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Anisotropic Damping in MEMS Oscillator

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Outline

1. Introduction
2. Model Definition
3. Use of **COMSOL Multiphysics® Software**
4. Model Validation
5. Results and Discussion
6. Conclusions

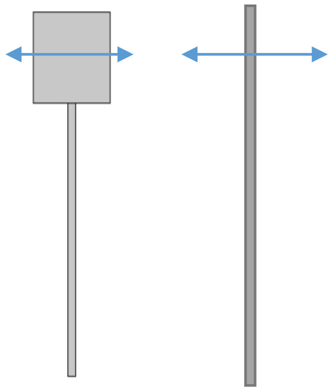
Introduction

- MEMS work in a significantly different environment with respect to larger size machine ⟹ strongly affected by the surrounding air.
- The air presents a counter reactive force on the moving elements of such devices.

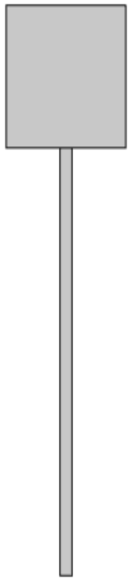
Introduction

- Damping effect of enveloping air is enforced if a plate is oscillating close to another plate, so that the air film is squeezed in between the two surfaces.

- It needs to vibrate with a high Q-factor in the horizontal plane and a low one along the transverse plane



Model Definition - Geometry



The model consists of one square proof-mass suspended by a thin cantilever beam. The cantilever beam is fixed at the end to the surrounding environment.

Side [µm]	200
Length [µm]	600
Beam Width [µm]	20
Thickness [µm]	10

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Model Definition – Coupling and Physics

The model uses **3D Solid-Mechanics Physics** interface to solve the squeezed film air/structure interaction using the **Thin-Film Damping** extension within the former domain.

Thin-Film Damping is a boundary physics, due to relative size with respect to the solid structure.

Zero-pressure thin-film edge condition used.

Model Definition – Material and Loads

- Solid Domain → Silicon
- Thin-Film gap → Air

Step response to a volume force: $F = \rho a$, where $a = \frac{g}{2}$, to study the oscillatory behaviour.

Use of COMSOL Multiphysics® Software

Studies	Extensions
☐ Eigenfrequency	☐ Parametric Sweep
☐ Time-Dependent	☐ Optimization
☐ Frequency Domain	

Thin-Film Damping boundary physics within 3D Solid Mechanics to simulate film/structure interaction.

Model Validation – Analitical Model

Physics of the phenomenon can be described by ***Reynolds equation***.

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y}\right)=\frac{\partial}{\partial x}\left(\frac{\rho h(u_a+u_b)}{2}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h(v_a+v_b)}{2}\right)+\rho(w_a-w_b)-\rho u_a\frac{\partial h}{\partial x}-\rho v_a\frac{\partial h}{\partial y}+h\frac{\partial \rho}{\partial t}$$

For small perturbations and parallel motion, it can be rewritten as:

$$p_a\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}\right)-\frac{12\mu\omega l^2}{h_0^2}\frac{\partial p}{\partial t}=\frac{12\mu p_a}{h_0^3}\frac{dh}{dt}$$

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Model Validation – Analitical Model

Cut-off frequency: $\omega_c = \frac{\pi^2 h_0^2 p_a}{12 \mu w^2}$

When a device owns a resonance frequency lower than the cut-off one

Viscous damping constant
Elastic damping negligible

Model Validation – Analitical Model

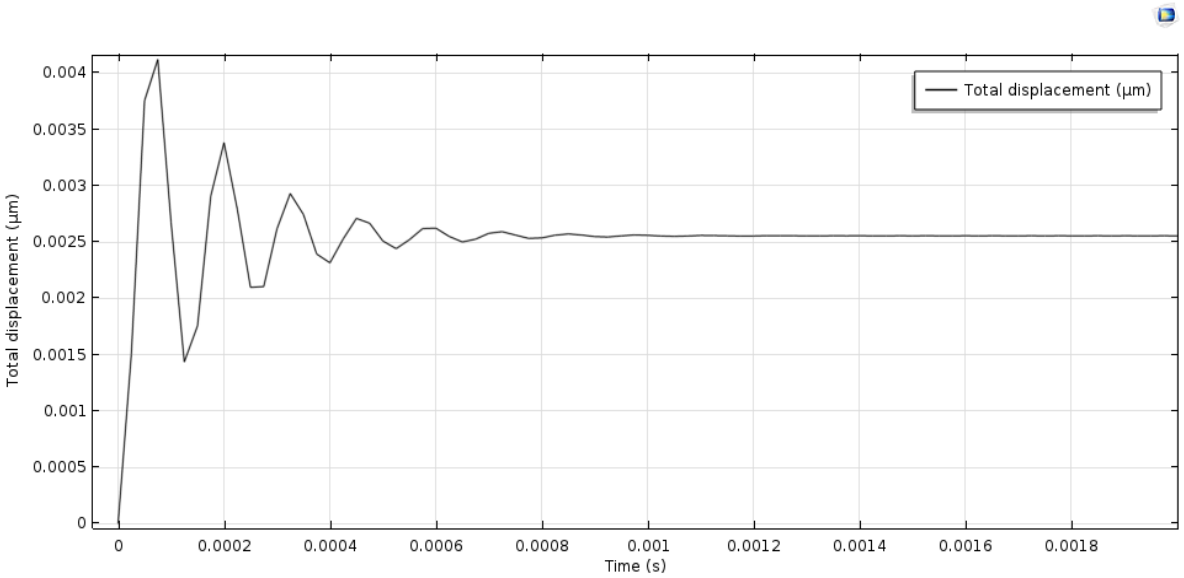
Standard second-order oscillator differential equation:

$$m\ddot{z} + c_d\dot{z} + (k_0 + k_e)z = \rho a$$

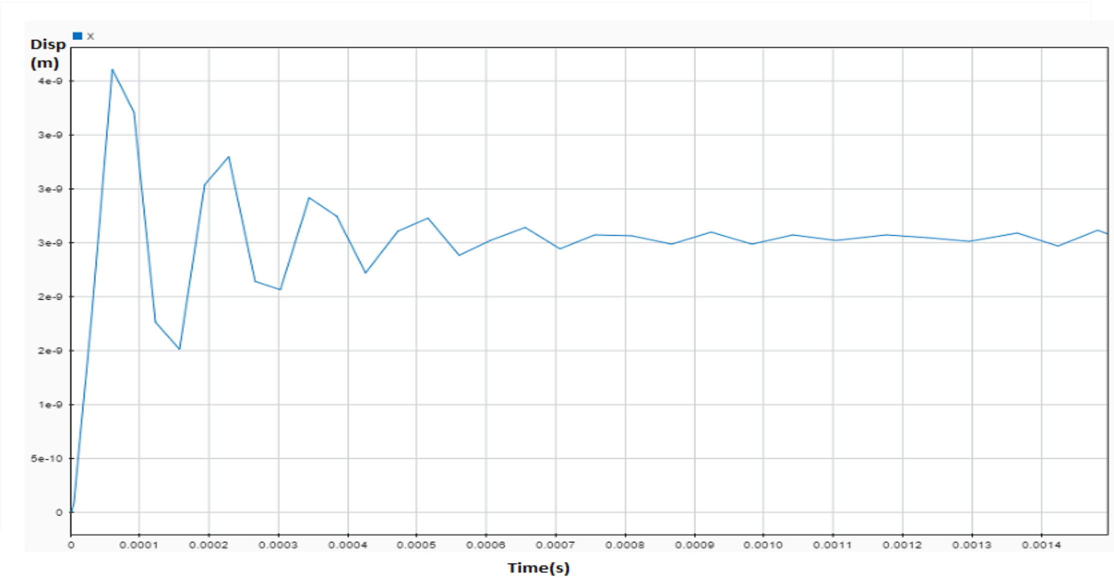
Where $c_d = 0.42\frac{\mu L w^3}{h^3}$, $k_e = 0$ and $k_0 = \frac{3EI}{l^3}$.

Model Validation – Analitical Model

Comsol simulation

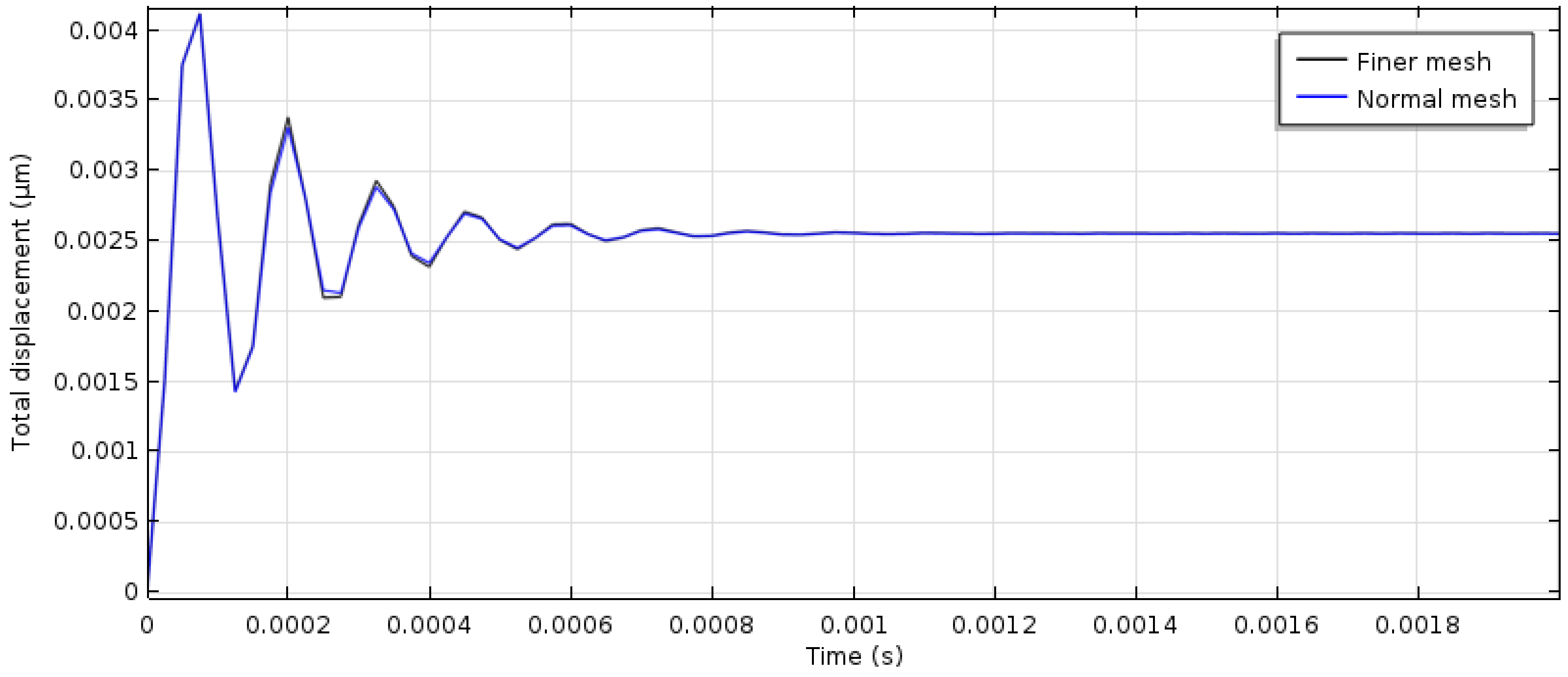


Differential-equation integrator



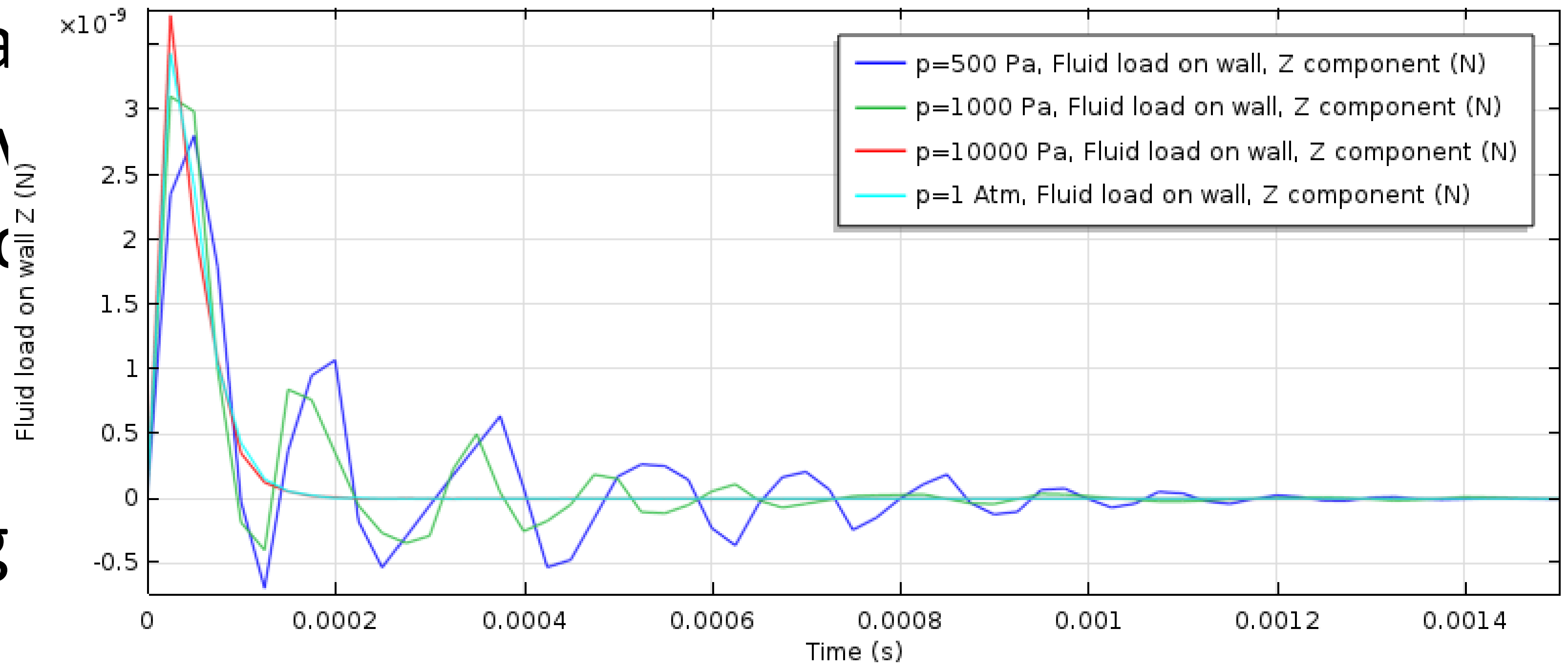
Model Validation – Analitical Model

Mesh convergence test: *extra fine* ⟷ *normal*



Results and Discussion – Pressure sweep

- The a… …ping in transv… …in the horizo…
- Swee… …only along…



Results and Discussion – Pressure sweep

Clearly the smaller the ambient pressure, the less significant is damping.

↓

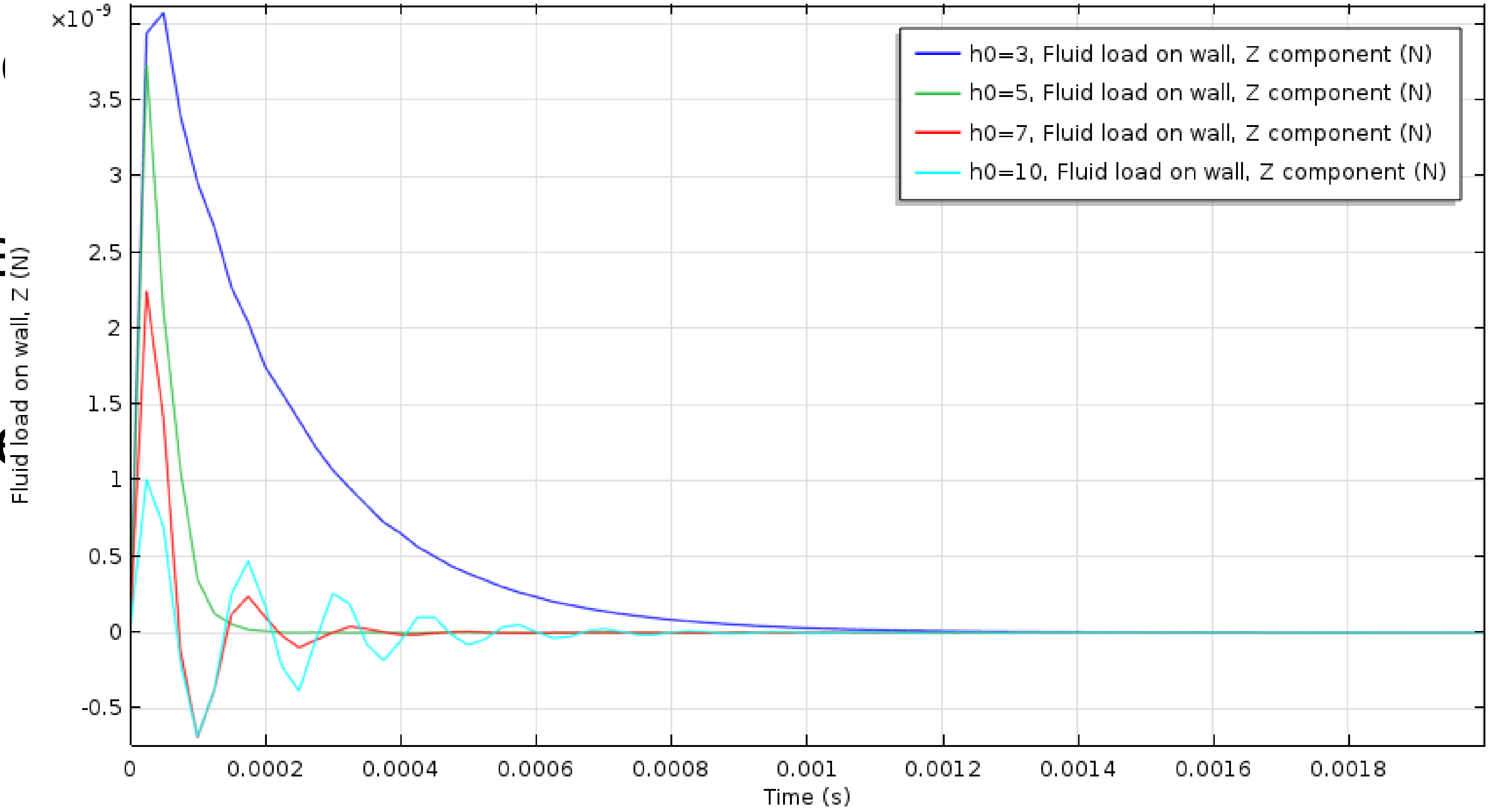
The ambient pressure should be kept relatively high in order to exploit thin-film damping to block the transverse oscillation.

↓

10 kPa asymptotic behavior

Results and Discussion – Gap height sweep

- The … inant whe … 3 times large



- Swee … ection

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Results and Discussion – Gap height sweep

From a graphical interpretation:

- **Overdamped** for h = 3 µm
- Nearly **Critically damped** for h = 5 µm
- **Underdamped** for h = 7,10 µm

Benefit from being critically damped → system to be brought back to stable position within the shortest time.

Results and Discussion – Frequency Response

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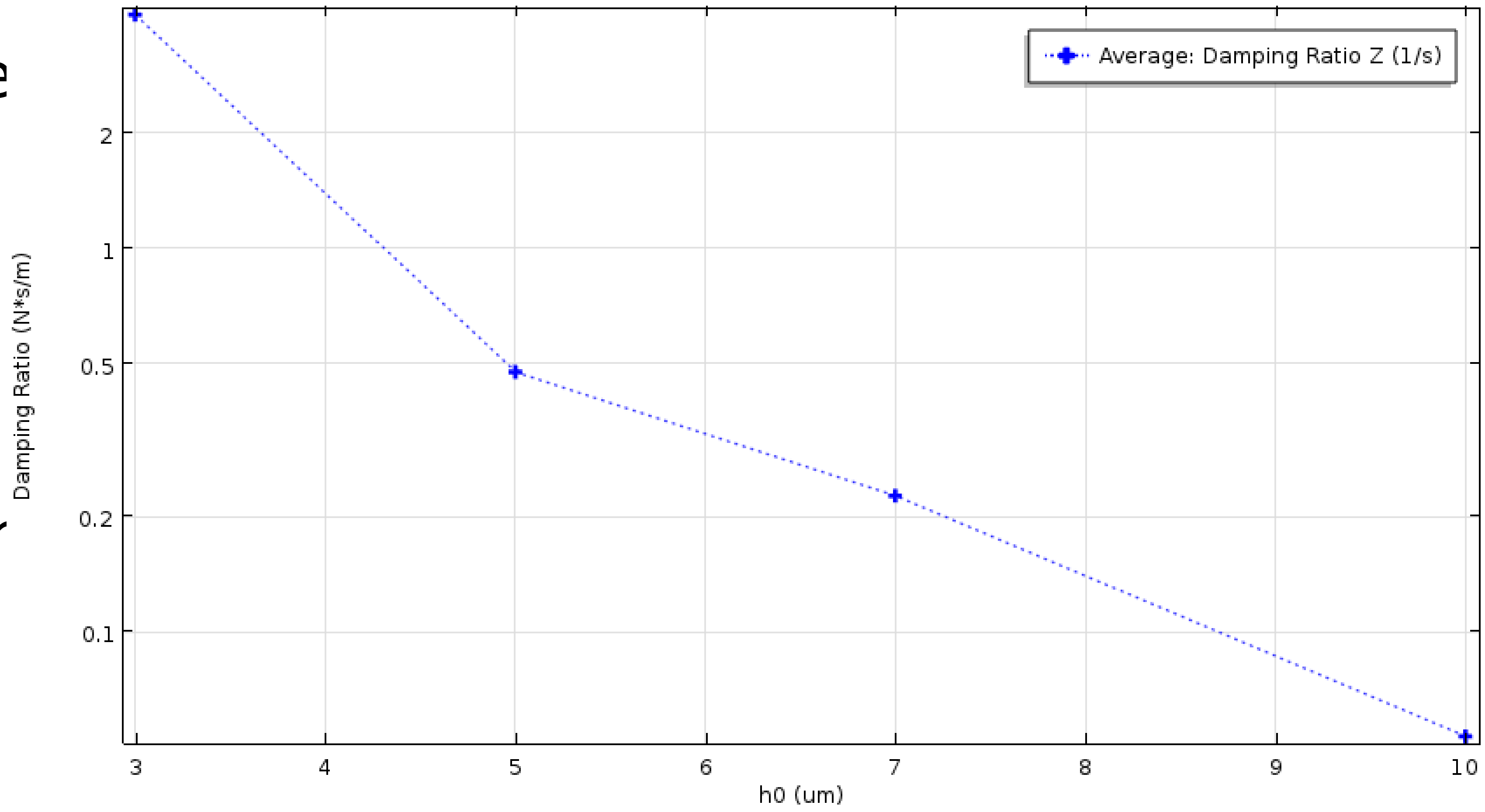
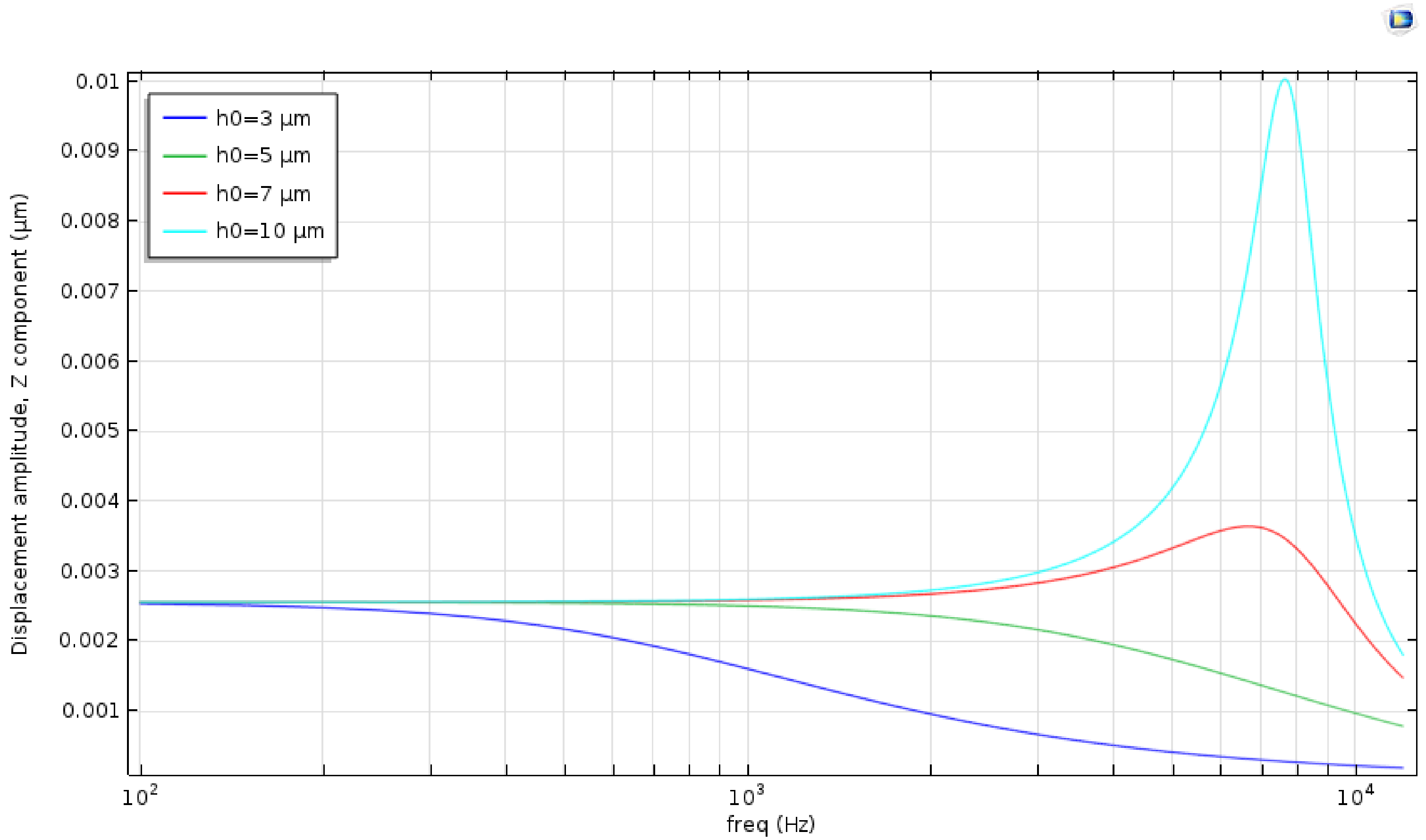


From wh

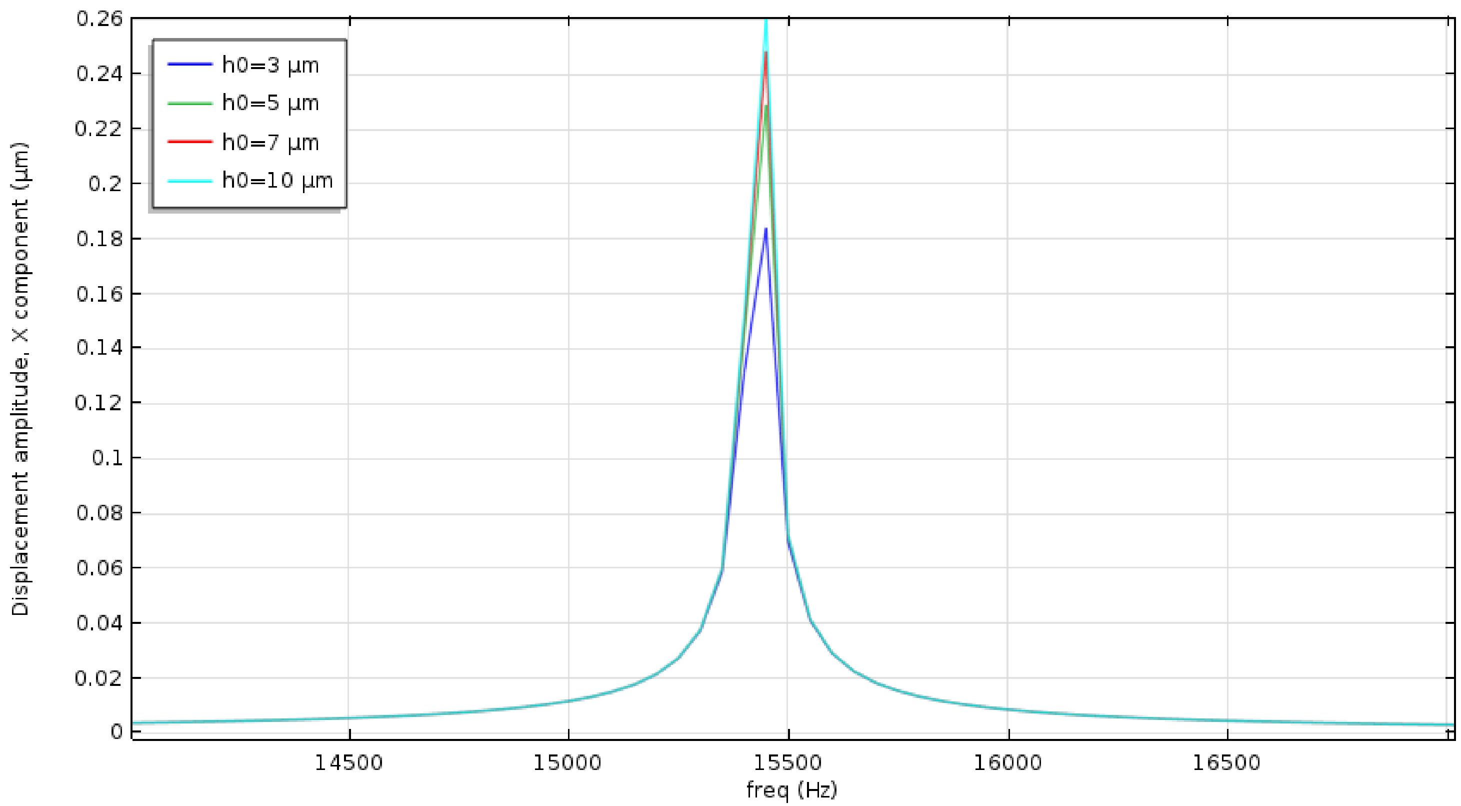
$$\frac{c_d}{2m\omega_0}$$

Results and Discussion – Frequency Response Z



The plot shows a typical set of second-order damped oscillator curves, as expected from the Time-Dependent study

Results and Discussion – Frequency Response X



Although each frequency response is typical of an underdamped system, the quality factor reduces as the gap height reduces.

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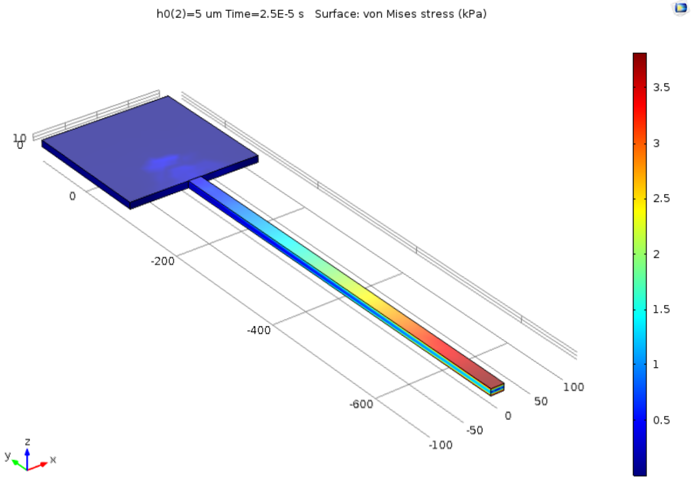
Results and Discussion – Frequency Response

- Not much damping is present in the horizontal motion along X
- Second-order damped oscillator curves along Z

Best-performing if
critically damped along Z



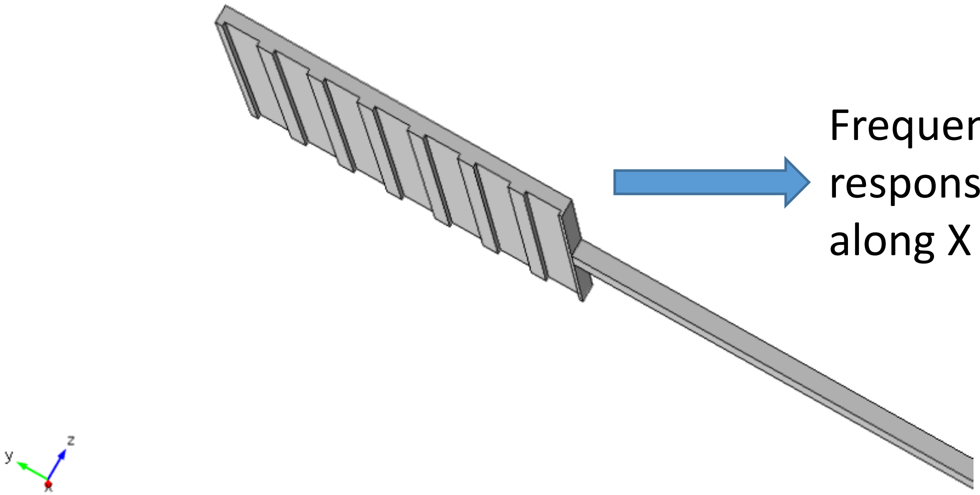
Results and Discussion – Optimization

An Optimization study was added to a Time-dependent along the Z direction to find out the gap height that would force the system to be critically damped.

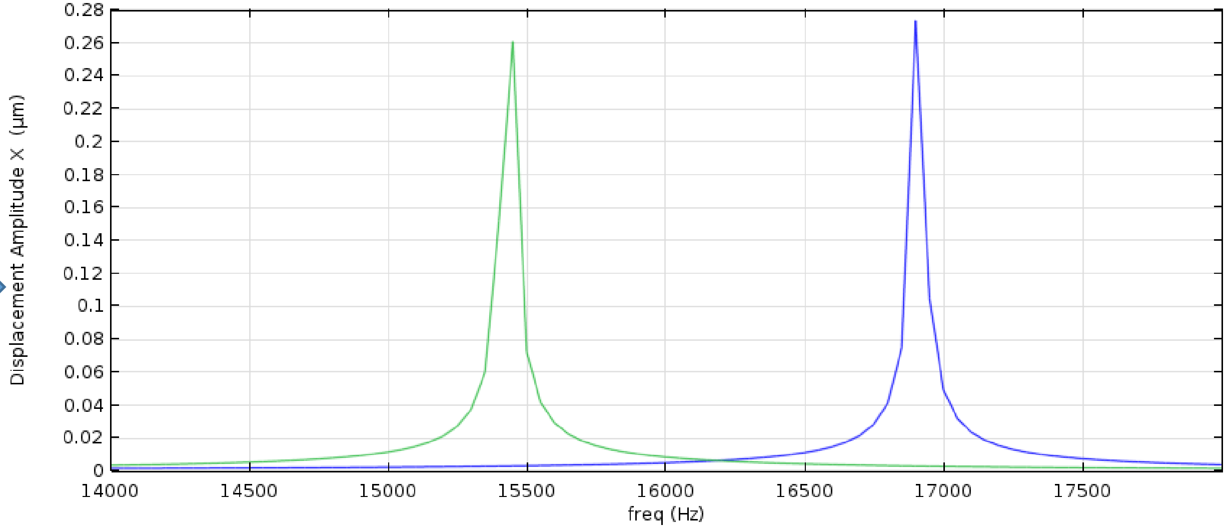
Nelder-Mead algorithm: $\mathrm{f(h)} = \zeta_z - 1 \longrightarrow \mathrm{min(f)}$

$\mathbf{h_{min} = 4.48\ \mu m}$

Results and Discussion – Surface Texture Variation



Frequency response along X



Maximum amplitude is higher then the best-case of previous scenario

Conclusions and Future Work

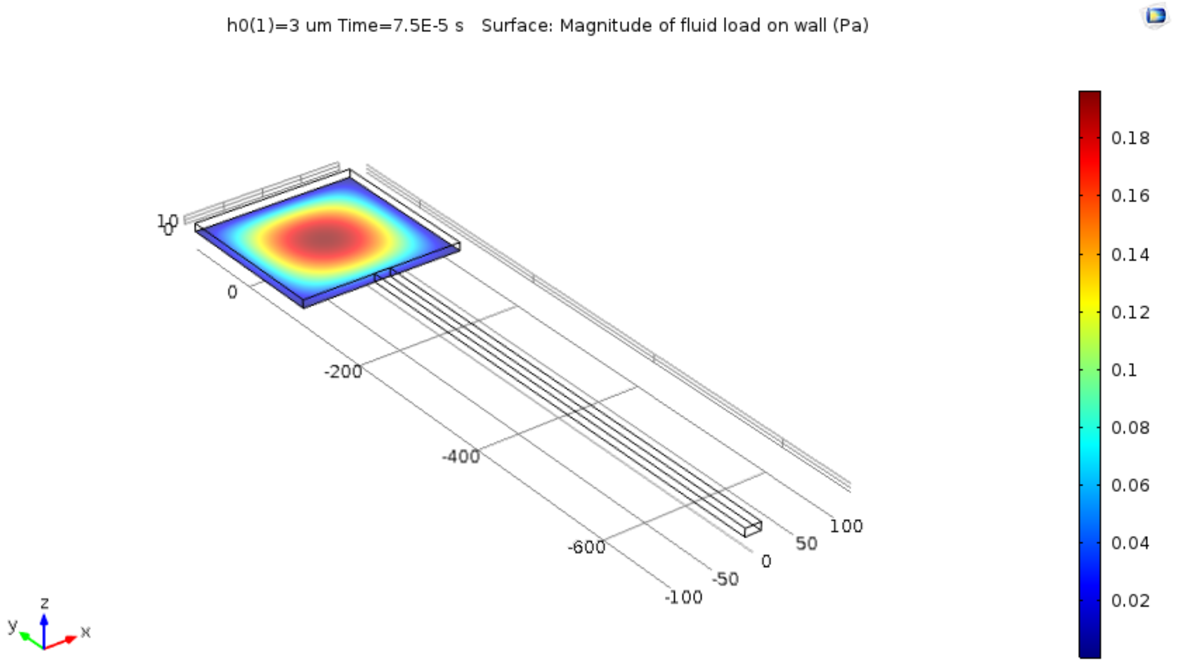
Conclusions

- Asymptotic behavior for pressure higher than 10 kPa
- Radial distribution of fluid load
- Major influence of thin-film thickness on Z damping
- Second-order oscillator along Z ⟹ critically damped as desired condition ⟹ **h_{min} = 4.48 µm**
- Model validation using analytical model

Future work

- Better modelling of the realistic MEMS environment (casing, etc)
- Topology optimization of the surface texture

Results and Discussion – Fluid Load



A typical radial distribution occurs, in which the inner fluid is trapped by the squeezing-effect resulting in a much higher reaction load on the wall.