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Chapter 7

Image distortions in high-speed imaging: influence of force and torque compensation

7.1 Introduction

In this chapter, we discuss high-speed images acquired with the Beetle STM scanner (described in chapter 4). In order to guide our recognition of the different types of image distortion that arise from fast scanning, we start this chapter with a short theoretical introduction to Fourier transforms and a discussion of the influence of actuation signal shapes on the images. The scanner was used with the stack piezo element with 1 $\mu m^3$ actuation range, combined with a compensating stack piezo element: the same configuration used for the scanner characterisation in chapter 6. Adding to the z-direction behaviour described in that chapter, the STM imaging reveals the behaviour in the x- and y-scanning directions. The image distortions at high imaging speeds reveal the in-plane mechanical characteristics of the scanner, specifically in the fast scan direction (the line scan direction). We discuss two methods to optimize these characteristics. The piezo motion can be made more ideal by elimination of higher harmonics from the line scan signal. In addition the counter piezo can be used to suppress the effect of the scanner resonances.

7.2 Scanner characterisation with STM data

STM images give real-space information on the atomic structure of the sample surface. The images can be deformed by vibrations in the scanner body, which may severely impair the image quality that can be obtained with the instrument. The atomic structure in an STM image and the distortions that are possibly present due to vibrations can be described using the Fourier transform of that image.
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7.2.1 Fourier analysis

With Fourier analysis, we can readily distinguish between different scenarios of periodic image distortions. Here, we briefly address amplitude modulation, frequency/phase modulation [140, 141], and direct addition of vibrations in the z-direction. In amplitude modulation, the amplitude A of the sine function:

\[ f(t) = A \sin(\omega_0 t) \] (7.1)

is modulated, for instance with another sine frequency with amplitude B:

\[ f(t) = A(1 + B \sin(\omega_m t)) \sin(\omega_0 t) \] (7.2)

as shown in figure 7.1. Using the convolution theorem, it can be shown that the Fourier transform for this type of signal modulation - multiplying the original sine function with another sine, without altering the original sine or cosine - is given by:

\[ F(\omega) = \pi [\delta(\omega + \omega_0) + \delta(\omega - \omega_0) + \delta(\omega + \omega_0 + \omega_m) + \delta(\omega - \omega_0 - \omega_m) + \delta(\omega + \omega_0 - \omega_m) + \delta(\omega - \omega_0 + \omega_m)] \] (7.3)

Here, \( \delta \) is the Dirac delta function. Amplitude modulation gives rise to peak splitting in the Fourier spectrum: on both the positive and negative frequency side, there is a \( \omega_0 \) peak (the frequency of the original sine function), a \( \omega_0 + \omega_m \) peak (the sum frequency) and a \( \omega_0 - \omega_m \) peak (the difference frequency), as is shown in the right panel of figure 7.1. If the amplitude of the original signal is not modulated with a perfect sine, but with a function with a certain bandwidth, the new peaks in the Fourier spectrum will not be delta functions but will have a finite width.

Frequency modulation and phase modulation are closely related. In both types of modulation, the phase of the signal is varied. In frequency modulation, the frequency of the waveform is varied with some modulating waveform \( \omega_m(t) \):

\[ f(t) = A \sin((\omega_0 + B \omega_m(t)) t) \] (7.4)

where B is the peak frequency deviation. In phase modulation, the modulation is applied to the phase of the signal wave directly, with a time-dependent function: \( \theta = \theta_0 + \theta_m(t) \). Because
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Figure 7.1: Upper left: \( f(t) = \sin(\omega_0 t) \), sine wave with 1 kHz frequency and amplitude 1. Lower left: Fourier transform of this function. Upper right: sine wave of left panel, amplitude-modulated with a sine wave of 4 kHz frequency and amplitude 0.5. Lower right: The Fourier transform shows the frequencies of the modulated sine wave: frequency peaks at 1, 3 and 5 kHz.

the frequency is the time derivative of the phase, the resulting modulated waveform is:

\[
f(t) = A \sin(\omega_0 + \frac{d\theta_m(t)}{dt})
\]  

(7.5)

These modulation types appear very similar in the Fourier spectrum. In case of sinusoidal modulation, there is only a time lag between the two. Unlike amplitude modulation, frequency modulation and phase modulation do not produce two sidebands, but a (theoretically) infinite number of sidebands besides the central frequency. The magnitude of the \( n^{th} \) sideband in the Fourier spectrum is given by the \( n^{th} \) Bessel function \( J_n(\beta) \). \( \beta \) is the modulation index of the signal, \( B/\omega_0 \), and \( \omega_0 \) is the frequency of the 'original' signal. The magnitude of the peak of the original signal is given by the zeroth-order Bessel function \( J_0(\beta) \). The peaks have a constant separation \( \omega_m \), the modulation frequency, as is shown in figure 7.2.

Let us consider the way in which an in-plane oscillation of the tip with respect to the sample distorts the image. We assume a (one-dimensional) sinusoidal height profile of the surface:

\[
h(x) = D \sin\left(\frac{2\pi}{a} x\right)
\]  

(7.6)

where \( a \) is the lattice constant and \( D \) is the height amplitude. When the piezo element is actuated with a triangular signal, the tip position for the left-to-right trajectory is given by \( x(t) = vt \), with \( v \) the constant scan speed.
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Figure 7.2: Upper left: \( f(t) = \sin(\omega_o t + 0.5 \sin(\omega_m t)) \), sine wave with 1 kHz frequency and amplitude 1, which is frequency-modulated with a 4 kHz sine wave with amplitude 0.5. Lower left: Fourier transform of this function, showing sidebands at a separation of \( \omega_m \). Since the sidebands are extending from both the positive and the negative sides, the sidebands appear at a separation of \( \omega_m/2 \). Upper right: \( f(t) = \sin(\omega_o t) + 0.5 \sin(\omega_m t) \), sine wave with 1 kHz frequency and amplitude 1 with addition of a sine wave with 4 kHz frequency and amplitude 0.5. Lower right: The Fourier transform shows the frequencies of both sine waves separately: 1 kHz and 4 kHz.

We suppose the vibration of the tip position to be sinusoidal, changing the time-dependent tip position to:

\[
x(t) = vt + B \sin(\omega_m t)
\]  
(7.7)

Substituting the height profile, equation 7.6, we find:

\[
h(t) = h(x(t)) = h(vt + B \sin(\omega_m t)) = D \sin\left(\frac{2\pi}{a} (vt + B \sin(\omega_m t))\right)
\]  
(7.8)

We see, that this corresponds to a frequency-modulated image that will give rise to the appearance of many higher-order peaks in the Fourier spectrum. Another type of “modulation” that we will encounter in STM images, occurs when a vibration couples directly to the z-direction. This is described as:

\[
f(t) = A \sin(\omega_o t) + B \sin(\omega_m t)
\]  
(7.9)

This function with its Fourier transform is shown in figure 7.2. Such addition can occur if the scanning motion excites a resonance in the z-direction of the scanner, causing the tip-sample distance to be changed unintendedly. We will refer to this type of distortion as “direct z-excitation”.

This description also applies to the two-dimensional case of STM images. A simulation of an STM image on a highly oriented pyrolitic graphite (HOPG)
7.2 Scanner characterisation with STM data

![Simulated STM image of the HOPG lattice along with its Fourier transform. The scale bars represent 256 × 256 pixels in the STM image. On a real HOPG surface, the interatomic distance is 2.46 Å. The STM image gives rise to a Fourier image of 256 × 256 points in which both the positive and negative frequencies are shown. Here, a cut-out of reciprocal space is shown, corresponding to the central 40 × 40 points.](image)

The effect of amplitude modulation is shown in figure 7.4. The image is modulated in the line scan direction with an amplitude that is half the principal amplitude. In the STM image, we can see an apparent, non-symmetric “narrowing” and “widening” of the atomic structure and vertical bands running through the image. In the Fourier transform, this leads to peak splitting, with the new peaks being visible next to four of the six atomic lattice peaks. The remaining two lattice peaks represent purely the y-directional structure and are therefore not affected by the distortion in the x-direction.

Frequency modulation is shown in figure 7.5. In the STM image, this leads to an apparent widening and narrowing of the lattice structure. In the Fourier transform, we see that also this effect gives rise to new peaks, next to the lattice structure peaks, similar to the case of amplitude modulation.
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Figure 7.4: Simulated HOPG lattice with amplitude modulation along with its Fourier transform. The scale bars represent $256 \times 256$ pixels in the STM image, which gives rise to a Fourier image of $256 \times 256$ points in which both the positive and negative frequencies are shown. Here, a cut-out of reciprocal space is shown, corresponding to the central $40 \times 40$ points. The modulation is applied along the fast, horizontal scan direction. The modulation amplitude is half the primary amplitude and its frequency is $7/15$ of the original frequency. Peak splitting along with a broadening of the peaks can be seen in the vibration direction in the Fourier transform.

An example of direct z-excitation is shown in figure 7.6. Here, we have mimicked the situation in which the z-resonance is induced by the turning points in the fast scan direction, which synchronizes the oscillations and makes them show up as vertical bands in the STM image. In the Fourier transform, this direct z-excitation shows up as two distinct extra peaks on the x-axis. We can measure the frequency of this resonance directly, as there is no coupling to the other frequencies. When the amplitude of the excitation is increased, such as in figure 7.7, we see that the atomic structure becomes obscured, and in the Fourier transform the peaks corresponding to the modulation become dominant. This type of image deformation can be corrected by filtering out the “unwanted” frequencies in the reciprocal-space image, followed by a retransformation to real space.
7.3 The role of the actuation signal shape

In an STM, in-plane scanning is usually divided in a “fast” and “slow” direction, here horizontal and vertical, respectively. Apart from the rapid motion due to the z-feedback, the highest accelerations are to be found in the components responsible for the fast scanning, usually the x-direction piezo element. These accelerations are the prime candidate for excitation of scanner resonances, especially when a large surface area is scanned. If the line frequency coincides with a resonant mode of the piezo element or other parts of the scanner, the image will show deformations. However, this is not the full story: the shape of the actuation signal is also important. Higher harmonics in the actuation signal may excite scanner- or piezo element resonances well above the scan line frequency, and limit the scanner rate to a small fraction of the first scanner or piezo resonance frequency. The excitation of higher harmonics can be suppressed by tuning of the actuation signal shape, as is discussed in [30, 33, 47]. Here we discuss the differences between actuation with a triangular actuation signal, a triangular signal with various degrees of

Figure 7.5: Simulated HOPG lattice with frequency modulation along with its Fourier transform. The scale bars represent 256 × 256 pixels in the STM image, which gives rise to a Fourier image of 256 × 256 points in which both the positive and negative frequencies are shown. Here, a cut-out of reciprocal space is shown, corresponding to the central 40 × 40 points. The modulation is applied along the fast, horizontal scan direction. The modulation amplitude is half the primary amplitude and its frequency is 7/18 of the original frequency. Frequency modulation gives rise to bands of widening and narrowing of the apparent structure of the atoms. In the Fourier image, we see a broadening and splitting of the peaks.
rounding, and a sinusoidal signal.

### 7.3.1 Appearance of higher harmonics in the linescan signal

In most STMs, the line-by-line scanning motion is actuated with a triangular waveform, with which the surface is mapped linearly in time. The Fourier transform of this actuation signal (figure 7.8, left panel) is composed of a fundamental frequency (the line frequency) and many higher harmonics. These higher harmonics are present to a lesser extent in a rounded triangular signal (figure 7.8, right panel). The relative amplitude of the sidebands is a measure of the relative strength, compared to the fundamental frequency, with which these resonances “hit” the scanner. The rounded triangular waveform shown here is composed of a triangular signal of which the upper 20% and the lower 20% are replaced by a sine. In practice, for the LPM [121] electronics that we used, the maximum rounding is 15%, which leaves 70% of the scan signal linear [30]. This means that in the real scan situation, the amplitude of the higher harmonics will be larger than shown here and therefore they will
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\[ \begin{align*}
7.3 \text{ The role of the actuation signal shape} \\
\end{align*} \]

**Figure 7.7:** Simulated HOPG lattice with direct z-excitation along with its Fourier transform. The scale bars represent \( 256 \times 256 \) pixels in the STM image, which gives rise to a Fourier image of \( 256 \times 256 \) points in which both the positive and negative frequencies are shown. Here, a cut-out of reciprocal space is shown, corresponding to the central \( 40 \times 40 \) points. The modulation is applied along the fast, horizontal scan direction. The modulation amplitude is twice the primary amplitude and its frequency is \( 7/15 \) of the original frequency. Due to the larger modulation amplitude, the image deformation is more severe than that in figure 7.6. In the STM image, the lattice structure is barely visible. Being a single additional frequency, this resonance shows up as two additional peaks (one negative, one positive) in the Fourier image that are significantly widened and of higher intensity than the six HOPG lattice peaks.

be more likely to excite scanner resonances.

A sinusoidal signal is composed of one frequency only (figure 7.9) and therefore cannot excite vibrational modes of the STM above the line frequency. In terms of mechanical stability, this is the ideal actuation signal shape. However, due to the non-linearity and delayed response of the piezo elements, typically used for scanning, higher-frequency resonances of the scanner or piezo element may still be excited by a sinusoidal scan signal. Nonlinearity becomes especially important at larger scan ranges [142].

**7.3.2 Image linearization after sinusoidal scanning**

A practical disadvantage of a sinusoidal actuation signal is that the scan speed is not constant. If the height signal is recorded at regular intervals in time, the images will appear stretched at the left and right edges and compressed in the middle. This effect is visible in the left panel of figure 7.10. It is
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Figure 7.8: Left: Triangular 1 kHz actuation signal with corresponding Fourier transform. Right: Example of a rounded triangular actuation signal at 1 kHz, with corresponding Fourier transform. The upper and lower 20% of the actuation signal were rounded into a pure sine form; still, higher harmonics are present in the signal.

Figure 7.9: Sinusoidal shaped 1 kHz actuation signal with corresponding Fourier transformation.

It is straightforward to transform the image by interpolation of the matrix of x and z values, where the x-values are of the form $\cos(t)$. The result of this linearization is shown in the right panel of figure 7.10, where the sinusoidal signature is largely removed, as can be judged from the atomically resolved pattern in the image.

7.3.3 Frequency modulation during sinusoidal scanning

Figure 7.11 shows an STM image on HOPG, imaged with 1 kHz line rate at an image size of $7.5 \times 7.5$ nm, at $512 \times 512$ pixels. Scanning was performed with a sinusoidal signal and the image shows the result after transformation to regular coordinates. When we compare the image with that in the right panel of figure 7.10, which was acquired at a lower line rate, we see an image deformation in the form of vertical bands in the image that are stretched or compressed in the x-direction. This deformation looks very similar to
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Figure 7.10: STM image on HOPG obtained with a sinusoidal scan motion along the x-direction with a line frequency of 488 Hz and 512 x 512 pixels. The sample bias was $V_{bias} = 80$ mV at a tunnel current of $I_{tunnel} = 1.7$ nA. Left: Raw data, showing the sinusoidal deformation along the x-direction. Right: Corrected image, with the pixel number transformed into the x-coordinate.

the result calculated for frequency modulation in image 7.5. The 2D-Fourier transforms of the two images are shown in figure 7.12. The hexagonal lattice structure can be clearly identified in the lower-frequency image (left). At the higher frequency, the peaks in the Fourier image are significantly broadened and show a number of satellite peaks. Figure 7.13 shows a cross section across peaks 2. At a line rate of 488 Hz, this peak, which corresponds to the lattice frequency, can be identified to be 13 kHz. At 1 kHz line rate, this peak is broadened and divided in several subpeaks. The total area in the combination of these subpeaks is larger than that in the original peak, showing that motion (vibration) is added to the STM height signal. The resolution in the Fourier transform is limited, but the satellite peaks can be recognised to have a more or less constant separation of approximately 2 kHz.

7.3.4 Influence of signal shape on image quality

The analysis presented above can also be applied to compare the deformations in images acquired at the same scan speed, but with different actuation signal shapes. The four images in figure 7.14 were obtained with (A) a sinusoidal signal, (B) a triangular signal, (C) a triangular signal with 10% rounding, and (D) a triangular signal with 15% rounding. These STM images show
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Figure 7.11: STM image on HOPG obtained at $V_{bias} = 80$ mV, $I_{tunnel} = 1.7$ nA, with a sinusoidal actuation signal at 1 kHz line rate. 512 × 512 pixels. Image corrected for sinusoidal imaging. The counter piezo was not actuated in this measurement. The vertical bands in the image indicate frequency modulation of the STM signal.

Figure 7.12: Fourier transforms of figure 7.10, measured with 488.28 Hz line frequency (left), and figure 7.11, measured with 1 kHz line frequency (right). Due to the mechanical vibration of the scanner at 1 kHz line frequency, the peaks in the right panel show sidepeaks and broadening along the x-direction.
7.3 The role of the actuation signal shape

Figure 7.13: Left: Profiles across peak 2 in the two Fourier images in figure 7.12. The two profiles were obtained by summing ten lines in the Fourier transform, centered around peak 2. A: Profile corresponding to STM image with 488 Hz line frequency (figure 7.10). B: Profile corresponding to STM image taken at 1 kHz line frequency (figure 7.11). In both graphs, we see the lattice frequency at 13 kHz for A and approximately 21 kHz in B, which is slightly shifted with respect to the expected value. In the 1 kHz image, the peak shows several sidebands with approximately 2 kHz spacing.

That sinusoidal scanning greatly improves the image quality. Even though a deformation is still present in image (A), it does not couple to the z-direction and the atomic structure remains well visible. In the other three images, we see that at the positions where the apparent lattice spacing is increased in image (A), dominating bands can be seen with hardly any fine structure remaining. This indicates that for these actuation signals, the in-plane deformation couples to the z-direction. In image (B), where the signal shape was triangular, the coupling of the scan motion to the z-direction is very large and dominates the image in the form of prominent vertical bands. Rounding of the triangular waveform, as was used for images (C) and (D), reduces this coupling, but does not come close to the case of scanning with a pure sine wave (A).

As before, Fourier analysis was used to distinguish these vibrations (figure 7.15). Remnants of the six hexagonal lattice peaks can be identified only in image (A): peak 1 is missing from the other images. Only atomic row resolution remains. Figure (B) shows a large signal (4) at low frequencies in x: this corresponds to the vertical bands in the STM image. Peak 3, which is clear in figure (A), is absent in figure (B) and only slightly visible in figures (C) and (D). Peak 2, which was already broadened in the sinusoidal scanning...
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going from 488 Hz to 1 kHz line frequency, is broadened even more for triangular scanning, and it is split in a large number of separate frequencies. The profile of this peak, compared for the different actuation signals, is shown in figure 7.16. The blue dashed line, corresponding to the sinusoidal scanning, is the same as shown in figure 7.13 (in green). All lines are normalised with respect to their own maximum value. Overall intensity differences between consecutive STM images occur frequently and are caused by tip changes. This complicates a direct comparison of the power spectra of the Fourier peaks, hence this normalisation. None of the graphs displays it maximum intensity at the lattice frequency; we also see, that the peak separation is not constant.

7.4 Pro’s and Con’s of a compensating piezo element

The implementation of a counter piezo element and its influence on z-direction vibrational modes was discussed in chapter 6. With the vibrometer measurements discussed there, we focused on the coupling of in-plane motion with the z-direction. Here, we study the influence of the compensating piezo element on the in-plane vibrations which lead to image deformation. We will address both the resonances excited by the x-piezo element and those that are excited by the y-piezo element. All vibrational modes were imaged with six different settings of the compensating piezo element: no compensation (A), force compensation in the z-direction (B), torque compensation in the fast scan direction (C), torque compensation in the fast scan direction with force compensation in z (D), force compensation in the fast scan direction (E) and force compensation in the fast direction with force compensation in z (F). No compensation was used for the slow scan direction. All images were measured with a triangular actuation signal with 15 % rounding and with active feedback, so the STM images shown here are topographic images.

7.4.1 Response to actuation of the compensating x piezo element

We have selected three line frequencies that display a distorted atomic lattice image, to illustrate the working of the counter piezo element. Each of these line frequencies excite a scanner resonance that is around 10 kHz. The first line frequency at which we observe a strong distortion is 551 Hz. This distortion increases in strength starting at approximately 535 Hz line frequency, and decreases in strength above 551 Hz until it is not visible anymore at 570 Hz line frequency. The second line frequency at which a distortion is observed is 600 Hz (this vibration is visible between line frequencies of 585 Hz and 610
7.4 Pro’s and Con’s of a compensating piezo element

Figure 7.14: STM images on HOPG, obtained with different actuation signals. All images were taken with 80 mV sample bias, 512 × 512 pixels and at a line frequency of 1 kHz. A: sinusoidal actuation signal. Image corrected for sinusoidal actuation. $I_{\text{tunnel}} = 1.7$ nA. B: triangular actuation signal. $I_{\text{tunnel}} = 1.3$ nA. C: triangular actuation signal with 10 % rounding. $I_{\text{tunnel}} = 1.3$ nA. D: triangular actuation signal with 15 % rounding. $I_{\text{tunnel}} = 1.3$ nA. The counter piezo element was not actuated in these measurements.
Figure 7.15: Fourier transforms of the 1 kHz STM images (figure 7.14), obtained with different actuation signals. A: sinusoidal actuation (Fourier transform on linearized image). B: triangular actuation. C: triangular actuation with 10% rounding. D: triangular actuation with 15% rounding.
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Figure 7.16: Profiles of peak 2 in image 7.15. All graphs are normalised with respect to their own maximum. A: sinusoidal actuation, B: triangular actuation, C: triangular actuation with 10% rounding, D: triangular actuation with 15% rounding. We see that none of the settings correctly displays the atomic structure peak at 26 kHz correctly. The multitude of peaks makes it practically impossible to separate the atomic structure frequency from the modulation signal.

Hz) the third line frequency is 949 Hz (with an excitation window from 900 Hz to 970 Hz).

At 550 Hz line frequency we see a strong distortion of the atomic lattice, as is shown in figure 7.17 for the six different settings of the x- and z-direction compensating piezo elements. Image (A), which was obtained without actuation of the compensating piezo element, shows alternating broadening and narrowing of the atomic lattice structure. The vibration is not very strongly coupled to the z-direction, and slightly couples to the y-direction. As indicated by the simulations from section 7.2.1, this is a frequency-modulated image. This is reflected in the Fourier transform (figure 7.18), which shows distinct satellite peaks in the x-direction around the lattice peaks. The intensity of the \( n^{th} \) peak is given by the \( n^{th} \) Bessel function \( J_n(\beta) \), with \( \beta \) the modulation index of the signal, i.e. the extent to which the vibration couples into the original signal. We see that the settings of the compensating piezo element change the intensities of the satellite peaks, which indicates that the modulation index is changed by applying compensation. Note, that because the height profile of HOPG is not purely sinusoidal, the hexagonal pattern with the satellites is repeated beyond the first-order maxima. Because the image is frequency modulated we expect the distortion to be lifted by either
torque or force compensation in the in-plane direction. From the STM images, we readily see that in image (E), with force compensation in the x-direction, the distortion is partially lifted (on the right side of the image). Image (F), which adds force compensation in the z-direction, shows still better imaging of the atomic lattice structure and reflects the optimal settings of the counter piezo element. This is confirmed by the Fourier analysis.

The second line frequency at which a strong distortion of the atomic lattice is observed, is 600 Hz (figure 7.19). Image (A) shows a significant variation of the apparent lattice constant. As was the case for the distortion at 551 Hz line frequency, this image is frequency modulated as confirmed by the Fourier transform (figure 7.20). Again, the image quality is improved when force compensation in both the x-direction and the z-direction is applied, although the atomic lattice is still imaged with a residual distortion.

At 949 Hz line frequency (figure 7.21), the image again appears frequency modulated, but both force and torque compensation increase the severity of the image deformation. This is confirmed by the Fourier transforms (figure 7.22), that shows an increased splitting of the lattice peaks as in-plane compensation is applied. Force compensation in only the z-direction (image (B)) does improve the image quality, as supported by the Fourier transform.

In conclusion, we have seen that force compensation in the z-direction improves the image quality with respect to the vibration characterised (at 551 Hz, 600 Hz and 949 Hz line frequencies). Force compensation in the fast scan direction proved beneficial to reduce vibrations excited at line rates of 551 Hz and 600 Hz.

### 7.4.2 Response to actuation of the compensating y piezo element

The y-direction piezo element is on a different position in the scanner than the x-direction piezo element: it is in the middle of the scanning piezo element, between x and z. This means that it does not carry as much weight as the x-direction piezo element (it only has to move the z-direction piezo element and tip holder) and that it is not really clamped or free on either side. Again we have selected two line frequencies at which a significant deformation of the apparent lattice structure is observed, to illustrate the working of the counter piezo element. The scanner resonance that is excited by these line frequencies is around 8 kHz.

The first deformation is observed at a line frequency of 792 Hz (figure 7.23), where a variation in the apparent lattice constant is observed in image (A). This is supported by the Fourier transform (figure 7.24), which shows a clear
7.4 Pro’s and Con’s of a compensating piezo element

Figure 7.17: Influence of the actuation of the counter piezo element on image distortion. Images on HOPG, the x-piezo element was used for the fast scanning direction, at a line frequency of 550.78 Hz with a triangular actuation signal with 15% rounding. All images are shown with the same colour scale. The images are 256 × 256 pixels. The y-direction compensating piezo element was not actuated in any of the images. A: Counter piezo element not actuated. $V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA}$. B: Force compensation in z. $V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA}$. C: Torque compensation in the fast direction. $V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA}$. D: Torque compensation in the fast direction, force compensation in the z-direction. $V_{\text{bias}} = 110 \text{ mV}, I_{\text{tunnel}} = 1.9 \text{ nA}$. E: Force compensation in the fast direction. $V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA}$. F: Force compensation in the fast direction, force compensation in the z-direction. $V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA}$. 


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Figure 7.18: Fourier transforms of the STM images obtained with 550.78 Hz line frequency, shown in figure 7.17. Image (F), made with force compensation in both the z-direction and the fast x-direction, has the best vibration characteristics.
Figure 7.19: Influence of the actuation of the compensating piezo element on image distortion. Images on HOPG, the z-piezo element was used for the fast scanning direction, at a line frequency of 599.61 Hz with a triangular actuation signal with 15 % rounding. All images are shown with the same colour scale. The images are 256 × 256 pixels. The y-direction counter piezo element was not actuated in any of the images. A: Counter piezo element not actuated. \( V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA} \). B: Force compensation in z. \( V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA} \). C: Torque compensation in the fast direction. \( V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA} \). D: Torque compensation in the fast direction, force compensation in the z-direction. \( V_{\text{bias}} = 110 \text{ mV}, I_{\text{tunnel}} = 1.9 \text{ nA} \). E: Force compensation in the fast direction. \( V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA} \). F: Force compensation in the fast direction, force compensation in the z-direction. \( V_{\text{bias}} = 80 \text{ mV}, I_{\text{tunnel}} = 2.0 \text{ nA} \).
Figure 7.20: Fourier transforms of the STM images obtained with 599.61 Hz line frequency, shown in figure 7.19. We see that the vibration, visible in the STM images, gives rise to satellite peaks in the Fourier analysis. Image (F), obtained with force compensation in both the z-direction and the x-direction, shows the best vibration characteristics.
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Figure 7.21: Influence of the actuation of the compensating piezo element on image distortion. Images on HOPG, the x-piezo element was used for the fast scanning direction, at a line frequency of 949.22 Hz with a triangular actuation signal with 100 % rounding. All images are shown with the same colour scale. The images are 256 × 256 pixels. The y-direction counter piezo element was not actuated in any of the images. A: Counter piezo element not actuated. $V_{\text{bias}} = 80 \text{ mV}$, $I_{\text{tunnel}} = 2.0 \text{ nA}$. B: Force compensation in z. $V_{\text{bias}} = 80 \text{ mV}$, $I_{\text{tunnel}} = 2.0 \text{ nA}$. C: Torque compensation in the fast direction. $V_{\text{bias}} = 80 \text{ mV}$, $I_{\text{tunnel}} = 2.0 \text{ nA}$. D: Torque compensation in the fast direction, force compensation in the z-direction. $V_{\text{bias}} = 110 \text{ mV}$, $I_{\text{tunnel}} = 1.9 \text{ nA}$. E: Force compensation in the fast direction. $V_{\text{bias}} = 80 \text{ mV}$, $I_{\text{tunnel}} = 2.0 \text{ nA}$. F: Force compensation in the fast direction, force compensation in the z-direction. $V_{\text{bias}} = 80 \text{ mV}$, $I_{\text{tunnel}} = 2.0 \text{ nA}$. 
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Figure 7.22: Fourier transforms of the STM images obtained with 949 Hz line frequency, shown in figure 7.21. Figure (B), corresponding to force compensation in the z-direction, shows the best image quality, with only a few satellites at the lattice peaks. Figure (F) shows vertical bands, corresponding to a high-bandwidth horizontal deformation in the STM image.
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peak splitting of four of the six lattice peaks. Images (B), (E) and (F) show a higher contrast which is probably due to differences in the tip condition during these measurements. Image (B) shows a low-frequency deformation in the vertical direction, that is present in the Fourier transform as vertical peak splitting.

To better understand this deformation we show profiles over peak 2 (figure 7.25). We see that in all images the lattice structure peak is split into several maxima and the genuine lattice peak is not visible among the high intensity of the sidebands. In images (A), (C) and (F) the higher-order peaks are of a larger intensity than in the other images. The peak separation is 8 to 11 kHz which corresponds to the observed vibration. From the two-dimensional Fourier transforms, we conclude that torque compensation in the fast direction combined with force compensation in the z-direction improves the image quality.

One of the other line frequencies that show prominent image distortion is 904 Hz, of which the STM images are shown in figure 7.26. This is very similar to the previous image. In image (A), without compensation, it can be seen that the individual atoms are deformed. From the Fourier transform (figure 7.27) it is clear that this image is frequency modulated. Compensation in the z-direction ((B), (D) and (F)) does not seem to improve the image quality and these settings even introduce a low-frequency vibration (encircled). In figure 7.28, the intensity profiles over peak 2 are shown. Again, the lattice frequency peak is obscured by the large number of sidebands. Again we find that torque compensation in the fast direction seems to work best at this frequency, with optional force compensation in the feedback direction.
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Figure 7.23: Influence of the actuation of the counter piezo element on image distortion. Images on HOPG, the y-piezo element was used for the fast scanning direction, at a line frequency of 791.99 Hz with a triangular actuation signal with 100 % rounding. All images are shown with the same colour scale and were measured at a sample bias of 80 mV. The images are 512 × 512 pixels. The z-direction counter piezo element was not actuated in any of the images. A: Counter piezo element not actuated. $I_{\text{tunnel}} = 1.0 \text{ nA}$. B: Force compensation in z. $I_{\text{tunnel}} = 1.0 \text{ nA}$. C: Torque compensation in the fast direction. $I_{\text{tunnel}} = 1.5 \text{ nA}$. D: Torque compensation in the fast direction, force compensation in the z-direction. $I_{\text{tunnel}} = 1.0 \text{ nA}$. E: Force compensation in the fast direction. $I_{\text{tunnel}} = 1.5 \text{ nA}$. F: Force compensation in the fast direction, force compensation in the z-direction. $I_{\text{tunnel}} = 1.0 \text{ nA}$. 

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Figure 7.24: Fourier transforms of the STM images obtained with 791.99 Hz line frequency, shown in figure 7.23. Image (C), measured with torque compensation in the fast scan direction and force compensation in the feedback direction shows the best image quality.
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Figure 7.25: Profiles over peak 2 of figure 7.24. All peaks are normalised with respect to their own maximum value. Indicated peaks are at the following frequencies: peak 1 - 1.5 kHz, peak 2 - 6.3 kHz, peak 3 - 17.5 kHz, peak 4 - 25.5 kHz, peak 5 - 33.2 kHz.

7.4.3 Compensation: conclusion

In the previous section, we have seen that reducing image distortion by applying compensation is not straightforward. Different compensation schemes are required at different line frequencies to optimize the result, as summarised in table 7.1. When performing the line-by-line scanning with the x-direction piezo element, a combination of force compensation in both the x-direction and the z-direction is most successful, except for a line rate of 949 Hz, where force compensation in only the z-direction is most successful.

The situation for the y-direction piezo element is even more complex since this piezo element is at a different location in the scanner: clamped between the x-direction and z-direction piezo elements. Because the y-direction piezo element is located further from the centre of mass of the scanner, it exerts a larger torque on the system than the x-direction piezo element. We indeed see that torque compensation in the y-direction along with optional force compensation in the z-direction improves the image quality. This is opposite to the effect observed in chapter 6, where we saw that to reduce vibrations in
7.4 Pro’s and Con’s of a compensating piezo element

Figure 7.26: Influence of the actuation of the counter piezo element on image distortion. Images on HOPG, the y-piezo element was used for the fast scanning direction, at a line frequency of 904.30 Hz with a triangular actuation signal with 100 % rounding. All images are shown with the same colour scale and were measured with a sample bias of 80 mV and at a tunnel current of 1.1 nA. The images are 512 × 512 pixels. The z-direction counter piezo element was not actuated in any of the images. A: Counter piezo element not actuated. B: Force compensation in z. C: Torque compensation in the fast direction. D: Torque compensation in the fast direction, force compensation in the z-direction. E: Force compensation in the fast direction. F: Force compensation in the fast direction, force compensation in the z-direction.
Figure 7.27: Fourier transforms of the STM images shown in figure 7.26. A low-frequency vibration can be identified (white circles). Figures (C) and (E) give the best result, corresponding to torque compensation in the y-direction (which is the line scan direction) with optional force compensation in the z-direction.
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Figure 7.28: Profiles over peak 2 from the images in figure 7.27. All graphs are normalised with respect to their own maximum value. Indicated peaks are at the following frequencies: peak 1 - 1.8 kHz, peak 2 - 11 kHz, peak 3 - 20 kHz, peak 4 - 28 kHz, peak 5: 36 kHz. Peak separation is 9 kHz ± 1 kHz.

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<th>Figure numbers</th>
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<td>550.78 Hz</td>
<td>Force compensation</td>
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<tr>
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<td>7.26, 7.27</td>
<td>Y</td>
<td>904.30 Hz</td>
<td>None or force compensation</td>
</tr>
</tbody>
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Table 7.1: Overview of optimal compensation schemes for various line frequencies.
the z-direction effectively, force compensation in the y-direction and torque compensation in the x-direction was beneficial. Thus, the in-plane vibrations require the “opposite” compensation with respect to the x- and y-induced z-vibrations.

From the analysis it also follows that the satellite peaks in the Fourier transform of “real” STM images are significantly broadened. A further complicating factor is that the STM images differ in intensity and contrast from one image to the other: this gives rise to varying intensities of the lattice peaks in their corresponding Fourier transforms, which complicates the quantitative comparison of different STM measurement series. Intensity differences between STM measurements are not necessarily due to poor mechanical behaviour of the scanner, but have other causes, such as tip changes.

Fourier analysis is a useful tool to characterise the nature of image deformations. Coupling of vibrations to the z-direction can be readily identified. Theoretically, such a deformation can be filtered out easily. The same holds for frequency modulated images where the intensities of the lattice peaks and the satellite peaks are given by Bessel functions $J_n(\beta)$, with $\beta$ the modulation index of the image. This can be used to calculate the modulation index from the Fourier transform of the STM images and to attempt to demodulate the measurement. However, due to the varying intensities in the STM measurements, the significant broadening of the peaks and the limited sizes of the STM images, filtering of Fourier images followed by a retransformation to real space should not be regarded as a practical method to linearize the images.

7.5 High-speed scanning

With a triangular scan signal and without actuating the compensating piezo element, the maximum achieved imaging frequency was 51.4 frames per second (fps). At higher frequencies, it was not possible to obtain atomic resolution because of strong image distortions. Figure 7.29 shows five consecutive images measured at this frequency. These images are $128 \times 128$ pixels, and were measured with a line rate of 6.58 kHz. Although the hexagonal lattice structure is not very clear, the atomic row structure can still be seen weakly on the right hand side of each image. We can greatly reduce the noise by averaging over these five images, as shown in figure 7.30. After the turning point of the scanner, on the left side of the image, the image suffers from deformation caused by piezo hysteresis. In addition, the image is frequency modulated.
7.5 High-speed scanning

Figure 7.29: 5 consecutive images obtained with a line rate of 6579.2 Hz, 90 mV sample bias, a tunnel current of 250 pA and $128 \times 128$ pixels, yielding a frame rate of 51.4 fps. No counter piezo was included in the scanner in this imaging series. The image was taken at a rotation of the scan direction by $-38^\circ$ from the x-direction, and obtained with a triangular actuation signal with 100 % rounding.

Figure 7.30: Average over the 5 images shown in figure 7.29. The atomic structure, although deformed, can be seen from the image. The fast scanning was performed by the y-piezo element, and obtained with a triangular actuation signal with 15 % rounding, without compensation by a counter piezo element.

For this image and all other images shown in this section, the y-direction piezo element was used to perform the fast scanning motion.

When the scanning is performed with a sinusoidal signal in combination with the use of the counter piezo element to suppress the excitation of scanner vibrations (figure 7.32), the resolution improves greatly and the hexagonal lattice structure can be distinguished, both in the real-space image, in the current variation image and in the Fourier transform of the latter (figure 7.33).
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Figure 7.31: Fourier transform of the leftmost image of figure 7.29.

Figure 7.32: 5 consecutive images obtained with a line rate of 5320 Hz, a sample bias of 70 mV, a tunnel current of 1.6 nA and 100 × 100 pixels, yielding a frame rate of 53.2 fps. The y-direction piezo element was used to perform the fast scanning motion and was actuated with a sinusoidal signal. The images are corrected for the sinusoidal actuation. The counter piezo was used to compensate torque in the fast scanning direction, force in the slow direction and force in the z-direction.

Figure 7.34 illustrates that minute differences in scan rate can lead to strong variations in the excitation of scanner vibrations. This demonstrates that at high imaging rates, it is possible to image in between scanner resonances, if the line rate is chosen carefully. Using this approach, the maximum achieved imaging speed was 103 fps, with 100 × 100 pixels at 10.34 kHz line rate (figure 7.35). Note, that the bandwidth of the z-feedback was set below the frequency of the atomic structure, so that in these measurements the atomic signature was mostly present in the current variation signal (left panel of figure 7.35; also referred to as “error signal”) rather than in the simultaneously recorded height signal (right panel; also referred to as “feedback signal”). Although
7.6 Conclusions

In this chapter, distortions in the STM images have been discussed and their dependence on imaging speed and optional compensation. First, we have discussed how different vibrational modes can couple to the STM measurement. Our calculations show that it is possible to differentiate, using two-dimensional Fourier analysis, between amplitude modulation (which is not seen in the STM images), frequency modulation and excitation of z-resonances by the lateral scan motion. After this, the role of the actuation signal shape on STM imaging was discussed. It was shown that changing the actuation signal from a triangular shape to a sinusoidal shape greatly improves the imaging quality, because the sinusoidal signal is composed of only one frequency, as opposed to a (rounded) triangular signal, which is composed of many frequencies. Therefore, a sinusoidal signal is less likely to excite resonances in the STM scanner. We have seen that sinusoidal imaging indeed works very well to reduce vibrations and that Fourier analysis enables us to differentiate between the different forms of vibrations.

the resolution of these images was far from perfect, the scanner motion was very stable and no tip crashes occurred.

Figure 7.33: Left: Current variation image corresponding to the leftmost figure of figure 7.32. Right: Fourier transform of the current variation image. The hexagonal structure can be seen from the Fourier image, along with low-frequency vibrations and a broadening of the atomic peaks.
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Figure 7.34: Left: Image acquired at 4915 Hz line frequency, \(V_{bias} = 70 \text{ mV}, I_{tunnel} = 1.6 \text{ nA} \) and 100 \(\times\) 100 pixels. Image corrected for sinusoidal imaging. Right: Image acquired at 5 kHz line frequency, 100 \(\times\) 100 pixels. Image corrected for sinusoidal imaging.

Figure 7.35: Still from 103 fps movie, taken with 100 \(\times\) 100 pixels at a line rate of 10.3 kHz, a bias voltage of 70 mV and a tunnel current of 1.0 nA. Image corrected for sinusoidal actuation. Left: Image from tunnel current channel with line-by-line background subtraction. Right: Height signal with line-by-line background subtraction.
7.6 Conclusions

Then, the influence of a counter piezo element on image distortions was studied. The illustrative vibrational modes shown in section 7.4 in the x- and y-directions, show that for each vibrational mode, a careful analysis should be done to determine whether a compensating piezo element can suppress this vibrational mode and, if so, which method of compensation -force or torque- should be applied. We have seen that, when using the x-direction piezo element for the fast scan direction, force compensation in both the x- and z-directions works best at the lower line rates, 550 Hz and 599 Hz, while force compensation in only the z-direction is better at the higher line rate, 949 Hz. When the y-direction piezo element is used for the fast scanning, we have seen that torque compensation in the y-direction combined with force compensation in the z-direction works best at the lower line rate, i.e. 791 Hz while only torque compensation in the y-direction works best at the higher line rate, 904 Hz. As the y-direction piezo element is further from the centre of mass than the x-direction piezo element, it introduces a larger torque than the x-direction piezo element. This can explain why torque compensation works better for the y-direction piezo element. We see that a counter piezo element cannot be implemented to easily reduce all vibrations of a scanner. To counterbalance resonances in the complete range of imaging speeds, it should be determined experimentally or by simulations which compensation method works best for each vibrational mode of the scanner. Based on the scanner model that arises from these simulations or measurements, the counter piezo element should be actuated to perform torque compensation, force compensation or no compensation at all at specified line rates. This also explains why compensation works best in combination with sinusoidal scan signals: other signal shapes introduce a multitude of frequencies, each of which could, in principle, require a different compensation strategy.

From the Fourier analysis of STM measurements with and without the counter piezo element, we have seen that it is possible to distinguish between frequency modulation and direct z-coupling, as was the case in the “ideal” measurement simulations. However, it is difficult to determine the frequency modulation index, and thus the “strength” of the modulation, from these measurements. This difficulty arises from the differences between consecutive STM measurements, for instance arising from tip changes, combined with the often high modulation index that results in the appearance of many peaks in the Fourier spectrum, often of higher intensity than the lattice structure peak.

In the last section, high-speed scanning has been discussed. Scanning speeds up to 51 fps and 6.6 kHz line rate have been obtained without compensating piezo element incorporated; image quality decreased with speed and many
vibrational modes were excited, which disqualified certain line rates. With a counter piezo element we have succeeded in imaging graphite with atomic resolution up to 103 fps with 10.3 kHz line rate. However, at these high imaging speeds, it was not possible to resolve the full hexagonal structure of the lattice without averaging over several images. Most of the high-speed scanning images shown there have severe image deformations and were difficult to obtain. At high scan speeds, only a few line rates were “allowed”, carefully avoiding the excitation of scanner resonances. It is unlikely that these high imaging rates, critically chosen between resonant modes of the scanner and with highly critical feedback settings, can easily be incorporated in the routine of STM imaging. However good, consistent scanner behaviour is obtained much more easily at intermediate speeds, up to 50 fps, which are still significantly higher than those in traditional STM imaging.