Magnetic force microscopy with frequency-modulated capacitive tip–sample distance control

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**Abstract**

In a step towards routinely achieving 10 nm spatial resolution with magnetic force microscopy, we have developed a robust method for active tip–sample distance control based on frequency modulation of the cantilever oscillation. It allows us to keep a well-defined tip–sample distance of the order of 10 nm within better than ±0.4 nm precision throughout the measurement even in the presence of energy dissipative processes, and is adequate for single-passage non-contact operation in vacuum. The cantilever is excited mechanically in a phase-locked loop to oscillate at constant amplitude on its first flexural resonance mode. This frequency is modulated by an electrostatic force gradient generated by tip–sample bias oscillating from a few hundred Hz up to a few kHz. The sum of the side bands’ amplitudes is a proxy for the tip–sample distance and can be used for tip–sample distance control. This method can also be extended to other scanning probe microscopy techniques.

**1. Introduction**

A magnetic force microscope (MFM) is a scanning probe tool that is particularly well suited for imaging stray magnetic fields emanating from a sample surface with high spatial resolution \(^1\) and in applied fields. Its performance is conditioned on various physical constraints that can be met in most cases with existing techniques. For instance, the minimum force gradient detectable in thermal equilibrium is inversely proportional to the square root of the MFM cantilever’s quality factor, so operation in vacuum is an obvious method to enhance the sensitivity of the instrument \(^2\). In some cases, however, better strategies have yet to be developed. For example, due to the fact that the high spatial frequency components of the stray field decay rapidly with increasing distance from their source, the MFM tip preferably scans at small tip–sample distances \(^3\)–\(^6\). Controlling this small distance, however, is challenging because magnetic and non-magnetic forces act on the tip simultaneously \(^7\). Under ambient conditions, a dual passage method is typically used \(^7,8\). In the first scan the intermittent contact mode is used to map the topography of the sample. The latter is then used to scan the magnetic signal with the tip lifted off the surface of the sample. A serious drawback of this technique is being incompatible with operation under vacuum conditions.

We have recently reported two single-passage operation modes suitable for operation under vacuum conditions. The first method \(^6\) mechanically excites the cantilever oscillation simultaneously on its first and second resonances. Because the oscillation amplitude of the first mode is selected to be more than one order of magnitude larger than that of the second mode, the frequency shift of the first mode reflects the longer-ranged magnetic interactions, while that of the second mode is dominated by the van der Waals forces. The latter contributes mainly when the tip is closer to the sample, given its shorter decay length. Evidently, the tip must be able to reach close proximity to the surface to map the van der Waals forces. Consequently, the tip–sample distance z-feedback speed must be sufficiently fast such that the tip can follow the topography on a local scale during the scan. Such a fast z-feedback however increases the noise in the tip–sample distance and therefore the
noise of the measured magnetic signal that depends on it. Moreover, an operation under constant average tip–sample distance, often used for quantitative data analysis, is not possible when using this method.

The second MFM operation method recently described by our group [9] overcomes these limitations. Again, the cantilever is excited mechanically on its first resonance to map the magnetic tip–sample interaction via the shift of the first mode resonance frequency. The second oscillation mode is driven electrostatically using an oscillatory tip-sample bias at half the cantilever resonance frequency of the second mode. This generates an oscillatory electrostatic force acting on the tip on the second resonance frequency. The second mode cantilever oscillation amplitude $A_2$ can then be used to control the tip–sample distance $z$. With a sufficiently fast $z$-feedback parameter, the tip follows the local topography. Alternatively, the $z$-feedback parameters can be kept slow such that the tip follows the local sample surface slope. Data acquired in this mode facilitates a posteriori quantitative data analysis [10–12]. The variation of $A_2$ is a measure of the sample topography and can for example be used to align images measured in different external magnetic fields [9].

However, as already discussed in [9], a tip–sample distance control based on the $A_2$-signal would fail if the second mode quality factor $Q_2$ of the cantilever changed. There are various mechanisms that can affect $Q_2$. We often found that it increases slightly over time, after the cantilever has been introduced to the vacuum system. We attribute this behavior to a reduction in the water layer thickness adsorbed on the cantilever. $Q_2$ also changes substantially with the applied magnetic field. Stipe et al. [13] showed strong dissipation for cobalt nanowires fabricated on cantilevers with force constants in the $\mu$N/m range with a low intrinsic dissipation, designed for detecting forces on the attonewton scale. Stipe et al demonstrated that the dissipation of such cantilevers can change by several orders of magnitude when magnetic fields up to 6T were applied at low temperatures. Later results obtained by Rast et al. [14] looked into the dependence of the frequency shift and energy dissipation for different hard magnetic particles attached to a cantilever. The decay of the quality factor for fields between 0–0.5 T was found to be inversely proportional to the anisotropy constant of the material of the particle, and proportional to its volume. Different from the work of Stipe et al. [13] and Rast et al. [14], the cantilevers used in MFM (and in most scanning force microscopy work) are not perpendicular to the surface but subtend a small angle with the latter, of about $10^\circ$. We usually find that the quality factor of such cantilevers creeps over hours after applying stronger fields (> 500 mT), particularly at lower temperatures. We attribute this slow and hysteretic variation in the quality factor over time to the changes of the magnetostriction of the magnetic layer on the cantilever as its magnetization rotates out of the plane of the cantilever in increasing fields. Furthermore, the magnetization of the tip, or that of the sample, may vary with the oscillating tip–sample distance at locations over the surface where the magnetic tip–sample interaction is strong. There, additional losses of the energy stored in the cantilever oscillation can take place, which amount to a decrease in the quality factor [15].

### 2. Method

Here we present a method by which accurate distance control becomes possible, independent from changes in the quality factor. A schematic of the setup is presented in figure 1. The cantilever is driven mechanically on the first flexural oscillation mode with a phase-locked loop (PLL) system that tracks changes in the cantilever resonance frequency $\Delta f'$ and also keeps the oscillation amplitude $A_0$ constant. Changes in the first mode quality factor are thus compensated with the appropriate adjustment of the driving amplitude. Further, the tip–sample bias $U_{sc}$ is oscillated at a frequency $f_{sc}$ of a few hundred Hz leading to the modulation of the cantilever resonance frequency (see green box in figure 1).

A signal $A(t) = A_0 \cdot \cos(\omega_c t)$ which is frequency-modulated by $f(t) = A_m \cdot \cos(\omega_m t)$ can be written as

$$A_{FM}(t) = A_0 \cdot \text{Re} \left[ e^{i\omega_c t} e^{i\beta \sin \omega_m t} \right]$$

$$= A_0 \cdot \sum_{n=\infty} J_n(\beta) \cos(\omega_c + n\omega_m) t,$$

where $\omega_c$ is the carrier frequency, $J_n$ is the $n$th Bessel function [17], and $\beta$ is the modulation index. The spectrum of the frequency-modulated (FM) signal (equation (2)) thus contains an infinite number of side bands even for a single modulation frequency $\omega_m = 2\pi f_m$. The amplitudes of these spectral components are proportional to the Bessel functions

$$J_n(\beta) = \sum_{k=0}^{\infty} \frac{(-1)^k \beta^{n+2k}}{k!(n+k)!}.$$

For our high resolution MFM work, cantilevers with high-aspect ratio tips with a radius smaller than 5 nm, and a resonance frequency $f_0$, of the order of 50 kHz, are used. To minimize the non-magnetic contribution of
the tip–sample force, the contact potential \( U_{dc}^{(K)} \) is compensated. We find that for an applied bias deviating 500 mV from the contact potential, i.e. for \( U_{dc} = U_{dc}^{(K)} \pm 500 \text{ mV} \), the electrostatic force gradient-induced frequency shift, \( \Delta f_{xy} \), remains smaller than 5 Hz at a tip–sample distance of 10 nm (see figure 4 in section 3.2). For \( f_m = f_{ac} = 1 \text{ kHz} \), the modulation index \( \beta = \Delta f_x / f_m \) thus remains smaller than \( 5 \times 10^{-3} \). The Bessel functions in equation (2) can then be approximated by

\[
J_0(\beta) = 1 - \frac{\beta^2}{4} + \frac{\beta^4}{32} - \ldots \approx 1 - \frac{\beta^2}{4}
\]  
\[J_1(\beta) < \beta, \quad \text{with} \quad \lim_{\beta \to 0} J_1(\beta) = \frac{\beta}{2}
\]

\[
J_n(\beta) \approx \left( \frac{\beta}{2} \right)^n \quad \text{for} \quad n > 1,
\]

\[
J_{-n}(\beta) = J_n(\beta) \cdot (-1)^n \quad \text{for} \quad n > 0.
\]

For \( \beta < 10^{-2} \), the spectrum of the frequency-modulated signal (figure 2) thus contains the carrier frequency and two side bands at \( f_c \pm f_m \). The amplitude of these side bands, \( A_0 \cdot J_1(\beta) \), is more than \( \beta \) times smaller than that of the carrier signal \( A_0 \) (typically 5 nm). Higher order side bands have correspondingly smaller amplitudes (see equation (6)) such that, in practice, they are below the noise floor of the deflection detector and can be neglected. Note that the side band at \( f_c - f_m \) has a phase shift of \(-\pi\) compared to the one at \( f_c + f_m \) (see equation (7)).
The electrostatic force acting on the tip is given by
\[
F_z(z, t) = \frac{1}{2} \frac{\partial C(z)}{\partial z} \cdot \left[ U_{dc} + U_{ac} \cos(2\pi f_{ac} t) \right]^2 \\
= \frac{1}{2} \frac{\partial C(z)}{\partial z} \cdot \left[ U_{dc}^2 + 2 U_{dc} U_{ac} \cos(2\pi f_{ac} t) \right. \\
\left. + U_{ac}^2 \cos^2(2\pi f_{ac} t) \right],
\]
where \( U_{dc} = U_{dc}^{(0)} + U_{dc}^{(1)} \) is the sum of the contact potential and applied potential, \( U_{ac} \) is the amplitude of the potential modulation, and \( C(z) \) is the distance dependent tip–sample capacitance that in principle can be calculated if the tip geometry is known [18]. Equation (8) shows that \( F_z \) has a dc-component proportional to \( U_{dc}^2 \), and components at frequencies \( f_{ac} \) and \( 2f_{ac} \). The carrier frequency can be expressed as \( f_c = f_0 + \Delta f_{vdb} + \Delta f_{g} + \Delta f_{mag} \), where \( f_0 \) is the free resonance frequency of the cantilever, \( \Delta f_{vdb} \) and \( \Delta f_{g} \) are the frequency shifts arising from van der Waals and the dc part of the electrostatic force, respectively, and \( \Delta f_{mag} \) depends on the magnetic tip–sample interaction. The two ac components of the electrostatic force generate two groups of first-order side bands at \( f_c \pm f_{ac} \) and \( f_c \pm 2f_{ac} \) (figure 2). Note that the side bands at \( f_c \pm 2f_{ac} \) are the first-order side bands of a modulation at the frequency \( 2f_{ac} \), and not the second order side bands of a modulation at the frequency \( f_{ac} \), because \( J_n \approx 0 \) for \( n > 1 \) (see equation (6)).

The amplitudes of the side bands at \( f_c \pm 2f_{ac} \) are given by
\[
A_{2f_{ac}} \propto A_0 \cdot J_1(\beta) \approx A_0 \cdot \frac{\beta}{2}
\]
where the approximation is valid for small \( \beta \). Similar to our previous work [9], we use the amplitudes of the second side bands at \( 2f_{ac} \) for the distance control, because their amplitudes are independent of \( U_{dc} \), and therefore of the contact potential difference. Provided that the tip–sample capacitance and its dependence on tip–sample distance are known, \( \beta \) can be calculated as
\[
\beta = \frac{U_{ac}^2}{4\pi k_e} \cdot \int_{-A_0}^{A_0} \frac{d^2C(z + A_0 - q)}{dz^2} \cdot \sqrt{A_0^2 - q^2} \cdot \frac{1}{2A_0^2} dq,
\]
where \( k_e \) is the first mode force constant of the cantilever. Thus the amplitude \( A_{2f_{ac}} \) is a proxy for the tip–sample distance, and can be used for tip–sample distance control (see the area highlighted by the blue color in figure 1).

Note that as long as the carrier signal amplitude, i.e. the fundamental mode oscillation of the cantilever \( A_0 \), is kept constant by \( A \)-feedback, the side band amplitudes are independent of changes in the quality factor \( Q \).

3. Results

In order to test the performance of frequency-modulated capacitive distance control method discussed in section 2, we used a low temperature magnetic force microscope operated in UHV [19]. The system contains a superconducting solenoid magnet that can provide magnetic fields up to 7 T. We utilized uncoated silicon cantilevers from Team Nanotech GmbH with a resonance frequency of about 50 kHz and nominal stiffness of 0.7 N/m. The cantilever backside was coated with Pt to increase the optical reflectivity and signal-to-noise ratio of our fiber–optical interferometer system. The sharp high-aspect ratio tip was made to be sensitive to stray
magnetic fields with a coating of 2 nm Ti and 6.5 nm Co (nominal thickness) coated on the backside of the tip at an angle of about 30° with respect to the cantilever surface. The sputter deposition for cantilevers and samples (described in the following two subsections) was performed in a UHV dc magnetron sputtering system from AJA International Inc. The typical base pressure prior to deposition is $1 \times 10^{-8}$ mbar or better.

### 3.1. Magnetic force microscopy in the case of strong tip–sample interaction

The frequency shift contrast in magnetic force microscopy arises from the interaction of the tip magnetization with the stray field of the sample or, conversely, from that of the tip stray field with the magnetization of the sample [20]. It is convenient to use low enough magnetic moment tips with high magnetic coercivity such that to a good approximation, neither tip nor sample magnetization is significantly affected by their proximity. The MFM contrast can then be calculated as a convolution of the tip magnetization with the gradient of the sample stray field and methods for a quantitative analysis of the measured frequency shift data can be applied [10, 21].

Here we designed an experiment where the tip scans over a sample whose domains generate a stray field that is strong enough to affect the micromagnetic state of the tip near some of the domain walls. Energy dissipation of the oscillating cantilever can therefore occur, leading to an increase in the amplitude of the cantilever excitation $A_{\text{exc}}$ if the micromagnetic state switches periodically between two states over an oscillation period of the cantilever; in this case $Q_2$ will have changed. We used a magnetic multilayer sample that exhibits perpendicular magnetic anisotropy, specifically (Si$_{\text{as}}$/Pt(5 nm)/[Co(0.4 nm)/Pt(0.7 nm)]$_{15}$/Pt(2 nm)) [22]. The sample was dc magnetron sputtered at room temperature in a 2 mbar Ar atmosphere onto a naturally oxidized Si substrate. The deposition rates of Co and Pt were 0.09 Å/s and 0.24 Å/s, respectively.

Figures 3(a) and (d) depict the MFM frequency shift data obtained with a fast and slow speed of $A$-feedback (A-P1 in the blue box of figure 1). The yellow ellipses highlight some of the areas of the domain walls where instabilities of the micromagnetic state of the tip occur [23, 24]. Figures 3(b) and (e) and figures 3(c) and (f) compare the fundamental mode oscillation amplitude $A_0$ of the cantilever (nominally 10 nm) and the sum of the amplitudes of the (second) side bands at $f_c \pm 2f_{\text{mod}}$, respectively; the actual $f_c$ is the fundamental mode resonance frequency of the cantilever (note that $\Delta f = f_0 - f_c$ is plotted in panels (a) and (d)). For a sufficiently fast $A$-feedback, the fundamental mode oscillation amplitude $A_0$ (figure 3(b)) deviates less than ±5 pm from the setpoint value of 10 nm. Then the sum of the amplitudes of the side bands at $f_c \pm 2f_{\text{mod}}$ solely reflects topography-induced changes of the tip–sample distance (granular contrast visible in figure 3(c)). This is no longer true for lower speeds of $A$-feedback. In that case, $A_0$ deviates significantly from its setpoint at the locations over the domain walls where energy dissipative processes occur (yellow ellipses in figure 3(e)), leading to a decrease in $A_{\text{mod}}$ (see equation (9)). For a slow $z$-feedback, the distance (defined as the lowest point in an oscillation cycle of the cantilever) becomes larger at locations of decreased oscillation amplitude $A_0$, resulting in a further reduction in $A_{\text{mod}}$ amplitude (equation (9)). These effects explain the strong relative contrast highlighted by the yellow ellipses in figure 3(f). Clearly, our frequency-modulated capacitive distance control method is valid even in the presence of energy dissipative processes, as long as the fundamental mode oscillation amplitude $A_0$ is kept constant.

### 3.2. Magnetic force microscopy in magnetic fields

Domains have been imaged in magnetic fields up to a few hundred mT by MFM already in 1995 by Manalis et al [25], and by Proksch et al [26]. Both groups performed MFM under ambient conditions using lift-mode operation [7, 8] to control the tip–sample distance. As alluded to previously, for magnetic force microscopes operated under vacuum conditions, the high quality factor increases the sensitivity but precludes the use of the intermittent contact mode for tip–sample distance control. Instead, many early MFM experiments performed in vacuum used the measured frequency shift for the distance $z$-feedback. Then contours of constant frequency shift were recorded. Alternatively, slow $z$-feedback parameters or an additional servo-force generated by an applied tip–sample bias [27] can be used, such that the tip–sample distance can be kept small and the tip scans roughly parallel to the average sample slope. The latter can also be achieved when the $z$-feedback is stopped and the average sample slope is compensated [28–30].

The application of higher magnetic fields (>500 mT) deflects the cantilever, and changes its resonance frequency substantially (even for the thin magnetic coatings used here, as can be seen in figure 5(c)). Moreover, we have often observed the resonance frequency to creep over tens of minutes after a change of the applied field from zero to more than 1 T. In fact, in order to prevent the tip from crashing onto the surface, the tip is typically retracted from the surface before the field is changed. The tip must then be re-approached to the surface, and the $z$-feedback setpoint must be reset (if a $z$-feedback is used) before further MFM data can be acquired [31, 32]. This makes reproducible MFM measurements in strong fields challenging, and presumably explains why only a few studies on MFM operated in fields of several Tesla have been reported to date [33, 34]. Yet such strong fields are required, e.g., for the study of samples exhibiting exchange bias effects [35], or for the analysis of the
magnetization behavior of $L_10$-FePt phase recording materials \[36\], exchange coupled media, and ferro/ferrimagnetic bilayers exhibiting giant exchange bias effects \[37\].

It is therefore important to quantify the effects from applied fields and assess the ability of the present method to compensate for changes in the resonance frequency and quality factor of the cantilever. We select a high coercivity material system with perpendicular anisotropy to discuss the MFM performance in applied fields up to 7 T. Specifically, we work at 10 K on a Si$\textsubscript{ox}$/Pt(10 nm)/TbFe(20 nm)/Pt(3 nm) film, where the Tb content is 25% (atomic ratio). The TbFe film was dc magnetron deposited by co-sputtering from separate Tb and Fe targets, with deposition rates of 0.20 Å/s and 0.22 Å/s, respectively. Vibrating sample magnetometry (VSM) measurements (not shown) that we performed on this sample reveal a strong perpendicular magnetic anisotropy and a high coercive field of about 5.4 T at 10 K. The high coercivity allows the study of the domain pattern in fields of several Tesla and the comparison of MFM data acquired in different fields.

To determine the frequency shift as a function of the tip–sample distance, we acquired scans in which we varied the $z$-distance over 50 nm on approaching the sample surface. Depending on the initial tip–sample distance and the applied bias, the curves will be different. The black curve displayed in figure 4 is the one for which the frequency shift at the closest tip–sample distance reached about $-50$ Hz, when the contact potential

**Figure 3.** (a), (d) MFM images recorded with fast and slow feedback of the fundamental oscillation mode amplitude $A_0$, respectively, on a [Co(0.4 nm)/Pt(0.7 nm)]$_{15}$-multilayer exhibiting perpendicular magnetic anisotropy. The strong tip–sample interaction near the domain walls (e.g. at the yellow ellipses) leads to changes in tip/sample magnetization that lower the quality factor of the cantilever. (b) For a sufficiently fast $A$-feedback, $A_0$ remains constant within ±5 pm around the setpoint of 10 nm. (c) The sum of the side band amplitudes then reflects local variations of the tip–sample distance arising from the topography of the sample. (e) For a slow $A$-feedback, the amplitude $A_0$ is significantly smaller at the locations with lower Q. (f) The side band amplitudes are also affected by the variations of $A_0$. 
was compensated by an applied bias. The gray curve is recorded with an applied dc-bias deviating 500 mV from the contact potential. The difference between the two curves is displayed in blue, indicating the frequency shift arising from 500 mV dc-potential. The green curve is the estimated frequency shift arising from 500 mV ac-potential, given that the applied bias is a sinusoidal function. The frequency shift generated by the 500 mV ac-potential (green line in figure 4) is about half of that arising from a 500 mV dc-potential (blue line in figure 4) because the time-averaged electrostatic force is proportional to the square of the effective value of the 500 mV ac-potential. The frequency shift arising from the capacitive force is roughly equal to that of the van der Waals force.

Figures 5(a) and (b) depict MFM data acquired with a side band amplitude setpoint of 4.5 pm corresponding to a tip–sample distance of \( z = 5 \) nm in zero field with up and down tip magnetization, respectively. The tip magnetization was set by the application of a field of \( \pm 50 \) mT. The MFM data acquisition was performed with a slow \( z \)-feedback that keeps the average second side band amplitude thus the average tip–sample distance constant. The \( z \)-feedback then compensates for distance changes for example arising from the deflection of the cantilever in an applied magnetic field or thermal drift, but not for local variations in the tip–sample distance arising from the topography. The contrast arising from a magnetic interaction between the tip and the domains inverts with the direction of the tip magnetization, but the contrast from topography-induced variations of the van der Waals and electrostatic forces appears as small and faint dark spots independent of the magnetization direction of the tip (e.g. the dark spot in the dashed black square highlighted by the yellow arrows in figures 5(a) and (b)). The electrostatic forces are minimized by the compensation of the contact potential, but the modulation of \( \pm 500 \) mV as-potential around the compensation potential generates an average electrostatic force that depends on the local tip–sample distance.

The magnetic and topographic contributions to the measured contrast can be disentangled by taking the half-difference (figure 5(c)) and half-sum (figure 5(f)) of data shown in panels (a) and (b), respectively. A pattern of extremely faint lines reminiscent of the domain walls is visible in figure 5(f). It arises either from a non-perfect alignment of the data before the summing, or from an extremely weak change of the magnetization of the tip or sample caused by their magnetic interactions. Apart from this, the well-visible dark dots arise from the (small) sample roughness. These topographical contributions to the measured contrast become better visible when the data is displayed in color (figures 5(g) and (h)), and at a smaller scale (see areas highlighted by the solid and dashed squares in panels (a), (b) and (f)).

Figures 5(c) and (d) depict the MFM data acquired with the same tip–sample distance control in the \( \pm 4 \) T field applied perpendicular to the sample surface, respectively. Note that the applied field changes the magnetization direction of the tip, but not that of the TbFe film due to its high coercivity. The topography data obtained from the half-sum of the 4 T data (from the areas highlighted by the solid and dashed squares in panels (c) and (d)) is displayed in figures 5(i) and (j), where the frequency shift offset has been removed. They look identical to those obtained from the zero field data in figures 5(g) and (h). Figures 5(k)–(n) display the topography (approximately \( \pm 1 \) nm) obtained from the convolution of the frequency shift versus distance data (from the green curve in figure 4) and the topography-induced frequency shift data (displayed in figures 5(g)–(j)). To estimate the deviation...
of the tip–sample distance between data taken at 0 T (figures 5(a) and (b)) and 4 T (figures 5(c) and (d)), the differences between the data in the panels (k), (m) and (l), (n), respectively, are calculated.

The results are displayed in panels (o) and (p), where the edges are cut-off due to the alignment of images measured in different fields. The maximum deviation is about ±0.4 nm over images (o) and (p), and the RMS deviation is about 0.1 nm. Note that the z-feedback typically adjusts the sample z-position by about 2–3 nm during the acquisition of one image (10 minutes) to compensate for the z-drift of the instrument. For the acquisition of the images taken in a field of 4 T, the z-feedback changes the sample z-position by 14 nm to keep the tip–sample distance constant despite the drift of the instrument (over 126 minutes) and the bending of the cantilever in the applied field. This demonstrates the robustness of the distance control in applied fields.

The hysteresis loop of high coercive materials with perpendicular magnetic anisotropy like amorphous TbFe-alloys can be several Tesla wide whereas the switching occurs within a few tens of milli-Tesla \cite{38}. Besides allowing separation of the topographical and magnetic signals, measurements in different applied fields can be used to analyze a reversal process with a high level of local detail. Typically, in order to observe domain
nucleation and the successive wall motion, a large number of MFM images must be acquired at small increasing field intervals, such that the different steps in the reversal process can be captured. The switching field would be more conveniently assessed by ramping the magnetic field while the same line is repeatedly scanned. We have already discussed, however, that the application of magnetic field would lead to additional energy dissipation, deflection of the cantilever and shift of its resonance frequency, rendering the method impractical if the field exceeds a few hundred mT and the tip–sample distance is to be maintained nearly constant.

Figure 6 (a) depicts repeated scans of the red line indicated in figure 5(a) in a magnetic field that increases from 0–7 T with 194 mT/minute, at a tip–sample distance of 14.3 nm. As found before (compare figures 5(a) and 5(c)), the applied field leads to a strong variation of the background frequency shift (figure 6(c)) of approximately 30 Hz that dominates the 5 Hz contrast arising from the magnetic forces. Frequency shift of scanlines taken in different fields are displayed in figure 6(b). Note that the dependence of the background frequency shift on the field is not monotonic (figure 6(c)) indicating that the magnetization processes of the different parts of the magnetic layer on the cantilever and on the tip contribute to the background frequency shift. The blue curve in figure 6(d) shows the excitation amplitude $A_{\text{exc}}$ as a function of the applied field $B$.

Interestingly, the highest dissipation does not occur in the highest field but in the relatively moderate field of 299 mT, where a first local minimum of the frequency shift is observed (see figure 6(c)). $A$-feedback (A-PI in the blue box shown in figure 1) operates sufficiently fast to keep the deviation of the amplitude from its setpoint of 5003 pm within less than 1‰ (red curve in figure 6(d)). When the field is increased from 0–299 mT the z-piezo...
retracts the sample by about 57 nm (blue curve in figure 6(e)) predominantly to compensate the deflection of the cantilever (blue curve in figure 6(f)). The speed of the z-feedback is slightly too slow to keep the tip–sample distance constant, so that the measured side band amplitude \(A_{2f_m}\) increases from about 2–3 pm (red line in figure 6(e)) corresponding to the decrease in the tip–sample distance from 13 pm to 8 nm. In principle, we could use a faster z-feedback, but at the cost of \(\Delta f\) signal-to-noise ratio. Since there is no resonance amplification of the electrostatic force at the bias oscillation frequencies \(f_m\) or \(2f_m\), and the amplitudes of the side bands are proportional to \(f_m/\beta\) which is approximately equal to \(\beta/2\) (see equation (5)), the side band amplitude and thus the signal-to-noise ratio remains small. This limits the speed of the z-feedback such that the tip cannot follow the local topography with an acceptably small error signal.

A comparison of the cantilever deflection (blue curve in figure 6(f)) with the z-piezo travel (blue curve in figure 6(e)) confirms that the z-piezo travel compensates the field-induced cantilever deflection to keep the tip–sample distance constant for fields below 2 T. In the field range of 2–7 T the cantilever deflection approaches a saturation at about +18 nm, while the z-piezo travel becomes proportional to the applied field up to about 6 T before a saturation at about –58 nm occurs. Thus the z-piezo travel is larger than the cantilever deflection for fields above 3 T, suggesting that the field also affects the tip–sample distance directly through the deformation of parts of the microscope. These contributions are disaggregated in figure 6(f). We can see that the proposed distance control method is able to provide insight into the various mechanisms contributing to the energy dissipation, and could conceivably be used for local characterization of the dissipation processes in thin magnetic films.

4. Conclusions

Our results demonstrate that average tip–sample distances in the range between a few nm and several tens of nm can be kept essentially constant, even during applied field ramps, at least when the height of topographical features does not exceed a few nm. Provided that the \(A\)-feedback is set to keep the fundamental oscillation mode amplitude constant, we show that the method is effective also when the quality factor of the cantilever unexpectedly changes, so that the distance control is unaffected by dissipative processes. Thus our work represents not only an improvement over using the second flexural mode for capacitive distance control described by Schwenk et al, but a major extension of the field of application of MFM to studying local reversal processes in large varying applied magnetic fields. It enables scanning at constant average height for reliable \(a\ posteriori\) quantitative processing of the measured data. The method presented here could also be applied for tip–sample distance control of other scanning probe methods mapping the magnetic fields above the sample, for example for scanning-NV-center-magnetometry [39], provided that cantilevers with sufficient thermal noise sensitivity are used. Due to its stability in varying conditions the method is well suited for automated measurement control.

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