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# Direct tip-sample interaction force control for the dynamic mode atomic force microscopy

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A control method, in which the tip-sample interaction force of each tapping cycle is directly regulated, is proposed for dynamic mode atomic force microscopy. It does not rely on the steady-state relationship between the cantilever's oscillation amplitude and tip-to-sample distance, and therefore the cantilever's transient dynamics and the time delay of rms-dc converter are irrelevant. Experimental results clearly demonstrate that the proposed method regulates the tip-sample interaction force for each tapping cycle and time delay effect is eliminated. Computer simulations also show that the proposed method reconstructs a step change in topography within two tapping cycles, independent of the cantilever's transient dynamics. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2203958]

Dynamic mode atomic force microscopy[1] (AFM), where a cantilever is oscillated near its resonance frequency and controlled to gently tap the sample surface, has several advantages over conventional contact mode operation such as greatly reduced lateral force and low sensitivity to cantilever thermal drift. The most commonly used method in dynamic mode operation is a form of amplitude modulation, in which the oscillation amplitude of the cantilever is modulated by variations of the tip-to-sample distance and its value is regulated by a closed-loop controller. However, in typical implementations, the transient response of the cantilever induced by changes of the tip-sample interaction force, the time delay of the amplitude measurement system, and the limited bandwidth of the actuator[2] lead to greater variations in tip-sample interaction via feedback, causing excessive tapping forces and/or possible loss of tapping during scanning, and thus sample distortions and imaging errors. Therefore, while dynamic mode AFM can have many potential applications,[3–5] the inability to achieve direct and precise control of the tip-sample interaction forces has been one of the key barriers that limit imaging rate and innovation leading to more applications. Active $Q$ control was employed to reduce the effective quality factor $Q$ of the cantilever so that its transient response vanishes quicker[6] but this method sacrifices the force sensitivity of the cantilever. Smaller cantilevers, whose resonance frequencies were two orders of magnitude higher than that of the usual cantilevers were used to reduce the settling time.[7,8] However, the short length of the cantilever, less than 20 $\mu$m, could lead to difficulties while engaging sample surfaces and with samples having large topographic variations. In an attempt to increase scanning bandwidth, a transient-signal-based sample detection method was developed by constructing an observer, providing an estimate of the transient state of the cantilever, to detect changes in tip-sample interaction.[9]

In this letter, we present a control method for dynamic mode AFM, in which the tip-sample interaction force of each tapping cycle is directly regulated during scanning. In this method, based on a linear dynamic model of the cantilever along with its transient response, an estimator is designed and implemented to estimate the tip-sample interaction force of each tapping cycle. The estimated interaction forces are then utilized by a model-based predictor to plan and control the next tapping by controlling the tip-to-sample distance. In order to attenuate the effects of modeling errors of the predictor, a feedback regulator is employed. Since the tip-sample interaction force of each tapping cycle is directly controlled, it does not rely on the steady-state relationship between the oscillation amplitude of the cantilever and the tip-to-sample distance. Therefore, tapping dynamics in amplitude modulation is irrelevant and the time delay effect[2] in

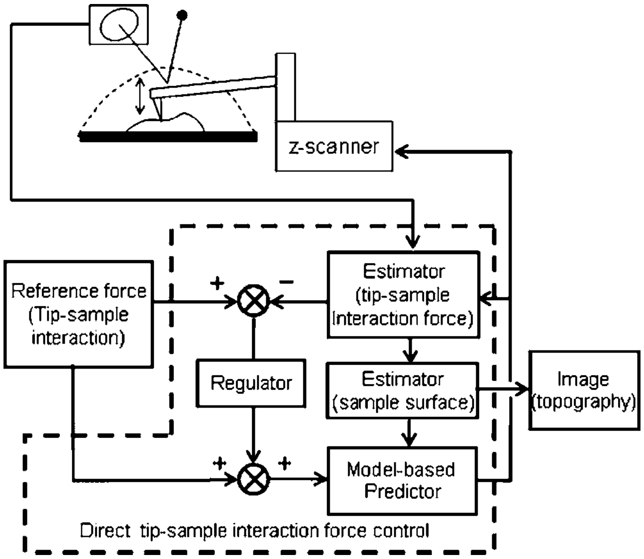

FIG. 1. A block diagram illustrating direct tip-sample interaction force control.

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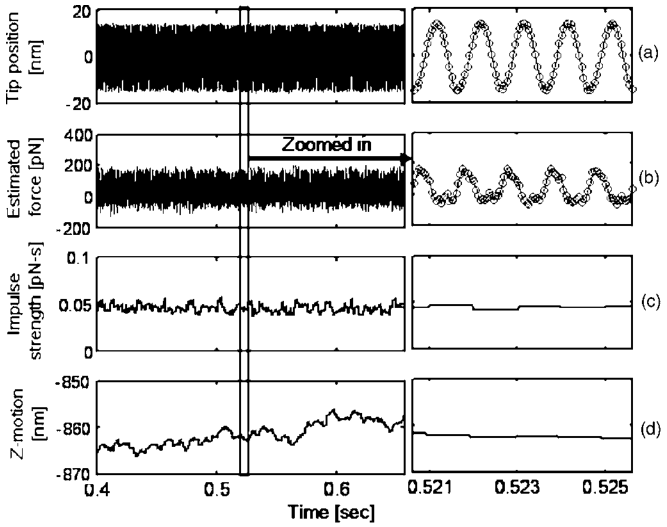

FIG. 2. Experimental results of direct tip-sample interaction force control: (a) tip position during tapping, (b) estimated tip-sample interaction force, (c) impulse strength, and (d) $z$-scanner motion. The results were taken from one scan line after imaging the plasma membrane patch of oocytes using the direct tip-sample interaction force control. The proposed method was implemented using a real-time control system (CP1104, dSPACE Inc) with a closed-loop rate of 20 kHz, and was integrated with a commercial AFM (PicoPlus, Molecular Imaging). In this experiment, an area of $1\times 1\ \mu\text{m}^2$ was scanned at a rate of 4 lines/s.

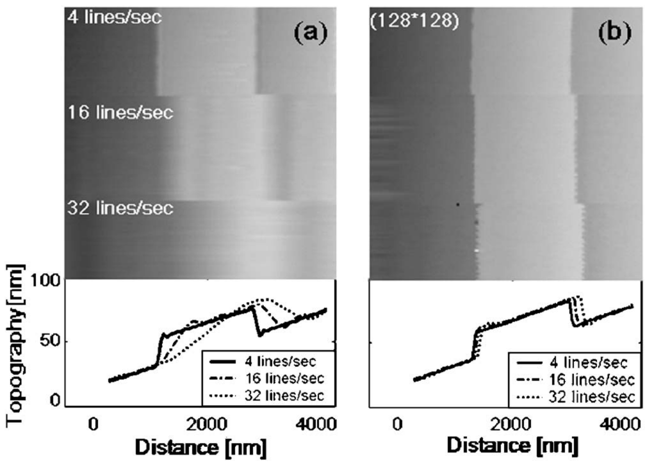

FIG. 3. Experimental results of scanning a grating: (a) amplitude modulation method and (b) direct force control method. The stiffness and the operation frequency of the cantilever are 0.1 N/m and 8 kHz, respectively. The effective $Q$ factor in the imaging buffer is identified to be 1.44. The sampling rate was 80 kHz and the D/A converter update rate was 8 kHz in a NI PXI real-time controller. The tilted angle of the grating along the slow scanning direction was manually corrected for the dissection analysis.

oscillation amplitude measurement is eliminated. Consequently, precise control of the tip-sample interaction force and high imaging rate can be achieved, independent of the quality factor $Q$ of the cantilever.

When tapping a sample surface, the tip-sample interaction force presents itself as a disturbance to the cantilever. The dynamical state vector of the cantilever, consisting of its tip position and velocity, is augmented to include this disturbance as an additional state variable. This augmented state vector along with the dynamic model of the cantilever is employed to construct a closed-loop observer that estimates the tip-sample interaction force as well as the tip position and velocity with a desired rate of convergence.[10] The estimated disturbance represents the tip-sample interaction force that may include the contact repulsive force and a long range force. Based on the tip position, the contact repulsive force of each tapping cycle can then be extracted. In addition, the sample position of the current tapping is estimated from the dynamic state vector and the estimated impulse strength.

A model-based predictor is designed to plan and control the next tapping through controlling the tip-to-sample distance. Since tapping occurs near the lowest tip position of the cycle, all the forces except the tip-sample interaction force during the period of contact are lumped into $ma_e$, where $m$ is the lumped mass of the cantilever and $a_e$ is the expected acceleration of the tip at the lowest position when assuming no contact. By employing a spring force model (sample stiffness: $k_s$) for the tip-sample interaction along with the lumped force $ma_e$, the impulse strength is approximated to be $2m(-v_{\text{in}})-ma_e\pi\sqrt{m/k_s}$ for the case in which the sample stiffness is greater than that of the cantilever, where $v_{\text{in}}$ is the velocity with which the cantilever is incident on the sample surface. The acceleration $a_e$ can be directly predicted from the dynamic state vector $\hat{\mathbf{x}}_t(k,t)$ where $k$ denotes the $k$th tapping cycle. A calibrated value is used for the sample stiffness $k_s$ in the current implementation. The velocity $v_{\text{in}}$ of the next $[(k+1)^{\text{th}}]$ tapping depends on the sample position $x_s(k+1)$, the long range force $\ell(k+1,t)$, and the $z$ motion $\delta z$. Therefore, for simplicity the impulse strength $\hat{p}(k+1)$ of the next tapping can be expressed as

$$\hat{p}(k+1) = P[\hat{\mathbf{x}}_t(k,t),\ell(k+1,t),x_s(k+1),\delta z]. \tag{1}$$

Using a zero-order predictor, $\hat{\ell}(k+1,t)\approx\hat{\ell}(k,t)$ and $\hat{x}_s(k+1)\approx\hat{x}_s(k)$, the solution to Eq. (1) yields the desired $z$ motion that regulates the impulse force of the next tapping to the reference value $p_r$,

$$\delta z = P^{-1}[\hat{\mathbf{x}}_t(k,t),\hat{\ell}(k,t),\hat{x}_s(k),p_r]. \tag{2}$$

The variations in the sample material property and the prediction error of $\hat{\ell}(k+1,t)$ and $\hat{x}_s(k+1)$ can cause errors in determining the required $z$ motion. A feedback regulator which uses the estimated tip-sample interaction force as the feedback signal is employed to attenuate these two effects and directly control the tip-sample interaction force. Figure 1 illustrates the proposed method.

Plasma membrane from *Xenopus* oocytes was used as a sample to illustrate the feasibility of the proposed method. A soft magnetized cantilever (stiffness: 0.01 N/m, Type IV MAClevers, Molecular Imaging) was excited at 1 kHz in the imaging buffer solution using a magnetic coil placed beneath the sample plate. The control of tip-sample interaction force was achieved via $z$-motion control, the desired value of which was determined by the predictor. Figure 2 illustrates the results of the proposed control scheme along a scanned line. By zooming into a very small time interval (5 ms), five tapping cycles can be clearly seen. The peak value of the estimated tip-sample interaction force is identified to be around 180 pN when the reference impulse strength is 0.05 pN s. These experimental results clearly demonstrate that the proposed control method has the capability to estimate the tip-sample interaction force and regulate it to a desired value for each tapping cycle.

Figure 3 compares the experimental results of scanning a grating (TGZ01: 20 nm depth, MikroMasch) in the image buffer solution. As the scanning speed increases, the ampli-

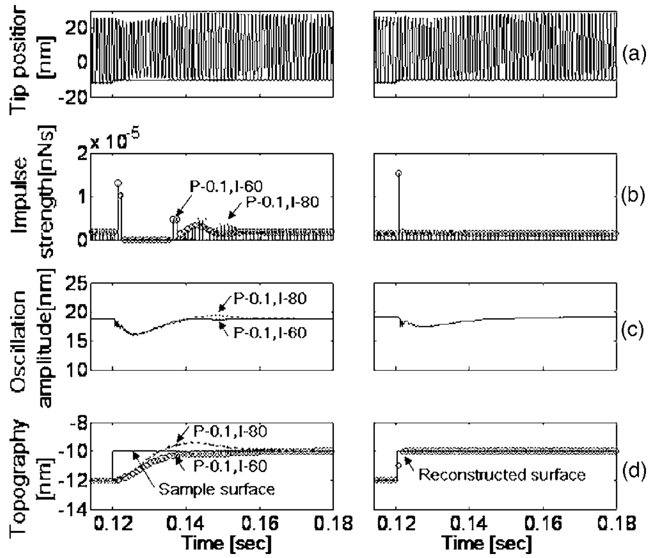

FIG. 4. Computer simulations of scanning a step change (2 nm) in topography with the amplitude modulation (left column) and the direct force control (right column): (a) tip position during tapping, (b) impulse strength, (c) oscillation amplitude, and (d) reconstructed topography. In these two simulations, the operation frequency of the cantilever is 1 kHz, the lumped stiffness is 0.01 N/m, and its $Q$ factor is 20. The sample stiffness was assumed to be 0.25 N/m. The discrete time loop rate in these simulations was 50 kHz.

tude modulation method results in greater topographical distortion, mainly due to the measurement time delay (around 5 ms) of the lock-in amplifier. The proposed method leads to significant improvement except the lateral mismatch caused by hysteresis and drift of the $x$-$y$ scanner.

In order to illustrate the independence of the proposed method from the cantilever's transient dynamics, computer simulations were performed. Computer simulations allow us to illustrate the sole effect of transient dynamics, with no contributions from the measurement's delay and the $z$-scanner's dynamics. In the case of the amplitude modulation method (the left column in Fig. 4), the transient response of the oscillation amplitude led to significant variations of the tip-sample interaction force, including loss of tapping (between 0.123 and 0.137 s), and introduced significant distortions in the reconstructed topography (based on the $z$ motion). In addition, it is evident that the reconstructed topography is sensitive to the controller gain. The right column in Fig. 4 shows the results of the proposed control scheme. It is seen that the impulse strength suddenly increases when the tip encounters the 2 nm step change, a result of prediction error in sample position $[\hat{x}_s(k+1)=\hat{x}_s(k)+2\text{ nm}]$. Nevertheless, the impulse force is regulated back to the specified value rapidly. Moreover, although the transient response of the oscillation amplitude still exists, the topography reconstructed by the proposed control scheme follows the real topography right from the second tapping cycle after the step change. These results clearly show that the proposed control method is capable of directly regulating the tip-sample interaction force of each tapping cycle and that the reconstructed topography is not affected by the transient response of the oscillation amplitude.

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