Out of equilibrium GigaPa Young modulus of water nanobridge probed by Force Feedback Microscopy

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Because of capillary condensation, water droplets appear in nano/micropores. The large associated surface interactions can deeply influence macroscopic properties as in granular media. We report that dynamical properties of such nanobridge dramatically change when probed at different time scales [1]. Using a novel AFM mode, the Force Feedback Microscopy [2], the gap between the nano-tip and the surface is continuously varied, and we observe this change in the simultaneous measurements, at different frequencies, of the stiffness G'(N/m), the dissipative coefficient G''(kg/sec) together with the static force [3] , see Figure 1.

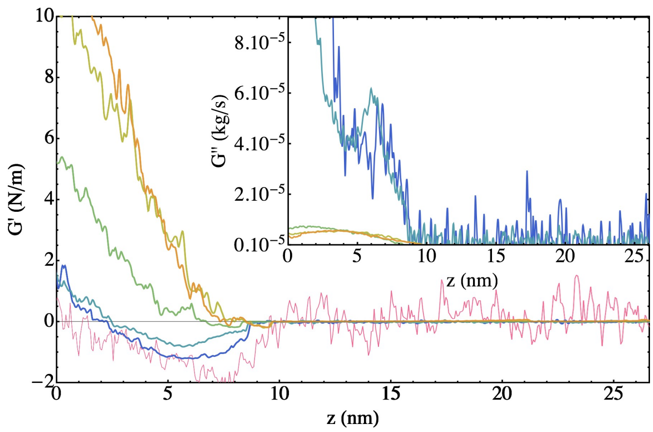

Figure 1: From blue to orange curves (with respect 300 Hz, 1 kHz, 44 kHz, 94 kHz and 114 kHz) show interaction stiffness G' versus tip surface distance as deduced from experimental measurements using linear transformation of the amplitude and phase change [3]. Red curve is the negative of the numerical derivative of the measured static force as the tip is pulled away from the surface. Inset: interaction dissipation G''(kg/sec) result from linear transformation of the amplitude and phase change [3]. It characterizes the mechanical energy dissipation increase during tip oscillation due to the capillary bridges. G'' at high frequencies is distinctively decreased as compared to G'' at low frequencies.

This is made possible thanks to feedback force which cancels in real time the force acting on the tip. It avoids the mechanical instabilities due to the nucleation of the nanobridge. The total force applied to the tip is then equal to zero and the tip remains immobile. To apply this force in real time, a piezoelement simply changes the DC position of the clamped end part of the microlever. This measured displacement multiplied by the lever stiffness k results in the static tip/surface force measurement. Adding subnanometers oscillations to the tip, we obtain the stiffness G'(N/m) and the dissipative coefficient G''(kg/sec) of the water nanobridge through the linear transformation of the amplitude and phase change at arbitrary frequency. As the measuring time approaches the microsecond, the liquid droplet exhibits a large positive stiffness (it is small and negative in the long time limit). Although clearly controlled by surface effects, it compares to the stiffness of a solid nanobridge with a 1 GigaPa Young modulus. We argue that as evaporation and condensation gradually lose efficiency, the contact line progressively becomes immobile, which explains this behavior [4]. The major result is that, despite the fact that the static interaction between surfaces associated to capillary bridges is always attractive, an apparent and highly positive stiffness appears at the nanoscale when the two surfaces interact with a short characteristic time, whereas, the friction measured in same conditions, is found strongly reduced.

[1] Simon Carpentier, Mario S Rodrigues, Luca Costa, Miguel V Vitorino, Elisabeth Charlaix, and Joel Chevrier. *Out of equilibrium gigapa young modulus of water nanobridge probed by force feedback microscopy.* arXiv preprint arXiv:1503.06756, 2015.

[2] Mario S Rodrigues, Luca Costa, Joël Chevrier, and Fabio Comin. *Why do atomic force microscopy force curves still exhibit jump to contact?* Applied Physics Letters, **101**(20):203105, 2012.

[3] Mario S Rodrigues, Luca Costa, Joël Chevrier, and Fabio Comin. System analysis of force feedback microscopy. Journal of Applied Physics, **115**(5):054309, 2014.

[4] J-B Valsamis, Massimo Mastrangeli, and Pierre Lambert. *Vertical excitation of axisymmetric liquid bridges.* European Journal of Mechanics-B/Fluids, **38**:47–57, 2013.