Fast imaging with alternative signal for dynamic atomic force microscopy

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In this paper, a method for imaging in amplitude-modulation atomic force microscopy is developed which enables accurate sample-profile imaging even at high scanning speeds where existing methods that use the actuator input signal fail. The central concept is to use a model of the vertical positioning actuator to compensate for the artifacts introduced due to its compliance in high scanning frequencies. We provide experiments that compare sample-profile estimates from our method with the existing methods and demonstrate significant improvement (by 70%) in the estimation bandwidth. The proposed design allows for specifying a trade-off between the sample-profile estimation error and estimation bandwidth. © 2010 American Institute of Physics. [doi:10.1063/1.3495987]

Amplitude-modulation atomic force microscopy (AM-AFM) (Ref. 1) is the most common mode used in AFM, especially for scanning biological surfaces, since the cantilever tip comes in contact only intermittently and gently with the sample without any shear forces and therefore does not damage the sample. In this mode, a microcantilever is made to oscillate sinusoidally over a sample surface, and the changes in the amplitude of the cantilever tip oscillations due to its interaction with the topographic features on sample are used to derive the sample profile. In a typical operation, the cantilever-oscillation amplitude is maintained at a constant value by using a piezoactuator to move the sample vertically in order to compensate for the features on the sample surface. The voltage input given to the actuator that compensates for the sample features provides a measure of the sample profile. The main disadvantage of this mode is that imaging bandwidth is limited since at high scanning frequencies, the piezoactuator is not rigid but is compliant. At these scanning frequencies, the voltage input to the actuator is indicative of both the deformation of the piezoactuator and the sample features, and therefore an inaccurate measure of the sample profile alone. Therefore, in typical AM-AFM, the imaging bandwidth is limited by the bandwidth of the piezoactuator. The main idea in this paper is to derive a measurable signal that exploits a dynamic model of the piezoactuator to give an accurate measure of the sample profile. Conceptually, it utilizes both the voltage input to the piezoactuator and the cantilever deflection signal, and therefore is not limited by the bandwidth of the piezoactuator.

A model of dynamic AFM is described in Fig. 1, where device components are represented by transfer functions.2 Transfer functions represent dynamics of components about a nominal operating point. The cantilever dynamics \( F \) which includes the tip-sample interaction force \( F_{ts} \), the external excitation force \( g(t) \) of dither piezo, and the thermal noise \( \eta \) is given by

\[
\begin{align*}
\mathbf{Q} &= \mathbf{G}(g, v, h, \eta) \mathbf{F} + \mathbf{P}_m \\
|y| &= |g\cos\omega t| + |\eta| + |\mathbf{P}_m|
\end{align*}
\]

FIG. 1. (Color online) (a) A schematic of imaging system of dynamic AFM. The cantilever is attached to a vertical positioner. The oscillation of the cantilever is sensed, and a feedback controller moves the positioner to maintain a constant amplitude of cantilever oscillation in AM-AFM. (b) The block diagram of the AFM. \( K, G_p, F, \) and \( Q \) represent the controller, the vertical piezopositioner, the cantilever dynamics model, and the lock-in amplifier or rms-to-dc converter, respectively. In AM-AFM, the dither piezo is oscillated at a frequency \( \omega \) close to the cantilever natural frequency. The controller, \( K \), is to regulate the difference, \( \epsilon \), between an amplitude, \( y \), of the deflection signal, \( p \), and the set point \( r \) to zero to compensate the effects of the sample topography \( h \). The deflection, \( p \), is due to the forcing of the nonlinear dynamic model \( F \), the dither piezoexcitation \( g \), the thermal noise \( \eta \), and the tip-sample interaction force \( F_{ts} \) that depends on the sample-position \( v \) by vertical piezoactuator and the sample height \( h \). The deflection measurements \( p_m \) are corrupted by sensor noise, that is, \( p_m = p + \eta \).

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The multi-input cantilever dynamics model \( F(x, v, h, \eta) \) and lock-in amplifier \( Q(\cdot) \) in Fig. 1 is approximated by the single input model \( F \).

In typical AM-AFM imaging, the control signal \( u \) (the voltage input to the actuator) is used to obtain an estimate of the sample topography \( h \). The rationale is that if the thermal noise \( \eta \) and sensor noise \( n \) are neglected, the amplitude of deflection \( p \) is maintained at a constant value when (averaged) interaction force \( F_p \) in one oscillation is approximately constant which in turn implies \(-h-v=0\). Since \( G_p \) is approximately a constant \( G_p(0) \) at low frequencies, the control signal \( u \) gives a measure proportional to \( h=−v=−G_p(0)u \) for low speed scans (or smooth samples). However, this signal yields distorted images for high speed scans (or rough samples) since \( G_p \) is not constant and \( u \) is not proportional to sample position \( v \) at high frequencies. Thus, for good imaging, the controller \( K \) is required to give an accurate estimate for the sample topography \( h \) as well as to regulate the amplitude of deflection \( p \) to compensate the effects of the sample topography, which is not easy to achieve simultaneously.

In the proposed method shown in Fig. 2, an alternative signal \( h \) for estimating the topography is generated by designing a separate estimator \( K_2 \) that fully utilizes the information in the system. (A similar signal was used for contact mode AFM (Ref. 3) but the derivation of the signal was based on a different approach.) The best estimate \( h \) of sample topography minimizes the estimation error \( \bar{h} = h - \hat{h} \). It is assumed that the set-point regulation controller \( K_1 \) is given or fixed. Here, \( F \) represents the map whose output is the amplitude \( y \) of the deflection signal when its input is the sum of the sample-topography \( h \) and the piezoactuation signal \( v \). The uncertainties in using \( F \), the effect of the thermal noise \( \eta \), and the sensor noise \( n \) are represented by \( \bar{n} \).

Based on our identification experiments using constant dither excitation \( g(t) = g_0 \cos \omega t \), the cantilever dynamics \( F \) is found to be nearly linear at low frequencies. When a cantilever of natural frequency \( f_n \approx 70 \text{ kHz} \) is used, the frequency response \( \approx 2 \text{ kHz} \) is almost linear, which also implies \( \bar{n} \) is dominant in high frequencies \( >2 \text{ kHz} \).

If we assume that the given controller \( K_1 \) and the vertical piezomodel \( G_p \) are linear, the input \( u \) is given by

\[
\ddot{p} + \frac{\omega_0^2}{Q} \dot{p} + \omega_p^2 p = -\frac{1}{m} F_p (p - h - v) + g(t) + \eta.
\]  

where the sensitivity transfer function is written as \( S = (1 + K_1 F G_p)^{-1} \). The transfer function from the sample profile \( h \) to the control signal \( u \) is given by \( T_{uh} = S K_1 F = K_1 F/(1 + G_p K_1 F) \) and approximated by \( T_{uh} \approx 1/G_p \) since typically \( K_1 \) is large at low frequencies for good amplitude regulation. This fortifies the conventional estimate \( |G_p(0)|u \) of the sample topography \( h \). However, \( K_1 \) cannot be designed to be

\[
u = SK_1 (r - \bar{n}) - SK_1 F h,
\]

and therefore the transfer function from the sample profile \( h \) to the designed estimation signal \( \bar{h} \) is given by \( T_{hh} = -K_2 F/(1 + G_p K_1 F) \). From Eq. (4), it is evident that the sample profile estimation design needs to consider effects of the sample profile \( h \) as well as the noise \( \bar{n} \). The estimator design \( K_2 = S^{-1} F^{-1} = (1 + K_1 F G_p)^{-1} \) amnuls the effect of sample topography \( h \); however, the effect of noise \( \bar{n} \) in sample-profile estimation error \( \bar{h} \) is then given by \( K_2 \bar{n} = F^{-1} \bar{n} \). We introduce a weight function \( W_h \) that allows us to specify a trade-off between the effects of \( \bar{n} \) and \( h \) whereby the estimator design is given by

\[
\bar{h} = K_2 S (r - \bar{n}) - K_2 F Sh,
\]

where the sensitivity transfer function is written as \( S = (1 + K_1 F G_p)^{-1} \). The transfer function from the sample profile \( h \) to the control signal \( u \) is given by \( T_{uh} = SK_1 F = K_1 F/(1 + G_p K_1 F) \) and approximated by \( T_{uh} \approx 1/G_p \) since typically \( K_1 \) is large at low frequencies for good amplitude regulation. This fortifies the conventional estimate \( |G_p(0)|u \) of the sample topography \( h \). However, \( K_1 \) cannot be designed to be

\[
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\]
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