ROBUST TWO-DEGREE-OF-FREEDOM CONTROL OF AN ATOMIC FORCE MICROSCOPE

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ABSTRACT

The performance of an atomic force microscope (AFM) is improved substantially by utilizing modern model-based control methods in comparison to a standard proportional-integral (PI) controlled AFM system. We present the design and implementation of a two-degree-of-freedom (2DOF)-controller to accomplish topography measurements at high scan-rates with reduced measurement error. An \( H_\infty \)-controller operates the AFM system in a closed loop while a model-based feedforward controller tracks the scanner to the last recorded scan-line. Experimental results compare the actual performance of the standard PI-controlled AFM and the 2DOF controlled system. The new controller reduces the control error considerably and enables imaging at higher speeds and at weaker tip-sample interaction forces.

KeyWords: Nanotechnology, fast scanning, AFM, robust control, scanning probe.

I. INTRODUCTION

The topography of a nano-scale specimen can be imaged using an atomic force microscope (AFM) by tracing the surface with a probing tip supported on a micro-mechanical cantilever [1]. The spatially resolved topography is measured by laterally scanning of the sample under the probing tip. A piezoelectric tube scanner (piezo scanner), capable of moving in all three spatial directions, is used as actuator [2]. The deflection of the cantilever due to the sample topography can be monitored by an optical lever (e.g. [3]) and a segmented photo diode (Fig. 1). For a detailed description of the function of the AFM and its components we refer to [1] and [4].

In the constant force mode, also referred to as “contact mode”, the tip-sample interaction force is held constant in a closed loop-operation (e.g. [1,5]). The cantilever deflection depends on the tip-sample interaction force and is tracked to a predetermined setpoint value by varying the position of the sample along the Z-direction, which is along the axis of symmetry of the piezoelectric tube scanner (see Fig. 1). In commercial realizations a proportional integral (PI) controller is used to operate the closed-loop AFM system consisting of the piezo’s voltage amplifier, the piezo scanner, the cantilever, the photodiode and the feedback element (see Fig. 2). From the control engineering point of view the sample’s topography can be regarded as disturbance affecting the AFM system between the piezoelectric tube scanner and the cantilever (cf. Fig. 2). The feedback controller compensates the disturbance by generating the input voltage to the piezo scanner according to the sample’s topography. The voltage amplifier of the piezoelectric tube scanner in Z-direction represents the input to the AFM system. The signal of the segmented photodiode is regarded as the output to be controlled. The voltage applied to the Z-axis of the piezo scanner is the manipulated variable and corresponds to the sample’s topography. By recording this voltage signal simultaneously with the lateral position of the sample, spatially resolved images of the sample surface can be drawn.

Currently a principal difficulty of the AFM is the relative low imaging speed, which is restricted by the bandwidth-limitation of the PI-controlled AFM set by the main dynamics of the piezoelectric tube scanner. Depending on the settings of the PI controller faster imaging will either result in oscillations of the piezo scanner or an increased cantilever deflection around the set point value. Both situations could cause damage to tip or
sample due to the varying imaging forces. In the former case the topography image additionally will be distorted by the oscillations of the closed-loop AFM system.

First advances to increase the performance of scanning probe microscopes in Z-direction have been made by insertion of fast piezo segments into the piezo scanner [6,7], or probe [8-10] for its Z-movement, or by implementing a modern model-based feedback controller [11].

In this article the design and implementation of a two-degree-of-freedom (2DOF) controller [12] is presented. A mathematical model of the AFM system’s dynamics is required for the design of the new controller and is obtained from a black-box identification [14]. Tests are performed on a NanoScope-IIIa Multi-Mode-AFM (Veeco, USA) with a “J”-class piezoelectric tube scanner. The Z-voltage amplifier of the piezo scanner is regarded as the input of the AFM system (cf. Figure 2). The extension and retraction of the scanner is detected by the topography measurement system of the AFM using a standard mica sample and a cantilever of type “NP-S Silicon Nitrite Probes, 200 wide” (Veeco, USA). The signal of the segmented photodiode represents the output of the AFM system.

II. IDENTIFICATION OF THE AFM DYNAMICS

A mathematical model of the AFM system’s dynamic behavior is obtained via black-box identification [14]. Tests are performed on a NanoScope-IIIa Multi-Mode-AFM (Veeco, USA) with a “J”-class piezoelectric tube scanner. The Z-voltage amplifier of the piezo scanner is regarded as the input of the AFM system (cf. Figure 2). The extension and retraction of the scanner is detected by the topography measurement system of the AFM using a standard mica sample and a cantilever of type “NP-S Silicon Nitrite Probes, 200 wide” (Veeco, USA). The signal of the segmented photodiode represents the output of the AFM system.

2.1 Measurement setup

A band-limited white noise signal is applied to the input of the AFM system to measure the input- and output data used for the system identification. Due to the constant power spectrum of the white noise signal the piezo scanner is excited at all frequencies within the bandwidth of interest. The “white noise block” of Matlab-Simulink running on a digital signal processor (DSP) [15] is used to generate the excitation signal. The DSP simultaneously records the input signal and the response of the AFM system to the applied excitation. The sampling time of the DSP is set to 16.5 µs to obtain the identified model with the same sampling rate used for the implementation of the controller presented in this article. The noise power of the excitation signal is adjusted to get a maximum excitation-amplitude varying between 100 mV and 600 mV.

2.2 Identification

We calculate a linear model of the piezoelectric tube scanner’s dynamics from the measured input and output data using a numerical subspace based state space system identification algorithm [13]. It was shown be-
fore [11], that for small oscillations the dynamic behavior of the cantilever does not have to be taken into account in this process. Thus the dynamics of the AFM system can be reduced to the dynamic behavior of the piezoelectric tube scanner and the gain factors modeling the piezo’s voltage amplifier and the deflection detection system which are included in the identified model.

The model order is set to 5 because an increased model order does not reduce the modeling error substantially but increases the order of the controller as well, which would compromise the sampling rate of the DSP system when implementing the new controller. In refs. [5] and [11] it is shown that the dynamic behavior of the piezo scanner in Z-direction can be modeled as a linear element. The quality of the identified model is tested using validation data not employed for the system identification (cross validation). Figure 3(b) compares the measured output of the AFM system (solid line) and the simulated output of the identified model (dashed line) in response to the applied excitation [Fig. 3(a)] showing a good agreement with only occasional, marginal separations.

The identified system shows low pass characteristics, two stable resonances, a pair of complex LHP zeros and two conjugate complex RHP zeros.

The discrete transfer function of the identified model with a sampling period of $16.5 \mu s$ is given by

$$G(z) = \frac{0.01024z^4 + 0.2688z^3 + 2.762z^2 - 1.253z + 2.494}{z^5 - 2.35z^4 + 2.825z^3 - 1.85z^2 + 0.7008z - 0.1784}$$

(1)

corresponding to the bode-diagram plotted in Fig. 4.

The PI-controller is not able to handle the high order dynamics of such oscillatory systems [11,16]. The control performance can be improved by implementing a more sophisticated controller, which is the focus of the next section.

III. CONTROLLER DESIGN

The two-degree-of-freedom controller is designed in two steps.

In the first part a model-based feedforward controller is presented, which applies the previously recorded scan-line to the Z-direction of the piezo scanner in an open-loop manner to reduce the cantilever deflection representing the measurement error.

The second part proposes the design of the feedback controller to improve the performance of the closed-loop system by utilizing modern model-based control methods [11]. The objectives of the feedback design are fast sequential control, suppression of disturbances, rejection of measurement noise and robustness against model uncertainties. A linear $H_\infty$-controller is calculated, because of the possibility to specify requirements to the closed-loop controlled system.

The main powerfulness of the $H_\infty$-controller is its robustness against model uncertainties, which in AFM-control occur as a variation of the sample mass affecting the resonance frequency of the piezoelectric tube scanner. Increasing the mass of the sample from 0.75 g to 1.23 g reduces the resonance frequency of the piezo scanner in the vertical direction by about 350 Hz. By increasing the sample mass further the shift of the piezo scanner’s resonance is even more pronounced. Since a typical AFM sample is used for the identification experiment the obtained mathematical model [eq. (1)] is chosen as the nominal model for the design of the new controller.

The desired objectives of the open-loop and closed-loop controlled system have to be specified by performance weights by which the identified model $G$ is extended (see Fig. 5). By minimizing the $H_\infty$-norm of the weighted mathematical model the feedforward- and feedback controller are calculated.
3.1 Feedforward

The extended mathematical model $T_{vr}$ for the design of the feedforward controller is shown in Fig. 5(a). The weight $W_{u}$ of the manipulated variable is chosen to damp the resonance of the piezo scanner [Fig. 6(a), dashed line]. To track the guidance signal at low frequencies and to reject modeling errors at frequencies beyond the bandwidth of the open-loop system, the weight $W_{y}$ for the sequential control performance is set to low-pass characteristics [Fig. 6(a), solid line]. The feedforward controller $K_{1}$ is calculated by minimizing the $H_{\infty}$-norm

$$T_{vr}=\left\| W_{y}^{-1} \cdot \begin{bmatrix} W_{u}^{-1} & \cdot \\ \cdot & \cdot \end{bmatrix} \cdot W_{y} \cdot K_{1} \right\|_{\infty}.$$  \hspace{1cm} (2)

The open-loop controller is designed as an $H_{\infty}$-filter resulting in a 6th-order model, which can be balanced [17] and reduced to a 4th-order model without noticeable loss of control performance.

3.2 Feedback

To design the feedback controller $K_{2}$ the mathematical model $G$ of the AFM is extended according to Fig. 5(b). The complementary sensitivity function $T=G \cdot K_{2} \cdot \left(1+G \cdot K_{2}\right)^{-1}$ is weighted by $W_{y}$ [Fig. 6(b), solid line], which is set to high-pass characteristics to suppress measurement noise and achieve robustness against model uncertainties at frequencies beyond the bandwidth of $T$ [Fig. 6(c), solid line]. The manipulated variable $u$ is weighted by $W_{u}$ [Fig. 6(b), dotted line] to damp the fundamental resonance of the piezoelectric tube scanner. The sensitivity function $S=(1+G \cdot K_{2})^{-1}$ [Fig. 6(c), dashed line] is weighted by $W_{e}$ [Fig. 6(b), dashed line], which is set to low-pass characteristics. For fast sequential control the bandwidth of $W_{e}$ is increased as much as possible under the condition, that the simulated step response of the feedback-controlled system settles as fast as possible without oscillations.

By minimizing the $H_{\infty}$-norm $T_{zr}$ of the extended mathematical model shown in Fig. 5(b)

$$T_{zr}=\left\| W_{e} \cdot S \right\|_{\infty}$$  \hspace{1cm} (3)

the feedback controller $K_{2}$ is calculated resulting in a 9th-order model, which without noticeable loss of control performance can be balanced [17] and reduced to a 7th-order model.

3.3 Implementation

The structure of the 2DOF controller combining the feedforward- and feedback controller is shown in Fig. 7. For acquisition of the topographic data the position of the sample is simulated using the identified model of the piezo scanner [11]. Additionally, the output of the simulation is delayed by $\Delta T$, given by the period of the AFM’s scanning signal minus the reaction time of the open-loop path, to generate the trajectory applied to the feedforward controller. The derived mathematical models of the piezo scanner [eq. (1)] and the reduced feedforward- and feedback controller are implemented in their state-space representation on the DSP [15] according to Fig. 7. The block “FB-gain” is used to adapt
changes in the loop-gain of the feedback path, which can occur due to changes in the optical deflection detection system by different alignment of the laser on the cantilever or using another type of cantilever. The block “FF-gain” is used to define the rate of the trajectory applied to the piezoelectric tube scanner by the feedforward controller and can be chosen between zero and hundred percent. For samples with a very unstructured surface a reduction of the feedforward gain might help to avoid imaging artifacts caused by a too intensive open-loop compensation of the topography. For structures that do not change too much from one scan line to the next, the feedforward compensation should be operated at 100 percent for maximum reduction of the control error.

Additionally, a model-based open-loop controller is implemented in X- and Y-direction [18] to avoid lateral oscillations of the piezoelectric tube scanner due to the scanning motion.

IV. EXPERIMENTAL RESULTS

The experiments shown in Figs. 8 and 9 are performed on the AFM system described above. The standard PI-controlled AFM system has to be adjusted by the user [19] and is tuned well for each experiment to compare the performance to our new 2DOF-controlled system. The AFM system is adjusted by the user [19] and is tuned well for each experiment to compare the performance to our new 2DOF-controlled system.

Fig. 7. Configuration of the 2DOF-controlled AFM system and the piezo scanner simulation for data acquisition. The blocks left from the dashed line are implemented on the DSP.

![Fig. 7. Configuration of the 2DOF-controlled AFM system and the piezo scanner simulation for data acquisition. The blocks left from the dashed line are implemented on the DSP.](image)

Fig. 8. 530-nm silicon calibration grid imaged at 10 Hz line-scan by the PI-controlled AFM [(a), (c), (e) and (g)] and the 2DOF-controlled system [(b), (d), (f) and (h)], respectively. Topography [(a) and (b)], topographical cross sections [(c) and (d)] marked in panel (a) and (b), cantilever deflection [(e) and (f)], and error signal cross sections [(g) and (h)] marked in panel (e) and (f). All images are recorded from right to left and measure 15 x 15 \(\mu m^2\).

![Fig. 8. 530-nm silicon calibration grid imaged at 10 Hz line-scan by the PI-controlled AFM [(a), (c), (e) and (g)] and the 2DOF-controlled system [(b), (d), (f) and (h)], respectively. Topography [(a) and (b)], topographical cross sections [(c) and (d)] marked in panel (a) and (b), cantilever deflection [(e) and (f)], and error signal cross sections [(g) and (h)] marked in panel (e) and (f). All images are recorded from right to left and measure 15 x 15 \(\mu m^2\).](image)

show the measured topography and Fig. 8(e and f) the cantilever deflection representing the control error. Images 8(c and d) and 8(g and h) show the cross sections marked in the panels 8(a and b) and 8(e and f), respectively. By comparing panels (e) to (f) and (g) to (h) the reduction of the control error operating the AFM system with our new 2DOF-controller can be seen. Single line scans of a silicon calibration grating (TGZ 01, MikroMasch, Estonia) showing 26-nm deep etched trenches with a pitch of 3 \(\mu m\) are shown in Fig. 9 comparing the control performance of the PI-controlled [panels (a), (c), (e), (g), and (i)] and the 2DOF-controlled AFM [panels (b), (d), (f), (h), and (k)] at selected line scan rates. Panels (a) and (b) show the measured topography imaged at a speed of 10 lines per second using a cantilever of type “NSC12/Si3N4/50 type E” (MikroMasch, Estonia). The control error is shown for a line scan rate of 10 Hz [panel (c) and (d)], 15 Hz [panel (e) and (f)], 20 Hz [panel (g) and (h)], and 30 Hz [panel (i) and (k)]. The control error is smaller at all scan rates in case of the 2DOF-controlled AFM compared to the PI-controlled system and increases with higher imaging speed. Thus, for a given maximum cantilever deflection, denoting a maximum...
Fig. 9. Single line scans of a 26-nm silicon calibration grating imaged by the PI-controlled AFM [(a), (c), (e), (g), and (i)] and the 2DOF-controlled system [(b), (d), (f), (h), and (k)] at selected line scan rates. Topography [(a) and (b)] imaged at 10 lines per second. Control error imaged at 10 Hz [(c) and (d)], 15 Hz [(e) and (f)], 20 Hz [(g) and (h)], and 30 Hz [(i) and (k)]. All line scans are recorded from right to left and measure 6 µm in width.

The measured topography is always a dilation of the sample topography and the probing tip [20,21]. Due to the conical or pyramidal shape of the tip steps that are much higher than the tip radius appear as topographical ramps. The topographical ramp is transformed into a time-domain ramp-signal via the constant imaging speed of the scanning motion. A closed-loop controlled system with just one simple pole in the origin of the Laplace plane (at \( s = 0 \)), such as the PI-controlled AFM, is not able to track a ramp signal exactly but with a constant delay resulting in a constant control error [22]. This causes an offset to the desired setpoint in the deflection signal during the topographical ramp when the AFM is operated by the PI-controller, which can be seen in Fig. 8(e and g). In case of our new 2DOF-controller the topographical ramp signal is applied to the piezoelectric tube scanner in an open-loop manner by means of the feedforward controller to reduce the variations in the imaging force and to minimize the measurement error [Fig. 8(f and h)]. Due to the reduction of the cantilever deflection the system can be operated closer to the minimum imaging force without loss of tip-sample contact. Both effects, reducing the maximum cantilever deflection and operating the AFM closer to the minimum imaging force reduce the maximum value of the tip-sample interaction force preventing damage to tip and/or sample.

V. CONCLUSIONS

In this article the performance of a commercial AFM system was improved considerably by implementing a two-degree-of-freedom controller. For the design of the model-based feedforward and feedback controller a mathematical model of the AFM system was obtained via system identification, which was also used to simulate the position of the sample for data acquisition. The feedforward and feedback controllers were calculated utilizing H\(_\infty\)-methods and subsequently implemented on a DSP. The simulated position of the sample was delayed by one period of the scanning motion to generate the target trajectory for the next scan line, which was applied to the feedforward controller.

Operating the AFM by our new 2DOF-controller reduces the measurement error significantly and enables faster scanning. Additionally, the 2DOF controller is designed for the complete dynamics of the AFM, thus, the user need no control engineering knowledge to tune the closed-loop AFM system further in contrast to the PI-controlled AFM [19]. The noticeable reduction of the cantilever deflection enables measurements at higher imaging speeds and weaker imaging forces preventing damage to tip and sample.

REFERENCES

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