Visualizing the jump-to-contact transition to describe the tip-sample energy exchange

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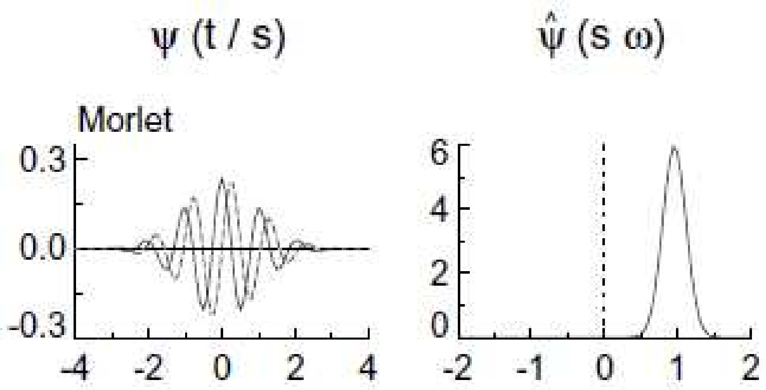


Usually, AFM techniques excites and samples the response at a single frequency at a time. Fast imaging and high signal levels are obtained, but information about the frequency-dependent response (and transients) is not probed.

Long acquisition times to achieve adequate signal to noise ratios must be avoided, incompatible with 1–30 ms/pixel data acquisition times required for practical AFM imaging.

Band excitation treats the excitation and detection over a broad frequency range simultaneously. However the process must be repeated at each single distance during approach (dwelling time).

Question: is it possible to have a broad frequency excitation and detection range without stopping at each distance (reducing the dwelling time) ?

See "The band excitation method in SPM for rapid mapping of energy dissipation on the nanoscale". Nanotechnology 18 (2007) 435503

-Broadband excitation: Thermal excitation

-To retrieve spectral information as a function of time during the approach to the surface: wavelet transform analysis.

How it works?

The wavelet transforms are computed by correlating the signal with families of time-frequency atoms. The time and frequency resolution of these transforms is thus limited by the time frequency resolution of the corresponding atoms.

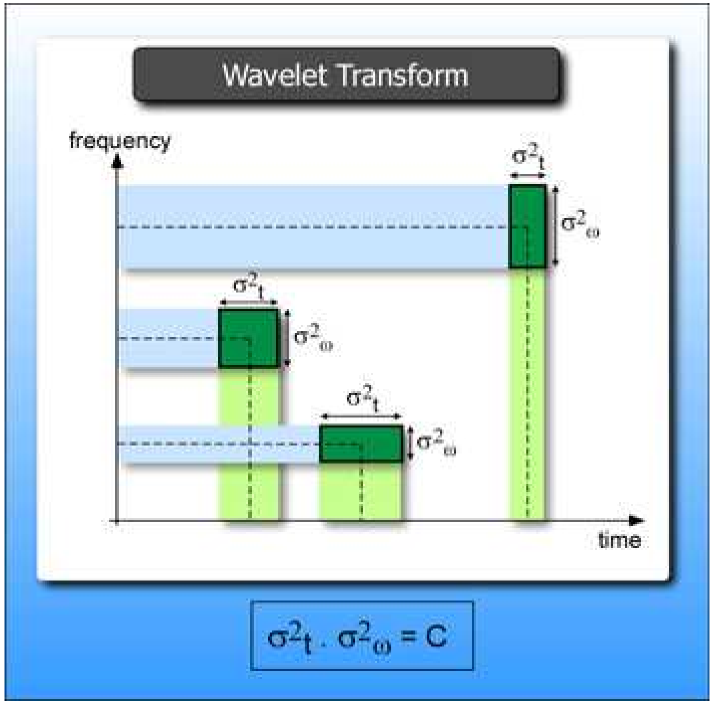
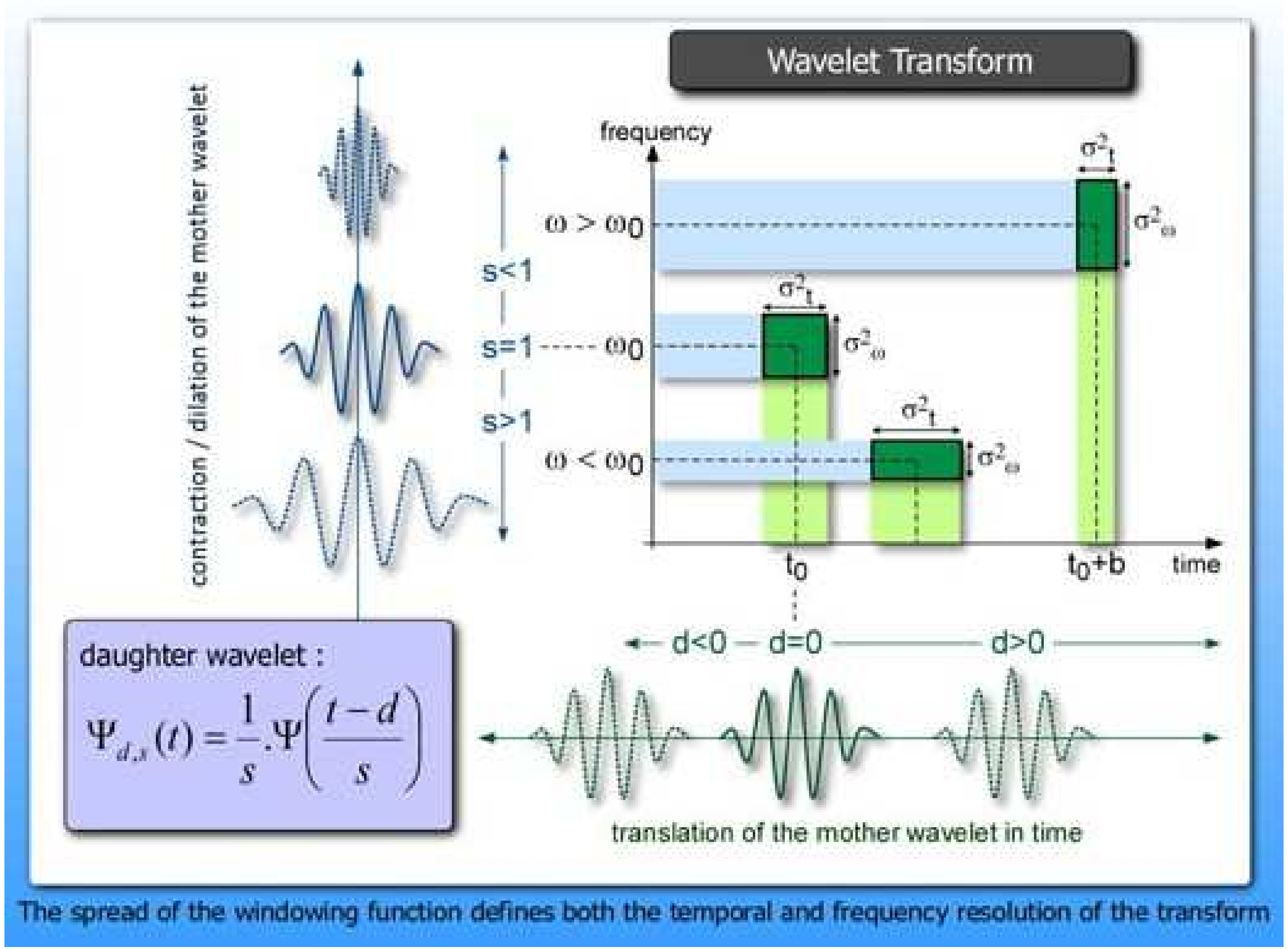
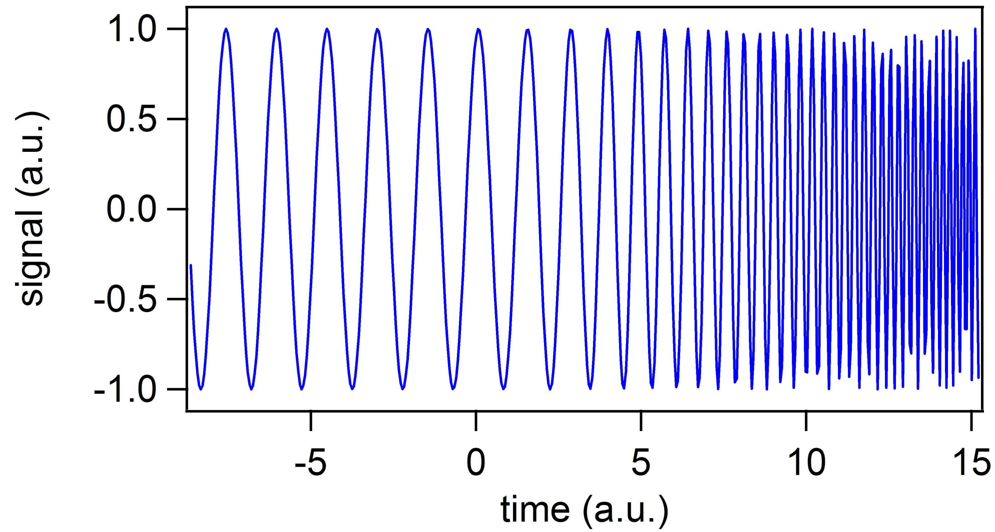


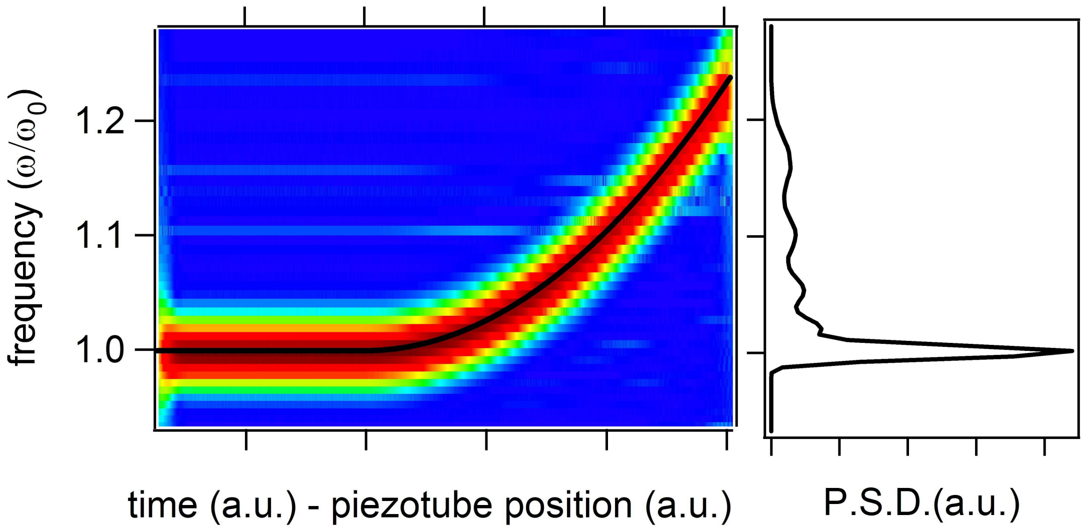
Image credits: André Mouraux *Faculté de médecine Université catholique de Louvain, Belgium*

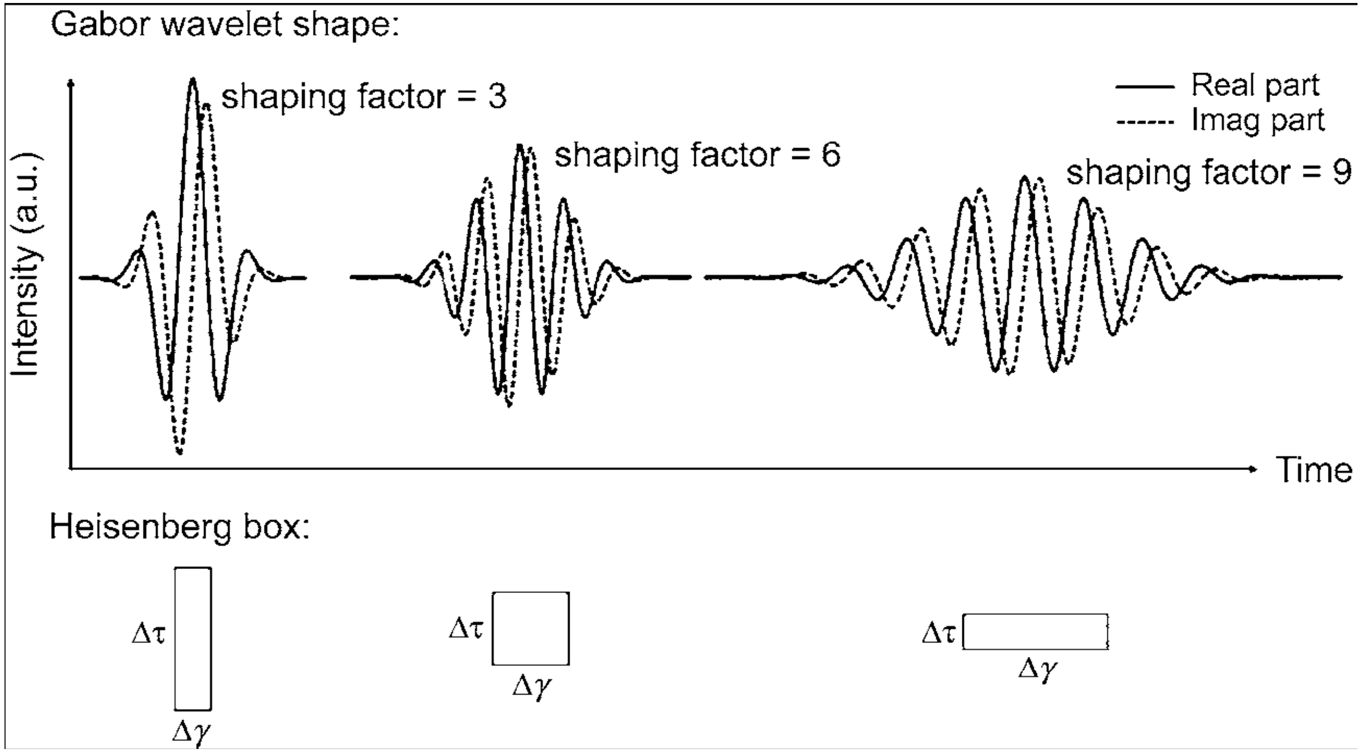


d=0, s=1 characterize the mother wavelet

Image credits: André Mouraux *Faculté de médecine Université catholique de Louvain, Belgium*


1.0
0.5
0.0
-0.5
-1.0
signal (a.u.)
-5
0
5
10
15
time (a.u.)


1.2
1.1
1.0
frequency (ω/ω0)
time (a.u.) - piezotube position (a.u.)
P.S.D.(a.u.)



the Gabor wavelet has the best time-frequency resolution, i.e. the smallest Heisenberg box.

The shape of the mother Gabor wavelet affects its time-frequency decomposition characteristics. Depending on signals to be analyzed, different Gabor wavelet shapes must be used.

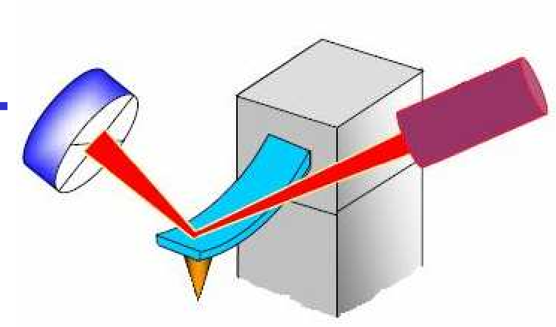
Y. Deng, C. Wang, L. Chai, Z. Zhang, Appl. Phys. B 81, 1107–1111 (2005)

Measure the dynamic properties of the cantilever-surface system during a force-distance curve continously.

Follow the rapid change in the resonant structure that occurs at transients, like the transition from the free to bound cantilever modes (jump to contact).

The wavelet analysis has sharp frequency localization at low frequencies, and sharp time localization at high frequencies. Possibility to measure the Q of the oscillator by spectral linewidth or decay time.

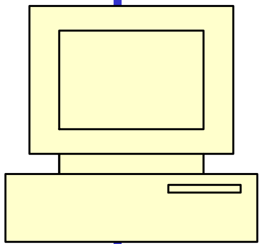
Quadrant PhotoDiode



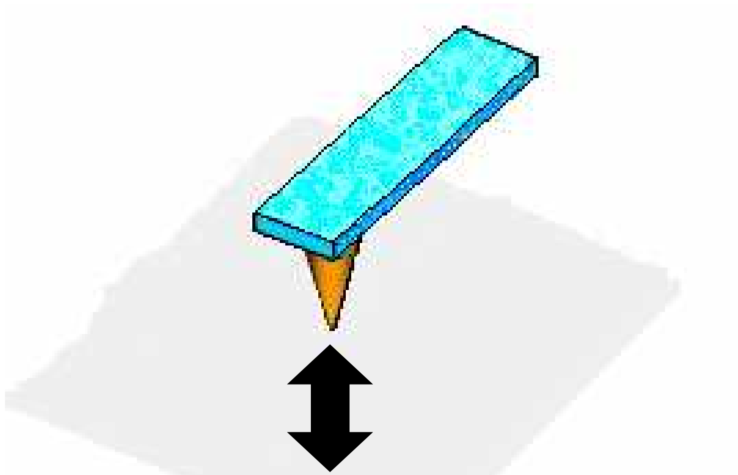
Laser

Acquisition system

- Bandwidth: > 1 MHz
- Buffer memory: 128MS
- Sensitivity: 50-200 nm/V



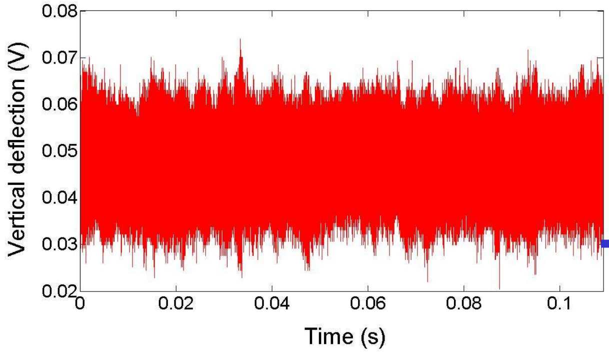
Cantilever tilt 15° → Sensitivity correction [*]



Time signal

Vertical → flexion

Lateral → torsion



off-line analysis

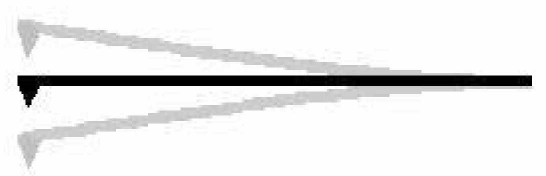
Tip-sample interaction on graphite, in air at room temperature

[*] J.L.Hutter, *Langmuir* **21**, 2630 (2005)

Free cantilever thermal motion → Langevin equation

$$m^* \frac{d^2u}{dt^2} + \gamma \frac{du}{dt} + ku = F_{rand}$$

- *u* cantilever displacement
- *k* spring constant
- *m** effective mass
- γ damping
- F_{rand} thermal stochastic force



$$\langle F_{rand}(t) \rangle = 0$$

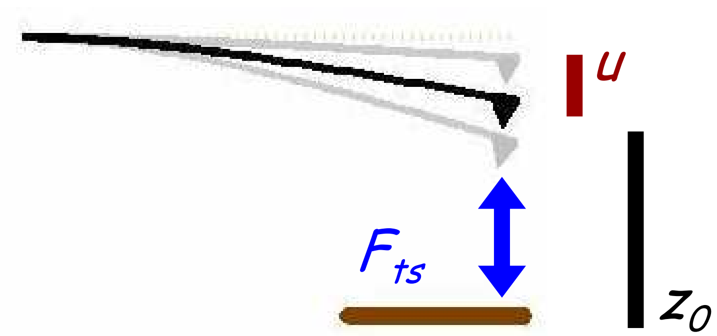
$$\langle F_{rand}(t_1), F_{rand}(t_2) \rangle = \delta(t_1 - t_2)$$

V.L.Mironov *Fundamentals of SPM* (2004)
F.J.Giessibl, *Rev. Mod. Phys.* **75**, 949 (2003)
D.T.Gillespie, *Am. J. Phys.* **61**, 1077 (1993)

Cantilever near the surface → F_{ts} tip-sample interaction force

$$m^* \frac{d^2u}{dt^2} + \gamma \frac{du}{dt} + ku = F_{rand} + F_{ts}(z)$$

$$F_{ts}(z) = F_{ts}(z_0) + \frac{\partial F_{ts}(z_0)}{\partial z} u + \dots$$

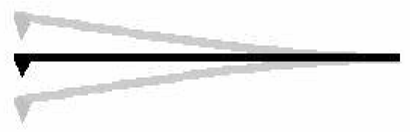


V.L.Mironov *Fundamentals of SPM* (2004)
F.J.Giessibl, *Rev. Mod. Phys.* **75**, 949 (2003)

The constant force $F_{ts}(z_0)$ only displaces the equilibrium position z_0 (static deflection)

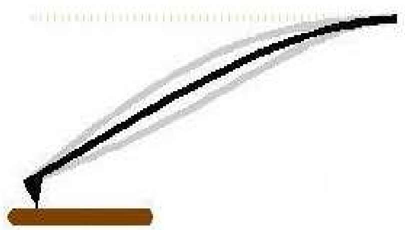
The force derivative influences the cantilever elastic constant and the oscillations u.

- The free AFM cantilever oscillates due to random thermal excitations

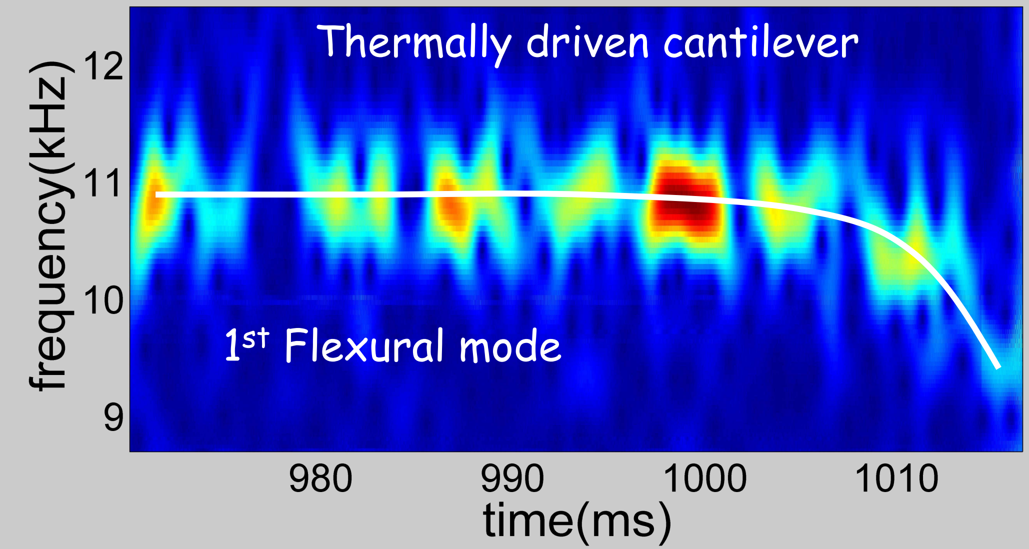


- *As the tip approaches the sample surface, the* tip-sample interaction deflects the cantilever and modifies its thermal vibrations → tip-sample force gradient

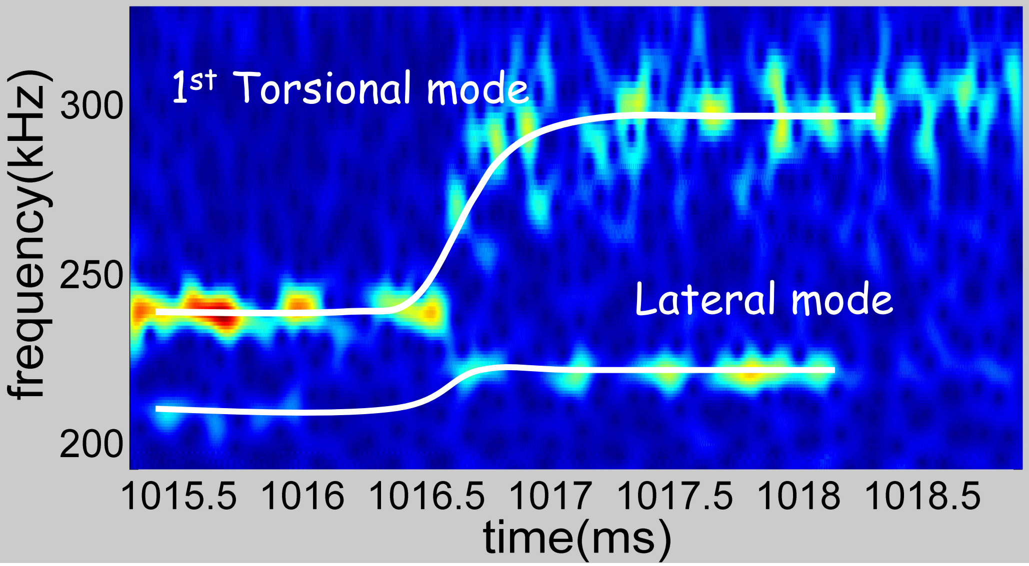
- The jump-to-contact occurs due to liquid meniscus pulling the tip (humidity) [*]



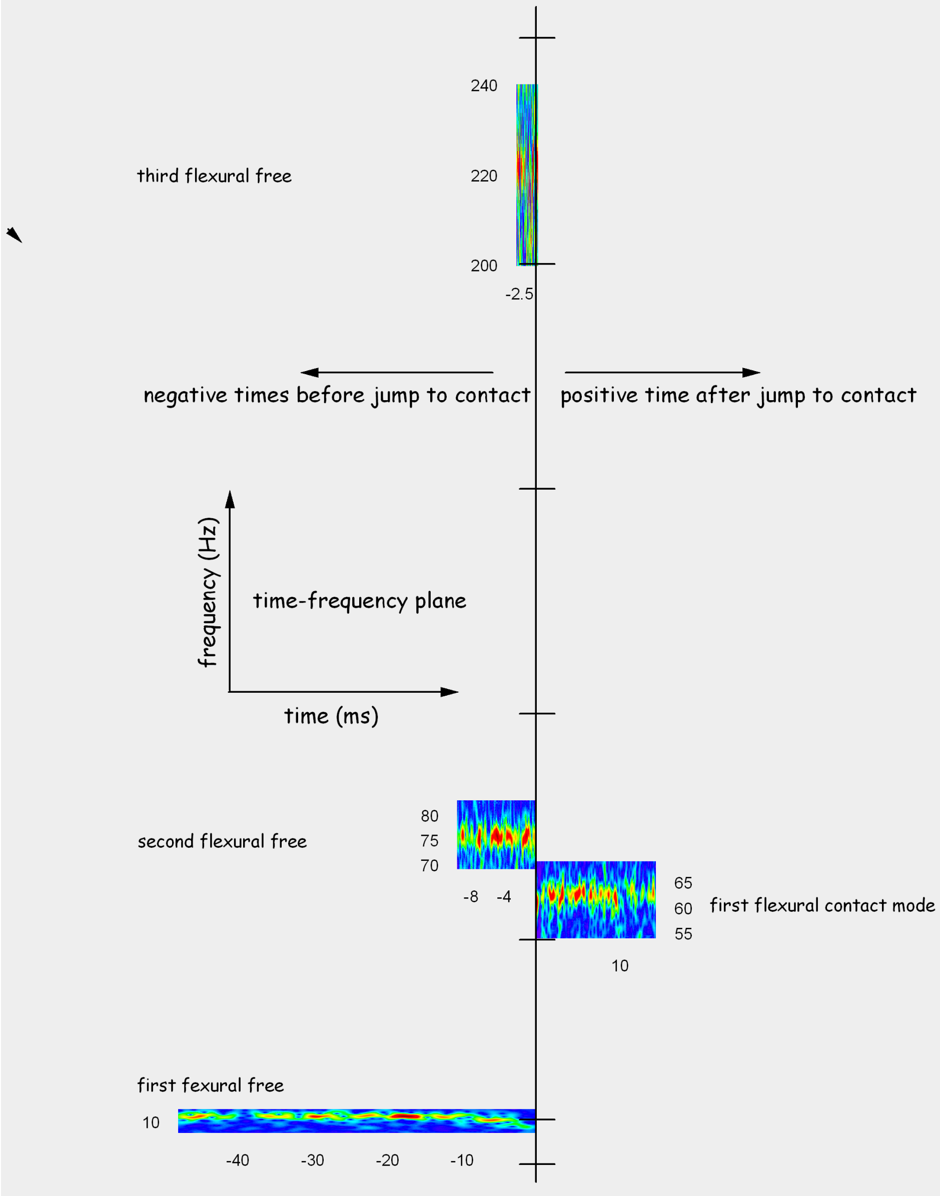
[*] M. Luna *et al. J. Phys. Chem B* **103**, 9576 (1999)



Flexural force-distance curve. The entire acquisition time is ~40 ms.



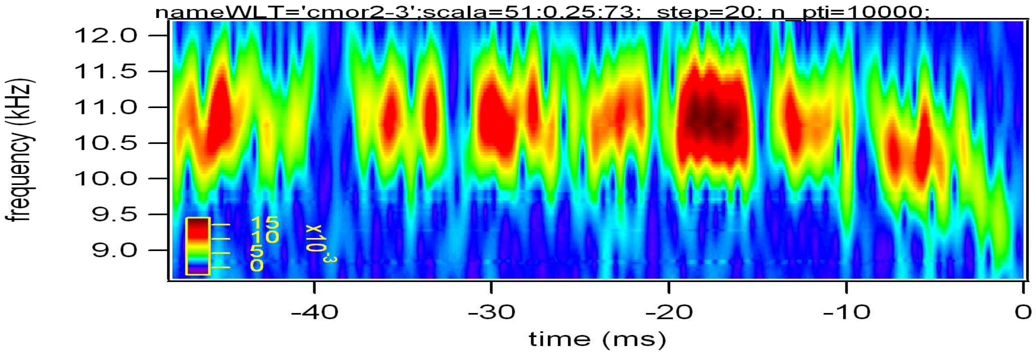
Torsional force-distance curve. The entire acquisition time is 3 ms!



Mode	1	2	3
f_n (kHz)	10.91	76.12	222.6
f_n / f_1 (exp.)		7	20.4
f_n / f_1 (th. [*])		6.27	17.55

This picture gives an idea of the time-frequency distribution of three free flexural modes and the first flexural contact mode. Zooming capability of wavelet analysis.

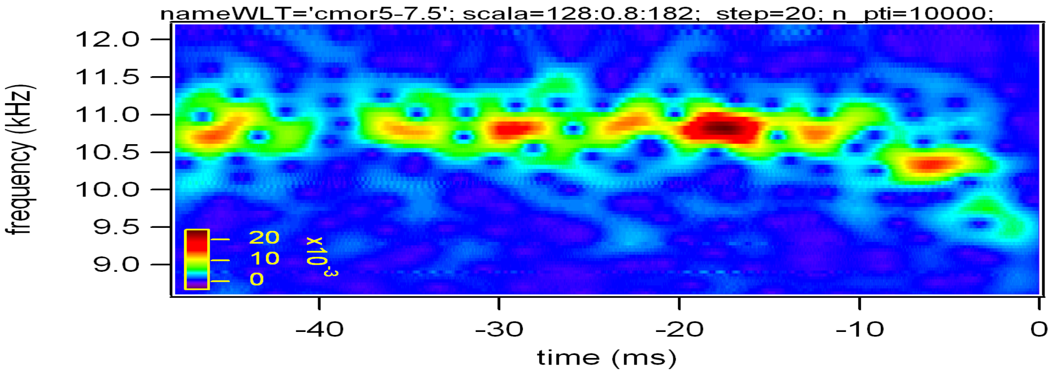
[*] H.J.Butt *et al.*, *Nanotecnology* **6**, 1 (1995)



$Q = \pi f \tau =$

$3.14 \times 11000 \times$ 0.001 $= 35$?

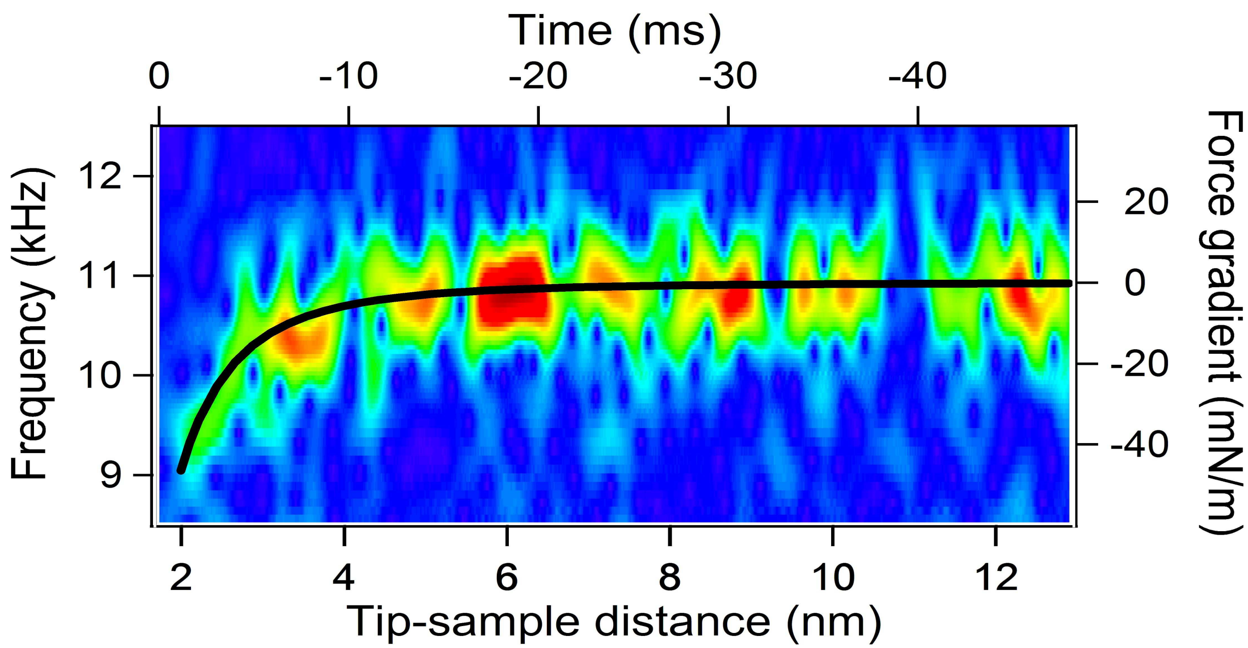
Heisemberg box (FWHM): 0.38 ms x 820 Hz



$Q = \omega / \Delta\omega =$
$11000/300 = 36$

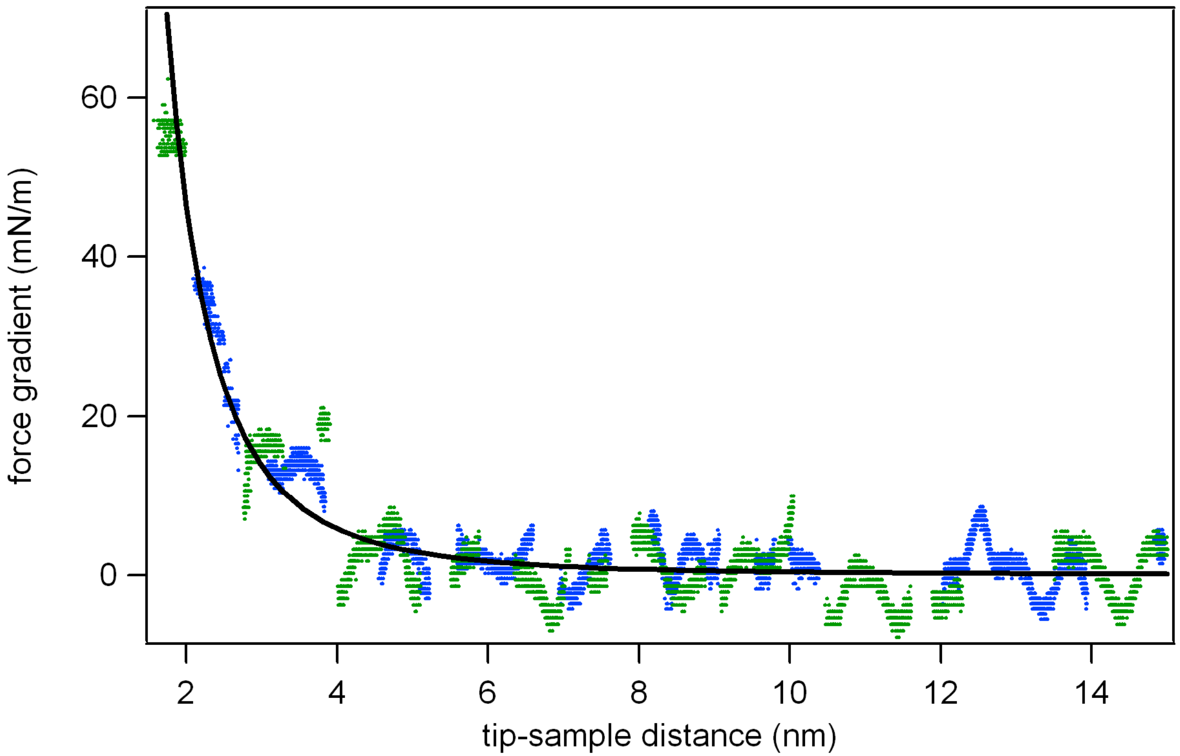
Heisemberg box (FWHM): 1.5 ms x 200 Hz

Experimental results: first flexural mode during approach



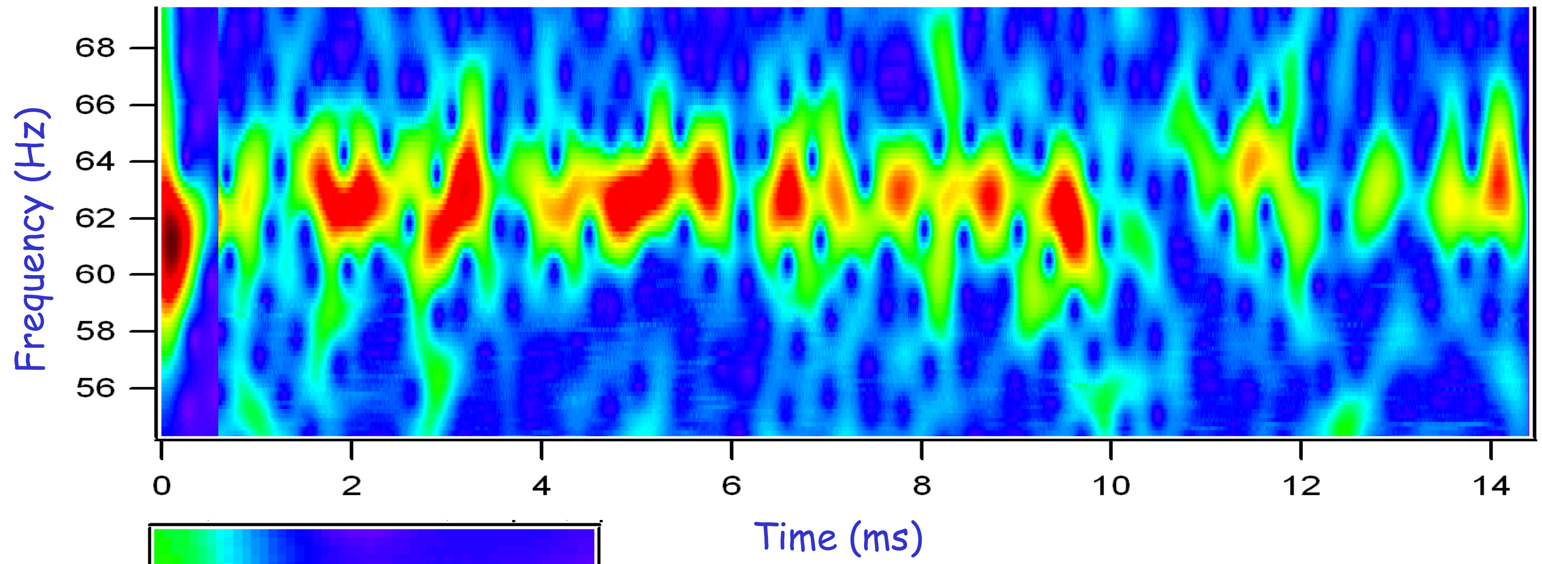
Heisenberg box (FWHM): 450 Hz x 0.7 ms

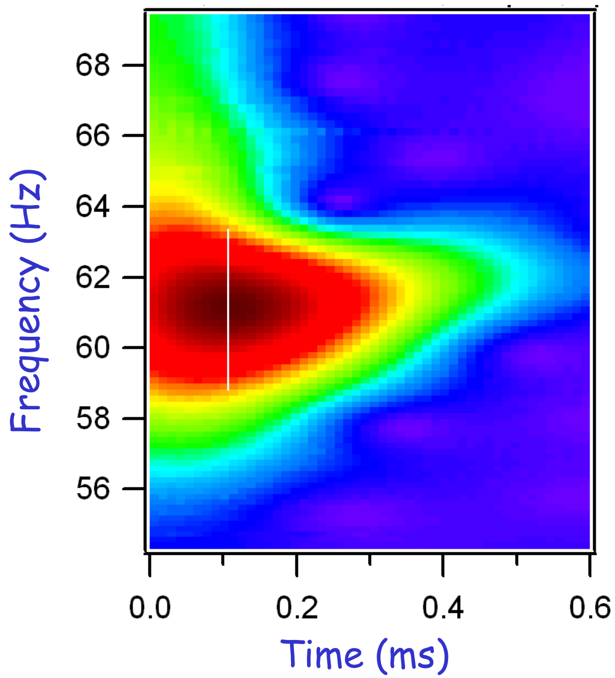
Hamaker curve fitting: HR = 1.1 10^{-27} Jm



Reproducibility: two different measurement with ridges analysis

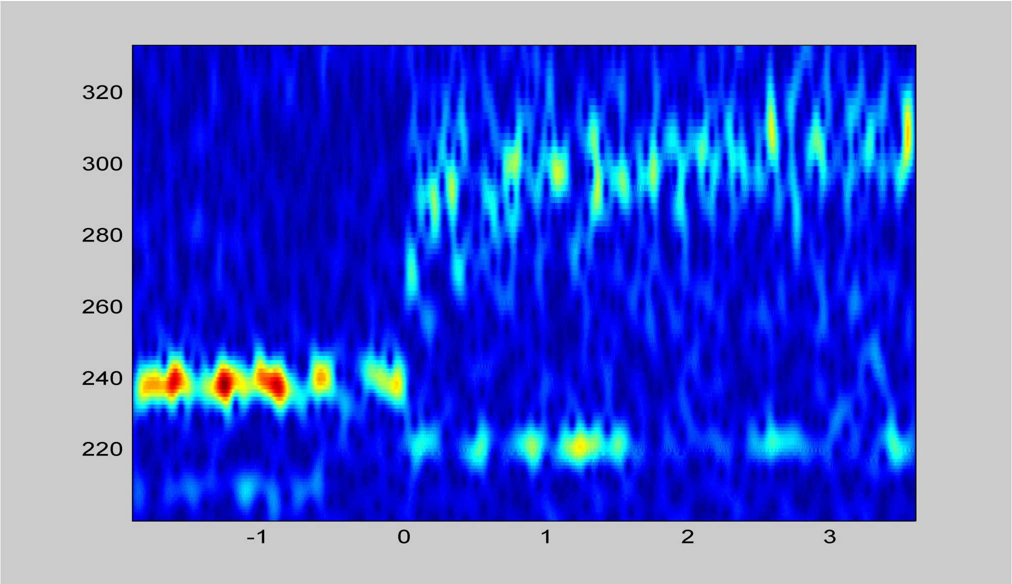
Experimental results: first flexural mode in contact





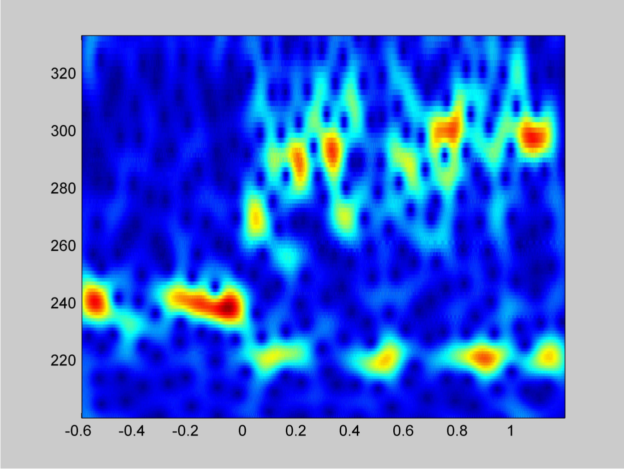
This image captures the time-frequency distribution just after the jump-to-contact transition. Virtual deflection! Changes mode shape!
Heisenberg box (FWHM): 1.62 kHz x 200 μs

FWHM~4.6 kHz Q=14



torsional mode

lateral mode



This image shows the time-frequency distribution across the jump-to-contact transition for the first torsional mode Jump-to-contact transition at zero time.

We are just at the beginning: a lot more application of wavelets can be thought.

The method must become quantitative.

The measurements of forces and the dissipation in various materials as a function of interaction time will hopefully help to characterize "instantaneous" material properties

AFM developed by A.P.E. Research NANOTECHNOLOGY