High-speed cycloid-scan atomic force microscopy

2010 Nanotechnology 21 365503

(http://iopscience.iop.org/0957-4484/21/36/365503)

Nanotechnology 21 (2010) 365503 (4pp) doi:10.1088/0957-4484/21/36/365503

High-speed cycloid-scan atomic force microscopy

Y K Yong[1], S O R Moheimani[1] and I R Petersen[2]

[1] School of Electrical Engineering and Computer Science, The University of Newcastle, Callaghan 2308, NSW, Australia
[2] School of Engineering and Information Technology, University of New South Wales at ADFA, Canberra, ACT 2600, Australia

E-mail: yuenkuan.yong@newcastle.edu.au, reza.moheimani@newcastle.edu.au and i.r.petersen@gmail.com

Received 5 May 2010, in final form 22 July 2010
Published 13 August 2010
Online at stacks.iop.org/Nano/21/365503

Abstract
A key hurdle in achieving high scan speeds in atomic force microscopes is that the probe is required to be scanned over the sample in a zig-zag raster pattern. The fast axis of the AFM scanner must track a signal that contains frequencies beyond its mechanical bandwidth. Consequently, fast raster scans generate distortions in the resulting image. We propose a smooth cycloid-like scan pattern that allows us to achieve scan speeds much higher than a raster scan. We illustrate how the proposed method can be implemented on a commercial AFM with minimal modifications.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In atomic force microscopy, a micro-cantilever with a very sharp tip is scanned over a sample at distances of the order of a few nanometers, or less in a zig-zag raster pattern. The most widely used scanning device is a piezoelectric tube scanner [1] introduced by Binnig and Smith [2]. However, flexure-based positioning stages have emerged as a viable alternative in recent years [3–5]. In either case, to achieve a raster pattern, one axis of the scanner is required to track a fast triangular signal while the other lateral axis is made to track either a ramp or a staircase setpoint. Limited mechanical bandwidth of the scanner together with its highly resonant nature is a key hurdle in achieving high scan speeds in raster scan AFM. A number of methods have been proposed to deal with this issue that range from using innovative mechanical designs to achieve high-bandwidth nanopositioners [4, 3] to using feedforward [6] or feedback control methods [7, 8]. For an exhaustive survey the reader is referred to [9].

There has been significant interest in developing video-rate atomic force microscopes in recent years [10]. Development of such systems requires scan speeds well beyond the reach of currently available commercial AFMs. The two successfully demonstrated video-rate AFMs [4, 11] are equipped with nanopositioning mechanisms that are different to those in commercial AFMs. The video-rate AFM reported in [4] uses a serial kinematics positioner, while [11] uses a tuning fork. In either case the requisite high scan speeds are obtained at the expense of scan range. Thus, there is significant interest in methods that can achieve high scan speeds over a large scan area and can be implemented on available AFM scanners. One such method was recently proposed in [12], where the scanner was made to follow a spiral pattern. Due to the smoothness of the trajectory, the scanner can track a spiral with significant precision, allowing for high-speed scans of a sample with much better quality compared with a raster-scanned image of similar speed.

In this paper we propose a cycloid-like scan pattern for high-speed AFM. An AFM scanner can be made to follow this pattern by forcing a lateral axis to track a sine signal and the second axis to track a cosine signal, with the same frequency, plus a slow ramp. Almost all existing AFM scanners are quite suitable to operate in this regime. In particular, we illustrate how the method can be implemented on an existing raster scan AFM with minimal modifications. The significance of this method is that it does not require specialized apparatus to develop high-quality images at very high scan speeds and it works quite satisfactorily without the need to dampen vibratory modes of the scanner, which is a necessity in high-speed raster scan AFMs [13]. The latter method is known to introduce sensor noise into the feedback loop, which is known to have an adverse effect on the positioning accuracy of the device [14].

The remainder of this paper is organized as follows. Section 2 describes how a cycloid-scan pattern can be realized in an AFM scanner and discusses how the measurements may be mapped to an image in Cartesian coordinates. Section 3 describes the implementation of the method on a commercial AFM and presents cycloid-scanned images. The cycloid-scanned images are compared with the raster-scanned images of the same sample, obtained at identical scan speeds. Section 4 concludes the paper.

2. Cycloid-scan

2.1. The cycloid-scan method

The proposed scan trajectory is plotted in figure 1 and is characterized by the following equations:

$$x(t) = \alpha t + r \sin \omega t, \qquad y(t) = r \cos \omega t \tag{1}$$

where $\omega = 2\pi f$ and f is the scan frequency, r is the amplitude of the input waveforms and α is the ramp rate of the x input signal.

Strictly speaking, the proposed scan pattern is not a cycloid. However, it has striking similarities to a prolate cycloid, in which the point tracing out the curve is outside the circle at a significant distance from its center. Thus, we have taken the liberty of naming this method, as stated in the title, above. An important property of this scan pattern is that it has a fixed pitch, P, that is related to the parameter

$$\alpha = \frac{P}{T} = \frac{P\omega}{2\pi} \tag{2}$$

where $\omega = 2\pi/T$ and T is the period of the sinusoidal signal. This is one of the appealing properties of this scan pattern. It implies that, under uniform sampling along the cycloid trajectory, horizontal distances between samples taken remain fixed. Thus, the resulting image will comprise of $P \times P$ sized pixels. We choose to set the pitch of the cycloid according to

$$P = \frac{4r}{2n - 1} \tag{3}$$

where n is the number of lines of the scan image along the minor axis (Y axis in this case). The number of lines along the X axis is $2n$.

AFM images are plotted by mapping sampling points recorded along the cycloid trajectory into appropriate raster points. The pitch of the raster image is chosen to be the same as the pitch P of the cycloid image. Figure 1 plots the relative positions of the cycloid points with respect to the raster points. Each raster point is mapped to the closest cycloid point using the Delaunay triangulation technique [15]. The error associated with the mapping of cycloid points to raster points can be evaluated using the technique documented in [16]. The length of the vector from a cycloid point A to a raster point B is calculated as

$$|BA_{ij}| = \sqrt{(A_x - B_x)^2 + (A_y - B_y)^2}. \tag{4}$$

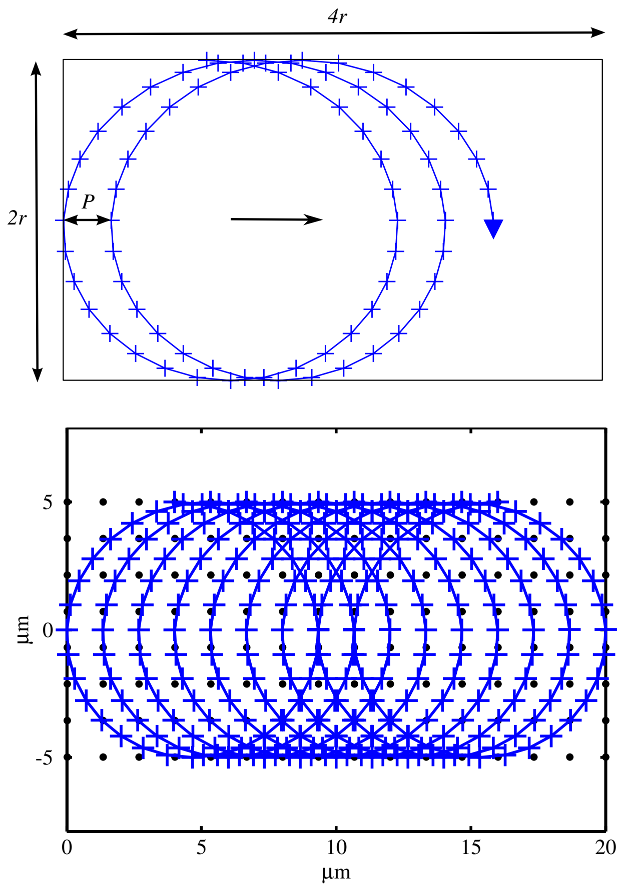

Figure 1. Top: the cycloid trajectory and its fixed pitch, P. Bottom: cycloid points ($\times$) are plotted on top of the raster points ($\cdot$). The scan frequency f is 1 Hz. The 10×20 μm area is scanned at a resolution of 8×16 pixels. The minimal sampling frequency F_s required for an accurate mapping is $4nf$. F_s is set to 32 Hz in this illustration.

where i and j are the index of a raster point. To ensure that each raster point is mapped with good accuracy, the value of $|BA|$ should be less than $P/2$. Also, each raster point has to be populated during mapping. This is achieved if

$$F_s \geqslant 4nf. \tag{5}$$

where F_s is the sampling frequency.

3. The experimental results

The cycloid-scan method was implemented on a commercial AFM (NT-MDT NTEGRA). The x and y signals of the cycloid trajectory were generated using a dSPACE-1103 rapid prototyping system. This system has a maximum sampling rate of 80 kHz. The generated signals were amplified by a NANONIS bipolar high voltage amplifier HVA4 with a gain of 15. The amplifier output signals were used to drive the X and Y axes of the piezoelectric tube scanner. The Z axis of the scanner was controlled using the AFM's software and circuitry during the 'landing' process of the cantilever. After the 'landing', the microscope was configured to function in constant height contact mode, where the vertical feedback controller was disabled. This was to avoid image artifacts

Table 1. RMS mapping error e_{rms} of $|BA|$.

f (Hz)	F_s (Hz)	e_{rms} (nm)	P (nm)	$e_{rms}/P \times 100\%$
1.95	2 000	1.8	39.1	4.6
39.06	20 000	2.1	39.1	5.4
78.13	40 000	2.0	39.1	5.1
156.25	80 000	4.1	78.4	5.2

that otherwise would have arisen due to the limited closed-loop bandwidth of the vertical feedback loop during high scan speeds, if the AFM were operated in constant force mode. The deflection of the cantilever was recorded in dSPACE for constructing the images.

To evaluate the effectiveness of our proposed scan method, we used a MikroMasch TFQ1 calibration grating with 3 μm period, 1.5 μm square side and 20nm height. A BudgetSensors (ContAl) contact mode cantilever probe with a resonance frequency of 13 kHz and a spring constant of 0.2 N m^{-1} was used to perform the scans. The resonance frequency of the piezoelectric tube scanner used in the experiments was approximately 580 Hz in both X and Y axes. The scanner was operated in open loop. Images of a 10 × 20 μm area of the grating were recorded at 1.95 Hz (256 × 512 lines), 39.1 Hz (256 × 512 lines), 78.1 Hz (256 × 512 lines) and 156.25 Hz (128 × 256 lines). The sampling speed of the data acquisition system used in our experiments was limited to 80 kHz. Thus, to satisfy the mapping criterion discussed above, the resolution of the image at 156.25 Hz had to be reduced to 128 × 256 pixels. As shown in table 1, the RMS values of the mapping error at all four frequencies are approximately 5% of the pitch size P, indicating that each image was mapped with good accuracy.

Figure 2 shows the scan images of the grating together with their cross-section profiles. For raster scans, scan-induced oscillations were observed at 39.1, 78.1 and 156.25 Hz. These effects can be observed in figure 3, which compares the ability of the AFM scanner in tracking raster and cycloid-scan signals. The lack of satisfactory tracking at high speeds is one source of distortion in raster-scanned images. Another cause is due to the fact that the cantilever was detached from the grating at high speeds due to severe oscillations. The detachment of the cantilever from the grating causes it to vibrate at its resonance frequency. This can be observed in the Z-direction profile plots as well as the images. For cycloid scans, images recorded at 39.1 and 78.1 Hz have similar quality as that obtained at 1.95 Hz. Scan-induced oscillations were not noticeable in these images, indicating that the cycloid-scan input signals did not excite the vibratory dynamics of the tube scanner. The image quality at 156.25 Hz was slightly lower than that of the other three cycloid-scanned images. This is expected as the quality of a scan will deteriorate with the increase of scan speed due to the oscillations of the cantilever [16]. Nevertheless, the image quality is much superior to the raster-scanned images.

To this end we point out that other scan methods have been proposed which result in better quality high-speed scans compared with raster-scanned images. One such non-raster scan method is the spiral-scan scanning probe microscopy proposed by Mahmood and Moheimani in [12] and [16]. The key idea is to force the scanner to follow a smooth

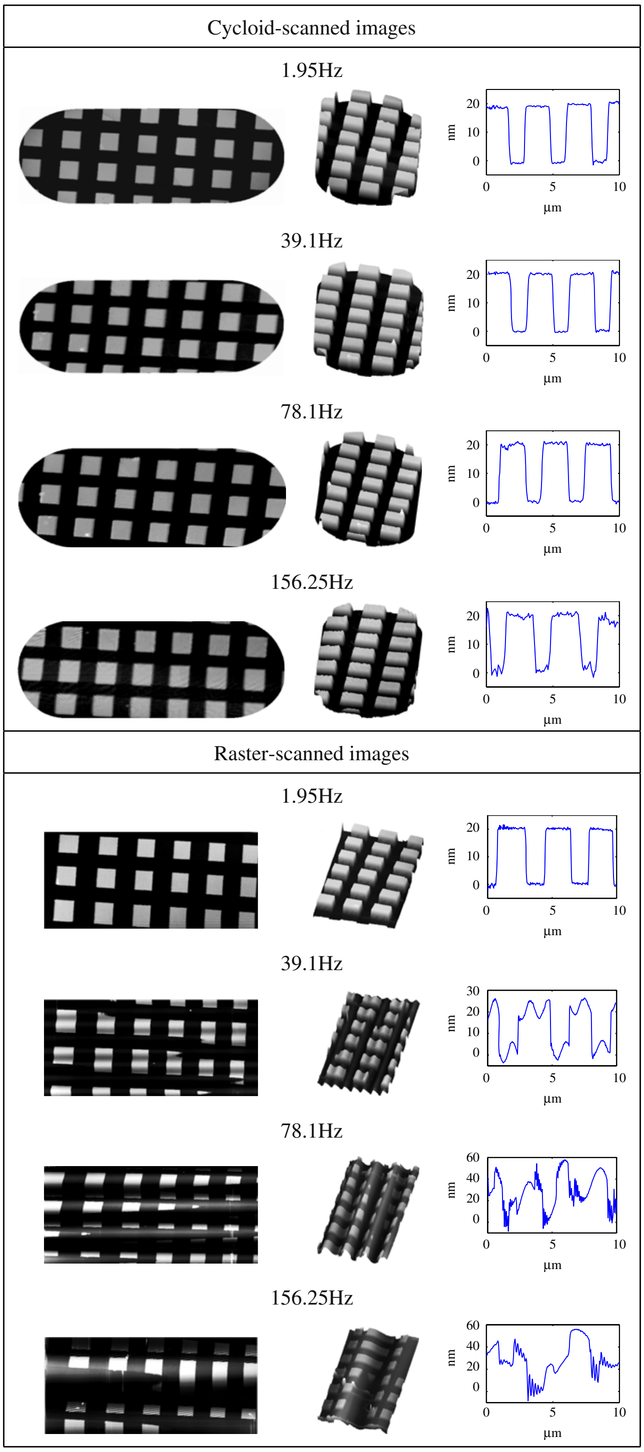

Figure 2. Scan images in 2D and 3D together with their Z-direction profiles of the sample.

spiral trajectory, which in a parallel-kinematics scanner can be obtained by tracking sinusoidal signals of 90° phase difference and slowly varying amplitudes. Spiral scanning can be performed in two modes: (i) constant angular velocity and (ii) constant linear velocity. The former is the faster of the two methods. However, given that the velocity with which the spiral is being traced varies as a function of distance from its center, regular sampling is not possible. A constant linear

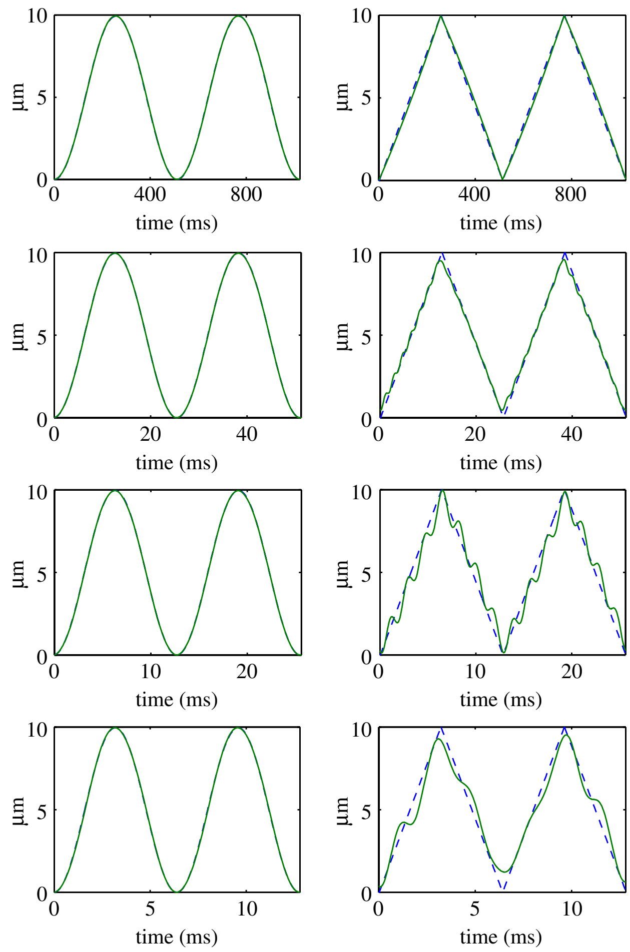

Figure 3. The X-axis displacement of the cycloid (left column) and raster (right column) scan patterns. From top to bottom, the scan frequencies are 1.95 Hz, 39.1 Hz, 78.1 Hz and 156.25 Hz, respectively. The reference trajectory is plotted in (- - - -) and the measured displacement is plotted in (——).

velocity spiral, however, allows for regular sampling and thus is preferred due to ease of implementation. However, it is slower and results in a small circular artifact at the center of the image, which is due to the finite mechanical bandwidth of the scanner. Another approach that has been investigated in the literature is the sinusoidal scan method [17], where one of the axes of the scanner is forced to track a sinusoidal signal, while the other axis undergoes a staircase motion. Thus, the scanner's path of motion in the x–y plane is a non-smooth trajectory. Furthermore, due to the sinusoidal nature of the motion the scanner's velocity varies as a function of position. Thus, regular sampling is not feasible. Compared with the above methods, the cycloid-scan approach has the advantage of being as fast as a constant angular velocity spiral scan, and allowing for regular sampling along the scan trajectory.

4. Conclusion

A non-raster scan method was proposed for high-speed atomic force microscopy, and was implemented on a commercial AFM. Images were successfully recorded up to 156.25 Hz scan speed on a scanner with a resonance frequency of 580 Hz. This was achieved without the use of feedback or feedforward controllers. The cycloid-scan signals did not excite the resonance of the piezoelectric tube scanner. The images are of much better quality than the raster-scanned images obtained at identical scan speeds.

References

[1] Moheimani S O R 2008 Invited review article: accurate and fast nanopositioning with piezoelectric tube scanners: emerging trends and future challenges *Rev. Sci. Instrum.* **79** 071101

[2] Binnig G and Smith D P E 1986 Single-tube three-dimensional scanner for scanning tunneling microscopy *Rev. Sci. Instrum.* **57** 1688–9

[3] Yong Y K, Aphale S and Moheimani S O R 2009 Design, identification and control of a flexure-based XY stage for fast nanoscale positioning *IEEE Trans. Nanotechnology* **8** 46–54

[4] Ando T, Uchihashi T, Kodera N, Yamamoto D, Miyagi A, Taniguchi M and Yamashita H 2008 High-speed AFM and nano-visualization of biomolecular processes *Pflügers Archiv. Eur. J. Physiol.* **456** 211–25

[5] Lee C and Salapaka S M 2009 Robust broadband nanopositioning: fundamental trade-offs, analysis, and design in a two-degree-of-freedom control framework *Nanotechnology* **20** 035501

[6] Clayton G M, Tien S, Leang K K, Zou Q and Devasia S 2009 A review of feedforward control approaches in nanopositioning for high-speed SPM *J. Dynamic Syst. Meas. Control* **131** 061101

[7] Shegaonkar A C and Salapaka S M 2007 Making high resolution positioning independent of scan rates: a feedback approach *Appl. Phys. Lett.* **91** 203513

[8] Salapaka S, De T and Sebastian A 2005 Sample-profile estimate for fast atomic force microscopy *Appl. Phys. Lett.* **87** 053112

[9] Devasia S, Eleftheriou E and Moheimani S O R 2007 A survey of control issues in nanopositioning *IEEE Trans. Control Syst. Technol.* **15** 802–23

[10] Rost M J, van Baarle G J C, Katan A J, van Spengen W M, Schakel P, van Loo W A, Oosterkamp T H and Frenken J W M 2009 Video-rate scanning probe control challenges: setting the stage for a microscopy revolution *Asian J. Control* **11** 110–29

[11] Humphris A D L, Miles M J and Hobbs J K 2005 A mechanical microscope: high-speed atomic force microscopy *Appl. Phys. Lett.* **86** 034106

[12] Mahmood I A and Moheimani S O R 2009 Fast spiral-scan atomic force microscopy *Nanotechnology* **20** 365503

[13] Bhikkaji B, Ratnam M, Fleming A J and Moheimani S O R 2007 High-performance control of piezoelectric tube scanners *IEEE Trans. Control Syst. Technol.* **15** 853–66

[14] Sebastian A, Pantazi A, Moheimani S O R, Pozidis H and Eleftheriou E 2008 Achieving sub-nanometer precision in a MEMS storage device during self-servo write process *IEEE Trans. Nanotechnol.* **7** 586–95

[15] de Berg M, Cheong O, van Kreveld M and Overmars M 2008 *Computational Geometry: Algorithms and Applications* (Berlin: Springer)

[16] Mahmood I A, Moheimani S O R and Bhikkaji B 2010 A new scanning method for fast atomic force microscopy *IEEE Trans. Nanotechnol.* at press doi:10.1109/TNANO.2009.2036844

[17] Humphris A D L, Hobbs J K and Miles M J 2003 Ultrahigh-speed scanning near-field optical microscopy capable of over 100 frames per second *Appl. Phys. Lett.* **83** 6–8