Anisotropic Damping in MEMS Oscillator

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Outline

1. Introduction
2. Model Definition
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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.

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<table>
<thead>
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<tbody>
<tr>
<td>Side [µm]</td>
<td>200</td>
</tr>
<tr>
<td>Length [µm]</td>
<td>600</td>
</tr>
<tr>
<td>Beam Width [µm]</td>
<td>20</td>
</tr>
<tr>
<td>Thickness [µm]</td>
<td>10</td>
</tr>
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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

- Eigenfrequency
- Time-Dependent
- Frequency Domain

Extensions

- Parametric Sweep
- Optimization

Thin-Film Damping boundary physics within 3D Solid Mechanics to simulate film/structure interaction.
Physics of the phenomenon can be described by *Reynolds equation*.

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

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

\[
p_a \left( \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} \right) - \frac{12 \mu \omega l^2}{h_0^2} \frac{\partial p}{\partial t} = \frac{12 \mu p_a}{h_0^3} \frac{dh}{dt}
\]
Model Validation – Analytical 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 \( c_d = 0.42 \frac{\mu LW^3}{h^3} \), \( k_e = 0 \) and \( k_0 = \frac{3EI}{l^3} \).
Model Validation – Analytical Model

Comsol simulation

Differential-equation integrator
Model Validation – Analytical Model

Mesh convergence test: extra fine $\rightarrow$ normal
Results and Discussion – Pressure sweep

- The aim is to find an optimum between high damping in transverse oscillation and very low damping in the horizontal motion.

- Sweeping ambient pressure from 500 Pa to 1 Atmosphere, only along the Z-direction (most sensitive).
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 effects of squeeze film damping becomes dominant when the characteristic size of the device is at least 3 times larger than the gap height.

- Sweeping gap height 3 - 10 µm, only along the Z-direction.

![Graph showing fluid load on wall, Z component (N) for different h0 values.](image)
Results and Discussion – Gap height sweep

From a graphical interpretation:

- **Overdamped** for $h = 3 \mu m$
- Nearly **Critically damped** for $h = 5 \mu m$
- **Underdamped** for $h = 7, 10 \mu m$

Benefit from being critically damped system to be brought back to stable position within the shortest time.
Results and Discussion – Frequency Response

The eigenfrequencies were found to be:

\[ f_0^Z = 7771 \, \text{Hz} \]
\[ f_0^X = 15432 \, \text{Hz} \]

From which the damping ratio can be determined:

\[ \zeta = \frac{c_d}{2m\omega_0} \]
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.
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: \[ f(h) = \zeta_z - 1 \rightarrow \min(f) \]

\[ h_{\text{min}} = 4.48 \, \mu m \]
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 \[ h_{\text{min}} = 4.48 \, \mu m \]
- 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.