Fundamentals of Atomic Force Microscopy
Part 2: Dynamic AFM Methods

Week 4, Lecture 3
Experimental Details

Arvind Raman
Mechanical Engineering
Birck Nanotechnology Center
Methods to convert $\Omega(Z)$ into $F_{ts}^{\text{CONS}}(d_{ltp})$

From the last lecture

$\Omega(Z) \equiv \frac{\Delta f(Z)}{f_0}$

$Z \leftrightarrow d^*$
What is required?

- High stability
- Must measure small frequency shifts accurately
- Large spring constant to eliminate jump to contact


stiff cantilever:
\[ k \sim 100 - 1000 \text{ N/m} \]

cantilever:
\[ k \sim 1 \text{ N/m} \]
The quartz tuning fork

$f_o = 2^N; \quad N = \text{integer}$

$f_o = 2^{15} = 32,768.0000 \text{ Hz}$

Bulova Accutron: 1960

Cost: ~0.25 USD

Source: wikipedia
Quartz: a piezoelectric material (highly anisotropic crystalline \( \text{SiO}_2 \))

Standard quartz cuts:

Electrical potential causes mechanical strain
Mechanical strain develops electric potential
Allows electrical actuation and sensing!

Quartz


Stable oscillation frequency!

\[ f = f_0 \left(1 - 0.04 \times 10^{-6} \left( T - T_{ref} \right)^2 \right) \]

Electrode geometry selects Vibrational Mode as well as which motion is sensed.

\[ V_{12} = V_o \sin(\omega t) \]
An example *

Raltron Model R26 Tuning Fork

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>3.20 ± 0.01</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.40 ± 0.01</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>0.33 ± 0.01</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2.65 × 10³</td>
</tr>
<tr>
<td>Effective mass (kg)</td>
<td>2.72 × 10⁻⁷</td>
</tr>
<tr>
<td>Spring constant (kN/m)</td>
<td>12.7</td>
</tr>
<tr>
<td>Resonance (kHz)</td>
<td>34.39</td>
</tr>
<tr>
<td>Young’s Modulus (Pa)</td>
<td>7.87 × 10¹⁰</td>
</tr>
</tbody>
</table>

Vibration Spectrum

Y. Qin, PhD thesis, Purdue University (2007).
Electrically measured tuning curves

**Antiresonance:**
- Maximum impedance

**Resonance:**
- Minimum impedance

Relative phase of branch currents important in both resonance and antiresonance

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Y. Qin, PhD thesis, Purdue University (2007)
Calibrating tip motion of quartz tuning fork

Infrared fiber optic interferometer

Y. Qin, PhD thesis, Purdue University (2007).
Quartz based probes

A. Both tines free

Quartz Tuning Fork from wrist watch

- $k \approx 1000 \text{ N/m}$
- $Q_{\text{vacuum}} \approx 45,000$
- $Q_{\text{air}} \approx 9,000$

B. One tine fixed - the QPlus sensor

courtesy, F. Giessibl

Y. Qin, PhD thesis, Purdue University
Tuning fork based AFM

No laser required to measure deflection
An example with constant excitation

W tip on freshly cleaved HOPG in air
Phase-Locked Loops (PLLs) track the frequency of an input "noisy" sinusoidal signal that is known to have a variable frequency.

The PLL consists of three components:
- Phase Detector (PD)
- Loop filter
- Voltage-Controlled Oscillator (VCO)
It is assumed that the frequency change of the input signal is not too large.

It is assumed that the approximate frequency range of the input signal is roughly known.

The PD estimates the phase difference between an input (noisy) signal and a clean signal (reference) produced by the VCO. The PD circuit generates a $\text{dc}$ voltage proportional to the phase difference between these two signals.

The loop filter “smoothes” the $\text{dc}$ voltage produced by the PD.

The VCO accepts the smoothed $\text{dc}$ voltage and generates a signal with a frequency that is continuously adjusted by the $\text{dc}$ voltage. This is accomplished by modifying the frequency of an internal oscillator (no noise) until a match to the frequency of the input signal is achieved.

When a match occurs, the $\text{dc}$ voltage produced by the filter goes to zero and the known output $(\omega_o, \phi_o)$ is said to match the input $(\omega, \phi)$.

The PLL-design goal is to select an appropriate loop filter that produces an acceptable transient and steady-state response of the closed-loop system.

The “bandwidth” of a PLL is the frequency at which the PLL begins to lose “lock” with the reference signal.
Appendix

Principle of Digital Phase-Lock Loops (PLL)

TASK: Instantly track and measure frequency of an input signal \( I(t) \) with high accuracy

Input Signal \( I(t) \) (unknown \( f \))

\[ \text{error}(t) = V_{dc}(t) \propto \Delta f \]

- Negative feedback!
- Goal is to make \( \Delta f = f - f' = 0 \)

Digital Voltage Control Oscillator

24 bit precision

Independent Output \( Y(t) \) (known \( f' \))

Phase Detector

Filter

Convert \( \Delta f \rightarrow dc \) feedback