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High-speed atomic force microscopy in slow motion—understanding cantilever behaviour at high scan velocities

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Abstract
Using scanning laser Doppler vibrometer we have identified sources of noise in contact mode high-speed atomic force microscopy images and the cantilever dynamics that cause them. By analysing reconstructed animations of the entire cantilever passing over various surfaces, we identified higher eigenmode oscillations along the cantilever as the cause of the image artefacts. We demonstrate that these can be removed by monitoring the displacement rather than deflection of the tip of the cantilever. We compare deflection and displacement detection methods whilst imaging a calibration grid at high speed and show the significant advantage of imaging using displacement.

Online supplementary data available from stacks.iop.org/Nano/23/205704/mmedia

(Some figures may appear in colour only in the online journal)

1. Introduction

At the time of writing, the atomic force microscope (AFM) [1], is celebrating the 26th anniversary of its invention. Over this period it has become one of the most significant tools in nanoscience, with applications across the entire field [2, 3]. One of the principal reasons for the popularity of AFM is that it is a very versatile instrument, able to produce nanometre resolution images in ambient, liquid and vacuum environments without requiring any staining or coating of the sample. However, the serial nature of AFM data collection (a point-by-point raster scan) means that imaging rates are typically of the order of tens to hundreds of seconds per frame, too slow to follow processes occurring on the millisecond timescale (i.e. bio-molecular interactions).

In the last ten years substantial effort has been spent on improving AFM imaging rates so that researchers can observe events on the second to millisecond timescales directly [4]. Development has focused on increasing the bandwidth of the various components of the AFM, namely feedback loops [5–7]; fast, high-stability scan stages [8–11]; and for AFMs operating in a dynamic mode (intermittent-contact or non-contact scanning), the production of micro-cantilevers with greater force sensitivity and higher resonant frequencies [12, 11].

The bandwidth of contact mode AFM is not limited by the resonant frequency of the cantilever. This removes one of the major constraints on the imaging rates that can be achieved. At the University of Bristol, a contact mode high-speed AFM (HSAFM) capable of video-rate imaging in both ambient and liquid environments has been developed [13]. This instrument monitors the deflection of the cantilever (and thus the motion of the imaging tip) via the commercial optical beam deflection (OBD) sensor [14] of a Dimension 3100 AFM (Bruker, USA) and, as such, the maximum imaging rate is dependent solely on the bandwidth of the photodiode. To date, scan...
This arrangement is similar to that reported previously by Payton et al. [15]. Rates in excess of 1200 frames s\(^{-1}\) have been reported [15]. The images collected using this technique are equivalent to the deflection/error signal images from a conventional AFM rather than topographic images. While this solution will not control the tip–sample interaction forces, previous work has shown that, even without a suitably fast feedback loop, the HSAFM can image large, soft specimens such as chromosomes in liquid [13].

Recently, the use of a scanning laser Doppler vibrometer (LDV) to determine the dynamic behaviour of a contact mode cantilever during periodic line scans was reported [16]. Here, an LDV is used to measure the true \(z\) displacement of the cantilever tip during high-speed contact mode AFM imaging, producing an instantly calibrated topographic map of the surface.

2. Method

This arrangement is similar to that reported previously by Payton et al [16]. Briefly, a custom-made positioning stage, figure 1, was assembled to provide the optical access required for LDV measurement of the cantilever tip displacement. The sample is mounted on a custom high-speed XY stage, as described elsewhere [13]. The cantilever is lowered towards the surface by a closed loop piezo stage (PI, Germany) and contact is distinguished by measuring the thermal spectra from the tip of the cantilever and looking for a reduction in the amplitude of the thermal fluctuations of the first flexural eigenmode due to the mode becoming a clamped mode at the point of engagement. Contact mode MSNL (Bruker, USA) cantilevers were used for HSAFM imaging throughout these experiments.

In order to reconstruct the shape of the cantilever with time the LDV’s laser dot can be placed at mesh coordinates over the top of the cantilever. Whilst the cantilever performs continuous line scans of a surface with known topography, the vibrometer records a velocity–time series at these measurement points over the surface of the cantilever. Integrating this data provides the \(z\) displacement of each specified measurement point along the cantilever as it scans the surface. The use of periodic line scans, with no slow scan (the high-speed stage oscillates purely perpendicular to the cantilever), permits the synchronization of each collected velocity–time series. Therefore, not only can the data be integrated, with respect to time, to determine the \(z\) displacement of the cantilever at each measurement point during the line scan, but the overall motion of the cantilever beam can also be reconstructed (with an in-plane spatial resolution dictated by the number of measurement points collected). Calculations of the angle of deflection and torsion of the cantilever can then be made. An advantage of using the LDV to measure the torsion and deflection is that the angle calculated does not need to be calibrated, as would be the case with the OBD method. Instead, simple trigonometry can be used to determine the angles directly from the relative \(z\) displacements of the LDV measurement points along the cantilever. Using this technique the torsion and deflection can be determined for every frame of the reconstructed LDV data.

The Polytek MSA-400 used here is capable of measuring at sample rates of up to 20 MHz, and thus one can compare the vertical displacement and angular deflection of the tip of the cantilever with nanosecond accuracy. Using a complex Fourier transform, eigenmode analysis of a contact mode cantilever can be carried out in a similar fashion to the studies of tapping mode cantilevers performed by Raman et al [17] or the work carried out by Reed et al [18]. The same custom software as described in [16] is used to animate the root mean square (RMS) motion of the cantilever at any frequency the user selects. In addition, the software can display a Fourier transform of the cantilever’s motion at any measurement point. Using these two tools, the torsional and flexural resonant frequencies of the cantilever can be located. Moreover, they can be matched to their corresponding reconstructed eigenmodes and animated (see figure 5).

3. Results

3.1. Calibration

A 1 \(\mu\)m pitch silicon calibration grid was used to assess the accuracy of the LDV detection system initially and then to compare the HSAFM topographical images created from the LDV vertical displacement data against deflection images collected using a standard OBD sensor. To test the LDV detection system the laser spot was located at the free end of the cantilever above the tip and periodic line scans were performed by the stage as shown in figure 2. The vertical displacement data from multiple line scans of the silicon calibration grid were overlaid on one another, as shown in figure 2, and have the correct horizontal pitch and vertical height.

3.2. Comparing displacement to deflection

To highlight the advantages of measuring the true \(z\) displacement of the cantilever tip over the conventional
Figure 2. Three line scan traces over a 1 μm pitch silicon calibration grid are shown. The data was collected by measuring the vertical displacement of the tip of the cantilever while scanning the calibration grid at a fast scan frequency of 1 kHz.

deflection measurements the stage was oscillated at a range of frequencies, enabling noise sources and image artefacts in the line scan data to be identified. In particular, the deflection and torsion of the end of the cantilever (typically where the OBD laser spot is placed) were studied.

Figure 3 shows the experimental time series data of a portion of trace and retrace scan line data taken over the calibration grid, with a line scan rate of 1 kHz. The data supports the FEA simulations of Humphris et al [19] which show oscillations in the deflection signal that are not apparent in the displacement signal as the cantilever passes over a step-like feature. Figure 3(b) shows the deflection of the tip of the cantilever and is representative of the data collected using a standard AFM OBD sensor. The line scan data illustrated in figure 3(b) shows that the 100 nm deep pits in the calibration grid cause the deflection signal from the cantilever tip to oscillate and ‘ring’ each time it descends into or climbs out of a pit. However, the corresponding vertical displacement data (displayed in figure 3(a)) indicates that, contrary to the conclusion one might draw from the deflection data, the tip remains in contact with the surface throughout the scan line. This implies that the deflection of the cantilever tip, as measured by conventional OBD detection systems, does not always accurately reflect the vertical height of the imaging tip. Methods for measuring the true vertical displacement of the cantilever tip directly, such as using an LDV as described here, are not sensitive to these sources of error and can provide more accurate images of the surface being imaged. The origin of noise sources such as the ringing seen in figure 3(b) can be better understood by analysing the motion of the cantilever during imaging.

3.3. Analysing eigenmodes

The eigenmodes of the cantilever can be visualized in the same program as used previously by Payton et al [16]. Observing the motion of the cantilever at each of the resonant peaks seen in figure 4 allows identification of the modes of oscillation that contribute most strongly to the cantilever dynamics. The program reconstructs the behaviour of the cantilever at any given frequency and animates the resultant motion (see figure 5).

In analysing the vertical displacement data in the frequency domain, one can determine the source of the ringing seen in the deflection signal. For this purpose, line scans across a freshly cleaved mica surface were obtained. From the results of Picco et al [13], it can be seen that the torsional signal changes sign at each turning point (where the trace switches to the retrace and vice versa), similar in appearance to a square wave. This modulation is responsible for the ‘forest’ of peaks at the lower frequencies of the torsional plot seen in figure 4(c). The peaks are introduced during line scans of a silicon calibration grid oscillating at a fast scan frequency of 1 kHz. A small slope of 20 nm μm⁻¹ can be seen, corresponding to an angle of 1.15°.

Figure 3. Plots of experimental data showing (a) the displacement, (b) deflection and (c) torsion of the cantilever tip with time over 2.5 periods of the scan stage. These were measured simultaneously during line scans of a silicon calibration grid oscillating at a fast scan frequency of 1 kHz. A small slope of 20 nm μm⁻¹ can be seen, corresponding to an angle of 1.15°.
Figure 4. (a)–(c) show the Fourier transforms of the displacement, deflection and torsion, respectively, using a triangle cantilever with a spring constant of 0.01 N m$^{-1}$ in its first flexural eigenmode. On plots (b) and (c) the eigenmodes have been labelled using the same conventions as Raman et al [20].

Figure 5. Frame from an animation displaying the reconstructed motion of the third flexural eigenmode of the cantilever. Enhanced online 5.10 MB .wmv file (available at stacks.iop.org/Nano/23/205704/mmedia).

reconstructing the motion of the cantilever for the frequency at which ringing was seen in figure 3 revealed that it is a result of excitation of the third flexural eigenmode. Figure 5 is an illustrative frame taken from an animation of this reconstructed motion. This observation is important because the OBD method assumes that the displacement of the tip due to surface topography is proportional to the slope at the end of the cantilever in its first flexural eigenmode. Since this slope will also change as a result of vibrations at the higher eigenmodes any excitation of them will convolute the deflection signal. This inability to distinguish between eigenmodes is further hindered by the fact that the angle of deflection of the tip for a given amplitude increases with flexural eigenmode number (though the stiffness also increases [21]). Figure 6 shows how the maximum tip deflection angle per RMS amplitude varies across the first four flexural eigenmodes, as measured from the reconstructed eigenmodes of the cantilever passing over a flat mica surface (figure 5). For each eigenmode the maximum deflection angle at the tip of the cantilever was divided by the maximum RMS amplitude across the whole cantilever.

Figure 6 shows that a given amount of energy in each eigenmode results in the angle of the tip while oscillating at its third eigenmode being larger than that of the first eigenmode. Therefore, any tip–sample interactions with sufficient energy to excite the third eigenmode will, in turn, generate significant tip angles and introduce imaging artefacts, such as ringing, to the deflection signal. Several approaches to identify and remove contributions from higher-order eigenmodes during tapping mode AFM have been suggested previously. The first of these is to transform the temporal data into the frequency domain and filter out the contributions from unwanted eigenmodes as for electronic noise. This approach is useful in tapping mode, where the RMS oscillation amplitude is used to control the tip–sample interaction, but not so well suited to contact mode where removing oscillations at a given frequency would also remove any surface detail corresponding to that frequency. Another
Figure 7. Images of a silicon calibration grid. Both images were taken using the same load, cantilever and fast scan frequency of 1 kHz. Image (a) was taken using a Dimension 3000 OBD detector and (b) using a Polytec MSA-300 LDV. Both images took 0.1 s to produce.

An example image collected using the OBD is shown in figure 7(a). Artefacts present in figure 7(a) due to higher mode cantilever vibrations are not present in figure 7(b), collected by the LDV. The vertical and horizontal features on image figure 7(a) are not actually present on the surface of the sample. They are artefacts caused by the ringing of the cantilever (in this case the third eigenmode) as seen in the line scans shown in figures 3(b) and 5.

4. Conclusion

We have shown that monitoring the displacement of the cantilever above the tip has advantages over the commonly used OBD method. The two principal benefits from adopting this detection technique are; the method ignores the oscillations of higher eigenmodes of the cantilever, which in an OBD-based AFM would induce image artefacts and the position data collected by the LDV requires no additional calibration steps before it is used to create a topographic image of the scanned surface. It is worth noting that the advantages of measuring the displacement of the tip rather than its deflection are not just limited to high-speed imaging; standard contact mode imaging will also benefit from this technique. The source of image artefact discussed is most apparent when imaging at high speed as the period of the oscillations causing the noise is longer than the time it takes to measure two consecutive pixels of topography. As the sample rates of standard contact mode AFM increase this source of image artefact will present itself in the data. As such, the authors think that the displacement technique described here is a worthwhile replacement for the traditional OBD sensor.

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