The handle http://hdl.handle.net/1887/20925 holds various files of this Leiden University dissertation.

Author: Tabak, F.C.
Title: Towards high-speed scanning tunneling microscopy
Issue Date: 2013-06-05
Chapter 6

Compensation of force and torque in piezo-based STM scanners

In this chapter, we present the mechanical and electronic characterisation of force and torque compensation in our Beetle-type STM scanner, that was performed prior to STM imaging, which will be discussed in chapter 7. We focus on the resonance behaviour of the scan unit as a result of the actuation of a piezo stack that has separate plates for the z-motion and the shear x- and y-motion and whether and how a so-called “counter piezo element” can reduce the effect of resonances.

The chapter starts with a numerical simulation of the response expected for the centre of mass of a scanplate to the actuation of a z-direction piezo element, with and without compensating piezo element. This is followed by measurements of the mechanical and electronic behaviour of the scanner. The electronic characterisation was done by measuring the response on one electrode of the piezo element during actuation on the other electrode. This provides us with a measure for the deformation of the piezo element. The mechanical behaviour was followed using a laser-doppler vibrometer, which measures the velocity at a location on the scanner by measuring the doppler shift of a reflected laser beam. Both types of characterisation are first presented for the z-direction piezo element with counter piezo element. This is followed by an explanation of the different compensation possibilities in the in-plane x- and y-directions, after which the same type of mechanical and electronic characterisation for the in-plane x- and y-direction piezo elements is presented.

6.1 Z-direction: force compensation

As has been shown previously by Ando et al. [31, 32] for a z-direction piezo element, the incorporation of a counter-piezo element, which is identical to the scanning piezo element (this configuration is shown in figure 6.1), can improve
Chapter 6 Compensation of force and torque in piezo-based STM scanners

the vibration characteristics of the scanner as a whole up to the fundamental resonance frequency of the piezo elements. This can be particularly useful in scanners which have spatial design restrictions and cannot be designed with a very stiff mechanical loop. We have modelled the response of the centre of mass of a scanplate, carrying either a single piezo element or a dual piezo element, of which one is serving to compensate in the z-direction (shown in the right panel of figure 6.1). The piezo elements used for this simulation are PZT-5A thickness-mode piezo elements, moving only in the z-direction and have dimensions of 5 mm × 5 mm × 2 mm and a mass of 0.38 grams. Both have a fundamental resonance frequency close to 100 kHz. The piezo element that we have used in our STM scanner has a resonance frequency, in the free-free situation, of 165 kHz in the z-direction. The main difference with the thickness mode piezo used in the simulation is that our scanning piezo element is a stack consisting of two shear piezo elements for the x- and y-direction scanning, combined with a thickness mode z-direction piezo element. The z-direction piezo elements in our scanner are separated not only by the scanplate, but also by the x- and y-direction piezo elements. Still, the working of force compensation in the z-direction is the same and this simulation should provide us with a good indication of the results of force compensation in the z-direction.

The response of the centre of mass of the scanplate with and without counter piezo element present is shown in figure 6.2. One would expect that, since the piezo elements are identical to each other, the forces on the scanplate would completely cancel and the net motion of the scan plate would be zero. However, from the finite-element simulation, we see that the motion of the centre of mass, induced by the moving piezo element(s), does not reduce completely to zero after the incorporation of the compensating piezo element but is instead reduced by a factor 12. This is due to numerical (meshing) differences. Because of the finite meshing size used in the simulation, there will be a small calculation error in the force exerted by either piezo element on the scan plate. The meshing differences between the piezo elements will give rise to a difference in the force they exert on the scan plate, and therefore the forces will not completely cancel and the resulting motion of the scanplate will not be reduced to zero. This effect also explains why the motion of the scan plate is not cancelled at the resonance frequency of the piezo elements. At the resonance frequency of each piezo element, its motion amplitude increases, and thereby the force it exerts on the scanplate. The piezo elements will have a slightly different resonance frequency because of the meshing differences, causing the net force on the scanner to increase at the resonance modes of
6.1 Z-direction: force compensation

Figure 6.1: Left: Concept of compensation of the force $\vec{F}_1$ exerted by the scanning z-piezo element on the membrane of the scanner by simultaneously actuating a compensating piezo element, that exerts an equal but opposite force on the same position of the scanner: $\vec{F}_2 = -\vec{F}_1$. The piezo motion is indicated by the dashed line. Right: Geometry of z-direction counter piezo effect simulation. Two thickness mode piezo elements are mounted on a central scan plate. The motion of the centre of mass upon actuation of one or both piezo elements is calculated numerically.

the piezo elements. In practice, the displacement of these commercial piezo elements is specified with an accuracy of only 30%. At the resonance frequencies of the piezo elements, the displacement difference will be too large to still result in significant cancelling of the motion on the centre of mass. Therefore, in practice as well as in the simulation, the counter piezo element will have beneficial effects only up to the first resonance frequency of the piezo element.

6.1.1 Electronic testing of the z-direction piezo elements

To characterise the behaviour of the z-direction piezo elements, both the scanning piezo element and the compensating piezo element, we have measured the impedance change on one of the contacts of the piezo elements due to
an actuation voltage on the other contact. This impedance change is caused by mechanical deformation of the piezo element. For this measurement, the circuit shown in figure 6.3 was used. Indicated in this schematic figure are the frequency generator V1, the piezo element to be tested (the shear piezo elements have a capacitance of 1.3 nF and the z-direction piezo element has a capacitance of 3 nF), the input impedance and parallel capacitance of the oscilloscope (1 MΩ and 10 pF, respectively) and a parallel capacitance of 2.2 nF that serves to keep a constant voltage division between the piezo element and the oscilloscope at increasing frequencies.

First, both piezo elements were characterised individually without actuating the other piezo element, i.e. the scanning piezo element was actuated while the voltage over the counter piezo element was left floating, and vice versa. The response of both piezo elements is shown in figure 6.4. The piezo elements were actuated with a sine wave with an amplitude of 1 V peak-to-peak.

We see that the shape of both response curves is very similar, which is important for successful force compensation. However, the amplitude of the response is different for each piezo element. The response of the scanning z-piezo element is about 30% lower than the response of the counter z-piezo element. The force on the centre of mass is reduced by a factor 12, up to the first resonance frequency of the piezo elements, where the displacement differences between the piezo elements become more significant.

Figure 6.2: FEM simulation of the displacement of the scanplate between two piezo elements to the motion of these piezo elements, along with the motion of the same position on the scanplate with only one piezo element present. The force on the centre of mass is reduced by a factor 12, up to the first resonance frequency of the piezo elements, where the displacement differences between the piezo elements become more significant.
6.1 Z-direction: force compensation

Figure 6.3: Circuit used for electronic testing of the piezo elements. The piezo is driven by a frequency generator. The oscilloscope has an input impedance of 1 MΩ and a parallel capacitance of 10 pF. To keep a constant voltage division at all frequencies, we introduce an additional parallel capacitance of 2.2 nF. The capacitance of the piezo elements is 1.3 nF for the x- and y-direction piezo elements, and 3 nF for the z-direction piezo element.

Figure 6.4: Impedance change on the ground electrode of the z-direction piezo element at 1V ptp actuation on the other electrode. Red: scanning z-piezo element. Black: counter z-direction piezo element. Although the general shape of the impedance change is very similar, the counter piezo element shows a larger response and does not show the 50 kHz peak which is present in the curve of the scanning piezo element.

element. This may be caused by aging of the scanning piezo element, which was used in the scanner for a few months before the counter z-piezo element was incorporated. Another indication for aging of the scanning piezo element was a reduction of the piezo capacitance, which had been observed over this period.

Both piezo elements show a resonance at 65 kHz and one at 135 kHz. Since the free-free resonance is given to be 150 kHz, we can attribute both the 65 kHz and the 135 kHz resonances to the clamped-free situation. The z-direction
scanning piezo shows a resonance at 50 kHz which is not seen in the counter piezo element response.
When force compensation is applied, we see that the responses of the two piezo elements change, as shown in figure 6.5. Both piezo elements show a resonance at 65 kHz and a flat response below this frequency. The 50 kHz resonance, which was apparent in the spectrum of only the z-direction scanning piezo element, is compensated. It is unclear why the 50 kHz resonance is not excited by the motion of the compensating piezo element or why it is reduced when both piezo elements are actuated. We also observe that the amplitude of the resonance at 65 kHz is increased with respect to actuation without force compensation. The actuation of the compensating piezo element effectively increases the stiffness of the scanplate, thereby reducing the dissipation in the scanplate and thus the damping of the piezo motion. Therefore, the amplitude of motion at a piezo resonance will be larger.
As was the case for the actuation without force compensation, the response of the counter piezo element is larger than the response of the scanning piezo element. This may cause an overshoot in the compensation of the force on the scanner body.

Figure 6.5: Impedance change on the ground electrode of the z-direction piezo element at actuation on the other electrode, combined with force compensation actuation of the counter piezo element. Red: scanning z-piezo element. Black: compensating z-direction piezo element.
6.1 Z-direction: force compensation

6.1.2 Mechanical characterisation

To characterise the mechanical motion of the scanner directly, we have recorded the mechanical response of the scanner using a laser doppler vibrometer [139], of which a schematical representation is shown in figure 6.6. This is, in essence, an interferometer that measures the doppler shift caused by the sample under investigation. A laser beam with frequency $f_0$ is split into a reference beam and a part that is directed at the sample. The latter is modulated with a frequency $f_b$ of several MHz, by use of a Bragg cell. The velocity of the sample introduces an added doppler frequency $f_d$, resulting in a frequency modulated signal with frequency $f_0 + f_b + f_d$. A photodetector responds to the interference signal of the reference beam and the doppler-shifted beam. This signal can be demodulated to extract the doppler frequency, and thus the velocity of the sample.

The velocity of the tip holder is measured under actuation of the piezo elements. This allows us to explore the effects of the compensating counter piezo elements. We have measured the spectral response of the tip holder to an actuation of the z-direction piezo elements with 60 V peak-to-peak white noise actuation at a bandwidth of 200 kHz. The velocity spectra of the tip holder are shown in figure 6.7. The most important part of the spectrum is the part up to the first resonance frequency of the piezo element, where the beneficial effects of the counter piezo element are predicted. The first resonance of the piezo is observed at 65 kHz; the next at 130 kHz. From the first resonance frequency of the piezo element and up, we expect that incorporation of the counter piezo element does not significantly change the resonance behaviour of the scanner/piezo element combination.

From figure 6.7, we see that the resonant peak at 50 kHz nearly disappears when the counter piezo element is actuated. This effect is also observed in the electrical response measurements, shown in figures 6.4 and 6.5. From the vibrometer measurement we further conclude that the noise level, also at lower frequencies, is slightly higher when both piezo elements are actuated. This higher noise level is not an effect of the measurement, but rather an effect of overcompensation of the counter piezo element. This effect of overcompensation at lower frequencies can also be seen in figure 6.8, which is the difference between both graphs in figure 6.7: the velocity amplitude with the counter piezo element actuated minus the velocity amplitude without the counter piezo element actuated. In this figure, peaks below zero indicate that the counter piezo has improved the scanner behaviour, while peaks above zero imply that the counter piezo has added to the resonance excitation. It is ob-
Chapter 6 Compensation of force and torque in piezo-based STM scanners

Figure 6.6: Schematic representation of a laser-doppler vibrometer. The laser beam is split into a reference beam of frequency $f_0$ and a beam that goes to the sample. The latter is modulated, by use of a Bragg cell, with a frequency of several MHz ($f_b$). This beam is reflected off the sample, adding a doppler shift ($f_d$) which is dependent on the velocity of the sample. The detector responds to the beating, at a frequency of $f_0 + f_d$, of the frequency $f_0$ of the reference beam and $f_0 + f_b + f_d$ of the reflected laser beam. This signal can be demodulated to extract the doppler frequency and thereby the velocity of the sample.

Figure 6.7: LDV measurement of the velocity amplitude spectrum of the tip holder capillary, resulting from 60 V ptp white noise actuation of the z-piezo. The counter piezo was included in the scanner in both tests. Red: z-direction scanning piezo element. Black: z-direction scanning piezo element with force compensation.
6.2 Out-of-plane force balancing: conclusion

Figure 6.8: Velocity amplitude difference spectrum between the regular actuation method and force compensation. The resonant mode at 50 kHz is suppressed, while the resonant mode at 65 kHz increases in amplitude.

erved that the resonance at 50 kHz is strongly suppressed by the counter piezo element. Since this is not the frequency of a piezo resonance, we have to conclude that it is a resonance of the scanner body, excited by the scan piezo. In addition to this beneficial effect, we also see an increase of the resonances at 65 kHz and higher frequencies, indicating that at these frequencies, the counter piezo does not help to reduce excitations. We ascribe this to the differences between the two piezo elements as is supported by the simulations in figure 6.2.

6.2 Out-of-plane force balancing: conclusion

In the previous sections, we have used three methods to investigate the effect of a counter piezo element on the excitation of undesired motion in the STM scanner, directed along the z-direction, normal to the surface in an STM experiment. These methods are finite-element analysis, impedance change measurements and laser-doppler vibrometer characterisation. Finite-element analysis proves to be consistent with the experimental data in the sense that it predicts a reduction of the amplitude of scanner body vibrations up to the first fundamental resonance frequency of the piezo element. On the other hand, we have seen from the laser-doppler vibrometry that the noise level below the first resonance frequency does increase when a counter piezo element...
Chapter 6 Compensation of force and torque in piezo-based STM scanners

is incorporated. This apparent contradiction results from overcompensation of the counter piezo element. This is supported by the measurements of the impedance changes. In these piezo-deformation measurements, a signal increase is observed when the piezo is driven at one of its resonance frequencies. Still, it may be that the piezo element shows a signal in response to a strong resonance mode of the scanner: if the scanner deforms, it might accelerate and thereby deform the piezo element. The laser-doppler vibrometry measurement is sensitive to both piezo and scanner resonances, and shows a reduction of the amplitude of the resonance at 50 kHz upon actuation of the counter piezo element. Summarising this part of the chapter, we can conclude that the counter piezo element has a beneficial effect in the z-direction up to the first resonance of the employed piezo elements in this direction.

6.3 In-plane actuation: force or torque?

In this section, the influence of the counter piezo element on in-plane motion will be discussed. We start with a description of the different compensation possibilities for in-plane scanning, followed by electrical measurements of the impedance change and laser-doppler vibrometry measurements of the velocity, as was done for the out-of-plane scanning.

Compensating piezo-induced motion in the x- and y-directions by use of a counter piezo element is not as straightforward as is the case for the z-direction. This is because the scanning piezo element not only exerts a force on the centre of mass of the scanner body, but, when it is actuated along x or y, it also introduces a torque. The counter piezo elements can be actuated to compensate for either of these, force or torque, but not at the same time. We refer to the two compensation schemes as “force compensation” and “torque compensation” (figure 6.9). The piezo elements are positioned exactly above each other. If the two x-piezo elements are actuated with opposite signals, they will move in opposite directions, thereby cancelling the net force on the scan plate, similar to what we have seen in the z-direction. However, even though the forces cancel, the torques do not. In fact, they add up and make the total torque twice as large. Conversely, when the two x-piezo elements are actuated in the same direction, the torques on the scanner body cancel, whereas the force is doubled.

Depending on the specific resonance mode of the scan plate, cancelling one of the two, force or torque, will be more effective than the other in improving the mechanical behaviour of the scanner. In this light, we may expect that
6.3 In-plane actuation: force or torque?

Figure 6.9: Two actuation schemes for compensating piezo elements: force compensation (left) and torque compensation (right). The dashed lines indicate the shearing motions of the piezo elements. When the total force is minimized, \( F_2 = -F_1 \), the total torque is maximized, \( T_2 = T_1 \), and vice versa. The resonance mode of the central plate dictates which of these actuation schemes is most applicable.

A different compensation actuation signal is required at each resonance frequency of the scan plate.

The y-direction piezo element is located further from the centre of mass than the x-direction piezo element and will thus introduce a larger torque to the system. Therefore, torque compensation may play a larger role in reducing the excitation of resonances for the y-direction piezo element.

If compensating force or torque with a counter piezo element proves effective, it will provide an opportunity to improve many existing SPM scanners.

6.3.1 Electronic characterisation

As was done for the z-direction piezo element, we have characterised the x- and y-direction piezo elements by measuring the impedance change as a function of actuation frequency. Because the maximum possible line frequency is
Chapter 6 Compensation of force and torque in piezo-based STM scanners

much lower than the maximum actuation frequency in z, we focus on relatively low-frequency resonances, up to 70 kHz. When using the piezo element in STM experiments, the higher-frequency modes in this range may also be excited by higher harmonics in the actuation signal, if a triangular actuation signal is used, even if the piezo is actuated with a low frequency (below 10 kHz). The first piezo resonance is at 65 kHz in the z-direction, which sets a natural limit to the actuation frequency. The influence of the actuation signal shape on the excitation of resonances and its effect on image distortion will be discussed more fully in chapter 7. Here, we focus on eliminating as many vibrations below the piezo resonance frequency as possible. Figure 6.10 shows the response of the x-direction scanning piezo element and the corresponding counter piezo element. As was the case for the z-direction piezo element, we again see that the piezo elements are not completely identical: the counter piezo element has a \( \pm 7\% \) lower response than the scanning x-piezo element, and introduces an additional resonance peak at 11.6 kHz. This is different from the situation observed for the z-direction piezo elements, which showed a higher response for the compensating piezo element.

Both the force compensation method (figure 6.11) and the torque compensation method (figure 6.12) show an increase of the amplitudes of the resonance modes of the scanning piezo element, when the compensating piezo element is actuated. This means that in both cases the deformation of the piezo is larger, but it does not necessarily mean that the response of the scanner body is also stronger. Each piezo might deform more, because less energy is dissipated into the scanner because of the counteracting motion of the other piezo element, effectively increasing the stiffness of the scanner.

The response of the y-direction piezo elements, actuating only one of them, is shown in figure 6.13. We see that force compensation (shown in figure 6.14) leads to a decreased response at the resonance frequencies at 17 kHz and 21 kHz. Torque compensation (figure 6.15) shows an increase of these resonances.

6.3.2 Mechanical characterisation

In this section, we explore the vibration spectrum in the z-direction, as measured in response to the actuation of the x- and y-direction piezo elements with and without compensation by the counter piezo elements using a laser doppler vibrometer. This gives a measure for the coupling of in-plane motion to vibrations in the z-direction. This coupling is, together with vibrations in the in-plane directions, responsible for scanning-induced image deformation.
6.3 In-plane actuation: force or torque?

Figure 6.10: Impedance change on the ground electrode of the x-direction piezo element at 1 V ptp sine wave actuation on the other electrode, without compensation. Red: x-direction scanning piezo element. Black: x-direction compensating piezo element.

Figure 6.11: Impedance change on the ground electrode of the x-direction piezo element at 1 V ptp sine wave actuation on the other electrode, while the other piezo element was actuated to compensate the force. Red: x-direction scanning piezo element. Black: x-direction compensating piezo element.
Chapter 6 Compensation of force and torque in piezo-based STM scanners

Figure 6.12: Impedance change on the ground electrode of the x-direction piezo element at 1 V ptp sine wave actuation on the other electrode, while the other piezo element was actuated to compensate the torque. The mechanical response of the piezo element at its resonance frequencies is decreased with respect to force compensation, figure 6.10. Red: x-direction scanning piezo element. Black: x-direction compensating piezo element.

Figure 6.13: Impedance change on the ground electrode of the y-direction piezo element at 1 V ptp actuation on the other electrode, without compensation. Red: x-direction scanning piezo element. Black: x-direction compensating piezo element.
6.3 In-plane actuation: force or torque?

Figure 6.14: Impedance change on the ground electrode of the y-direction piezo element at 1 V ptp actuation on the other electrode, while the other piezo element was actuated to compensate the force. The amplitude of the resonance at 25 kHz is reduced with respect to actuation without compensation. Red: x-direction scanning piezo element. Black: x-direction compensating piezo element.

Figure 6.15: Response on the ground electrode of the y-direction piezo element at 1 V ptp actuation on the other electrode, while the other piezo element was actuated to compensate the torque. Red: x-direction scanning piezo element. Black: x-direction compensating piezo element.
Chapter 6 Compensation of force and torque in piezo-based STM scanners

Because of the scanner and vibrometer geometries, the in-plane directions were not easily accessible. The characterisation of in-plane vibrations, excited by actuation of the piezo elements, remains to be done.

We again explore frequencies up to 70 kHz. The z-velocity amplitude spectrum of the tip holder, in response to white-noise actuation of the x-piezo, is given in figure 6.16. In this experiment, the counter piezo electrodes were not actuated, but left floating. We see various small resonance peaks, starting at 7 kHz, before the first “large” resonance at 45 kHz. The low-frequency resonances are not associated with the piezo element and are resonances of the scanner body. Actuation of the compensating piezo element changes these resonances, as shown in figure 6.17. A clear difference between torque and force compensation is observed. Neither of the compensation modes “kills” all resonances, and there are some resonances that are not decreased by either of the modes. The lowest frequency resonance, at 7 kHz, is lowered by force compensation. Also the resonance at 12 kHz is significantly reduced by force compensation. The resonance mode at 25 kHz, however, is reduced most by torque compensation.

The difference between the two actuation methods is most clearly seen in the velocity-amplitude-difference graphs, figure 6.18. We see that the force compensation increases the excitation of the resonances at 12 kHz, 25 kHz and 65 kHz (and above), while reducing the resonance at 45 kHz. The torque compensation method reduces the resonance mode at 25 kHz, while also reducing the resonant mode at 45 kHz. An increase of the 50 kHz and 65 kHz resonant modes is also observed. From these measurements, we conclude that different resonant modes of the scanner are reduced or increased by either force or torque compensation. This suggests that for different line frequencies, the choice has to be made whether to use force or torque compensation.

Even though the y-piezo is the same type of shear piezo element as the x-piezo, the resonant behaviour it induces is different from that of the x-piezo. This is because the y-piezo is “clamped” between the x- and z-piezo elements; on both sides, it is not completely free, but also not completely clamped. This causes a different coupling between the motion of the y-direction piezo element and the scanner. In addition, because of this configuration, the y-direction piezo element is located further from the centre of mass of the scanner than the x-direction piezo element, and therefore introduces a larger torque on the system at the same actuation signal. In figure 6.19 the z-velocity characteristics of the scanner with y-actuation but without actuation of the y-direction counter piezo is shown. We see that the y-direction piezo element excites the 45 kHz resonance much less strongly than the x-direction piezo element. The
6.3 In-plane actuation: force or torque?

Figure 6.16: Velocity amplitude spectrum in the z-direction of the tip holder, resulting from white noise actuation at 60 V peak-to-peak of the x-piezo. The counter piezo was included in the scanner in this test but not actuated: the electrodes were left floating.

Figure 6.17: Velocity in the z-direction of the tip holder, resulting from white noise actuation of the x-piezo with force compensation (black) and torque compensation (red) from the counter piezo element.
Chapter 6 Compensation of force and torque in piezo-based STM scanners

Figure 6.18: Difference in measured z-direction velocity amplitude of the tip holder between actuation with and without force compensation (black) or torque compensation (red) of the x-piezo motion.

Resonance at 65 kHz is due to the piezo element itself. We further observe that the amplitude of the vibrations is lower for actuation of the y-piezo element than for actuation of the x-piezo element. Force compensation and torque compensation again have a different impact on each of the resonances (see figure 6.20). Both compensation schemes reduce most of the low-frequency peaks. Very striking is the reduction of the 25 kHz peak by force compensation, and its increase by torque compensation. This difference is also visible in figure 6.21, which shows the difference in tip holder velocities with force and torque compensation. This is precisely opposite to the situation with the x-piezo. This suggests that the 25 kHz peak results from the thickness change of the (x- and y-direction) shear piezo elements when they are sheared. This generates a direct coupling between the in-plane motion, x and y, and the z motion. Since the counter piezo stack was identical to the scan piezo stack and it was oriented upside down with respect to the scan stack, only for one of the two directions, in this case y, the actuation voltage had to be of the same sign for scan and counter piezo elements, in order to get force compensation. For the other direction, in this case x, the two signals had to be of the same sign for torque compensation. These situations are shown schematically in figure 6.22. As the direct z-response to x- or y-actuation depends on the sign of the voltage, we should then indeed expect that the 25 kHz peak is reduced by torque compensation for the x-direction.
6.4 Force and torque compensation: conclusion

From figure 6.21 we can also see that the piezo resonant mode at 65 kHz is reduced by both force and torque compensation. From this figure it is also seen that actuation of the y-direction counter piezo element reduces the low-frequency resonances that are excited by actuating only the y-direction scanning piezo element.

6.4 Force and torque compensation: conclusion

In this chapter, it has been shown that force or torque compensation can be a useful method to improve the vibration characteristics of the mechanical part of an STM scanner. Two types of compensation have been considered. The first is force compensation, where a z-direction scanning piezo element moves perpendicular to its mounting plate and exerts only a normal force on this plate. This force can be balanced by applying a force of the same magnitude but opposite direction on the plate, which is realised in the Beetle-type STM by incorporation of a compensating z-direction piezo element. It was shown with electronic and mechanical characterisation measurements that this method improves the low-frequency vibration characteristics of the scanner, while the vibrations above the first resonance frequency of the piezo elements increased in amplitude. This is most likely caused by the inequality of the
Chapter 6 Compensation of force and torque in piezo-based STM scanners

Figure 6.20: Velocity amplitude in the z-direction of the tip holder, resulting from white noise actuation of the y-piezo with force compensation (black) or torque compensation (red) from the counter piezo element.

Figure 6.21: Difference in measured z-direction velocity amplitudes of the tip holder between actuation with and without force compensation (black) or torque compensation (red) of the y-piezo motion.
6.4 Force and torque compensation: conclusion

Figure 6.22: Effect of piezo actuation at the same or opposite polarity, with motions of the piezo elements indicated. In the left panel, the piezo elements are actuated with the same polarity, which induces the same, unintended, thickness change of the shear x and y piezo elements. Because of the geometry of the piezo stacks this situation corresponds to torque compensation in the x-direction and force compensation in the y-direction. In the right panel, the piezo elements are actuated with opposite polarity, which induces an opposite, unintended thickness change of the shear piezo elements. This corresponds to force compensation in the x-direction and torque compensation in the y-direction.

two piezo elements, yielding different amplitudes of motion, which is especially important around and above the piezo eigenfrequencies. This problem can be circumvented by the introduction of a separate actuation driver for the compensating piezo element which would allow different actuation signal amplitudes for the scanning and compensating z-direction piezo elements.

More complicated is the situation for in-plane motion. The x- and y-direction piezo elements exert a force on the scanner, but also introduce a torque and can thereby excite vibrations in the scanner. Both can be compensated using a counter piezo element, but, in this geometry, not simultaneously. Alternative geometries can be imagined where force and torque are compensated at the same time, for example a configuration where a compensating piezo element is incorporated on the same side of the support plate as the scanning piezo element.

In addition, the shearing of the piezo element also induces a deformation of the piezo element in the z-direction. This exerts a z-direction force on the scanner, which can also be compensated by the counter piezo element. This effect is probably responsible for the resonance observed at 25 kHz.

Measurements of the impedance change, and laser-doppler vibrometer measurements give insight into the mechanical behaviour of the scanner body.
Chapter 6 Compensation of force and torque in piezo-based STM scanners

and scanning piezo elements. Particularly, laser-doppler vibrometry velocity measurements give a measure of the coupling of in-plane motion to out-of-plane resonances. By measuring the response difference between force and torque compensation, as is shown in, for instance, figure 6.17, it is possible to determine which compensation method should be used at a specific actuation frequency. The laser-doppler vibrometry measurements do not give information on the in-plane motion of the scanner, which means that additional scanner characterisation is required.

In conclusion, compensating piezo motion works for the relatively simple configuration where the scanning piezo element moves perpendicular to its base. Compensation can also work for in-plane scanning, where the scanning piezo element(s) move parallel to their base. However, this yields two possibilities: force and torque compensation. Both methods can be useful, in reducing different resonances and thus improving the behaviour of the scanner, but for each scan line frequency, a different type may be required.