Measuring cantilever bending modes and displacements with sub-pm resolution

SmarAct GmbH

Abstract

When using micro-cantilevers as sensors it is important to have methods to monitor their displacements at high resolution. Key example is atomic force microscopy where knowing the dynamic behavior of the cantilever allows a better control of the interactions between cantilever and sample. This helps to minimize sample damage and to maximize resolution. Furthermore, the spring constant of a cantilever, an essential parameter in force spectroscopy measurements, can be calibrated by measuring the thermal vibrations which can be as small as a few hundred femtometer. SmarAct's **PICO**SCALE *Vibrometer* can be used to image cantilever bending modes and provides sub-pm resolution measurements of its vibrations.

1. INTRODUCTION

The common method to measure displacements of micro cantilevers is the optical beam deflection (OBD) scheme [1]. Here, the incident laser beam is focused at the free end of the cantilever and reflected onto a quadrant photodiode (QPD). When the cantilever bends, the direction of the reflected beam changes which can be accurately measured with the QPD. Due to its simplicity, the OBD scheme is used in the majority of atomic force microscopes (AFM). Nevertheless, it has some serious shortcomings:

1. The electrical signal (in Volt) from the QPD has to be converted into a cantilever displacement (in length units). For this, a preliminary step is required to estimate the linear conversion parameter. Usually, it consists of the lowering and pushing of the cantilever onto a stiff surface with a pre-calibrated piezo scanner. Assuming that the measured electrical changes on the QPD arise solely from the bending of the cantilever and because the displacement of the piezo is known, the relation between the displacement and QPD signal is directly obtained. The obvious drawback of this procedure is that the tip can get contaminated or even damaged while contacting the surface.
2. OBD measures changes in the inclination of the cantilever rather than the true displacement. However, the latter is required for the physical models used to calibrate the normal spring constant of cantilevers in force spectroscopy experiments. Therefore, to apply these models, mathematically derived corrections are necessary that include parameters such as the size of the laser spot and the type of bending mode [2].
3. Forces that originate from torsion of the cantilever in frictional force experiments are notoriously difficult to quantify. The quantification of frictional forces requires the calibration of the torsional spring constant for which the relation between the (torsional) displacement and QPD signal needs to be obtained. In the case of torsion, this requires a well-controlled and frictionless lateral displacement of the AFM tip that is mounted at the end of the cantilever. Unfortunately, this specific motion of the tip is very difficult to implement.

A contactless method that would measure displacements directly in length units at any position on the cantilever avoids the above-mentioned limitations of the OBD scheme. Interferometry represents an appealing alternative as the interferometric measurements are intrinsically calibrated by the wavelength of the used laser source. Furthermore, approaches in which the laser of an interferometer was scanned over a cantilever have been shown to produce superior results for the calibration of AFM cantilevers as compared to the OBD scheme [3].

In this application note we show how the **PICO**SCALE *Vibrometer*, a raster-scanning Michelson interferometer, can be used to visualize different vibrational modes of micro cantilevers. In addition, the closed-loop positioners of the instrument allow the exact positioning of the focused laser beam on the cantilever. This facilitates the local measurement of vibrations with sub-pm resolution which can be used for the accurate calibration of spring constants.

2. RESULTS

Visualizing vibrational modes

To identify the resonance modes of the first test cantilever the laser spot was initially positioned near its free end and time series of its vibrations were recorded at a sampling rate of 5 MHz. In this case, the vibrations were actively induced by driving the standard shaker stage of the **PICO**SCALE *Vibrometer*

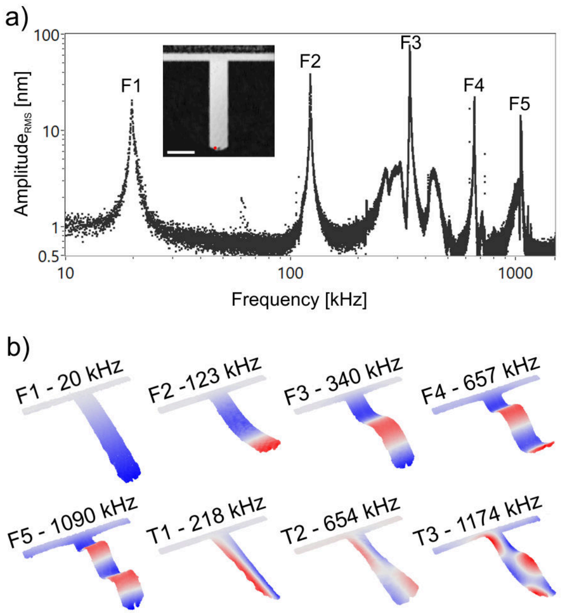

Figure 1. Identifying different cantilever bending modes. *(a) An FFT of the recorded displacements, the multiple resonance peaks suggest different bending modes. The inset microscopy image shows the measurement position on the cantilever (red dot), the scale bar is 60 µm. (b) Vibrations were imaged at the peaks labeled with F1 to F5. The 3D renderings show the first 5 flexural bending modes at the indicated frequencies. In addition, the first 3 torsional modes are shown. To obtain the torsional resonance peaks, an addition FFT was obtained by measuring the cantilever displacements at the side of the cantilever (not shown).*

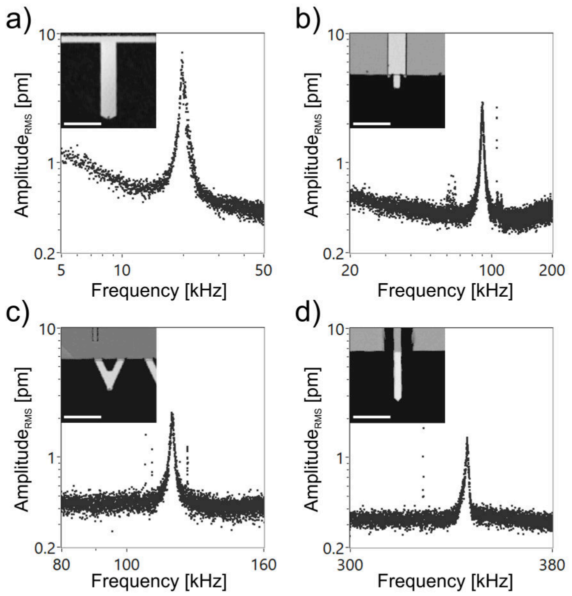

Figure 2. Measuring thermal vibrations with sub-pm resolution. *(a-d) Measurements on 4 cantilevers of different sizes. The spring constant of the cantilevers increases from a to d. Accordingly, the height of the measured noise peaks in the FFT graphs decreases from a to d. The results show that over a high frequency range the noise floor is well below 1 pm, which allows the detection of sub-pm vibrations. The insets show the microscopic recordings, the scale bars are 100 µm. The vibrations were measured at the free ends of the respective cantilevers.*

on which the cantilever is mounted with a linear chirp from 0.5 Hz to 2 MHz. To lower the noise floor, 10 one-second time series were averaged. The amplitude spectrum in Figure 1a, obtained after Fourier transformation of the time series, shows defined peaks, each corresponding to a yet unknown resonance mode. The identification of the different modes becomes possible after imaging the cantilever vibrations while driving the cantilever at one of its eigenfrequencies. The on-the-fly analysis of the vibrations with a digital dual-phase lock-in amplifier delivers the amplitude, A, and phase, ϕ (with respect to the shaker stage drive signal) of the oscillations at each pixel of the microscopy image. From this data, the deflection, d, can be calculated according to $d = A \cdot \cos(\phi + \delta)$ with the **PICO**SCALE *Vibrometer* View software. Here, δ is a phase offset which is added to show the mode shape at different points during the oscillation cycle. For representation purposes we chose δ such to show the maximal deflection. Figure 1b displays the first 5 flexural and first 3 torsional modes.

Measuring thermal vibrations

The thermal noise calibration of the spring constant, k, of a cantilever relies on measuring its thermal vibrations[1] and assuming that it can be described by a simple harmonic oscillator (SHO) in thermal equilibrium with its environment. The equipartition theorem tells us that the average potential energy stored in a SHO, $E = 1/2 \cdot k \cdot \overline{d^2}$ ($\overline{d^2}$ is the mean squared displacement of the cantilever), should equal in this case the thermal energy of the system, which is given by $E = 1/2 \cdot K_B \cdot T$ (K_B is the Boltzmann constant and T the absolute temperature of the system). Thus k can be directly obtained by measuring $\overline{d^2}$ as $k = K_B \cdot T / \overline{d^2}$ [4]. In practice $\overline{d^2}$ is often determined in the frequency domain to selectively obtain the displacements at the cantilever eigenfrequency which helps to eliminate other noise sources. Further refinements and correction factors have made the thermal calibration method widely accepted by the AFM community [5]. Figure 2a-c show the measurements of the thermal vibrations of 4 different cantilevers. For each, the noise floor is less than 1 pm which allows to resolve sub-pm amplitude vibrations. This is particularly interesting when calibrating stiff cantilevers that will have very small oscillation amplitudes (the amplitude is inversely proportional to the stiffness) (Figure 2b). It should be noted that the measured amplitude represents the effective amplitude at the measurement positions. For calibrating the cantilever, it is thus important to position the measurement spot at the exact location where the cantilever will contact the sample, mostly defined by the location of the tip that is mounted at the free end of the

---

[1] Thermal vibrations are vibrations induced by the thermal motion of the molecules that make up the cantilever and by those in the surrounding liquid or gaseous environment.

cantilever.

3. CONCLUSION

SmarAct's **PICO**SCALE *Vibrometer* allows the contactless analysis of bending modes and vibration amplitudes of micro cantilevers at sub-pm resolution. As compared to the commonly used OBD method, the interferometric technique offers multiple unique advantages:

- Because the displacement measurements are intrinsically calibrated by the used laser wavelength, no further calibration steps are required to obtain a reading in length units.
- The whole procedure is contactless so that the spring constant calibration can also be performed when the cantilevers are packed in a box or are still mounted in a wafer. Furthermore, the measurement laser can be directed to either side of the cantilever, depending on which side has the best optical access.
- Also torsional spring constants can be calibrated with this technique.
- The measured displacement is independent from the local bending of the cantilever, so that no additional correction factors are required for the size of the laser spot or when measuring higher order bending modes. The presence of fewer assumptions in the calibration procedure will further help to increase the accuracy of the calibration.

REFERENCES

[1] Gerhard Meyer and Nabil M. Amer. Optical-beam-deflection atomic force microscopy: The NaCl-(001) surface. *Applied Physics Letters*, 56(21):2100–2101, May 1990.

[2] Tilman E. Schäffer and Harald Fuchs. Optimized detection of normal vibration modes of atomic force microscope cantilevers with the optical beam deflection method. *Journal of Applied Physics*, 97(8):083524, April 2005.

[3] Richard S Gates and Jon R Pratt. Accurate and precise calibration of AFM cantilever spring constants using laser Doppler vibrometry. *Nanotechnology*, 23(37):375702, 2012.

[4] Jeffrey L. Hutter and John Bechhoefer. Calibration of atomic force microscope tips. *Review of Scientific Instruments*, 64(7):1868–1873, July 1993.

[5] N A Burnham and X Chen and C S Hodges and G A Matei and E J Thoreson and C J Roberts and M C Davies and S J B Tendler. Comparison of calibration methods for atomic-force microscopy cantilevers. *Nanotechnology*, 14(1):1, 2003.

Sales partner / Contacts

Germany

SmarAct GmbH

Schuette-Lanz-Strasse 9
26135 Oldenburg
Germany

T: +49 441 - 800 879 0
Email: info-de@smaract.com
www.smaract.com

France

SmarAct GmbH

Schuette-Lanz-Strasse 9
26135 Oldenburg
Germany

T: +49 441 - 800 879 956
Email: info-fr@smaract.com
www.smaract.com

USA

SmarAct Inc.

2140 Shattuck Ave. Suite 1103
Berkeley, CA 94704
United States of America

T: +1 415 - 766 9006
Email: info-us@smaract.com
www.smaract.com

China

Dynasense Photonics

6 Taiping Street
Xi Cheng District,
Beijing, China

T: +86 10 - 835 038 53
Email: info@dyna-sense.com
www.dyna-sense.com

Natsu Precision Tech

Room 515, Floor 5, Building 7,
No.18 East Qinghe Anning
Zhuang Road,
Haidian District
Beijing, China

T: +86 18 - 616 715 058
Email: chenye@nano-stage.com
www.nano-stage.com

Shanghai Kingway Optech Co.Ltd

Room 1212, T1 Building
Zhonggeng Global Creative Center
Lane 166, Yuhong Road
Minhang District
Shanghai, China

Tel: +86 21 - 548 469 66
Email: sales@kingway-optech.com
www.kingway-optech.com

Japan

Physix Technology Inc.

Ichikawa-Business-Plaza
4-2-5 Minami-yawata,
Ichikawa-shi
272-0023 Chiba
Japan

T/F: +81 47 - 370 86 00
Email: info-jp@smaract.com
www.physix-tech.com

South Korea

SEUM Tronics

801, 1, Gasan digital 1-ro
Geumcheon-gu
Seoul, 08594,
Korea

T: +82 2 - 868 10 02
Email: info-kr@smaract.com
www.seumtronics.com

Israel

Trico Israel Ltd.

P.O.Box 6172
46150 Herzeliya
Israel

T: +972 9 - 950 60 74
Email: info-il@smaract.com
www.trico.co.il