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Feedback scheme for improved lateral force measurement in atomic force microscopy

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Abstract— **This paper proposes a signal based on a feedback scheme that gives a measure of lateral forces in atomic force microscopy. This measure, unlike the typically used lateral deflection signal, is not corrupted by the geometrical crosstalk between the normal and lateral signals, accounts for inertial forces experienced by the cantilevers during scans, and misinterpretations due to irregular sliding. This measure varies linearly with the lateral forces for a larger range of forces and scanning bandwidth than the lateral deflection signal. The sensing bandwidth depends on the control design for the feedback scheme. We also present the design of an actuator that enables the lateral feedback scheme. Experimental results are presented that show the inaccuracies in the lateral deflection method for lateral measurement and how these are addressed by the feedback scheme.**

I. INTRODUCTION

Friction is a familiar concept in everyday life, but the underlying physical mechanisms are poorly understood. Theories of microscopic friction are, for the most part, still being developed on a phenomenological basis [1], [2], [3]. This phenomenological approach results in a need for clearly defined experiments for measuring the effects of friction. The Atomic Force Microscope (AFM)[4] lends itself by its very nature to these experiments, and has led to observation of phenomena such as "stick-slip" motion of the tip over a surface, which have aided in the understanding of atomistic mechanisms of friction. However, friction on the nanoscale, and the contribution of atomic scale friction to macroscopic friction is still unclear. Part of this difficulty lies in the fact that determination of friction (and lateral forces in general) using AFM depends on multitude of factors such as velocity of scans, cantilever tip wear, humidity, temperature and other environmental effects besides typical factors such as contact surface material and surface condition. This complex dependence makes it extremely difficult to produce models of friction that account for all the factors and it is even more difficult to design and implement experiments that validate these models. This emphasis on empirical studies places severe demands on the experimental apparatus. It becomes essential to have sensing mechanisms that measure the lateral force signals accurately and that they are devoid of any artifacts due to device inaccuracies.

The system theoretic tools, which are being increasingly used for nanopositioning and cantilever-based imaging aspects of AFM, are virtually non existent in the exploration of the lateral (friction) forces and their effects. This paper is a step in this direction. This work is further motivated by observing that there is a close parallel in the problem of estimating friction and lateral forces to the imaging problem where sample profile estimation forms the objective [5], [6]. The existing measures of lateral forces in experiments based on AFM suffer from spurious artifacts, inaccurate measurements and data misinterpretations. The imprecision in the optical assembly and practically unavoidable asymmetry in cantilever placement lead to deviation from the intended optical path for laser, which in turn leads to spurious crosstalk between the normal and the lateral force measurements. The resulting artifacts are particularly significant in small (nanoscale) scans. Typically the inertial forces experienced by the cantilevers are ignored in estimating the lateral forces even when they are estimated in dynamic environments which result in inaccurate measurements. This problem is even more exaggerated when the linearity assumption between the lateral forces and its measurement signals is violated, especially at high values of lateral forces and the rates at which they change. The irregular sliding between the cantilever tip and the sample typically manifests as misinterpretations in the location of lateral forces on the sample. In this paper, we present a measure of the lateral force based on a feedback scheme that simultaneously addresses all these problems and gives an accurate measure of lateral forces. We also present the design of the actuator that enables this feedback scheme. This feedback capability provides an additional degree of freedom in the design of experiments to explore various aspects of models for lateral forces.

II. LATERAL DEFLECTION SIGNAL AS A MEASURE FOR LATERAL FORCES AND RELATED PROBLEMS

A. Device Description

A schematic of an AFM that demonstrates its working principle is shown in Figure 1. A micro-cantilever forms the main sensor that is soft enough (typically the stiffness is in 0.1 N/m to 10 N/m range) to detect interatomic forces between its tip and the sample, and has resonant frequency high enough (typically in order of tens of kHz) to isolate other disturbances. The cantilever reacts to the inter-atomic forces between its tip and the sample features and deflects up and down as the sample features move under it. The cantilever deflections are detected by focusing a laser on the

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back of the cantilever and collecting the reflected laser on a four quadrant photodiode. One of the advantages of this method is its ability to simultaneously record the normal and the lateral interaction forces between the sample surface and the cantilever tip. The difference signal between the upper and the lower halves of the diode, known as the *normal deflection signal*, is used as a measure of the tip-sample normal interaction force which is normal to the sample surface topography. Similarly, the difference signal between the left and the right halves of the diode, *the lateral deflection signal*, is used as the measure of the tip-sample lateral interaction force which is along the sample surface and perpendicular to the cantilever's longitudinal axis. This lateral interaction force acts on the cantilever-tip which results in its twisting, which in turn, manifests as the lateral deflection signal. For determining lateral forces, typically the AFM is used in *contact mode* operation, where the cantilever is always in contact with the sample (In some operating modes, such as intermittent contact mode, the microcantilever base can be forced using a dither piezo and estimate the interaction force by monitoring the deflections under the forcing). Some of the problems with the current method in determining a measure for lateral force interaction has a close analogy with that of sample profile estimation problem in imaging. Therefore, we present a brief description of the contact-mode imaging method and how the related problems are addressed. In contact mode, when the normal deflection signals are directly used as a measure of the sample features, the contact forces can vary which typically result in unreliable and distorted images and sometimes in tip-sample damage. Therefore in a typical contact mode operation, the cantilever deflection is regulated at a setpoint (i.e. the tip-sample force is kept constant) while scanning the sample. This is achieved by moving the vertical positioning system (z- piezo), on which the sample is placed (or in some cases, to which the cantilever and optical assembly is attached), up or down to compensate for the undulations in the sample surface by using a feedback controller. The input to the vertical positioner, i.e. the compensating control signal, is traditionally used as a measure of the sample profile. This constant force method avoids force impulses felt by a cantilever (say due to encountering a sudden large feature on the sample) that can potentially damage the cantilever or the sample, and also avoids the difficulty in discerning the topography from the nonlinear voltage-deflection relationship that models the cantilever deflection and the photodiode voltage under the influence of the sample. In the same way, when the cantilever is not regulated and free to react to lateral forces, sudden changes in them result in distorted lateral force images. The discerning of true lateral forces from these images becomes difficult.

B. Problems with the lateral deflection signal as a measure of lateral forces

1) Misinterpretations due to irregular sliding: In typical AFM scanning, the cantilever is free to move in the lateral direction under the action of lateral forces. As a consequence, the relative motion between the cantilever and the sample is irregular. A consequence of this irregular sliding is misinterpretation of the position of the cantilever tip with respect to the sample. This is clearly seen, especially in high resolution (sub-nanometer scale) imaging, where the lateral position is misinterpreted due to *tip-sample stick*. Due to the lateral force acting on the cantilever, it twists and occasionally sticks to the sample surface. As a result, the lateral deflection signal corresponds to the "stuck" location rather than to the intended location, which leads to misinterpretations in mapping the position of lateral forces on the sample.

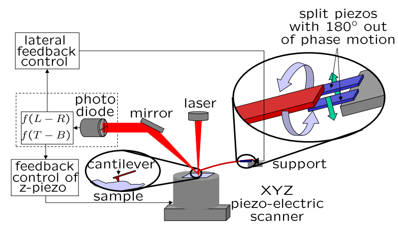
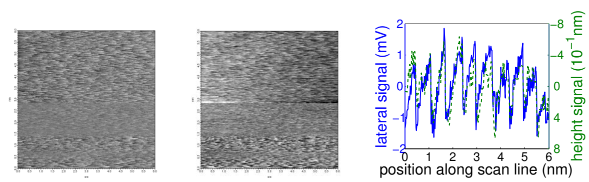


Fig. 1. Schematic of an AFM. The optical beam bounce method is used to detect the interaction force between the cantilever tip and sample. The normal deflection signal (obtained from the difference of top and bottom cells of the photodiode) is used as a measure of the normal interaction force and the lateral deflection signal (obtained from the difference of left and right cells of the photodiode) is used as a measure of the lateral interaction force between the cantilever tip and the sample. We have modified the AFM by adding a mechanism for Lateral Compensation(top right circle). Two split piezos with 180° out of phase motion are used to demonstrate lateral actuation. Lateral signal from the laser sensitive photodiode is fed to a controller which provides the compensating signal to the lateral actuator through an amplifier.



(a) (b) (c)

Fig. 2. (a) Lateral image of mica, hairy structure [1], [7] indicates lattice scale stick slip (b) Height image of mica, hairy structure similar to that in the lateral image can be seen. This structure is an artifact with image expected to be more flat. (c) Height (dotted) and Lateral (solid) image data superimposed from the same scan line obtained from the images (a) and (b). Height signal, which was expected to be more flat, shows a spurious signal proportional to the lateral signal indicating geometrical crosstalk.

These effects are seen in the lattice averaged atomic scale imaging of mica. Due to the lateral dynamics of the cantilever and the lateral interaction force between the cantilever tip and mica surface, the cantilever undergoes a stick-slip motion [1], [7] with a periodicity of 5.2 Å, the lattice constant of mica. This stick slip motion of the cantilever results in a triangular waveform in the lateral channel as seen in the scan line image data in Figure 2(c). The linear portion of the triangular wave in the lateral channel corresponds to the situation where the cantilever is stuck to a particular location on the mica surface and the cantilever twist is increasing in approximately linear trend, while the sudden fall in the lateral signal corresponds to the cantilever *slip* when the cantilever suddenly starts sliding since its restoring forces become more than the lateral friction forces. Thus, for an apparent travel range of about a lattice dimension of 5.2 Å, the tip is stuck to a single location and the corresponding lateral deflection signal during this stick regime represents the force at the stuck location rather than the intended locations along the scan line. In fact, this irregular sliding also leads to misinterpretations in imaging (that is, in mapping the normal deflection signals to locations on the sample) as demonstrated in Figure 2.

2) Inertial Forces in dynamic scans and Nonlinearity: In lateral force microscopy, typically the sliding between the cantilever tip and the sample is irregular, which can result in different lateral deflection signals for the same lateral force depending on the cantilever twist angle during contact. Since the cantilever is free in the lateral direction, the operating point (cantilever twist angle) can vary for same lateral forces during the same scan. This gives distorted lateral force images. These distortions become significant especially in scans where there are sudden changes in the lateral forces. This is analogous to constant height imaging of sample topography. When the normal force is not regulated, the cantilever tip-sample force can vary over a scan. Since the cantilever deflections are smaller when the tip-sample contact forces are smaller, same topographic features can produce different height images depending on the tip-sample contact force operating point.

The lateral deflection signal ignores the dynamic effects of scanning which can be significant especially in scans with high accelerations or rapidly varying lateral forces. At any given moment, the instantaneous lateral deflection (twisting) of the cantilever is not only determined by the instantaneous lateral interaction force but also depends on the inertial effects of the lateral forces which are related through the non-linear higher order dynamics of the cantilever. For example, if we assume a simple second order system to describe the twisting dynamics

$$\ddot{\theta} + 2\zeta\omega_n\dot{\theta} + \omega_n^2\theta = f, \quad y = k\theta, \tag{1}$$

where $\theta, f, \zeta,$ and ω_n denote the twisting angle of the cantilever, the scaled lateral forces f, the damping ratio, and the lateral natural frequency, the lateral deflection signal y (for some constant sensitivity k) is an inaccurate measure of lateral forces f as it ignores the the dynamic terms $\ddot{\theta}$ and $2\zeta\omega_n\dot{\theta}$.

In view of nonlinear dynamic relationship between the twisting and lateral forces (especially at high twist angles) this problem becomes even more significant. The relation between the lateral deflection signal and the cantilever twist angle is given by

$$y = \frac{-S_z \sin 2\theta(M_x^2(L+D_x) + M_z^2(D_x - L)L - 2M_x)}{M_z^2 S_x + 4M_x M_z \cos^2\theta S_z - 2M_x M_z S_z - M_x^2 S_x}, \tag{2}$$

where the cantilever is placed on x-y plane and its reflection point has the coordinate $(L, 0, 0)$, the plane of mirror in the optical assembly is defined by $M_x x + M_z z = 1$, the plane in which the detector lies is defined by $x = D_x$ and the source coordinates are given by $(S_x, 0, S_z)$ (see Figure 3(a)). The nonlinear relationship between the twisting and lateral forces is shown in Figure 3(b)

Moreover, the twisting in the cantilever leads to a spurious change in the normal signal (in z-direction) which depends on the geometrical parameters (introduced in (2) in the optical assembly (see Figure 3(c)). In constant force contact mode imaging, the control design compensates for this spurious signal which results in inaccurate measure of the normal forces and therefore topographical features. In addition, this adjustment of normal forces, leads to changes in the tip-sample contact forces which in turn leads to unwarranted changes in the cantilever twist angle. This spurious twist angle leads to spurious measurements of the lateral forces.

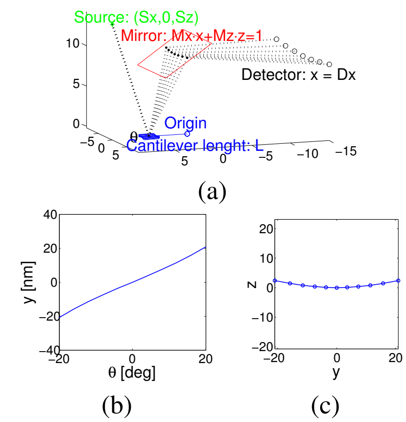


Fig. 3. (a) The optical assembly and the related geometry (b) The nonlinear relationship between the cantilever twist angle and the lateral deflection signal (c) The spurious coupling between the normal deflection signal and the lateral deflection signal.

3) Geometrical Crosstalk: Geometrical Crosstalk between the normal and the lateral signal is the spurious signal created in one signal due to the deflection in other direction. The lateral and the normal interaction forces between the sample and the cantilever tip are typically assumed to be independent of each other. This crosstalk is attributed to the relative geometrical misalignment between the laser and the cantilever axes. This misalignment is caused by fabrication inaccuracies and the practically unavoidable asymmetric loading (which is typically done manually) of cantilever substrate. These misalignments in photodiode sensor, laser source or cantilever, give spurious non-zero readings along the axis which under perfect alignment is orthogonal to the actual cantilever motion and is expected to show zero reading. For the lateral force measurement, we are more interested in the inaccuracy in the lateral deflection signal due to the crosstalk from the normal signal.

The spurious signal in the lateral channel due to the normal deflection of the cantilever in the presence of misalignment is experimentally demonstrated through force curves, shown in Figure 4. Due to lateral symmetry, we expect no lateral force on the cantilever tip and hence expect neither any lateral twisting of the cantilever nor any change in the lateral signal during a force curve experiment. But contrary to this expectation, typical experiments show varying non-constant lateral signals. This artifact of spurious variation in lateral signal can be misconstrued as lateral twisting of the cantilever. This signal is spurious since the lateral interaction force acting on the cantilever tip does not change once the cantilever touches the sample surface and it experiences only a repulsive normal force perpendicular to the surface. This variation is, in fact, the result of the geometrical crosstalk caused by the combination of gross misalignment in the optics and the change in the normal deflection as discussed in [8], [9], [10].

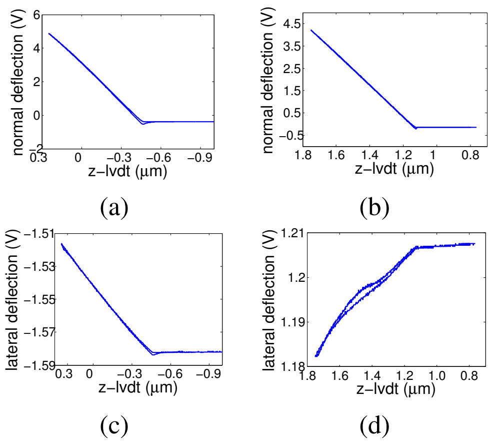


Fig. 4. (a,c) Normal and the lateral signals obtained during a force curve. Lateral channel shows a spurious signal proportional to the normal signal indicating existence of geometrical crosstalk. (b,d) Normal and the lateral signals obtained during another force curve. The sign of the cantilever misalignment is opposite to that in (a,c). The spurious signal (d) in the lateral channel with an opposite slope as in the force curve (b) confirms existence of geometrical dependence.

The effect of misalignment of the axes of the cantilever with respect to the axes of the photodiode can be changed by loading the cantilever substrate into the cantilever holder at different angles and when this is done till the angle of misalignment changes from positive to negative or vice versa, the sign of the effect of the normal deflection on lateral signal reverses sign (see Figure 4(c,d)). This substantiates the claim that the lateral signal during the force curve is indeed a spurious signal where the variation in the normal deflection of the cantilever is spilled over into the lateral signal by the unavoidable geometrical misalignment. Note that increasing this misalignment increases further the magnitude of the signal in the lateral channel.

III. Proposed Signal for Lateral Force Estimation

A. Feedback Scheme

In this paper, we propose a new measure, which *simultaneously* corrects, in real time, all the problems listed in the section above. Our solution is to simultaneously maintain the *lateral* and the *normal* deflection signals constant at their corresponding setpoints through feedback. The control effort in the lateral direction that regulates the lateral deflection signal at a setpoint gives a measure of lateral forces (analogous to the control effort in the normal direction that is used as the measure of sample profile in constant force contact mode microscopy). This lateral control signal provides a more accurate measure of the lateral interaction force which can be explained as follows. When lateral compensation is used, the lateral twisting motion of the cantilever is held constant and the corresponding lateral control signal dynamically compensates for the overall lateral dynamics of the cantilever. In terms of the second order model in (1) the dynamical equation is given by

$$\ddot{\theta} + 2\zeta\omega_n\dot{\theta} + \omega_n^2\theta = f - u, \ y = k\theta, \tag{3}$$

where the control signal u is designed to regulate θ at a constant (say zero) value. This implies that the u is proportional to the lateral force f. Thus, by avoiding the lateral dynamics of the cantilever, the lateral control signal contains a better estimate of the instantaneous friction force rather than the lateral signal in the absence of the lateral compensation. This argument is analogous to the explanation given for the better imaging capability of the constant force mode as compared to the constant height mode in contact mode imaging. Further since this control design regulates the cantilever twist angle at a constant value, this has the additional advantage of avoiding the non-linear relation between the lateral deflection of the cantilever and the lateral signal captured by the photodiode. The typically used lateral deflection signal as the measure of the lateral force is valid only under the assumption that the lateral signal is linear with respect to the lateral deflection of the cantilever, which is not true when twist angles are large. This assumption is not required when the lateral deflection is maintained at a constant level as done in lateral compensation. Thus, lateral compensation provides a more accurate measure of lateral force than the standard lateral deflection signal.

It should be noted that this geometric crosstalk is the result of both misalignment and a *varying* normal deflection signal caused by the variation in the normal deflection of the cantilever. In other words, if there is no normal deflection, there is no spurious lateral signal even in the presence of optical misalignment and vice versa i.e. if there is no lateral twisting of the cantilever, there is no spurious normal signal even in the presence of optical misalignment. Since the lateral and normal deflection signals are regulated at a constant value by the proposed feedback, the crosstalk between them is significantly reduced and since a constant twist angle leads to smooth sliding between the cantilever tip and the sample, the corresponding misinterpretations are practically eliminated.

B. Actuator Design and Implementation of Feedback Scheme

We use a split piezo arrangement to enable the lateral actuation of the cantilever. A schematic of lateral compensation used along with normal z feedback is shown in Figure 1 (top right circle). As argued above, the lateral control signal provides a more accurate measure of the lateral interaction force (than the lateral deflection signal) between the sample and the probe tip. In order to enable lateral compensation

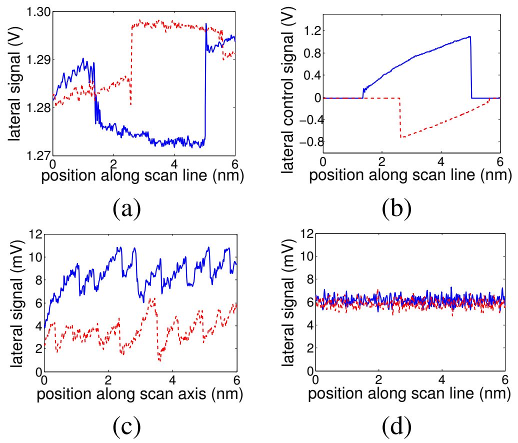


Fig. 5. (a) Lateral signal and (b) Lateral control signal while imaging mica. The lateral compensator is switched on and off once each along both the trace (blue, solid) and retrace (red, dotted). When switched on, the lateral compensator maintains a constant lateral signal and hence a constant lateral deflection (twist) of the cantilever. During this scan, the lateral signal has a linear trend which is eliminated when the compensator is switched on. During the on time of the compensator, the lateral control signal provides the measure of the lateral interaction force which can be seen by the linear trend shown by the lateral control signal. (c) Lateral signal trace (blue, solid) and retrace (red, dotted) indicate the stick slip friction characteristic of mica. The difference between the trace and retrace also indicates friction hysteresis. (d) This hysteresis and the stick-slip behavior is practically eliminated by lateral feedback compensation.

feedback scheme, the cantilever holder in the AFM (molecular force probe 3D (MFP-3D) from Asylum Research Inc., Santa Barbara) was modified to incorporate a rudimentary lateral actuator. The existing high frequency dither piezo used to excite the cantilever for intermittent contact operation, below the base of the cantilever clamp is replaced with a set of split piezos, each of which are actuated by voltage inputs that are 180° out of phase. As a consequence, the piezos move 180° out of phase with each other. When one piezo expands, the other contracts creating a rotational effect on the cantilever clamp. This rotation of the cantilever clamp has the effect of laterally rotating the free end of the cantilever reflective surface. The split piezo assembly rotates the whole cantilever along with its substrate, and thereby providing a control over the lateral twisting of the cantilever reflective surface caused by the torque due to the tip-sample lateral interaction force. This modified cantilever holder is used as the lateral actuator to demonstrate implementation of the lateral compensation feedback scheme. In order to drive these split piezos, a coupled high voltage amplifier was designed which provides with the necessary power requirements to actuate the assembly. A bridge amplifier circuit was designed around two PA78 power operational amplifiers from Apex Microtechnology Corporation, Tucson, USA. This modified cantilever holder assembly is used to perform experiments and confirm the capability of lateral compensation by maintaining the lateral deflection of the cantilever constant. These experiments are discussed below. A proportional-integral controller was designed to compute the control signal depending on the error between the reference setpoint and the sensor reading (lateral signal from the quadrant photodiode) with the aim of reducing this error to zero. The control signal was then applied to the split piezo assembly through the amplifier. The feedback scheme was implemented on a 100 KHz sampling frequency DSP from Analog devices, ADSP 21160M.

The dynamic relationship between the lateral deflection signal and the actuator input depends on the cantilever tip-sample contact force regulation. This requires identification of the model for the lateral actuator at every operating point of contact mode operation. However, the purpose of regulating a constant lateral force deflection can be easily achieved by designing a high gain (at low frequencies) feedback law. Therefore a simple proportional-integral controller ($K(s) = 90+11/s$) was implemented to achieve the setpoint regulation. Once, the set point regulation is achieved, the deviations from the set point are small that further validate the use of linear control design.

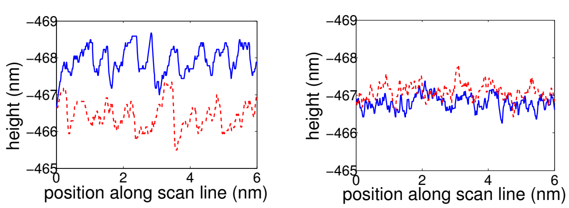
IV. Experimental Results

1) Regulation at different setpoints: The effective performance of this lateral actuator can be seen from Figure 5. These scan line images were obtained while imaging mica. The lateral compensator is switched on and off once along each of the trace and retrace. When the lateral compensator is off, the lateral signal is linearly increasing indicating change in the lateral deflection (twisting) of the cantilever due to the lateral interaction force between the cantilever tip and the sample. When the lateral compensator is switched on, it maintains a constant lateral deflection as seen in the Figure 5(a).

2) The control signal as an estimate of the lateral force: Since the lateral compensator ensures smooth sliding of the cantilever tip on the sample surface, the constant lateral signal no longer carries the information of the lateral force acting on the cantilever tip. The lateral force information gets reflected in the lateral control signal which helps maintain this constant lateral deflection. This is demonstrated in Figure 5(a,b). When the lateral compensator is switched on, the lateral control signal starts following the pattern (a linear trend) which otherwise would be shown in the lateral signal when the compensator was off. Thus, while the lateral signal is maintained constant, the lateral control signal captures the lateral interaction force between the cantilever tip and the sample surface.

3) Diminishing tip-sample stick-slip effects and the geometrical crosstalk: The plots in Figure 5(c,d) were obtained by performing a constant force contact mode scan on mica that maintained a constant normal deflection. Because of this, there are no spurious signals in the lateral channel in spite of the unavoidable misalignment in cantilever placements and optical assembly. Figure 5(c) shows the stick-slip behavior (characterized by the triangular waveform) in the lateral force estimation when lateral compensation feedback was not used. The lateral compensator is then switched on and a constant lateral deflection was maintained as seen in Figure 5(d). There is no 'stick-slip' and hence there is no misinterpretation in the mapping between lateral force to the sample location. The effectiveness of the lateral control scheme is demonstrated by maintaining a constant lateral deflection of the cantilever as seen in Figure 5(d). When the lateral compensation was not on, the difference between the average trace friction and average retrace friction was 4.83 mV and when the lateral compensation was switched on, this difference reduced to 0.29 mV, indicating successful compensation of lateral deflection.

This control design, in fact results in removing the artifacts due to geometrical crosstalk effects of lateral signal on the normal signal. The mica used for imaging is an atomically flat sample. Hence we expect a flat height signal with the trace and retrace overlapping each other within the error of the z resolution. But as seen from Figure 6(a), the height image along a scan line shows a triangular waveform very similar to the one seen in the lateral channel in Figure 5(c). This triangular waveform in the height signal (z control signal) is because the z feedback compensated for the normal signal which was corrupted by the geometrical crosstalk and the variations in the lateral deflection of the cantilever. The difference between the trace and retrace is 1.489 nm, obtained by taking the difference between the average height along trace and retrace, as against an ideal value of zero for perfect overlap. The lateral compensator is then switched on and a constant lateral deflection was maintained as seen in Figure 5(d). The corresponding height signal along the same scan line (Figure 6(b)) is flatter than the one in Figure 6(a). With the lateral compensation on, the difference between the height trace and retrace is 0.288 nm. This value indicates an overlap of the height trace and retrace within the limits of z resolution (the z resolution is in the order of 0.300 nm) and is an improvement of 81% over that obtained when there is no lateral compensation. This effectively demonstrates the removal of crosstalk using lateral compensation.



(a) (b)

Fig. 6. (a) The normal signal corresponding to the lateral signal in Figure 5(c), which was expected flat, shows a spurious signal proportional to the lateral signal. The trace (blue, solid) and retrace (red, dotted) height signals which are supposed to overlap, have a difference of 1.489 nm. (b) Lateral compensation was switched on and the corresponding normal signals obtained along the scan line. Since there is no more lateral twisting, the spurious signal in the normal channel due to the geometrical misalignment is eliminated and the trace and retrace overlap each other. The difference between the height trace and retrace with the lateral compensation on is 0.288 nm which is within the error of z resolution.

V. Conclusions

From the above experimental results, we have demonstrated the effectiveness of the feedback scheme that implements simultaneously the setpoint regulation of the lateral and normal deflections of the cantilever. With the normal deflection signal maintained at a constant setpoint, the spurious signals in the lateral channel due to the unavoidable crosstalk are eliminated. Since the lateral compensator dynamically compensates for the lateral dynamics of the cantilever, the cantilever tip no longer sticks to the surface of the sample. This ensures perfect smooth sliding of the tip on the surface preventing misinterpretations due tip-sample stick. Also by simply modifying the cantilever holder to incorporate a lateral actuator for the cantilever, we have demonstrated lateral compensation to remove artifacts in high resolution imaging. This scheme significantly diminished the problems of geometrical misalignment, tip-sample stick, nonlinear effects, and dynamic effects simultaneously, and in real time, as against when it is not used.

An additional advantage of the proposed scheme is that normal deflection signal is insensitive (robust) to the geometrical misalignment. It can improve the accuracy in height images. This method depends on maintaining a constant position of the laser spot on the photodiode thus making this mechanism *independent* of the alignment of the axes on the photodiode sensor with respect to the cantilever axes. That is, the misalignments in cantilever placement and optical assembly does not affect this scheme, and therefore the images, since the location of the laser spot on the diode is independent of the axes chosen and the spot is maintained constant. This provides a significant conceptual and practical advantage over the solutions for geometrical crosstalk in [8], [9], [10] (and other similar solutions), which is sensitive, as pointed by its authors, to the way the axes of the photodiode are aligned and therefore its precision depends on how well the rotary stage mechanism aligns these axes with the cantilever axes.

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