euspen's 17th International Conference &
Exhibition, Hannover, DE, May 2017
www.euspen.eu

Bringing metrology to high-speed atomic force microscopy (HS-AFM)

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Abstract

National metrology institutes (NMIs) have directed considerable effort to bringing traceability to AFM, however metrological AFMs tend to be slow and remain the preserve of NMIs. In parallel there has been growth in the area of high-speed AFM which offers the possibility of video rate scanning over micrometre ranges. However, until recently, these instruments have been lacking fully traceable metrology. The University of Bristol has developed the world's fastest contact mode high-speed AFM with line scan rates of several kilohertz corresponding to speeds of more than 10 millimetres per second and a data density of 0.5 x 10^6 pixels per image. NPL and Bristol have collaborated to bring metrology to their high-speed AFM and turn it into a traceable instrument. The scanning stages have been error mapped using both grating and optical interferometric techniques. Using high speed interferometry, errors in scanning stages have been mapped in real time and corrections applied to remove the effects of crosstalk and non ideal motion. The application of metrology increases the accuracy of the high-speed AFM measurements, enabling the generation of very large composite images.

Metrology, high speed atomic force microscopy, traceability, nanometrology, nanotechnology

1. Introduction

The last few years have seen rapid growth in high-speed AFM systems based on a number of different approaches [1]. A common feature of many of these systems is the lack of metrology and measurement traceability. Initial work with UoB, NPL, and CMI [2] showed that lateral positioning errors (typically ~ 3 % of the scanning range) could be identified using a calibration grating and post processing of data. Within the scope of a recently completed EMRP project [3], NPL and UOB have directly measured stage positioning errors using optical interferometry in a metrological high speed AFM system.

2. HS-AFM

Line scan rates of several kilohertz are achieved using small, low mass flexure stages for lateral motion of the sample. The stages are driven using piezo actuators with high bandwidth voltage amplifiers operating in open loop and are therefore susceptible to piezo actuators' hysteresis and non-linearity. The main emphasis on stage design is for speed over a range of several micrometres. A full description of the HS-AFM is given the paper by Payton et al [4]. Figure 1 shows an example of the differences between trace and re-trace images when they are superimposed. Note the apparent ghosting of the images. In order to be able to correct the image distortion, it is necessary to know the actual position of the stage in x and y rather than relying on the signals provided to the piezo actuators. Although, to some extent, this is achievable by post processing the data and synchronizing the trace and retrace signals, there is still a fundamental lack of traceability. To map the stage and correct for scanning errors, a metrological platform for the assessment of HS-AFM scanning stages has been constructed.

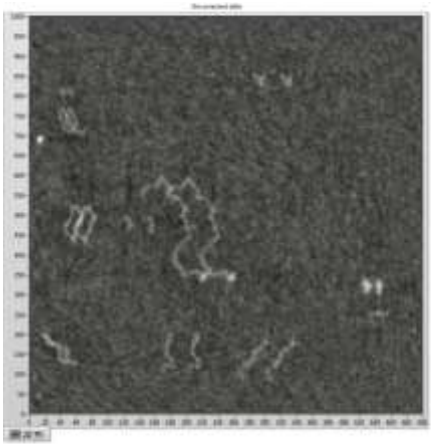

Figure 1. An image of DNA molecules obtained with HS-AFM. Image size 4 µm x 4 µm, trace and retrace images superimposed

Figure 2 shows the platform comprising the high-speed scanning stage mounted on a slip stick stage system for coarse positioning in x, y and z, two Plane Mirror Differential Optical Interferometers [5] used for measurement of the stage position and a laser Doppler vibrometer used for detection of cantilever displacement [6]. The vibrometer and interferometer measurements are traceable via the laser wavelength. A close-up of the high-speed stage is shown in figure 3. Although the parallel flexures are there to limit crosstalk, and the flexure design limits out of plane motions there will nevertheless be errors associated with the stage motion; the stage design represents a compromise between speed and stage errors.

The scan range of the stage is up to 5 µm x 5 µm. Two small mirrors were attached to the sides of the central square platform of the stage and holes were machined into the sides of the frame opposite the mirrors to facilitate access by the interferometer beams. The interferometers collected data at 2 MHz simultaneously with the vibrometer signal. Scanning rates were 1 kHz for the fast axis and 1 Hz for the slow axis giving a maximum spatial resolution for the interferometers of 4 nm. Data was post processed to obtain the actual (x, y) coordinates for each measurement of cantilever displacement. Interferometer nonlinearity was removed using a Heydemann correction. A series of measurements was performed to determine stage errors and consistency of the stage error. In normal operation the stage is repeatedly scanned and then translated using the coarse stage so that larger areas can be scanned.

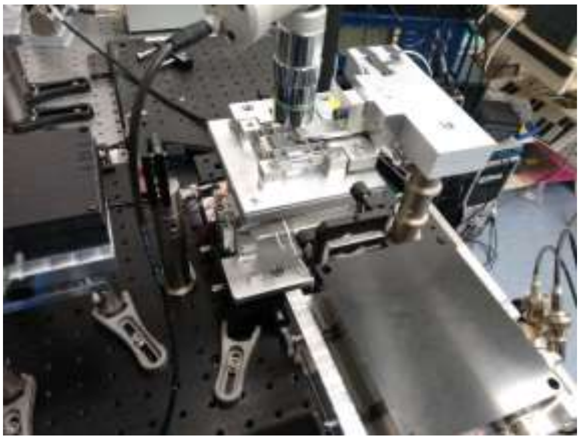

Figure 2. Metrological platform showing interferometers for measurement of stage position. AFM cantilever motion detected using a vibrometer.

Figure 3 The HS-AFM stage. Stage size 70 mm x 70 mm, mirrors for optical interferometers not shown.

3. Results

A series of (4 x 4) µm images were taken of a titanium grid structure on a silicon substrate. Figure 5 (a) and (b) shows two images of the structure where the effects of the hysteresis and stage errors can clearly be seen; (a) the lateral positions are calculated based on the drive signal to the piezo actuators and (b) lateral positions based on interferometer signals. The interferometer measurements showed, in addition that there could be as much as 30 nm cross talk between the x and y axes. In order to scan larger areas, the slip stick stage on which the high-speed stage was mounted was scanned through a range of approximately (50 x 50) µm with a 2 µm overlap to allow for stitching. The time taken for this image was deliberately extended from 11 minutes to 90 minutes to demonstrate the temporal stability of the system. The data density of 625 megapixels is in excess of what would be achievable with a normal AFM within this timescale. The stitched images are shown in figure 6.

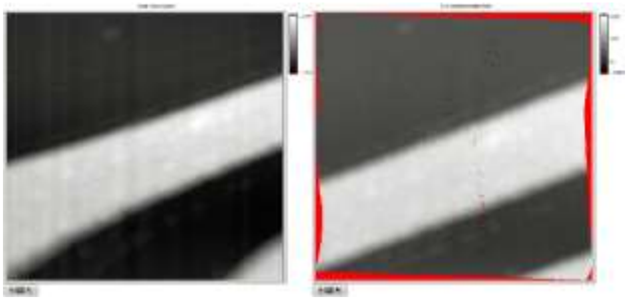

Figure 5 (a) showing an image based on piezo actuator signals and (b) based on the interferometer signal; image size (4 x 4) µm

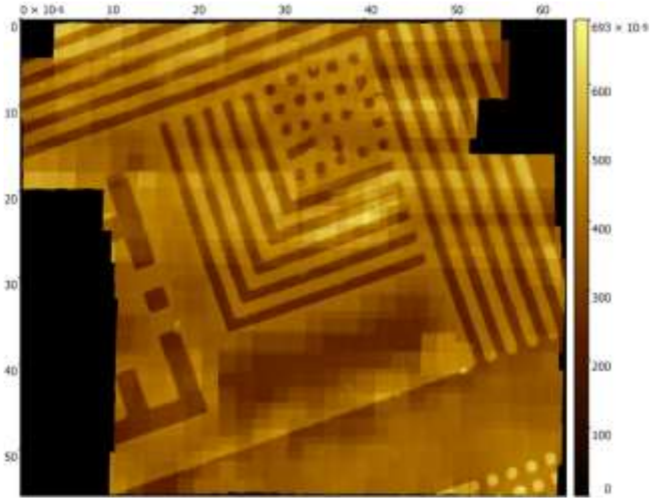

Figure 6 Stitched (50 x 50) image comprising 625 images total image size (50 x 50) µm

In an image the first and last trace and retrace lines correlate to better than 0.9999. The standard deviation in the slow scan amplitude is 12.98 nm and in the fast scan amplitude it is 0.91 nm. The difference can be attributed to different scan rates: 1 kHz and 1 kHz respectively.

4. Conclusion

We have shown that errors in high-speed AFM systems can be quantified and compensation applied. Further work is in progress to produce an uncertainty budget for the system.

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