« Noiseless » thermal noise measurement with optical beam deflection technique

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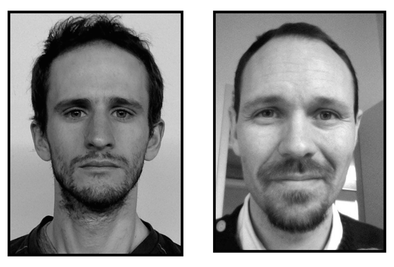


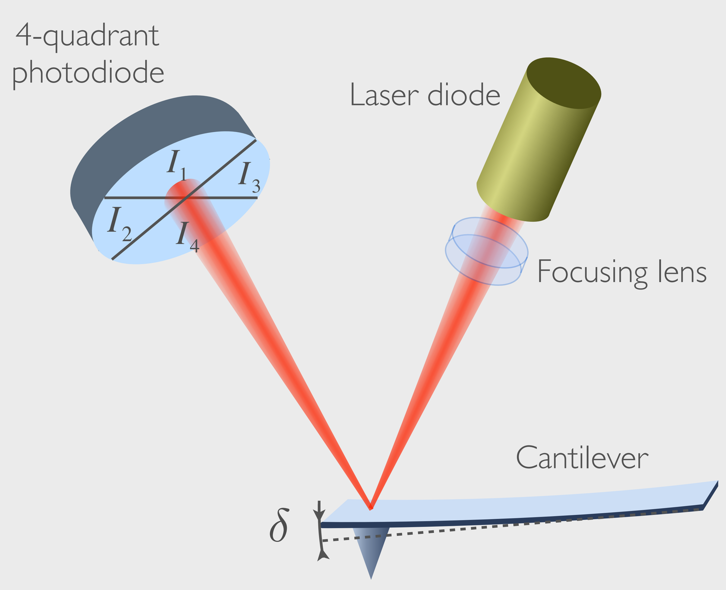
Noise reduction method through correlations

The optical beam deflection technique introduced by Meyer and Amer, because of its simplicity, is the most widely used in laboratory and commercially available AFMs.

Its signal-to-noise ratio is high enough to achieve atomic resolution and allows to measure spectrum of thermal fluctuations of cantilever deflection. As any measurement involving photoelectric conversion, the fundamental limit of this technique is set by the shot noise, whose origin is quantum.

We present a noise reduction method which allows measurements below this shot noise level. This method consists in measuring the same deflexion signal at the same time with another physically independent detector and in averaging the correlation of these two signals in order to statistically reduce the shot noise contribution.

Optical beam deflection technique



noisy signal (contrast) — signal (deflection) — noise (shot noise)

$$C = \delta + N$$

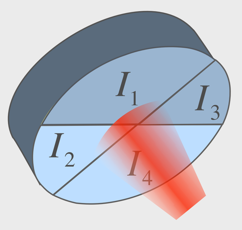
$$\left\langle |\tilde{N}_{SN}|^2 \right\rangle = \frac{2e}{I_{total}}$$

e electron charge

tilde : denotes Fourier Transform

Question: how to reduce the contribution of shot noise in the measured spectrum?

Classically



$$C = \frac{(I_1+I_3)-(I_2+I_4)}{I_{total}}$$

$$C = \delta + N$$

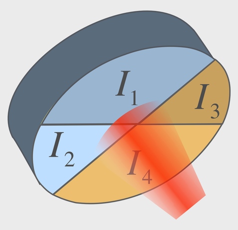
Power spectral density

$$\boxed{\left\langle |\tilde{C}|^2 \right\rangle = \left\langle |\tilde{\delta}|^2 \right\rangle + \left\langle |\tilde{N}|^2 \right\rangle}$$

problem when $\left\langle |\tilde{\delta}|^2 \right\rangle \ll \left\langle |\tilde{N}|^2 \right\rangle$

thermal spectrum masked by the noise!

Cross correlation technique



$$C_1 = \frac{I_1 - I_2}{I_1 + I_2} \qquad C_2 = \frac{I_3 - I_4}{I_3 + I_4}$$

$$C_1 = \delta + N_1$$
$$C_2 = \delta + N_2$$

N_1, N_2 are decorrelated

Cross power spectral density

$$\left\langle \tilde{C}_1 \tilde{C}_2 \right\rangle = \left\langle |\tilde{\delta}|^2 \right\rangle + \cancel{\left\langle \tilde{\delta}\tilde{N}_1 \right\rangle} + \cancel{\left\langle \tilde{\delta}\tilde{N}_2 \right\rangle} + \cancel{\left\langle \tilde{N}_1\tilde{N}_2 \right\rangle}$$

$$\boxed{\left\langle \tilde{C}_1 \tilde{C}_2 \right\rangle \rightarrow \left\langle |\tilde{\delta}|^2 \right\rangle}$$

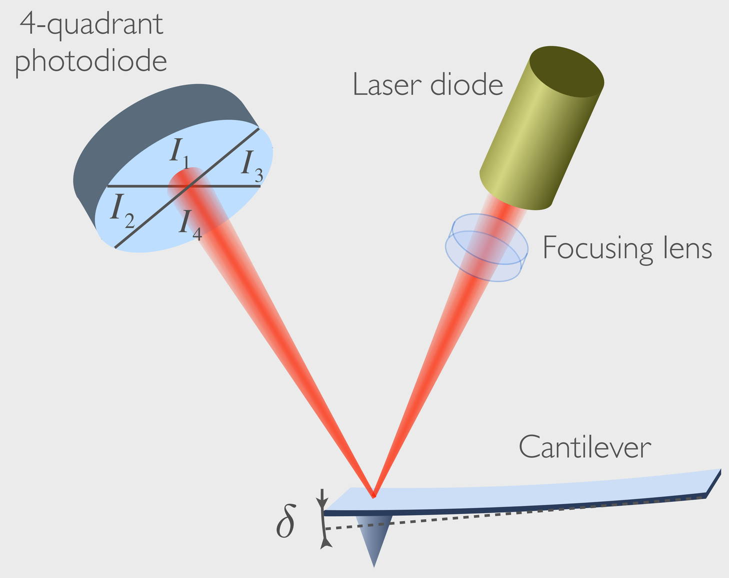
Application to calibration of stiff cantilevers

In AFM operation, measuring and controlling the interaction between the cantilever tip and the underlying substrate is of great importance and requires accurate knowledge of the cantilever spring constant.

The most common technique for calibrating the spring constant is the thermal noise method, which exploits the equipartition theorem and relates thermal energy to the elastic potential energy of the cantilever. In this technique, the spring constant is given by

$$k = \frac{k_B T}{\left\langle \delta^2 \right\rangle} \quad \text{equipartition theorem}$$

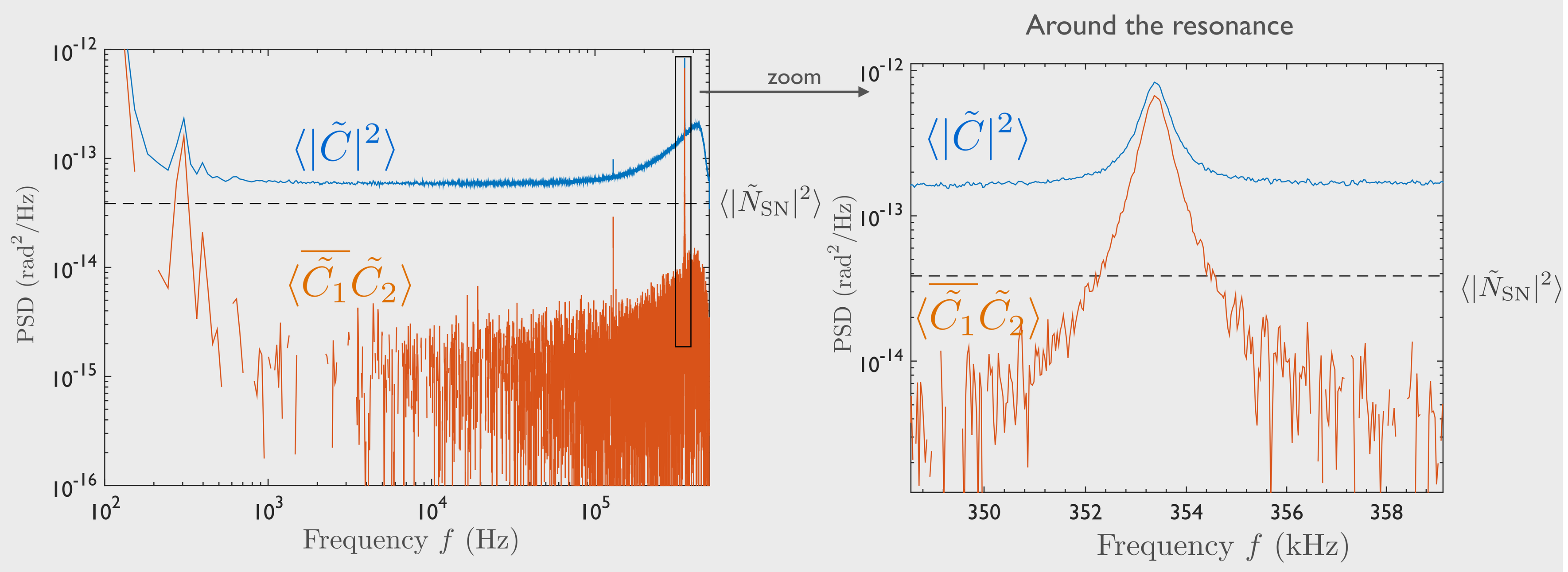
This significant gain of the signal-to-noise ratio obtained with our noise reduction method is particularly attractive if one wants to calibrate stiff AFM cantilevers by the thermal noise method where the spectrum around the resonant frequency needs to be accurately measured.



Calibrated $k \longrightarrow F(z) = k\delta$

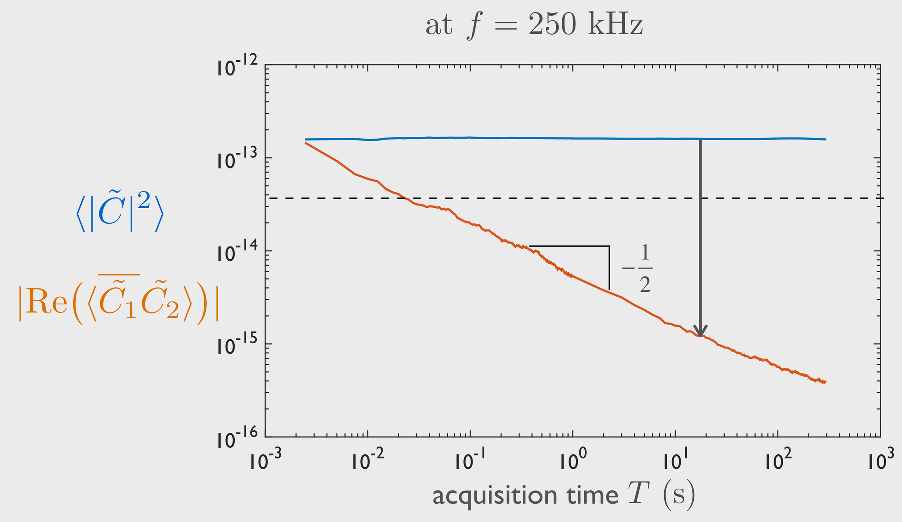
Results for a stiff cantilever (Brucker MPP, $f_{res} = 353$ kHz)

acquisition time $T = 1$ min



Efficiency of the noise reduction technique with time

at $f = 250$ kHz



We gain 2 orders of magnitude in 20 secondes!

L. Bellon, *Procédé d'estimation d'une raideur d'une partie déformable* (**2015**) Brevet FR15/63492

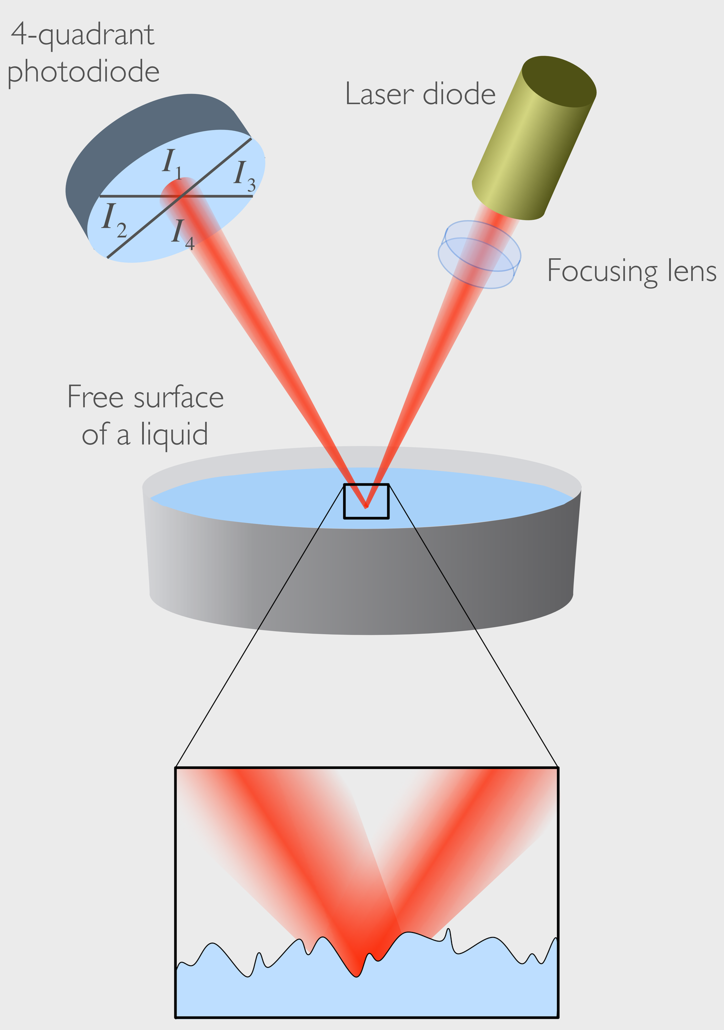
Application to the rheology of liquids and soft solids

Another application of the optical beam deflection technique is to measure the capillary waves thermally excited. The sample surface acts partially as a mirror and its inclination can be obtained regarding its optical lever.

The obtained power spectrum provides information on the mechanical properties of the probed medium.

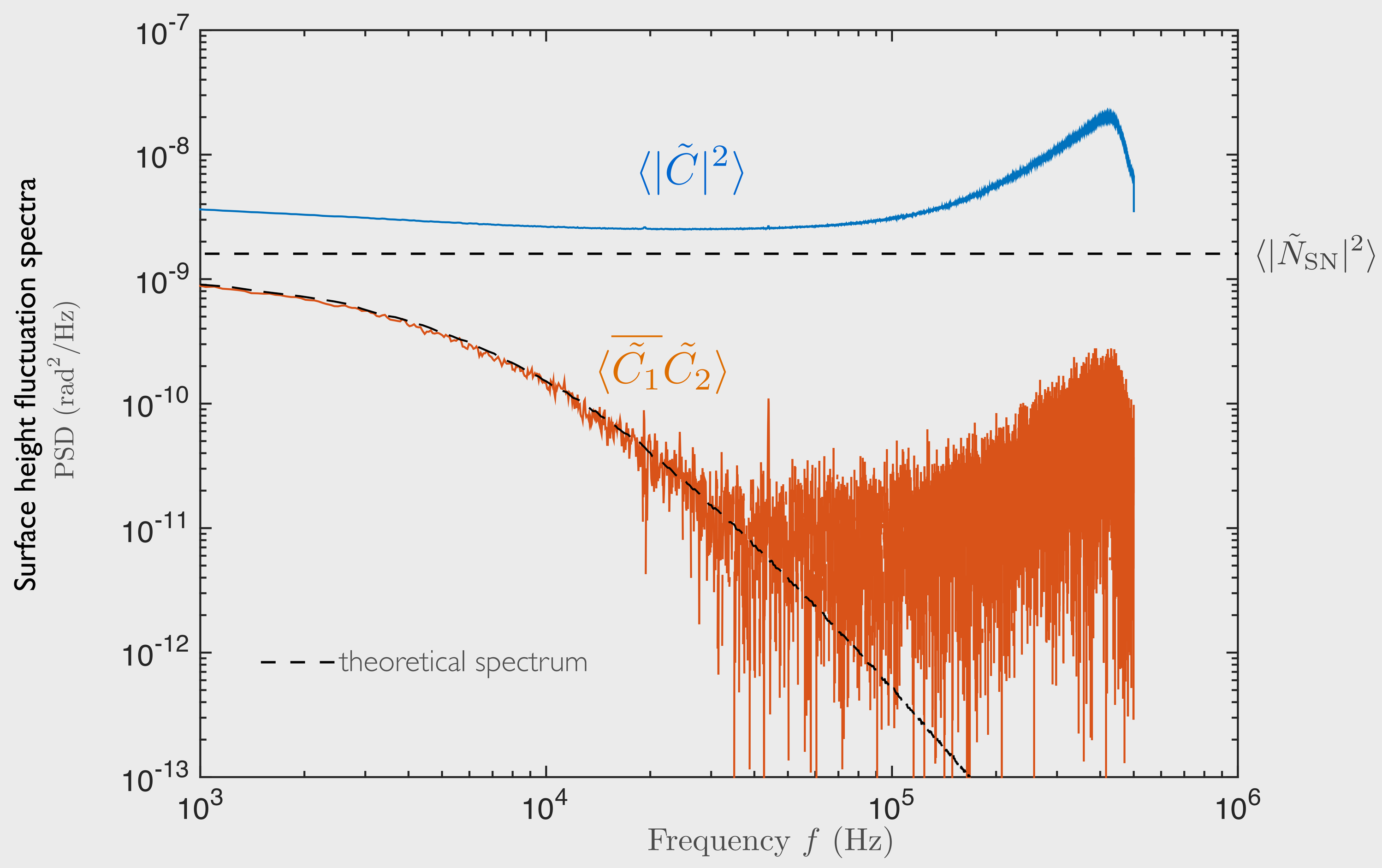
In that case, the noise reduction method allows us to measure thermal fluctuations down to a few orders of magnitude below the shot-noise level.

The obtained spectra should thus give access to rheological properties in a frequency range hitherto inaccessible and for more rigid materials.



Results for a Newtonian liquid (silicone oil)

acquisition time $T = 17$ minutes



B. Pottier et L. Bellon, *Procédé de caractérisation des propriétés rhéologiques d'un matériau* (**2015**) Brevet FR15/63493