Tech Note

ASYLUM RESEARCH

Quadrature Phase Differential Interferometry (QPDI) technology in the Asylum Research Vero AFM

Introduction

Vero is a next-generation AFM from Oxford Instruments Asylum Research. Building on its flagship Cypher AFM platform, Vero is the first AFM to use a patented 1 Quadrature Phase Differential Interferometry (QPDI) detector to provide unprecedented performance without compromise in terms of accuracy, range, and noise.

This document describes the historical background of AFM detection methods, the design, and technical specifications achieved by the new Vero AFM design and explains how its high standards for accuracy and noise will enable the next generation of AFM scientific research.

Historical Background

Shortly after the inception of the atomic force microscope (AFM)[2] in 1986, researchers explored a variety of cantilever detector approaches. Many of the early designs[3–8] were based on interferometric detection. These systems typically had good noise performance and benefitted from their inherent calibration reference: the wavelength of light. However, their intricate designs and other performance disadvantages may have limited their widespread adoption.

In a simple Michelson interferometer, shown in Figure 1, the detection range is limited to cantilever displacements much smaller than the wavelength of light since the resulting sine wave signal is only linear around zero, and the signal dies off at the sine wave's peak and trough. Furthermore, since the reference mirror is typically far away from the cantilever, this approach can be vulnerable to noise, especially at low frequencies, due to vibrations and drift between those components.

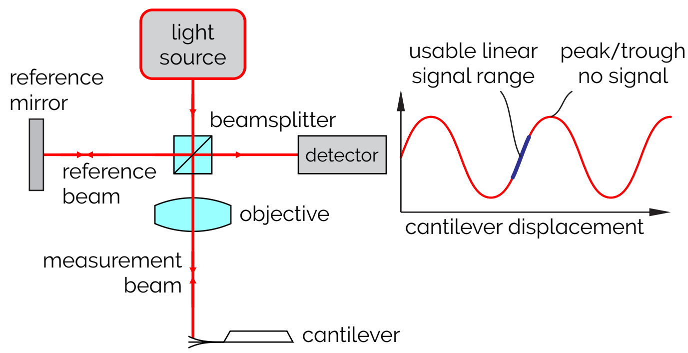

Figure 1: A simple Michelson interferometer has several limitations. Among them, the output is sinusoidal, and therefore only linear across a small fraction of the wavelength of light. Also, any vibration or drift occurring in either the measurement or reference beam causes noise in the measured cantilever displacement signal.

While more involved interferometric designs were actively addressing some of these issues of linearity, range, and low frequency noise, a much simpler method for measuring the deflection of a cantilever was invented by Meyer and Amer[9] in 1988: the optical beam detection (OBD) method. Likely due to its simplicity and the unobstructed optical view of the cantilever and sample which was not available on early interferometric AFMs, this OBD method quickly became the *de facto* detector for most commercial AFMs.

The OBD method has a theoretical noise floor that is equivalent to interferometric AFMs[10] and limited only by the shot noise of light to a few fm•$Hz^{-1/2}$. However, the OBD method has several practical limitations that cause the noise floor to be one or two orders of magnitude above this theoretical limit even on state-of-the-art AFMs. For example, the noise limit can only be reached by filling the full length of a cantilever with the OBD spot.[11] This cannot be achieved with a simple AFM design for all sizes of cantilevers; therefore, the noise performance of an AFM can only be optimized for a specific cantilever length.

As for accuracy, hundreds of journal articles on the topic of calibration are testament to the limitations of the OBD method in providing accurate displacement and force measurements.[12] The problem with OBD accuracy is not simply quantitative in nature; it is fundamentally limited by the fact that OBD measures the angle of the cantilever, rather than the relevant metric in nearly all AFM experiments: the tip displacement. Converting an angular measurement of the cantilever into a tip displacement measurement requires assumptions about the mode shape of the cantilever. These assumptions are often violated in practice, thereby leading to inaccurate measurements.[13]

All these practical and fundamental limitations of the OBD method are well understood by AFM experts, and recently led Asylum Research to release the Cypher IDS[14]: an AFM interfaced with an external laser Doppler vibrometer that measures the tip motion directly. Since its inception, the IDS has become the "gold standard" in nanoscale electromechanical measurements, successfully resolving a series of very challenging materials science problems.[15–19] It has also been extensively used to improve long-standing spring constant and sensitivity challenges in AFM.[20,21] Despite these successes, the IDS velocity signal is noisy at frequencies below 10 kHz, thus limiting widespread general AFM use.

Building on the IDS and decades of extensive experience in design and application of quantitative nanoscale science, Asylum Research has taken the next step in AFM with the launch of Vero - the first commercial AFM to incorporate a QPDI detector.

Principles of QPDI Design

The Vero AFM QPDI detector is based on two key principles that were adopted and significantly developed by Bellon *et al.*[22]

The "Differential" in QPDI refers to the principle of maintaining a common optical path for both the measurement and reference light beams. In fact, the reference beam in Vero reflects on the back of the cantilever chip, as shown in Figure 2, which is within 1 mm of the measurement beam near the cantilever tip. This ensures that the displacement of the cantilever is measured relative to the stationary cantilever chip, which reduces low frequency noise caused by vibration and drift between the measurement and reference beams.

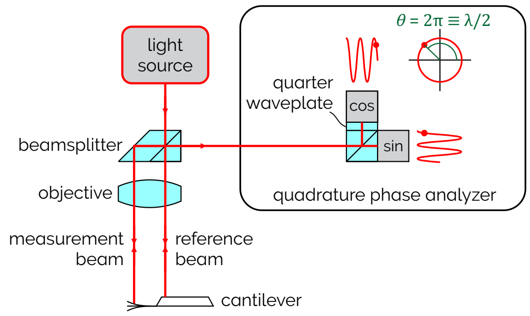

Figure 2: Diagram of the QPDI principle used to measure cantilever displacement in a Vero AFM. A light beam is split into two beams that are focused onto the cantilever and the backside of the chip. A quadrature phase analyzer measures the difference in the distance travelled by both beams to determine the displacement of the cantilever. A full 2π cycle in phase is equivalent to a _ /2 displacement, and multiple cycles may be measured.

The "Quadrature Phase" in QPDI refers to the principle whereby a second interferometric signal is generated with a 90° phase delay with respect to the first signal, using a quarter waveplate, as illustrated in Figure 2. This ensures that when the sensitivity of one signal goes to zero (at the peak and trough of the aforementioned sine wave), the other signal provides maximum sensitivity, and vice versa. Calculating the arctangent of the two signals extracts the phase between the light beams that reflected off the cantilever and its chip. The measured phase can be converted directly into a displacement in nanometers since the wavelength of light is known with high accuracy. Not only does this quadrature scheme linearize the measured cantilever displacement across a full interferometric cycle, but it allows the detector to unwrap an unlimited number of cycles despite the finite range of the photodetectors measuring the two signals. In practice, this means that the measurable motion ranges from the sub-picometer noise floor of the interferometer up to many microns, enough to accommodate even the most extreme conditions in AFM.

No crosstalk between vertical and lateral forces

In this section, the QPDI and OBD methods are compared in a very simple experiment: a large force curve on silicon, as shown in Figure 3. The QPDI force curve exhibits ideal behavior resembling that of a theoretical simulation, while the OBD force curve demonstrates very different behavior.

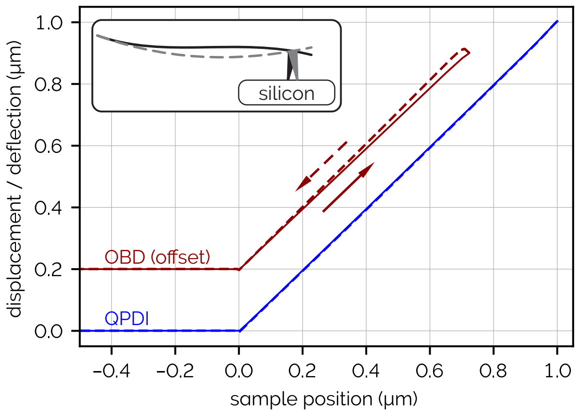

Figure 3: Force curve using an Adama 2.8-AS cantilever on silicon sample with large deflection range. In-plane forces cause hysteresis in the OBD-measured force curve that relates to rotation of the cantilever rather than the tip displacement. The inset shows how the cantilever end can rotate between approach and retract which is incorrectly measured by OBD deflection signal as hysteresis. QPDI measures tip displacement directly, with no measurable hysteresis.

In both force curves, the in-plane frictional forces between the tip and the sample lead to a rotation of the end of the cantilever, which bends slightly downwards during the approach and slightly upwards during the retract portion of the force curve.[23] This rotation causes an apparent hysteresis in the OBD-measured force curve which does not represent the true motion of the tip. Conversely, the QPDI-measured force curve demonstrates nearly perfect overlap between the approach and retraction. It directly measures the true displacement of the cantilever tip and there is no measurable compliance between the tip and silicon surface throughout the force curve, producing unity slope as expected.

While there are certainly interesting physics occurring due to the in-plane forces, it is undesirable to mix those forces with the interactions occurring perpendicular to the sample, as happens in OBD. In contrast, the QPDI detector provides an accurate measure of the perpendicular tip displacement itself, without such crosstalk.

Improved measurement sensitivity

For OBD, the size of the light spot can be chosen to either enable the use of small cantilevers, or to minimize the noise floor on large levers, but not both. Even in the best scenario, a noise floor below 20 fm•Hz$^{-½}$ is deemed excellent, achieved only with short cantilevers.

On the other hand, the Vero AFM light spot has a diameter of ~3 µm and is therefore compatible with nearly all standard levers. Since the QPDI noise performance does not depend on matching the spot size to the cantilever size, it achieves a typical noise floor < 10 fm•Hz$^{-½}$ on cantilevers irrespective of their size.

The QPDI and OBD methods are compared in images of the piezoresponse of $ErMnO_3$, shown in Figure 4, taken with the same Spark™ 70 Pt (NuNano) cantilever at the same location. This is a typical type of cantilever used for electromechanical measurements (length ~225 µm and free resonance ~70 kHz).

The single-frequency-PFM signal measured by OBD is buried under noise (see Figure 4a). A common approach to mitigate this problem is to use dual AC resonance tracking (DART),[24–26] where the contact resonance amplifies small signals (see Figure 4b). While DART resolves the issue of sensitivity, it is still an OBD technique and therefore suffers from significant crosstalk between in-plane and out-of-plane motion. Therefore, it is a *priori* impossible to discern the orientation of the grains using any OBD technique.

On the other hand, the image of single-frequency-PFM measured by QPDI (see Figure 4c) reports the vertical motion of the sample without crosstalk. It can therefore clearly distinguish between grains that are in-plane and out-of-plane, some of which are outlined in Figure 4. Note that the DART image shows seemingly out-of-plane response in grains where the QPDI image does not.

Another challenge of DART is that the cantilever sensitivity in the vicinity of resonance is very difficult to quantify. The amplitude range in Figure 4 b is based on a sub-resonant calibration factor related to the angular motion of the cantilever as opposed to the vertical motion of the tip. Conversely, the QPDI image provides an accurate measure of the vertical motion of the tip in all locations of the image.

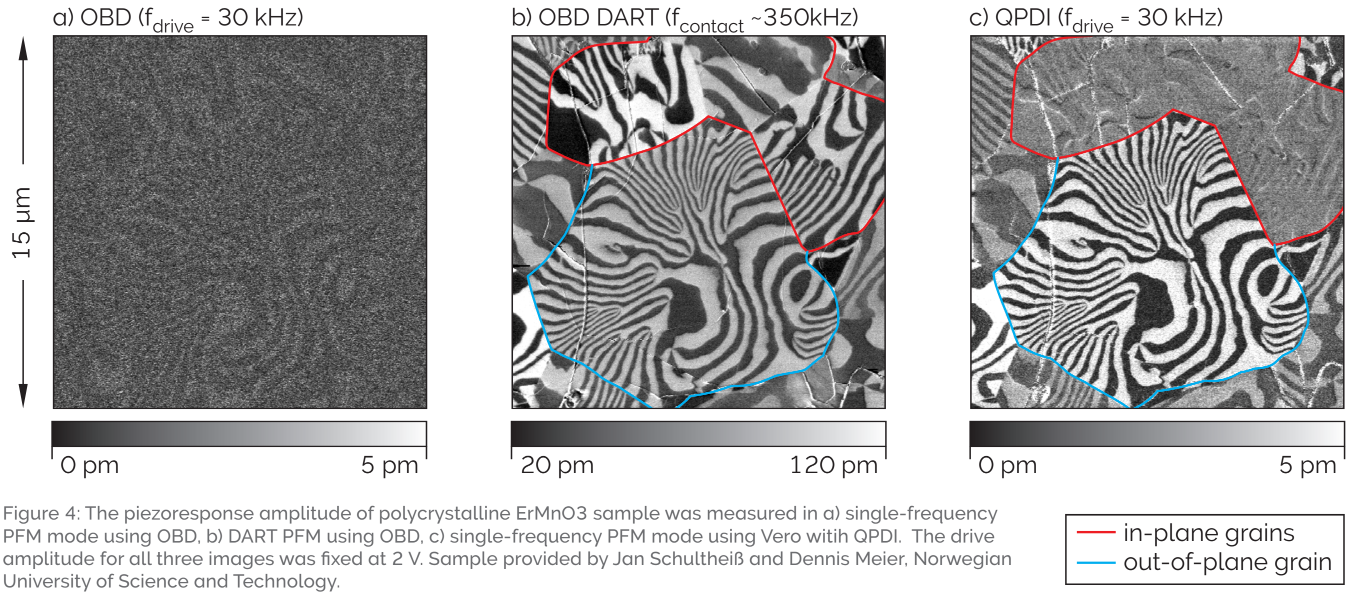

Figure 4: The piezoresponse amplitude of polycrystalline ErMnO3 sample was measured in a) single-frequency PFM mode using OBD, b) DART PFM using OBD, c) single-frequency PFM mode using Vero witih QPDI. The drive amplitude for all three images was fixed at 2 V. Sample provided by Jan Schultheiß and Dennis Meier, Norwegian University of Science and Technology.

Accurately calibrated stiffness and tip displacement

While some research can be fulfilled by acquiring qualitative AFM images, many AFM measurements can be made quantitative by calibrating the relevant signals. Tip displacement is one such critical signal since it is used in many measurements themselves and in the calibration of cantilever spring constants. Here, the greatly improved accuracy of QPDI offers advantages over OBD that is difficult to calibrate.

To verify the absolute accuracy of the QPDI detector, an absolute stiffness measurement was performed on seven NIST-calibrated cantilevers[27]. These levers were independently calibrated using a HeNe-based laser Doppler vibrometer and an electrostatic balance with impeccable agreement.

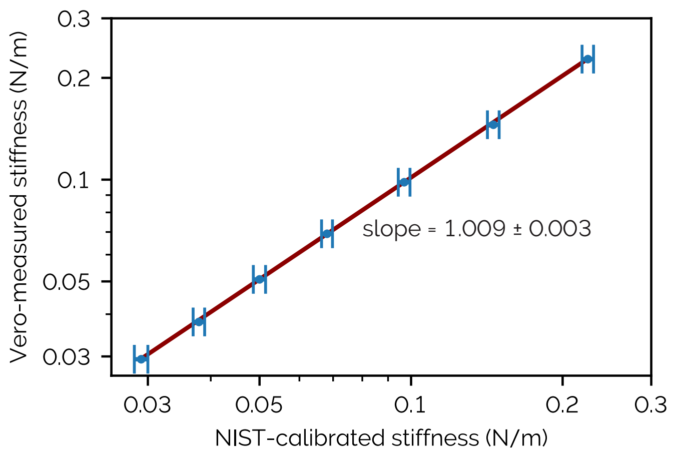

Figure 5: Stiffness measurement of 7 NIST-calibrated cantilevers using the Vero AFM showing absolute accuracy correspondence within 0.9 ± 0.3 %. The horizontal error bars represent combined expanded uncertainties provided by NIST. The error on the mean from repeated measurement for the Vero-measured stiffnesses are not shown since they are smaller than the marker size.

Figure 5 demonstrates that the stiffnesses measured by Vero were correct within 1% of the NIST-calibrated values (measured deviation was 0.9 ± 0.3 %). Note that this error is well within the combined expanded uncertainty between 2.6 % and 3.0 % provided by NIST for these cantilevers.

Furthermore, the < 1 % deviation in stiffness quoted above implies a deviation in measured displacement of < 0.5 %, demonstrating that the wavelength of light can be used as a reliable “meterstick” between different interferometry-based instruments.

Summary

Vero is the first commercial AFM to use QPDI cantilever sensing to directly measure the true vertical tip displacement. It makes these measurements with a noise floor that is often >10× lower than OBD and avoids the crosstalk between vertical and lateral tip forces that occurs with OBD. Since it uses interferometry, the displacements are accurately calibrated by the wavelength of the light. Together, these advantages of QPDI combine to make Vero AFM results more accurate and repeatable.

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