Characterization and Control of an Atomic Force Microscope

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Characterization and Control of an
Atomic Force Microscope

MASTER OF SCIENCE THESIS

For the degree of Master of Science in Systems and Control at Delft
University of Technology

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October 20, 2010

Faculty of Mechanical, Maritime and Materials Engineering (3mE) · Delft University of Technology
The work in this thesis was supported by Veeco Instruments. Their cooperation is hereby gratefully acknowledged.

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The undersigned hereby certify that they have read and recommend to the Faculty of Mechanical, Maritime and Materials Engineering (3mE) for acceptance a thesis entitled

**CHARACTERIZATION AND CONTROL OF AN ATOMIC FORCE MICROSCOPE**

by

**RINY VERMUE**

in partial fulfillment of the requirements for the degree of

**MASTER OF SCIENCE SYSTEMS AND CONTROL**

Dated: October 20, 2010

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Abstract

The Atomic Force Microscope (AFM) is an instrument used for studying the topography of samples with nanometer resolution. Possible samples include specific materials or biological samples. The AFM is a mechanical microscope, since a three dimensional topography image is constructed by raster scanning a sharp tip and a sample surface in close proximity to each other and monitoring tip-sample interactions. The tip-sample interaction is controlled in all three dimensions by means of a piezoelectrical scanning unit which consists of a vertical positioner and a lateral positioner. The vertical positioner is controlled via a feedback operation to control the tip-sample distance. The topography image is based on the control signal being sent to the vertical positioner to move it up or down. The vertical positioner consists of a piezo actuator which suffers from nonlinear behavior due to hysteresis and creep. Due to the nonlinearities, the ratio between the control signal and the resulting vertical displacement is not constant over the full positioning range of the piezo actuator. In current dynamic modes of AFM a large part of the piezo positioning range is used. Therefore, a more direct method to obtain the displacement of the vertical positioner is desired which enables a more accurate estimate for the sample topography. To this end, in this thesis a displacement sensor is added to the vertical positioner of the AFM. The resulting displacement sensor yields a variation in measured step height in the order of 6%, compared to 35% for the conventional control signal when imaging a calibration sample. The lateral positioner is controlled via a feedback operation to maintain high positional accuracy in spite of unknown disturbances and model uncertainty. In this feedback operation, the dynamics of the lateral positioner limit the speed of the AFM. Therefore, for the lateral positioner modern control methods can be used to improve the speed of the AFM. The simulation results for the lateral positioner show that with the use of model based control and $H_\infty$ control the scanning speed can be increased with a factor of 5 when compared to the standard PI controlled system. At the same time the control error for the model based controlled system and the $H_\infty$ controlled system becomes smaller with a factor of 4 and 8, respectively. The bandwidth for the PI controlled system is only 50 [Hz], which is much smaller than the bandwidth for the model based controlled system (1900 [Hz]) and the $H_\infty$ controlled system (3000 [Hz]). This means a bandwidth improvement with a factor of 38 and 60, respectively. However, further experiments must be carried out to validate the simulation results.
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I would like to thank my supervisor professor Georg Schitter for introducing me to the exciting and challenging field of Atomic Force Microscopy. I am very grateful for the guidance and inspiration he has given me during this thesis project. Furthermore, by helping me to set up the contact between Veeco Instruments in Santa Barbara already in 2008, I was able to experience working in a professional research environment and doing my experiments. I would like to thank Stefan Kuiper for showing me around in our high-tech lab in Delft and the many useful insights he gave me regarding my thesis.

I am grateful to my supervisor Nghi Phan at Veeco Instruments for providing me with the necessary equipment and for the time he took to guide me within the company. I would like to thank Bill Muller for arranging the internship. Furthermore, I would like to thank my co-workers Fritz Krainer, Eamon Searson and Jason Osborne for the many fruitful discussions we had on several topics related to AFM.

I would like to express my words of gratitude to professor Michel Verhaegen and professor Paul van den Hof from DCSC for their continuous inspiration already from the early stages of my Master.

I will not list all of them here, but I would like to thank all my friends and fellow students in Santa Barbara for all the good times we had together. Johannes, Joseph and Helen, thanks for the many challenging hikes we did together, the many jokes we laughed about, and the joyful dinners we had.

I am very grateful to my fellow Control students Lodewijk, Robert, Vincent and Roel for all the encouragement and inspiration you gave me during my whole Master. I also enjoyed all study-unrelated adventures we pursuit together!

The most important words of gratitude go to my friends and family in Holland for giving their unconditional support and love during this challenging academic experience.
Acknowledgements
This MSc thesis presents the results of a research project for an Atomic Force Microscope (AFM), carried out within the Delft Center for Systems and Control (DCSC). Before starting this project, a literature survey was carried out [1]. Most of the project work has been done as part of an internship program at Veeco Instruments, located in Santa Barbara, CA, USA. This thesis consists of a characterization of a new displacement sensor for the vertical positioner. Furthermore control algorithms are presented to improve the performance of the AFM. In this introductory chapter the reader is provided with the goal of this thesis. First a description of the working principles of an AFM is given in Section 1-1. Next, the current state of AFM research and the problem statement are presented in Section 1-2 and Section 1-3, respectively. The project goal is presented in Section 1-4. The outline of this thesis is given in Section 1-5.

1-1 Atomic Force Microscope

The Atomic Force Microscope (AFM) is an instrument used for studying the topography of samples with a scale size ranging from microns to sub nanometers [2, 3]. A schematic of an AFM is depicted in Figure 1-1. The basic components are the scanning unit, the cantilever with a sharp tip, the optical detection system, and the feedback electronics.

In AFM the cantilever acts as a force sensor: while raster-scanning the sharp tip over the sample surface, the cantilever deflection is a measure for the interaction forces between the tip and the sample. Typical cantilever dimensions are in the order of hundreds of microns. The tip-sample interaction provides the possibility to measure sample topography, but also other properties can be measured by analyzing the tip-sample interaction (e.g. variations in local stiffness [4], friction force [5] and lateral stiffness [6]).

A piezoelectric scanner is used to control the position of the probe with respect to the surface with high precision, both in the lateral (X, Y) and vertical (Z) directions. While performing the lateral scan, the cantilever deflects due to the sample topography and twists around its longitudinal axis due to in-plane friction forces. The flexural and torsional bending of the cantilever are measured using an optical detection system. This optical detection system
Figure 1-1: Schematic representation of an Atomic Force Microscope. The schematic shows a scanned tip design, where the sample is fixed and the cantilever tip is moved over the sample by the scanner, which consists of piezoelectric actuators for positioning in all three spatial directions (X,Y, and Z). During the lateral scan, the sample topography causes the cantilever to deflect. The deflection of the cantilever is sensed with optical detection.

consists of a photodetector that collects a laser beam that is reflected off the back of the cantilever. The photodetector is segmented into four quadrants (see Figure 1-1), such that both the flexural and torsional signals can be obtained by measuring the difference in optical powers between either the upper and the lower half, or the left and the right half of the photodetector, respectively. Finally, the optical power difference is normalized according to

\[
e = \frac{(A + D) - (B + C)}{A + B + C + D} \\
f = \frac{(A + B) - (C + D)}{A + B + C + D}
\]  

where \(e\) is the deflection signal, \(f\) is the torsional signal, and \(A, B, C, D\) are the powers belonging to the segments of the photodetector, respectively.

A compact definition of AFM can be stated as follows.

Atomic Force Microscopy is a technique to provide spatially localized information by raster scanning a sharp tip and a surface in close proximity to each other and monitoring tip-sample interactions.

To assess the performance of the AFM it can be split up in two parts, i.e. the lateral positioner and the vertical positioner. Both positioners consist of piezoelectric actuators, which suffer from nonlinear behavior. This will be considered in the next section.
1-1-1 Nonlinearities for Piezoelectric Actuators

Piezoelectric actuators are widely used in nanopositioning applications because they have large operating bandwidth, they can deliver a large force and because of their compact design. Important nonlinear effects which limit the bandwidth and resolution are hysteresis, creep, and vibrational effects [7].

Hysteresis can be considered as a range-dependent static input nonlinearity to the piezo actuator [8]. The current output of the piezo actuator is not only dependent on its current input, but also on its past output extremum. When a larger positioning range is required, the hysteresis effects become more apparent. In Figure 1-2(a) the effect of hysteresis is shown for a positioning range of 4 [\( \mu m \)]. For this experiment first the input to the piezoelectric actuator is increased from -30 [V] to 175 [V] and then decreased to -30 [V]. Due to hysteresis there is a difference between the two curves.

The second nonlinearity occurring in piezoelectric actuators is creep behavior, which is drift in the position output of the piezoelectric actuator over extended periods of time [8].

The third nonlinearity is due to vibrational effects which result from the mechanical resonances of the piezoelectric actuator. When the input to the piezoelectric actuator is exciting the mechanical resonances, severe oscillations in the position output can result. An example is shown in Figure 1-2(b). Here also a time delay can be seen between input and output, which is due to a limited bandwidth of the system.

From the previous discussion it can be concluded that the nonlinearities in piezoelectric actuators must be taken into account when high positional accuracy, precision, speed and a large positioning range are desired.

In this thesis both the lateral and the vertical positioner are controlled via a feedback operation. Reasons to apply feedback to both positioners are described next.

1-1-2 Feedback Operation for Lateral Positioner

The lateral positioner consists of the X scanner and the Y scanner, which are both piezoelectric actuators. In this thesis the X and Y scanner are operated in closed loop with the use of a feedback controller. This is shown in Figure 1-3. Reasons to apply feedback are the presence of unknown disturbances and model uncertainty [9]. Other reasons to apply feedback are that the nonlinear effects arising from hysteresis and creep associated with piezoelectric actuators can be compensated [7][10][11][12]. A disadvantage of feedback control is that the lateral scanning speed can be slower than with open loop control. However, when positioning accuracy and precision are required, which is the case in AFM, feedback control can be more effective than open loop control. The feedback controller \( K \) in Figure 1-3 manipulates the control signal \( u \) such that the control error \( e \) remains small in spite of disturbances \( d \) acting on the system. Due to the presence of sensor noise \( n \), there can be a difference between the true output \( x \) and the measured output \( x_m \). The control error \( e \) is the difference between the reference signal \( r \) and \( x_m \). In this thesis feedback controllers for the X and Y scanner are designed which enable high scanning speeds, while benefiting from the advantages of closed loop operation. The reference signals for the X and Y scanner are shown in Figure 1-4. The X scanner motion is typically a triangular wave, where the speed is constant during imaging,
(a) Hysteresis effects in the piezoelectric actuator cause a difference between the two curves.

(b) The mechanical resonances of the piezoelectric actuator can cause oscillations in the output signal (blue line, solid). The input signal is a triangular waveform (black line, solid).

**Figure 1-2:** Nonlinearities for piezoelectric actuators.
except at the turnaround points. The Y scanner is moving much slower with constant speed. It can be seen that a lateral scanning motion results when the two scan signals are combined. For each forward scan in the X direction, topography data is collected at each pixel. Also during the return scan of the X scanner topography data is collected. The two scan directions are not typically combined because the nonlinear tip-sample interaction is different in each direction and combining them would result in a distorted image.

**Figure 1-3:** Control diagram for the X and the Y scanner. The controller $K$ tries to minimize the control error $e$ by applying a control signal $u$ to the system $G$. The system is perturbed by noise $d$. Furthermore there is noise $n$ acting on the sensor. The true output of the system is represented by $x$ and the measured output by $x_m$. The control error is the difference between the reference $r$ and $x_m$.

**Figure 1-4:** The two reference signals are shown which are applied to the X and Y scanner, respectively. The lateral scanning motion is constructed by combining the two signals. At each pixel topography data is collected.

### 1-1-3 Feedback Operation for Vertical Positioner

The vertical positioner will be referred to as Z scanner for the remainder of this thesis. It is desired to minimize damage to the tip and the sample. Therefore the Z scanner is operated in closed loop, using a feedback operation to minimize the tip-sample forces. The signal used for the feedback operation is the measured deflection signal. In most commercial AFMs a Proportional-Integral (PI) controller is used for the feedback operation. The feedback configuration for the Z scanner is given in Figure 1-5. By comparing the measured cantilever deflection with a reference value $r$ a control error $e$ results. The PI controller will try to reduce the control error to zero by applying the control signal $u$ (which is converted to a
voltage) to the Z scanner to move it with respect to the sample in the vertical direction. This way the sample topography is tracked during the raster scan. In most commercial AFMs the control signal \( u \) being sent to the scanner is used as a representation for the sample topography. Here a linear relation is used between the control signal \( u \) being sent to the Z scanner and the resulting displacement \( p \). However, because of nonlinear behavior associated with piezo actuators \cite{7} this might not give an accurate representation of the sample topography. Therefore, in this thesis a displacement sensor which directly measures the vertical displacement of the Z scanner will be characterized.

![Control diagram for the Z scanner that is used in most commercial AFMs. Based on the control error \( e \) the PI controller produces a control signal \( u \) to move the Z scanner - represented by \( G_z \) - up or down. The resulting position of the Z scanner is given by \( p \). The sample topography is acting as a disturbance at the output of the Z scanner. The deflection detection system - consisting of the cantilever and the photodetector - is represented by \( G_d \). The measured cantilever deflection is compared with a reference \( r \), producing the control error \( e \) for the feedback operation. The topography estimate is based on the control signal applied to the Z scanner, to control the tip-sample interaction.](image)

1-1-4 Imaging Modes

In AFM there is a distinction between *static* and *dynamic* modes of operation, referring to the interaction forces between the tip and the sample. Three imaging modes will be described next, i.e. *contact mode*, *tapping mode*, and *peak force tapping mode*. Contact mode is classified as a static mode of operation, as the tip-sample interaction is held constant during imaging. Tapping mode and peak force tapping mode are both dynamic modes of operation, as the tip-sample interaction is varied during imaging.

**Contact Mode**

A common AFM imaging mode is called *contact mode*. The contact mode was partially described above. In contact mode, the tip is in continuous contact with the sample. The tip is attached to the end of a cantilever with a low spring constant. During scanning in the lateral direction, the feedback operation of the Z scanner tries to gently trace the sample under the tip by moving the cantilever tip in the vertical direction, thereby maintaining the tip-sample interaction force as constant as possible. The voltage applied to the Z scanner is a measure for the sample topography. Due to the continuous contact between the tip and the
sample, in-plane shear forces are present, which limits the use of contact mode for imaging soft samples, while they are easily destroyed as a result of the tip ‘scraping’ over the sample surface [13].

**Tapping Mode**

To avoid sample damage due to the lateral forces, another commonly used, dynamic imaging mode operates in intermittent contact and is called *tapping mode* [13, 14]. By intermittently tapping the surface with a frequency much faster than the lateral scan, the lateral forces between the tip and the sample are not exerted. In tapping mode the freely oscillating cantilever is driven near its resonant frequency using an additional dither piezo. The interaction forces between tip and sample give rise to nonlinear dynamics. The motion of the cantilever is caused by both the nonlinear tip-sample interaction force and the sinusoidal driving force. During each oscillation period the cantilever tip taps on the sample surface. The rest position of the vibrating tip is brought in a short distance from the sample. The oscillation amplitude is in the order of ten to hundred nanometers. In a typical tapping mode experiment the Z scanner adjusts the tip-sample separation to track a reference, which is an amplitude setpoint.

To represent tapping mode operation, the control diagram in Figure 1-5 needs to be extended with a sinusoidal driving force acting on the cantilever. Similar to contact mode, the voltage applied to move the Z scanner is a measure for the sample topography. In Figure 1-6 the deflection and control signals are shown when imaging a sample surface. For the tapping mode the deflection signal is demodulated using an rms-to-dc modulation before it goes into the controller.

![Feedback operation to measure sample topography.](image)

**Figure 1-6:** Feedback operation to measure sample topography. (A) Deflection of the AFM tip in contact mode. Note that the optical lever gives a signal proportional to an error signal. The control signal being sent to the actuator is a good, albeit band-limited, representation of the surface. (B) Deflection of the AFM tip in tapping mode. In tapping mode, the drop in oscillation amplitude results in the feedback loop raising the position of the Z scanner, which restores the oscillation amplitude. A rise in oscillation amplitude results in the controller lowering the position of the Z scanner. The control signal can then be used as a representation of the surface. Image adopted from [15].
Peak Force Tapping Mode

In this thesis an analysis is done for a new AFM that can also operate in a recently found new imaging mode, called Peak Force Tapping (PFT) mode [16]. In PFT mode the tip-sample distance is also modulated, but at a much lower frequency than in tapping mode. Another difference with tapping mode, is that in peak force tapping mode the used reference is the maximum allowed tip-sample interaction force. This is a more direct way of controlling the interaction force than in tapping mode, where the used reference is an amplitude setpoint. This can enable even gentler imaging and can result in a better capability for imaging narrow deep features, where tapping mode imaging is limited due to damping issues. An estimate for the sample topography is constructed by combining the cantilever deflection signal and the position of the Z scanner. In most commercial AFMs the Z scanner position is derived from the control signal, however in this thesis a displacement sensor is developed which directly measures the position of the Z scanner. A more detailed description of PFT mode can be found in Appendix B.

1-2 Current State of AFM Research

In this thesis the focus is on a new displacement sensor for the Z scanner and on modern control methods for the X and Y scanner. However, before introducing the problem statement in Section 1-3, the reader is provided with the current state of AFM research.

In AFM the lateral (X, Y) scanning motion is performed together with the vertical (Z) topography measurement. Current AFMs are quite slow: it can take several minutes to obtain a high-quality image [17]. The long imaging time limits the use of AFM for studying fast dynamical processes (e.g. biological processes [18] and crystal growth [19]). Both the lateral scanning motion and the vertical topography measurement need to be assessed when an overall speed improvement of the AFM is desired.

Various research has been done to improve the lateral scanning motion, either by improved mechatronical design [20], input-shaping [8, 21], or scanning in closed-loop [12]. Also it has been proposed to use charge control instead of voltage control [22, 23] to reduce the nonlinearities associated with voltage driven piezoelectric actuators. Furthermore the lateral scan can be improved by using iterative learning control (ILC) [24]. In [25] it is demonstrated that the tracking performance of the lateral scan can go beyond the sensor noise by using ILC. These improvements have resulted in an improvement of the lateral scanning motion.

To enhance the overall operation of the AFM, also the performance of the Z scanner was considered before. Over the past few years, several research has been done to speed up the Z scanner, including active damping of the Z scanner [26], the use of dual actuators [27], gain scheduling [28], and the use of previous scan line information [29].

Furthermore, the electronics involved in controlling the AFM have an effect on the overall performance. To this end high-speed data acquisition has been demonstrated successfully [30] enabling sampling and processing the data at high speed.

Over the past years most of the work has been done only for the contact mode, while not so much has been done for the tapping mode. In tapping mode, the damage to the tip and the sample due to lateral forces is minimized because of the tapping motion. During scanning,
it is important to maintain a constant tapping amplitude in order to minimize the vertical tip-sample forces, thereby avoiding damage to the sample or the tip. Besides the advantage of gentle interaction forces in tapping mode, it has been experimentally demonstrated that the tip-sample interaction forces reveal quantitative information about nanoscale local material properties including chemical composition [31], short and long range forces [32], elasticity [33], plasticity [34] and friction [35]. When compared to contact mode, tapping mode is encumbered by slow imaging speed arising from several factors, i.e. the dynamics of the Z scanner, the response time of the cantilever, and the time required for the rms-to-dc conversion [36].

In AFM the sample topography is tracked by the vertical displacement of the Z scanner. In most commercial AFMs the vertical displacement is not directly measured, but based on the control signal being sent to the scanner. Here a linear relation is used between the control signal and the vertical displacement. However, because of nonlinearities such as hysteresis and creep [7][8], this might not yield an accurate representation of the true sample topography. Therefore, over the past few years so-called metrological AFMs have been developed which use a capacitive sensor [37], laser interferometer [38] or strain gage sensor [39] to measure the vertical displacement of the Z scanner. This way the Z scanner displacement is measured directly instead of being constructed from the control signal. Using this method requires careful selection of sensors with a low noise floor and nanometer resolution.

The required scanning speed in AFM is determined by both the vertical topography measurement and the lateral scanning motion. In this thesis feedback controllers for the lateral positioner will be designed which enable high scanning speeds, while benefiting from the advantages of feedback control which were mentioned earlier in Section 1-1-2.

### 1-3 Problem Statement

In most commercial AFMs the topography estimate is based on the control signal, where a linear relation is used between the control signal to the Z scanner and the resulting displacement. Hence the Z scanner is modeled as a linear element with a fixed ratio between input and output, called the sensitivity. Because of nonlinearities such as hysteresis and creep [7][8][40], the sensitivity is not constant over its full displacement range. This means the control signal may not yield the best estimate for the sample topography. Hence, it is desirable to look for a better way to obtain the topography estimate than using the control signal. The idea is to use an additional displacement sensor which directly measures the displacement of the Z scanner. This sensor will be implemented on a new AFM system (Veeco Instruments, Santa Barbara, CA, USA). In this thesis a characterization is done for the new sensor. The lateral positioner is controlled via a feedback operation to maintain high positional accuracy in spite of unknown disturbances and model uncertainty. In this feedback operation, the dynamics of the lateral positioner limit the speed of the AFM. Therefore, in this thesis modern control methods will be used to improve the performance of the lateral positioner, in both frequency and time domain.

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1-4 Project Goal

The goal of this MSc thesis project can be stated as follows:

“To develop a displacement sensor for the vertical positioner which gives a more accurate estimate for the sample topography than the control signal to the vertical positioner, and to use modern control methods to improve the speed of the lateral positioner.”

1-5 Outline of Thesis

In Chapter 2 a displacement sensor is characterized and implemented on the new AFM system. Next, in Chapter 3 modern control methods are applied to the lateral positioner. Conclusions and recommendations can be found in Chapter 4. In Appendix A a system identification is carried out for the Z scanner. Next, in Appendix B a description of peak force tapping mode can be found. Then in Appendix C a comparison is given between different low pass filters for filtering the output of the displacement sensor. Furthermore, in Appendix D an analysis of a piezo stack actuator is carried out for another AFM system.
Chapter 2

Displacement Sensor for Vertical Positioner

The quantity of interest in this chapter is the actual displacement of the Z scanner, which can be used as a measure for the sample topography. In most commercial AFMs a linear relation is assumed between the control signal being sent to the Z scanner and the resulting displacement. However, because of nonlinearities associated with the Z scanner, this way of obtaining the displacement may yield inaccurate results. Therefore in this chapter a displacement sensor is characterized which directly measures the Z scanner displacement. Two different configurations of the sensor are analyzed, represented by A and B. The nonlinearity of the sensor configuration is obtained by inspecting the sensitivity variation of the sensor over the full displacement range of the Z scanner. First, for sensor configuration A a test on a vibrometer setup is conducted to inspect the sensitivity variation in response to a small sinusoidal excitation voltage. Then for both sensor configurations the nonlinearity of the sensor is inspected by scanning a calibration step feature for different Z scanner position offsets on the AFM setup, similar to what was done in [37]. The variation in measured step height is then a measure for the nonlinearity of the sensor and can be compared to the height obtained using the control signal. The desired maximum variation in measured step height using the displacement sensor was specified beforehand and is 4% of the nominal step height [40].

First a description of the Z scanner is given in Section 2-1. Then a simulation is carried out in Section 2-2 to analyze the piezoring deformation. Some issues regarding the sensor are considered in Section 2-3. After that, two different sensor configurations are presented. Sensor configuration A is presented in Section 2-4, and an improved sensor configuration B is presented in Section 2-5. The sensor noise for configuration B is analyzed in Section 2-6.

2-1 System Representation

A schematic of the AFM with an exploded view of the Z scanner is given in Figure 2-1. The Z scanner consists of a piezoring, clamped inside a mechanical housing. Due to the mechanical
design, the movement of the piezoring is translated into the movement of the cantilever base (indicated by the red square).

Figure 2-1: Schematic of the AFM with an exploded view of the Z scanner. The Z scanner consists of a piezoring, which is enclosed by a nozzle. The vertical movement of the piezoring is translated into vertical movement of the cantilever base. The position of the cantilever base is indicated by the red square.

The piezoring itself consists of active piezoplates, which are stacked on top of each other and enclosed by an inactive insulation layer on the outside. The piezoring is driven by an input voltage to track the sample surface. When a positive voltage is applied to its electrodes, the piezoring expands vertically, while applying a negative voltage will result in vertical contraction of the piezoring. It is desired to have precise knowledge about the actual vertical displacement of the piezoring, to enable an accurate estimate for the sample topography. Therefore a displacement sensor will be implemented which directly measures the vertical displacement of the piezoring. The resulting control diagram is shown in Figure 2-2, where the displacement sensor is represented by $G_s$.

2-2 Piezoring Deformation

Before analyzing the displacement sensor, in this section a simulation study is carried out to inspect the displacement of the piezoring.

2-2-1 Simulation

The piezoring has an outer diameter of 12 [mm], an inner diameter of 6 [mm] and a height of 2.5 [mm]. In Figure 2-5 a simulation result is shown which is generated using finite element analysis software (ANSYS Inc., Canonsburg, PA, USA). A model of the piezoring was built consisting of a large number of linear elements to approximate the deformation of the
piezoring. From Figure 2-3(b) it can be seen that the piezoring attains a dome shape when it expands vertically. The simulation results show that for a point located at mid height on the outside of the piezoring, the vertical strain and the contraction in the horizontal direction are of the same order of magnitude when the piezoring is fully extended.

Figure 2-3: Simulation result for piezoring deformation. Courtesy of N. Phan.

### 2-2-2 Validation

The simulation results show that the strain in the horizontal and in the vertical direction are within the same order of magnitude. To validate this, an experiment is carried out, where a DC offset voltage is applied to the piezoring. Two strain gages are glued onto the piezoring, as shown in Figure 2-5(a). The extension of the piezoring induces strain in the strain gages. The resistance of the vertical and the horizontal strain gage are measured simultaneously. The DC offset voltage is slowly varied to inspect the resistance of the strain gages over the full displacement range of the piezoring. The full displacement range of the piezoring is 4 $\mu m$, which corresponds to an input voltage range of -30 to +175 [V DC]. The piezoring goes from full vertical extension to full vertical contraction, and then back to full vertical...
extension with increments of 1 [V]. After each increment a period of twenty seconds is waited before recording the strain gage resistance, such that creep effects can be suppressed. Using the measured resistance values, the induced microstrain in the strain gages can be computed according to

$$\epsilon_i = \frac{\Delta R_i}{R_0} \cdot \frac{1}{GF} \quad i = 1, 2$$ (2-1)

where $\epsilon_1$, $\epsilon_2$ are the vertical and horizontal microstrain, respectively. The nominal resistance $R_0$ and the strain gage factor $GF$ are constant values specified by the manufacturer. The microstrain is the induced strain expressed in $[\mu m/m]$. The resistance change due to the induced strain in the vertical and horizontal direction are given by $\Delta R_1$ and $\Delta R_2$, respectively.

The resulting microstrain for both the vertical and the horizontal strain gage is shown in Figure 2-4. Note that in Figure 2-4(a) there is strain present at 0 [V]. This is due to the used nominal resistance value in the computation for the induced microstrain. The motivation to use one fixed value for the nominal resistance is that the end points of the extend and retract curves coincide in this case, resulting in the typical hysteresis curves. Furthermore, note that in Figure 2-4(b) the strain is negative for all voltages. This could be interpreted as if the horizontal strain gage is in compression all the time. However, this is also caused by the fixed value for the nominal resistance used in the computation. Therefore, the presented values for the strain in Figure 2-4 should be interpreted not as absolute values, but more as relative values. Nonetheless the results show that the induced microstrain is of the same order of magnitude for the vertical and horizontal direction at the measured positions. This corresponds with the simulation results from Section 2-2-1.

### 2-3 Sensor Issues

In this section several issues regarding the displacement sensor are considered, i.e. the location of the sensor with respect to the position of interest, the linearity of the sensor itself, and rejection of noise from the surroundings and quantization noise due to a limited bit resolution of the Data Acquisition (DAQ) system.

- The quantity of interest is the vertical displacement of the piezoring at the position of the cantilever base, indicated with a red square in Figure 2-1. Recall that from the simulation a dome shape is expected when a positive voltage is applied to the piezoring. Therefore, the sensor must be placed in such a way, that the resulting sensor output is linearly related to the vertical displacement at the point of the cantilever base. This is conform the *Abbé principle* [41]. It has to be kept in mind that the dynamics of mechanical parts in between the sensor and the position of interest may affect the measurement when they are not collocated.

- The linearity of the sensor itself is also important. For example, when strain gages are used as a sensor it is desired that they show linear behavior over the operating range. The strain gages used in this thesis have a linearity better than $\pm 1.5\%$ up to a microstrain of 1500 $[\mu m/m]$ (specified by the manufacturer), which is sufficient for the required operating range.
Figure 2-4: Induced microstrain.
- A low noise floor of the sensor is required, such that the measurements are not perturbed by noise from the surroundings.
- The limited bit resolution of the DAQ system introduces quantization noise which can affect the measured value.

There are several types of sensors which can be used to measure the displacement of the Z scanner, e.g. a capacitive sensor [37], a laser interferometer [38] or a strain gage sensor [39]. Before starting this project, the choice to use a strain gage sensor was already made, because of low manufacturing costs and ease of implementation. In the following sections two different sensor configurations will be analyzed, represented by A and B.

## 2-4 Configuration A: Strain Gages on Side

A common way to implement a strain gage sensor is via a Wheatstone bridge, consisting of four strain gages, as shown in Figure 2-5(b). The circuit is implemented such that two gages are under compression, while the remaining two are in tension, and vice versa. The first implementation of the sensor is a Wheatstone bridge configuration with four strain gages glued onto the side of the piezoring, and is called configuration A. This is shown in Figure 2-5(c).

![Figure 2-5: Schematics of displacement sensor.](image)

### Figure 2-5: Schematics of displacement sensor.
2-4-1 Experiment Description for Vibrometer Setup

To analyze the linearity of sensor configuration A, an experiment is carried out. The experimental setup is depicted in Figure 2-6. An excitation voltage $V_{\text{input}}$ is applied to the piezoring. The positioning range of the piezoring is $4 \, \mu\text{m}$, which corresponds to an input voltage range of -30 to $+175 \, \text{V DC}$. Due to the induced strain there is a resistance change $(\Delta R_1, \Delta R_2)$ in the strain gages, which results in a change in the sensor output voltage $V_{\text{sens}}$. The supply voltage to the bridge, $V_{\text{DC-supply}}$, is provided by a DC voltage source. Ideally, the sensor output voltage is linearly related to the vertical displacement of the piezoring at the position of the cantilever base. The vertical displacement at this position is measured using a laser Doppler vibrometer (MSV-400, Polytec GmbH, Waldbronn, Germany), which is used as a reference to inspect the linearity of the sensor.

The bridge output voltage is given in Eq. (2-4).

$$V_{\text{sens}} = V_{\text{DC-supply}} \left( \frac{R_1 - R_2}{R_1 + R_2} \right)$$

$$= V_{\text{DC-supply}} \left( \frac{(R_0 + \Delta R_1) - (R_0 - \Delta R_2)}{(R_0 + \Delta R_1) + (R_0 - \Delta R_2)} \right)$$

$$= \frac{V_{\text{DC-supply}}}{2R_0} (\Delta R_1 + \Delta R_2)$$

where $\Delta R_1, \Delta R_2 << R_0$, and $R_0$ is the nominal resistance of a strain gage.

![Figure 2-6: Vibrometer setup. The input signal ($V_{\text{input}}$) and three output signals ($V_{\text{vib,displ}}$, $V_{\text{vib,test}}$, $V_{\text{sens,test}}$) are simultaneously captured using a Digital Signal Processor.](image)

To analyze the linearity of the strain gage sensors over the full vertical piezo positioning range, the following experiment is carried out.

- a low frequency triangular waveform voltage is applied to the piezoring to ramp it over its full positioning range: 205 $\text{Vpp}$ at 0.05 $\text{Hz}$ with an offset value of 72.5 $\text{V}$. This corresponds to a displacement range of $4 \, \mu\text{m}$. 

• using a summing stage, a high frequency sinusoidal test signal is added to the low frequency triangular waveform: 0.2 [Vpp] at 1 [kHz]. The resulting sum signal is called \( V_{\text{input}} \). This input signal is shown in Figure 2-7.

• the response to the sinusoidal test signal is measured by using two lock-in amplifiers (Stanford Research Systems SR830, Sunnyvale, CA, USA): one for the strain gage bridge output and the other for the vibrometer output. The outputs are captured simultaneously using a Data Acquisition system (National Instruments, Austin, TX, USA).

• the internal oscillator frequencies of both lock-in amplifiers are set equal to the frequency of the applied sinusoidal test signal. The outputs of the lock-in amplifiers are the rms (root mean square) values of both the vibrometer and the strain gage response to the sinusoidal test signal. These are represented by \( V_{\text{vib,test}} \) and \( V_{\text{sens,test}} \), respectively. By only looking at the rms-value, the phase difference between the input of the lock-in amplifier and its internal oscillator signal is neglected. The rms output voltage \( V_{\text{rms}} \) of a lock-in amplifier is given as

\[
V_{\text{rms}} = \sqrt{\frac{1}{T} \int_{0}^{T} V^2(t) \, dt}
\]  

where \( V(t) \) is the time domain voltage at the frequency of the sinusoidal test signal and \( T \) is the period of the test signal.

• the piezoring input, \( V_{\text{input}} \), and both outputs coming from the lock-in amplifiers are captured while ramping the piezoring over its full displacement range. During one ramp period the vertical displacement of the piezoring goes from fully contracted to fully expanded and back. The measurements are averaged over several ramp periods to suppress the influence of random noise. The displacement measured by the vibrometer \( V_{\text{vib,displ}} \) is also captured, so without being filtered by the lock-in amplifier.

### 2-4-2 Experimental Results for Vibrometer Setup

The input signal \( V_{\text{input}} \) is shown in Figure 2-7. The response to the test signal is shown in Figure 2-8 for both the strain gage sensor and the vibrometer. The rms values coming from the lock-in amplifiers have been normalized by dividing them by their mean values to be able to compare them. The total displacement measured by the vibrometer is also shown in Figure 2-8. The ratio between the strain gage signal and the vibrometer signal is a measure for the nonlinearity of the displacement sensor. This ratio is called the sensitivity. In Figure 2-9 it can be seen that there is a change in sensitivity when ramping over the full piezo displacement range. The sensitivity varies between 94.8-104.2%, hence a sensitivity variation around 10%. To reduce the sensitivity variation, an improved sensor configuration is presented in Section 2-5.

### 2-4-3 Experiment Description for AFM Setup

The Z scanner with sensor configuration A is implemented on the new AFM system. An experiment is carried out, where a silicon calibration sample (NanoDevices Inc, Santa Barbara,
Figure 2-7: Top: the input voltage $V_{input}$ is the summation of a low frequency triangular signal with large amplitude and a high frequency test signal with small amplitude. The triangular input voltage is at 0.05 [Hz] and with 205 [V] peak-to-peak amplitude to ramp over the full piezo displacement range. The test signal is a sine at 1 [kHz] and with 0.2 [V] peak-to-peak amplitude. Bottom: zoomed in on input signal between time instants $t=1$ and $t=1.045$ [s].

Figure 2-8: Top: vibrometer measurement of piezo displacement. Bottom: the response to the test signal for both the strain gage sensor (blue line, solid) and the vibrometer (red line, dashed). Both signals are coming from a lock-in amplifier, which passes only the response to the test signal.

CA, USA) with square pits with a size of 5x5 [$\mu$m] and a depth of 200 [nm] is scanned in tapping mode. The line scan rate is 1 [Hz] at a resolution of 4096 samples per line and 16 lines per image. The scanned area is 30 [$\mu$m] x 7.5 [$\mu$m]. A fast scanning probe with a resonance frequency of 1 [MHz] is used (Arrow-UHF-20, Nanoworld, Neuchâtel, Switzerland).

To inspect the linearity of the height sensor and the conventional control signal, the step feature is scanned for different center positions of the Z scanner, covering the full positioning range. The experiment is carried out according to the following steps.

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Figure 2-9: The sensitivity variation for sensor configuration A, where the strain gages are put on the side of the piezo. The sensitivity is computed as the ratio between the strain gage signal and the vibrometer signal. The sensitivity varies between 94.8-104.2%, hence a sensitivity variation around 10%.

- a center position offset is applied to the vertical positioner. The Z scanner was calibrated in advance such that the Z scanner center position is well-known.
- the step feature is scanned.
- to suppress measurement errors due to random noise and local irregularities on the surface (e.g. dust particles), the scan is performed with both the X and Y axis enabled. This results in an AFM height image of the step feature.
- for every center position, covering the full positioning range, 10 AFM height images are collected and averaged. From the averaged height image, the average step height is computed.
- the above steps are repeated for 10 different scanner center positions, covering the full displacement range of the scanner.

2-4-4 Experimental Results for AFM Setup

The resulting average measured step height for each position offset is shown in Figure 2-10. In Figure 2-10(a) it can be seen that the step height measured with the displacement sensor varies between 187-209 [nm]. Hence, there is a difference of 22 [nm] in measured step height over the full displacement range. Comparing this to the true step height of 200 [nm], the sensitivity variation is computed as the ratio of this difference and the true step height. Hence, a sensitivity variation in the order of \( \frac{22}{200} \approx 11\% \).

In Figure 2-10(b) it can be seen that the step height measured using the control signal varies between 182-252 [nm]. Hence, there is a difference of 70 [nm] in measured step height over the full displacement range. Thus, a sensitivity variation in the order of \( \frac{70}{200} \approx 35\% \).
(a) Linearity of the height sensor. The sensitivity variation is 11%.

(b) Linearity of the measurement which is based on the control signal. The sensitivity variation is 35%.

Figure 2-10: Sensitivity variation for configuration A on the new AFM system. The graphs show the average measured height of the 200 [nm] step feature, for 10 different scanner positions. At each scanner position 10 images are collected and averaged.

2-5 Configuration B: Diving Board

Because sensor configuration A sensor exceeds the requirement of 4% sensitivity variation, sensor configuration B is designed where a diving board is used, as shown in Figure 2-5(d). The diving board is equipped with two strain gages glued onto each side, resulting again in a Wheatstone bridge configuration. The displacement of the piezoring is translated into bending of the diving board by using a connecting rod. The output of the Wheatstone bridge then gives a direct measure for the vertical displacement of the piezoring.
2-5-1 Experimental Results for AFM Setup

The experiment on the AFM setup that was described in Section 2-4-4 is now conducted for sensor configuration B. The resulting average measured step height for each position offset is shown in Figure 2-11.

In Figure 2-11(a) it can be seen that the step height measured with the displacement sensor varies between 196-208 [nm]. Hence, there is a difference of 12 [nm] in measured step height over the full displacement range. Comparing this to the true step height of 200 [nm], the sensitivity variation is $12/200 = 6\%$. Hence, using sensor configuration B results in a smaller sensitivity variation than with configuration A, which was 11\%. However, the required specification of 4\% which was stated at the beginning of this chapter, is not met.

In Figure 2-11(b) it can be seen that the step height measured using the control signal varies between 183-254 [nm]. Hence, there is a difference of 71.3 [nm] in measured step height over the full displacement range. Thus, a sensitivity variation in the order of $71.3/200 = 35\%$. Since this is the same experiment as before and only the sensor configuration was changed, the control signal shows the same sensitivity variation.

Cross Section of the Step Feature

The step feature is scanned for a Z scanner center position of 0 [µm]. The height images coming from the displacement sensor and the conventional control signal are shown in Figure 2-12(a). A cross section of the height images can be seen in Figure 2-12(b) for the displacement sensor and for the control signal for a single step feature. When both cross sections are compared, a difference can be seen in the overshoot at the edges of the step feature. The measurement which is based on the control signal shows a larger overshoot at the edges. This image artifact does not show up in the height image coming from the displacement sensor. Hence, the displacement sensor enables a more accurate topography estimate at the edges.

2-6 Sensor Noise

The noise acting on the strain gage sensor may affect the precision and accuracy of the measurement. Therefore a new AFM height image is captured, where the scanned area is set to 0.1 x 0.1 [nm]. This way the movement of the X and Y scanner does not affect the measurement. The AFM is not engaged on the sample, such that the height image coming from the displacement sensor consists of noise only. The resulting AFM height image is shown in Figure 2-13(a). The line scan rate is 11.1 [Hz] and the resolution is 4096 samples per line. This corresponds to a sampling frequency of 45 [kHz]. Therefore, the amplitude spectrum of the noise for frequencies up to 22.5 [kHz] can be computed using the fast Fourier transform, which is shown in Figure 2-13(b). In the time domain it can be seen that the amount of sensor noise is about 0.7 [nm] peak-to-peak. In the frequency domain it can be seen that the amplitude of the noise is smaller than 10 [pm] for all frequencies from 100 [Hz] up to 22.5 [kHz]. Hence, when the Z scanner position has to be measured with nanometer resolution, the sensor noise is a limitation.
In this chapter an analysis was done for a new displacement sensor for the Z scanner. In most commercial AFMs the estimate for the sample topography is based on the control signal being sent to the Z scanner. Because of hysteresis and creep effects, the Z scanner suffers from nonlinear behavior. The new displacement sensor measures the Z scanner displacement directly and enables a better estimate for the sample topography. In order to do quantitative measurements on the new AFM system, it is desired that the sensitivity variation of the sensor is minimized. Two sensor configurations are analyzed, represented by A and B. Sensor configuration A shows a sensitivity variation over the full displacement range in the order of

Figure 2-11: Sensitivity variation for configuration B on the new AFM system. The graphs show the average measured height of the 200 [nm] step feature, for 10 different scanner positions. At each scanner position 10 images are collected and averaged.

2-7 Concluding Remarks

(a) Linearity of the height sensor. The sensitivity variation is 6%.

(b) Linearity of the measurement which is based on the control signal. The sensitivity variation is 35%.
11% when scanning a calibration step feature, whereas sensor configuration B shows an even lower sensitivity variation of 6%. Sensor configuration B still does not satisfy the requirement of 4%. However, the sensitivity variation is almost 6 times lower than the one obtained from the control signal, which is 35%. Hence, using sensor configuration B in the new AFM system enables a more accurate topography estimate than when using the control signal.
(a) AFM height images. The blue lines indicate where the cross-section is taken. Top: height sensor. Bottom: conventional Z output.


Figure 2-12: Cross section of step feature for sensor configuration B.
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(a) Noise measured on height sensor. The blue line indicates where the cross-section is taken.

(b) Cross section of height image. Top: time domain signal. Bottom: frequency domain signal.

**Figure 2-13**: Noise measurement for sensor configuration B.
To improve the overall performance of the AFM, it is desired to characterize and improve the performance of the lateral positioner, also denoted as the XY scanner. The new AFM is a scanning tip design, which means the tip is scanned across the sample. The XY scanner consists of the X scanner and the Y scanner, connected in a parallel way with the use of flexures. Due to the flexures the mechanical coupling between the X and the Y scanner is minimized. In Figure 3-1 it can be seen that both the X and the Y scanner consist of a single piezo stack actuator which is attached on one end to the baseframe and on the other end to a flexure which is connected to the Z scanner. Strain gages are glued onto the piezos to measure the piezo extension. The piezo stack actuators have a length of 30 [mm] and a positioning range of 30 [\mu m]. In Section 3-1 modern control methods are used to improve the performance of the X scanner. A summary of the performance for the different control methods is given in Section 3-1-8. In Section 3-2 a characterization is done for the Y scanner.

Figure 3-1: Flexure-based XY scanner.
3-1 Control for the X Scanner

In this section the X scanner will be characterized and modern control methods will be used to improve the performance, in both frequency and time domain.

3-1-1 System Representation

The X scanner is controlled by a feedback operation shown in Figure 3-2. Recall from Section 1-1 that reasons to apply feedback are the presence of unknown disturbances $d$, model uncertainty [9], and to compensate the nonlinear effects arising from hysteresis and creep associated with piezoelectric actuators [7]. Note that also sensor noise $n$ is shown in Figure 3-2. Due to a too low bit resolution of the used Data Acquisition (DAQ) system (NanoScope V, Veeco Instruments, Santa Barbara, CA, USA) for the X and Y scanner, no noise measurements could be done.

![Control diagram for the PI-controlled X scanner.](image)

**Figure 3-2:** Control diagram for the PI-controlled X scanner. The controller is represented by $K_{PI}$ and the X scanner by $G_x$. The input of the feedback system is a reference $r$ and the output is a displacement $x$. The controller tries to minimize the control error $e$ by producing a control signal $u$ to move the scanner. The scanner is perturbed by system noise $d$. Furthermore, the measured output signal can be perturbed by sensor noise $n$, which occurs mainly at high frequencies. The resonance of the scanner is limiting the control bandwidth at a much lower frequency.

3-1-2 System Identification

An identification experiment is carried out in open loop to characterize the X scanner, represented by $G_x$. All measurements for the X and Y scanner are done on the new AFM where a NanoScope V controller (Veeco Instruments, Santa Barbara, CA, USA) is used for generating and capturing the signals.

- the input voltage is a sinusoidal sweep signal. The input is coming from the NanoScope V controller and is used to excite the X piezo stack.
- the output voltage is coming from the strain gage displacement sensor, which is glued onto the piezo as shown in Figure 3-1. The output is captured with the NanoScope V controller.

The response data for the X scanner is collected for 512 equidistantly spaced frequency points between 0 and 8 [kHz]. The results are shown in Figure 3-3. Some low frequency phase lead
below 20 [Hz] is caused by the AC coupling characteristics of the NanoScope V controller, which attenuates the response for low frequencies. Therefore, for the identified model (Figure 3-3), this low frequency artifact due to the measurement equipment is not taken into account. In the frequency response data a resonance can be seen around 2614 [Hz]. By manual placement of a complex pole pair and a first-order Padé approximation \( R \) for a time delay of 50 [\( \mu s \)], a third order model is obtained as shown in Eq. (3-1). In the X scanner on the real setup there is a time delay stemming from A/D and D/A conversion and the time needed to compute the controller on the DSP.

\[
G_x = K \cdot R \cdot \frac{1}{s^2 + 2\zeta \omega s + \omega^2} \tag{3-1}
\]

where the values are given in Table 3-1.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K )</td>
<td>2.7332 ( \cdot ) ( 10^8 )</td>
</tr>
<tr>
<td>( \omega )</td>
<td>2614 [Hz]</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>0.065</td>
</tr>
</tbody>
</table>

Table 3-1: Parameter values for identified model of X scanner.

\[\text{Figure 3-3: Measured data (black line, dashed) and model fit } G_x \text{ (blue line, solid).}\]

3-1-3 PI Control

A Proportional-Integral (PI) controller is taken of the form given in Eq. (3-2).

\[
K_{PI}(s) = \frac{K_p s + K_i}{s} \tag{3-2}
\]
where $K_p$ and $K_i$ are the proportional and integral gains, respectively. The closed loop transfer function from the commanded step input $r$ to the displacement output of the piezo stack $x$ is given in Eq. (3-3).

$$T(s) = \frac{x}{r} = \frac{G_x(s)K_{PI}(s)}{1 + G_x(s)K_{PI}(s)} \quad (3-3)$$

and is called the complementary sensitivity $T$.

The complementary sensitivity $T$ describes the ability to track a reference step. Another important closed loop transfer function is called the sensitivity $S$ and describes the system’s ability to reject a step disturbance $d$ at the displacement output $x$. The sensitivity $S$ is given in Eq. (3-4).

$$S(s) = \frac{x}{d} = \frac{1}{1 + G_x(s)K_{PI}(s)} \quad (3-4)$$

**Frequency Domain Performance**

Examining Eq. (3-3) it can be seen that there is a possibility of infinite gain for the feedback system, that is, when the magnitude of the open loop gain $L(s) = G_x(s)K_{PI}(s)$ is unity and its phase is $-180^\circ$. In control engineering there are two criteria that investigate the stability of the feedback system by looking at the open loop gain. The Gain Margin (GM) measures the difference between the magnitude of the open loop gain at the frequency where the phase of the open loop gain is $-180^\circ$ and unity. The Phase Margin (PM) measures the phase difference between the phase of the loop gain at the frequency where the magnitude of the open loop gain is unity and $-180^\circ$.

**Time Domain Performance**

The time domain performance can be addressed by analyzing the closed loop step response, where the rise time and settling time indicate the speed of the response, whereas overshoot, decay ratio and steady-state error indicate the quality of the response.

**Controller Tuning**

The PI controller is tuned according to the following method.

- set the proportional gain $K_p = 0$ and increase the integral gain $K_i$ until the system starts oscillating.
- increase $K_p$ to add a zero to the controller to get a higher phase margin (see Eq. (3-2)).
- increase the integral gain $K_i$ further to get a higher bandwidth, until the system starts oscillating again.
After some tuning, the following values are chosen: $K_p = 0$, $K_i = 320$. The Bode plot of the open loop gain $L(s) = G_x(s)K_{PI}(s)$ is plotted in Figure 3-4. It can be seen that for the PI-controlled system the gain margin is 18 [dB] and the phase margin is 88.9 [deg].

The Bode plot of the complementary sensitivity $T$ for the PI-controlled system is given in Figure 3-5. Recall that the bandwidth is defined as the frequency range where the complementary sensitivity has a gain larger than $1/\sqrt{2}$ (= -3 [dB]). The bandwidth of the PI-controlled system is approximately 50 [Hz].

The step response of the complementary sensitivity (reference tracking) is given in Figure 3-6. In Figure 3-6 it can be seen that the reference step height is reached within approximately 0.015 [s]. Because the integral action is kept sufficiently low, no oscillations can be seen in the step response.
The tracking error in response to a triangular reference signal $r$ with a frequency of 10 [Hz] is shown in Figure 3-7. It can be seen that the control error reaches a maximum absolute value of 0.12 [a.u.] for this specific reference signal. Due to the ramp-tracking problem [42] for a system with just one integrator in the loop there will always be a control error when tracking a ramp.

Adding Derivative Action

When derivative action is added to the PI-controller, a PID-controller results, given in Eq. (3-5).
\[ K_{PID}(s) = \frac{K_p s + K_i + K_d s^2}{s} \]  \hspace{1cm} (3-5)

Simulation results showed no significant improvement when derivative action is added to the PI-controller. In real systems, adding derivative action is often omitted because of uncertainty in the modeling of the piezo actuator [15] and amplification of sensor noise.

**Increasing Integral Gain**

When the integral action is doubled from \( K_i = 320 \) to \( K_i = 640 \), oscillatory behavior can be seen in the step response in Figure 3-8. The oscillating behavior is stemming from the resonance of the X scanner, which is excited due to smaller phase and gain margins. Because oscillatory behavior is unwanted, the integral action is set back to \( K_i = 320 \).

![Figure 3-8: Step response of the complementary sensitivity for the PI-controlled system when more integral action is added (\( K_p = 0, K_i = 640 \)).](image)

**Low-Pass Filter in Forward Path**

The resonance of the X scanner is limiting the performance of the system. In Figure 3-3 a wide resonance peak can be seen around the resonance frequency. To suppress the effect of the resonance peak, a low-pass filter with a cutoff frequency of 1 [kHz] is added to the system, as shown in Figure 3-9.

![Figure 3-9: Control diagram for the PI-controlled X scanner with the low pass filter in the forward path \( K_{lp} \). The controller is represented by \( K_{pi} \) and the X scanner by \( G_x \). The input of the feedback system is a reference \( r \) and the output is a displacement \( x \).](image)
The low-pass filter $K_{lp}$ is given in Eq. (3-15).

$$K_{lp}(s) = \frac{2\pi f}{s + 2\pi f}$$  \hspace{1cm} (3-6)

where the cutoff frequency $f$ is set to 1 [kHz].

When adding the low pass filter, the complementary sensitivity from Eq. (3-3) changes according to Eq. (3-7).

$$T(s) = \frac{x}{r} = \frac{G_x(s)K_{lp}(s)K_{PI}(s)}{1 + G_x(s)K_{lp}(s)K_{PI}(s)}$$  \hspace{1cm} (3-7)

Because the control signal is low pass filtered below the resonance of the scanner, the controller gains can be increased to get a higher bandwidth, resulting in a faster system. After tuning the PI controller, the following values are chosen: $K_p = 0.05$, $K_i = 800$. The new complementary sensitivity is shown in Figure 3-10 (red line, dashed). The resulting gain margin is 5.2 [dB] and the phase margin is 85.2 [deg]. Recall that for the PI-controlled system without the notch filter, the resulting gain margin is 18 [dB] and the phase margin is 88.9 [deg].

It can be seen in Figure 3-10 (red line, dashed) that the resulting bandwidth is approximately 140 [Hz]. This is almost three times larger than the bandwidth for the PI-controlled system without the low pass filter, which was only 50 [Hz].

![Figure 3-10: Frequency response of the complementary sensitivity for the PI-controlled system (blue line, solid) and for the PI-controlled system with the low pass filter in the forward path (red line, dashed).]

The step response of the complementary sensitivity is given in Figure 3-11 (red line, dashed). It can be seen that the reference step height is reached within approximately 0.006 [s]. This is two times faster than the settling time of the PI-controlled system without the low pass filter, which was 0.015 [s].

The tracking error in response to a triangular reference signal with a frequency of 10 [Hz] is shown in Figure 3-12. It can be seen that the control error reaches a maximum absolute value of 0.05 [a.u.] for this specific reference signal.
Figure 3-11: Step response of the complementary sensitivity for the PI-controlled system (blue line, solid) and for the PI-controlled system with the low pass filter in the forward path (red line, dashed).

Figure 3-12: PI-controlled system with the low pass filter in the forward path. Difference between triangular reference signal and simulated output. The frequency of the triangular reference signal is 10 [Hz]. Top: triangular reference signal (black line, solid) and simulated output (blue line, solid). Bottom: tracking error.
3-1-4 Model Based Control

The resonance of the X scanner is limiting the performance of the system. The resonance of the X scanner can be attenuated by adding a notch filter $K_F$ to the plant $G_x$ in Eq. (3-1). The resulting control configuration is presented in Figure 3-13.

$$K_F(s) = \frac{s^2 + 2\zeta_z\omega_0s + \omega_0^2}{s^2 + 2\zeta_p\omega_0s + \omega_0^2}$$  \hspace{1cm} (3-8)

The used values are given in Table 3-2.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$</td>
<td>2614 [Hz]</td>
</tr>
<tr>
<td>$\zeta_z$</td>
<td>0.065</td>
</tr>
<tr>
<td>$\zeta_p$</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3-2: Parameter values for notch filter.

The notch zeros are matched to the poles of $G_x$. The damping of the notch poles $\zeta_p$ is set to 1 to have no overshoot and fast response time.

When adding the notch filter, the complementary sensitivity from Eq. (3-3) changes according to Eq. (3-9).

$$T(s) = \frac{x}{r} = \frac{G_x(s)K_F(s)K_{PI}(s)}{1 + G_x(s)K_F(s)K_{PI}(s)}$$  \hspace{1cm} (3-9)

Because the resonance of the scanner is attenuated by the notch filter, the controller gains can be increased to get higher bandwidth, resulting in a faster system. After tuning the PI controller, the following values are chosen: $K_p = 1$, $K_i = 7500$. The new complementary sensitivity is shown in Figure 3-14 (red line, dashed). The resulting gain margin is infinite and the phase margin is $82.4$ [deg]. Recall that for the PI-controlled system without the notch filter, the resulting gain margin is $18$ [dB] and the phase margin is $88.9$ [deg].
It can be seen in Figure 3-14 (red line, dashed) that the resulting bandwidth is approximately 1.9 [kHz]. This is 38 times larger than the bandwidth for the PI-controlled system without the notch filter, which was only 50 [Hz].

The step response of the complementary sensitivity is given in Figure 3-15 (red line, dashed). It can be seen that the reference step height is reached within approximately 0.001 [s]. This is 15 times faster than the settling time of the PI-controlled system without the notch filter, which was 0.015 [s].

The tracking error in response to a triangular reference signal with a frequency of 50 [Hz] is shown in Figure 3-16. It can be seen that the control error reaches a maximum absolute value of 0.027 [a.u.] for this specific reference signal. Recall that for the PI-controlled system without the notch filter, the control error reaches a value of 0.12 [a.u.] for a 10 [Hz] reference signal. Thus, the notch filter enables a faster system and a smaller control error.
3-1-5 H-Infinity Control

In this section a more sophisticated model based controller is considered to control the X scanner. A linear $H_{\infty}$ controller is chosen, because the $H_{\infty}$ framework enables the user to specify performance requirements (e.g. magnitude of steady-state error, rejection of measurement noise, and robustness against model uncertainties) with the use of weighting functions. The X scanner is controlled by a feedback operation shown in Figure 3-17.

The $H_{\infty}$ methodology from [9] and simulation software MATLAB (Mathworks, Natick, MA, USA) are used to design the controller. In the $H_{\infty}$ framework weightings on the sensitivity, the complementary sensitivity and the control sensitivity need to be specified. The weighting functions will be described next.

- **Weighted sensitivity.** The sensitivity $S$ is an indicator of closed loop performance and describes the ability to reject a step disturbance. The advantage of considering $S$ is that because ideally $S$ is small, it is sufficient to consider just its magnitude $\|S\|$; that is, we need not worry about its phase. Typical specifications in terms of $S$ include:

  1. Minimum bandwidth frequency $\omega_B$ (defined as the frequency where $\|S\|$ crosses 0.707 [-3 dB] from below).
2. Minimum tracking error at selected frequencies.
3. The maximum steady-state tracking error, $A$.
4. Shape of $S$ over selected frequency ranges.
5. Maximum peak magnitude of $S$, $\| S(j\omega) \|_\infty \leq M$.

- **Weighted complementary sensitivity.** The weighted sensitivity only puts a lower bound on the bandwidth. To specify an upper bound on the bandwidth and to specify the roll-off of the loop gain above the bandwidth, a weighting function $W_x$ that shapes the complementary sensitivity $T$ can be specified. A possible requirement is fast roll-off of the loop gain at high frequencies.

- **Weighted control sensitivity.** Furthermore, to achieve robustness or to restrict the magnitude of the control signal $u$, an upper bound $1/\|W_u\|$ is specified on the magnitude of the control sensitivity $K_S$.

The $H_\infty$ norm for the feedback controller ($\|N\|_\infty$) is given in Eq. (3-10).

$$\|N\|_\infty = \left\| \begin{array}{c} W_c \cdot S \\ W_u \cdot K_{H_\infty} \cdot S \\ W_x \cdot T \end{array} \right\|_\infty < 1 \quad (3-10)$$

The weighting functions are given in Eq. (3-11).

$$\begin{align*}
W_c &= \frac{s/M+\omega_B^2}{s+\omega_B A} \\
W_u &= c \\
W_x &= \frac{s+\omega_B^2/M}{A s+\omega_B}
\end{align*} \quad (3-11)$$

The used values are given in Table 3-3.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>1</td>
</tr>
<tr>
<td>$\omega_B$</td>
<td>3000 [Hz]</td>
</tr>
<tr>
<td>$A$</td>
<td>0.001</td>
</tr>
<tr>
<td>$c$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 3-3:** Parameter values for weighting functions.

The resulting controller is given in Eq. (3-12).

$$K_{H_\infty} = \frac{8.483 \cdot 10^6 s^3 + 1.599 \cdot 10^{14} s^2 + 3.437 \cdot 10^{17} s + 4.314 \cdot 10^{22}}{s^4 + 2.193 \cdot 10^7 s^3 + 5.828 \cdot 10^{13} s^2 + 3.045 \cdot 10^{18} s + 5.737 \cdot 10^{19}} \quad (3-12)$$

The inverse weighting functions and the control functions $S$, $T$ and $K_S$ are shown in Figure 3-18. It can be seen that the requirement for the sensitivity $S$ is not exactly met, because
Figure 3-18: Bode magnitude plot of $S$ (red line, solid), $T$ (blue line, solid), $KS$ (green line, solid) and their respective inverse weighting functions $1/W_e$ (red line, dashed), $1/W_x$ (blue line, dashed), $1/W_u$ (green line, dashed).

Figure 3-19: H-infinity controlled system. Tracking and disturbance response for a step.
the sensitivity $S$ exceeds the inverse weighting function $1/W_e$ for low frequencies. However, the disturbance rejection for a step looks good as shown in Figure 3-19(b). The tracking response for a step is shown in Figure 3-19(a).

When using the $H_\infty$ controller, the complementary sensitivity changes according to Eq. (3-13).

$$T(s) = \frac{x}{r} = \frac{G_x(s)K_{H_\infty}(s)}{1 + G_x(s)K_{H_\infty}(s)}$$ (3-13)

The resulting complementary sensitivity is shown in Figure 3-20 (blue line, solid) and compared with the PI-controlled system with the notch filter (red line, dashed). The gain margin is 3127 [dB] and the phase margin is 74.0 [deg]. Recall that for the PI-controlled system with the notch filter, the resulting gain margin is infinite and the phase margin is 82.4 [deg].

It can be seen in Figure 3-20 (blue line, solid) that the resulting bandwidth is 3 [kHz]. This is larger than the bandwidth for the PI-controlled system with the notch filter, which was only 1.9 [kHz].

The step response of the complementary sensitivity is given in Figure 3-21 (blue line, solid). It can be seen that the reference step height is reached within approximately 0.00025 [s]. This is 4 times faster than the settling time of the PI-controlled system with the notch filter, which was 0.001 [s].

The tracking error in response to a triangular reference signal with a frequency of 50 [Hz] is shown in Figure 3-22. It can be seen that the control error reaches a maximum absolute value of 0.015 [a.u.] for this specific reference signal. Recall that for the PI-controlled system with the notch filter, the control error reaches a value of 0.027 [a.u.] for the same reference signal. Thus, the $H_\infty$ controller enables an even smaller control error.

### 3-1-6 Smoothing the Reference Signal

In Section 3-1-3 the time-domain tuning for the PI controller was mainly done to obtain good tracking performance for a reference step signal. In most AFMs a triangular reference signal is
Figure 3-21: Step response of the complementary sensitivity for the H-infinity controlled system (blue line, solid) and for the PI-controlled system with the notch filter (red line, dashed).

Figure 3-22: H-infinity controlled system. Difference between triangular reference signal and simulated output. The frequency of the triangular reference signal is 50 [Hz]. Top: triangular reference signal (black line, solid) and simulated output (blue line, solid). Bottom: tracking error.
used. For demonstration purposes, now the controller is tuned to track a triangular reference signal and the step response is ignored. This enables an increase of the controller gains to $K_p = 0.5$, $K_i = 2100$. The tracking performance for an 80 [Hz] triangular reference signal is shown in Figure 3-23(a). The sharp turnaround points in the reference signal limit the achievable control bandwidth, because they contain higher frequencies which can excite the mechanical resonances of the scanner, resulting in unwanted oscillations. To smoothen the turn-around points, a rounded triangular reference signal $r(t)$ is constructed using a Fourier series expansion with a limited order $n$ according to Eq. (3-14).

$$r(t) = \frac{8}{\pi^2} \sum_{i=1,3,5,..}^{n} \frac{(-1)^{(i-1)/2}}{i^2} \sin \left( \frac{i\pi t}{0.5T} \right)$$ (3-14)

where $T$ is the period of the reference signal.

The result is shown in Figure 3-23(b). The Fourier expansion is limited to $n = 11$. It can be seen that using the smoothed reference signal results in less oscillations. The maximum value of the tracking error is approximately the same as before.

### 3-1-7 Low-Pass Filter in Feedback Path

It is desired that the new AFM system is compatible with an old AFM head. Therefore a low-pass filter $K_{lp, fb}$ is added in the feedback path. In this section the effect of adding the low pass filter to the standard PI controlled system will be investigated. The resulting control diagram is shown in Figure 3-24.

The low-pass filter $K_{lp, fb}$ is given in Eq. (3-15).

$$K_{lp, fb}(s) = \frac{2\pi f}{s + 2\pi f}$$ (3-15)

Where $f$ is the cutoff frequency of the low-pass filter, given in [Hz]. In the current AFM system the cutoff frequency is set to $f = 160$ [Hz]. The effect of adjusting the cutoff frequency will be considered in this section.

When adding the low-pass filter, the complementary sensitivity from Eq. (3-3) changes according to Eq. (3-16).

$$T(s) = \frac{x}{r} = \frac{G_x(s)K_{PI}(s)}{1 + K_{lp, fb}(s)G_x(s)K_{PI}(s)}$$ (3-16)

In Eq. (3-16) it can be seen that the loop gain is now $L(s) = K_{LP}(s)G_x(s)K_{PI}(s)$. Using the loop gain, the gain margin and phase margin can be derived again.

First the cutoff frequency is set to $f = 160$ [Hz]. The controller gains are kept the same as for the PI-controlled system without the low-pass filter in the feedback path. Thus, $K_p = 0$, $K_i = 320$.

The resulting gain margin is 182 [dB] and the phase margin is 72.7 [deg]. Recall that for the PI-controlled system without the low-pass filter, the resulting gain margin is 18 [dB] and the phase margin is 88.9 [deg].
(a) Top: triangular reference signal (black line, solid) and simulated output (blue line, solid). Bottom: tracking error.

(b) Top: smoothed triangular reference signal (black line, solid) and simulated output (blue line, solid). Bottom: tracking error.

**Figure 3-23**: Effect of smoothing the triangular reference signal for the PI-controlled system. Difference between (a) triangular and (b) smoothed triangular reference signal. The frequency of the reference signal is 80 [Hz]. $K_p = 0.5$, $K_i = 2100$.

**Figure 3-24**: Control diagram for the PI-controlled X scanner with the low-pass filter in the feedback path. The controller is represented by $K_{PI}$ and the X scanner by $G_x$. The low-pass filter is represented by $K_{lp,fb}$. The input of the feedback system is a reference $r$ and the output is a displacement $x$. 

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It can be seen in Figure 3-25 (red line, dashed) that the resulting bandwidth is approximately 50 [Hz], which is the same as for the PI-controlled system without the low-pass filter in the feedback path.

![Figure 3-25: Frequency response of the complementary sensitivity for the PI-controlled system (blue line, solid) and for the PI-controlled system with the low-pass filter in the feedback path (red line, dashed).](image)

The step response of the complementary sensitivity is shown in Figure 3-26 (red line, dashed). It can be seen that the reference step height is reached within approximately 0.008 [s]. This is two times as fast as the settling time for the PI-controlled system without the low-pass filter in the feedback path, which was 0.015 [s].

![Figure 3-26: Step response of the complementary sensitivity for the PI-controlled system (blue line, solid) and for the PI-controlled system with the low-pass filter in the feedback path (red line, dashed).](image)

The tracking error in response to a 10 [Hz] triangular reference signal is shown in Figure 3-27. It can be seen that the control error reaches a maximum absolute value of 0.12 [a.u.] for this specific reference signal, which is the same as for the PI-controlled system without the low-pass filter in the feedback path.
low-pass filter in the feedback path.

Figure 3-27: PI-controlled system with the low-pass filter in the feedback path. Difference between triangular reference signal and simulated output. The frequency of the triangular reference signal is 10 [Hz]. Top: triangular reference signal (black line, solid) and simulated output (blue line, solid). Bottom: tracking error.

Adjusting the Cutoff Frequency

The effects of adjusting the cutoff frequency of the low-pass filter in the feedback path are presented in Table 3-4. The corresponding simulation results for a 50 [Hz] triangular reference signal are shown in Figure 3-28. If moderate time delay and moderate error are considered equally important, a cutoff frequency of 160 or 180 [Hz] gives the best tradeoff.

<table>
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<th>frequency [Hz]</th>
<th>time delay [ms]</th>
<th>error [a.u.]</th>
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<tr>
<td>120</td>
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<tr>
<td>140</td>
<td>1.78</td>
<td>±0.64</td>
</tr>
<tr>
<td>160</td>
<td>1.79</td>
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</tr>
<tr>
<td>180</td>
<td>1.81</td>
<td>±0.62</td>
</tr>
<tr>
<td>200</td>
<td>1.82</td>
<td>±0.61</td>
</tr>
<tr>
<td>400</td>
<td>1.84</td>
<td>±0.59</td>
</tr>
</tbody>
</table>

Table 3-4: Time delay and control error for different cutoff frequencies.

3-1-8 Summary of Control Methods

In Table 3-5 a comparison between the different control systems is shown based on the speed of the triangular reference signal, the tracking error, and the system bandwidth. Note that the PI-controlled system with the low pass filter in the feedback path is not included in the table.
3-1 Control for the X Scanner

Figure 3-28: PI-controlled system with the low-pass filter, for different cutoff frequencies of the low-pass filter. The frequency of the triangular reference signal is 50 [Hz]. Top: triangular reference signal (black line, solid) and simulated outputs. Bottom: tracking error (absolute value). Frequencies [Hz]: 120 (blue line, solid), 140 (red line, dashed), 160 (green line, dash-dotted), 180 (black line, dotted), 200 (magenta line, solid), 400 (yellow line, dashed).

<table>
<thead>
<tr>
<th>System</th>
<th>Reference speed (triangular signal) [Hz]</th>
<th>Tracking error [a.u.]</th>
<th>Bandwidth [Hz]</th>
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<tr>
<td>PI Control</td>
<td>10</td>
<td>0.12</td>
<td>50</td>
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<td>PI Control with low-pass filter in forward path</td>
<td>10</td>
<td>0.05</td>
<td>140</td>
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<tr>
<td>Model Based Control</td>
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<td>0.027</td>
<td>1900</td>
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<tr>
<td>$H_{\infty}$ Control</td>
<td>50</td>
<td>0.015</td>
<td>3000</td>
</tr>
</tbody>
</table>

Table 3-5: Performance for different control systems.

3-1-9 Implementation

In this section it is described how to implement a controller on the available hardware. The notch filter that was simulated in Section 3-1-4 will be used as an example. The continuous transfer function which represents the notch filter is first converted to digital format to be able to implement it on the Digital Signal Processor (DSP), using a sample time of 6 [µs]. This is done using MATLAB (Mathworks, Natick, MA, USA). To enable implementation on the DSP, the discretized transfer function is represented in Infinite Impulse Response (IIR) format given in Eq. (3-17).

$$K_{F,\text{disc}}(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$  (3-17)

where the used values are given in Table 3-6.
Stability of the discrete-time causal filter is guaranteed when the poles of its transfer function fall inside the unit circle of the complex z-plane. In Figure 3-29 it can be seen that the IIR filter has two poles at 0.9062 and a pair of complex zeros at 0.9888±0.0976i, which means the filter is stable. Furthermore, the discrete-time filter is minimum-phase because its zeros fall inside the unit circle in the complex z-plane. Before implementation, stability of the IIR filter is also verified by feeding through band-limited white noise in the simulation. The discrete-time filter is converted to 4-byte floating point format to be able to add it to the C-code on the DSP.

Due to limited hardware availability the filter could not be implemented on a real setup. Therefore no experimental results are available.

### 3-2 Characterization for the Y Scanner

For the lateral scanning motion in AFM there used to be a distinction between the slow axis - denoted as Y scanner - and the fast axis - denoted as X scanner. Using the parallel scanner design as shown in Figure 3-1 the Y scanner should be able to achieve the same speed as the X scanner. The same control methods that were used for the X scanner can be applied to improve the speed of the Y scanner. This enables full image rotation. Because the applied

<table>
<thead>
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<td>$b_0$</td>
<td>0.9134</td>
</tr>
<tr>
<td>$b_1$</td>
<td>-1.806</td>
</tr>
<tr>
<td>$b_2$</td>
<td>0.9018</td>
</tr>
</tbody>
</table>

Table 3-6: Parameter values for IIR filter.
control methods would be the same as the ones showed before, in the next section only a system identification is done for the Y scanner.

### 3-2-1 System Identification

An identification experiment is carried out to characterize the Y scanner, represented by $G_y$.

- the input voltage is a sinusoidal sweep signal. The input voltage comes from a voltage amplifier and is used to excite the Y piezo stack.
- the output voltage is coming from a strain gauge displacement sensor, which is glued onto the flexures.

The response data for the Y scanner is collected for 512 equidistantly spaced frequency points between 0 and 8 [kHz]. The results are shown in Figure 3-3. Some low frequency phase lead below 20 [Hz] is caused by the AC coupling characteristics of the measurement equipment (Nanoscope), which attenuates the response for low frequencies. For the identified model (Figure 3-30), this low frequency artifact due to the measurement equipment is not taken into account. In the frequency response data a resonance can be seen around 2614 [Hz]. By manual placement of a complex pole pair and a first-order Padé approximation $R$ for a time delay of 50 [$\mu$s], a third order model is obtained as shown in Eq. (3-18).

$$G_y = K \cdot R \cdot \frac{1}{s^2 + 2\zeta \omega s + \omega^2} \quad (3-18)$$

where the values are given in Table 3-7.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>$2.7332 \cdot 10^8$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>2614 [Hz]</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>0.097</td>
</tr>
</tbody>
</table>

**Table 3-7**: Parameter values for identified model of Y scanner.

Comparing this to the X scanner, it can be seen that the resonance frequency is the same, but the damping is larger. This has to do with the way the cables are connected to the AFM head, which add extra damping in the Y direction.

### 3-3 Concluding Remarks

The simulation results for the X scanner show that with the use of model based control and $H_\infty$ control the scanning speed can be increased with a factor of 5 when compared to the PI-controlled system. At the same time the control error for the model based controlled case
and the $H_\infty$ controlled case are smaller with a factor of 4 and 8, respectively. The bandwidth for the PI-controlled system is 50 [Hz], which is much smaller than the bandwidth for the model based controlled system (1900 [Hz]) and the $H_\infty$ controlled system (3000 [Hz]). This means a bandwidth improvement with a factor of 38 and 60, respectively. However, further experiments must be carried out to validate the simulation results. The used control methods could also be used to improve the speed of the Y scanner, enabling full image rotation.
Chapter 4

Conclusions and Recommendations

In this final chapter a review of this MSc thesis project is given, together with some concluding remarks and future recommendations. The conclusions are presented in Section 4-1 and the recommendations in Section 4-2.

4-1 Conclusions

This thesis focuses on a new displacement sensor for the Z scanner, to enable a more accurate measurement of the sample topography. Furthermore a characterization of the vertical and lateral positioner of the AFM was carried out to identify their dynamic behavior. The dynamics of both positioners limit the overall speed of the AFM. To this end modern control methods are applied to improve the performance of the lateral positioner.

In most commercial AFMs the topography estimate is based on the control signal being sent to the vertical positioner to move it up or down. The vertical positioner consists of a piezo actuator which suffers from nonlinear behavior due to hysteresis and creep. Due to the nonlinearities, the ratio between the control signal and the resulting vertical displacement is not constant over the full positioning range of the piezo actuator. In current dynamic modes of AFM a large part of the piezo positioning range is used. Therefore, a more direct method to obtain the displacement of the vertical positioner is desired which enables a more accurate estimate for the sample topography.

In this thesis a displacement sensor was added to the Z scanner to enable a more accurate estimate for the sample topography. In Chapter 2 an analysis was done for two different configurations of the displacement sensor. The sensitivity variation of the sensor is the variation in measured step height when scanning a calibration sample, and is expressed as a percentage of the true step height. The resulting displacement sensor shows a sensitivity variation over the full displacement range of the Z scanner of 6% when scanning a calibration sample. This is lower than the sensitivity variation obtained from the control signal, which is 35%. Hence, the displacement sensor enables a more accurate estimate for the sample topography.
In Chapter 3 a characterization was done for the X scanner and the Y scanner. Furthermore, modern control methods are applied to improve the performance of the X scanner. The simulation results for the X scanner show that with the use of model based control and $H_\infty$ control the scanning speed can be increased with a factor of 5 when compared to the standard PI controlled system. At the same time the control error for the model based controlled system and the $H_\infty$ controlled system becomes smaller with a factor of 4 and 8, respectively. The bandwidth for the PI controlled system is only 50 [Hz], which is much smaller than the bandwidth for the model based controlled system (1900 [Hz]) and the $H_\infty$ controlled system (3000 [Hz]). This means a bandwidth improvement with a factor of 38 and 60, respectively. However, further experiments must be carried out to validate the simulation results.

4-2 Recommendations

Experiments on a real setup need to be carried out to validate the simulation results for the X scanner. The same methods applied to the X scanner can be used for the Y scanner, such that the speed of both axes can be improved. This enables full image rotation. Furthermore noise measurements should be done for the lateral positioner to inspect the noise acting on the strain gages. The strain gage sensor noise could not be measured on the available AFM system due to a too low bit resolution for the X and Y scanner.

In the new AFM it is desired that the movement of the cantilever base is exactly known. In the AFM the movement in the X and Y direction are measured on the X and Y piezo stack actuators and not at the position where the cantilever base is located on the Z scanner. Because the sensors which measure the lateral movement are not collocated with the position of interest, the dynamics of parts in-between may distort the measurement. This should be considered when the overall performance of the new AFM is assessed.

There are also different sensor types available to measure the displacement, for example capacitive or optical sensors. These sensors may outperform the strain gage sensors, as was shown for optical sensors in [43].
Appendix A

Characterization for Vertical Positioner

The dynamics of the vertical positioner - also denoted as the Z scanner - affect the performance of the AFM. In Section A-1 a system identification is carried out to characterize the Z scanner.

A-1 System Identification

The experimental setup used for the identification of the Z scanner dynamics is schematically depicted in Figure A-1. The used laser Doppler vibrometer system (MSV-400, Polytec GmbH, Waldbronn, Germany) consists of a laser Doppler vibrometer, an internal signal generator and a data acquisition system. The Z scanner is sitting on a large lump mass which is air damped to suppress noise from the surroundings.

- the input signal is coming from the signal generator and is amplified by a custom made high voltage amplifier.
- the output signal is coming from the laser Doppler vibrometer.

The input and output signals are captured using the data acquisition system. The bandwidth of the custom made high voltage amplifier is 100 [kHz] which is large enough to excite the relevant Z scanner dynamics.

![Figure A-1: Experimental setup used for the identification of the Z scanner dynamics, represented by $G_z$. The input signal and the output signal are captured using a data acquisition system.](image-url)
The response data for the Z scanner is collected for 3200 equidistantly spaced frequency points between 0 and 100 [kHz]. The results are shown in Figure A-2. By manual placement of complex pole and zero pairs, a sixth order model is obtained as

$$G_z = K \cdot \prod_{i=1}^{2} \frac{s^2 + 2\zeta z_i \omega z_i s + \omega z_i^2}{\prod_{j=1}^{3} s^2 + 2\zeta p_j \omega p_i s + \omega p_i^2}$$  \hspace{1cm} (A-1)$$

where the used values are given in Table A-1.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>$2.0184 \cdot 10^{11}$</td>
</tr>
<tr>
<td>$\omega_{p1}$</td>
<td>47060 [Hz]</td>
</tr>
<tr>
<td>$\omega_{p2}$</td>
<td>70780 [Hz]</td>
</tr>
<tr>
<td>$\omega_{p3}$</td>
<td>81310 [Hz]</td>
</tr>
<tr>
<td>$\omega_{z1}$</td>
<td>50660 [Hz]</td>
</tr>
<tr>
<td>$\omega_{z2}$</td>
<td>74690 [Hz]</td>
</tr>
<tr>
<td>$\zeta_{p1}$</td>
<td>0.015</td>
</tr>
<tr>
<td>$\zeta_{p2}$</td>
<td>0.03</td>
</tr>
<tr>
<td>$\zeta_{p3}$</td>
<td>0.015</td>
</tr>
<tr>
<td>$\zeta_{z1}$</td>
<td>0.02</td>
</tr>
<tr>
<td>$\zeta_{z2}$</td>
<td>0.035</td>
</tr>
</tbody>
</table>

**Table A-1**: Parameter values for identified model of Z scanner.

**Figure A-2**: Measured data (black line, dashed) and model fit $G_z$ (blue line, solid).

A-2  Concluding Remarks

In this chapter a system identification was carried out for the Z scanner, resulting in a sixth-order model which captures the main dynamics. In AFM it is desired to do fast measurement
of sample properties, requiring a high bandwidth for the controlled system. To avoid the
dynamics of the Z scanner deteriorating the measurements, modern control methods can be
used to improve the dynamics of the controlled system.
Peak Force Tapping (PFT) mode is a recently found new imaging mode (Veeco Instruments, Santa Barbara, CA, USA) [16][40]. The AFM that is used in this thesis is capable of imaging in PFT mode, where the Z piezoring is modulated with a 2 [kHz] sinusoid. During AFM operation in PFT mode a series of force curves is obtained while scanning the sample. The obtained force curves are used to obtain local stiffness, adhesion, and peak interaction force. Recall that in tapping mode the feedback operation is based on the tapping amplitude. In PFT mode however, the feedback operation is based on the peak interaction force, which is a more direct way of controlling the force and thus avoiding damage to tip and sample. The amplitude-based feedback that is used in tapping mode is in fact a way to control the average interaction force. This results in a resolution limitation when probing narrow deep trenches in tapping mode, where excessive damping of the tapping cantilever occurs.

In tapping mode, where the cantilever is oscillated at its resonance frequency (typically 300 [kHz] to 1 [MHz]) the main bottleneck to the scanning speed is that the cantilever is acting as a low-pass filter. The main resonance of the Z scanner for the AFM system used in this thesis is 47 [kHz]. In PFT mode the tip-sample interaction is modulated at a frequency of 2 [kHz], which is much lower. Because of this the cantilever and Z scanner dynamics are not the main bottleneck to the scanning speed.

The working principles of PFT are shown in Figure B-1 and are described next [16].

- In Figure B-1(a) it is shown what happens when the sinusoidally modulated tip is interacting with the sample surface. The top line (black, dashed) represents the Z-position of the modulation for one full cycle plotted as a function of time. The lower line (solid) represents the interaction force during the approach of the tip to the sample (blue) and when the tip moves away from the sample (red). Because the modulation frequency of the Z-position is 2 [kHz], the time from point A to E is 0.5 [ms].
  - When the tip is far from the sample the interaction force is almost zero (point A).
  - During the approach of the tip to the sample the tip is pulled down by attractive forces as represented by the negative force (point A to B).
As the attractive forces overcome the cantilever stiffness the tip is pulled onto the sample surface (point B).

The force then increases until the Z modulation reaches its bottom most point. This is where the peak force occurs (point C). The peak force is kept constant by the feedback operation of the system.

Next, the tip starts to withdraw from the surface and the force decreases until it reaches a minimum force. The adhesion is given by the force at this point (point D).

Once the tip is going further away from the surface, the interaction forces are almost zero (point E).

In Figure B-1(b) the force curve is plotted as a function of tip-sample distance. The distance is known from the deflection signal and the known modulation of the Z piezo. In old AFMs the position of the Z piezo is based on the control signal, however a more direct way is to use an additional displacement sensor which is implemented in the Z piezo. In this thesis such a displacement sensor was analyzed in Chapter 2. To enable quantitative measurements the system must be calibrated beforehand, either by comparing to a reference sample (relative method) or by measuring the tip end radius and the cantilever spring constant (absolute method).

The retract curve is used to calculate the modulus of elasticity using a Derjaguin-Muller-Toporov model [44].

The adhesion force is calculated as the minimum force in Figure B-1(b).

The energy dissipation can be calculated from the area between the approach and retract curves, shown in yellow in Figure B-1(b).

(a) Plot of force and piezo Z position as a function of time, including (B) jump-to-contact, (C) Peak Force, (D) Adhesion. (b) For fitting purposes it is more useful to plot Force vs. Separation where the separation is calculated from the Z piezo position and the cantilever deflection.

Figure B-1: Representation of PFT mode. Images adopted from [16].
In the new AFM system a displacement sensor is implemented to measure the vertical displacement of the piezoring. The signal coming from the displacement sensor is low pass filtered to suppress the influence of high frequency noise. The cutoff frequency is set to 18 [kHz], which means a $-3$ [dB] reduction in magnitude at that frequency. The current hardware is limited to a first order low pass filter. The Signal Processing Toolbox in simulation software MATLAB (Mathworks, Natick, MA, USA) is used to compute four different low pass filters designs. The Bode magnitude and phase plots for the filters for a desired cutoff frequency of 18 [kHz] are shown in Figure C-1.

- **First order.** The first order low pass filter has a rolloff of -20 [dB] per decade after the cutoff frequency and reaches $-90^\circ$ phase delay for high frequencies. The analog variant of this filter is given in Eq. (C-1).

- **Second order Butterworth.** The Butterworth filter has a very flat response, i.e. it shows no ripples in the magnitude plot. The roll-off is -40 [dB] per decade for high frequencies. The filter rolls of more more slowly around the cutoff frequency than the Chebyshev and Elliptical filters and reaches a phase delay of $-180^\circ$ for high frequencies. The analog variant of this filter is given in Eq. (C-2).

- **Second order Chebyshev (Type I).** The Chebyshev filter rolls off faster around the cutoff frequency than the Butterworth filter, but has a ripple in the passband. There is no ripple in the stopband. A phase delay of $-180^\circ$ is reached for high frequencies. The analog variant of this filter is given in Eq. (C-3).

- **Second order Elliptical.** The Elliptical filter has a faster transition in gain compared to the other filters, and the ripple in both the passband and the stopband can be independently specified. Unlike the other filters, this filter contains two zeros, resulting in a notch after the cutoff frequency. The analog variant of this filter is given in Eq. (C-4).
\[ H_{lp}(s) = \frac{2\pi \cdot 18 \cdot 10^3}{s + 2\pi \cdot 18 \cdot 10^3} \]  
\[ H_{butter}(s) = \frac{1.279 \cdot 10^{10}}{s^2 + 1.599 \cdot 10^8 s + 1.279 \cdot 10^{10}} \]  
\[ H_{Cheby}(s) = \frac{1.048 \cdot 10^{10}}{s^2 + 1.342 \cdot 10^8 s + 1.06 \cdot 10^{10}} \]  
\[ H(s) = \frac{0.01s^2 + 1.049 \cdot 10^{10}}{s^2 + 1.335 \cdot 10^5 s + 1.061 \cdot 10^{10}} \]

**Figure C-1:** Bode diagram for different low-pass filters for a desired cutoff frequency of 18 [kHz]. First order filter: single pole low pass filter (blue line, solid). Second order filters: Butterworth filter (red line, dashed), Type I Chebyshev filter (green line, dash-dotted), and Elliptical filter (magenta line, solid).
Analysis of Piezo Stack Actuator

In this chapter a selection has to be made between five different piezo stack actuators with a square footprint of 3 x 3 [mm] and a height of 2 [mm].

The following requirements should be met.

- vertical positioning range of 300 [nm] peak-to-peak amplitude
- minimal change in positioning range for frequencies from 1-8 [kHz]
- straight movement in the vertical direction without out-of-plane bending
- available drive voltage is 20 [V] peak-to-peak amplitude

D-1 First Test

In the first test five different piezo stack actuators are compared. The experimental setup is depicted in Figure D-1.

The following experiment is carried out.

- the piezo stack actuator is waxed onto a non-conducting polymer plate
- a sinusoidal voltage with a 20 [V] peak-to-peak amplitude is applied to the piezo stack actuator. The frequencies being tested are 1, 2, 4, 6, and 8 [kHz]. The applied voltage is coming from a custom-made high voltage amplifier (Veeco Instruments, Santa Barbara, CA, USA) and is inspected on an oscilloscope.
- for each frequency the resulting peak-to-peak amplitude of the vertical displacement is measured at the position on top of the piezo stack (indicated with the red circle in Figure D-1) using the vibrometer (MSV-400, Polytec GmbH, Waldbronn, Germany).
The results for each of the five piezo stack actuators are shown in Figure D-3. The reported displacements are given as peak-to-peak amplitudes. Based on the requirement for the positioning range only the *Noliac CMAP01* and the *PI* are analyzed further with a second test.

### D-2 Second Test

The *Noliac CMAP01* and the *PI* piezo stack actuator are analyzed further to inspect the movement in the lateral direction. The same experiment is carried out as before, but now the vibrometer also measures the peak-to-peak amplitude of the displacements in the X- and Y-direction. The positions where the measurements are taken are indicated with red circles in Figure D-1. Furthermore, the piezo stack is glued with Locktite E120 adhesive (Henkel AG, Düsseldorf, Germany) onto the base plate instead of using wax.

The results for the *Noliac CMAP01* and the *PI* piezo stack are shown in Figure D-3. It can be seen that the use of adhesive suppresses the vertical movement more than the use of wax.

### D-3 Third Test

It is found that adhesive spilling out underneath the piezo stack and covering part of the sides of the stack is restricting the piezo displacement [45]. Therefore, two blocks of plastic (poly methyl methacrylate) with a cavity in the middle are glued onto the piezostack as shown in Figure D-2. The cavity is filled with adhesive, resulting in a strong connection with the piezo stack with less adhesive spilling out on the edges. Reflective tape is put onto the upper block, such that the displacement in all three spatial directions can be measured using the vibrometer. The resulting vertical and in-plane displacements are measured at the locations indicated on the upper block and are shown in Figure D-3.
D-4 Concluding Remarks

In Figure D-3 it can be seen that the input voltage going into the piezo stack actuators is lower for higher frequencies. This is because the capacity of the piezo stack is loading the circuit, resulting in a smaller available voltage for the piezo displacement. The capacitance for the Noliac CMAP01 was measured and is 510 [nF], which is much larger than the capacitance of the PI, which is only 48 [nF]. Therefore, for the Noliac CMAP01 the loading effect is much larger. This can be seen from the large change in the available voltage for the displacement.
Figure D-3: The results for the first test (top), the second test (middle) and the third test (bottom). The displacements are given as peak-to-peak amplitudes.
Bibliography


Glossary

Acronyms and Abbreviations

AFM Atomic Force Microscope
DAQ Data Acquisition
DCSC Delft Center for Systems and Control
PFT Peak Force Tapping
PI Proportional-Integral

Symbols

e control error
$G_x, G_y, G_z$ X, Y, Z scanner dynamics
$K_{F,\text{disc}}$ discrete-time notch filter for controlled X scanner
$K_F$ notch filter for controlled X scanner
$K_{H,\infty}$ H-infinity controller
$K_{lp,\text{fb}}$ low-pass filter in feedback path of controlled X scanner
$K_{lp}$ low-pass filter in forward path of controlled X scanner
$K_{PID}$ Proportional-Integral-Derivative controller
$K_{PI}$ Proportional-Integral controller
$KS$ Control Sensitivity
$n$ sensor noise
$r$ reference signal
$S$ Sensitivity
$T$ Complementary Sensitivity
$W_e, W_u, W_x$ Weighting functions for H-infinity control