Dynamic approach curves in AM-AFM

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Dynamic AFM in Ambient/UHV

\[ E_c, I_c, \rho_c, A_c, \gamma_c, L_c \]

\[ k \]

\[ c = \frac{\omega_0}{Q} \]

\[ m = \frac{k}{\omega_0^2} \]

\[ w(x, t) \]

\[ w(L_c, t) \]

Sample
### Tuning curves - inputs

**Application:**
- Frequency Sweep (basic: ambient or UHV only)

**Operating conditions and cantilever properties**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choose excitation method</td>
<td>Acoustic excitation</td>
</tr>
<tr>
<td>Excitation scheme</td>
<td>Linear Ramp Frequency Sweep</td>
</tr>
<tr>
<td>Unconstrained Amplitude (nm)</td>
<td>10</td>
</tr>
<tr>
<td>k1 (N/m)</td>
<td>0.87</td>
</tr>
<tr>
<td>Q1</td>
<td>33</td>
</tr>
<tr>
<td>f1 (kHz)</td>
<td>44</td>
</tr>
<tr>
<td>fd_start (kHz)</td>
<td>28</td>
</tr>
<tr>
<td>fd_stop (kHz)</td>
<td>100</td>
</tr>
<tr>
<td>Sweep time (s)</td>
<td>0.3</td>
</tr>
<tr>
<td>Tip mass</td>
<td>0.0</td>
</tr>
<tr>
<td>Use setpoint</td>
<td>No</td>
</tr>
<tr>
<td>Set point ratio</td>
<td>0.9</td>
</tr>
<tr>
<td>Z separation (nm)</td>
<td>35</td>
</tr>
<tr>
<td>Choose Lock-In Filter Order</td>
<td>2nd order (40 dB/decade)</td>
</tr>
<tr>
<td>Lock-in time constant</td>
<td>200 us (5 kHz Bandwidth)</td>
</tr>
</tbody>
</table>

**Tip-sample interaction properties**
Tuning curves - inputs

Tip-sample interaction model: Hertz contact

$F_z$ (nN)

0
Tuning curves - outputs

Application:
Frequency Sweep (basic: ambient or UHV only)

Result: First harmonic amplitude

Graph showing the tuning curves with axis labels for frequency (kHz) and amplitude (nm).
Tuning curves - outputs

Application:
Frequency Sweep (basic: ambient or UHV only)

Result: First harmonic phase

Graph showing phase angle (deg) vs. frequency (kHz).
Dynamic approach curves in AM-AFM
(no feedback regulation)
Dynamic approach curves in AM-AFM
(no feedback regulation)

Experimental observables:
- $Z$: base displacement
- $A_0$: unconstrained amplitude
- $\phi_0$: unconstrained phase

Sample
Dynamic approach curves in AM-AFM
(no feedback regulation)

Experimental observables:
- $Z$: base displacement
- $A_0$: unconstrained amplitude
- $\phi_0$: unconstrained phase
- $A$: reduced amplitude
- $\phi$: phase
Dynamic approach curves in AM-AFM
(no feedback regulation)

Experimental observables:
- $Z$: base displacement
- $A_0$: unconstrained amplitude
- $\phi_0$: unconstrained phase
- $A$: reduced amplitude
- $\phi$: phase
AM-AFM Approach Curves: Example 1

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Tip-sample interaction properties

Example loader:

Tip-sample interaction model: Hertz contact

Hertz

F_{ls} (nN)

0
AM-AFM Approach Curves: Example 1

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Number of points plotted: 500
Deflection points per cycle: 500
Plot a higher harmonic?: no
Number of higher harmonics: 2
Choose higher harmonics: 7, 9
Include time histories?: yes
Number of time histories: 3
Choose amplitude ratio(s): 0.9, 0.8, 0.5
Number of cycles: 5
Choose X-axis variable: Z-distance (nm)

(Note: Scroll up to see simulation tabs)
AM-AFM Approach Curves: Example 1

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Result: First harmonic amplitude

Z distance (nm) vs. Z distance (nm) graph with a line indicating the first harmonic amplitude.
AM-AFM Approach Curves: Example 1

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Result: First harmonic phase

Graph showing the relationship between phase and Z distance (nm).

1 result  Parameters...  Clear

< Simulation parameters
AM-AFM Approach Curves: Example 1

**Question:** At what amplitude ratio are peak forces maximized?
**AM-AFM Approach Curves: Example 1**

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![Graph showing peak force vs. A_1/A_0 ratio](image)

Peak repulsive force: 2.94nN @ 0.522
AM-AFM Approach Curves: Example 1

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Tip-sample interaction properties
Example loader:

Non-conservative forces
Non-conservative solvation forces (viscous): no
Scaling (kg/s): 1e-05
Decay (nm): 1
Include sample visco-elastic forces?: Kelvin-Voigt viscoelasticity (enter viscosity directly)
Sample viscosity (Pa-s): 1000

WARNING: The model used for dynamic elastic modulus (Loss modulus) is an approximation. Make sure you know and understand the limitations of this approximation before using it. Improper use may lead to significant errors depending on the sample. See the manual for more detail.

Loss modulus (GPa): 10
Kelvin-voigt viscoelasticity damping coefficient (N-s/m): 0
Include capillary forces?: no
Critical gap, D_0 (nm): 0.6
Energy dissipated, dE (eV): 5

< Operating conditions and cantilever properties
AM-AFM Approach Curves: Example 1

Question: What amplitude ratio should we choose in order to enhance phase contrast?
AM-AFM Approach Curves: Example 1

*Question:* What amplitude ratio should we choose in order to enhance phase contrast?

*Application:* Amplitude Modulated Approach Curves (basic: ambient or UHV only)

*Result:* First harmonic phase

- Young's modulus of sample (GPa) = 1
- Include sample visco-elastic forces? = 2
- Sample viscosity (Pa·s) = 1000
AM-AFM Approach Curves: Example 2

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Tip-sample interaction model: Hertz contact
### AM-AFM Approach Curves: Example 2

**Application:**
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

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<td>2</td>
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<tr>
<td>Choose higher harmonics</td>
<td>7,9</td>
</tr>
<tr>
<td>Include time histories</td>
<td>yes</td>
</tr>
<tr>
<td>Number of time histories</td>
<td>3</td>
</tr>
<tr>
<td>Choose amplitude ratio(s)</td>
<td>0.8,0.3,0.1</td>
</tr>
<tr>
<td>Number of cycles</td>
<td>6</td>
</tr>
<tr>
<td>Choose X-axis variable</td>
<td>Amplitude ratio</td>
</tr>
</tbody>
</table>

(Note: Scroll up to see simulation tabs)
AM-AFM Approach Curves: Example 2

Result: First harmonic amplitude

Initial Z separation (nm) = 0
Final Z separation (nm) = 15
AM-AFM Approach Curves: Example 2

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Result: Mean interaction forces

- Mean force (nN)
  - 0.1
  - 0
  - -0.1

- A_1/A_0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1

2 results Parameters...

- Simulation = #2
  - Initial Z separation (nm) = 0
  - Final Z separation (nm) = 15

Clear

< Simulation parameters
AM-AFM Approach Curves: Example 2

Application:
Amplitude Modulated Approach Curves (basic: ambient or UHV only)

Result: First harmonic phase

Simulation = #2
Initial Z separation (nm) = 0
Final Z separation (nm) = 15
AM-AFM Approach Curves: Example 2

Questions:
1. What amplitude ratio (set-point) should we choose in order to image in a monostable regime.
2. What kind of artifacts can occur in the topography for an imaging set-point in a bistable regime?
3. What can we do to reduce the bistable regime?
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\[ \frac{A_1}{A_0} = [0.2, 0.3] \]

\[ \frac{A_1}{A_0} > 0.95 \]
AM-AFM Approach Curves: Example 2

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\[ \Delta Z \approx 0.5 \text{ nm} \]