Future of MEMS: a Mechanical Perspective

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MEMS and mechanics

**Mechanics** is the branch of science concerned with the behavior of physical bodies when subjected to forces or displacements, and the subsequent effects of the bodies on their environment. (from Wikipedia)

- **Devices**: accelerometers, gyroscopes, pressure sensors, Lorentz-force magnetometers, micro-energy harvesters, …
- **Multi-physics coupling**: chemo- electro- thermo- magneto-… mechanical,
- **Fabrication** processes: CTE mismatch, thermo-mechanical stresses, anisotropy, heterogeneity, …
- **Reliability**: fracture, fatigue, stiction, moisture absorption, accidental drop, eigen-stresses,…
MEMS and mechanics

Mechanics in MEMS: from the initial idea to the final product

Idea → design → fabrication → product
Future of MEMS?

- **Fabrication and materials**: additive manufacturing, 3D and ink-jet printing, smart materials inside MEMS, meta-materials,…

  More than silicon

- **Modelling & simulation**: full and reduced order simulation, real time computing, identification and diagnosis,…

  More than simulation

- **Complete mastering of “complex” phenomena**: damping sources, adhesion-stiction, fracture, fatigue, multi-physics coupling,…

  More than linear

- **New applications**: biomedical, wearable devices, flexible electronics, extremely harsh environment, IOT, IOE, pervasive sensing, metamaterials,…

  More than MEMS
More Ms in MEMS!

- Modelling & simulation
- Multi-physics
- Multi-scale
- Mechanics
- Materials
- Manufacturing
- …
Modelling & simulation: plane resonator

![Diagram of a plane resonator](image)

\[ f_0 = \frac{\sqrt{c_{11} + c_{12}^2 - 2c_{12}^2 / c_{11}^2}}{\rho / 2L} \]

\( L = 320 \, \mu m \)

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>( E )</td>
<td>100</td>
<td>GPa</td>
</tr>
<tr>
<td>Structure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass density</td>
<td>( \rho )</td>
<td>2330</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>( \nu )</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Air gap</td>
<td>Electric permittivity</td>
<td>( \varepsilon )</td>
<td>( 8.854 \times 10^{12} , C^2/(Nm^3) )</td>
</tr>
</tbody>
</table>

Multi-physics modelling: plane resonator

Electro-mechanical coupled solution: comparison of different strategies

<table>
<thead>
<tr>
<th>Method</th>
<th>Total time</th>
<th>Error w.r.t stag.</th>
<th>Gain w.r.t Stag. (%)</th>
<th>n° POM</th>
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<tbody>
<tr>
<td>S ($t_{tot}=4\cdot10^{-5}$)</td>
<td>24370</td>
<td>-</td>
<td>-</td>
<td>--</td>
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<td>S-POD ($t_{snap}=3\cdot10^{-7}$)</td>
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<td>8,32·10^{-2}</td>
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<td>35</td>
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<td>8,33·10^{-2}</td>
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<td>SD-POD ($t_{snap}=2\cdot10^{-7}$)</td>
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<td>S-POD ($t_{snap}=1.5\cdot10^{-7}$)</td>
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<tr>
<td>SD-POD ($t_{snap}=1.5\cdot10^{-7}$)</td>
<td>2826</td>
<td>5,86·10^{-2}</td>
<td>-88,4</td>
<td>34</td>
</tr>
<tr>
<td>SD-POD updated</td>
<td>2664</td>
<td>9,98·10^{-2}</td>
<td>-89,1</td>
<td>31</td>
</tr>
</tbody>
</table>

Reduction of 90% w.r.t. reference method!
Multi-scale modelling: spontaneous adhesion

Dry conditions: van der Waals attraction

Results at varying surface roughness

Capillary attraction, plastic strain

Results at varying relative humidity


$\gamma \times 10^{-5}$

Experimental data
Hu-Tonder surface
Spherical caps

Differential resonant micro-accelerometer

Non-linear response of the torsional resonator

Threshold shock sensor based on a bi-stable mechanism

Threshold shock sensor based on a bi-stable mechanism

Ultra wide bandwidth Energy Harvester

- Nonlinear Resonance
- Hardening effect at high amplitudes due to stretching mode
  - Smaller device
  - High frequencies
  - Lower amplitudes
  - **Wider Bandwidth**
  - Reliability issues

Increase of the natural frequency

Optimal power generation

Ultra wide bandwidth Energy Harvester

- **Mesoscale Prototype**
  - PZT patches with microfibrers and interdigitated electrodes
  - Lead central mass (16.5 grams)
  - 0.3 mm thick beam
  - Open circuit analyses at various input acceleration levels

High Mechanical damping due to: Big devices, Glued PZT, Sliding clamping
Good agreement between model and experimental data

Meta-materials

**Artificial materials** engineered to have properties that may not be found in nature. … (From Wikipedia)

Design material properties at will

Electromagnetic, acoustic, mechanical … metamaterials

Negative refractive index
Negative electric and magnetic permittivity
Negative Poisson ratio
Negative compressibility …

Other strange properties

**MEMS based meta-materials**

&

**Meta-materials in MEMS**
Reconfigurable anisotropic metamaterials at terahertz frequencies, artificial “atoms” reorient within unit cells in response to an external stimulus. Planar arrays of split ring resonators on bimaterial cantilevers designed to bend out of plane in response to a thermal stimulus. Tunability of the electric and magnetic response as the split ring resonators reorient within their unit cells. **Adaptive meta-materials** offer significant potential to realize novel electromagnetic functionality ranging from thermal detection to reconfigurable cloaks or absorbers.

Orthotropic materials for negative or zero compressibility

\begin{align*}
E \text{ matrix} & = \begin{bmatrix}
0.046 & 0.001 & 0.042 \\
0.001 & 0.046 & 0.042 \\
0.042 & 0.042 & 0.095 \\
\end{bmatrix} \\
C \text{ matrix} & = \begin{bmatrix}
66.575 & 44.215 & -49.480 \\
44.215 & 66.575 & -49.480 \\
-49.480 & -49.480 & 54.752 \\
\end{bmatrix} \\
\end{align*}

\begin{align*}
E \text{ matrix} & = \begin{bmatrix}
0.068 & 0.008 & 0.063 \\
0.008 & 0.068 & 0.063 \\
0.063 & 0.063 & 0.141 \\
\end{bmatrix} \\
C \text{ matrix} & = \begin{bmatrix}
33.302 & 16.538 & -22.171 \\
16.538 & 33.302 & -22.171 \\
-22.171 & -22.171 & 26.807 \\
\end{bmatrix} \\
\end{align*}

3D micro additive manufacturing

- Scalable Additive Manufacturing
  - Stereolithography
  - Selective Laser Sintering
  - 3D printing
  - Inkjet printing processes
  - Fused Deposition Modeling
  - Laminated Object Manufacturing

- 3D Direct Writing
  - Ink-based DW processes:
    - Nozzle dispensing: Precision pump and Syringe based methods
    - Aerosol jet
  - Laser transfer DW:
    - Laser-induced forward transfer (LIFT)
    - Matrix assisted pulsed laser direct write (MAPLE)
  - Beam deposition:
    - Laser chemical vapor deposition (LCVD)
    - Focused Ion beam DW
    - Electron beam DW

- Hybrid processes
  - Electrochemical Fabrication (EFAB)
  - Shape Deposition Modeling (SDM)

3D micro additive manufacturing

3D photonic crystal produced by 2 Photon Polymerization 2PP process

3D microparts produced with Micro Laser Sintering (MLS) process

Gyroscope produced by Electrochemical FABrication (EFAB) process

Printing MEMS

Goal:
enabling printing of 3D silicon micro- and nano- structures directly from computer-generated 3D drawings
Closing remarks

More Ms in MEMS!

Mechanical and other non-linearities: not only to avoid!

New Materials and Meta-materials

New Micro-fabrication technologies

New @ Polimi!

Polifab: micro and nano technology facility

MEMS&3D lab: laboratory for MEMS and 3D fabrication
THANK YOU FOR YOUR ATTENTION!