An experimental study on the role of inter-particle friction in the shear-thinning behavior of non-Brownian suspensions

Supplementary Materials

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Here we give further details on the calibration procedure that is used to determine k_n. In the main article, we presented the determination of the normal stiffness of the cantilever using a single experiment where the substrate approached the sphere at a constant velocity of $39\,\mu m/s$. Here we show that we obtain the same value for the conversion factor k_n when the approach velocity is doubled or when the substrate moves away from the particle.

By means of a function generator, a triangular voltage is applied to the piezoelectric quartz that moves by $4.88\,\mu m/V$. The amplitude of the output signal is fixed to $8V$ and two frequencies have been tested: $0.5\,Hz$ and $1\,Hz$ which correspond respectively to approach (or withdraw) velocity values of 39 and $78\,\mu m/s$. Fig.1 shows an example of the photodiode response and a zoom of the region

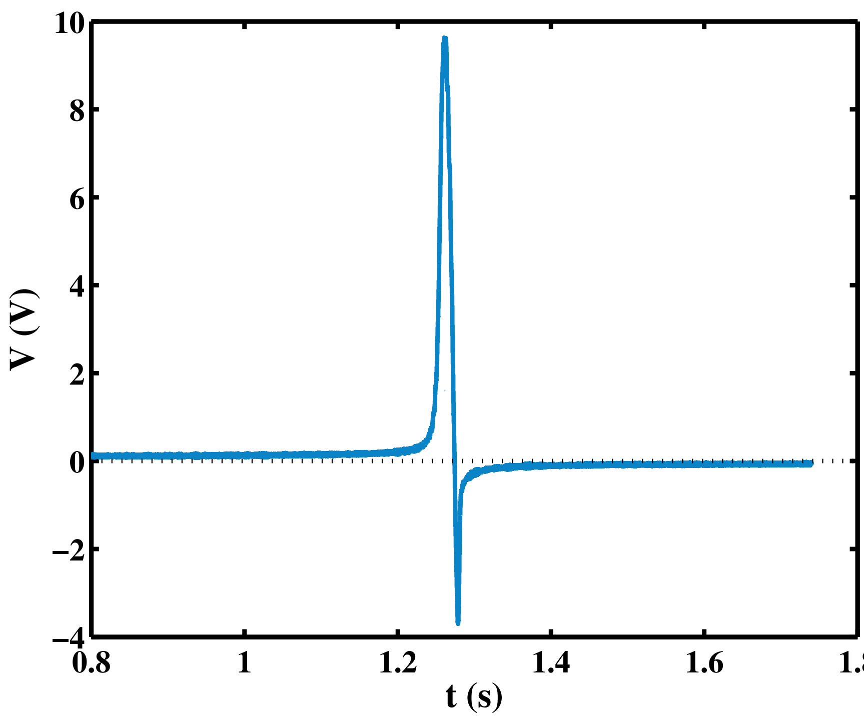

Figure 1 Photodiode response when a triangular signal (frequency $1\;Hz$, amplitude $8V$) is applied to the piezo actuator. The total displacement of the piezo actuator is $39\,\mu m$.

corresponding to the velocity inversion (transition from the approach to the withdrawal) is given in Fig.2. In this figure, the region where the sphere and the substrate are in contact (represented by the blue curve) is clearly visible. In this region, the photodiode voltage varies linearly with time and so with the vertical displacement of the substrate. In this region, the photodiode signal is given only by the flexion of the cantilever which is also the variation of the vertical position of the substrate driven by the piezo actuator. The particle deformation is negligible since, according to Hertz theory, the order of magnitude of the indentation of the particle –or more precisely of an asperity on the surface of the particle– can be calculated by:

$$\varepsilon = \left(\frac{3}{4}\frac{(1-\nu^2)F}{E\sqrt{r_c}}\right)^{2/3} \tag{1}$$

with $r_c \approx 100\,nm$ the radius of curvature of the asperity, $E \approx 3\,GPa$, $\nu \approx 0.4$ the Young modulus and the Poisson ratio of Polystyrene.

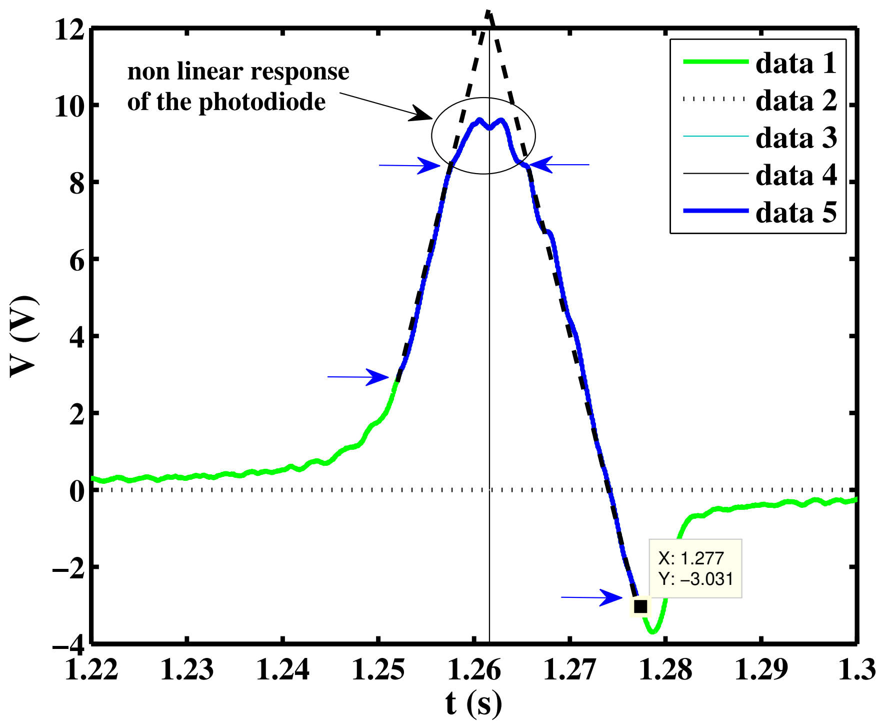

Figure 2 Zoom of the photodiode response near the contact region. When the probe is in contact with the substrate, V_z varies linearly with time (or with the piezo displacement). The deviation from this linear behavior observed for the highest values of V_z is associated to the non-linearity of the photodiode that arises for voltage values close to the maximum nominal value of $10V$. The expected idealized response is represented by the black dashed lines. The conversion factor that relates the photodiode output voltage to the deflection of the cantilever is given by the slope of the blue curve in the regions comprised between the arrows.

We obtain $\varepsilon \approx 10\,nm$ for the maximum normal force $F \approx 1\,\mu N$.

Following Ducker & Senden [1], we make use of this constant compliance regime to convert the photodiode response into the deflection of the cantilever, $\delta = C_n V_z$. This factor is used to calculate changes in particle-surface separation by adding the displacement of the substrate to the deflection of the cantilever: $h_0 = z + \delta = z + C_n V_z$. In addition, the onset (approach curve) or the end (withdrawal curve) of the constant compliance region is used to identify the position at which the probe and the substrate are in contact ($h_0 = 0$).

At last, to relate the hydrodynamic force $F = 6\pi\eta\, a^2 U/h_0$, to the photodiode signal, V_z is corrected to account for the drag force on the cantilever. To this aim, the photodiode output recorded at $h_0 \to \infty$ is subtracted from V_z.

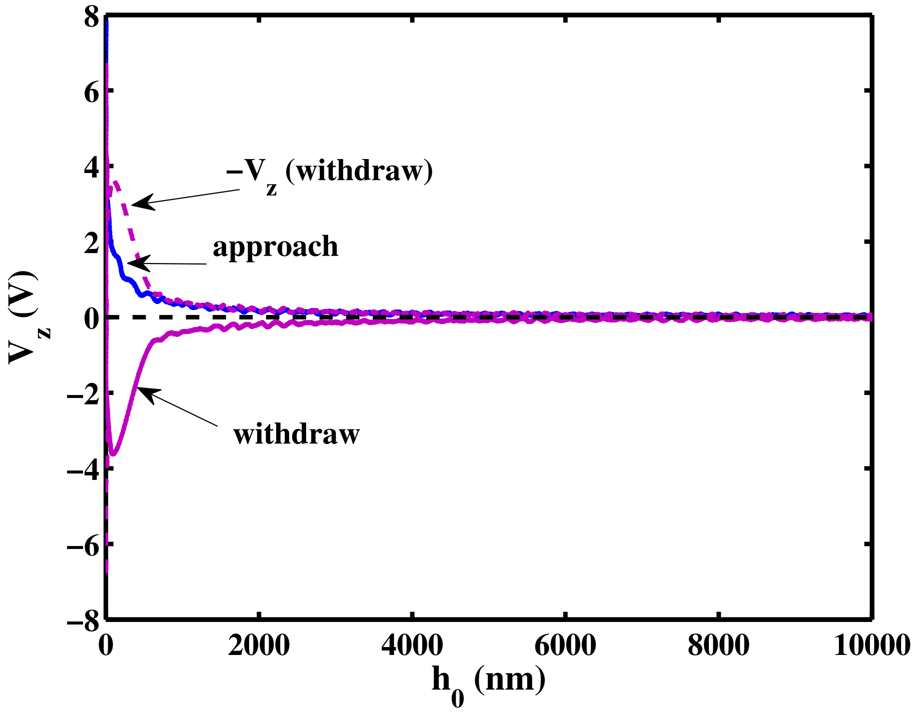

Figure 3 Force- distance curves obtained either in approach or withdrawal.

An example of a force (corrected photodiode output voltage)- distance curve is shown in Fig.3 either for approaching or withdrawing velocity of $78\,\mu m/s$. The approach and withdrawal curves are different at small separation distances likely because of adhesion between the silica substrate and the probe but are superimposed for higher distances.

At each separation distance, the separation velocity is calculated (see Fig.4): $U = \frac{dh_0}{dt}$. From these curves together with the force (photodiode signal)-distance curves, we can plot the variation of the ratio of the velocity to the photodiode response with h_0 either for approach or withdraw experiments. An example is shown in Fig.5. where it can be observed that (within error) the U/V_z curves are the same while U and V_z profiles on withdrawal differ significantly from those on approach (see Fig.4).

At last, calibration has been performed with a piezo driving velocity two times lower and again, the conversion factor $k_n = 6\pi\,\eta\, a^2 \frac{U/V_z}{h_0}$ is found the same for both calibration experiments but the value of h_c varies which probably means that the contact position is not defined with a high degree of accuracy (see Fig. 6).The challenge of precisely determining the contact position has already been pointed out [2] and is beyond the scope of the present paper.

Notes and references

[1] W. A. Ducker, T. J. Senden and R. M. Pashley, *Langmuir*, 1992, **8**, 1831–1836.

[2] C. D. Honig and W. A. Ducker, *Physical review letters*, 2007, **98**, 028305.

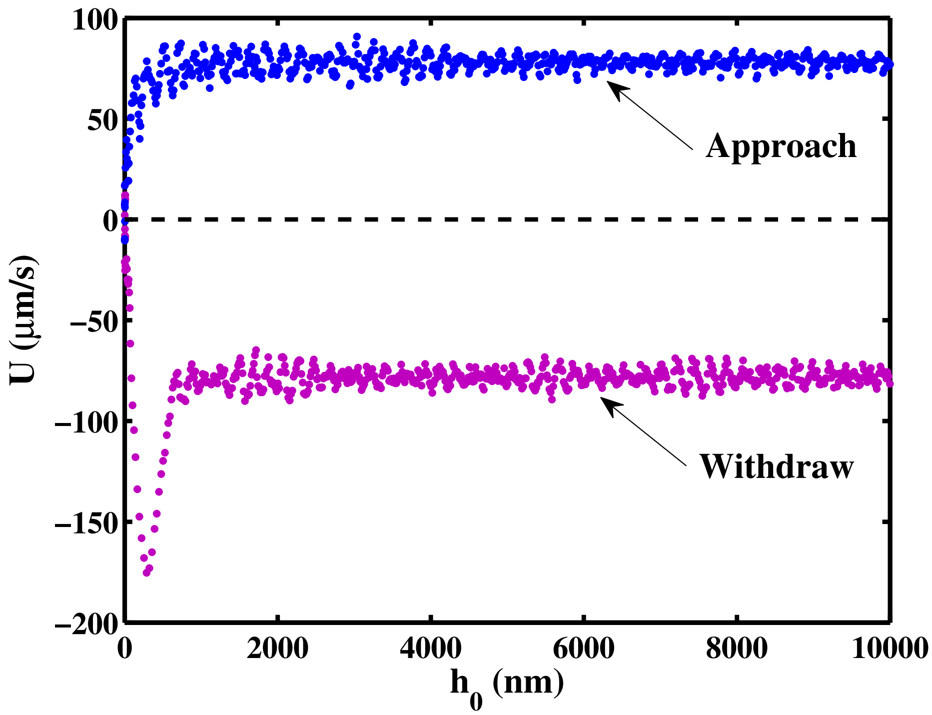

Figure 4 Relative velocity of the probe with respect to the substrate as a function of the separation distance. $U_\infty = 78\,\mu m/s$

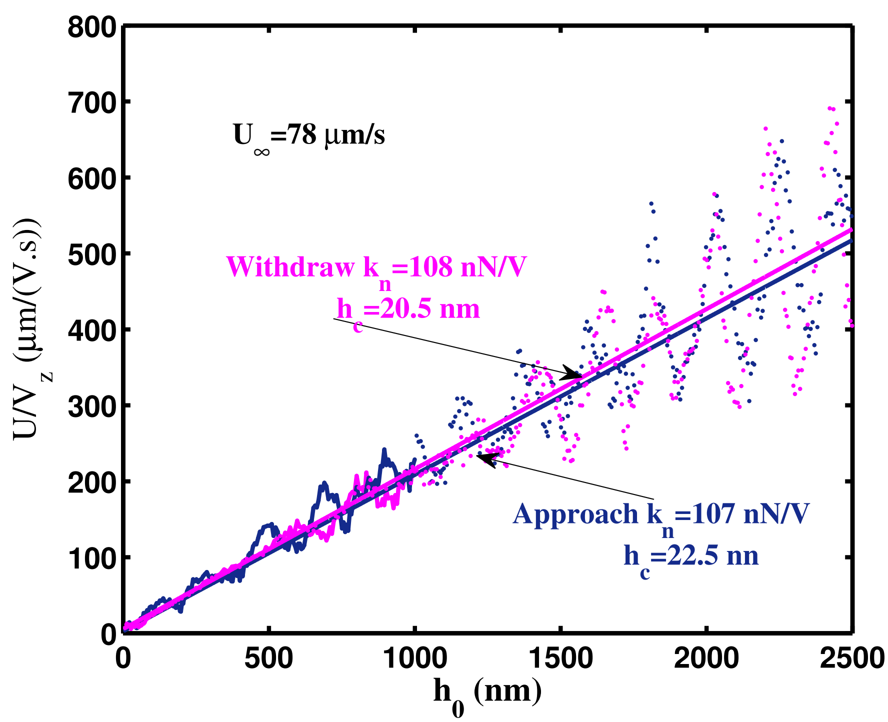

Figure 5 Calibration curves obtained by moving the substrate toward (blue curve) or away from the probe (pink curve). $\eta_0 = 0.065\,Pa.s$, $2a = 40\,\mu m$.

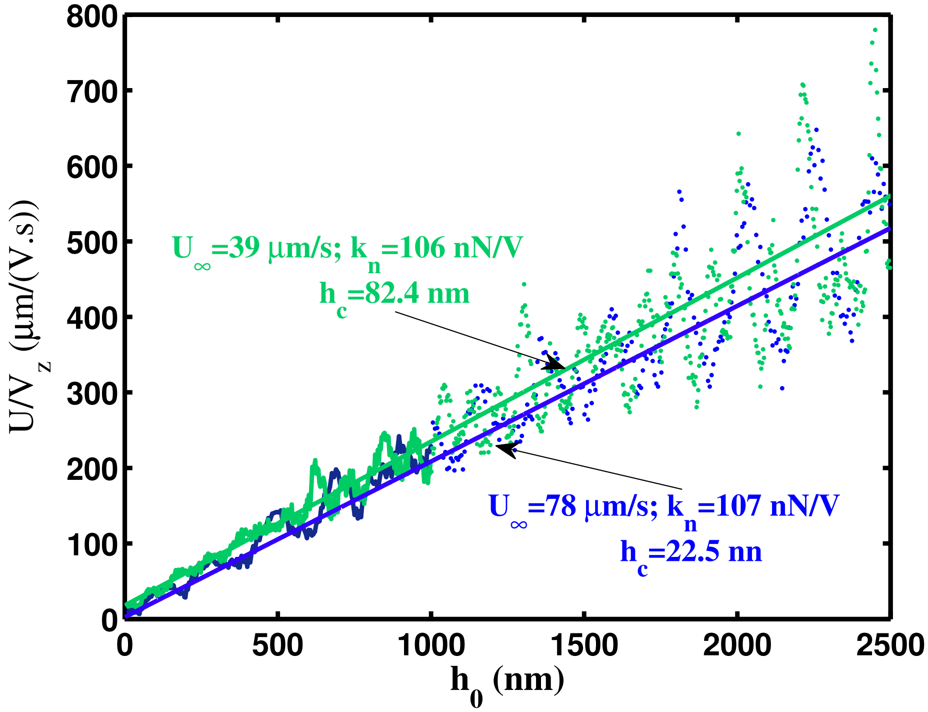

Figure 6 Calibration curves obtained with two different approaching piezodisplacement rate values: 39 and $78\,\mu m/s$. $\eta_0 = 0.065\,Pa.s$. $2a = 40\,\mu m$.