Direct tip-position control using magnetic actuation for achieving fast scanning in tapping mode atomic force microscopy

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This article presents the development of a faster control loop for oscillation amplitude regulation in tapping mode operation of atomic force microscopy. Two techniques in relation to actuation and measurement are developed, that together significantly increase the bandwidth of the control loop. Firstly, magnetic actuation is employed to directly control the tip position of the cantilever to improve both the speed and the dynamics of the positioning system. Secondly, the signal path for oscillation amplitude regulation is separated from that for topography estimation in order to eliminate measurement delay that degrades the performance of the feedback loop. As a result, the phase-crossover frequency and gain margin of the control system are both increased, leading to a faster and more stable system. Two experiments are performed, one in air and the other in aqueous solution, to compare the developed control system with a commercial one and demonstrate the improvement. The results verify that the combination of the two techniques along with other existing methods eliminates all limitations associated with the instrument for the purpose of oscillation amplitude regulation, which is therewith dictated by the bandwidth of the cantilever.


I. INTRODUCTION

In the tapping mode operation of atomic force microscopy (AFM), a cantilever is oscillated at its resonance frequency and controlled to gently tap the surface of a sample. The intermittent contact greatly reduces lateral force when compared with contact mode operation. The most commonly used method is a form of amplitude modulation, in which the oscillation amplitude of the cantilever is modulated by variations of the tip-to-sample distance. By feeding back changes in oscillation amplitude to adjust the cantilever z position, the amplitude is regulated at a set point while scanning a sample. The resulting changes in z position of a piezo-based positioner yields the topography of the sample surface. Faster changes in topography, which result from scanning the sample faster, necessitate faster response of the amplitude control system. Thus, while tapping mode AFM has found many applications,1 the speed of the z-control loop has been one of the key barriers that limit imaging rate and inhibit innovation leading to new applications.

The dynamics of the z-control loop consists of several elements. Its response speed is directly related to the bandwidth of each element and is dictated by the slowest element in the loop. Some elements are connected with the instrument while others are related to the bandwidth of the cantilever and the tapping dynamics itself. In order to optimize the overall speed of the control loop, the speed of every element within the loop has to be optimized to match the fastest component in the feedback loop, which is usually the AFM cantilever. A key element connected with the instrument is the piezo-based z positioner whose bulky nature and underdamped dynamics severely restrict the closed-loop bandwidth even when other elements are significantly faster. Smaller piezopositioners increase positioning speed owing to correspondingly higher bandwidth, but at the cost of achievable z range.2–4 In addition, the AFM has to be either custom designed or significantly modified to incorporate this feature. Integrated cantilevers with microfabricated piezoactuators5,6 also solve this problem although practical considerations restrict the choice of the cantilever and its dynamical properties.7 Two other significant factors that limit speed, namely, the bandwidth of tapping operation and the delay introduced by amplitude measurement with rms-to-dc converters, are decided by the bandwidth of the cantilever. Decreasing the quality factor using Q control increases the tapping bandwidth and alleviates the former problem,8 but the latter issue has often limited the achievable speed of the control loop,9 particularly when the bandwidth of the tapping dynamics and the speed of the z actuation have been improved.

In this article, two techniques in relation to actuation and measurement are developed, that together significantly increase the bandwidth of the control loop. Firstly, a magnetic actuator is proposed and implemented to directly control the position of the cantilever tip. The primary motivation for using magnetic actuation in tip-position control arises from the high bandwidth of this actuation technique and a significantly better dynamics of the actuator, namely, the actuation coil. In addition, virtually any cantilever can be modified to implement this technique. Although the magnetic actuator can also provide harmonic excitation to the cantilever, similar to that in MAC (magnetic ac) mode10 operation, its purpose is to control the dc component of the tip position, not ac oscillation. Therefore, its design and implementation are different from those of usual MAC mode actuators. Secondly, the signal path for oscillation amplitude regulation is sepa-
rated from that for topography estimation. This eliminates
the rms-to-dc converter from the $z$ control loop and its
attendant time delay, thereby improving both the speed and sta-
bility of the control system.

Two experiments are performed, one in air and the other
in aqueous solution, to compare the developed control sys-
tem with a commercial one and demonstrate the improve-
ment achieved in tracking fast-changing topography. The re-
results verify that the combination of the two techniques along
with other existing methods eliminates all limitations associ-
ated with the instrument for the purpose of oscillation ampli-
tude regulation, which is therewith dictated by the bandwidth
of the cantilever. The article has been divided into five parts.
Section II discusses the principle of operation of the standard
$z$-control loop and of the proposed modifications. Section III
describes the experimental methods while Sec. IV discusses
the results. Section V summarizes the advantages and flex-
ibility of magnetic actuation-based $z$-position control.

II. PRINCIPLE OF OPERATION

A. Conventional control loop for oscillation amplitude
regulation

Figure 1 is a schematic showing the elements of a stan-
standard control system used in most commercial AFMs for os-
cillation amplitude regulation. The principle of its operation
is as follows: The cantilever is excited at resonance and con-
trolled to tap the sample with amplitude $A_0$ which is close to
its resonant amplitude. The sample topography $T(s)$, which
changes as the sample is scanned, is a disturbance input to
the amplitude control system. The effect of this disturbance
is sensed as changes in the oscillation amplitude $e(s)$
$=A_0(s)-A(s)$, which drives the $z$-piezo to change the posi-
tion of the cantilever $z(s)$ to reject the effect of sample to-

FIG. 1. A schematic showing the elements of a standard control system used
in most commercial AFMs for oscillation amplitude regulation. The $z$-piezo,
which is several centimeters long, is used to control the position of the
cantilever during scanning.

pography and restore the set oscillation amplitude $A_0$. If the
disturbance rejection is perfect, $z(s)$ would equal $T(s)$, so
topography is tracked perfectly. This is approximately valid
at slow scan speeds and hence $z(s)$ is used to reconstruct the
sample topography.

Figure 2 shows a block diagram to illustrate the dynamics
of each element in this closed-loop control system. The cantilever taps the sample at its resonant frequency. The
natural frequency of the cantilever $\omega_0/2\pi$ is typically in the
range of 50–150 kHz. As the tapping cantilever is scanned
over a surface, changes in topography excite transient dy-
namics in the cantilever and the tapping amplitude responds
according to the dynamics of tapping operation. Assuming
no loss of tapping and no other energy dissipation besides
that characterized by the quality factor $Q$, tapping dynamics

FIG. 2. A block diagram illustrating the dynamics of each element in the
conventional amplitude control loop that uses $z$-piezo actuation and rms-
to-dc conversion.

can be approximately modeled with a first-order filter, whose
bandwidth is limited to the value $\omega_0/2Q$. While the quality
factor $Q$ is dependent on the surrounding medium, it can also
be controlled using a $Q$ controller. In other words, tapping
dynamics can be controlled using existing methods.

While scanning a sample, in order to acquire the neces-
sary feedback signal to control the oscillation amplitude of
the cantilever, a lock-in amplifier or a rms-to-dc converter is
employed to yield a dc signal in proportion to the oscillation
amplitude. The output signal of the converter is averaged
over several multiples of the input period so as to avoid
leakage of the raw oscillation. This process introduces a cor-
responding measurement delay element ($e^{-\tau}$) within the con-
trol loop.

A controller, typically of the proportional-integral type,
is used to adjust the position of the cantilever, by moving a
$z$-piezo upon which the cantilever is mounted, based on the
discrepancy $e(s)$ between the measured amplitude and the set
point. Due to the small bandwidth ($1–2$ kHz = $\omega_0/2\pi$) and
underdamped nature of the $z$-piezo, more conservative
choices of control gains are necessary to stabilize the control
system. This problem is compounded by the existence of
delay within the loop, which reduces the phase-crossover
frequency and the gain margin. Thus, topography is tracked
accurately only within a small closed-loop bandwidth.

B. Magnetic actuation for direct tip-position control

Previous applications of magnetic actuation in AFM in-
clude measurement of sample stiffness and dynamics,11 $Q$
control,12 and providing ac excitation in tapping mode.12 In
this article, magnetic actuation is used to control $z_0$, the mean
$z$ position of the cantilever tip, by controlling the mean def-
lection of the cantilever. The principle of operation is based
on torsional actuation,12 wherein an orthogonal arrangement
of the magnetic moment $m$ of the cantilever and an external
magnetic field $B$ exert a torque $m \times B$ on the cantilever. If
both these vectors are confined to the plane of motion of the
cantilever, the torque $\tau = m \times B$ acts normal to this plane and

\[ m \times B = (m_y B_x - m_x B_y) \hat{k}. \]

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deflects the cantilever in proportion to its compliance. This deflection translates the cantilever tip along the z axis to the desired z position. A magnetic moment can be placed on the back surface of the cantilever tip either by coating the surface with a magnetic material or by rigidly attaching a magnetic particle. A solenoid coil is used to generate the field \( B \) necessary to position the cantilever tip. The current through the coil exhibits first-order low-pass dynamics whose bandwidth is decided by the coil inductance \( L_c \) and the circuit resistance \( R \). Thus, within the position-control loop, the second-order underdamped dynamics of the z-piezo is replaced by a more favorable first-order dynamics of the coil.

The actuation speed of this technique is decided by the bandwidth of the coil. This is determined by its physical characteristics including the wire diameter and the number of windings. In general, fewer windings result in smaller inductance \( L_c \) and correspondingly larger coil bandwidth, but at the cost of producing lesser magnetic field \( B \). This does not, however, result in serious trade off between actuation range and actuation speed. The actuation range also depends on the magnetic moment \( m \) of the cantilever and the current through the coil. Therefore, a higher actuation current and attachment of larger magnetic particles restore the necessary positioning range without sacrificing the coil bandwidth. Moreover, the coil inductance \( L_c \) itself can be actively changed to control the coil’s bandwidth. With this flexibility, the application of direct tip-position control using magnetic actuation is not limited to conventional tapping mode operation of AFM. It can be used for other AFM applications and for any control techniques that require fast actuators to regulate the z position of the cantilever.

### C. Separation of signal paths for high-speed tip-position control

The process of rms-to-dc conversion improves the quality of topography reconstruction as it reduces leakage, and thus noise. However, it also results in measurement delay, which is detrimental to the stability and dynamic performance of the control system. Therefore, having a rms-to-dc converter in the control loop introduces a trade off between the speed of the control system and the image resolution of the microscope. Although the leakage signal is a spurious input to the system, its frequency is much higher than the closed-loop bandwidth of the control system. Therefore, the leakage signal widely separates in the frequency domain from the control signal of the z-position loop, and this renders the control system to be insensitive to this signal. These properties can be exploited to remove the process of signal averaging from the control loop while measuring the control signal to reconstruct topography after the leakage component is filtered outside the loop. In the absence of delay within the control loop, the phase-crossover frequency of the open-loop system is much higher, leading to a higher closed-loop bandwidth. This also increases the open-loop gain margin thereby increasing the stability of the control system.

Thus, the rms-to-dc converter is replaced by a simple full-wave rectifier within the control loop. The dc value of the rectifier’s output is proportional to the oscillation amplitude. The higher frequency components are harmonics of cantilever oscillation beginning at twice its oscillation frequency. Hence, these harmonics are outside the bandwidth of even the fastest element of the control loop, the AFM cantilever, and well outside the closed-loop bandwidth of the control system. This is particularly valid when operating in air, where the high \( Q \) naturally limits the closed-loop bandwidth to a fraction of the cantilever bandwidth. In water, the advantage is lesser due to the low \( Q \) of the oscillating system, which results in a correspondingly high tapping bandwidth. Nevertheless, higher-order low-pass filters can be used in place of rms-to-dc conversion to attenuate the contribution of leakage and improve the performance over the existing control system. Separation of signal paths, therefore, removes the trade off between the speed of the control system and the image resolution of the microscope.

Figure 3 shows a block diagram of the closed-loop control system that uses magnetic actuation and feedback measurement as described in this section. The notable differences from Fig. 2 are in the replacement of a first-order transfer function for actuation and the absence of delay element arising from rms-to-dc conversion. In addition, since the magnetic actuation scheme is colocated with tip-position measurement, it does not introduce an open-loop zero in the transfer function of the cantilever.

### III. EXPERIMENTAL METHODS

#### A. Experimental objective

In the closed-loop block diagram of the proposed control system (Fig. 3), the set point \( A_0 \) can be viewed as the reference signal and the topography \( T(s) \) as the disturbance input to the control system. The control objective is to cancel the effect of this disturbance. Equivalently, topography \( T(s) \) can be viewed as an unknown input, with the tip motion \( z_c(s) \) being an estimate of the unknown topography. In the former case, the amplitude error \( e(s) \) is a measure of the rejection of disturbance, while in the latter case \( e(s) \) is related to the tracking error in tracking \( T(s) \). Due to its importance as a useful measure in either case, the experimental objective was to measure \( e(s) \) under the influence of \( T(s) \) for the conventional and new control systems. This measurement was used to compare the performances of the two systems.
of the filter was sufficiently high as to not introduce any significant delay into the control system, but sufficiently low as to attenuate the harmonics at the output of the rectifier. Since the experiments were conducted with two cantilevers whose natural frequencies were in the range of 50–70 kHz, the low-pass filter cutoff was set in the range of 20–30 kHz.

D. Simulation of topography

The advantages of the proposed changes to the control loop were evident in the frequency domain description as the increase in the phase-crossover frequency and gain margin of the open-loop system. Thus, the control systems were also compared in the frequency domain by providing a sinusoidal topographic disturbance $T(j2\pi f_m)$ and recording the error $e(j2\pi f_m)$ as a function of the “topographic frequency” $f_m$.

Since the control system is sensitive only to changes in the mean position of oscillation of the cantilever using an external sinusoidal input. This modulated the cantilever-sample gap while the cantilever tapped at a fixed point on the sample, and simulated sinusoidal topography. The second method was realized by mounting the sample on a commercial piezoxciter (CMA-P4, Noliac Inc.) whose position was sinusoidally changed, thereby modulating the cantilever-sample gap. In either experiment, a commercial lock-in amplifier (model 7280, Perkin Elmer) provided the necessary sinusoidal voltage input and measured the amplitude-error $e(j2\pi f_m)$ at each frequency $f_m$. The topographic frequency $f_m$ was swept over a wide range to study the dynamics of disturbance rejection.

This technique also added flexibility in choosing the sample and the height of topography unlike scanning a grating, which constrains the test wave form (usually to a non-sinusoidal one), its amplitude, and the sample material.

A schematic of the magnetically actuated control system is shown in Fig. 4. A centimeter-sized coil generates vertically directed magnetic field $B$. The inset shows the approximate relative orientations of the magnetic moment $m$ of the attached particle and the magnetic field $B$ of the coil. Figure 5 shows photographs of the experimental arrangement and a micrograph of the cantilever.

IV. RESULTS

All experiments were performed using a Molecular Imaging PicoPlus™ AFM.

A. Elimination of measurement delay

Elimination of measurement delay comprises an important aspect of improvements to the proposed control loop. This is demonstrated by measuring the transfer function for tapping dynamics in Fig. 3. In conventional systems, this is cascaded with the measurement delay introduced by the rms-to-dc converter (Fig. 2). Thus, a linearly decreasing phase lag due to the delay is superposed on the actual phase response.
of the tapping dynamics. Replacement of the rms-to-dc converter with a precision rectifier enables extraction of the true phase response of this transfer function.

To measure the tapping dynamics, the amplitude control system was switched off during the experiment and changes in tapping amplitude were recorded under the influence of sinusoidal topographic input. The amplitude of the input $T(j2\pi f_m)$ was $2-3$ nm and was realized using the first method described in Sec. III D, wherein the mean tapping position $z_c$ of the cantilever was magnetically changed at frequency $f_m$. The phase lag of the sinusoidal response of the tapping amplitude $A(j2\pi f_m)$ was measured at the output of the rms-to-dc converter and the precision rectifier, respectively. They are plotted together in Fig. 6 as functions of $f_m$. The phase response measured at the output of the rectifier clearly demonstrates a change of approximately $90^\circ$ across the tapping bandwidth, in accordance with the predicted first-order model for tapping dynamics. The slight droop in the phase beyond 10 kHz is from the low-pass filter cascaded with the rectifier. The linearly decreasing phase contributed by the rms-to-dc converter appears as an exponentially increasing phase lag in the log-frequency phase plot and obscures the true phase response of tapping dynamics. The corresponding measurement delay $\tau$ of 0.62 ms results in a phase-crossover frequency of 800 Hz, which also limits the control bandwidth to this value in closed loop.

B. Comparison of control performances in air

The experiments in air were designed to highlight the limitations primarily from components of the control loop other than the tapping dynamics. To this end, $Q$ control was used to widen the tapping bandwidth and minimize its influence by reducing the $Q$ of the cantilever to 125.2.19 Before performing the experiment, the conventional controller’s proportional and integral gains were tuned to their optimal best beyond which its control system displayed instability. The topography was simulated using the second method described in Sec. III D, wherein a SiO$_2$ sample was mounted on a piezoactuator and vibrated at $f_m$ with an amplitude of $2-3$ nm. The magnetically actuated control loop employed a lag compensator as the controller which was built using MATLAB® and SIMULINK™ and implemented in DS1104 (dSPACE Inc.) real-time controller. The location of the pole, zero, and the dc gain of the controller reported here corresponds to the best response measured with several different settings. The actuation bandwidth of the coil was set to around 20 kHz by appropriately choosing the circuit resistance. The amplitude error $e(j2\pi f_m)$ was measured at the output of the respective measurement devices for each control loop, namely, rectifier and rms-to-dc converter.

A preliminary measurement was made without amplitude control to read out the tapping dynamics. This was normalized to unity within the tapping bandwidth and represents amplitude variation without position control. Figure 7 compares the performances with the two control systems in operation. The proposed system suppresses amplitude error $e(j2\pi f_m)$ almost uniformly to 4% of the uncontrolled variation at all frequencies $f_m$ within the tapping bandwidth. The performance of the conventional control loop is comparable to this at low frequencies (i.e., for slow changes in topography). However, the error increases with increasing frequency $f_m$ and the amplitude variation at 400 Hz is 55% of the uncontrolled value. Equivalently, while the proposed system uniformly demonstrates 4% error in tracking topography, the conventional system demonstrates significantly higher error.
for faster topography. Since both control systems were tuned to achieve the greatest possible rejection of topographic disturbance, the difference in performance is a result of the intrinsic limitations imposed by the bandwidth of the components of the conventional system.

C. Comparison of control performances in aqueous solution

Tracking performance in aqueous medium was compared with a similar experiment as described above. However, the $Q$ of the cantilever in water was 7, so that the tapping bandwidth was more than 10% of the cantilever’s bandwidth. This was comparable to the bandwidth of the measurement scheme of the new system. This resulted in inclusion of phase lag from the low-pass filter that was cascaded with the rectifier, thereby reducing the gain margin. Integral control was therefore employed to increase the gain margin. To avoid problems such as integrator wind up, a low pass filter with very low cut-off frequency was used instead of an actual integrator.

Due to the wider closed-loop bandwidth of the control system, larger disturbance rejection was achieved at low frequencies. Thus, a log-log plot is used to compare the tracking errors $\varepsilon(j2\pi f_m)$ (Fig. 8). The amplitude error $\varepsilon$ due to topographic variation $T$ without amplitude control is normalized to unity (0 dB) within the tapping bandwidth as before. Since both the controllers employ integral control, the error increases with frequency at 20 dB/decade. However, the tracking error achieved by magnetic control is over 16 dB (6.3 times) lesser than the error achieved by the conventional system within the tapping bandwidth. This once again reflects the improved ability of the proposed control system in rejecting high-frequency topographic disturbance.

V. DISCUSSION

The experimental results demonstrate that the proposed system tracks fast-changing topography significantly better than the conventional control system both in air and in aqueous medium. This is directly the result of simultaneously improving the bandwidths of all the key elements of the control loop. The proposed methods solve two of the three key limitations of conventional systems, namely, actuator dynamics and measurement delay. Existing methods for $Q$ control address the final limitation due to the tapping dynamics.

Since the bandwidth of the $z$-control loop is now decided by the bandwidth of the actuation coil, it is still a property of the instrument. A useful feature of magnetic actuation is that the inductance of the coil can be actively changed using current feedback to modify the bandwidth of the actuation circuit (see Appendix). This can be used to customize the coil bandwidth to any cantilever that is chosen to operate with. Large changes in bandwidth are easily achieved with relatively small control efforts. On the other hand, the high stiffness, second-order dynamics, and low sensitivity of the $z$-piezo impose theoretical limitations to changes in its bandwidth and practical challenges to realize them due to the necessary high voltages.

Hence, the combination of magnetic actuation, $Q$ control, and elimination of delay removes all limitations associated with the instrument for the purpose of oscillation amplitude regulation. It improves the control system speed, which is therewith dictated by the bandwidth of the cantilever.

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APPENDIX: TECHNIQUE TO ACTIVELY TUNE ACTUATION BANDWIDTH

A home designed and built circuit is discussed here to achieve flexibility by actively controlling the bandwidth of the actuation coil. The original coil is modeled by its inductance $L_c$ and resistance $R_c$. Another coil of impedance $L_1$ is added in series and the potential difference across its ends is amplified by a factor $K$ and fed back (Fig. 9). For an externally applied voltage $V_{in}$ the circuit current $i$ obeys the following equation:

$$V_{in} = [L_c - (K - 1)L_1] \frac{di}{dt} + R_c i.$$
Thus, the effective inductance of the circuit is 
\[ L_c - \frac{1}{K} < L_1 \]. For stability of the closed-loop system, we require 
\[ (K-1)L_1 < L_c \]. For \( K > 1 \) the effective inductance is less than 
\[ L_c \], thereby reducing the time constant of the circuit. The dc 
gain of the coil is decided by \( R_c \), which remains the same. While the experiments reported in this article did not necessitate the use of this technique, separate tests easily achieved tenfold improvement in the coil bandwidth, although significant second-order behavior of the closed-loop system was noticed for higher feedback gain \( K \). This was probably due to the unmodeled output capacitance of the feedback operational amplifiers.

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