Control Techniques for Increasing the Scan Speed and Minimizing Image Artifacts in Tapping-Mode Atomic Force Microscopy

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The atomic force microscope (AFM) [1] is a mechanical microscope capable of producing three-dimensional images of a wide variety of sample surfaces with nanometer precision in air, vacuum, or liquid environments. This article provides an overview of the AFM and its three main modes of operation, with a focus on the tapping mode of operation. The challenges associated with obtaining high-speed images with a tapping-mode AFM while minimizing image artifacts are outlined and control techniques that have been developed to overcome these challenges are reviewed.
The AFM evolved from the scanning tunneling microscope (STM) [2], a device that earned its inventors the 1986 Nobel Prize in Physics for its ability to image conductive surfaces with unprecedented resolution. The STM measures variations in tunneling current that flows from a sharp probe tip onto a conductive sample surface through a vacuum gap as the sample is scanned below the tip. The tunneling current has an exponential dependence on tip-sample separation, making it highly sensitive to variations in sample height. A feedback controller regulates the sample height to maintain the tunneling current at a set-point value and a three-dimensional image is produced through measurement of the controller signal.

The desire for an instrument with the resolution of the STM and the ability to image nonconductive samples in air, various gases, liquid, or vacuum led to the invention of the AFM in 1986. Rather than measuring tunneling current, the AFM obtains images of a sample by recording the variation in force between a sharp probe tip, located on the underside of a microcantilever, and the sample surface. As the sample is scanned underneath the cantilever, the variations in tip-sample force are proportional to variations in sample topography. A three-dimensional image of the sample surface is obtained by plotting the measured force as a function of the lateral scan position. Unlike the STM, the AFM is not restricted to imaging conductive or semiconductive samples in a vacuum environment, which has allowed exploration of a wide variety of samples with resolutions previously unattainable. Images of the atomic structure of materials such as mica [3], silicon [4], and graphite [5] have been recorded with the AFM. The ability of the AFM to image samples with minimal preparation in liquid environments has made it a particularly attractive tool for imaging biological samples [6], [7]. The most widely used application of the AFM is high-resolution imaging; however, adaptations of the AFM may be used to measure chemical [8], [9], magnetic [10], electrical [11], and material properties [12]. Other nonimaging applications of the AFM include probe-based data storage [13]–[15], nanolithography [16], [17], and manipulation of single atoms and molecules [18].

The vertical resolution of the AFM is on the order of 0.01 nm with a lateral resolution as fine as 0.1 nm [19]. This resolution is significantly better than optical microscopes, which are limited in resolution by the wavelength of visible light of about 400–700 nm. The high image resolution of the AFM is attributable to the size of the probe tip (which may be only a few atoms wide), the high force sensitivity of the cantilever, and the high positioning resolution of the scanner.

While its high resolution and ability to image surfaces in a broad range of environments has made the AFM a vital tool for imaging and characterizing sample surfaces in a variety of fields such as biology, chemistry, materials science, and the electronics industry, the relatively slow scan speed of the instrument has limited its potential. In many imaging applications, it is desirable to increase the scan speed to increase productivity. One such application is characterization and defect detection of electronic grade silicon devices [20], [21]. As the size of electronic devices such as integrated circuits is decreasing at a rapid rate, the AFM has emerged as one of the few instruments capable of imaging these devices at the desired resolution without the risk of damaging the sample. The ability of the AFM to image biological samples in any environment with resolutions far higher than obtainable by optical microscopes has created significant interest in obtaining AFM images at video rates [22]. Dynamic biological processes [23] occur on millisecond timescales. Commercially available AFMs are too slow to observe such processes, as they may take up to a minute to image one frame of a biological sample. Dynamic biological processes, such as protein synthesis [24] and DNA replication [25], have been observed with custom-built AFMs. For the full potential of the AFM to be realized, further improvements in image speed need to be achieved, which will be lead to increased productivity and new scientific discoveries.

The reliance on feedback control within the AFM to produce an accurate image of the sample provides several interesting challenges for control engineers in achieving higher scan speeds with minimal imaging artifacts.

**MODES OF AFM OPERATION**

The three most common imaging modes of AFM operation are contact mode [26], noncontact mode [27], and tapping mode (also termed intermittent contact, semicontact, or ac...
the controller is proportional to the sample height during scanning and provides a good representation of the sample topography as the sample is scanned below the cantilever. Measurements of sample topography obtained with contact mode imaging occur at low frequency. These measurements are affected by flicker noise [31], which significantly reduces the SNR. Continuous lateral force on the sample from the probe tip [32], [33] may lead to excessive wearing of the probe tip, image distortion, damage to soft/delicate samples, and displacement of particles that are weakly attached to a substrate. The dynamic modes of operation, noncontact and tapping modes, were developed to reduce these lateral forces between the probe tip and the sample and to increase the SNR of the measured signal.

Noncontact and tapping modes measure the dynamic behavior of the cantilever as it is oscillated at, or close to, its first resonance frequency. Variations in tip-sample force result in a shift of the cantilever resonance, as illustrated in Figure 2. This shift in resonance is proportional to variations in sample height and may be measured by monitoring the change in cantilever resonance frequency, tip oscillation amplitude, or the phase difference between the actuation signal and the tip oscillation.

When operating in noncontact mode, the cantilever is oscillated (with an amplitude typically in the order of 1–10 nm) above the sample surface but never touching it. The cantilever is oscillating under the influence of attractive forces that reduce the effective cantilever spring constant, resulting in a reduction of the cantilever resonance frequency, as shown in Figure 2. Variations in the resonance frequency, oscillation amplitude, or phase are measured, and the feedback control loop operates on the vertical position of the sample, similar to the operation in contact mode, to maintain this measured value at a setpoint and produce an image of the sample. The main advantage of operating in noncontact mode is that there is little force exerted on the sample surface, avoiding distortion and damage to the sample and tip.

When exposed to ambient conditions, most samples are coated with a thin layer of water, which may be several nanometers in thickness, dependent on the relative humidity. Noncontact mode requires that the tip must be kept close enough to the sample for interatomic forces to be detectable but far enough from the sample to avoid the tip from becoming stuck in the fluid layer due to the strong attractive capillary forces. A slower scan speed must be used for this reason. The above problems have limited the widespread use of noncontact mode imaging. Noncontact operation is a viable option when operating in ultrahigh vacuum conditions, as the adsorbed fluid layer is reduced in these conditions. Images with atomic resolution are obtainable when operating in such conditions [4].

Tapping mode combines the benefits of contact mode and noncontact mode by oscillating the cantilever close enough to the sample such that the probe tip briefly contacts the sample...
once every oscillation cycle. This significantly decreases the lateral forces associated with contact mode imaging and the risk of the cantilever sticking to the sample due to capillary forces. To ensure that the probe tip has enough energy to overcome the attractive capillary forces and avoid sticking to the sample when coming in contact with the surface, the tip oscillation amplitude is set higher than in noncontact mode (10–100 nm [34]) and cantilevers with a high quality (Q) factor (50–1000) and spring constant (20–50 N/m in air) are used. The reduced lateral forces and the ability to image in liquid have made the tapping mode popular for imaging soft biological samples [33], [35], [36] and samples that are held loosely to a substrate. Also, tapping mode may be used for imaging hard samples to reduce the tip wear associated with contact-mode imaging. A worn tip leads to reduced lateral image resolution. One drawback of using tapping mode is that the imaging speed tends to be substantially slower than contact mode.

As the remainder of this article is focused on the performance of the AFM operating in tapping mode, a more detailed description of this AFM mode of operation is presented next.

**TAPPING-MODE AFM**

Prior to bringing the cantilever into intermittent contact with the sample, the cantilever is oscillated at or near to its first flexural resonance frequency. When the probe tip is intermittently contacting the sample while scanning, variations in the sample height modify the force between the tip and the sample. The cantilever experiences both attractive and repulsive forces; however, the average force experienced by the cantilever is repulsive. This repulsive force between the tip and sample alters the effective stiffness of the cantilever [28], [37], [38], causing its resonance to shift to the right, as shown in Figure 2. The effective cantilever Q factor will also be modified due to energy losses from the tip contact [38]. Variations of the cantilever resonance and Q factor lead to variations in the tip oscillation amplitude \( A(t) \). This amplitude \( A(t) \) is the most common measure of tip-sample force, rather than frequency or phase, when imaging with a tapping-mode AFM.

A schematic showing the typical instrumentation of an AFM operating in tapping mode is shown in Figure 3. The main components are the microcantilever, the cantilever actuator, the deflection measurement system, the demodulator, the XYZ scanner, and the feedback controller.

**Microcantilever**

The microcantilever body is usually rectangular in shape with a length of 50–400 \( \mu \)m, width of 5–10 \( \mu \)m, and constructed from monocrystalline silicon (Si) or silicon nitride (Si\(_3\)N\(_4\)). Lateral resolution is dependent on the geometry of the probe tip, which is located on the underside of the cantilever. A sharp tip with a radius of 1–10 nm [39] is required to ensure high lateral image resolution. Typical resonance frequencies are between 50 and 500 kHz with some next-generation cantilevers having resonance frequencies exceeding 1 MHz [40], [41].

**Cantilever Actuation**

The cantilever tip is commonly oscillated by applying a sinusoidal voltage to a piezoelectric actuator positioned at the base of the cantilever. Other methods of actuation include electrostatic actuation [42], magnetic actuation [43], and coating the cantilever with piezoelectric material to act as a bimorph actuator [44].
**Cantilever Deflection Measurement**

Accurate measurement of cantilever tip displacement is fundamental for high-resolution imaging. The optical lever method [45], [46] is the most common way to measure cantilever displacement in commercial AFMs. A laser beam generated by a solid-state diode is focused onto the surface of the cantilever and reflected onto a photodiode sensor. Many cantilevers are coated with gold on one side to increase reflectivity.

The photodiode sensor is a four-quadrant detector whose output signal is fed to a differential amplifier. When the cantilever is in its equilibrium position, the reflected laser spot is adjusted so that all photodiodes measure the same light intensity at this reference point. As the cantilever deflects, the angle at which the beam reflects off the cantilever changes, resulting in the reflected laser spot shifting position on the photodiode sensor. Differences in light intensity for each quadrant are measured to give an indication of laser movement on the photodiode sensor.

The difference between the upper and lower photodiode signals is proportional to the normal deflection of the cantilever. Cantilever tip displacement is magnified significantly by the length of the reflected light path. The optical lever measurement is sensitive enough to measure tip displacement in the order of $10^{-4}$ Å [45].

The optical deflection sensing technique introduces a significant amount of noise into the deflection measurement. In addition to electronic noise, two other forms of noise are introduced by the optical sensor. The first form of noise is from stray beams of light reflecting off the sample surface back into the photodiode sensor [47]. The second form of noise is from light reflecting back from the cantilever and the sample into the laser source [47]. Imaging in a liquid environment is particularly problematic due to reflection and refraction of the laser beam at the interface between air and water.

Other problems with the optical deflection sensing technique include the time taken to align the laser beam and the size of the sensor. The laser beam must be realigned every time that the cantilever is changed, which can be a tedious and time-consuming task. The optical sensor occupies a relatively large amount of space. Reducing the size of the sensor is advantageous for applications that use an array of cantilevers [48], [49] and for reducing the overall size of the AFM [49] for applications such as the investigation of matter in interplanetary explorations [50].

Despite these problems, the optical lever method has remained the most popular means of measuring cantilever deflection due to its simplicity. Other possible measurement techniques include interferometric [51], [52], piezoresistive [53], [54], capacitive [55], thermal [54], [56], magnetoresistive [57], and piezoelectric [44], [58], [59] sensors.

**Demodulator**

To regulate the tip-sample force and produce an estimate of the sample topography, the feedback controller requires the cantilever oscillation amplitude to be extracted from the cantilever displacement signal provided by the photodiode sensor. The two most commonly employed techniques to demodulate the displacement signal are the RMS-to-dc converter [60], [61] and the lock-in amplifier [62].

The RMS-to-dc converter is a nonsynchronous demodulator that consists of a rectifier circuit and a low-pass filter. The lock-in amplifier is a synchronous demodulator that uses the oscillation signal applied to the cantilever as a reference signal. This reference signal is multiplied by the cantilever displacement signal, and then the resulting signal is passed through a low-pass filter to provide the cantilever oscillation amplitude and phase shift. The lock-in amplifier

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**Figure 4** Development of the raster scan pattern. The (a) raster scan pattern is obtained by applying (b) a pseudoramp signal to the Y axis and (c) a triangular signal to the X axis of the scanner. The data points, represented by blue dots, are stored during the forward scan (shown in red).
has a much higher SNR than the RMS-to-dc converter, making the lock-in amplifier the preferred method of demodulation in modern instruments.

**XYZ Scanner**

A piezoelectric scanner positions either the cantilever or the sample in the X, Y, and Z directions. It is most common for the sample holder to be fixed to the scanner, with the sample scanned below the stationary cantilever. Systems that scan the cantilever require the deflection measurement instrumentation to move with the cantilever to maintain alignment, which can complicate the design.

Scanning in the lateral direction is typically in a raster pattern. To obtain a raster scan, a triangular waveform is applied to the scanner in the X direction (the fast-scan axis), and a pseudoramp signal is applied in the Y direction (the slow-scan axis). This combination of signals results in the scan pattern illustrated in Figure 4. The data points, which represent pixels of the image, are typically gathered on the forward scan (horizontal path).

The piezoelectric tube scanner [63], developed in 1986 [64], is the most popular scanner currently used in commercial AFMs. The tube scanner consists of a tube of radially polarized piezoelectric material with an internal electrode and four equally sized and spaced external electrodes down the length of the tube. Application of a voltage to the appropriate electrodes results in the tube bending laterally for movements in the X or Y axis and extending or contracting for movements in the Z axis.

The flexure-based scanner is an alternative means of positioning the sample relative to the probe in an AFM [65]–[69], which consists of a platform connected to a base by several flexures (thin beams). The platform on which the sample is mounted is actuated by piezoelectric stack actuators that cause the flexures to bend when they expand or contract. Flexure scanners outperform tube scanners in many areas, including having reduced cross coupling between axes, a higher mechanical bandwidth, and a larger range of motion. Despite these advantages, flexure scanners are still not as common as tube scanners in commercial AFMs due to the complexity of the design and higher manufacturing cost.

**Z-Axis Feedback Controller**

To reduce the forces between the tip and the sample when a large abrupt increase in sample height is encountered [70] and to improve tracking of sample features, a feedback control loop is employed to regulate the tip-sample force by moving the sample stage in the vertical (Z) direction. By maintaining $A(t)$ at a setpoint value $A_{set}$ (typically 10–100 nm [34]), the feedback loop maintains a constant average tip-sample force.

A block diagram of the Z-axis feedback loop is shown in Figure 5. Cantilever deflection is measured by the optical sensor and demodulated to produce a dc signal representing the oscillation amplitude $A(t)$. The value of $A(t)$ is then subtracted from $A_{set}$ to provide the error signal for the Z-axis feedback controller. To keep the tapping force on the sample to a minimum, $A_{set}$ is chosen to be slightly less than the free air oscillation amplitude $A_0$.

The Z-axis controller must compensate for changes in the cantilever oscillation amplitude due to variations in sample height by sending an appropriate signal to the Z-axis actuator. The sample topography may be viewed as a disturbance to the feedback loop. If an upward step is encountered in the sample topography, $A(t)$ will decrease. The controller responds to the error signal $e(t) = A_{set} - A(t)$ by driving the scanner downward in the Z axis, restoring $A(t)$ to the value of $A_{set}$. The controller output is therefore proportional to the sample topography as the sample is...
scanned underneath the cantilever. The controller output at each lateral coordinate is processed by a computer to form a three-dimensional image of the sample. As the sample is scanned underneath the cantilever, the probe tip should track the sample topography. The faster the feedback loop is able to reject disturbances due to topography variation, the more accurate the estimated sample topography.

Most modern commercial AFMs use a proportional-integral (PI) controller [71], [72] to regulate tip-sample force. Modern control methods such as $H_\infty$ control [72] have been applied to contact-mode imaging. However, the easily tunable PI controller has remained popular because parameters, such as the cantilever, sample, and environmental conditions, in the AFM change so frequently.

**THE INFLUENCE OF CANTILEVER Q FACTOR ON FORCE SENSITIVITY**

The slope of the resonance curve for high $Q$-factor cantilevers is steeper than that of low $Q$-factor cantilevers. As illustrated in Figure 6, for a cantilever oscillating at $f_r$ (equal or close to the cantilever’s resonance frequency $f_r$ when not interacting with the sample), changes in sample height cause $f_r$ to shift. A change in sample topography as the sample is scanned underneath the cantilever will result in a larger change in $A(t)$ for a cantilever that has a higher $Q$ factor. The force sensitivity is therefore higher when the cantilever $Q$ factor is high.

When imaging a sample surface that has very fine features, increasing the $Q$ factor of the cantilever would be desirable to increase the force sensitivity and image resolution of the cantilever. Many biological specimens need to be imaged in a liquid environment. When scanning in liquid [75], the $Q$ factor of the cantilever is reduced by a factor of ten to 100, due to hydrodynamic forces [76], [77]. Therefore, increasing the $Q$ factor of the cantilever may be desirable to increase the cantilever force sensitivity for improved image resolution. This increase may be accomplished using active $Q$ control, which is detailed in a later section of this article.

**FIGURE 6** Response to a change in the sample height of cantilevers with different quality ($Q$) factors. The cantilever is initially set to oscillate at $f_r$ (equal or close to its resonance frequency $f_r$ when not interacting with the sample). Changes in sample height cause $f_r$ to shift. A change in sample topography as the sample is scanned underneath the cantilever will result in a larger change in $A(t)$ for a cantilever that has a higher $Q$ factor. The force sensitivity is therefore higher when the cantilever $Q$ factor is high.

The cantilever $Q$ factor is inversely proportional to the energy dissipated per oscillation cycle. The energy dissipated per oscillation cycle is proportional to tip-sample force. A cantilever with a low $Q$ factor will therefore result in higher tapping forces than a cantilever with a high $Q$ factor [78], [77]. The average tip-sample force ($\hat{F}_{TS}$) [74] is a function of the cantilever $Q$ factor, the cantilever stiffness $k$, $A_{perm}$, and the cantilever oscillation amplitude in free air ($A_0$), as shown by [79], [80]

$$\hat{F}_{TS} \propto \frac{k}{Q} \sqrt{(A_0^2 - A_{perm}^2)}.$$  (1)

Reducing the tip-sample force is desirable for several reasons. Force sensitivity is inversely proportional to the tip-sample force. High tapping forces will cause mechanical deformation of soft samples, resulting in a distorted image. Several studies have demonstrated differences in the imaged height of sample features when the cantilever $Q$ factor is increased with active $Q$ control [81]–[83]. The increase in imaged height of sample features was attributed to the lower tapping forces on the sample when the cantilever $Q$ factor was increased. High tapping forces also increase the risk of cantilever and sample damage [19]. Low tapping forces allow sharper tips to be used on soft samples without damage to the sample, which improves lateral image resolution. It is also beneficial to minimize tip-sample force when imaging samples with a hard surface to reduce tip wear.

Maintaining $A_{perm}$ close to $A_0$ will reduce the tip-sample force but will reduce the magnitude of the error signal sent to the $Z$-axis feedback controller when a sharp drop in sample topography is encountered, increasing the likelihood that the probe tip will lose intermittent contact with the sample. When the probe tip loses intermittent contact with the sample, artifacts appear in the resulting image. This phenomenon is commonly referred to as “parachuting” [84] or “probe loss” [85] and is described in detail later in this article.

**TAPPING-MODE AFM SCAN SPEED LIMITATIONS**

While tapping mode has an advantage over contact mode for reducing tip and sample damage, tapping mode is hindered by a relatively slow scan speed. As the scan speed is increased, the ability of the probe to track the sample topography is reduced. Advances in control and instrumentation have led to high-speed AFMs capable of imaging
dynamic biological processes [86]–[90]. However, there is still the desire and potential for further improvement in imaging speed.

The bandwidth of the scanner in the lateral axes and the bandwidth of the $Z$-axis feedback loop determine the maximum imaging speed, with the bandwidth of the $Z$-axis feedback loop being the fundamental limitation.

**Bandwidth of the Scanner in the Lateral Axes**

The triangular waveform applied to the scanner in the $X$ axis to produce a raster scan pattern has sharp edges at the turning points, which introduce high-frequency components to the signal. The piezoelectric tube scanners used in most AFMs are highly resonant systems, typically with a first resonance frequency no more than 1 kHz. As the scan speed is increased, the likelihood of the high-frequency components of the raster signal exciting the mechanical resonance of the scanner increases. The resulting unwanted vibration in the scanner leads to image distortion [63]. An example of this type of image distortion is shown in Figure 7(c).

A common practice is to limit the raster scan frequency to less than 1% of the scanner’s first resonance frequency to avoid image distortion resulting from scanner vibration [91]. For a scanner with a first resonance frequency of 1 kHz, this practice would limit the scan speed to 10 Hz, with a typical image taking several minutes to acquire.

New scan trajectories [92] such as spiral [93], cycloid [94], and Lissajous [95], [96] have recently been developed to remove high-frequency components from the scan signal, avoiding excitation of the scanner’s mechanical resonance. Another approach to reduce induced vibration in the scanner, to increase scan speed, is to increase the damping factor of the first resonance mode of the scanner with a feedback controller [97], [91], [90].

**Z-Axis Feedback Loop Bandwidth**

The bandwidth of the $Z$-axis feedback control loop determines the speed at which the probe can track the sample topography accurately. The bandwidth of the $Z$-axis feedback loop may be increased by increasing the $Z$-axis controller gain, which is limited by the stability margins of the feedback loop.

When the probe tip is interacting with the sample, the dynamics of the cantilever are modified temporarily, due to

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**Figure 7** Demonstration of the improvement in imaging speed using transient force atomic force microscopy (TF-AFM) compared to conventional atomic force microscope (AFM) imaging. The sample is Lambda DNA imaged in air with a scan area of $2 \, \mu m \times 2 \, \mu m$. Image (a) is a conventional AFM height image taken at 4 $\mu m/s$. Images (d), (e), and (f) are conventional AFM height, amplitude, and phase images taken at 97.68 $\mu m/s$, respectively. Images (b) and (c) are TF-AFM images taken at 97.68 and 162.8 $\mu m/s$, respectively. The vertical lines appearing in image (c) are due to excitation of the scanner’s resonance. (Figure reproduced with permission from [128].)
the influence of the tip-sample force $F_{TS}$, causing a shift in the resonance frequency and $Q$ factor of the cantilever. It is important to maintain significant stability margins in the $Z$-axis feedback loop to accommodate these parameter deviations as the sample is scanned below the cantilever. If the feedback loop bandwidth is too low, oscillations will appear in the sample image as the scan speed is increased due to the loop becoming unstable.

**Analysis of the Z-Axis Feedback Loop Stability Margins**

The main limitations to the stability margins of the $Z$-axis feedback loop are the bandwidth of the $Z$-axis actuator, the time taken to demodulate the cantilever oscillation amplitude, and the bandwidth of the cantilever in cascade with the demodulator.

Piezoelectric tube scanners used in most commercial AFMs to move the sample in the $X$, $Y$, and $Z$ directions are highly resonant with a mechanical resonance frequency of 500 Hz to 20 kHz [26] in the $Z$ axis. The $Z$-axis actuator transfer function may be approximated by [98]

$$G_{zp}(s) = \frac{K_{zp} \omega_n^2}{s^2 + \omega_n^2 s + \omega_n^2}, \quad (2)$$

where $K_{zp}$ is the dc gain of the actuator, $Q_{zp}$ is the actuator $Q$ factor, and $\omega_n$ is the actuator resonance frequency.

Common methods used to demodulate the cantilever displacement signal, such as an RMS-to-dc converter or lock-in amplifier, may need up to ten cycles to acquire an accurate measure of the oscillation amplitude, due to the tradeoff between elimination of the oscillation waveform and obtaining an accurate measure of the amplitude waveform [99], [100]. Such methods result in a delay $T_D$ in the feedback error signal and controller response.

The energy dissipated or gained per oscillation cycle, when the cantilever is interacting with the sample, is inversely proportional to the cantilever $Q$ factor. The transient response of a low $Q$-factor cantilever is therefore faster than a high $Q$-factor cantilever, so a cantilever with a low $Q$ factor will have a higher bandwidth when placed in the $Z$-axis feedback loop.

When oscillating in free air, the cantilever may be modeled by the second-order transfer function [101]

$$G(s) = \frac{D(s)}{V(s)} = \frac{\beta \omega_n^2}{s^2 + \omega_n^2 s + \omega_n^2}, \quad (3)$$

where $D(s)$ is cantilever displacement, $V(s)$ is the voltage applied to the cantilever actuator, $\beta$ is the steady-state gain, and $\omega_n$ is the natural frequency of the cantilever. The demodulator removes the sinusoidal component from the cantilever displacement signal to provide the oscillation amplitude signal $A(t)$ for the feedback controller. The cantilever in cascade with the demodulator has a first-order transfer function

$$G_{CD}(s) = \frac{\beta e^{-T_D s}}{2Q s + 1}, \quad (4)$$

with a bandwidth of $\omega_n / 2Q$ [102] and a time delay $T_D$.

The $Z$-axis controller must incorporate some form of integral action to remove steady-state error from the image. For illustration purposes, let the $Z$-axis feedback controller be a PI controller with transfer function

$$C_{p}(s) = \frac{K_Z (1 + TS)}{TS}, \quad (5)$$

where $K_Z$ is the proportional/controller gain with the integral gain equal to $K_Z / \tau$.

The open-loop transfer function of the $Z$-axis feedback loop is

$$G_{OL}(s) = \left(\frac{K_Z (1 + TS)}{TS}\right) \left(\frac{K_{zp} \omega_n^2}{s^2 + \omega_n^2 s + \omega_n^2}\right) \frac{\beta e^{-T_D s}}{2Q s + 1}. \quad (6)$$

For accurate tracking of the sample topography at high scan speeds, the controller gain $K_Z$ must be set as high as possible while maintaining sufficient stability margins to allow for variations of the cantilever resonance and $Q$ factor that occur during the scan.

The $Z$-axis feedback loop stability margins are dependent on the bandwidth of the $Z$-axis actuator, the demodulator delay $T_D$, and the bandwidth of the cantilever in cascade with the demodulator. Widening the stability margins will allow an increased controller gain $K_Z$ and higher scan speeds with minimal imaging artifacts caused by poor tracking of the sample topography.

If the cantilever has a resonance frequency between 50 and 500 kHz and a $Q$ factor equal to 250, the bandwidth of the cantilever in cascade with the demodulator will be in the range of 100–1000 Hz. In most cases, this bandwidth will be less than the bandwidth of the $Z$-axis actuator. If the demodulator requires ten cycles to demodulate the cantilever
oscillation signal, the phase delay due to \( T_D \) will be less than 1° at the bandwidth of the cantilever in cascade with the demodulator. Therefore, the major limitation to the stability margins of the \( Z \)-axis feedback loop will be the bandwidth of the cantilever in cascade with the demodulator. If the bandwidth of the cantilever in cascade with the demodulator is increased by increasing the cantilever resonance frequency or reducing the cantilever \( Q \) factor, then further increases in the \( Z \)-axis feedback loop bandwidth may be possible by reducing \( T_D \) and/or increasing the bandwidth of the \( Z \)-axis actuator.

The low bandwidth of the cantilever in cascade with the demodulator is the main reason why tapping mode is considerably slower than contact mode. When operating in contact mode, the cantilever deflection is directly measured from the photodiode sensor, which removes the low-pass filtering effect and the delay that occurs as a result of demodulating the oscillating cantilever in tapping mode. The main limitation to the \( Z \)-axis feedback loop bandwidth in contact mode is the bandwidth of the \( Z \)-axis actuator.

A high \( Q \)-factor cantilever is desirable for high force sensitivity/image resolution and low tapping forces. This high cantilever \( Q \) factor places a limitation on the achievable scan speed. The tradeoff between image resolution and bandwidth is a fundamental challenge that engineers face when designing controllers to improve the operation of the tapping-mode AFM.

WIDENING THE \( Z \)-AXIS FEEDBACK LOOP STABILITY MARGINS TO INCREASE SCAN SPEED

Several approaches have been used by researchers to increase the stability margins of the \( Z \)-axis feedback loop with the aim of increasing scan speeds. These approaches include increasing the cantilever resonance frequency, reducing the cantilever \( Q \) factor, reducing the demodulator delay, increasing the \( Z \)-axis scanner bandwidth, and using alternative signals for topography estimation. A review of each these approaches is presented next.

Increasing the Cantilever Resonance Frequency

Many of the advances in high-speed tapping-mode AFMs have been achieved through the use of smaller cantilevers [103], [86], [89], [90], which have higher resonance frequencies. These designs improve the stability margins of the \( Z \)-axis feedback loop in two ways, by increasing the bandwidth of the cantilever in cascade with the demodulator and by reducing the demodulation time. The reduced length of the cantilever, however, may limit the ability of the cantilever to track samples with large topographic features. The conventional optical lever deflection measurement system must be modified to focus the laser beam onto these smaller cantilevers [76], [86], [104]. A lens focuses the laser beam onto the cantilever, which reflects the light back into the same lens. The reflected beam is separated from the incident beam using a polarizing beam splitter and quarter wavelength plate.

Reducing the Cantilever \( Q \) Factor with Active \( Q \) Control

Active \( Q \) control utilizes velocity feedback to modify the effective \( Q \) factor of the cantilever. The controller \( K(s) \) estimates the cantilever tip velocity from the tip displacement \( D(s) \) and applies a gain to obtain the desired cantilever \( Q \) factor.

The differential equation describing the motion of the cantilever when the AFM is operating in tapping mode, is

\[
m^2 \ddot{d}(t) + \frac{ma_0}{Q} \dot{d}(t) + kd(t) = A_s \cos(\omega_s t) + F_{TS}(t),
\]

where \( m \) is the effective mass of the cantilever, \( \dot{d} \) is vertical tip displacement, and \( k \) is the cantilever spring constant. Two external forces act on the cantilever, with \( A_s \cos(\omega_s t) \) being the force produced by the piezoelectric actuator with an oscillation amplitude of \( A_s \) and an oscillation frequency of \( \omega_s \) and \( F_{TS}(t) \) is the force due to tip-sample interaction. Equation (7) suggests that the effective cantilever \( Q \) factor \((Q^*) \) may be modified by adding an additional force proportional to the probe velocity via feedback. If the velocity signal is multiplied by a gain \( G \) and subtracted from the probe actuation signal, the cantilever equation of motion becomes

\[
m^2 \ddot{d}(t) + \frac{ma_0}{Q} \dot{d}(t) + kd(t) = A_s \cos(\omega_s t) + F_{TS}(t) - G \dot{d}(t),
\]

or equivalently

\[
m^2 \ddot{d}(t) + \left( \frac{ma_0}{Q} + G \right) \dot{d}(t) + kd(t) = A_s \cos(\omega_s t) + F_{TS}(t),
\]

which simplifies to

\[
m^2 \ddot{d}(t) + \frac{ma_0}{Q} \dot{d}(t) + kd(t) = A_s \cos(\omega_s t) + F_{TS}(t),
\]
where

\[
Q^* = \frac{1}{Q + \frac{G}{m \omega_n}}.
\]

(11)

The effective \( Q \) factor of the cantilever is decreased when the gain \( G \) is positive and increased when \( G \) is negative.

Commercially available AFMs are typically fitted with a displacement sensor to measure variations in the sample topography. The addition of a velocity sensor would be difficult to implement in the AFM and would also add to the size and cost of the device. For these reasons, cantilever velocity is most commonly estimated from the displacement signal. The use of a differentiator to estimate the cantilever tip velocity is not recommended as differentiators amplify high-frequency noise in the feedback loop.

When active \( Q \) control is applied to commercial AFMs, it is most common to obtain an estimate of the cantilever velocity by applying a phase shift to the displacement signal using a time-delay circuit [19], [105]. This phase-shifted signal is then multiplied by a gain \( G \) and the resulting signal is subtracted from the cantilever oscillation signal before being applied to the cantilever actuator. This arrangement is shown in the active \( Q \) control feedback loop of Figure 8, where

\[
K(s) = Ge^{-T_{cd}s}
\]

and \( T_{cd} \) is the time delay required to estimate the cantilever tip velocity at the cantilever oscillation frequency \( f_o \). As the displacement signal is sinusoidal, a delay of \( 3\pi/2 \) rad is required to estimate the velocity signal, which is achieved by setting \( T_{cd} \) to \( 3/4f_o \). To increase the cantilever \( Q \) factor, \( G \) must be negative, which implies that the required delay is \( \pi/2 \) rad. In this case, \( T_{cd} \) should be set \( 1/4f_o \).

**Degradation of Active \( Q \) Control Performance Due to Unmodeled Dynamics**

When implementing active \( Q \) control with a time-delay controller, there is a risk that the controller may inadvertently degrade system performance or even cause the cantilever to become unstable. Flexible structures such as cantilevers have an infinite number of resonant modes. When designing an active \( Q \) controller for an AFM microcantilever, only the first resonance mode is modeled. When using a truncated model of a flexible structure to design a controller, problems may arise if the unmodeled resonance modes are excited by the control action. This phenomenon is termed the *spill-over effect* [107], [108].

Time-delay active \( Q \) control does not guarantee stability in the presence of unmodeled cantilever dynamics. The phase delay of the time-delay controller \( K(s) \) increases as frequency increases. To increase scan speed, it is desirable to decrease the transient response time of the cantilever, which is achieved by decreasing the \( Q \) factor of the cantilever’s first resonance mode. To reduce the cantilever \( Q \) factor by a desired amount, the delay of the controller at the cantilever oscillation frequency is set to \( T_{cd} = 3/4f_o \) and \( G \) is set at an appropriate value. There is a possibility that the delay of the controller at the resonance frequency of the cantilevers second flexural mode may have the effect of increasing the \( Q \) factor of this mode, pushing the poles of this mode closer to the imaginary axis, which may have the adverse effect of increasing the cantilever transient response time. If the controller gain is high enough, the closed-loop poles of the second mode may be pushed past the \( j\omega \) axis, making the system unstable. Instability in the \( Z \)-axis feedback loop was observed [109] when reducing the cantilever \( Q \) factor with a time-delay active \( Q \) controller. Alternative approaches are needed to active \( Q \) control that ensure the control action has no spill-over effects on higher order modes of the cantilever.

**Alternative Approaches to Active \( Q \) Control**

Another technique for active \( Q \) control [110] uses a resonant controller [111], [112] to approximate a differentiator in a narrow band of frequencies, applying a gain at only these frequencies. The resonant controller is implemented in the active \( Q \) control feedback loop shown in Figure 8. The transfer function of the resonant controller is

\[
K(s) = \frac{\alpha s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2},
\]

(13)

where \( \alpha \) and \( \zeta \) are control design parameters that determine the gain at the frequency of interest (\( \omega = \omega_n \)) and the bandwidth of control.
To reduce the effective cantilever $Q$ factor with the resonant controller, the value of $\alpha$ will always be positive. The frequency response of the controller when $\alpha$ is positive is shown in Figure 9. As the phase of the controller is $\pi/2$ rad at the cantilever’s resonance frequency, the controller approximates a differentiator at this frequency. This controller eliminates amplification of high-frequency noise and ensures that unmodeled cantilever dynamics are not excited by the control action. The stability of the resonant control feedback loop in the presence of unmodeled cantilever dynamics was demonstrated in [110], [112], and [113].

The desired $Q$ factor may be obtained by placing the closed-loop poles at desired locations using a pole placement optimization technique [110]. The $Q$ factor may then be tuned by varying the gain of the controller $\alpha$. Increasing $\alpha$ results in a decrease in the cantilever $Q$ factor and vice versa. The benefits of decreasing the cantilever $Q$ factor with the resonant controller are illustrated in Figure 10. The speed at which the Z-axis feedback controller could track the sample topography with minimal imaging artifacts was significantly increased by reducing the cantilever $Q$ factor from 178.6 to 37.5.

Another alternative approach to active $Q$ control is to design an observer to estimate the probe velocity [114], [115]. It has been demonstrated that the tradeoff between high imaging bandwidth and high force sensitivity/low tip-sample force may be overcome, to some extent, by varying the observer gain [114]. It was found that, while imaging in air, the $Q$ factor may be reduced to improve the imaging bandwidth while the force sensitivity may be increased and tip-sample force decreased by reducing the observer gain. This approach overcomes, to some extent, the tradeoff between imaging bandwidth and image resolution/reliability.

Passive piezoelectric shunt control [116] is an alternative technique for reducing the $Q$ factor of a self-actuated piezoelectric AFM microcantilever. This control technique removes the optical sensor from the feedback loop to reduce sensor noise in the loop. If the cantilever displacement is measured with the piezoelectric transducer [44], [58], [59], it is possible to remove the optical sensor from the AFM altogether, overcoming the limitations of the optical sensing technique mentioned earlier. Passive piezoelectric shunt control [117] involves attaching a passive electrical impedance to the terminals of a piezoelectric transducer, which is bonded to a structure, to modify the damping of the structure. In [116], passive piezoelectric shunt control was applied to reduce the $Q$ factor of a self-actuated piezoelectric AFM microcantilever, resulting in reduced imaging artifacts when imaging a hard sample surface in air at high scan speeds. It was shown that the system may be viewed as a negative feedback loop with the controller being a function of the applied shunt impedance; see “Piezoelectric Shunt Control Viewed in a Feedback Context” for more details. Viewing the system in this context allows standard control techniques to be used for pole placement to obtain the desired cantilever $Q$ factor. A synthetic impedance emulating an inductance and resistance was placed in series with the oscillation voltage to create an $LRC$ circuit that was tuned to a mechanical resonance of the cantilever. By choosing an appropriate value of resistance, the effective $Q$ factor of the cantilever was reduced by a factor of eight. Like the resonant control technique, this controller has guaranteed stability in the presence of unmodeled cantilever dynamics.

The use of a synthetic impedance to emulate the shunt impedance allows the development of more advanced controllers, such as switched gain controllers for reducing probe loss or the use of an active impedance for further reduction or enhancement of the cantilever $Q$ factor. When increasing the cantilever $Q$ factor, energy must be added to the system, therefore a passive impedance cannot be used. An active impedance, such as a negative resistance in series
Piezoelectric Shunt Control Viewed in a Feedback Context

When implementing piezoelectric shunt control on a self-actuating piezoelectric microcantilever, an electrical impedance is placed in series with the oscillation voltage source $v_s$, as shown in Figure S1. The piezoelectric transducer is modeled electrically as a strain-dependent voltage source $v_p$ in series with a capacitance $C_p$. Placement of an electrical impedance $Z(s)$, consisting of a resistance in series with an inductance in the oscillation circuit results in an $LRC$ circuit. Tuning the resonance of the electrical circuit to the cantilever’s mechanical resonance results in an interaction between the electrical and mechanical dynamics of the cantilever. This system may be viewed in a control systems perspective to allow for tuning of the impedance to produce the desired cantilever $Q$ factor.

The electrical and mechanical system depicted in Figure S1 may be represented by the block diagram in Figure S2, where the piezoelectric cantilever may be modeled by the system $G$. Here $w$ is a disturbance strain on the cantilever due to a change in the sample topography, $d$ is the displacement of the cantilever tip, $v$ is with an inductance, is required to increase the cantilever $Q$ factor. Significant increases in cantilever $Q$ factor have been demonstrated with this technique [118].

Reducing the Demodulator Delay

Faster methods of demodulating the cantilever displacement signal have been presented by several researchers. A low-latency coherent demodulation technique that can extract the oscillation amplitude from the displacement signal in one oscillation cycle was presented in [100] and [119]. A sample-and-hold circuit and a low-pass filter that detects the peak of the sine wave and holds that value for a predefined time enables accurate demodulation in up to half an oscillation cycle was introduced in [120].

Another alternative is to replace the demodulator with a full wave rectifier [121], which has no delay. The dc content of the rectifier signal is used as the error signal for the feedback controller. The harmonic content of the signal produced by the rectifier is double that of the cantilever resonance frequency and therefore much higher than the bandwidth of the $Z$-axis feedback loop.

Increasing the Bandwidth of the Scanner in the $Z$ Axis

If the bandwidth of the cantilever in cascade with the demodulator can be improved, then further improvements in the $Z$-axis feedback loop bandwidth may be achieved by widening the bandwidth of the $Z$-axis actuator. Active damping of the $Z$-axis actuator resonance [98] may be used to increase the bandwidth of the $Z$-axis feedback loop. One alternative to using the piezoelectric tube for $Z$-axis actuation is to integrate the actuator into the cantilever by coating the surface of the cantilever with a thin layer of piezoelectric material. The cantilever acts as a bimorph, bending when a voltage is applied to the piezoelectric layer.
the voltage across the piezoelectric transducer terminals, \( q \) is the charge generated by the piezoelectric transducer, \( v_z \) is the voltage across the shunt impedance, \( \alpha \) is the actuator voltage to displacement coefficient (\( \alpha = v_z/d_v \)), \( d_v \) is the initial displacement due to a sample perturbation, \( G_{aw}(s) \) is the transfer function from \( v(s) \) to \( d'(s) \), and \( G_{aw}(s) \) is the transfer function from \( w \) to \( d_w \). In the standard second-order transfer function form

\[
G_{aw}(s) = \frac{d(s)}{v(s)} = \frac{\beta_v \omega_n^2}{s^2 + \omega_n^2 s + \omega_n^2}
\]

and

\[
G_{aw}(s) = \frac{d_w(s)}{w(s)} = \frac{\beta_w \omega_n^2}{s^2 + \omega_n^2 s + \omega_n^2}
\]

where \( \beta_v \) and \( \beta_w \) are the steady-state gains of \( G_{aw}(s) \) and \( G_{aw}(s) \), respectively.

The transfer function from \( v_z(s) \) to \( d'(s) \) is [101]

\[
G_{aw}(s) = \frac{H(s) G_{aw}(s)}{1 + K(s) G_{aw}(s)}.
\]

where

\[
H(s) = \frac{1}{1 + sZ(s) C_p}
\]

and

\[
K(s) = \frac{sZ(s) C_p \alpha}{1 + sZ(s) C_p}.
\]

The system \( G_{aw} \) may be viewed as a negative feedback loop with a filter \( H(s) \), due to the electrical dynamics of the shunt impedance, in the feedforward path. \( H(s) \) acts as a filter in the cantilever transfer function from \( v_z \) to \( d' \). For accurate tracking, the driving signal must be prefiltered by \( H^{-1}(s) \) to compensate for \( H(s) \).

\[
G_{aw}(s) = \frac{\lambda G_{aw}(s)}{1 + K(s) G_{aw}(s)}.
\]

as shown in Figure S3, where \( \lambda = \beta_w/\beta_v \). Therefore, it can be seen that the transfer function from a perturbation in the sample topography to tip displacement may be viewed as a negative feedback system. The controller \( K(s) \) may be designed using standard feedback control techniques, allowing the poles of \( G_{aw}(s) \) to be placed according to the desired performance objectives.

When scanning slowly, the \( Z \)-axis feedback loop will be fast enough to track the sample with minimal error. If the scan speed is well below the bandwidth of the scanner in the \( Z \)-axis, a scaled value of the controller output is sufficient for sample topography estimation. As the scan speed approaches the bandwidth of the scanner, the dynamics of the scanner must be taken into account, as it is the movement of the scanner in the \( Z \)-axis that gives a true representation of the sample topography. As the scan speed approaches the bandwidth of the feedback control loop, the error signal will no longer be zero and the controller will only capture sample features that are within the bandwidth of the feedback loop. At high scan speeds, the error signal contains high-frequency information of the sample topography. Therefore, a more accurate representation of the sample topography should account for the actuator dynamics and include information contained in the error}

**Alternative Signals for Topography Estimation**

The tradeoff between imaging bandwidth and accurate tracking of the sample has been addressed by multiple authors through alternative methods of sample topography estimation. In conventional AFMs, the sample topography is estimated from the controller output. The bandwidth of the estimated signal is therefore limited by the bandwidth of the \( Z \)-axis feedback control loop.

The smaller size of the cantilever results in a much higher mechanical resonance frequency. Increases in imaging bandwidth by a factor of over 30 times, compared to a tube scanner, have been observed using this method [122], [99]. A dual-stage vertical positioner that uses the tube scanner \( Z \)-axis actuator coupled with an additional high-bandwidth stack actuator has been proposed [123] to provide an increase of 33 times the scan speed.

**FIGURE S3** Feedback interpretation of the transfer function from a disturbance \( w \) to cantilever tip displacement \( d' \), where \( G_{aw}(s) \) is the transfer function from the piezoelectric terminal voltage \( v \) to cantilever tip displacement \( d' \), and the controller \( K(s) \) is a function of the shunt impedance \( Z(s) \).
The alternate sample topography estimation techniques in [124] and [125] provide an estimate of the sample topography based on the controller output, the transfer function of the Z-axis actuator, and the error signal to provide accurate estimation of sample topography at higher scan speeds.

A new method of estimating the sample topography, which removes the tradeoff between imaging bandwidth and the cantilever Q factor, is based on the estimation of the cantilever states with an observer [126]–[128]. This method of imaging is termed transient force atomic force microscopy (TF-AFM). An observer is designed based on the cantilever dynamics in free air. When the cantilever is interacting with the sample, its dynamics are modified by the tip-sample force, resulting in a nonzero error between the observer output and the cantilever output. Therefore, the tip-sample force/sample height may be estimated from this signal. The improvement in imaging speed using this technique is demonstrated in [128] where Lambda DNA was imaged in air using conventional AFM imaging and TF-AFM imaging (refer to Figure 7). The scan speed achieved using TF-AFM was over 40 times that obtainable with conventional AFM imaging. Further experiments using TF-AFM were conducted where the cantilever Q factor was increased with velocity feedback, using the velocity estimate from the observer. The improvement in scan speed achieved through the use of TF-AFM was identical, with the added benefit of increased image contrast due to the increased cantilever Q factor.

SCAN SPEED LIMITATIONS DUE TO PROBE LOSS

It is important that \( F_{TS} \) be kept to a minimum to reduce image distortion from sample compression and to avoid damage to the probe tip or sample. Equation (1) shows that \( F_{TS} \) may be reduced by reducing \( k \), increasing \( Q \), or increasing \( A_{set} \). Softening the cantilever by decreasing \( k \) will reduce the resonance frequency of the cantilever. For high-speed scanning, reducing the cantilever resonance or increasing \( Q \) is undesirable due to the associated reduction in the bandwidth of the Z-axis feedback loop. Therefore, increasing \( A_{set} \) is the most suitable approach for minimizing \( F_{TS} \). It is common to set \( A_{set} \) at 80–90% of \( A_0 \) to minimize \( F_{TS} \) when imaging soft delicate samples. Such a large \( A_{set} \), however, may limit the maximum achievable scan speed if the sample contains abrupt variations in height. If the image being scanned contains a sharp drop in topography, the cantilever tip will likely lose intermittent contact with the sample for some period of time. As the probe tip is not interacting with the sample, the resulting signal provides no information about the sample topography, resulting in image artifacts. If the drop in topography is large enough, saturation of the Z-axis feedback-loop error signal is likely to occur, which will increase the duration of probe loss. The image artifacts due to probe loss are worsened as \( A_{set} \), and the scan speed are increased.

The probe loss problem is illustrated in Figure 11. When the probe encounters the sharp drop in topography and detaches from the sample, \( A(t) \) increases exponentially according to the relationship [99]

\[
A(t) = A_{set} + (A_0 - A_{set})(1 - e^{-\frac{t}{\tau}}),
\]

where the time \( t \) begins at zero from the edge of the step. During this transient time, the error signal is smaller than the change in sample topography. This low error signal

---

**Figure 11** Simulation of a high-speed scan of a sample with a sharp downward step. The oscillation amplitude is limited to the free air oscillation amplitude \( A_0 \) after the step is encountered. As the set-point amplitude \( A_{set} \) is set close to \( A_0 \), the error signal saturates at \( A_{set} - A_0 \), limiting the ability of the feedback loop to track the sample topography.
The ability of the AFM to image samples with minimal preparation in liquid environments has made it a particularly attractive tool for imaging biological samples.

will delay the speed of response of the Z-axis feedback controller to bring the sample back in contact with the probe tip. The length of this transient depends on the cantilever Q factor and resonance frequency. A time delay also occurs in the feedback error signal due to the delay in demodulating the cantilever displacement signal.

The cantilever oscillation amplitude $A(t)$ continues to increase exponentially until $A(t) = A_0$. Once $A(t) = A_0$, the magnitude of the error signal has saturated and is limited to $\epsilon_{\text{max}} = [A_{\text{set}} - A_0]$. The relatively small magnitude of $\epsilon_{\text{max}}$ constrains the Z-axis feedback loop to a slow response, causing the cantilever to oscillate in free air with an amplitude of $A_0$ until the Z-axis actuator can bring the sample back into contact with the probe. This slow response prolongs the time that the probe is detached from the sample.

When the probe tip is not in contact with the sample, the controller output will not be an accurate representation of the sample topography. When the error signal is saturated, the integral action in the feedback controller will cause the sample to appear linear with a slope proportional to the controller gain and the value of $\epsilon_{\text{max}}$, and inversely proportional to the scan speed.

When probe loss occurs, it is desirable that the feedback controller output is as large as possible to ensure that the controller brings the sample back into contact with the probe tip in as short a time as possible. A high value for $A_{\text{set}}$ may be a limitation on downhill slopes of the sample, as it limits the magnitude of the maximum error signal ($\epsilon_{\text{max}} = [A_{\text{set}} - A_0]$), which increases the probability of error signal saturation occurring [99], [129]. A high value for $A_{\text{set}}$ however, is an advantage when imaging uphill regions of the sample, as it allows for a larger value for the maximum error signal ($\epsilon_{\text{max}} = A_{\text{set}}$) presented to the Z-axis feedback controller in these regions. A controller that compensates the error signal on steep downhill regions to allow for a high value of $A_{\text{set}}$ provides significant benefits, such as an increased maximum error signal in upward regions of topography, reduced tip-sample force, and improved sample tracking.

Methods of Reducing Image Artifacts Due to a Sharp Drop in Sample Topography

Image artifacts due to probe loss are affected by the scan speed, feedback controller gain, and the value of $\epsilon_{\text{max}}$. These parameters are normally fixed for the duration of a scan. Several researchers have shown that by modifying these parameters dynamically, according to the profile of the sample, significant improvements in image quality at high scan speeds can be achieved. These strategies all involve some form of detection to determine whether the probe is detached from the sample.

\[ \text{Detect} \]

\[ \text{Select} \]

\[ \text{Actuator} \]

\[ \text{Probes} \]

\[ \text{Sensor} \]

\[ \text{FPAA} \]

\[ \text{D(s)} \]

\[ \text{Peak Detect} \]

\[ A \]

\[ A_{\text{Thresh}} \]

\[ K(s) \]

\[ V_{\text{out}} \]

\[ G_1 \]

\[ G_2 \]

\[ \text{Figure 12 Switching-gain resonant-control feedback loop used to minimize probe loss. The blocks inside the dotted line are implemented in a field programmable analog array (FPAA). The peak detect block demodulates the cantilever displacement signal to produce the oscillation amplitude signal $A(t)$. The resonant controller ($K(s)$) is set to modify the effective $Q$ factor of the cantilever. The gain of the resonant controller is modified by the comparator (shown in the shaded section) according to the level of $A(t)$. If $A(t)$ is below the threshold value $A_{\text{thresh}}$, it is inferred that the probe has not lost contact with the sample. In this case, the comparator switches the gain of the resonant controller to a high value to reduce the cantilever $Q$ factor for high-speed scanning. If the probe loses contact with the sample, $A(t)$ will be larger than $A_{\text{thresh}}$. In this case, the comparator switches the resonant controller gain to a low value, which has the effect of increasing the cantilever $Q$ factor, in turn increasing the free air oscillation amplitude of the cantilever resulting in a larger error signal sent to the feedback controller. This approach reduces the time that the probe is not in contact with the sample, resulting in a reduction of image artifacts.} \]
sample and a switching controller dependent on the detection signal.

**Reducing Scan Speed**

When a sharp drop in sample topography of height $\Delta h$ is encountered by the probe tip, the duration that the probe is detached from the sample depends on $\Delta h$, the $Z$-axis feedback controller gain, and $e_{\text{max}}$. If the scan speed is reduced, a smaller area of the sample will be scanned during this period of probe loss, reducing the affected area. In most cases, however, a high scan speed is desirable. A feedforward controller that controls the scan speed depending on the predicted sample topography was presented in [130]. If a region of the sample topography is predicted to be flat by the controller, then the scan speed would be set at a high rate. If a drop in the sample topography is encountered, the rate of change in the cantilever oscillation amplitude signals to the controller that a downward slope is encountered and the scan speed is reduced by the controller.

**Increasing the Controller Gain**

The $Z$-axis controller gain and cantilever $Q$ factor must be chosen to ensure that the $Z$ axis feedback loop has sufficient stability margins to accommodate for the variation of cantilever parameters when scanning. This design will avoid oscillations appearing in the image due to the feedback loop approaching instability. If the stability margins are widened, this approach will allow for an increase in the controller gain that will reduce the duration of probe loss.

Artificially reducing the cantilever $Q$ factor results in an increase in bandwidth of the $Z$-axis feedback loop, allowing for a higher controller gain in the loop, which may be achieved by the use of active $Q$ control. This method reduces the probe loss time at the cost of increased tip-sample force [99].

When the tip has lost contact with the sample, the problem of high tip-sample force and oscillations from instability is not present, which means that, when the tip is off-sample, the controller gain may be set higher than the maximum gain allowable for on-sample stability. Momentarily increasing the controller gain to increase the $Z$-axis feedback response speed when the tip is off-sample will reduce or eliminate error signal saturation without induced instability in the feedback loop. The controller gain must be reduced back to the appropriate on-sample value when the tip regains contact with sample to avoid large tip-sample forces and instabilities in the feedback loop.

A dynamic proportional-integral-derivative (PID) $Z$-axis feedback controller was developed [84] to address the error saturation problem. The cantilever oscillation amplitude signal $A(t)$ is used to determine whether or not the probe tip has detached from the sample. If $A(t)$ exceeds a threshold value $A_{\text{thresh}}$ (set close to $A_0$), then it is inferred that the cantilever has lost contact with the sample. When probe loss is detected, the error signal $A_{\text{sat}} - A_0$ is multiplied by a gain before it is sent to the controller, which has
the effect of increasing the actuator’s response speed and reducing the time that the probe is detached from the sample surface. When the probe regains contact with the sample, \( A(t) \) quickly falls below the threshold value and the gain is removed from the error signal, avoiding any instabilities in the feedback loop.

The reliability index method [85] may be used to determine if the tip has lost contact with the sample, rather than using the measured value of \( A(t) \). The reliability index is obtained in the same way that the image signal is obtained for TF-AFM. An observer is designed to model the dynamics of the cantilever in free air. When the tip interacts with the sample, the forces between the tip and sample modify the dynamics of the cantilever. The reliability index is obtained from the error between the observer model and the cantilever. When the cantilever is detached from the sample, the reliability index is small as the observer dynamics closely match the dynamics of the cantilever but increases when the tip is tapping the sample, giving an indication of when the probe has lost contact with the sample. This method has been demonstrated to reduce the time in which probe loss is detected. A switched-gain PID controller with a threshold value of the reliability index determining the switching between gains was proposed [131] to reduce the problem of error saturation.

Another approach [132] combines switching scan speed and feedback gain to reduce image artifacts occurring as a result of error saturation. The scan speed was reduced in uphill regions of the sample to allow for a higher on-sample feedback gain and the feedback gain was increased when probe loss was detected on downward sloping regions of the sample.

### Increasing the Maximum Error Signal

The duration of probe loss may be reduced by increasing \( \varepsilon_{\text{max}} \), which can be achieved for downward slopes of the sample by setting \( A_{\text{set}} \) much lower than \( A_0 \). The disadvantage of this approach is that \( \tilde{F}_Z \) is increased [according to (1)] and \( \varepsilon_{\text{max}} \) on upward slopes of the sample is reduced.

For a cantilever oscillating in free air near its resonance frequency, the amplitude of oscillation is proportional to the cantilever \( Q \) factor. If the cantilever \( Q \) factor is increased when probe loss occurs, \( A_0 \) will increase as a result of this higher \( Q \) factor, leading to an increase in \( \varepsilon_{\text{max}} = |A_{\text{set}} - A_0| \).

When the probe is on-sample, the \( Q \) factor should be set at a value low enough to maintain sufficient stability margins in the \( Z \)-axis feedback loop. \( A_{\text{set}} \) should be set close to \( A_0 \) to minimize \( \tilde{F}_Z \) and to increase \( \varepsilon_{\text{max}} \) in upward sloping regions of the sample. When the probe is off-sample, instabilities occurring in the \( Z \)-axis feedback loop are no longer an issue. Therefore, the cantilever \( Q \) factor may be increased in this region to increase \( A_0 \) (and consequently \( \varepsilon_{\text{max}} \)) to reduce the probe loss duration.

One approach is to have the controller switch the \( Q \) factor of the probe, depending on the profile of the sample [133]. The controller uses the principle of active \( Q \) control, multiplying probe velocity by a gain \( G \) and then subtracting it from the probe oscillation signal, to set the on-sample cantilever \( Q \) factor. If the oscillation amplitude of the probe exceeds a threshold value \( A_{\text{thresh}} \), indicating that the probe has lost contact with the sample, then \( G \) is reduced to increase the cantilever \( Q \) factor. As the sample comes back into close proximity with the probe, the forces between the tip and the sample will modify the \( Q \) factor and resonance frequency of the cantilever, causing \( A(t) \) to return below \( A_{\text{thresh}} \). As \( A(t) \) is now less than \( A_{\text{thresh}} \), the controller increases \( G \) back to its on-sample value, which has the effect of reducing the cantilever \( Q \) factor to ensure that the stability margins of the loop are wide enough to avoid instabilities occurring. This controller was implemented on a custom-built AFM that measured probe velocity with a laser Doppler vibrometer and integrated this signal to obtain the probe displacement signal required for imaging. The velocity signal obtained from the vibrometer was used in the active \( Q \) control loop. The control technique was demonstrated to significantly reduce imaging artifacts caused by probe loss, while maintaining a high value for \( A_{\text{set}} \) to limit tip-sample forces and maintain a high value for \( \varepsilon_{\text{max}} \) in upward sloping regions of the sample. The drawback of this controller is that it cannot be easily implemented into existing commercial AFMs.

The switched gain resonant controller, detailed in [134], is based on the above control philosophy of switching the cantilever \( Q \) factor according to the sample profile. A block diagram of the switched gain resonant controller is presented in Figure 12. This controller uses a resonant controller to modify the cantilever \( Q \) factor [110]. The controller demodulates the cantilever oscillation signal and then compares this demodulated signal to a threshold value, switching the gain of the resonant
controller accordingly. The controller is implemented with a field programmable analog array [135] to allow for easy integration of the demodulator and switching controller and also to allow for the control parameters to be easily changed. The demodulator is based on the “peak detect” method [120] to increase the speed at which probe loss is detected. A significant reduction in image artifacts was achieved with this controller as can be seen from Figures 13–14. The Z-axis feedback error signal, taken from a cross section of the scan of Figure 13, shown in Figure 15, illustrates the compensation of the error signal by the controller.

CONCLUSION

This article has reviewed the applications and performance of the AFM operating in tapping mode. The applications and scientific discoveries that have been achieved so far with the AFM offer a glimpse into its capabilities. However, there is still a long way to go until the AFM reaches its full potential. Further increases in the imaging speed, while minimizing image artifacts, will allow researchers to observe dynamic processes with the AFM that are impossible to observe with currently available instruments.

The limitations to increasing the scan speed of the AFM operating in tapping mode are the bandwidth of the scanner in the lateral axes and the bandwidth of the Z-axis feedback loop, with the latter being the main limitation. Factors that affect the bandwidth of the Z-axis feedback loop are the bandwidth of the cantilever in cascade with the demodulator, the time taken to demodulate the cantilever tip oscillation amplitude, and the bandwidth of the Z-axis actuator. The bandwidth of the cantilever in cascade with the demodulator is the major restriction on the bandwidth of the Z-axis feedback loop. A high cantilever Q factor is highly desired to achieve high force sensitivity and to minimize tip-sample force when scanning a sample. The bandwidth of the cantilever in cascade with the demodulator is inversely proportional to the cantilever Q factor. This tradeoff between force sensitivity/tip-sample force and scan speed is a fundamental challenge that engineers must overcome when designing control systems to improve the performance of the tapping-mode AFM.

Several control techniques developed to increase imaging speed while minimizing image artifacts have been reviewed in this article. The development of new control techniques combined with those highlighted in this article will play an important role in the future development of this instrument, which is playing a key role in many fields of research. Further advancement of the AFM’s capability will require a multidisciplinary approach that combines the expertise of researchers in the fields of physics, materials science, and mechanical and electrical engineering. However, the control systems engineer will play a pivotal role in the challenge of increasing the imaging speed of this device while maintaining minimal image artifacts and avoiding damage to the sample.

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