AC Mode Imaging: Scientific Background and Theory

Chapter Contents

1. Feedback

In AC mode, the cantilever is typically oscillated mechanically by a small piezo electric actuator very near the cantilever chip. Prior to imaging, the Drive Frequency is swept over a broad range to locate the first resonance of the cantilever. The Drive Frequency is then set at or near that Resonance Frequency. The name “AC mode” stems from the tip oscillation: Think of AC current vs. DC current. The optical detector senses the oscillatory motion of the cantilever, and the electronics inside the controller measure the amplitude of this oscillation and also the phase with respect to the drive signal.

When thinking about AC mode, it is a useful experiment to dissect an AC mode force plot. An AC mode force plot collects the cantilever amplitude as the oscillating tip is moved towards the surface and away again. This is shown in Figure 5.3 on page 38. On the right side of the graph, the cantilever is oscillating 100 nm above a flat sample surface. In this force plot, the cantilever was oscillating at resonance with an amplitude of 60 nm. That means the tip swings sinusoidally from 60 nm below the rest to a position 60 nm above. Now we move the base of the lever (as well as the resting point of the lever) towards the surface, and we follow on the graph from right to left (Figure 5.3 on page 38). The amplitude remains constant until the resting position of the cantilever gets within 60 nm of the surface, then the bottom of the oscillation is just barely touching the surface. As we bring the cantilever closer to the surface, the tip oscillation must be reduced. You may think that the tip motion will now have the form of a truncated sine wave, but in reality, the equations of

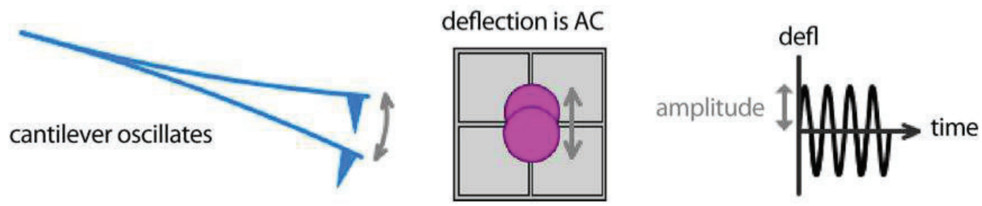

Figure 5.1.: An oscillating cantilever leads to an oscillating signal on the photodetector

Pause to consider the absolute magnitude of these oscillations. Picture a 12 μm tall cone. The absolute motion is twice the amplitude (120nm) or only 1% of the entire conical tip structure. Clearly, this is quite exaggerated as it shows an oscillation amplitude a thousand times larger than reality. Keep in mind that the oscillation amplitudes are quite small and that nearly any figure you see in any paper, book, or manual, will greatly exaggerate the amplitude of oscillation.

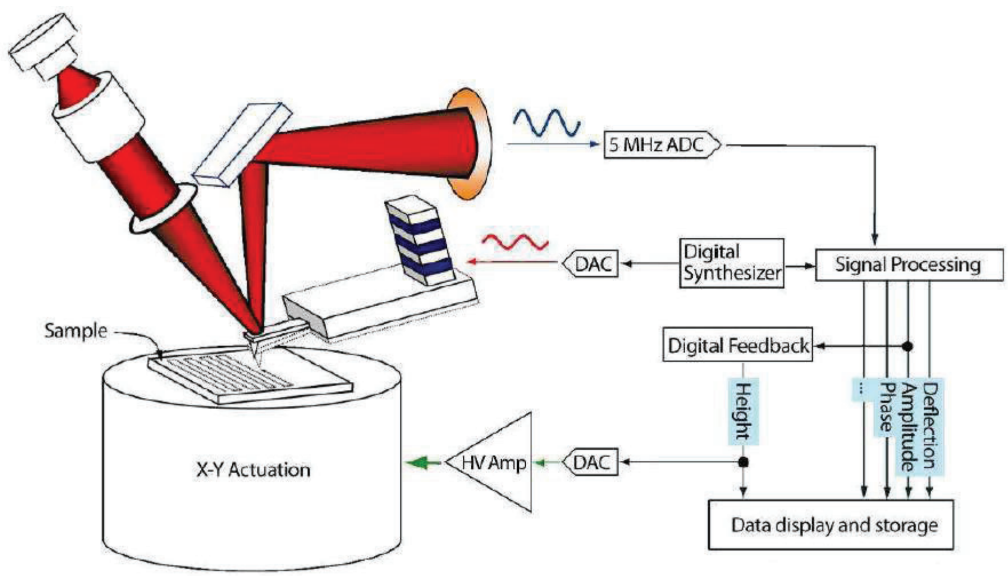

Figure 5.2.: Basic diagram of AC mode imaging.

motion produce something that is very nearly a sine wave with a reduced amplitude. You can see this in the plot; the amplitude is linearly decreasing as the surface inhibits the oscillation.

This linearly sloping amplitude with Z is well suited for feedback signal. In continuing our example, an amplitude setpoint of 40 nm will cause the feedback to reduce the average tip sample separation (z-position) to 40 nm. If, during scanning, the surface suddenly slopes up, the oscillation amplitude will decrease, and the feedback will drive the z piezo up until the amplitude is back at its setpoint.

2. Phase Image

A Phase image has a wealth of information; it is equivalent to a map of dissipation. Polymer samples may show little of interest in terms of topography but contain a lot of phase contrast in terms of nano variations in sample mechanical properties. While previous sections explain a lot

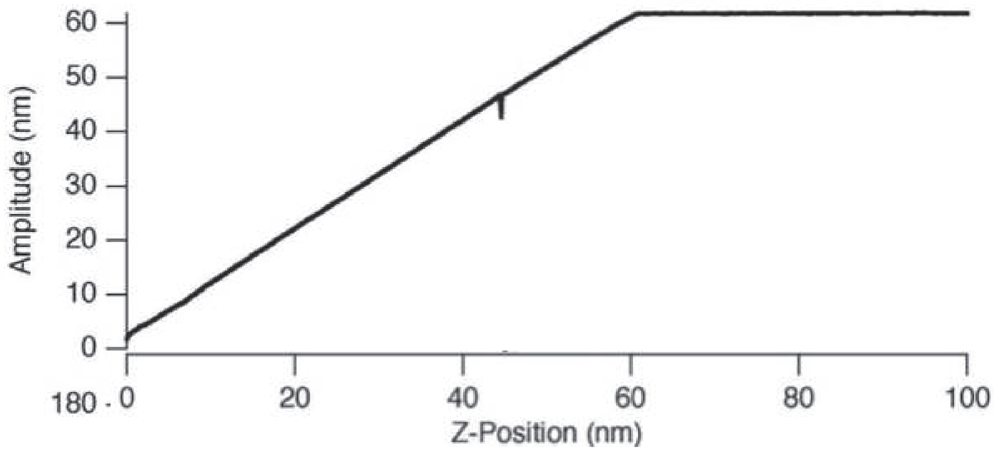

Figure 5.3.: Tip oscillation amplitude as it approaches the surface. The small glitch in amplitude is explained later. See 5.4.

about AC mode imaging in terms of amplitude, it is only half the story, as any driven oscillator has both amplitude *and* phase. Phase is expressed in degrees. A cantilever driven a good deal below resonance is said to be in phase (0°), i.e., while the base of the cantilever is slowly driven up, the entire lever moves up at the same speed. A cantilever driven a good deal above resonance will do the opposite at its tip and base. This condition is called “out of phase” (180°). At resonance, it is neither in-phase nor out, but in between. We can think about this with a human scale example, a swing. When swinging, you change the sign of the drive when the amplitude of the swing is at a maximum, meaning the drive signal is 90° behind the amplitude signal.

3. Attractive and Repulsive Behavior

Let’s revisit Figure 5.4 on page 39. This time we will show the phase signal as well.

Again, we’ll start at the right side of the graph. The cantilever is driven nearly at resonance. The Amplitude is 60 nm, and the Z-Position is 100 nm. The tip does not touch the surface, even at its lowest point. The Phase is nearly at 90°, slightly larger, indicating that the cantilever is almost being driven at resonance.

As soon as Z-Position decreases to the point where the tip starts interacting with the surface, the Phase starts to grow larger than 90°. This behavior can be explained by the attractive force the tip experiences from the sample, during the brief time of each oscillatory cycle that it spends near the surface. The closer we move the cantilever to the sample, the more attractive force experienced, and the larger the phase grows. But as the tip gets closer to the surface, there is also repulsive forces, damping the oscillation. At some point during the decreasing of z-position, the repulsive forces are greater than the attractive forces, and the phase shifts to below 90°. The attractive forces are pulling down on the lever at the bottom of the cycle, and the repulsive forces are pushing at the bottom of the cycle. The attractive forces will shift the resonance frequency to lower frequencies, so if you started driving on resonance, the shift of the resonance to lower frequency means your phase is > 90°. Then when the repulsive forces exceed the attractive forces, it is net repulsive. That repulsive pushing at the bottom of the oscillation shifts the resonance frequency to higher

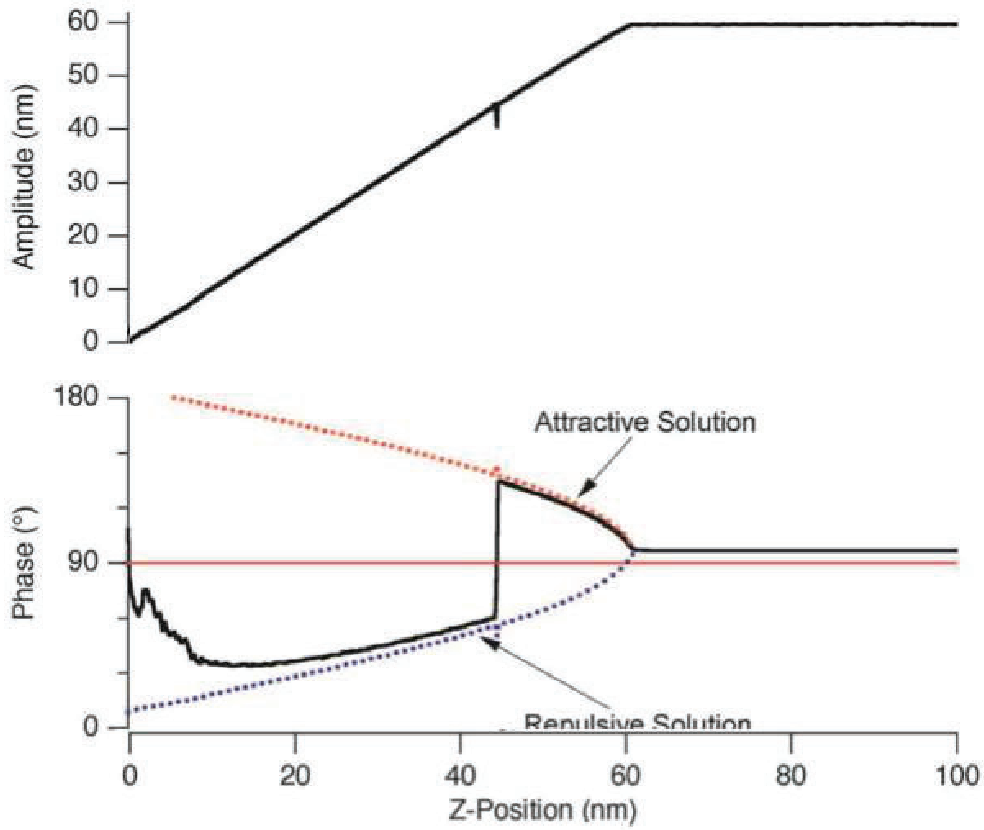

Figure 5.4.: Cantilever amplitude and phase as a function of average tip-sample separation

frequencies, meaning the drive frequency is below resonance, and you see a phase < 90°. This shift in resonance frequency is further illustrated in Figure 5.6 on page 41.

Notice from Figure 5.6 on page 41 that if you choose a negative Target Percent amplitude during an Auto Tune (Section 4.3 on page 30), it helps keep the tip in Repulsive mode during AC mode imaging . Likewise, positive target percent amplitudes help the tip stay in Attractive mode

For more on this topic, see references[1,2,3,4].

3.1. Selecting Attractive vs. Repulsive

In practice, it can be qite dfficult to select between Attractive mode and Repulsive mode imaging. For the specific case shown in Figure 5.5 on page 40, a setpoint chosen too close to 60nm will lead to unstable imaging. A setpoint chosen too close to 43 nm will cause the phase to constantly flip between attractive and repulsive. Luckily, we have not explored the option of choosing a dfferent free amplitude. The 60 m free amplitude used in the examples so far was arbitrary.

[1] J. Tamayo, R. Garcia, Appl. Phys. Lett., 1998 73(20), p2926.
[2] J.P. Cleveland, B. Anczykowski, A.E. Schmid, V.B. Elings, Appl. Phys. Lett., 1998 72(20) , p2613
[3] A. San Paulo, R. Garcia, Biophys. Journ., 2000 78, p1559.
[4] R. Garcia, R. Perez, Surface Science Reports, 2002 47 p197-301.

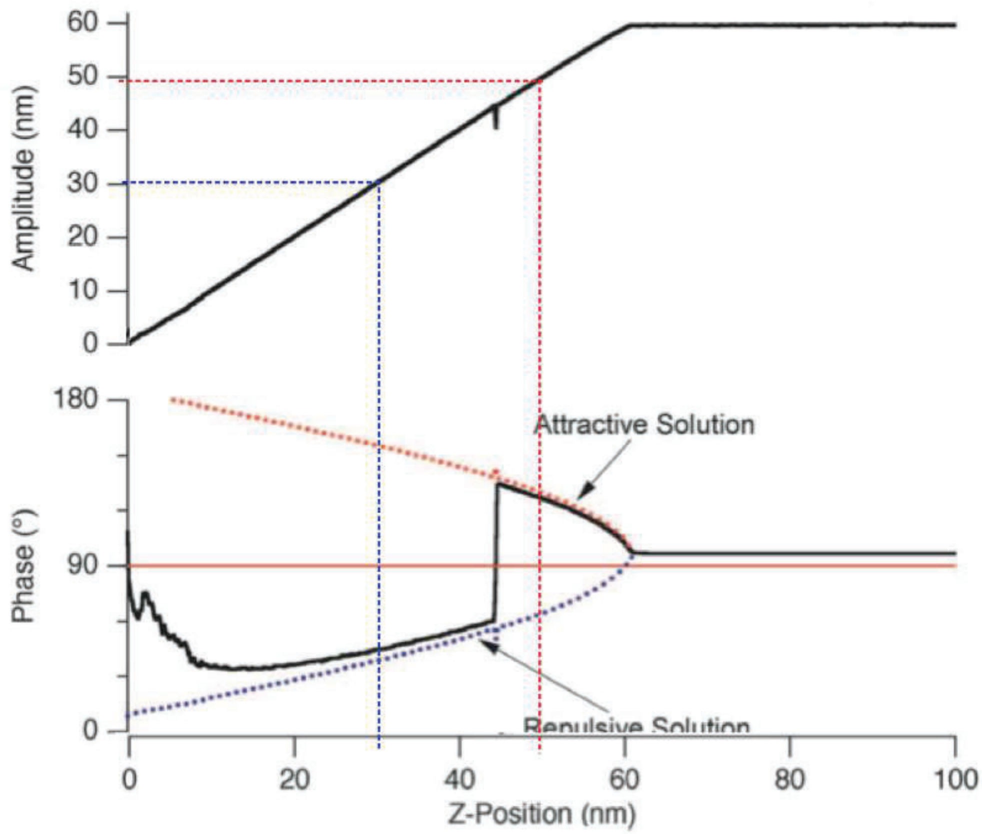

Figure 5.5.: AC mode feedback setpoint of 50nm (red dashed lines) gives attractive mode imaging, a setpoint of 30nm (blue dashed lines) gives repulsive mode imaging.

Take a look at Figure 5.7 on page 42. This is a busy graph, but to get some frame of reference, the red curves on the graph are the same as we have been looking at in the few previous figures. The other curves are just repetitions but with higher or lower free amplitudes. For instance, for the top black curve, the cantilever is oscillating with an Amplitude of nearly 300 nm when it is well above the surface. Note that from the corresponding phase curve, the cantilever only oscillates in Attractive mode (phase > 90°) for a very small range of setpoints very close to that free amplitude and then stays repulsive (phase < 90°) for lower setpoints.

The green, blue, purple, and pink curves are for successively lower and lower cantilever drive amplitudes. The behavior is similar, but there is a growing trend of attractive behavior with setpoints near the free amplitude.

For the blue curve with a 50 nm free amplitude and the black curve with 20 nm free amplitude, there is a remarkable change of general behavior. No matter what setpoint you choose (below the free amplitude), the cantilever always oscillates in the attractive regime. Now we can make some fairly good rules of thumb for imaging in purely Attractive mode, purely Repulsive mode, or something prone to switching between the two.

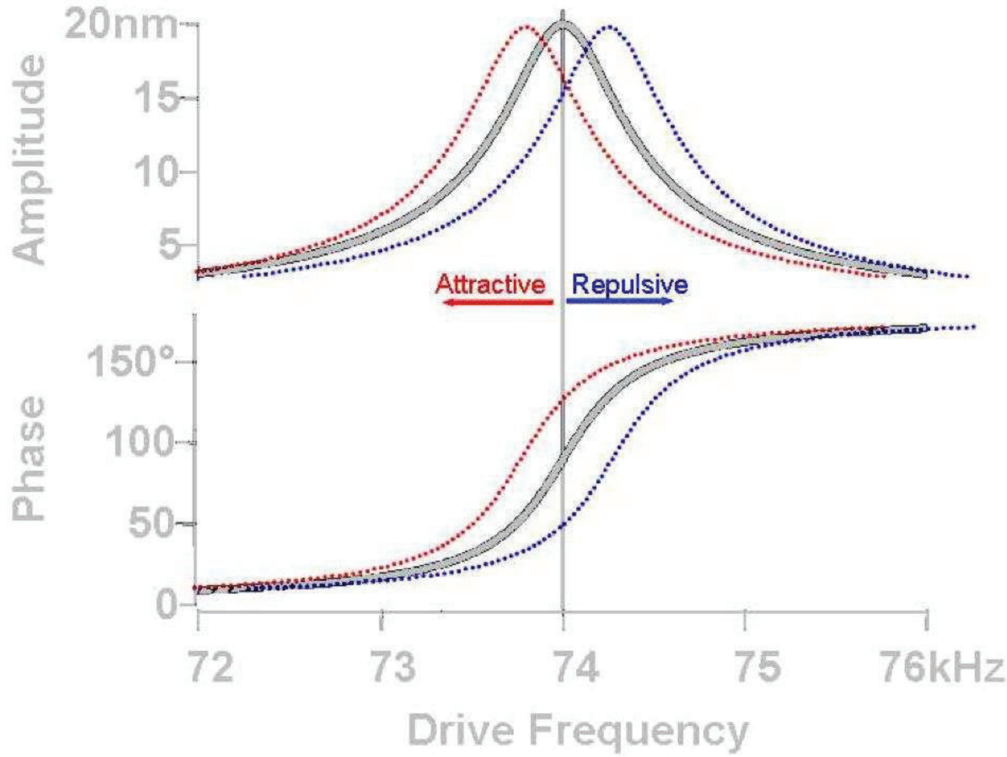

Figure 5.6.: A shift in resonance frequency, f_o (at constant amplitude) as the tip interacts with surface results in phase shift of the AC signal: Decrease in f_o results in phase increase (attractive mode), while increase in f_o results in phase decrease (repulsive mode). The colors represent the color of the phase on the Sum and Deflection Meter Panel.

3.2. Rules of Thumb for Attractive or Repulsive Mode Imaging

Repulsive Mode More Likely	Attractive Mode More Likely
Bigger free amplitude	Smaller free amplitude
Stiffer cantilever	Softer cantilever
Drive frequency lower than resonance	Drive frequency higher than resonance
Lower Q, Negative Q gain	Higher Q, Positive Q gain
Sample with smaller attractive forces	Sample with bigger attractive forces
Sharp tip	Dull tip

Table 5.1.: Attractive vs. Repulsive AC mode imaging "rules of thumb"

3.2.1. Free amplitude

Bigger or smaller free amplitude are relative terms. Only once you perform a series of AC force curves with a particular cantilever and a particular sample, you will be able to quantify what bigger and smaller mean. For instance, the experiments in Figure 5.7 on page 42 show for that cantilever and sample bigger means > 150 nm and smaller means < 50nm.

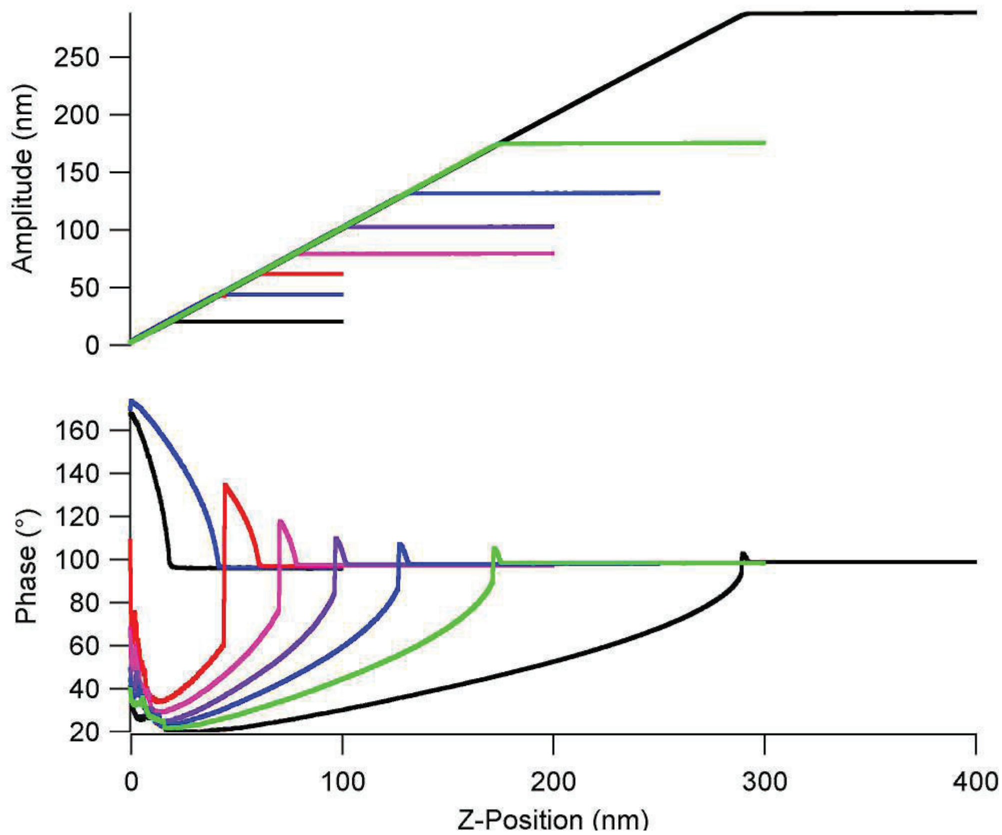

Figure 5.7.: A family of AC force curves for different free amplitudes

3.2.2. Cantilever choice

Stiffer and softer are relative terms, but for the sake of simplicity we will consider the two most common AC mode levers. On the Asylum Research Probe Store some general use AC mode probes are listed. The first choice for general AC mode imaging should probably be the Olympus AC160. With a spring constant of around 40 N/m it is considered a relatively stiff probe good for repulsive mode imaging. The next most commonly used AC mode lever is the AC240, it is 20 times softer, and considered a good probe for attractive or repulsive mode imaging. Note that the data presented in earlier in this section were for a probe similar to the AC240.

3.2.3. Drive frequency above or below resonance

In practice, the AR software makes it very easy to tune the cantilever slightly above or below resonance. Under the *Tune* tab of the Master Panel, you can select 'Target Percent'. A value of -10% is good to promote Repulsive mode imaging, and +10% helps promote Attractive mode imaging. Alternatively, you can right-click on the resonance curve after tuning and manually select the drive frequency.

3.2.4. Q (Quality Factor)

The Q factor of the cantilever is a result of both the lever and the environment (liquid or gas). If you have a relativity low Q (<30), you may find it difficult to stay in Attractive mode. In such cases, consider using the Q control feature of the AR SPM software. By means of digital processing in the SPM controller, it allows you to increase or decrease the Q. Y

3.2.5. Sample attractive forces

You typically don't have much control over sample attractive forces; but if you find it particu-larly difficult to achieve attractive or repulsive mode imaging, it may be due to your sample.

3.2.6. Tip sharpness

A dull tip has more contact area and is more strongly attracted to a surface than a sharp tip and increases the probability of Attractive mode imaging.