

NANO EXPRESS

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Scan speed control for tapping mode SPM

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Abstract

In order to increase the imaging speed of a scanning probe microscope in tapping mode, we propose to use a dynamic controller on 'parachuting' regions. Furthermore, we propose to use variable scan speed on 'upward step' regions, with the speed determined by the error signal of the closed-loop control. We offer line traces obtained on a calibration grating with 25-nm step height, using both standard scanning and our scanning method, as experimental evidence.

Keywords: tapping-mode SPM, scan speed, closed-loop control

Background

Tapping mode is considered to be the most precise mode of the scanning probe microscope [SPM] [1-4]. The main disadvantage of this SPM mode is low performance; it takes a long time to obtain the topographic image of the sample surface. The main limiting parameter of increasing imaging speed in tapping mode is the time constant [τ_c] of the cantilever. In contact mode, this limitation is absent. This fact allows the imaging speed to be higher when using, for instance, a high-speed piezoelectric stack actuator [5,6]. However, it's desirable to use tapping mode in many instances since it reduces the lateral forces exerted by the tip on the sample, thereby reducing tip-sample wear [1,4].

The following methods are known to reduce scanning time:

- 1) The cantilever resonant frequency [ω_0] is increased by reducing cantilever size (and mass) and increasing its stiffness. However, this can be done only by completely changing the probe construction [1].
- 2) The cantilever quality factor [Q] is reduced by means of cantilever external excitation. In this instance, the total signal consists not only of the excitation signal but also of an extra component proportional to the speed of the cantilever deflection. Reducing the cantilever Q factor, however, will result in a reduction in the image resolution [3].

3) A dynamic controller (a switching gain proportional-integral [PI] controller) is used on the base of the error signal which increases in a 'parachuting' region [2,4].

The scan speed is assumed constant in each of the above instances. A variable-speed scanning method [7] allows the determination of the scan speed value according to a particular transient response of the PI controller output signal.

In the present paper, we used both the dynamic controller method and variable-speed scanning to obtain the topographic image of the sample surface. In contrast to Zhang et al. [7], the scanning speed was determined by the behavior of the error signal controls (which was the input signal for the PI controller). The PI controller output bandwidth can be determined from the time constant of the loop control. The error signal bandwidth can be determined from the time constant of an AM (or FM) detector of the probe deflection signal. This time constant is an order of magnitude smaller than the time constant of the loop control [1-4]. This allows faster adaptation of the scan speed to a particular sample surface topography.

Methods

The cantilever oscillation amplitude $A(t)$, while scanning a step of height Δz , is expressed as [1]

$$A(t) = A_{sp} + \Delta z \cdot (1 - \exp(-\omega_0 t / 2Q)), \quad (1)$$

where ω_0 is the cantilever resonant frequency, Q is the cantilever quality factor, and A_{sp} is the set point amplitude. Thus, the cantilever transfer function $C(s)$ takes

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the form $C(s) = \frac{1}{(1 + s\tau_c)}$, where τ_c is the time constant of the cantilever and is equal to $\tau_c = \frac{2Q}{\omega_0}$. The frequency response of the actuator $G(s)$ and the cantilever deflection signal detector $K(s)$ has a constant gain equal to DC gain and don't add extra phase lag (it can be assumed that $G(s) \cdot K(s) = G_0 \cdot K_0 \approx 1$) in the bandwidth of interest. Indeed, the pole frequency of the detector transfer function $[\omega_{\text{det}}]$ should be at least ten times less than the cantilever resonant frequency $\omega_{\text{det}} = \omega_0/10$. The pole frequency of the transfer function $C(s)$ is equal to $\tau_c^{-1} = \omega_0/2Q \ll \omega_{\text{det}}$ (if $Q \sim 100$).

Suppose the feedback controller is an integral controller with time constant τ_i whose transfer function $R(s)$ is $R(s) = -\frac{1}{s\tau_i}$. Then, the frequency-dependent open-loop gain becomes $\left(-\frac{1}{s\tau_i} \cdot G_0 \cdot K_0 \cdot \frac{1}{(1 + s\tau_c)}\right)$. Thus, the characteristic polynomial of the loop control's frequency response $D(s)$ can be written as

$$D(s) = s^2 + \frac{1}{\tau_c}s + \frac{G_0K_0}{\tau_c\tau_i} \approx \left(s + \frac{1}{\tau_c}\right) \left(s + \frac{G_0K_0}{\tau_i}\right). \quad (2)$$

For stability of the loop control, we need to have significantly different frequencies for the real poles of the transfer function:

$$\frac{G_0K_0}{\tau_i} \ll \frac{1}{\tau_c}. \quad (3)$$

In the case of such characteristic polynomials, the transient response is described by two exponential function, the fast function having time constant τ_c and the slow function, $\frac{\tau_i}{G_0K_0}$. As a result, the speed of a closed-loop control system (that is, without loss of surface) is determined by the time constant $\frac{\tau_i}{G_0K_0}$. Feedback speed, the speed of the actuator, is limited in tapping mode by the stability condition of the loop control (Equation 3). Thus, the feedback speed is limited by the cantilever time constant τ_c .

Increasing scan speed leads to a loss of surface when a 'downward step' is scanned or a parachuting effect. If an 'upward step' is scanned, it leads to instability of the loop control [1,2].

Let us find the maximum scan speed without loss of surface. The transient response of the loop control to a capacitive displacement sensor output (if the high-frequency pole (frequency τ_c^{-1} , Equation 2) is ignored) can be written as

$$\frac{\Delta Y(s)}{\Delta Z(s)} = \frac{1}{(1 + s\tau_i/G_0K_0)}. \quad (4)$$

Then, the transient response of the loop control for a downward step of height Δz takes the form

$$\Delta y(t) = \Delta z \cdot \left(1 - e^{-G_0K_0 t/\tau_i}\right). \quad (5)$$

In the latter case the initial vertical actuator speed is

$$v_v = \frac{\Delta y(0)}{\Delta t} = \frac{\Delta z \cdot G_0K_0}{\tau_i}. \quad (6)$$

Assuming that there is no loss of surface by the probe, the horizontal scan speed v_H is related to the vertical actuator speed v_v by

$$v_H = v_v \cdot \text{tg}(a/2) = \frac{\Delta z \cdot G_0K_0 \cdot \text{tg}(a/2)}{\tau_i}, \quad (7)$$

where a is the apex angle of the diamond tip.

From Equation 3, it follows $\frac{\tau_i}{G_0K_0} \approx 10\tau_c = \frac{20 \cdot Q}{\omega_0}$ yielding

$$v_H = \frac{\Delta z \cdot \omega_0 \cdot \text{tg}(a/2)}{20 \cdot Q} \quad (8)$$

An increase in the actuator speed is caused by an increase in the error signal $e(t) = A(t) - A_{\text{sp}}$. For a step of height $\Delta z < A_{\text{fr}} - A_{\text{sp}}$, where A_{fr} is the free-air amplitude (the amplitude of the cantilever oscillation without touching the surface), the error signal is $e(0) = \Delta z$. That's why the velocity v_H depends on the step height Δz . For $\Delta z = (A_{\text{fr}} - A_{\text{sp}})$, the scan speed becomes

$$(v_H)_{\text{lim}} = \frac{(A_{\text{fr}} - A_{\text{sp}}) \cdot \omega_0 \cdot \text{tg}(a/2)}{20 \cdot Q}. \quad (9)$$

For higher steps, the initial probe speed doesn't increase as the error signal is saturated at $e_{\text{max}} = A_{\text{fr}} - A_{\text{sp}}$. For scan speed $v_H > (v_H)_{\text{lim}}$, the tip doesn't touch the surface and loses sample surface.

For example, let us find the scan speed limit for the SPM NanoScan-3D [8] where the probe is a piezoceramic cantilever with a diamond tip. This device allows you to scan the surface topography and to produce indentation and sclerometry simultaneously. If the set point amplitude is $A_{\text{sp}} = 0.8 \cdot A_{\text{fr}}$ (where the cantilever free-air amplitude is $A_{\text{fr}} = 100$ nm), the cantilever resonance frequency is $f_0 = 11.5$ kHz, the quality factor is 100, and the apex angle of a diamond tip is 120° [8], then the scan speed limit is approximately $(v_H)_{\text{lim}} \approx 12.5$ $\mu\text{m/s}$.

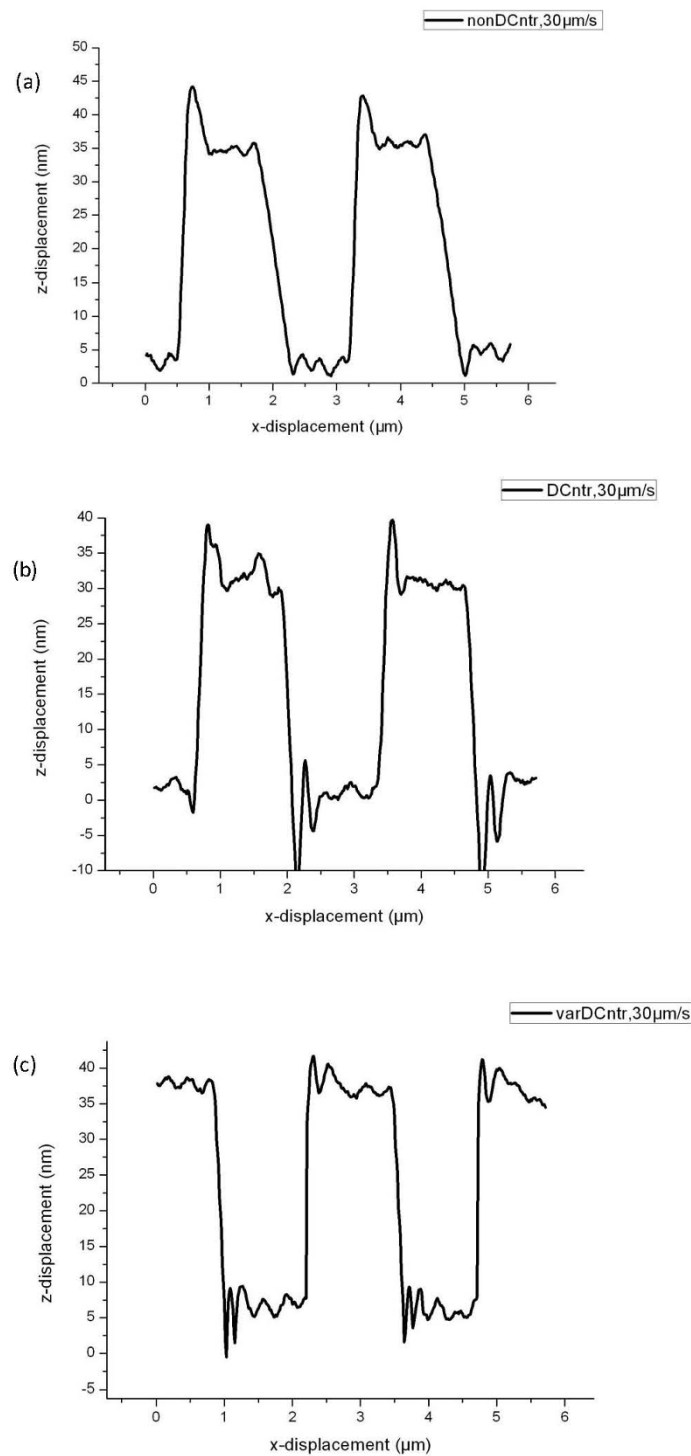
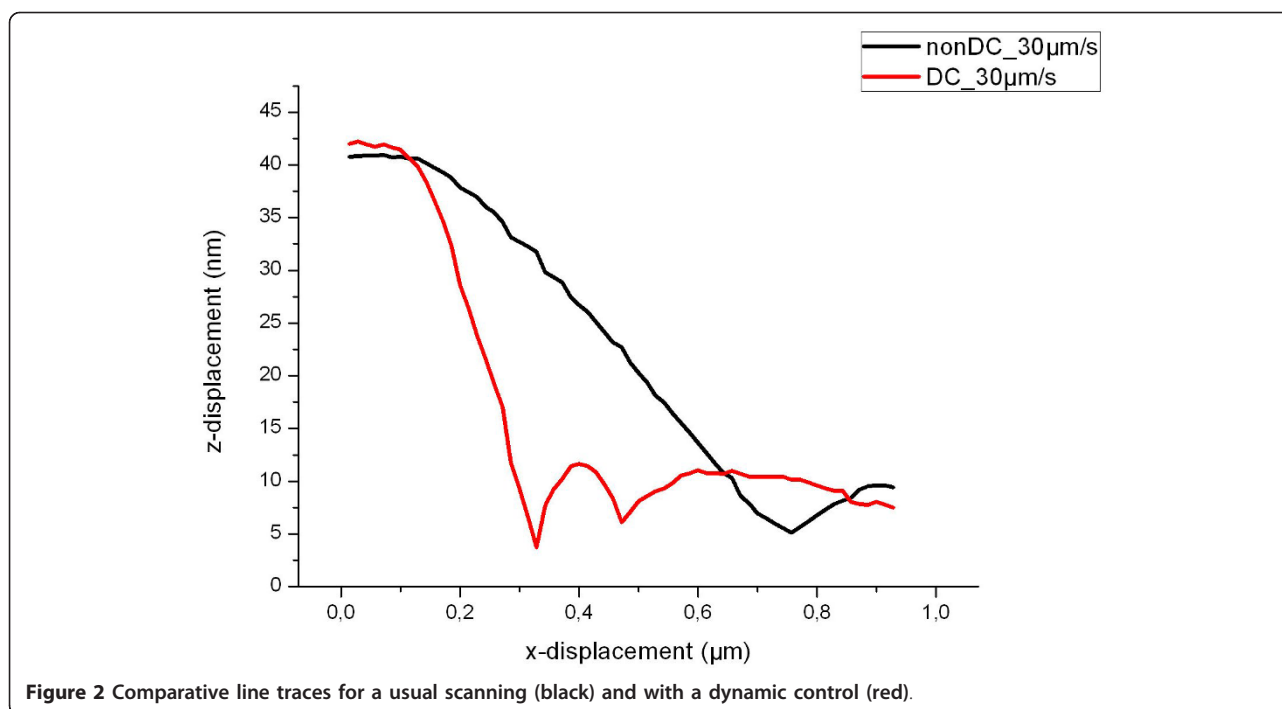


Figure 1 The line traces of the calibration grating with the step height equal to 25 nm. At a constant speed of 30 $\mu\text{m/s}$ (a), with a dynamic control (b), and with a dynamic control and at a variable speed (c).

The loop control is a high-pass filter for the error signal which is related to the height step Δz by
$$e(t) = \Delta z \cdot K_0 \cdot e^{-\frac{tG_0K_0}{\tau_i}}$$
. In the case of parachuting, the

loop control is opened by the loss of sample surface by the probe. The error signal is saturated at $e_{\max} = (A_{\text{fr}} - A_{\text{sp}}) \approx 0.2 A_{\text{fr}}$. To avoid, or at least reduce, the parachuting region, the dynamic controller should increase the



error signal e_{\max} [2] or reduce the integral controller time constant τ_i .

According to the algorithm implemented on FPGA, if the error signal is more than a threshold e_{th} , the integrator time constant is reduced according to

$$\tau_i(t) = \tau_i - g \cdot (e(t) - e_{th}), \quad (10)$$

where g is the 'gain' of the dynamic controller.

As the tip scans over an upward step, the probe oscillation amplitude is reduced. It can be reduced to zero for the height step $\Delta z > A_{sp}$ and scan speed $v_H > (v_H)_{lim}$ (Equation 9). A higher scanning speed can damage both the sample and the tip. A decrease of the time constant τ_i can cause instability of the closed-loop. According to the found algorithm, the scanning speed is reduced for the threshold of the amplitude $A_{low} < A_{sp}$. Scanning at the lower speed is continued as long as the error signal is reduced and the oscillation amplitude is restored.

Results and discussion

A calibration grating with a step height of 25 nm was used as the sample. A line trace with constant scan speed of 30 $\mu\text{m/s}$ is shown in Figure 1a. A typical scan has a parachuting over a downward step and a peak over an upward step.

The time constant of the implemented dynamic controller is four times decreased in the parachuting region. Figure 1b shows a scan line trace using the algorithm of the dynamic controller. There is practically no parachuting, as shown in the figure. However, the peak over the

upward step stayed. In addition, there formed another peak due to a significant increase in the error signal of the loop control after the probe reached the bottom after a downward step. It was decided to reduce the scanning speed in this region.

Figure 1c shows the line over a downward step trace in the case of a dynamic control and over an upward step for a variable scanning velocity. For a detailed comparison, Figure 2 shows a part of the line traces (parachuting region) in the case of the usual scanning with a constant speed of 30 $\mu\text{m/s}$ and in the case of using dynamic control with variable scanning velocity. For dynamic control, the length of parachuting is reduced by three times.

Conclusions

The novelty of the presented scanning method consists of using a dynamic controller on a downward step and variable scan speed on an upward step, with scan speed determined by the magnitude of the error signal. As the experimental data on a calibration grating show, assuming equivalent image quality, our method has an advantage of up to three times in imaging speed.

Acknowledgements

The authors would like to thank the Federal target programme Research and Pedagogical Cadre for Innovative Russia for 2009-2013 (grant no 14.740.11.1449) for providing financial support to this project.

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Authors' contributions

AVM and WM contributed equally to this work. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Received: 30 September 2011 Accepted: 14 February 2012

Published: 14 February 2012

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doi:10.1186/1556-276X-7-121

Cite this article as: Meshtcheryakov and Meshtcheryakov: Scan speed control for tapping mode SPM. *Nanoscale Research Letters* 2012 **7**:121.

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