Simulation Methods for Electrostatic MEMS Switches and Resonators

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NXP Semiconductors

- Established in September 2006 (formerly a division of Philips)
- ~38,000 employees
- Headquarters: Eindhoven, The Netherlands
- Main product: transistors on Silicon
- But also other electronic devices on Silicon…
Outline

MEMS: Micro Electrical Mechanical Systems

- RF MEMS switches
  - Calculation of the C-V curve using Comsol

- MEMS resonators
  - Equivalent parameters m, k and Q of a MEMS resonator using Comsol

**RF MEMS capacitive switch**

**MEMS resonator**
Electrical switches

Morse telegraph key (1844)
Mechanical switch

Advantages
• Low loss/resistance
• High linearity
• High power handling

Transistor (1947)
Semiconductor switch

Advantages:
• Very small size
• High switching speed
• Low cost

Radio Frequency MicroElectroMechanical Switch (RF MEMS)

Best of both worlds: Mechanical switch on semiconductor substrate.
• Low loss
• High linearity
• High RF power handling
• Intermediate size
• Intermediate switching speed
• Intermediate cost
RF MEMS switch physics

- **Forces**
  - **Static**
    - Spring forces
    - Electrostatic force
    - Contact force
  - **Dynamics**
    - Gas damping force
    - Inertial forces
MEMS switch under study
MEMS Capacitance-Voltage curve in Comsol

- Approximations:
  - Electrostatic parallel plate approximation.
  - Use Mindlin elements for mechanical domain.
  - Hard contact.

- Simulation in Comsol structural mechanics domain
  - Implement electrostatic and contact forces as pressures on the structure.
Parametric solver

- How to get C(V)?

- Problem with voltage control:
  - Multiple solutions for 1 voltage.
  - Discontinuities in the shape at pull-in and release voltage.
  - Convergence problems.

- Solution:
  - Position control of control node.
  - Determine C and V at each position.
Implementation of position control in Comsol

- Define point integration variable wcontrol1 on control node.
Parametric solver

- Parameter par goes from 0-100.
- wset=-g*par/100.
Define extra degree of freedom $py$

- ODE will vary $py$ until: $wcontrol1 = wset$ \hspace{1cm} ($wset = -g \cdot par / 100$)

- This will ensure that the control node is moved from open to closed position.
Apply adaptive electrostatic and contact force

- In Comsol a pressure $P_e = p_y \frac{(g+a/\varepsilon_r)^2}{(g+w+a/\varepsilon_r)^2} = \frac{V^2}{2\varepsilon_0} \frac{(g+w+a/\varepsilon_r)^2}{2}$ is applied.
- Extra degree of freedom $p_y \propto V^2$
- The ODE finds $V^2$ such that $w_{control1} = w_{set}$!
- $C$ is obtained from subdomain integration: $C = \int dA \frac{\varepsilon_0}{(g+w+a/\varepsilon_r)}$.
- Contact pressure is modelled by a steep parabola if $(g+w<0)$.
- $C(V)$ curve is obtained.
Calculated CV curve
Simulation and measurement
disp0(50)=5e-10 Surface: z-displacement [m].

Max: 4.564e-21 Max: -3.072e-8

Min: -3.072e-6 Min: -3.041e-6
Outlook: dynamics

- Each second in the interferometric slow-motion movie is about 2 μs in reality.
- If we would play a 1 hour movie recording of the switch at this slow-motion rate, we would not be able to see the end of the movie within our lifetime.
- Therefore I only show 50 μs.
More complications
Electrostatic see-saw structure
MEMS resonators

- Application:
  - Oscillator (clock)

Quartz resonator is large and expensive
Goal: replace Quartz crystal by Silicon crystal

Simulating MEMS resonators

- Simplistic way to analyze MEMS resonators with Comsol:
  - Put geometry and material parameters in Comsol.
  - Run eigenfrequency analysis.
  - Select required mode shape by hand.
  - Examine frequency.

- How can we get more information from this simulation?
Parameter extraction

- Method to extract the 3 mechanical parameters by postprocessing of the eigenmode.
Equivalent circuit

- Assume everything is linear.
- Electrical admittance $Y$ can be determined if $k_i, m_i$ and $b_i$ are known for all eigenmodes.

\[ Y = \frac{i_{ac}}{V_{ac}} = j\omega C_w + \eta^2 \sum_{i=1}^{N} \left( j\omega m_i + b_i + \frac{k_i}{j\omega} \right)^{-1} \]
Determining \( m \) and \( k \) by postprocessing of eigenmodes

\[
E_{\text{tot}} = E_{\text{el, max}} = \frac{1}{2} k_i |x_i|^2 = \left| \int_V W_s \, dV \right|
\]

Max. elastic energy

\[
E_{\text{tot}} = E_{\text{kin, max}} = \frac{1}{2} m_i |\omega_i x_i|^2 = \frac{1}{2} \left| \int_V \rho \omega_i u_i^2 \, dV \right|
\]

Max. kinetic energy

Therefore:

\[
k_i = \frac{2}{\left| x_i \right|^2} \left| \int_V W_s \, dV \right|
\]

\[
m_i = \frac{k_i}{|\omega_i|^2} = \frac{1}{\left| x_i \right|^2} \left| \int_V \rho u_i^2 \, dV \right|
\]
Determining the damping coefficient $b$

- Damping in our resonators seems to be dominated by support losses:
  - Energy in traveling waves disappears via the anchors to the substrate.

- Substrate is very large. How to model the traveling waves?
  - Absorb them using an artificial boundary layer in the substrate.
  - Artificial material should have the following properties:
    - No reflection (matched layer).
    - Energy of traveling waves needs to be absorbed to prevent wave from coming back.

- Comsol 3.3: Perfectly Matched Layer (PML) in Structural Mechanics Module
  - Only available in frequency response analysis mode.
  - PMLs will be implemented in eigenfrequency analysis in future Comsol version.
  - Eigenfrequency analysis mode is much faster.
Matched layer (artificial material $E', \rho', \nu'$)

- Zero reflection: $Z = Z'$
- Wave absorption: $\text{Im} \rho' < 0$

- Only perfectly matched for normal incidence.

\[
\begin{align*}
E' &= jE / \alpha \\
\rho' &= -j \alpha \rho \\
\nu' &= \nu
\end{align*}
\]
Determining $b$

- Complex material parameters of Matched Layer
- Therefore: Complex eigenfrequencies $\omega$.

\[ Q_i = \frac{\text{Re} \omega_i}{2 \text{Im} \omega_i} \]

- Damping coefficient $b_i$ is obtained using:

\[ b_i = \frac{\sqrt{k_i m_i}}{Q_i} \]
Example: MEMS disk resonator

- Check method on diamond disk resonator

- Analytically verified:
Geometry (cylindrical symmetry)
Script to analyze all eigenmodes

- Analyze all eigenmodes up to 700 MHz.
- Select modes with $Q>10$.  
- Dominant mode is selected using Comsol script.

<table>
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<tr>
<th>fres (MHz)</th>
<th>k (N/m)</th>
<th>m (kg)</th>
<th>b (kg/s)</th>
<th>Q</th>
<th>Ymax (1/Ohm)</th>
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<td>26.34</td>
<td>4.41E+11</td>
<td>1.61E-05</td>
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</tbody>
</table>
Total displacement in the first radial bulk-mode of the disk resonator at 489.27 MHz.
Acoustic waves traveling in the substrate
Acoustic waves traveling in the substrate
Comsol eigenfreq.

Analytic

Measurement

Reducing disk radius R from 13 to 8 µm

Measurement comparison
Comparison with frequency response and PML

- Eigenfrequency analysis 60x faster than frequency response.
- ML in good agreement with PML result.
Conclusions

Simulation methods for electrostatic MEMS devices:

- Static C-V curve of capacitive RF MEMS switches.
  - Position control efficiently implemented using Comsol ODE.

- Admittance calculation of MEMS resonators
  - Support losses implemented using matched layer material model.
  - Equivalent parameter k, m and b extracted by postprocessing of eigenmodes.
  - Script to analyze all mode shapes.
  - See my Comsol 2007 proceedings article for more details.