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Quantifying Amplitude Reduction Mechanism in Tapping Mode Atomic Force Microscopy

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In this paper the research question is why the amplitude reduces when the tip interacts with sample in Tapping Mode Atomic Force Microscopy (TM-AFM)? This question has already been answered in the late 1990's [1], briefly: "The amplitude reduces because the resonance frequency of the system changes". The explanation arises from a nonlinear dynamics study of the cantilever in presence of nonlinear Hertzian contact and van der Waals forces and contains no restrictive assumptions. However, some behavior of AFM cantilever in tapping mode can hardly be explained with the existing theory. For example, we have observed that the tip-sample interaction forces in TM-AFM are very sensitive to the excitation frequency. Two different excitation frequencies; one higher, and one lower than the resonance frequency apply very different forces on the sample. This holds even if the excitation voltage, free air amplitude, and amplitude set-point are the same for both frequencies. As shown in Fig.1a, the maximum of interaction force, i.e. the Peak Repulsive Force (PRF), have a saddle shape trend with respect to amplitude ratio and normalized excitation frequency. In Fig.1b we experimentally confirm this observation and we introduce a mask-less patterning technique by tuning the tip-sample forces via the excitation frequency. More details on this application can be found in [2].

Since the previous theory does not explain the sensitivity of the tip-sample interaction forces, we present a new explanation for origin of amplitude reduction in TM-AFM

We consider the cantilever as a linear one DOF resonator which is excited by a dither signal and an unknown tip-sample interaction force. Due to the linearity of the cantilever, the amplitude of the cantilever at a certain frequency reduces, if and only if the amplitude of the total force at that specific frequency reduces. Also, the amplitude reduction ratio (A_r), should be equal to force reduction ratio, see (1). I.e., one can ignore effects of all other frequency contents of the tip-sample forces when measuring the amplitude and phase at a certain frequency.

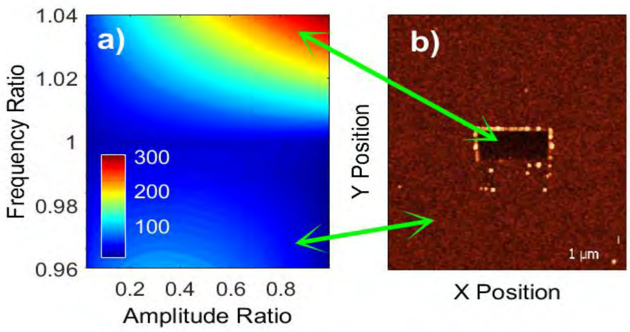

Fig. 1: a) Peak repulsive force vs. amplitude ratio and excitation frequency. b) example of nano-lithography with changing the excitation frequency.

If the contact between the tip and the sample is perfectly conservative, the phase of the tip-sample force is π radian behind the displacement. Because the maximum amount of the force is aligned with the end of the stroke of the cantilever. On the other hand, according to dynamics of the linear resonator, displacement signal is $\tan^{-1}\frac{\xi}{1-\omega^2}$ radian behind the total force where ξ and ω are damping ratio and normalized excitation frequency respectively. Mathematically it reads:

$$\begin{aligned}\overrightarrow{F_{tot}} &= \overrightarrow{F_d} + \overrightarrow{F_{ts}^{(1)}} \\ &= |F_{tot}|e^{i\left(\omega t+\varphi_1-\pi-\tan^{-1}\frac{\xi}{1-\omega^2}\right)} \\ &= \left|F_{ts}^{(1)}\right|e^{i(\omega t+\varphi_1)} + |F_d|e^{i\omega t}\end{aligned} \quad (1)$$

$$|F_{tot}| = A_r|F_d| \quad (2)$$

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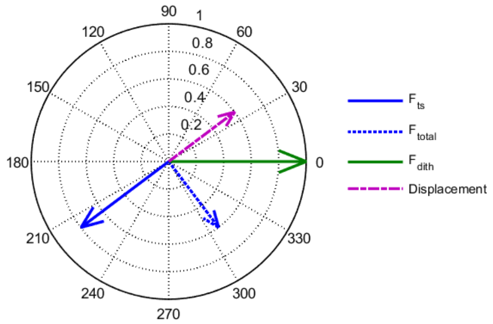

Fig. 2: Phasor plot of the forces and displacement in TM-AFM: explanation of amplitude reduction.

Eq.(1,2) are graphically demonstrated as a phasor plot in Fig.3

As shown in Fig.2, the summation of the dither force and the first Fourier component of the tip-sample force has a lower absolute amount than the dither force, which in time domain reads as destructive interference between tip-sample interactions and dither force.

The phase delay of the cantilever ($\tan^{-1}\frac{\xi}{1-\omega^2}$) determines the sensitivity of the absolute value of the total force to the tip-sample interactions. Fig.3 shows the phasor plot of the forces for two different excitation frequencies. Both frequencies have equal dither force (green arrow), free air amplitude and amplitude set-point. However, to reduce the total force (dashed arrows), the one with higher excitation frequency (red arrows) requires higher tip-sample force, than the one with lower excitation frequency (blue arrows).

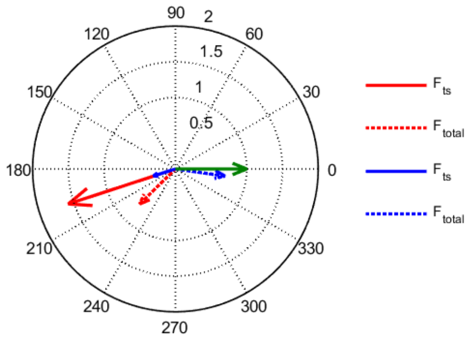

Fig. 3: Phasor plan of the forces in TM-AFM. green: dither force, blue: excitation frequency lower than resonance, red: excitation frequency higher than resonance.

We have verified the new explanation by comparing the average force calculated from (1,2) with the numerical solution of the nonlinear problem considering DMT force model for different amplitude ratios, excitation frequencies, and DMT modulus and we achieved a good agreement between the two models.

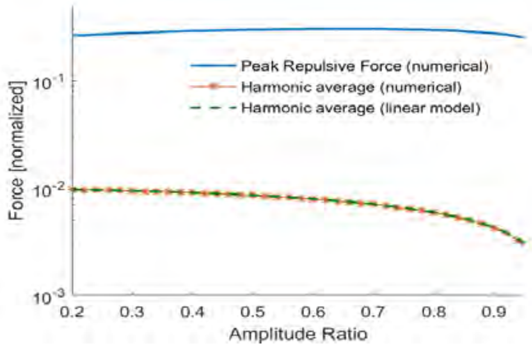

Fig. 4: Peak Repulsive Force and first Fourier component of the force vs. amplitude ratio (w=1)

As an example, Fig.4 compares the PRF and $\left|F_{ts}^{(1)}\right|$ achieved with the presented linear model and numerical solution of the nonlinear model for different amplitude ratios, in which the first harmonic of the force in both methods are the same.

Note that the presented hypothesis does not consider any force model. Thus, it cannot provide the PRF. The $\left|F_{ts}^{(1)}\right|$ achieved by this method agrees with the nonlinear model, regardless of the parameters of the force model. Thus, It can be concluded that nano-mechanical properties of the sample do not have any effect on the amplitude and phase signals. Consequently, cannot be estimated from TM-AFM observables.

ACKNOWLEDGMENTS

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