A PLATFORM FOR OBSERVING THE BEHAVIOR OF AFM CANTILEVERS DURING QUASI-STATIC LOADING

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INTRODUCTION

This paper describes a platform for studying the bending behavior of ultra-compliant (stiffness less than 1 N/m) atomic force microscope (AFM) cantilevers. The fundamental issue is that a cantilever does not represent an ideal design for precision force measurement due to the parasitic motion of the tip under load. For ultra-compliant cantilevers, the combination of a high adhesive force at the tip and parasitic motion can lead to proportionally substantial lateral (in-plane) forces. In addition, the tip-surface adhesive force can increase the propensity for sticking which is a considerable concern for colloidal probes due to the increased contact surface. These effects can manifest as deviate bending behavior and have been suggested as confounding contact style force calibration/measurement [1] since force is commonly related to tip displacement by an assumed bending model [2].

DESIGN OVERVIEW

The primary components of the apparatus are a scanning white light interferometer (SWLI) and the cantilever positional staging; see Fig. 1. The SWLI collects topographical information via analysis of the interference pattern between the sample and reference surfaces. The inference pattern is varied in a controlled fashion by translating either the sample or reference surface. Since white light has a short coherence length, there is a large variation in absolute interference intensity over a small change in optical path length. This can be related to the position of points on the sample surface; see [3] for a review. The method is non-contact and images through standard microscope objectives. The SWLI is combined with positional staging to provide the relative motion needed for cantilever loading experiments. Naturally, it is required that the staging does not obscure top down viewing of the cantilever system. Detailed specifications of the components in Fig. 1 are provided in Table 1.

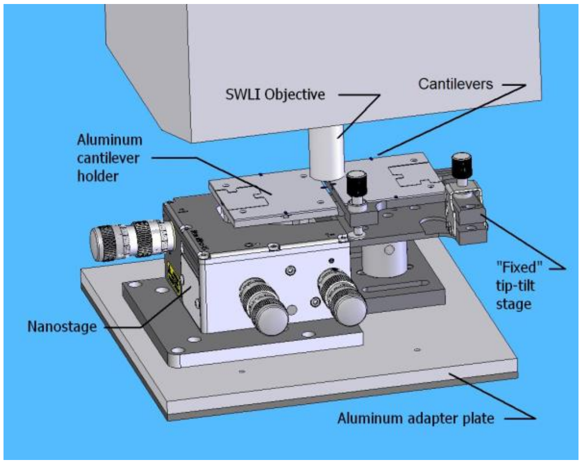

FIGURE 1. Full apparatus: SWLI for topographical measurement, nanostage for translational motion, tip-tilt stage for alignment, and AFM cantilever holders for easy handling.

TABLE 1. List of components, manufacturer, and selected specifications.

SWLI	Zygo NewView 5010	100 mm (Z) z-drive +2/-4 deg (pitch), +/- 4 deg (roll), 150 mm (X/Y) motorized stage 640x480 pixel camera
Nanostage	Thorlabs MAX301	4 mm (X/Y/Z) thumbscrews 20 µm (X/Y/Z) piezos
Tip-tilt stage	Thorlabs AMA501	+/- 4 deg (pitch/roll) thumbscrews
Holders & Adapter	Custom machined Custom polished	Aluminum (no particular grade selected)

SWLI measurements represent a paradigm shift from traditional AFM metrology. Beyond moving from a single point to full, topographical measurement, there is also the imposition of new constraints. Primarily, a single topographical measurement takes time on the order of seconds, which prevents instantaneous measurement of the cantilever position. The effect is that experiments must be quasi-static, where motion is stopped periodically to perform a measurement. While strobing may provide an alternative, it requires a specific interferometric arrangement and is not discussed here. Secondly, there is a maximum measurable surface angle (off-parallel angle from the objective plane) due to limited lateral resolution and the necessity for sufficient reflected light to return to the detector. The maximum angle varies depending on the objective and system magnification with values ranging from about 1 deg (high magnification) to approximately 34 deg (low magnification). The effect is that two cantilevers cannot be imaged simultaneously if their relative angle is outside the maximum angle. Further, the deflection of a cantilever is limited such that the maximum slope in a profile must fall within the measurement capabilities.

The selected staging provides angular alignment of the cantilevers, a parameter often uncontrolled in traditional AFM platforms. Angular alignment enables different AFM system configurations, such as the standard 12 deg cantilever tilt, to be reproduced. Additionally, it enables the system to be adjusted as closely as possible to the assumed model. Alignment is verified by SWLI measurements, typically using a line or plane fit to the alignment surface. However, one difficulty is that many cantilevers have non-planar profiles due to fabrication-induced internal stresses. Therefore, they do not provide ideal alignment surface candidates. One alternative is to use the cantilever's macroscopic base/chip as the alignment surface since it is flat and nominally parallel to the cantilever. This method is applied here. Using the SWLI to measure this alignment is an iterative process due to the lack of real-time feedback (i.e., it requires a measure, adjust, re-measure sequence).

The holder system consists of flat aluminum plates that adapt to the staging and are large enough to be placed by hand. An important consideration is vertical clearance between the sample and objectives with high magnifications since these objectives typically have short working distances (e.g., a 100x objective may have a working distance of only 0.55 mm). Therefore, in our design, cantilevers are mounted using an adhesive rather than a mechanical clamp to minimize encroachment on the available clearance. As shown in Fig. 2, the mount locations are symmetric, enabling different cantilevers to be rotated into the same work volume with minimal realignment and handling. Since the cantilevers can be aligned to a variety of angles, they are mounted with sufficient overhang to prevent collision with the staging.

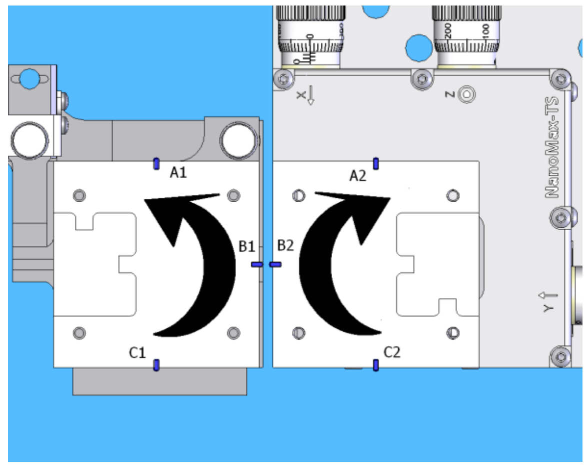

FIGURE 2. Rotating the holders enables rapid reconfiguration. This shows the generically identified chips switching from an experiment between chips B1 and B2 to C1 and C2.

DATA ANALYSIS

Regardless of the type of analysis being performed, there are some cautions worth addressing. First, there is a limited lateral resolution (plan view) of the cantilever which depends on system magnification and the number of pixels in the SWLI camera. For a 10x magnification with a 640x480 pixel camera, for example, the corresponding lateral resolution is 1.18 µm. This places an upper bound on the cantilever length measurement accuracy, which is a sensitive parameter in the Euler-Bernoulli stiffness equation. Next, as previously noted, there is a maximum measurable angle for any given feature by SWLI. Some cantilevers, due to isotropic etching, have sloping edges which cannot be detected by SWLI; see Fig. 3. Not only does this make the cantilever appear shorter, it also affects the ability to locate the tip over a sample. Finally, there is often significant noise in the measured height at sharply inclining edges as shown in Fig. 4. This further complicates data interpretation at the tip and the base (in some cantilevers). It can also cause problems when there is dust contamination on the cantilever. Keeping the above cautions in mind, the Euler-Bernoulli beam equation is fit to measured cantilever profiles. The procedure used to provide the best fit is described below.

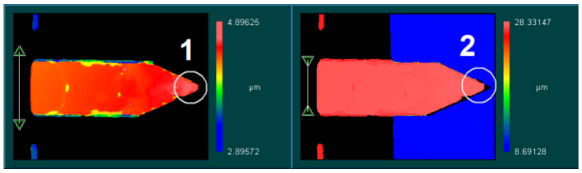

FIGURE 3. Cantilever edge (1) does not register since the feature is too angular. Measurement with a backdrop reveals the edge (2).

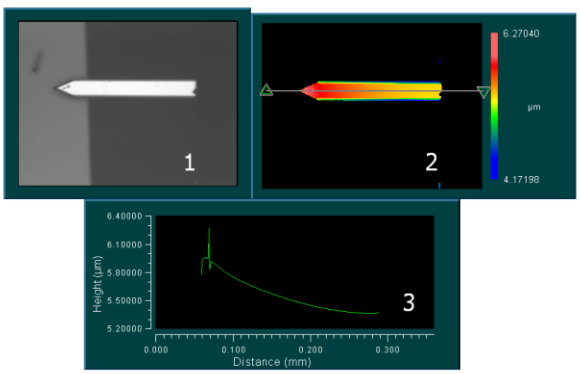

FIGURE 4. Top side of a cantilever as viewed through the objective (1); pyramidal tip is not visible since it resides on the bottom side. A sectional slice (2) shows noise near the edge due to a few specs of dust and the sharp decline of the edge (3).

Profile Extraction

All cantilevers are measured prior to loading and the pre-loaded images subtracted from the loaded images on a per pixel basis to isolate relative motion. This prevents cantilever shape (typically non-planar) from affecting the fit. Lateral drift of the image due to stage settling can occur for long measurement sequences and must be compensated prior to data subtraction using, for example, fiducial monitoring. Next, a slice through the middle of the cantilever is selected in order to reduce the problem to two dimensions, height and length; see Fig. 5.

Profile Smoothing

So that subsequent fitting is performed on a pristine dataset, noise is fenced off using the statistical definition for outliers. If Q_1 and Q_3 are the first and third quartiles and $IQR = (Q_3 - Q_1)$ is the interquartile range, then the outer fence of the data is $Data > Q_3 + 1.5 \cdot IQR$ for mild outliers and $Data > Q_3 + 3 \cdot IQR$ for extreme outliers [4]. The data is iteratively compared for closeness to a polynomial curve fit and outliers are rejected based on the mild outlier criteria. All data, including previous outliers, are re-analyzed for closeness each iteration. The final iteration uses the extreme outlier criteria so that the smallest amount of data is rejected; see Fig. 6.

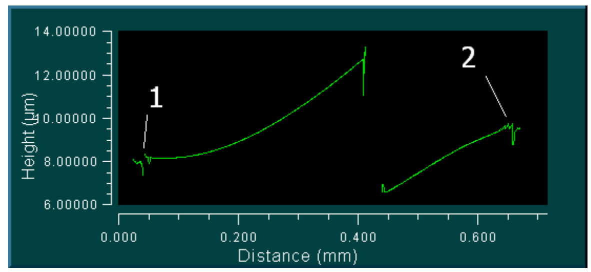

FIGURE 5. A sectional view of two cantilevers. The height gap between levers is occupied by the tip of (1). Noise appears at both the base and edge of (1) and (2).

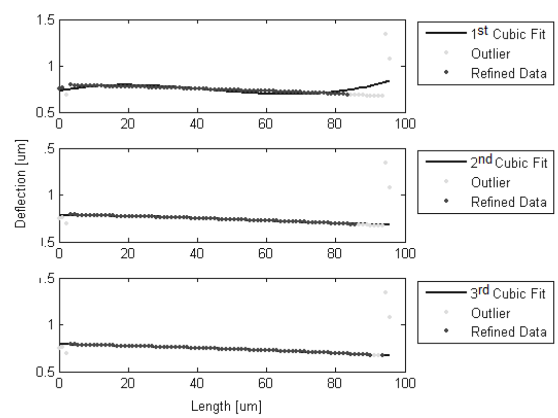

FIGURE 6. A three iteration solution to finding outliers. Since all data is re-analyzed each iteration, only the most extreme outliers are rejected.

Coordinate Transforming

The smoothed data is coordinate transformed into the model space of the Euler-Bernoulli beam bending equation, where the base location is (0, 0). It is common for the cantilever base data to be rejected in the previous step (the base is position invariant during bending and was used as the fiducial). In order to perform the transformation the base position is extrapolated from the remaining data by a polynomial fit (order 4 is used here); see Fig. 7.

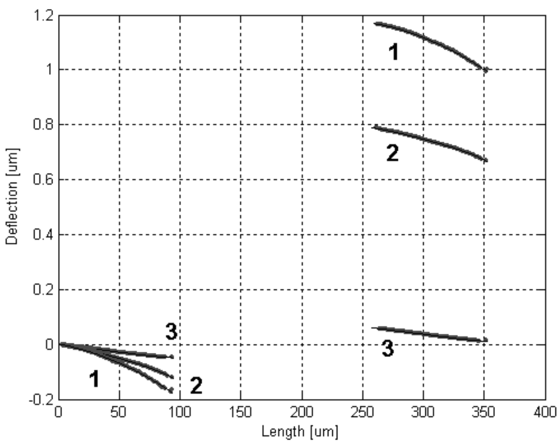

FIGURE 7. Scan-to-scan, data is not guaranteed to be aligned. Coordinate transformation moves each dataset to a common origin. A polynomial fit extrapolates the based position.

<u>Beam Fitting</u>

The Euler-Bernoulli beam equation for a fixed-free beam is compared to the smoothed, coordinate shifted data. The form of the beam equation for tip loading is,

$$y = F\frac{x^2}{6EI}(3L - x)$$

where x is the distance along the length of the beam, y is the beam deflection at x, L is the measured length of the cantilever, $EI = kL^3/3$, k is the stiffness specified by the manufacturer, and F is the force. In a standard AFM, $x = L$, y is measured at a single point, and F is calculated. In this study, there are multiple (x, y) pairs which are used to calculate a least squares fit of F. This fit is plotted on top of the data and compared; see Fig. 8. These results are for 0.027 N/m and 2 N/m cantilevers, respectively, loaded against a rigid surface. The results of the 2 N/m lever show possible deviation from the beam bending model.

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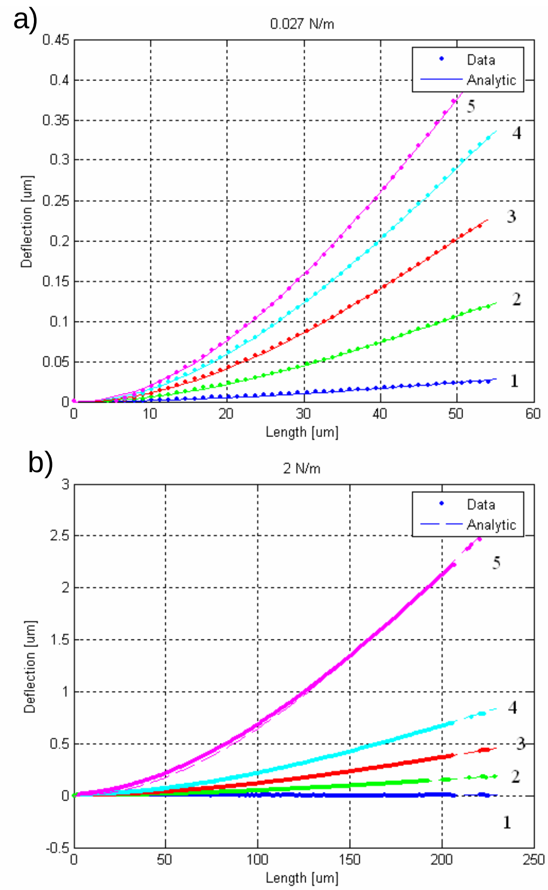

FIGURE 8. Cantilever loaded against a rigid surface. Snapshots (1-5) show the lever from just after contact with the surface to the maximum deflection imposed of about (a) 400 nm, and (b) 2.5 µm.

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