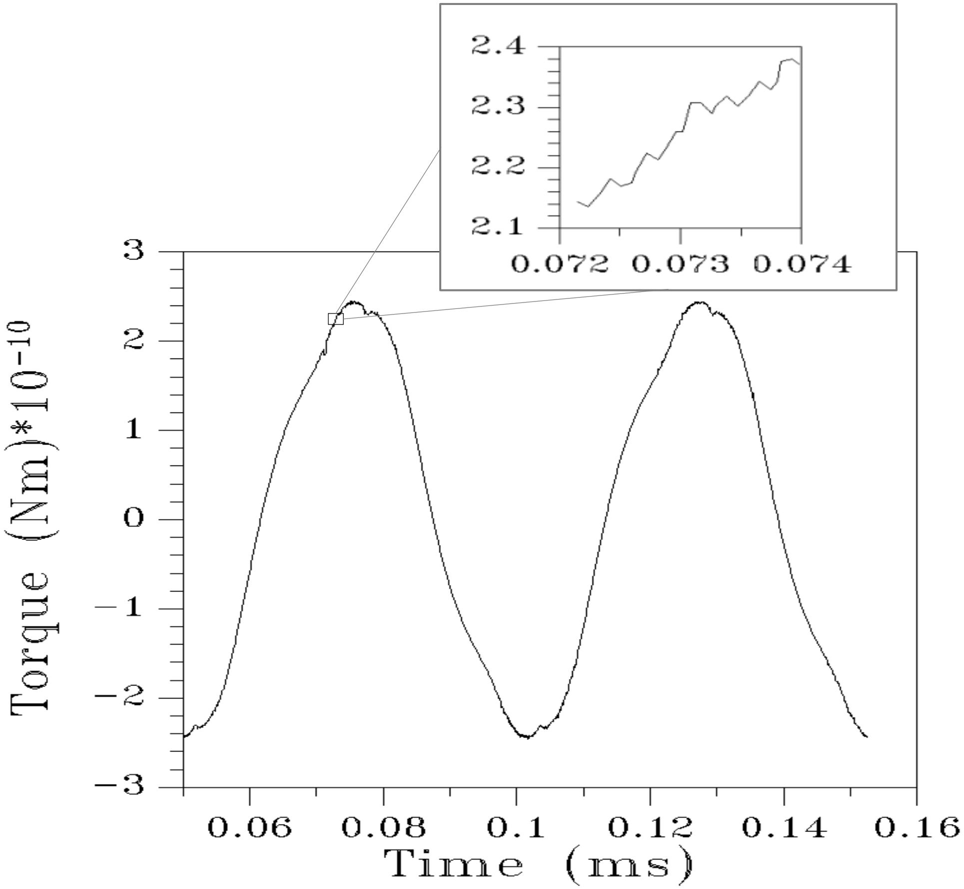
Rotational- large oscillation

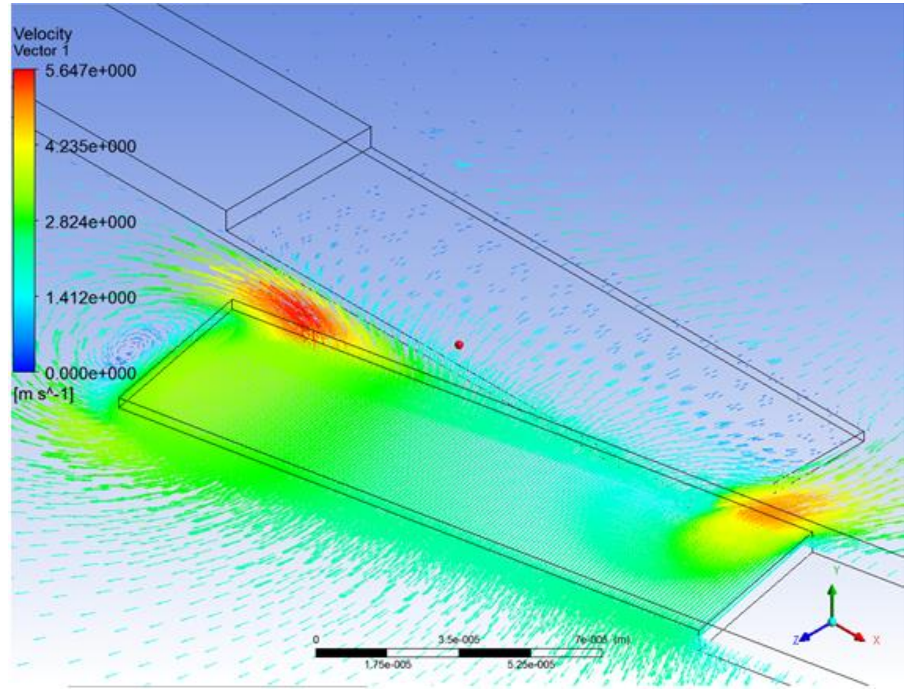
- Air velocity vectors evolving during large oscillations

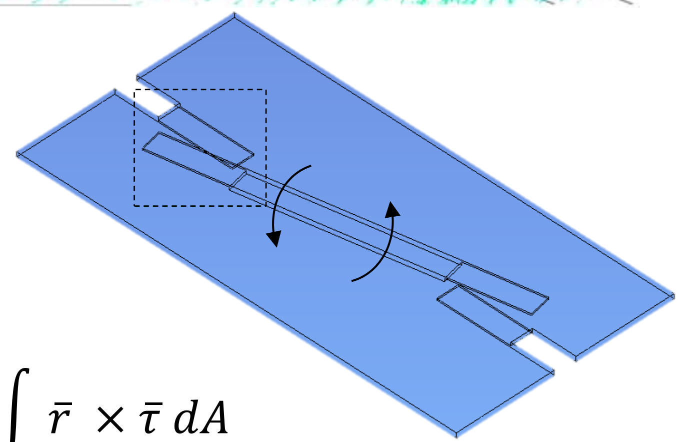


Rotational- large oscillation

- The finite size of plates results in having complex flow during large oscillations
- Small fluctuations at each remeshing



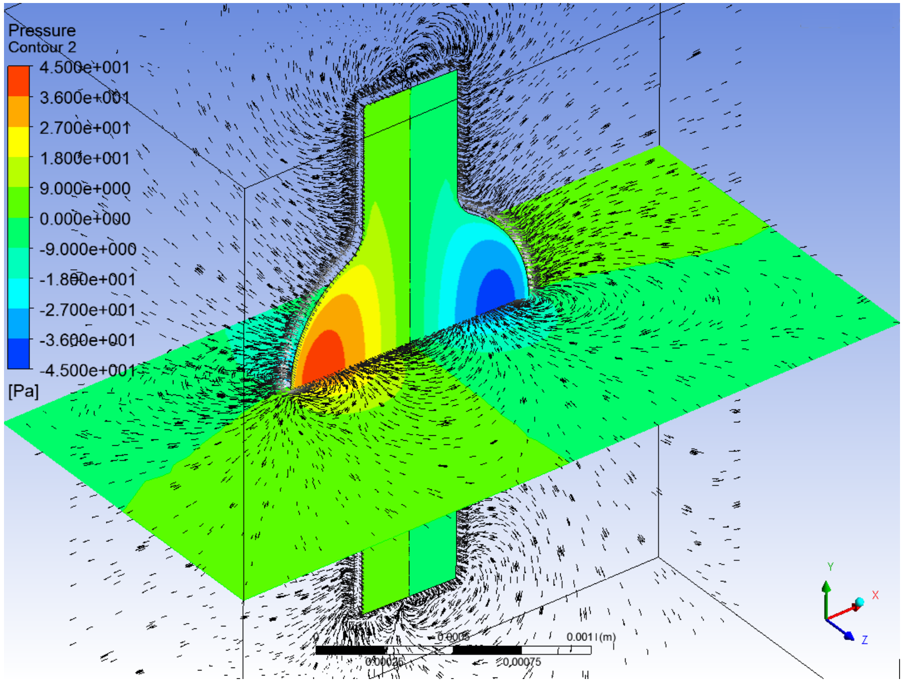


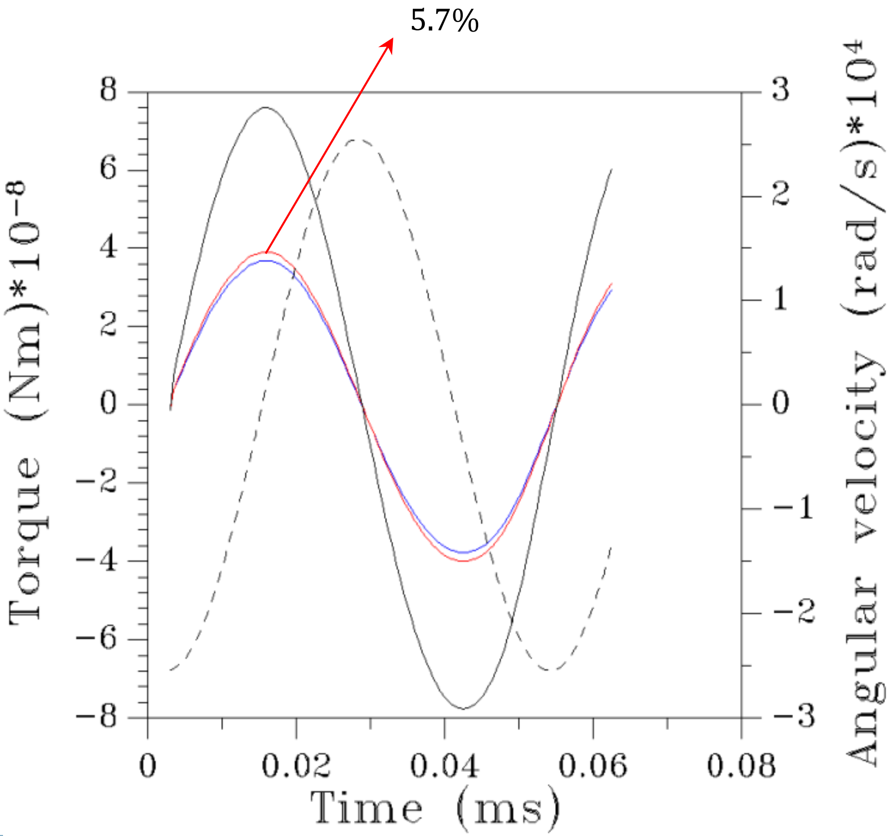


$$\bar{T}_{\tau} = \int_{A} \bar{r} \times \bar{\tau} \, dA$$

Dissipation in the mirror plate

Negligible squeeze effect

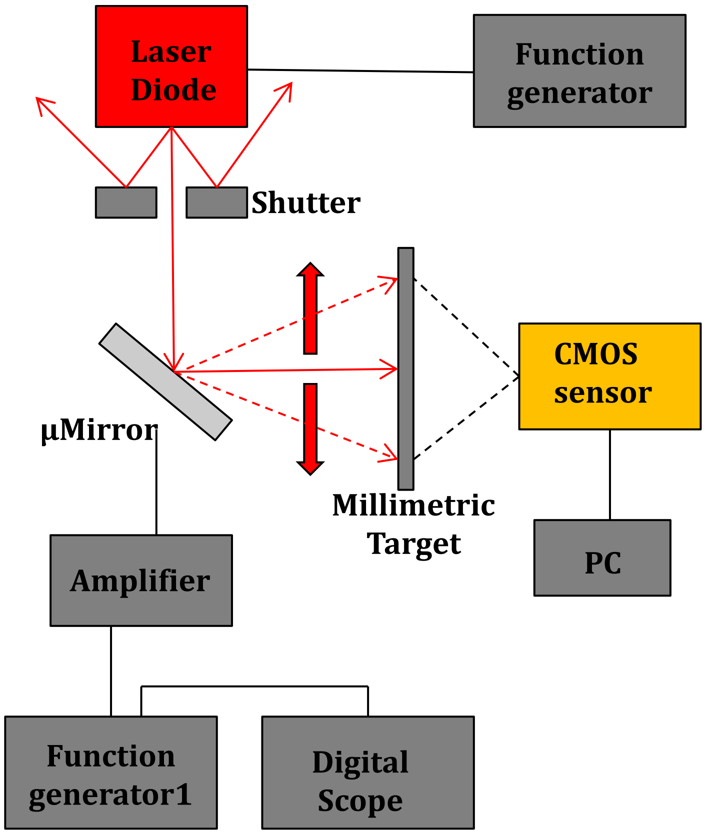


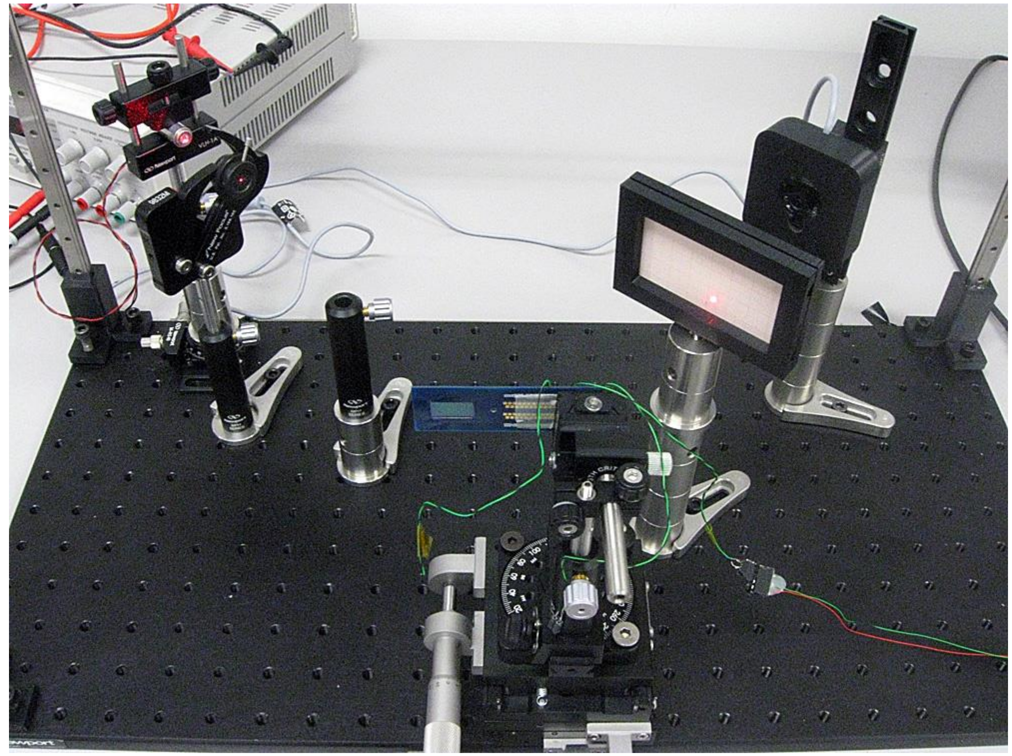


$$\bar{T}_p = \int_A \bar{r} \times p\, \bar{n}\, dA$$

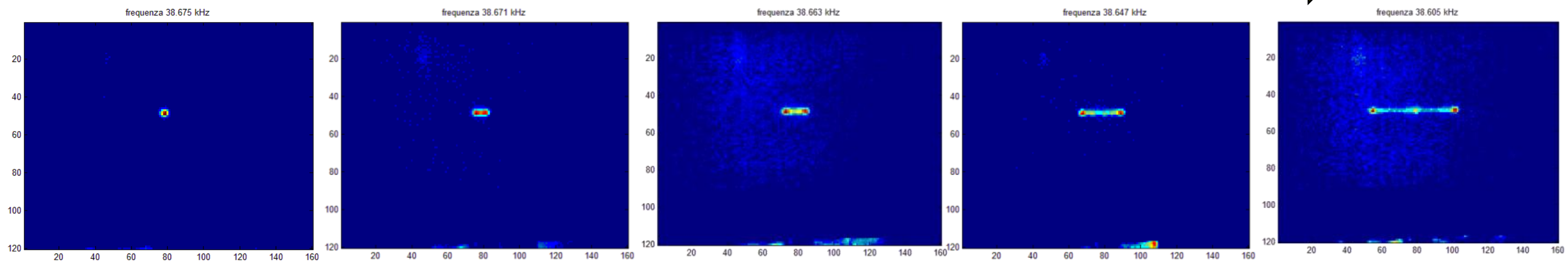
Total torque	———
Torque on top	——— (blue)
Torque on Bottom	——— (red)
Angular velocity	- - - - - -

Optical test setup



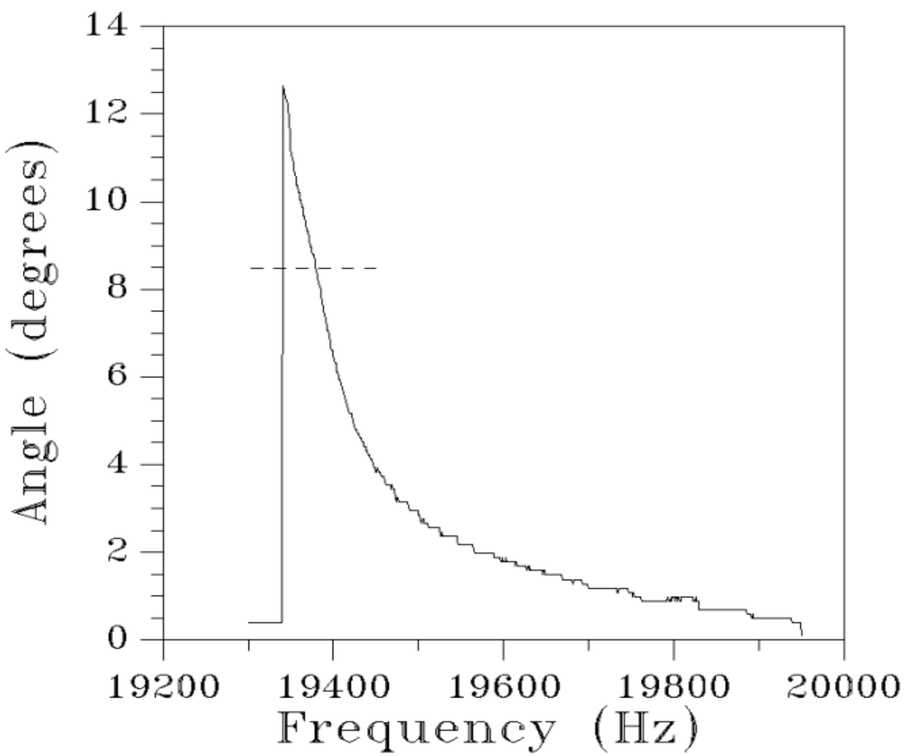


High **Frequency** Low



Quality factor

	E_{loss}(J)	E_{st}(J)	Quality factor
Comb fingers	1.78e-8	-	1 074
Mirror plate	1.18e-8	-	1 618
Total	2.96e-8	3.04e-6	645



$$Q = 2\pi \frac{E_{st}}{E_{loss}} \qquad Q_{total} = \frac{1}{\frac{1}{Q_{comb}} + \frac{1}{Q_{plate}}}$$

$$HBP \rightarrow Q_{exp} = 623$$

→ Model modifications: Including comb fingers at the drag damping and slip BC

Remarks

- At large oscillations **the end-effect/finite size** has an important role, which contributes in large energy dissipations
- **Individual quality factors** for different damping mechanisms have been obtained and the **overall quality factor** shows good agreement with the **experimental one**

- Analysis of the **electrostatic field** at the comb fingers to characterize the system excitation. This would give a complete model for the **dynamics of the micromirror**