A micro-meso model to predict van der Waals and capillary induced stiction in micro-structures

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Introduction

• Stiction in MEMS
  – Reasons
    • Relatively high surface area: volume ratio (1,000:1 to 10,000:1 m⁻¹)
  – Adhesive forces
    • Electrostatic force,
    • Van der Waals force,
    • Capillary force
    • Hydrogen bridging…

• How can it be predicted / simulated?

Stiction failure in a MEMS sensor
(Jeremy A. Walraven Sandia National Laboratories. Albuquerque, NM USA)
Introduction

- Multiscale approach

Single asperity adhesive-micro contact

Adhesive elastic contact model between rough surfaces

Integration with FEM
Van der Waals forces

- **Asperity level: Adhesive-elastic contact (Hertz) theories**
  - Johnson, Kendall, and Roberts (JKR)
    - Short ranged surface forces
    - Act only inside the contact area
    - Soft, compliant materials with high adhesion energy
  
  - Derjaguin, Muller and Toporov (DMT)
    - Long-ranged adhesive forces
    - Outside of the contact area
    - Harder, less compliant materials with low adhesion energy and small asperity tip radius

- Maugis transition solution
  - Intermediate cases between JKR and DMT
  - For all elastic materials
Van der Waals forces

- Asperity level: Maugis – Dugdale semi-analytical solution
  - Approximate potential

  \[ F_n \]

  \[ a \neq 0 \]
  \[ c \neq 0 \]

- Force-distance curve
  - Can be solved for given
    - Sphere radius
    - Adhesion energy
    - Sphere Young modulus

<table>
<thead>
<tr>
<th>Surface energy ( \varpi )</th>
<th>Aperity Radii ( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.54 J/m(^2)</td>
<td>260.5 nm</td>
</tr>
</tbody>
</table>
Van der Waals forces

• Rough surfaces
  - Representations
  - Parameters
    • Asperity height follows a Gaussian distribution
      \[ \varphi(h) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(\frac{-h^2}{2\sigma^2}\right) \]
    • \( N \) asperities per square meters
    • Asperity radius \( R = \text{cst} \)
  - \( N, R, \sigma \) are calculated from real surface (AFM)
    • Variance of height \( m_0 \),
    • Variance of slope \( m_2 \),
    • Variance of curvature \( m_4 \),
Van der Waals forces

- Rough surfaces
  - Integrate the sphere responses

\[
F_s(d) = N \int_{\delta_{low}}^{-d+2.5\sigma} F(\delta) \frac{\phi(d + \delta)}{\Phi(d + 2.5\sigma)} d(\delta).
\]

- Cut-off effect
  - Gaussian tail distribution decreases slower than Hertz contact force increases
  - Effect of (much) higher asperities overvalued
Van der Waals forces

- Rough surfaces
  - Integrate the sphere responses

\[
F_s(d) = N \int_{\delta_{low}}^{-d+2.5\sigma} \frac{\phi(d + \delta)}{\Phi(d + 2.5\sigma)} d(\delta).
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<thead>
<tr>
<th>Surface energy $\sigma$</th>
<th>Asperity density $N$</th>
<th>Aperity Radii $R$</th>
<th>Standard derivation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.54 J/m$^2$</td>
<td>$80 \times 10^{12}$ /m$^2$</td>
<td>260.5 nm</td>
<td>2.5 nm</td>
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Capillary effects

- Integration on the rough surface is modified
  - Meniscus
    - Size depends on Relative Humidity (RH)
    - Uniform Laplace pressure
  
  New adhesion energy

\[ \omega_C = \Delta P \times h_C = 2\gamma_{LV} \cos(\theta) \]

- Interaction distance \( h_C \)
  - Depends on the relative humidity
  - Below 30% the height comparable to molecular height

- Absorbed surface layer
  - Modifies the interaction height
  - Height from literature (measures)
Capillary effects

- Force on a single asperity is modified*
  - At high humidity, meniscus are merged to create the continuous layer

- Saturation: to avoid duplication in the integration process $h_C$ is reduced to $d_a$

Capillary effects

- Adhesive-contact curves
  - In air
  - For different humidity levels

<table>
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<tr>
<th>VDW surface energy $\sigma$</th>
<th>Asperity density $N$</th>
<th>Aperity Radii $R$</th>
<th>Standard derivation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.167 J/m$^2$</td>
<td>$80 \times 10^{12}$/m$^2$</td>
<td>260.5 nm</td>
<td>2.5 nm</td>
</tr>
</tbody>
</table>
Capillary effects

- **Validation**
  - De Boer’s experiments(*)
    - Apparent adhesion energy from the shortest S-shaped stuck beam
  - Can be compared to the model
    - Adhesive area of the rough surfaces curves

\[ \Gamma = \frac{3}{2} E \frac{g^2 t^3}{s^4} \]

Beam multi-scale framework

- Design example: cantilevers
  - Finite element model
  - Timoshenko Beams
  - Interacting with pad

- Use adhesive micro-contact law at interface
Beam multi-scale framework

• Finite element model
  – Put into contact
  – Release the external forces

• After contacting, three final configurations are possible
Beam multi-scale framework

• Validation
  – De Boer’s experiments(*)
    • From shortest stuck beams
  – Can also be computed from FE solutions
    • Apparent adhesion energy from the shortest Arc-shaped stuck beam

\[ \Gamma = \frac{3}{2} \frac{E g^2 t^3}{s^4} \]

\[ \Gamma = \frac{3}{8} \frac{E g^2 t^3}{s^4} \]

Perspective: Plasticity effect

- **Surface impact: modification of asperity shapes**
  - Effect of maximum interference $\delta_{\text{max}}$ reached during loading
  - Material parameters: yield $\sigma_Y$, yield interference $\delta_{\text{CP}}$

- **Model: new asperity profile**

\[
\delta_{\text{res}} = \delta_{\text{max}} (1 - (\frac{\delta_{\text{CP}}}{\delta_{\text{max}}})^{0.28}) (1 - (\frac{\delta_{\text{CP}}}{\delta_{\text{max}}})^{0.69})
\]

\[
R_{\text{res}} = R(1 + 1.275 (\frac{S_y}{E})^{0.216} (\frac{\delta_{\text{max}}}{\delta_{\text{CP}}} - 1))
\]

- **Loading/unloading curves differ**
  - Ruthenium surfaces
  - Model vs FEM*

Perspective: Plasticity effect

- Rough surfaces adhesive curves
  - Unloading curves depend on the maximum loading (impact energy)
  - Ruthenium surfaces

<table>
<thead>
<tr>
<th>VDW surface energy</th>
<th>Yield $\sigma_Y$</th>
<th>Aperity Radii $R$</th>
<th>Standard derivation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 J/m²</td>
<td>3.42 GPa</td>
<td>4 nm</td>
<td>7.81 nm</td>
</tr>
</tbody>
</table>

- Cyclic loading
  - Unloading curves modified at each cycle
Perspective: Surfaces uncertainties

• Inside stiction model
  – Using descriptions of the surface to build the equivalent surface:
    • $N$ asperities per square-meter,
    • Radius $R$, and
    • Standard derivation $\sigma$
  – These parameters are calculated from surface AFM measures

Surface 1: $m_0, m_2, m_4$  
Surface 2: $m_0, m_2, m_4$  
Eq. surface: $N, R, \sigma$

• Effect on the uncertainties
  – In: $m_0, m_2, m_4$
  – On the apparent energy $\Gamma$
Conclusions

• **Stiction model**
  – Capillary effects
    • Accounts for RH range
  – Cut-off distance?
    • New distribution

• **Surface uncertainties**
  – Ongoing work

• **Multi-scale approach**
  – To be coupled with BEM