Bridging the scales: Direct SEM imaging of nanometer vibrations for the analysis of stick-slip behavior at microscales

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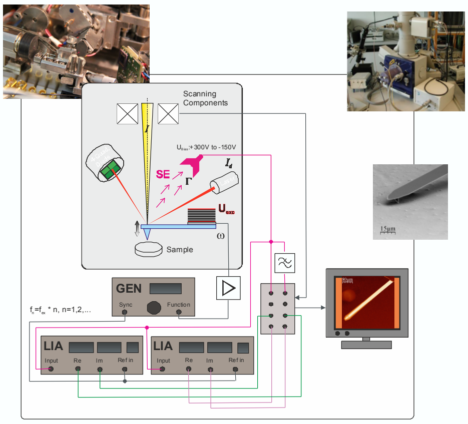
Motivation

Frictional properties at the nanoscale can be regarded as a basic unit describing stick-slip behavior [1]. Since earthquakes are a result of stick-slip motions between plate boundaries, understanding of nanotribology phenomena possibly play a role in seismology, in particular in understanding the nucleation phase of large scale events. We present direct observations of freely oscillating cantilevers through scanning electron microscopy [2].

A theoretical model is proposed for the interpretation of the obtained measurements, relating the images to the physical interaction between electron beam and cantilever. We compare quantitatively such a model with numerical results based on the Euler-Bernoulli equation [3]. The presented results are required for planned experiments of interactions between oscillating structures and matter at nanoscale.

Experimental setup



- A cantilever is placed in a hybrid of an Environmental Scanning Electron Microscope (ESEM) and a Scanning Force Microscope (SFM) [4].
- The oscillation is excited by a piezoelectric crystal U_{exc} at the base of the cantilever
- A fixed experimental detection characteristic is provided.
- The electron beam scans the oscillating cantilever.
- The vibrational dynamics are analysed with the help of the synchronous dynamic response of the electron detector signal using lock-in techniques sychronized to the excitation frequency.
- Max. U_{Bias} is applied → approximately all electrons leaving the cantilever are detected →independency of setup geometry.

Fundamentals

The numerical results based on the standard linear elastic beam theory for small deflections of a beam. The Euler-Bernoulli partial differential equation describes the flexural vibration in time of a one-dimenional beam:

$$\frac{E h^2}{12\rho}\frac{\partial^4 z(x,t)}{\partial x^4} + \frac{\partial^2 z(x,t)}{\partial t^2} = 0$$

$z(x,t)$ is the displacement of the beam at position x and time t. The beam is assumed to have a uniform density ρ and Young's modulus E, length L and thickness h. The boundary conditions for a cantilever clamped $x=0$ leads to

$$\cos\beta_n \cdot \cosh\beta_n = -1 \qquad n = 1, 2, \ldots$$

$$(\Rightarrow \beta_1 = 1.8751, \beta_2 = 4.9641, \beta_3 = 7.8548, \beta_4 = 10.996, \ldots)$$

and the eigenfrequencies are given by:

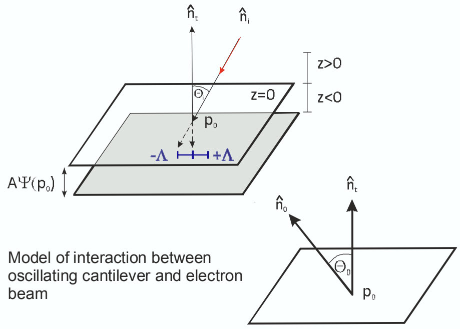
$$f_n = \frac{\beta_n^2}{2\pi}\frac{h}{L^2}\sqrt{\frac{E}{12\rho}}$$

Theoretical Model

Periodic movement of an excited cantilever:

$$z(x,y,t) = A\cos(\omega t)\,\Psi(x,y)$$

with Amplitude A, excited function Ψ, excitation frequency ω.



p_0 as instantaneous intersection point between incoming electron beam $\hat{n}_i$ and the oscillating cantilever surface and with $\hat{n}_t$ unit vector of tangent plane, $\hat{n}_o$ unit vector of outgoing beam.

The amplitude of the electron beam oscillation ("scanline") at the cantilever surface is

$$\Lambda = \Lambda(p_0) = A\Psi(p_0)\tan(\Theta_i)$$

The ESEM image shows at every point p_0 the detected intensity I_d over one oscillation period T

$$ESEM(p_0) = \frac{1}{T}\int_0^T I_d\,dt \qquad \text{with} \qquad \omega = \frac{2\pi}{T}$$

and

$$I_d = I\Gamma = I f_o R\left(p_0 + \Lambda\cos(\omega t)\hat{n}_i^H\right)$$

where Γ is the fraction of detected scattered electrons. For isotropic materials Γ can be factorized into a part describing the local scattering density R along the „scanline" and a characteristic angular outscattering distribution f_o.

The LIA images show the Fourier coefficients of the time series:

$$LIA_c^n(p_0) = \frac{I}{T}\int_0^T \Gamma\cos(n\omega t)\,dt = \frac{2 I f_o}{T\Lambda}\int_{-\Lambda}^{+\Lambda} R(p_0 + v\hat{n}_i^H)\,K_n\left(\frac{v}{\Lambda}\right)dv$$

with the kernels

$$K_n\left(\frac{v}{\Lambda}\right) = \frac{T_n\left(\frac{v}{\Lambda}\right)}{\sqrt{1-\left(\frac{v}{\Lambda}\right)^2}} \qquad \text{(figure a)}$$

where T_n is the Tchebychev polynomial of degree n.

The integrated kernels:

$$K_n^I(u) = \int_u^1 K_n\left(\frac{v}{\Lambda}\right)d\left(\frac{v}{\Lambda}\right) \qquad \text{(figure b)}$$

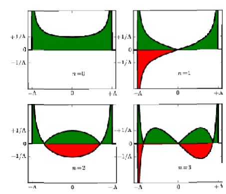


figure a

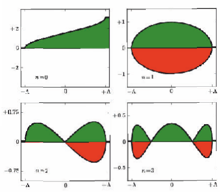
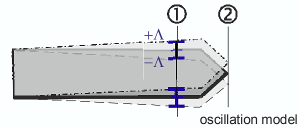
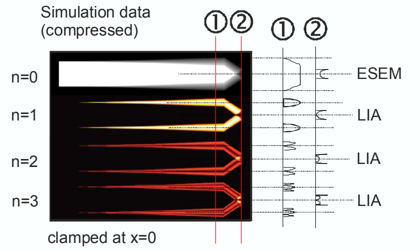


figure b

Discussion

very good comparison between simulation and measurement

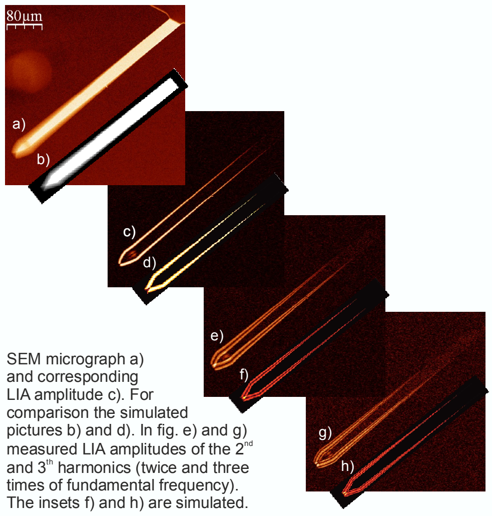




Interpretation

- length scale of kernels is given by Λ
- Λ depends on x-position

➔ ESEM/LIA images are locally described by:
- integrated kernels K_n^I for a Heavyside-Function of R at the interface near edges ①
- kernels K_n at a δ-type singularity of R (e.g. at the tip) ②



SEM micrograph a) and corresponding LIA amplitude c). For comparison the simulated pictures b) and d). In fig. e) and g) measured LIA amplitudes of the 2nd and 3th harmonics (twice and three times of fundamental frequency). The insets f) and h) are simulated.

Future Prospects

- Interaction of oscillating structure with matter
- Influence of dynamical vibrations on friction
- ESEM/LIA analysis of frictional behavior at nanoscale

References

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