Gentle imaging of soft materials in solution with amplitude modulation atomic force microscopy: *Q* control and thermal noise

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Increasing the effective Q factor using feedback (Q control) decreases tip-sample interaction forces for amplitude modulation atomic force microscopy. However, the feedback loop amplifies thermal noise compromising the signal to noise ratio. Simulations, which include thermal excitations, reveal that average tip-sample forces scaled for signal to noise ratio remain roughly unchanged as Q factor changes for intrinsically low Q environments such as liquids. Furthermore, increased Q causes the tip-sample interaction to become sporadic and hinders consistent imaging. Thus, it is preferable to image with small amplitudes instead of higher effective Q factor. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2824576]

Atomic force microscopy (AFM) is an indispensable technology for nanoscience due to its versatility and fine resolution.[1] While AFM routinely produces high resolution images of hard materials, imaging of soft materials in solution, such as proteins and other biological structures, remains elusive because tip-sample interaction forces can cause deformation and obscure topographical information. Contact mode has achieved low normal interaction forces and produced stunning images of protein subunits in membranes.[2–7] However, the sample must have negligible topography and be well supported since lateral forces associated with contact mode can dislodge and damage the sample. ac techniques significantly reduce lateral forces and as a result, the simplest technique, amplitude modulation atomic force microscopy (AM-AFM), has become widely used in the AFM community. When working in solution, the fluid strongly damps cantilever oscillation. The extra damping requires more energy input to maintain the oscillation which leads to higher peak forces when interacting with the sample. Similarly, the added mass of the fluid along the length of the cantilever can excite higher order motion during tip-sample contact possibly causing increased peak forces.[8] Also, acoustic excitation of the cantilever in high damping environments is complicated by poor excitation of the tip by shaking the chip[9] and the "forest of peaks" from hydrodynamic modes of the surrounding fluid and enclosure requiring the user to be vigilant about choosing the real resonance to avoid unnecessarily high interaction forces.[10,11] The higher forces associated with ac modes in solution can cause significant sample deformation,[12,13] causing the researchers to seek methods to reduce normal tip-sample forces. Phase modulation atomic force microscopy offers great promise for high speed gentle imaging due to the fast-time response and strong distance dependence of the phase signal.[14–18] However, many researchers may still prefer AM-AFM since the polarity of the feedback signal for AM-AFM is the same for both attractive and repulsive interactions leading to more robust imaging. For AM-AFM, many have suggested increasing the effective Q factor using feedback (Q control) to reduce tip-sample interaction forces for AFM (Refs. 19–24) and for tuning forks.[25] However, some researchers claim to show insignificant benefit and instead advocate optimizing scan parameters to accomplish the same purpose.[26,27] This apparent contradiction can be explained when the effects of thermal noise are considered. In this letter, it is shown that reduction of tip-sample interaction forces by Q control is accompanied by amplification of thermal noise and degradation of the signal to noise ratio. Normalizing peak contact force by the signal to noise ratio reveals that Q control confers little advantage compared to reducing the amplitude for gentle imaging for small initial Q factors. Furthermore, sporadic interactions associated with high Q produce larger peak forces and an inconsistent error signal which degrades image quality.

Q control modifies the effective cantilever Q factor by using a feedback loop where the 90° ($\pi/2$) phase shifted deflection signal is summed with the cantilever drive signal.[28,29] Within the simple harmonic oscillator approximation, the resulting transfer function $A(f)$ is

$$|A(f)| = \frac{k}{\sqrt{\left(1-\frac{f^2}{f_0^2}\right)^2 + \left(\frac{f}{Q_i f_0} + \frac{G}{k}\right)^2}}(\langle F_T\rangle + F_D).$$

In the equation, k, f_0, and Q are the cantilever parameters, spring constant, resonant frequency, and cantilever Q factor, respectively, f is frequency, $\langle F_T\rangle$ is the time averaged thermal fluctuation force, F_D is the ac drive force, and G is the Q-control feedback loop gain. The damping term dominates the denominator when $f \cong f_0$. In which case, the effective Q-factor term absorbs the feedback gain term such that $Q_e = Q_i/(1+M)$, where $M \equiv GQ_i/k$. Thus, changing the gain of the feedback loop modulates the effective cantilever quality factor.

The hydrodynamic environment of the cantilever determines the thermal excitation forces experienced by the cantilever. At thermal equilibrium, energy for each degree of freedom is constant and the fluctuation dissipation theorem can be used to calculate the thermal excitation forces: $\langle F_T\rangle = \sqrt{2k_BTk/\pi f_0 Q} = \sqrt{4k_BTb}$, where b is the cantilever damping. Q-control feedback does not change the inherent damping of the cantilever nor the excitation forces but instead provides another mechanism for energy to be removed or imparted to

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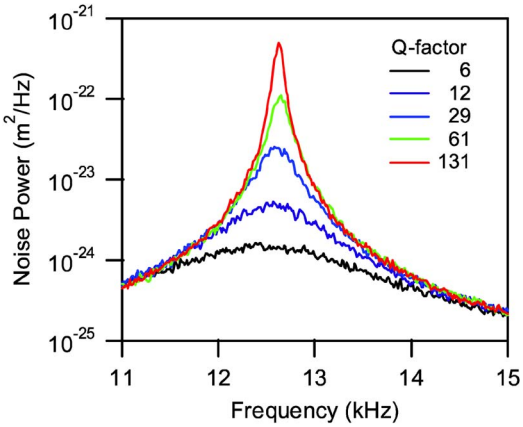

FIG. 1. (Color online) Noise power spectra for multiple effective Q-factor values. Q control amplifies the thermal noise as Q is increased.

the cantilever and shifts the system from equilibrium to a nonequilibrium steady state. Figure 1 contains experimental thermal noise spectra for different feedback gain values revealing that the change in cantilever effective thermal energy as the effective quality factor is modulated.[30] Q-control was implemented using analog circuitry with a low pass filter as the phase shifter and magnetic excitation of the cantilever.

The amplitude signal for AM-AFM contains frequency components higher and lower than the reference frequency. Thus, the noise in the amplitude signal is typically dominated by thermal noise components especially when amplified by the Q-control feedback loop.[31,32] Consequently, a trade-off exists as Q control is used to modulate the Q factor. Increased Q at constant free amplitude and set point decreases tip-sample interaction forces, but the signal to noise ratio suffers since the higher Q amplifies the thermal noise. To keep the same signal to noise ratio, the amplitude must be increased which increases the tip-sample interaction forces, essentially negating the advantage gained by using Q control.

Numerical simulations of cantilever trajectories were used to investigate the merit of using Q control for gentle imaging in the presence of noise. Numerical methods are important since they can best model the stochastic nature of thermal excitation. The data consist of a set of cantilever trajectories with different values of initial free amplitude ranging from 0.2 to 3 nm in 0.1 nm steps and Q-factor values ranging from 2 to 100 in 28 logarithmic steps. The equation of motion was integrated with the cantilever near the surface at a set point of 60%. Other set point values produce qualitatively similar results. Tip-sample interactions were modeled as Hertzian deformations to capture the characteristics of soft materials with no adhesion. The parameters used were tip radius of 5 nm, tip elastic modulus of 170 GPa and Poisson ratio of 0.3, and sample elastic modulus of 1 GPa and Poisson ratio of 0.3. A medium stiffness cantilever, $k=1.5$ N/m, in a high damping environment, $Q_i=5$ and $f_0=28\,000$ Hz, was used to mimic AM-AFM in water. Thermal force noise was generated using a random number generator from a Gaussian distribution with standard deviation scaled to $\sqrt{2k_BTb/dt}$, where dt is the time increment of the simulation, ~70 nS. Q control was implemented by using a damping factor corresponding to the effective Q-factor value during integration of the wave equation. Implementing Q control with an effective damping value is quantitatively similar to modeling a deflection feedback loop and phase shifter. A sinusoidal driving force at the resonance frequency induced oscillations. At the point of maximum displacement toward the sample during each oscillation, the tip-sample interaction force was recorded as a measure of impact force. The amplitude signal was computed from the tip trajectory simulating a 1 ms time constant. Amplitude signal to noise ratio was computed by dividing the mean of the amplitude values by the standard deviation of the amplitude. The normalized tip-sample interaction force is the mean of impact force values divided by the amplitude signal to noise ratio. The amplitude signal to noise ratio, impact force, and normalized impact force are depicted in Fig. 2 for the array of free amplitude and effective Q-factor values. The color scale is logarithmic with bluer colors representing advantageous values such as high signal to noise ratio, small interaction force, or small normalized interaction force.

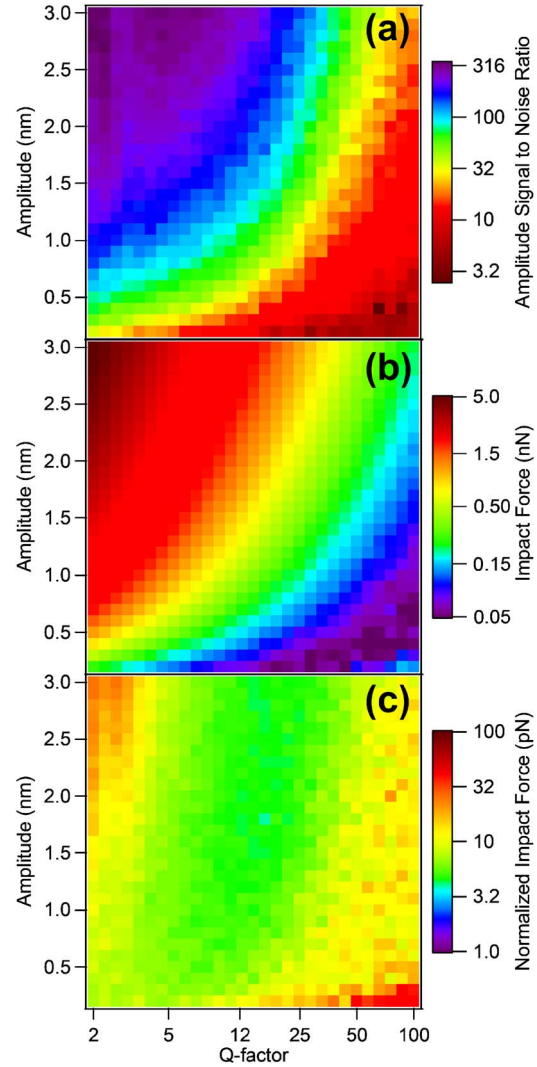

FIG. 2. (Color online) Amplitude signal to noise (a), impact force (b), and normalized impact force (c) as a function of tapping amplitude and effective Q factor. High Q has low impact force and low signal to noise. Normalized impact force reveals that Q control provides little advantage.

Previous papers analyzing Q control have not considered contributions from thermal noise. However, thermal noise is frequently the largest source of noise for AM-AFM placing limits on sensitivity. Increasing the effective Q factor compromises performance by increasing the thermal noise. Similarly, the changing shape of the thermal noise spectrum places a larger percentage of the total thermal noise in the

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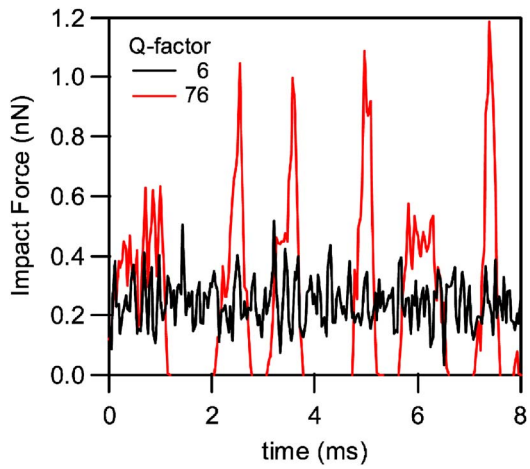

FIG. 3. (Color online) Impact force as a function of time for an amplitude of 0.4 nm and Q of 6.1 (black) and an amplitude of 2.6 nm and Q of 76 (red). Both traces have the same average impact force, however, the low Q oscillator has much more consistent tip-sample interactions.

imaging bandwidth. Thus, the amplitude signal to noise ratio is a function of both amplitude and effective Q factor, and a specific signal to noise ratio can be achieved through different combinations of oscillation amplitude and effective Q factor. As expected, higher effective Q factor does lead to lower impact forces but decreasing the oscillation amplitude serves the same purpose. The normalized impact forces reveal that no combination of amplitude and effective Q factor confers a significant advantage while maintaining a specific average impact force [Fig. 2(c)]. A region with moderate increase in Q factor does provide a slightly lower normalized force, but using increased Q factor has other deleterious consequences.

While using moderately increased Q values provides a slight advantage, the advantage for imaging is lost because the interaction force becomes sporadic. Figure 3 plots maximum interaction force of each oscillation as a function of time for two amplitude/Q-factor pairs (A_0=0.4 nm/Q=6.1 and A_0=2.6 nm/Q=76). The pairs were chosen for having the same signal to noise ratio and average impact force but different effective Q factors. The low amplitude and low Q-factor curve reveals that the interactions with the sample are consistent. However, increasing the thermal excitations while making the oscillator more resistant to changes in energy, by increasing the effective Q factor, causes the oscillator to fluctuate between pounding and not interacting with the sample. The resulting image will become grainy. However, the amplitude must be large enough to avoid lateral forces when encountering topography. In this situation, Q control maybe a satisfactory technique for reducing tip-sample interaction forces while retaining sufficient amplitude. For imaging gently and quickly, it is most effective to use the smallest amplitudes allowable and retain the intrinsic Q factor than increase the Q factor using feedback.

The ability to modulate the effective Q factor electronically produced great excitement since it promised to reduce tapping forces and deformation. However, previous treatments failed to consider the role of thermal excitations of the cantilever and their amplification by the Q-control feedback loop. The simulations presented here reveal that Q control confers little advantage in signal to noise ratio for a specific average tip-sample interaction force. Furthermore, increased effective Q-factor values make the tip-sample interaction more sporadic hindering good imaging. It is more advantageous to use the intrinsic Q factor and small oscillation amplitudes for gentle imaging of soft samples in solution with ac-mode AFM.

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