Tech Note

MFM with capacitive distance control

Active tip–sample stabilization using the Nanonis Mimea SPM controller

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Abstract

Magnetic force microscopy (MFM) is a widely established technique for mapping stray magnetic fields with nanoscale resolution. However, during extended measurements, mechanical instabilities—specifically thermal drift and piezoelectric creep—along with varying electrostatic interactions can alter the effective tip–sample distance potentially leading to changes or distortions in the recorded magnetic contrast during constant-height imaging. In this tech note, we demonstrate a capacitive distance feedback method implemented with the attoAFM I and the Nanonis Mimea SPM controller to actively control the tip–sample distance, thus not only correcting for the drift and creep but also for the non-magnetic corrugations. A small AC bias is applied and the second harmonic (2ω) electrostatic response is digitally demodulated to yield a capacitance-gradient signal, which drives the Z-feedback loop to stabilize the tip–sample separation. The method is illustrated using MFM measurements on Co–Dy multilayer thin films, showing stable magnetic contrast during distance-controlled scanning. Z-spectroscopy measurements provide a straightforward means of selecting suitable modulation and feedback parameters. Beyond its use in MFM, this distance-feedback concept can be applied to other non-contact AFM techniques, including Kelvin probe force microscopy.

1. Introduction

Magnetic force microscopy (MFM) is a widely used scanning probe technique for imaging nanoscale magnetic domains by measuring long-range magnetic interactions between the magnetized probe and the sample surface [1,2].

In conventional implementations, MFM is commonly performed using a dual-pass (lift-mode) scanning mode. In this method, the surface topography is acquired during a first pass, while the magnetic signal is measured during a second pass that follows the recorded topography with a fixed lift offset. Dual-pass MFM provides good separation between short-range topographic forces and long-range magnetic interactions and is therefore widely used for routine magnetic imaging.

In MFM, the magnetic signal arises from the force gradient between a magnetized tip and the sample, which decays rapidly with increasing tip–sample separation. As a result, the measured phase or frequency-shift contrast depends sensitively on the lift-height used during the magnetic imaging pass [2,3].

Despite its robustness, dual-pass MFM presents several practical limitations. Because topography and magnetic signals are acquired in separate passes, the method inherently increases the total acquisition time. This can become a significant constraint in extended measurement series, such as magnetic-field-dependent or temperature-dependent studies. In addition, during the topography pass, the magnetized tip may interact strongly with the sample surface, which can perturb metastable magnetic states or materials with low magnetic anisotropy [3].

Single-pass constant-height MFM offers an attractive alternative. In this mode, the cantilever is scanned at a fixed height above the surface after an initial approach, enabling faster image acquisition and minimizing repeated tip–sample interactions. Constant-height MFM is therefore well suited for rapid imaging and systematic studies where series of scans are critical.

However, the absence of an active distance control loop in constant-height MFM presents a fundamental challenge. Thermal drift, piezoelectric creep, and slow environmental fluctuations can lead to variations in the effective tip–sample separation during the scan. Given the strong distance dependence of magnetic forces, even nanometer-scale changes in separation can result in significant variations in magnetic contrast [2,3], thereby limiting the reproducibility and reliability of constant-height MFM measurements.

To overcome this limitation while retaining the advantages of single-pass operation, an independent distance-sensitive feedback mechanism is required [4,5]. This tech note demonstrates how the Nanonis Mimea SPM controller enables precise capacitive feedback operation in single-pass MFM, ensuring improved phase stability and consistent magnetic contrast during long scans.

2. Theoretical Background

When a conductive AFM tip is biased relative to the sample with a combined DC and AC voltage V(t) = $V_{DC} + V_{AC}\,\sin(\omega t)$, the resulting electrostatic force [6,7] is given by:

$$F_{el} = \frac{1}{2}\frac{\partial C}{\partial z}(V_{DC} - V_{CPD} + V_{AC}\,\sin(\omega t))^2, \qquad (1)$$

where $C(z)$ is the tip–sample capacitance, z is the separation, and V_{CPD} is the contact potential difference [8].

Expanding Eq. (1) yields force components at DC, ω, and 2ω:

$$F_{el} = F_{DC} + F_{\omega} + F_{2\omega}$$

$$\begin{aligned} F_{\mathrm{el}} &= \frac{1}{2}\frac{\partial C}{\partial z}\left[(V_{\mathrm{DC}} - V_{\mathrm{CPD}})^2 + \frac{1}{2}V_{\mathrm{AC}}^2\right] \\ &+ \frac{\partial C}{\partial z}(V_{\mathrm{DC}} - V_{\mathrm{CPD}})V_{\mathrm{AC}}\sin(\omega t) \qquad (2) \\ &- \frac{1}{4}\frac{\partial C}{\partial z}V_{\mathrm{AC}}^2\cos(2\omega t). \end{aligned}$$

These three force components are:

- DC term → static electrostatic attraction
- 1st harmonic (ω) → Kelvin probe signal (depends on DC voltage V_{DC})
- 2nd harmonic (2ω) → purely capacitive term (depends on capacitance gradient and AC modulation voltage V_{AC})

The third second-harmonic (2ω) component is proportional to

$$F_{2\omega}(z) \propto \frac{\partial C}{\partial z}V_{\mathrm{AC}}^2, \qquad (3)$$

is independent of the contact potential difference and increases monotonically as the tip approaches the surface [6,10]. Because $\partial C/\partial z$ depends primarily on geometry and separation, the 2ω response provides a sensitive, CPD-independent distance signal for use in feedback control [9,10].

Demodulating the cantilever response at 2ω therefore yields a distance-sensitive signal suitable for use in a *Z-feedback* controller.

3. Experimental Setup

All MFM measurements were performed using an *attoAFM I* system equipped with a Nanonis Mimea SPM controller consisting of:

- **SC5 scan control** unit for piezo actuation and analog interfacing, and
- **OC4 oscillation control** unit for cantilever excitation and readout.

An AC voltage modulation ($V_{\mathrm{AC}} =$ 1-10 V, $f =$ 3-10 kHz) was applied between the conductive MFM tip and sample. The resulting cantilever response was demodulated 2ω using the built-in digital lock-in amplifier of the Nanonis controller. The in-phase demodulated output, proportional to the capacitance gradient, was used as the input to a *Z-feedback* controller to stabilize the tip–sample separation during scanning.

Measurements were performed on Co–Dy thin films with different compositions. Imaging was conducted at nominal lift heights with and without capacitive distance feedback for direct comparison.

Under capacitive distance control the *Z-feedback* maintains a constant capacitance-gradient rather than a fixed geometric height. The Z-output therefore correlates with topography and local dielectric structure and should be treated as pseudo-topography; the magnetic channel is recorded independently and is not demodulated at the electrical drive frequency.

4. Data Acquisition and Analysis

4.1 Z-Spectroscopy

To characterize the capacitive interaction, *Z-spectroscopy* measurements were performed by sweeping the tip from 300 nm above the surface into contact while recording demodulated 2ω signal.

Two parameter sweeps were carried out:

1. Varying modulation voltage (1 V – 10 V) at fixed 5 kHz
2. Varying modulation frequency (1 kHz – 10 kHz) at fixed 2 V

Figure 1a shows Z-spectroscopy sweep of the demodulated signal as a function of tip–sample distance for modulation voltages ranging from 1 V to 10 V at a fixed modulation frequency of 5 kHz. The signal amplitude increases strongly with increasing modulation voltage, consistent with the quadratic dependence $F_{2\omega} \propto V_{\mathrm{AC}}^2$ as per Eq. 3. Higher modulation voltages therefore improve the signal-to-noise ratio of the capacitive distance signal.

At the same time, excessively large modulation voltages can introduce unwanted effects, including increased electrostatic force gradients and partial suppression of the cantilever oscillation amplitude. Consequently, the modulation voltage must be chosen as a compromise between signal strength and minimal perturbation of the cantilever dynamics.

Figure 1b shows *Z-spectroscopy* sweeps acquired at a fixed modulation voltage of 2 V while varying the modulation frequency from 1 kHz to 10 kHz. At low frequencies, the signal is limited by increased susceptibility to low-frequency noise and

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drift. As the modulation frequency increases into the kilohertz regime, the signal-to-noise ratio improves significantly due to reduced environmental noise and efficient phase-sensitive detection.

At higher frequencies, the response begins to decrease due to limitations imposed by the cantilever transfer function and detector bandwidth. An optimal modulation frequency is therefore typically found in the range of a few kilohertz, where the capacitive signal is strong while mechanical cross-coupling remains minimal.

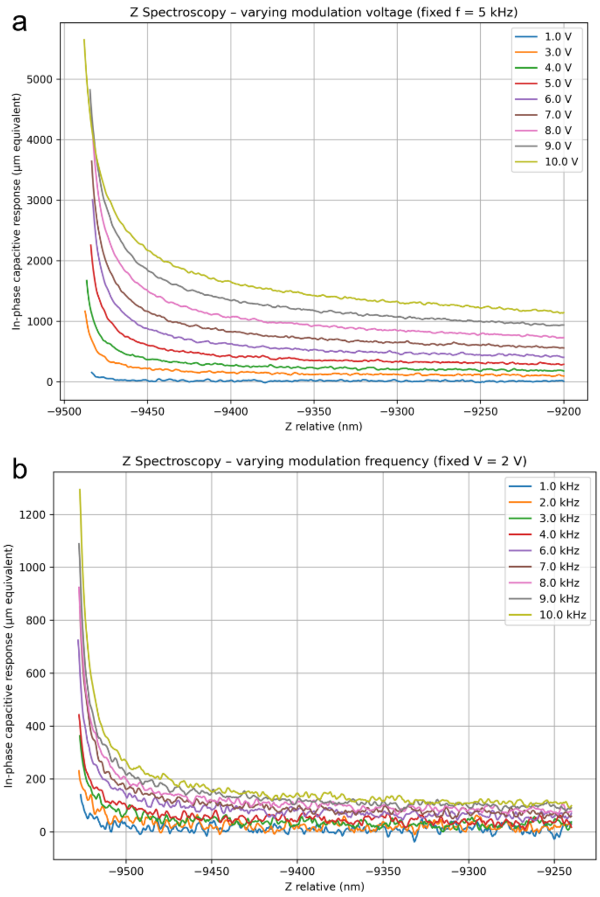

Fig 1: Approach curves showing the demodulated electrostatic response amplitude as a function of tip–sample separation. The tip approaches the surface from right (non-contact) to left (contact). (a) Dependence on applied modulation voltage V_{AC} (1-10 V at fixed 5 kHz). (b) Dependence on modulation frequency (1–10 kHz at fixed 2 V). The sharp rise at the left corresponds to tip–sample contact, where mechanical deflection dominates the response.

4.2 Distance dependence of capacitive signal

The increase of the demodulated 2ω signal upon approaching the sample surface (as shown in Figure 2) reflects the increasing capacitance gradient at small tip–sample separations. For typical AFM tip geometries, the capacitance gradient can be approximated by a power-law dependence [11,12]:

$$\frac{\partial C}{\partial z} \propto (z + z_0)^{-n},$$

where z_0 accounts for the effective tip radius and n depends on the specific tip geometry and electrostatic boundary conditions. As a result, the capacitive signal increases sharply as the tip approaches the surface, providing a highly sensitive measure of distance.

This strong distance dependence makes the 2ω capacitive signal ideally suited for feedback stabilization, as small changes in tip–sample separation produces readily detectable changes in signal amplitude.

4.3 Implementation of capacitive feedback

Based on the optimization of the modulation parameters in Figure 1, the demodulated 2ω signal was used as the input to the *Z-feedback* controller during the single-pass MFM scan. Proportional and integral gains were adjusted to ensure stable operation with a loop bandwidth sufficient to compensate for slow drift while avoiding oscillations. Typical parameter ranges were P = 0.1 – 0.5 and I = 0.5 – 5 Hz.

Once engaged, the feedback loop continuously adjusted the Z-piezo position to maintain a constant capacitance-gradient setpoint, thereby compensating drift throughout the scan.

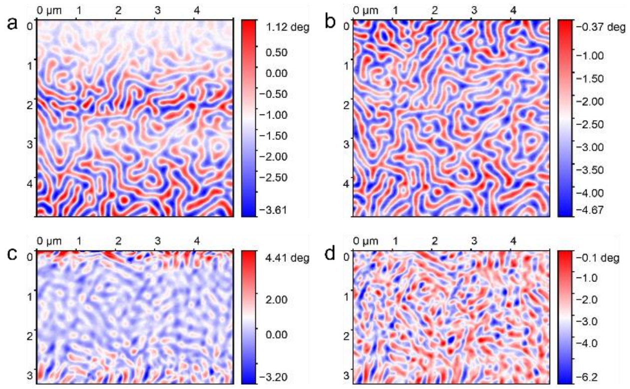

Fig 2: Comparison of MFM Images on Co–Dy multilayer with and without feedback. (a,c) MFM phase images acquired in 30 nm lift height operation without additional Z-feedback. (b,d) Corresponding images recorded with the demodulated 2ω signal used as the input for the Z-controller.

Figure 2 compares MFM images of Co–Dy multilayer films acquired without and with capacitive distance control.

Without feedback, the magnetic phase contrast gradually decreases along the slow scan direction (Figure 2a and 2c). This behavior is attributed to an increasing effective lift height caused by drift, reducing the magnetic force gradient sensed by the cantilever.

With capacitive feedback enabled, the tip–sample separation is actively stabilized, leading to consistent magnetic contrast across the entire scan (Figure 2b and 2d). Domain features such as domain walls and labyrinthine textures remain well resolved, even over long scan durations, confirming the robustness of the feedback mechanism.

These results demonstrate that capacitive distance control effectively reduces the influence of slow mechanical drift in magnetic imaging.

5. Conclusion

In this tech note, we have demonstrated that capacitive distance feedback provides a robust and practical solution for stabilizing the tip–sample separation during single-pass MFM measurements. By utilizing a distance-sensitive capacitive signal obtained through second-harmonic lock-in demodulation, slow drift and piezoelectric creep effects can be effectively compensated without compromising magnetic contrast.

The implementation relies solely on existing capabilities of the Nanonis SPM controller, including its flexible signal routing, digital lock-in demodulators, and multi-loop feedback control, and does not require additional hardware. Z-spectroscopy measurements provide a straightforward route for selecting optimal modulation voltage and frequency, ensuring high signal-to-noise ratio and stable feedback operation.

Beyond MFM, the demonstrated capacitive distance feedback scheme is readily applicable to other non-contact scanning probe techniques. In particular, it can be combined with Kelvin probe force microscopy to enable drift-stabilized single-pass KPFM, where distance control and electrostatic potential compensation operate in parallel. Overall, capacitive distance feedback expands the measurement capabilities of the *attoAFM I*, enabling faster and more stable nanoscale imaging.

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