

Feedback Control of the Atomic Force Microscope

Micro-cantilever for Improved Imaging

by

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Dedicated to my wife Joanna.

Acknowledgments

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Declaration

The thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to the final version of my thesis being made available worldwide when deposited in the Universitys Digital Repository, subject to the provisions of the Copyright Act 1968.

Matthew W. Fairbairn

January, 2013

List of Publications and Awards

During the course of this research a number of papers have been submitted to international journals and conferences. The following is a list of those articles which have been published in international journals or accepted for publication, as well as a list of conference papers which have been presented or accepted for presentation. A number of conference papers were recognized by awards, as indicated.

Journal Articles

1. *Q-Control of an Atomic Force Microscope Micro-cantilever: A Sensor-less Approach*
M. W. Fairbairn, S. O. R. Moheimani, A. J. Fleming
IEEE/ASME Journal of Microelectromechanical Systems
Volume 20, Number 6, page 1372-1381, 2011
2. *Resonant Control of an Atomic Force Microscope Micro-cantilever for Active Q Control*
M. W. Fairbairn, S. O. R. Moheimani
Review of Scientific Instruments
Volume 83, Number 8, page 083708-083717, 2012
3. *A Switched Gain Resonant Controller to Minimize Image Artifacts in Intermittent Contact Mode Atomic Force Microscopy*
M. W. Fairbairn, S. O. R. Moheimani

IEEE Transactions on Nanotechnology

Volume 11, Number 6, page 1126-1134, 2012

4. *Control Techniques for Increasing the Scan Speed and Minimizing Image Artifacts in Tapping Mode Atomic Force Microscopy*

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5. *Sensorless Enhancement of an Atomic Force Microscope Micro-cantilever Quality Factor Using Piezoelectric Shunt Control*

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Conference Proceedings

1. *Passive Piezoelectric Shunt Control of an Atomic Force Microscope Micro-cantilever*

M. Fairbairn, S. O. R. Moheimani, A. J. Fleming

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July 3-7, 2011

2. *Improving the Scan Rate and Image Quality in Tapping Mode Atomic Force Microscopy with Piezoelectric Shunt Control*

M. W. Fairbairn, S. O. R. Moheimani, A. J. Fleming

Proc. Australian Control Conference, page 26–31

November 10-11, 2011

3. *Quality Factor Enhancement of an Atomic Force Microscope Micro-cantilever Using Piezoelectric Shunt Control*

M. W. Fairbairn, S. O. R. Moheimani

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4. *Minimizing Probe Loss in Tapping Mode Atomic Force Microscopy Using a Switched Gain Resonant Controller*

M. W. Fairbairn, S. O. R. Moheimani

Proc. Australian Control Conference

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5. *A New Approach to Active Q Control of an Atomic Force Microscope Micro-cantilever Operating in Tapping Mode*

M. W. Fairbairn, S. O. R. Moheimani

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Awards

1. Winner of best student paper award.
Australian Control Conference. 2011.
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Abstract

The Atomic Force Microscope (AFM) is a mechanical microscope capable of producing three-dimensional images of a wide variety of sample surfaces with nanometer precision in air, vacuum, or liquid environments. Tapping mode Atomic Force Microscopy has become a popular mode of operation due to the reduced lateral forces between the probe and sample compared to other modes of AFM operation.

The reliance on feedback control and the complex dynamics associated with this device have made it an interesting topic of research for control systems engineers over the past two and a half decades. Despite the amount of research which has been undertaken to improve the operation of this instrument there is still more room for improvement. The ideas presented in this work provide solutions to several problems associated with imaging in tapping mode with the AFM. These new tools, combined with those of other researchers, are providing scientists with an instrument which can image faster with improved image quality than its predecessors.

When operating an AFM in tapping mode the quality (Q) factor of the cantilever probe places a limitation on scan speed and image quality/resolution. A low Q factor cantilever is required for high scan speeds, whereas a high Q factor cantilever is required for high resolution and to minimize image distortion when scanning soft samples.

One other limitation to scan speed is the ability of the cantilever to track the sample after a large steep downward step in sample topography is encountered. As the

scan speed is increased the likelihood of artifacts appearing in the image is increased due to the probe tip losing contact with the sample.

This work introduces new methods of controlling the Q factor of an AFM micro-cantilever to improve the scan speed and image quality of the AFM operating in tapping mode.

Active Q control, which is based on velocity feedback, is commonly used to modify the effective Q factor of the AFM micro-cantilever to achieve optimal scan speed and image resolution for the imaging environment and sample type. Time delay of the cantilever displacement signal is the most common method of cantilever velocity estimation. Spill-over effects from unmodeled cantilever dynamics may degrade the closed-loop system performance, possibly resulting in system instability, when time delay velocity estimation is used. A resonant controller is proposed in this work as an alternate method of velocity estimation. This new controller has guaranteed closed-loop stability, is easy to tune and may be fitted into existing commercial AFMs with minimal modification. Significant improvements in AFM image quality are demonstrated using this control method.

The feedback signal in the active Q control feedback loop comes from an optical sensor which produces a significant amount of measurement noise. Piezoelectric shunt control is introduced as a new method of controlling the Q factor of a piezoelectric self actuating AFM micro-cantilever. The use of this control technique removes the noisy optical sensor from the Q control feedback loop. The mechanical damping of the micro-cantilever is controlled by placing an electrical impedance in series with the tip oscillation circuit. Like the resonant controller the closed-loop stability of this controller, in the presence of unmodeled cantilever dynamics, is guaranteed. A passive impedance is used to reduce the cantilever Q factor to improve the scan speed when imaging hard sample surfaces in air. An active impedance is used to increase the cantilever Q factor for improved image quality when imaging soft samples, samples with fine features or samples immersed in a fluid. A synthetic impedance

was designed to allow easy modification of the control parameters, which may vary with environmental conditions, and to implement the active impedance necessary for cantilever Q factor enhancement.

The switched gain resonant controller is presented as a new method of improving the ability of the cantilever to track the sample when imaging at high speed. The switched gain resonant controller is implemented to switch the cantilever Q factor according to the sample profile during the scan. If the controller detects that the probe tip has lost contact with the sample the cantilever Q factor is increased leading to a faster response of the feedback controller, expediting the resumption of contact. A significant reduction in image artifacts due to probe loss is observed when this control technique is employed at high scan speeds.

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Chapter 1

Introduction

1.1 The Atomic Force Microscope

The Atomic Force Microscope (AFM) [1] evolved from the Scanning Tunneling Microscope (STM) [2], a device which earned its inventors the 1986 Nobel prize in physics for its ability to image conductive surfaces with unprecedented resolution. The STM measures variations in tunneling current which flows from a sharp probe tip onto a conductive sample surface through a vacuum gap as the sample is scanned below the tip. The tunneling current has an exponential dependence on tip-sample separation making it highly sensitive to variations in sample height. A feedback controller regulates the sample height to maintain the tunneling current at a set-point value and a three-dimensional image is produced through measurement of the controller signal.

The desire for an instrument with the resolution of the STM and the ability to image non-conductive samples in air, various gases, liquid or vacuum led to the invention of the AFM in 1986. Rather than measuring tunneling current, the AFM obtains images of a sample by recording the variation in force between a sharp probe tip, located on the underside of a micro-cantilever, and the sample surface. As the sample is

scanned underneath the cantilever the variations in tip-sample force are proportional to variations in sample topography. A three-dimensional image of the sample surface is obtained by plotting the measured force as a function of the lateral scan position. Unlike the STM, the AFM is not restricted to imaging conductive or semiconductive samples in a vacuum environment which has opened up doors to explore a wide variety of samples with resolutions previously unattainable. Images of the atomic structure of materials such as mica [3], silicon [4] and graphite [5] have been recorded with the AFM. The ability of the AFM to image samples with minimal preparation in liquid environments has made it a particularly attractive tool for imaging biological samples [6, 7]. The most widely used application of the AFM is high resolution imaging, however adaptations of the AFM may be used to measure chemical [8], magnetic [9], electrical [10] and material properties [11]. Other non-imaging applications of the AFM include probe based data storage [12], nanolithography [13, 14] and manipulation of single atoms and molecules [15].

The vertical resolution of the AFM is in the order of 0.01 nm with a lateral resolution of up to 0.1 nm [16]. This is significantly higher than that of optical microscopes which are limited in resolution by the wavelength of visible light, which is approximately 400 - 700 nm. The high image resolution of the AFM is attributed to the size of the probe tip (which may be only a few atoms wide), the high force sensitivity of the cantilever and the high positioning resolution of the scanner.

While the high resolution and versatility of the AFM has made it a vital tool for imaging and characterizing sample surfaces in a variety of fields such as biology, chemistry, materials science and the electronics industry, the relatively slow scan speed of the instrument has limited its potential. In many imaging applications it is desirable to increase the scan speed to increase productivity. One such application is characterization and defect detection of electronic grade silicon devices [17, 18]. As the size of electronic devices such as integrated circuits is decreasing at a rapid rate the AFM has emerged as one of the few instruments capable of imaging these

devices at the desired resolution without the risk of damaging the sample. The ability of the AFM to image biological samples in any environment with resolutions far higher than those obtained by optical microscopes has created significant interest in obtaining AFM images at video rates [19]. Dynamic biological processes [20] occur in the range of milliseconds. Commercially available AFMs are too slow to observe such processes as they may take up to a minute to image one frame of a biological sample. Dynamic biological processes such as protein synthesis [21] and DNA replication [22] have been observed with custom-built AFMs. For the full potential of the AFM to be realized, further improvements in image speed need to be achieved leading to increased productivity and new scientific discoveries.

The reliance on feedback control within the AFM to produce an accurate image of the sample provides several interesting challenges for control engineers in achieving higher scan speeds with minimal imaging artifacts.

1.2 Modes of AFM Operation

The three most common imaging modes in which the AFM may be operated are contact mode [23], non-contact mode [24] and tapping mode (also termed intermittent contact, semi-contact or AC mode) [25, 26]. Each of these modes differ in the way that the tip interacts with the sample during a scan.

The force between the tip and the sample (used as a measure of sample height) may be predominantly attractive or repulsive [27], varying as a function of the tip-sample separation distance, as illustrated in Fig. 1.1. Repulsive forces are dominant when the tip-sample separation is very small (< 1 nm). As the tip-sample separation is increased the attractive force becomes dominant. The tip-sample separation distance may be increased to several tens of nanometers before the interaction force becomes negligible.

When imaging in contact mode the tip is brought close enough to the sample so

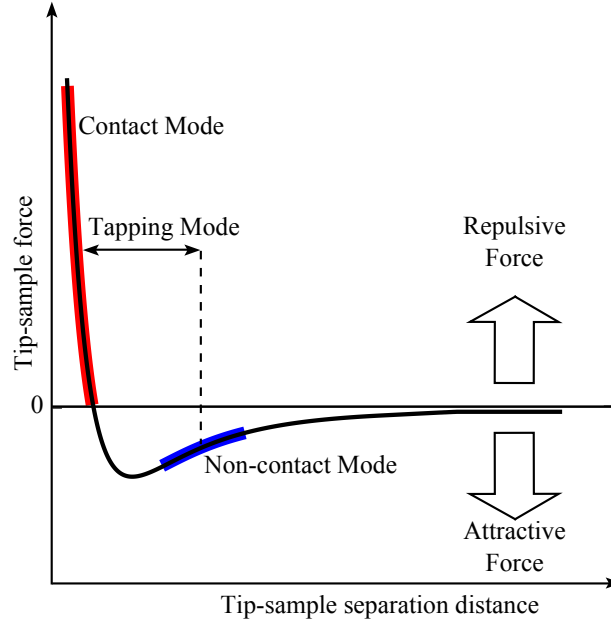


Figure 1.1: Tip-sample force versus tip-sample separation distance. The tip-sample separation distance for the three main modes of AFM operation are shown on the curve. As the tip first approaches the sample attractive forces dominate. When the tip gets closer to the surface repulsive forces dominate.

that the force between the tip and the sample is repulsive, causing the cantilever to deflect away from the sample. The amount of deflection in the cantilever is proportional to the sample height as the sample is scanned underneath the probe. Cantilevers with low stiffness ($< 1 \text{ N/m}$) must be used when operating in contact mode to ensure a sufficient signal to noise ratio (SNR) and minimize tip-sample force.

The contact force between the sample and probe tip is held constant by measuring the static deflection of the cantilever and comparing it with a set-point value to produce an error signal. A feedback controller regulates the cantilever deflection/force by controlling the vertical height of the sample holder according to the error signal. The output of the controller is proportional to the sample height during scanning and provides a good representation of the sample topography as the sample is scanned below the cantilever.

Measurements of sample topography obtained with contact mode imaging occur at

low frequency. These measurements are affected by $1/f$ noise [28] which significantly reduces the SNR.

Continuous lateral force on the sample from the probe tip [29, 30] may lead to excessive wearing of the probe tip, image distortion, damage to soft delicate samples and displacement of particles which are weakly attached to a substrate. The dynamic modes of operation, non-contact mode and tapping mode, were developed to reduce these lateral forces between the probe tip and the sample and increase the SNR of the measured signal.

Non-contact and tapping modes measure the dynamic behavior of the cantilever as it is oscillated at or close to its first resonance frequency. Variations in tip-sample force result in a shift of the cantilever resonance, as illustrated in Fig. 1.2. This shift in resonance is proportional to variations in sample height and may be measured by monitoring the change in cantilever resonance frequency, tip oscillation amplitude or the phase difference between the actuation signal and the tip oscillation.

When operating in non-contact mode the cantilever is oscillated (with an amplitude typically in the order of 1-10 nm) above the sample surface never touching it. The cantilever is oscillating under the influence of attractive forces which reduce the effective cantilever spring constant, resulting in a reduction of the cantilever resonance frequency as shown in Fig. 1.2. Variations in the resonance frequency, oscillation amplitude or phase are measured and the feedback control loop operates on the vertical positioning of the sample, similar to the operation in contact mode, to maintain this measured value at a set-point and produce an image of the sample.

The main advantage of operating in non-contact mode is that there is little force exerted on the sample surface, avoiding sample distortion and damage to the sample and tip.

When exposed to ambient conditions most samples are coated with a thin layer of water which may be several nanometers in thickness, dependent on the relative humidity. Non-contact mode requires that the tip must be kept close enough to the

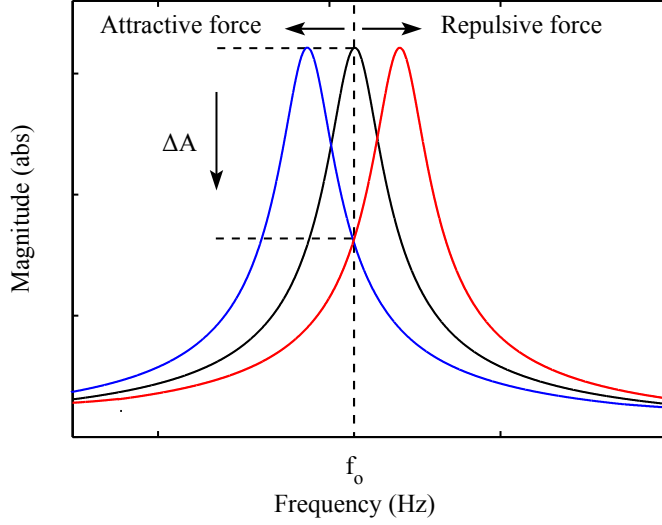


Figure 1.2: Resonance shift of an oscillating cantilever as a result of a change in tip-sample force. Prior to placing the cantilever in close proximity or intermittent contact with the sample the cantilever is oscillated at f_o which is equal or close to its resonance frequency. The resonance curve shown in black is the cantilever resonance with no tip-sample interaction. Interactions with the sample cause a change in the effective stiffness of the cantilever resulting in a shift of the resonance curve. This leads to a change in the cantilever oscillation amplitude ΔA which is proportional to changes in the sample height. The influence of an attractive force results in a decrease in the effective stiffness of the cantilever which causes the resonance curve to shift to the left. The influence of a repulsive force has the opposite effect shifting the resonance curve to the right.

sample for inter-atomic forces to be detectable, but far enough from the sample to avoid the tip from becoming stuck in the fluid layer due to the strong adhesive capillary forces. A slower scan speed must be used for this reason. The aforementioned problems have limited the widespread use of non-contact imaging mode. This AFM mode of operation is a viable option when operating in an ultra-high vacuum environment as the adsorbed fluid layer is reduced in these conditions. It is possible to obtain images with atomic resolution when imaging in an ultra-high vacuum environment [4].

Tapping mode combines the benefits of contact mode and non-contact mode by oscillating the cantilever close enough to the sample such that the probe tip intermittently contacts the sample once every oscillation cycle. This significantly decreases

the lateral forces associated with contact mode imaging, and the risk of the cantilever sticking to the sample due to capillary forces associated with non-contact mode. To ensure that the probe tip has enough energy to overcome the attractive capillary forces and avoid sticking to the sample when it comes in contact with the surface the tip oscillation amplitude is set higher than non-contact mode (10-100 nm [31]) and cantilevers with a high quality (Q) factor (50-1000) and spring constant (20 to 50 N/m) in air are used. The reduced lateral forces and the ability to image in liquid have made tapping mode popular for imaging soft biological samples [30,32,33] and samples which are held loosely to a substrate. It is also advantageous to image hard samples using tapping mode as lateral forces in contact mode may lead to excessive wearing of the tip. A worn tip leads to reduced lateral image resolution. One drawback of using tapping mode is that the imaging speed tends to be substantially slower than contact mode.

As the remainder of this thesis is focused on the performance of the AFM operating in tapping mode a more detailed description of this AFM imaging mode is presented in the following.

1.3 Tapping Mode Atomic Force Microscopy

Prior to bringing the cantilever into intermittent contact with the sample, the cantilever is oscillated at or near to its first flexural resonance frequency. When the probe tip is intermittently contacting the sample while scanning, variations in the sample height modify the force between the tip and the sample. The cantilever experiences both attractive and repulsive forces, however the average force experienced by the cantilever is repulsive. This repulsive force between the tip and sample alters the effective stiffness of the cantilever [25,34,35] causing its resonance to shift to the right as shown in Fig. 1.2. The effective cantilever Q factor decreases due to energy losses from the tip contact [35].

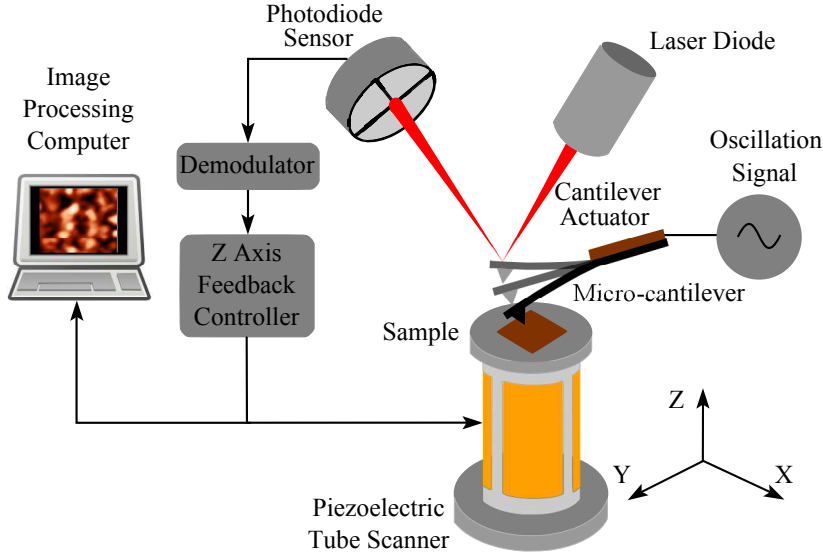


Figure 1.3: Schematic of the instrumentation of a typical AFM operating in tapping mode. The sample is scanned laterally in a raster pattern below the oscillating cantilever as the probe tip lightly taps the sample once every oscillation cycle. Cantilever deflection is measured by reflecting a laser beam off the top surface of the cantilever into a photodiode sensor. Movement of the reflected beam on the photodiode sensor is proportional to cantilever deflection. The signal from the photodiode sensor is passed through a demodulator to produce the probe tip oscillation amplitude. A feedback controller aims to maintain the oscillation amplitude at a set-point value by controlling the height of the sample stage. The output of the feedback controller, which is proportional to sample height, is mapped as a function of the lateral scan position by the image processing computer to produce a three-dimensional image of the sample.

Variations of the cantilever resonance and Q factor lead to variations in the tip oscillation amplitude $A(t)$. The cantilever oscillation amplitude is the most common measure of tip-sample force, rather than frequency or phase, when imaging with tapping mode AFM.

A schematic showing the typical instrumentation of an AFM operating in tapping mode is shown in Fig. 1.3. The main components are the micro-cantilever, the cantilever actuator, the deflection measurement system, the demodulator, the XYZ scanner and the Z axis feedback controller.

1.3.1 Micro-cantilever

The micro-cantilever body is usually rectangular in shape with a length of 50 - 400 μm , width of 5 - 10 μm and constructed from monocrystalline silicon (Si) or silicon nitride (Si_3N_4). Lateral resolution is dependent on the geometry of the probe tip which is located on the underside of the cantilever. A sharp tip with a radius of 1 - 10 nm [36] is required to ensure high lateral image resolution. Typical resonance frequencies are between 50-500 kHz with some ‘next generation’ cantilevers having a resonance frequency exceeding 1 MHz [37].

1.3.2 Cantilever Actuation

The cantilever tip is commonly oscillated by applying a sinusoidal voltage to a piezoelectric actuator positioned at the base of the cantilever. Other methods of actuation include electrostatic actuation [38], magnetic actuation [39] and coating the cantilever with piezoelectric material to act as a bimorph actuator [40].

1.3.3 Cantilever Deflection Measurement

Accurate measurement of cantilever tip displacement is fundamental for high resolution imaging. The optical lever method [41, 42] is the most common means of measuring cantilever displacement in commercial AFMs. A laser beam generated by a solid state diode is focused onto the surface of the cantilever and reflected onto a photodiode sensor. Many cantilevers are coated with gold on one side of the beam to increase reflectivity.

The photodiode sensor is a four quadrant detector whose output signal is fed to a differential amplifier. When the cantilever is in its equilibrium position the reflected laser spot is adjusted so that all photodiodes measure the same light intensity at this reference point. As the cantilever deflects, the angle at which the beam reflects off the cantilever changes resulting in the reflected laser spot shifting position on

the photodiode sensor. Differences in measured light intensity for each quadrant are measured to give an indication of laser movement on the photodiode sensor. The difference between the upper and lower photodiode signals is proportional to the normal deflection of the cantilever.

Cantilever tip displacement is magnified significantly by the length of the reflected light path. The optical lever measurement is sensitive enough to measure tip displacements in the order of sub-Ångstroms [41].

The simplicity of the optical lever method has made it the most popular means of measuring cantilever deflection despite the availability of other measurement techniques such as interferometric [43,44], piezoresistive [45,46], capacitive [47], thermal [46] and piezoelectric [40,48,49] sensors.

1.3.4 Demodulator

To regulate the tip-sample force and to produce an estimate of the sample topography the feedback controller requires the cantilever oscillation amplitude to be extracted from the cantilever displacement signal provided by the photodiode sensor. The two most commonly employed techniques to demodulate the displacement signal are the lock-in amplifier [50] and the RMS to DC converter [51,52].

1.3.5 XYZ Scanner

A piezoelectric scanner positions the probe or sample in the X , Y and Z directions. Piezoelectric materials expand or contract when a voltage is applied depending on the polarity of the applied voltage, or conversely, produce a voltage when the material is expanded or contracted [53]. Piezoelectric materials are ideal for building actuators with nanometer precision as high voltages correspond to very small changes in the width of the material.

It is most common for the sample holder to be fixed to the scanner, with the

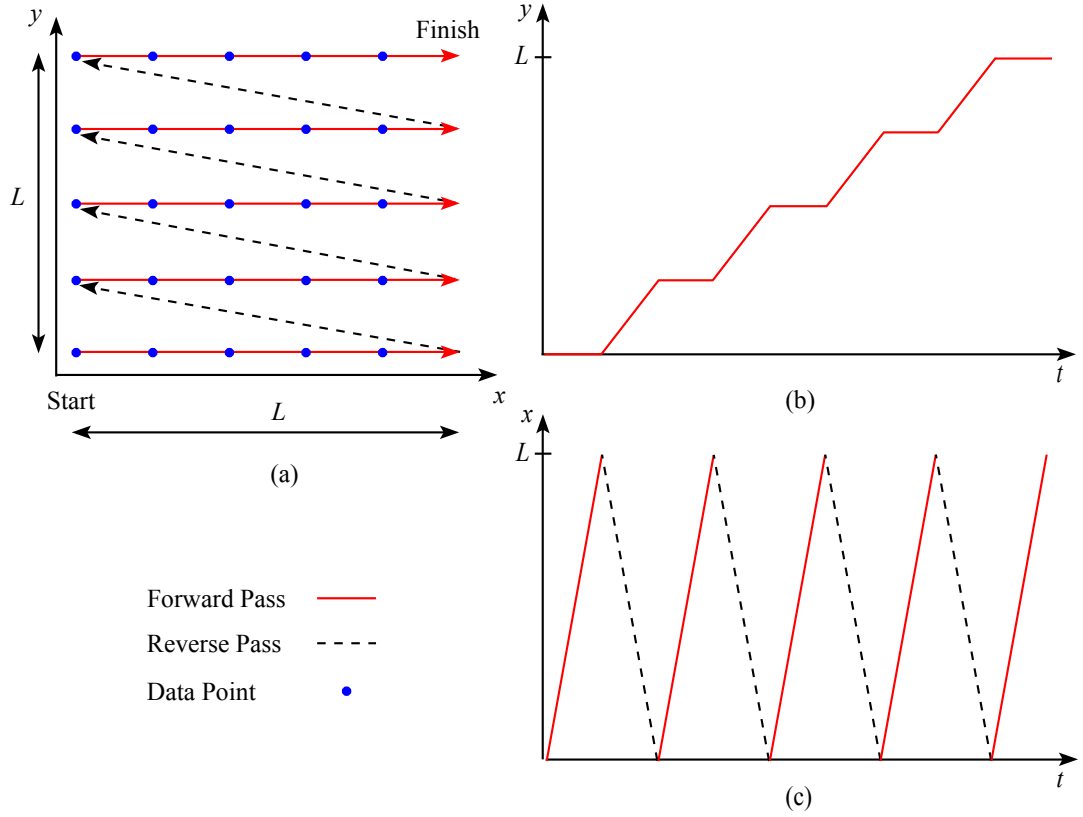


Figure 1.4: Development of the raster scan pattern. The raster scan pattern (a) is obtained by applying a pseudo-ramp signal (b) to the Y axis and a triangular signal (c) to the X axis of the scanner. The data points, represented by blue dots, are stored during the forward scan (shown in red).

sample scanned below the stationary probe. Systems which scan the probe require the deflection measurement instrumentation to be scanned with the probe, which may complicate the design.

Scanning in the lateral direction is typically in a raster pattern. To obtain a raster scan a triangular waveform is applied to the scanner in the X direction (the fast scan axis) and a pseudo-ramp signal is applied in the Y direction (the slow scan axis). This combination of signals results in the scan pattern illustrated in Fig. 1.4. The data points, which represent pixels of the image, are gathered on the forward scan (horizontal path).

The piezoelectric tube scanner [54], developed by Binnig and Smith in 1986 [55],

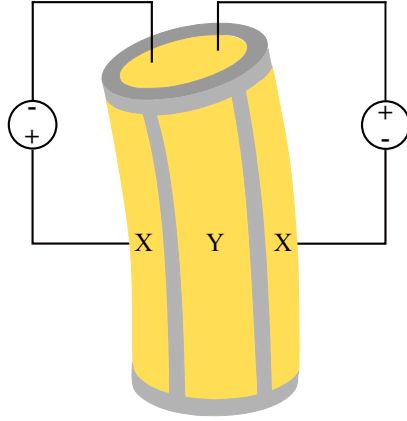


Figure 1.5: A typical piezoelectric tube scanner showing displacement in the X axis. A voltage applied to one of the X electrodes will cause the scanner to expand in that quadrant, tilting the scanner in that direction. An equal negative voltage applied to the opposite X electrode doubles the range in that direction.

is the most popular scanner used in current commercial AFMs. The tube scanner, shown in Fig. 1.5, consists of a tube of radially polarized piezoelectric material with an internal electrode and four equal sized and spaced external electrodes down the length of the tube. A voltage between the inner and outer electrodes will result in an increase or decrease in the length of the tube in the area between those electrodes, depending on the polarity of the applied voltage. If the voltage is applied to one of the four X - Y electrodes, the tube will bend. If equal and opposite polarity voltage is applied to electrodes on opposite sides of the tube, as shown for the X axis in Fig. 1.5, the magnitude of the bending is doubled. The resulting displacement is proportional to the magnitude of the applied voltage and the tube length. Displacement in the Z direction is achieved by applying a voltage between all four outer electrodes and the inner electrode simultaneously. A separate external electrode around the tube's circumference may be included on some scanners to allow for independent movement in the Z axis.

The flexure based scanner [56–58], which consists of a platform connected to a base by several flexures, is an alternative means of positioning the sample relative

to the probe in an AFM. The platform on which the sample is mounted is actuated by piezoelectric stack actuators which cause the flexures to bend when they expand or contract. Flexure scanners outperform tube scanners in many areas. They have reduced cross coupling between axes, a higher mechanical bandwidth and a larger range of motion. Despite these advantages, flexure scanners are still not as common as tube scanners in commercial AFMs due to the complexity of the design and higher manufacturing cost.

1.3.6 Z Axis Feedback Controller

To reduce the forces between the tip and the sample when a large abrupt increase in sample height is encountered [59] and to allow improved tracking of sample features, a feedback control loop is employed to regulate tip-sample force by moving the sample stage in the vertical (Z) direction. By maintaining $A(t)$ at a setpoint value A_{set} (typically 10-100 nm [31]) the feedback loop maintains a constant average tip-sample force.

A block diagram representation of the Z axis feedback loop is shown in Fig. 1.6. Cantilever deflection is measured by the optical sensor and demodulated to produce a DC signal representing the oscillation amplitude $A(t)$. $A(t)$ is then subtracted from A_{set} to provide the error signal for the Z axis feedback controller. To keep the tapping force on the sample to a minimum, A_{set} is chosen to be slightly less than the free air oscillation amplitude A_0 .

The Z axis controller must compensate for changes in the cantilever oscillation amplitude, due to variations in sample height, by sending an appropriate signal to the Z axis actuator. The sample topography may be viewed as a disturbance to the feedback loop. If an upward step is encountered in the sample topography, $A(t)$ will decrease. The controller responds to the error signal ($e(t) = A_{set} - A(t)$) by driving the scanner downward in the Z axis, restoring $A(t)$ to the value of A_{set} . The controller output is therefore proportional to the sample topography as the sample is scanned

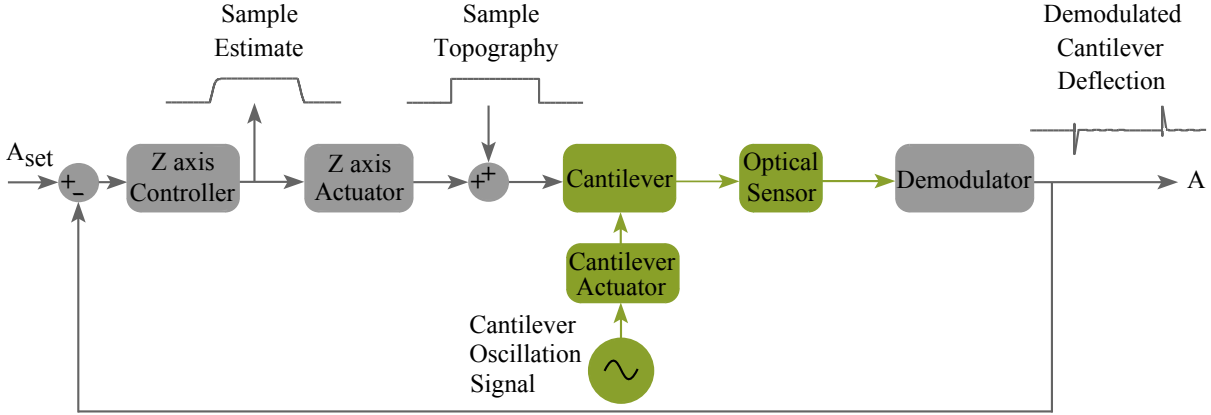


Figure 1.6: Z axis feedback control loop. The controller maintains the cantilever oscillation amplitude A at the set-point A_{set} . The sample topography is an input disturbance to the feedback loop. Therefore the output of the controller is proportional to the sample height within the bandwidth of the loop. The section of the loop shown in green is the high frequency component of the loop. Modulation of the topography measurement with this high frequency signal ensures a high SNR and reduces tip-sample forces.

underneath the cantilever. The controller output at each lateral scan coordinate is processed by a computer to form a three-dimensional image of the sample. As the sample is scanned underneath the cantilever the probe tip should track the sample topography. The faster the feedback loop is able to reject the disturbance, due to topography variations, the more accurate the estimate is of the sample topography.

Most modern commercial AFMs use a proportional-integral (PI) controller [60,61] to regulate tip-sample force. Modern control methods, such as H_∞ control [61], have been applied to contact mode imaging. However, the easily tunable PI controller has remained popular as parameters such as the cantilever, sample and environmental conditions in the AFM change so frequently.

1.3.7 Force Sensitivity

The slope of the resonance curve for high Q factor cantilevers is steeper than that of low Q factor cantilevers. When scanning the sample the cantilever is oscillated at

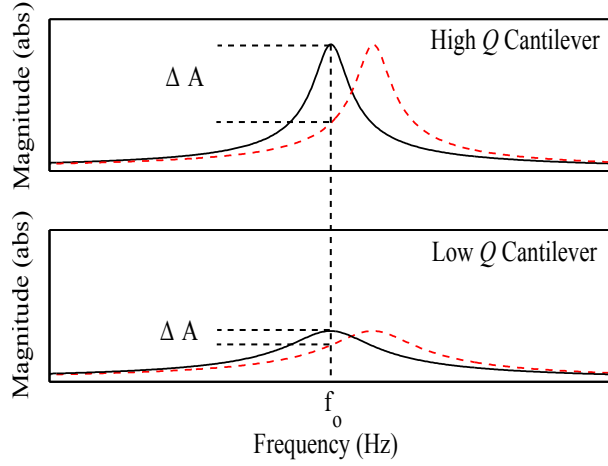


Figure 1.7: Response to a change in sample height of cantilevers with different Q factors. The cantilever is initially set to oscillate at f_0 (equal or close to its resonance frequency f_r when not interacting with the sample). Changes in sample height cause f_r to shift. A change in sample topography as the sample is scanned underneath the cantilever will result in a larger change in $A(t)$ for a cantilever that has a higher Q factor. The force sensitivity is therefore higher when the cantilever Q factor is high.

f_o , which is equal or close to the cantilevers resonance frequency f_r when not interacting with the sample. A cantilever with a higher Q factor oscillating at f_o will produce a larger change in $A(t)$ in response to a shift in the cantilever resonance, resulting from a change in sample topography, as illustrated in Fig. 1.7. This demonstrates that a cantilever with a high Q factor may provide a higher force sensitivity/image resolution than a cantilever with a low Q factor [16, 62, 63].

When imaging a sample surface which has very fine features it is desirable to increase the Q factor of the cantilever to increase the force sensitivity/image resolution of the cantilever. Many biological specimens need to be imaged in a liquid environment. When scanning in liquid [64], the Q factor of the cantilever is reduced by a factor of ten to one-hundred, due to hydrodynamic forces [65, 66]. It may therefore be desirable to increase the Q factor of the cantilever to increase the cantilever force sensitivity for improved image resolution. This may be accomplished using active Q control which is detailed in Chapter 2 Section 2.3.3.

1.3.8 Tip-sample Force

The cantilever Q factor is inversely proportional to the energy dissipated per oscillation cycle. The energy dissipated per oscillation cycle is proportional to tip-sample force. A cantilever with a low Q factor will therefore result in higher tapping forces than a cantilever with a high Q factor [66, 67].

The average tip-sample force ($\hat{F}_{TS}$) [63] is a function of the cantilever Q factor, the cantilever stiffness k , A_{set} and the cantilever oscillation amplitude in free air (A_0), as shown by [68, 69]

$$\hat{F}_{TS} \propto \frac{k}{Q} \sqrt{(A_0^2 - A_{set}^2)}. \quad (1.1)$$

High tapping forces will cause mechanical deformation of soft samples resulting in a distorted image. Therefore the true height of the sample will not be recorded in the image produced by the AFM. Several studies have demonstrated the differences in the imaged height of sample features when the cantilever Q factor is increased with active Q control [70–72]. The increase in imaged height of sample features were attributed to the lower tapping forces on the sample when the cantilever Q factor is increased. High tapping forces also increase the risk of cantilever and sample damage [16]. Low tapping forces allow sharper tips to be used on soft samples without damage to the sample, improving lateral image resolution. It is also beneficial to minimize tip-sample force when imaging samples with a hard surface to reduce tip wear.

Maintaining A_{set} close to A_0 will reduce the tip-sample force. However, this will reduce the magnitude of the error signal sent to the Z axis feedback controller when a sharp drop in sample topography is encountered, increasing the likelihood that the probe tip will lose intermittent contact with the sample. As the probe tip is no longer in intermittent contact with the sample, artifacts appear in the resulting image. This phenomenon is commonly referred to as ‘parachuting’ [73] or ‘probe loss’ [74] and a more detailed description is provided in Chapter 2 Section 2.5.

Chapter 2

Tapping Mode AFM Scan Speed Limitations

While tapping mode has an advantage over contact mode for reducing tip and sample damage it is hindered by a relatively slow scan speed. As the scan speed is increased the ability of the probe to track the sample topography is reduced. Advances in control and instrumentation have lead to high speed AFMs which are capable of imaging dynamic biological processes [75–79]. However, there is still the desire and potential for further improvement in imaging speed.

The bandwidth of the scanner in the lateral axes and the bandwidth of the Z axis feedback loop determine the maximum imaging speed, with the bandwidth of the Z axis feedback loop being the fundamental limitation.

2.1 Bandwidth of the Scanner in the Lateral Axes

The triangular waveform applied to the scanner in the X axis to produce a raster scan pattern has sharp edges at the turning points which introduce high frequency components to the signal. The piezoelectric tube scanners used in most AFMs are

highly resonant systems typically with a first resonance frequency no higher than 1 kHz. As the scan speed is increased, the likelihood of the high frequency components of the raster signal exciting the mechanical resonance of the scanner is increased. This results in unwanted vibration in the scanner leading to image distortion [54].

It is common practice to limit the raster scan frequency to less than 1% of the scanner's first resonance frequency to avoid image distortion resulting from scanner vibration [80]. For a scanner with a first resonance frequency of 1 kHz this would limit the scan speed to 10 Hz, with a typical image taking several minutes to acquire.

New scan trajectories [81] such as spiral [82], cycloid [83] and Lissajous [84, 85] scan signals have recently been developed to remove high frequency components from the scan signal, avoiding excitation of the scanner's mechanical resonance.

Another approach to reduce induced vibration in the scanner, in order to increase scan speed, is to increase the damping factor of the first resonance mode of the scanner with a feedback controller [79, 80, 86].

2.2 Z Axis Feedback Loop Bandwidth

The bandwidth of the Z axis feedback control loop determines the speed at which the probe can track the sample topography accurately. The bandwidth of the Z axis feedback loop may be widened by increasing the gain of the Z axis controller, which is limited by the stability margins of the feedback loop.

When the probe tip is interacting with the sample, the dynamics of the cantilever are modified due to the influence of the tip-sample force F_{TS} causing a shift in the resonance frequency and Q factor of the cantilever. It is important that significant stability margins are maintained in the Z axis feedback loop to accommodate for these deviations in parameters as the sample is scanned below the cantilever. If the feedback loop bandwidth is too low oscillations will appear in the sample image as the scan speed is increased due to the loop becoming unstable.

2.2.1 Analysis of the Z Axis Feedback Loop Stability Margins

The main limitations to the Z axis feedback loop stability margins are the bandwidth of the Z axis actuator, the time taken to demodulate the cantilever oscillation amplitude and the bandwidth of the cantilever in cascade with the demodulator.

Piezoelectric tube scanners used in most commercial AFMs to move the sample in the X, Y and Z directions are highly resonant with a mechanical resonance frequency of 500 Hz to 20 kHz [23] in the Z axis. The Z axis actuator transfer function, within the bandwidth of interest, may be approximated by the transfer function [87]

$$G_{zp}(s) = \frac{K_{zp}\omega_{zp}^2}{s^2 + \frac{\omega_{zp}}{Q_{zp}}s + \omega_{zp}^2}, \quad (2.1)$$

where K_{zp} is the DC gain of the actuator, Q_{zp} is the actuator Q factor and ω_{zp} is the actuator resonance frequency.

Common methods used to demodulate the cantilever displacement signal, such as the RMS to DC converter or lock-in amplifier, may take up to 10 cycles to acquire an accurate measure of the oscillation amplitude. This is due to the trade-off between elimination of the oscillation waveform in minimal time and obtaining an accurate measure of the amplitude waveform [88,89]. This results in a delay T_D in the feedback error signal and controller response.

The cantilever Q factor is inversely proportional to the energy dissipated/gained per oscillation cycle. The transient response of a low Q factor cantilever is therefore faster than a high Q factor cantilever. This means that a cantilever with a low Q factor will have a higher bandwidth when placed in the Z axis feedback loop.

The first mode of the cantilever may be modeled by the second order transfer function

$$G(s) = \frac{D(s)}{F(s)} = \frac{\beta\omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2}, \quad (2.2)$$

where $D(s)$ is cantilever tip displacement, $F(s)$ is a force applied to the cantilever,

β is the steady state gain and ω_n is the natural frequency of the cantilever. The demodulator removes the sinusoidal component from the cantilever displacement signal to provide the oscillation amplitude signal $A(t)$ for the feedback controller. The cantilever in cascade with the demodulator has a first order transfer function

$$G_{CD}(s) = \frac{\beta e^{-T_D s}}{\left(\frac{2Q}{\omega_n} s + 1\right)}, \quad (2.3)$$

with a bandwidth of $\frac{\omega_n}{2Q}$ [90] and a time delay T_D .

The Z axis controller must incorporate some form of integral action to remove steady state error from the image. For illustration purposes let the Z axis feedback controller be a PI controller with a transfer function

$$C_{PI}(s) = \frac{K_Z (1 + \tau s)}{\tau s}, \quad (2.4)$$

where K_Z is the proportional/controller gain with the integral gain equal to K_Z/τ .

The open loop transfer function of the Z axis feedback loop is

$$G_{OL}(s) = \left(\frac{K_Z (1 + \tau s)}{\tau s}\right) \left(\frac{K_{zp} \omega_{zp}^2}{s^2 + \frac{\omega_{zp}}{Q_{zp}} s + \omega_{zp}^2}\right) \left(\frac{\beta e^{-T_D s}}{\left(\frac{2Q}{\omega_n} s + 1\right)}\right). \quad (2.5)$$

For accurate tracking of the sample topography at high scan speeds, the controller gain K_Z must be set as high as possible while maintaining sufficient stability margins to allow for variations of the cantilever resonance and Q factor which occur during the scan.

The Z axis feedback loop stability margins are dependent on the bandwidth of the Z axis actuator, the demodulator delay T_D and the bandwidth of the cantilever in cascade with the demodulator. Widening of the stability margins will allow for an increase in the controller gain K_Z to allow for higher scan speeds with minimal imaging artifacts caused by poor tracking of the sample topography.

If the cantilever has a resonance frequency between 50-500 kHz and a Q factor equal to 250, the bandwidth of the cantilever in cascade with the demodulator will be in the range of 100-1000 Hz. In most cases this bandwidth will be less than the

bandwidth of the Z axis actuator. The major limitation to the stability margins of the Z axis feedback loop will therefore be the demodulator delay and the bandwidth of the cantilever in cascade with the demodulator. The stability margins may be widened by reducing T_D or increasing the bandwidth of the cantilever in cascade with the demodulator. If the bandwidth of the cantilever in cascade with the demodulator is widened by increasing the cantilever resonance frequency or reducing the cantilever Q factor, then further increases in the Z axis feedback loop bandwidth may be possible by increasing the bandwidth of the Z axis actuator.

2.3 Increasing the Z Axis Feedback Loop Stability Margins for Faster Scan Speeds

Several approaches have been undertaken by researchers to increase the stability margins of the Z axis feedback loop with the aim of achieving faster scan speeds. Some of these approaches are highlighted in the following.

2.3.1 Reducing the Demodulator Delay

Faster methods of demodulating the cantilever displacement signal have been presented by several researchers. A low latency coherent demodulation technique which can extract the oscillation amplitude from the displacement signal in one oscillation cycle was presented in [89,91]. A sample and hold circuit and a low pass filter which detects the peak of the sine wave and holds that value for a predefined time, enabling accurate demodulation in up to half an oscillation cycle was introduced in [92].

Another alternative is to replace the demodulator with a full wave rectifier [93], which has no delay. The difference between the DC content of the rectifier signal and A_{set} is used as the error signal for the Z axis feedback controller. The harmonic content of the signal produced by the rectifier is double that of the cantilever resonance

frequency and therefore much higher than the bandwidth of the Z axis feedback loop.

2.3.2 Increasing the Cantilever Resonance Frequency

Many of the advances in high speed tapping mode AFM have been achieved through the use of smaller cantilevers [75, 78, 79, 94] which have higher resonance frequencies. This improves the stability margins of the Z axis feedback loop in two ways. It increases the bandwidth of the cantilever in cascade with the demodulator and reduces the demodulation time. The reduced length of the cantilever may, however, limit the ability of the cantilever to track samples with large topographic features. The conventional optical lever deflection measurement system must be modified to focus the laser beam onto these smaller size cantilevers [65, 75, 95]. The laser beam is focused onto the cantilever with a lens and reflected back into the same lens. The reflected beam is separated from the incident beam using a polarizing beam splitter and a quarter wavelength plate.

2.3.3 Reducing the Cantilever Q Factor With Active Q Control

Active Q control utilizes velocity feedback to modify the effective cantilever Q factor. In [31, 88] it was demonstrated that a reduction in the cantilever Q factor using active Q control [90, 96] improves the bandwidth of the Z axis feedback loop allowing for faster scans of hard surfaced samples in air. Reducing the cantilever Q factor may also be employed to increase scan speeds when imaging in vacuum [97], where the high cantilever Q factor is a major limitation to scan speed.

The differential equation describing the motion of the cantilever, when the AFM is operating in tapping mode, is

$$m\ddot{d}(t) + \frac{m\omega_n}{Q}\dot{d}(t) + kd(t) = A_a \cos(\omega_o t) + F_{TS}(t), \quad (2.6)$$

where m is the effective mass of the cantilever, d is vertical tip displacement and k is the cantilever spring constant. Two external forces are acting on the cantilever: $A_a \cos(\omega_o t)$ is the force produced by the piezoelectric actuator with an oscillation amplitude of A_a and an oscillation frequency of ω_o , and $F_{TS}(t)$ is the force due to tip-sample interaction.

From (2.6) it can be seen that the effective cantilever Q factor (Q^*) may be modified by adding an additional force proportional to the probe velocity via feedback. If the velocity signal is multiplied by a gain G and subtracted from the probe actuation signal the cantilever equation of motion now becomes

$$m\ddot{d}(t) + \frac{m\omega_n}{Q}\dot{d}(t) + kd(t) = A_a \cos(\omega_o t) + F_{TS}(t) - G\dot{d}(t), \quad (2.7)$$

or equivalently

$$m\ddot{d}(t) + \left(\frac{m\omega_n}{Q} + G \right) \dot{d}(t) + kd(t) = A_a \cos(\omega_o t) + F_{TS}(t). \quad (2.8)$$

This simplifies to

$$m\ddot{d}(t) + \frac{m\omega_n}{Q^*}\dot{d}(t) + kd(t) = A_a \cos(\omega_o t) + F_{TS}(t), \quad (2.9)$$

where

$$Q^* = \frac{1}{\left(\frac{1}{Q} + \frac{G}{m\omega_n} \right)}. \quad (2.10)$$

The effective Q factor of the cantilever is decreased when the gain G is positive and increased when G is negative.

Commercially available AFMs are typically fitted with a displacement sensor to measure variations in the sample topography. The addition of a velocity sensor would be difficult to implement in the AFM and would also add to the size and cost of the device. For these reasons cantilever velocity is most commonly estimated from the displacement signal.

The use of a differentiator to estimate the cantilever tip velocity is not recommended as differentiators amplify high frequency noise in the feedback loop. The

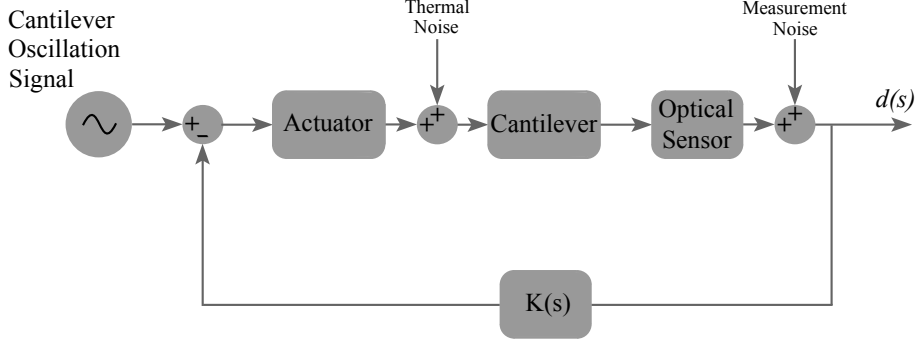


Figure 2.1: Block diagram of the active Q control feedback loop. Active Q control utilizes velocity feedback to modify the effective Q factor of the cantilever. The controller $K(s)$ estimates the cantilever tip velocity from the tip displacement $d(s)$ and applies a gain to obtain the desired cantilever Q factor.

active Q control feedback loop is influenced by two forms of noise: thermal noise and noise from the optical deflection measurement sensor [98].

Thermal noise is due to surrounding molecules randomly hitting the cantilever and causing random movements [35]. Thermal noise is modeled as an input to the cantilever in Fig. 2.1. The magnitude of thermal noise is significant at the resonance frequencies of the cantilever [99].

When active Q control is applied to commercial AFMs it is common to obtain an estimate of the cantilever velocity by applying a phase shift to the displacement signal using a time delay circuit [16, 96]. This phase shifted signal is then multiplied by a gain G and the resulting signal is subtracted from the cantilever oscillation signal before being applied to the cantilever actuator. This arrangement is shown in the active Q control feedback loop of Fig. 2.1, where

$$K(s) = Ge^{-T_{cd}s}. \quad (2.11)$$

In the above equation T_{cd} is the time delay required to estimate the cantilever tip velocity at the cantilever oscillation frequency f_o . As the displacement signal is sinusoidal a delay of $\frac{3\pi}{2}$ radians is required to estimate the velocity signal. This is achieved by setting T_{cd} to $\frac{3}{4f_o}$. To increase the cantilever Q factor G must be neg-

ative. Therefore, the required delay is $\frac{\pi}{2}$ radians. In this case T_{cd} should be set to $\frac{1}{4f_o}$.

2.3.4 Increasing the Bandwidth of the Scanner in the Z Axis

If the bandwidth of the cantilever in cascade with the demodulator can be improved then further improvements in the Z axis feedback loop bandwidth may be achieved by widening the bandwidth of the Z axis actuator.

Active damping of the Z axis actuator resonance [87] may be used to increase the bandwidth of the Z axis feedback loop.

A dual stage vertical positioner which uses the tube scanner Z axis actuator coupled with an additional high bandwidth stack actuator was proposed in [100] to provide an increase of 33 times the scan speed.

One alternative to using the piezoelectric tube for Z axis actuation is to integrate the actuator into the cantilever by coating the surface of the cantilever with a thin layer of piezoelectric material. The cantilever acts as a bimorph, bending when a voltage is applied to the piezoelectric layer. The smaller size of the cantilever results in a much higher mechanical resonance frequency. Increases in imaging bandwidth by a factor of over 30 times, compared to a tube scanner, have been observed using this method [88, 101].

2.4 Alternative Signals for Topography Estimation

The trade-off between imaging bandwidth and accurate tracking of the sample has been addressed by several authors through alternative methods of sample topography estimation. In conventional AFMs, the sample topography is estimated from the

controller output. The bandwidth of the estimated signal is therefore limited by the bandwidth of the Z axis feedback control loop.

When scanning slowly the Z axis feedback loop will be fast enough to track the sample with minimal error. If the scan speed is low enough to ensure that the frequency content of the sample topography is well below the bandwidth of the scanner in the Z axis, a scaled value of the controller output is sufficient for sample topography estimation. As the scan speed approaches the bandwidth of the scanner, the dynamics of the scanner must be taken into account as it is the movement of the scanner in the Z axis which gives a true representation of the sample topography. As the scan speed approaches the bandwidth of the feedback control loop the error signal will no longer be zero and the controller will only capture sample features which are within the bandwidth of the feedback loop. At high scan speeds the error signal contains high frequency information of the sample topography. Therefore a more accurate representation of the sample topography should account for the actuator dynamics and include information contained in the error signal. The alternate sample topography estimation techniques presented in [102] and [103] provide an estimate of the sample topography based on the controller output, the transfer function of the Z axis actuator and the error signal to provide accurate estimation of sample topography at higher scan speeds.

A new method of estimating the sample topography which removes the trade-off between imaging bandwidth and the cantilever Q factor, based on the estimation of the cantilever states with an observer, was reported in [104] and [105]. This method of imaging is termed transient force atomic force microscopy (TF-AFM). An observer is designed based on the cantilever dynamics in free air. When the cantilever is interacting with the sample its dynamics are modified by the tip-sample force resulting in a non-zero error between the observer output and the cantilever output. Therefore, the tip-sample force/sample height may be estimated from this signal. The improvement in imaging speed using this technique is demonstrated in [105] where Lambda

DNA was imaged in air using conventional AFM imaging and TF-AFM imaging. The scan speed achieved using TF-AFM was over 40 times that obtainable with conventional AFM imaging. Further experiments using TF-AFM were conducted where the cantilever Q factor was increased with velocity feedback, with the velocity estimated using the observer. The same improvement in scan speed was achieved through the use of TF-AFM with the added benefit of increased image contrast due to the increased cantilever Q factor.

2.5 Scan Speed Limitations Due to Probe Loss

It is important that $\hat{F}_{TS}$ be kept to a minimum to reduce image distortion from sample compression and avoid damage to the probe tip or sample. Equation (1.1) shows that $\hat{F}_{TS}$ may be reduced by reducing k , increasing Q or increasing A_{set} . Softening the cantilever by decreasing k will reduce the resonance frequency of the cantilever. For high speed scanning it is undesirable to reduce the cantilever resonance frequency or increase Q as this will reduce the bandwidth of the Z axis feedback loop. Therefore, increasing A_{set} is the most suitable approach for minimizing $\hat{F}_{TS}$. It is common to set A_{set} at 80%–90% of A_0 to minimize $\hat{F}_{TS}$ when imaging soft delicate samples. Such a large A_{set} may, however, limit the maximum achievable scan speed if the sample contains abrupt variations in height.

If the image being scanned contains a sharp deep drop in topography it is likely that the cantilever tip will lose intermittent contact with the sample for some period of time. As the probe tip is not interacting with the sample the resulting signal provides no information about the sample topography resulting in image artifacts. If the drop in topography is large enough saturation of the Z axis feedback loop error signal is likely to occur which will increase the duration of probe loss. The image artifacts due to probe loss are worsened as A_{set} and the scan speed are increased.

When probe loss occurs it is desirable that the feedback controller output is as

large as possible to ensure that the controller brings the sample back into contact with the probe tip in as short a time as possible. A high value for A_{set} may be a limitation on downhill slopes of the sample as it limits the magnitude of the maximum error signal ($e_{max} = |A_{set} - A_0|$), which increases the probability of error signal saturation occurring [88, 106]. A high value for A_{set} , however, is an advantage when imaging uphill regions of the sample as it allows for a larger value for the maximum error signal ($e_{max} = A_{set}$) presented to the Z axis feedback controller in these regions. A controller which compensates the error signal on steep downhill regions, to allow for a high value of A_{set} , provides significant benefits such as an increased maximum error signal in upward regions of topography, reduced tip-sample force and improved sample tracking.

2.5.1 Analysis of Imaging Artifacts Due to a Large Steep Drop in Sample Topography

The probe loss problem is illustrated in Fig. 2.2 with a simulation of a high speed scan over a vertical step drop in sample topography.

Before point a is reached on the sample shown in Fig. 2.2, the probe is scanning a flat surface and oscillating at $A(t) = A_{set}$. At point a the probe encounters the sharp drop in topography and detaches from the sample. This causes $A(t)$ to increase exponentially according to the relationship [88]

$$A(t) = A_{set} + (A_0 - A_{set}) \left(1 - e^{\frac{-\omega_n}{2Q}t} \right), \quad (2.12)$$

where the time t begins at zero from the edge of the step. During this transient time the error signal is smaller than the change in sample topography. This low error signal will delay the speed of response of the Z axis feedback controller to bring the sample back in contact with the probe tip. The length of this transient depends on the cantilever Q factor and ω_n .

The feedback error signal does not respond to the change in $A(t)$ immediately

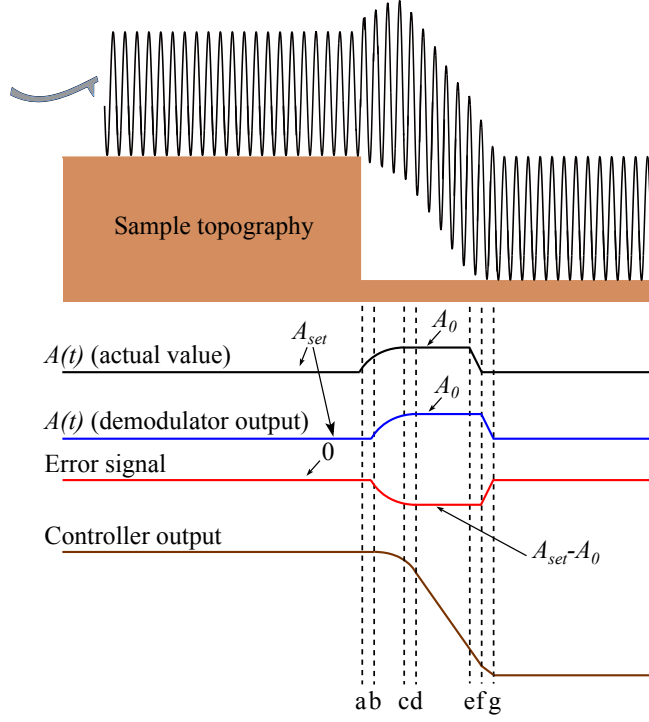


Figure 2.2: Simulation of a high speed scan of a sample with a sharp downward step. The oscillation amplitude is limited to the free air oscillation amplitude A_0 after the step is encountered. As the set-point amplitude A_{set} is set close to A_0 , the error signal saturates at $A_{set} - A_0$ limiting the ability of the feedback loop to track the sample topography.

due to the delay in demodulating the cantilever displacement signal. The controller output will be delayed as a result of this. This delay occurs between points *a* and *b* in Fig. 2.2.

At point *b* the controller output begins to reflect this exponential increase of $A(t)$. The amplitude $A(t)$ will continue to increase until $A(t) = A_0$. At point *c* in the diagram the cantilever has reached its free air oscillation amplitude A_0 . Another delay occurs due to demodulation before this is reflected in the control signal at point *d*.

At point *d* the magnitude of the error signal has saturated and is limited to $e_{max} = |A_{set} - A_0|$. The relatively small magnitude of e_{max} constrains the *Z* axis feedback loop to a slow response causing the cantilever to oscillate in free air with

an amplitude of A_0 until the Z axis actuator can bring the sample back into contact with the probe. This slow response prolongs the time that the probe is detached from the sample.

When the probe tip is not in contact with the sample the controller output will not be an accurate representation of the sample topography. When the error signal is saturated, the integral action in the feedback controller will cause the sample topography to appear linear with a slope proportional to the controller gain and the value of e_{max} , and inversely proportional to the scan speed. This can be seen in the region between points d and e in Fig. 2.2.

At point f the probe regains contact with the sample. This is reflected in the control output at point g .

2.5.2 Methods of Reducing Image Artifacts Due to a Sharp Drop in Sample Topography

The image artifacts due to probe loss are affected by the scan speed, feedback controller gain and the value of e_{max} . These parameters are normally fixed for the duration of a scan. Several researchers have shown that by modifying these parameters dynamically, according to the profile of the sample, significant improvements in image quality at high scan speeds can be achieved. These strategies all involve some form of detection to determine whether the probe is detached from the sample and a switching controller dependent on the detection signal.

2.5.2.1 Reducing scan speed

When a sharp drop in sample topography of height Δh is encountered by the probe tip, the duration that the probe is detached from the sample depends on Δh , the Z axis feedback controller gain and e_{max} . If the scan speed is reduced, a smaller area of the sample will be scanned during this period of probe loss reducing the affected

area. However, in most cases a high scan speed is desirable. A feedforward controller which controls the scan speed, depending on the predicted sample topography, was presented in [107]. If a region of the sample topography is predicted to be flat by the controller then the scan speed would be set at a high rate. If a drop in the sample topography is encountered, the rate of change in the cantilever oscillation amplitude signals to the controller that a downward slope is encountered and the scan speed is reduced by the controller.

2.5.2.2 Increasing the controller gain

The Z axis controller gain and cantilever Q factor must be chosen to ensure that the Z axis feedback loop has sufficient stability margins to accommodate for the variation of cantilever parameters when scanning. This will avoid oscillations appearing in the image due to the feedback loop approaching instability. If the stability margins are widened this will allow for an increase in the controller gain which will reduce the duration of probe loss.

Artificially reducing the cantilever Q factor results in an increase in bandwidth of the Z axis feedback loop allowing for a higher controller gain in the loop. This may be achieved by the use of active Q control. This method reduces the probe loss time at the cost of increased tip-sample force [88].

When the tip has lost contact with the sample the problem of high tip-sample force and oscillations from instability is not present. This means that when the tip is off-sample the controller gain may be set higher than the maximum gain allowable for on-sample stability. Momentarily increasing the controller gain, to increase the Z axis feedback response speed, when the tip is off-sample will reduce or eliminate error signal saturation without induced instability in the feedback loop. The controller gain must be reduced back to the appropriate on-sample value when the tip regains contact with the sample to avoid large tip-sample forces and instabilities in the feedback loop.

A dynamic Proportional Integral Derivative (PID) Z axis feedback controller was

developed in [73] to address the error saturation problem. The cantilever oscillation amplitude signal $A(t)$ is used to determine whether the probe tip has detached from the sample or not. If $A(t)$ exceeds a threshold value A_{thresh} (set close to A_0) then it is inferred that the cantilever has lost contact with the sample. When probe loss is detected the error signal $(A_{set} - A_0)$ is multiplied by a gain before it is sent to the controller. This has the effect of increasing the actuator's response speed and reducing the time that the probe is detached from the sample surface. When the probe regains contact with the sample $A(t)$ quickly falls below the threshold value, and the gain is switched to unity avoiding any instabilities in the feedback loop.

The reliability index method developed in [74] may be used to determine if the tip has lost contact with the sample, rather than using the measured value of $A(t)$. The reliability index is obtained in the same way that the image signal is obtained for TF-AFM [105]. An observer is designed to model the dynamics of the cantilever in free air. When the tip interacts with the sample the forces between the tip and sample modify the dynamics of the cantilever. The reliability index is obtained from the error between the observer model and the cantilever. When the cantilever is detached from the sample the reliability index is small, as the observer dynamics closely match the dynamics of the cantilever, and is large when the tip is tapping the sample, giving an indication of when the probe has lost contact with the sample. It has been demonstrated that this method reduces the time in which probe loss is detected. A switched gain PID controller, with a threshold value of the reliability index determining the switching between gains, was proposed in [108] to reduce the problem of error saturation.

In [109] the approaches of switching scan speed and feedback gain were combined to reduce image artifacts occurring as a result of error saturation. The control philosophy involved reducing the scan speed in uphill regions of the sample to allow for a higher on-sample feedback gain and switching the feedback gain when probe loss is detected on downward sloping regions of the sample.

2.5.2.3 Increasing the maximum error signal

The duration of probe loss may be reduced by increasing e_{max} , which can be achieved for downward slopes of the sample by setting A_{set} much lower than A_0 . The disadvantage of doing this is that $\hat{F}_{TS}$ is increased (according to (1.1)) and e_{max} on upward slopes of the sample is reduced.

For a cantilever oscillating in free air near its resonance frequency the amplitude of oscillation is proportional to the cantilever Q factor. This means that e_{max} , on downward sloping regions of the sample, may be increased by increasing the cantilever Q factor.

When the probe is on-sample the Q factor should be set at a value low enough to maintain sufficient stability margins in the Z axis feedback loop. A_{set} should be set close to A_0 to minimize $\hat{F}_{TS}$ and increase e_{max} in upward sloping regions of the sample. When the probe is off-sample, instabilities occurring in the Z axis feedback loop are no longer an issue. Therefore the cantilever Q factor may be increased in this region to increase A_0 (and consequently e_{max}) in order to reduce the probe loss duration.

In [110] a controller which switches the Q factor of the probe depending on the profile of the sample was introduced. The controller uses the principle of active Q control, multiplying probe velocity by a gain G then subtracting it from the probe oscillation signal, to set the on-sample cantilever Q factor. If the oscillation amplitude of the probe exceeds a threshold value A_{thresh} , indicating that the probe has lost contact with the sample, then G is reduced to increase the cantilever Q factor. As the sample comes back into close proximity with the probe the forces between the tip and the sample will modify the Q factor and resonance frequency of the cantilever causing $A(t)$ to return below A_{thresh} . As $A(t)$ is now less than A_{thresh} the controller increases G back to its on-sample value which has the effect of reducing the cantilever Q factor to ensure that the stability margins of the loop are wide enough to

avoid instabilities. This controller was implemented on a custom-built AFM which measured probe velocity with a laser doppler vibrometer and integrated this signal to obtain the probe displacement signal required for imaging. The velocity signal obtained from the vibrometer was used in the active Q control loop. The control technique was demonstrated to significantly reduce imaging artifacts caused by probe loss while maintaining a high value for A_{set} to limit tip-sample forces and maintain a high value for e_{max} in upward sloping regions of the sample. The drawback of this controller is that it can not be easily implemented into existing commercial AFMs.

Chapter 3

Modification of Cantilever Quality Factor Using Resonant Control

It is advantageous to be able to modify the Q factor of the AFM micro-cantilever according to the sample and imaging environment. If the sample has a hard surface and the imaging environment is air or vacuum then it would be desirable to reduce the Q factor of the cantilever to increase scan speeds. In other imaging applications it may be desirable to increase the cantilever Q factor for increased force sensitivity and reduced tip-sample force.

Active Q control is currently the most common method used to modify the effective Q factor of the AFM micro-cantilever. When active Q control is applied to commercial AFMs it is common to obtain an estimate of the cantilever velocity by applying a phase shift to the displacement signal using a time delay circuit. A detailed description of active Q control is provided in Chapter 2 Section 2.3.3.

3.1 Degradation of Active Q Control

Performance Due to Unmodeled Cantilever Dynamics

When implementing active Q control with a time delay controller there is a risk that the controller may inadvertently degrade the system performance or even cause the cantilever to become unstable.

Flexible structures such as cantilevers have an infinite number of resonance modes. When designing an active Q controller for an AFM micro-cantilever only the first resonance mode is modeled. When using a truncated model of a flexible structure to design a controller, problems may arise if the unmodeled resonance modes are excited by the control action. This phenomenon is termed the spill-over effect [111,112].

This spill-over effect may degrade the closed-loop system response by shifting the poles of higher order modes closer to the $j\omega$ axis of the complex plane than the first mode, which is being controlled. To increase the scan speed it is desirable to decrease the transient response time of the cantilever. This is achieved by decreasing the Q factor of the cantilever's first resonance mode. In doing so it is possible that one of the higher order resonance modes may become excited by the control action and have its poles pushed closer to the $j\omega$ axis than the first mode. This will have the adverse effect of increasing the cantilever transient response time. If the control gain is high enough it may even push the poles of the higher order mode past the $j\omega$ axis making the system unstable.

When designing a controller to enhance the cantilever Q factor the spill-over effect is not a problem as the poles of the first resonance mode are being pushed closer to the $j\omega$ axis by the controller and will remain to be the dominant poles of the system. In this case the user must carefully set the parameters of the controller to ensure that the cantilever remains stable.

The time delay active Q controller does not have guaranteed stability in the presence of unmodeled cantilever dynamics. Stark [113] observed instability resulting from the spill-over effect when reducing the cantilever Q factor with a time delay active Q controller.

The phase delay of the time delay controller $K(s)$ increases as frequency increases. A frequency response of a typical time delay active Q controller set to reduce the cantilever Q factor is presented in Fig. 3.1. The delay of the controller at the cantilevers first resonance frequency (f_{r1}) is set to $T_{cd} = \frac{3}{4f_{r1}}$ and the gain G is set at an appropriate value to reduce the cantilever Q factor by a desired amount. It can be seen from the frequency response of the cantilever given in Fig. 3.2 that the Q factor of the first cantilever resonance mode has been decreased as desired. As a side effect of this reduction in Q factor of the first resonance mode, the Q factor of the second resonance mode has increased. The reason for this is that the phase of the controller at the resonance frequency of the second mode (f_{r2}) is close to $-\frac{5\pi}{2} \equiv -\frac{\pi}{2}$ which is the same as having a gain of $-G$. In this example G is high enough to push poles of the second resonance mode into the right half of the complex plane.

If the phase delay of $K(s)$ at the resonance frequency of any of the higher order cantilever modes is close to $-2\pi N - \frac{\pi}{2}$ radians, for any integer N , the Q factor of that mode will be enhanced. As G is increased its poles will be pushed closer to the $j\omega$ axis. If G is high enough the poles will cross the $j\omega$ axis making the system unstable.

This highlights the need for alternative approaches to active Q control which will ensure that the control signal will not spill over to higher order modes of the cantilever.

An alternative approach to active Q control, which has guaranteed closed-loop stability, is to design an observer to estimate the probe velocity [114, 115]. It was demonstrated in [114] that the trade-off between high imaging bandwidth and high force sensitivity/low tip-sample force may be overcome to some extent by varying the observer gain. It was found that while imaging in air the Q factor may be reduced

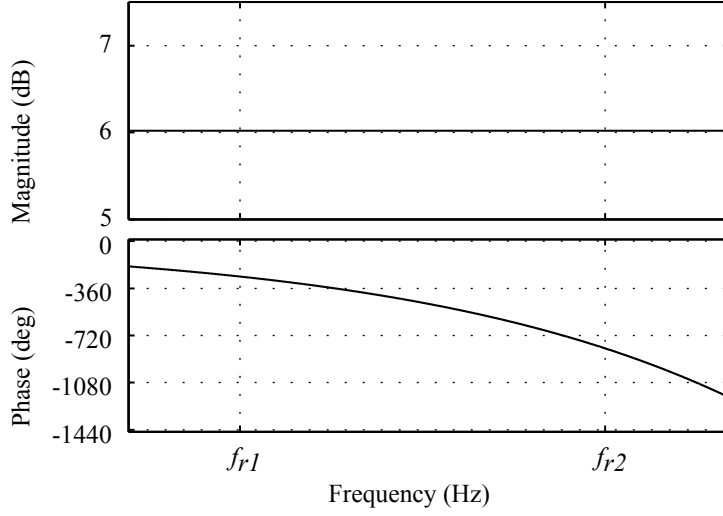


Figure 3.1: Frequency response of the controller $K(s) = Ge^{-T_{cd}s}$ used to reduce the Q factor of an AFM micro-cantilever with the active Q control time delay method.

to improve the imaging bandwidth while the force sensitivity may be increased and tip-sample force decreased by reducing the observer gain. This overcomes, to some extent, the trade-off between imaging bandwidth and image resolution/reliability.

3.2 Guaranteed Stability of Feedback Systems With Unmodeled Dynamics

A useful technique for analyzing the closed-loop stability of controllers for highly resonant systems with unmodeled dynamics is the negative imaginary systems theory [116]. When two negative imaginary systems are interconnected in a positive feedback loop, with at least one of the systems being strictly negative imaginary, closed-loop stability is guaranteed if the DC loop gain is less than one [117].

A negative imaginary transfer function is defined as a stable transfer function whose Nyquist plot for $\omega \geq 0$ lies on or below the real axis. A negative imaginary transfer function $M(s)$ satisfies the condition [117]

$$j [M(j\omega) - M^*(j\omega)] \geq 0, \quad (3.1)$$

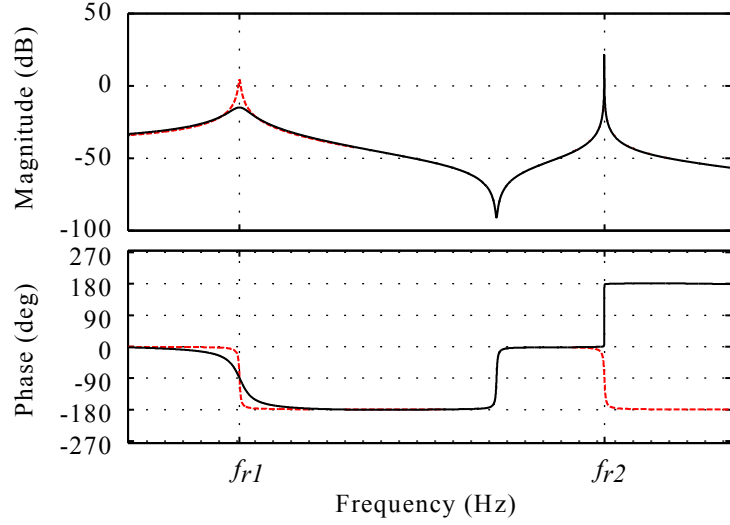


Figure 3.2: A frequency response of a typical AFM micro-cantilever showing the first two resonance modes. (—) is the frequency response of the cantilever with active Q control using the time delay method. The controller effectively reduces the Q factor of the first mode. As a side effect, the Q factor of the second mode is increased leading to instability of this mode.

for all $\omega \geq 0$.

A strictly negative imaginary transfer function is defined as a stable transfer function whose Nyquist plot for $\omega > 0$ lies below the real axis. A strictly negative imaginary transfer function $N(s)$ satisfies the condition [117]

$$j [N(j\omega) - N^*(j\omega)] > 0, \quad (3.2)$$

for all $\omega > 0$.

When the higher order modes of the cantilever are included in the model its transfer function, from a voltage applied to the piezoelectric actuator $v(s)$ to cantilever displacement $d(s)$, is

$$G(s) = \frac{d(s)}{v(s)} = \sum_{i=0}^{\infty} \frac{\beta_i \omega_i^2}{s^2 + 2\zeta_i \omega_i s + \omega_i^2}, \quad (3.3)$$

where ω_i is the natural frequency of the i -th mode, β_i is the steady state gain of the

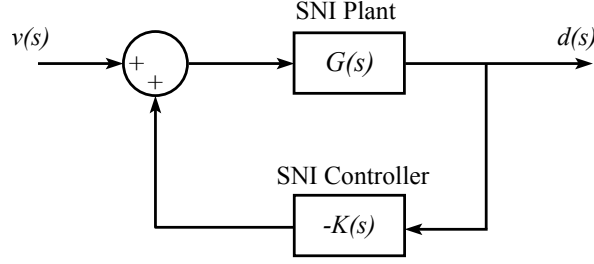


Figure 3.3: Resonant control feedback loop arranged in a positive feedback context. The plant and controller both have strictly negative imaginary transfer functions. If the DC gain condition is satisfied then the closed-loop system has guaranteed stability.

i -th mode, and ζ_i is the damping factor of the i -th mode.

$$j [G(j\omega) - G^*(j\omega)] = \sum_{i=0}^{\infty} \frac{4\beta_i \zeta_i \omega_i^3 \omega}{(\omega_i^2 - \omega^2)^2 + (2\zeta_i \omega_i \omega)^2} \quad (3.4)$$

is greater than 0 for all $\omega > 0$. $G(s)$ is therefore strictly negative imaginary as it is stable and satisfies condition (3.2).

To design a controller which guarantees closed-loop stability when the model of the cantilever is truncated to a first mode approximation,

$$G(s) = \frac{\beta \omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2}, \quad (3.5)$$

the feedback structure of the active Q control feedback loop is viewed in a positive feedback context by multiplying $K(s)$ by -1 as shown in Fig. 3.3. The closed-loop system will have guaranteed stability if $-K(s)$ is negative imaginary and the DC loop gain is less than one.

3.3 A Resonant Controller for Cantilever Q Factor Modification

The method of resonant control was developed to dampen vibrations in flexible structures [118–120]. The resonant controller approximates a differentiator over a narrow range of frequencies. As a gain is applied only in the bandwidth of control the problem of high frequency noise being amplified by the differentiator is eliminated.

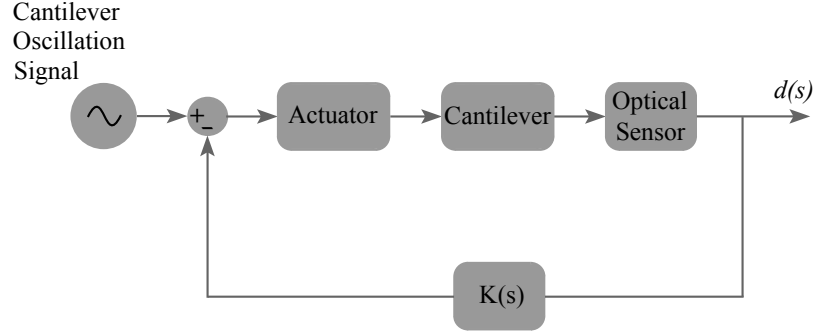


Figure 3.4: Block diagram of the active Q control feedback loop. The controller $K(s)$ estimates the cantilever tip velocity at the cantilever oscillation frequency and applies an appropriate gain to modify the cantilever Q factor.

The transfer function of the resonant controller used in this work to modify the effective cantilever Q factor is

$$K(s) = \frac{\alpha s^2}{s^2 + 2\zeta_c \omega_* s + \omega_*^2}, \quad (3.6)$$

where α and ζ_c are parameters which determine the gain at the frequency of interest ($\omega_* = \omega_n$) and the bandwidth of control.

The resonant controller is implemented in the active Q control feedback loop shown in Fig. 3.4. The input signal to the controller is the displacement measured by the photodiode sensor. The controller output signal is subtracted from the cantilever oscillation signal and then applied to the cantilever actuator.

To reduce the effective cantilever Q factor with the resonant controller the value of α will always be positive. The frequency response of the controller when α is positive is shown in Fig. 3.5. As the phase of the controller is $\frac{\pi}{2}$ rad at the cantilever's resonance frequency, it approximates a differentiator at this frequency. At higher frequencies the phase rolls off to 0 rad which avoids the problems associated with the large phase delay of the time delay active Q controller.

If α is set to be negative the effective cantilever Q factor is enhanced. The frequency response of the controller when α is negative is shown in Fig. 3.6. The phase at the cantilever's resonance frequency is now $-\frac{\pi}{2}$. This will have the effect of

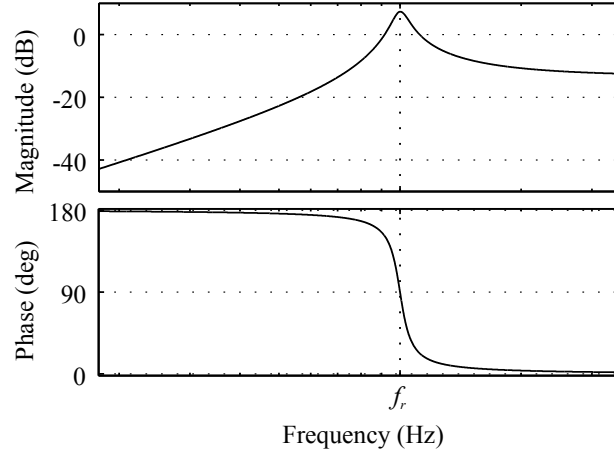


Figure 3.5: Frequency response of the resonant controller $K(s)$ when α is positive ($\alpha = 0.2190$ and $\zeta_c = 0.0472$).

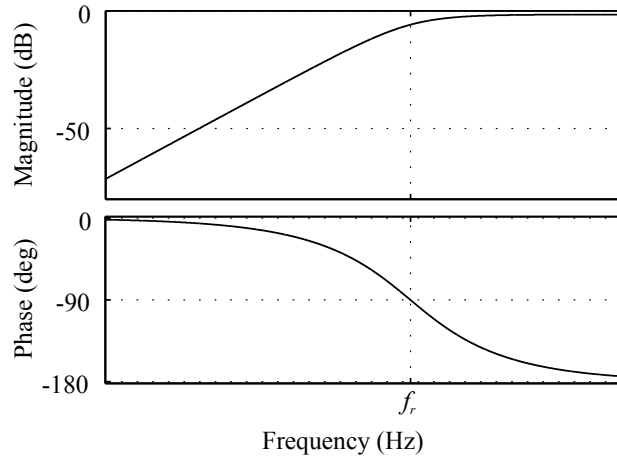


Figure 3.6: Frequency response of the resonant controller $K(s)$ when α is negative ($\alpha = -0.8441$ and $\zeta_c = 0.8263$).

pushing the closed-loop poles closer to the $j\omega$ axis, increasing the cantilever Q factor.

The closed-loop complementary sensitivity function, when the resonant controller

is applied, is

$$\begin{aligned}
T(s) &= \frac{d(s)}{v(s)} = \frac{G(s)}{1 + G(s)K(s)} \\
&= \frac{\beta\omega_n^2(s^2 + 2\zeta_c\omega_n s + \omega_n^2)}{(s^2 + 2\zeta\omega_n s + \omega_n^2)(s^2 + 2\zeta_c\omega_n s + \omega_n^2) + \beta\omega_n^2\alpha s^2} \\
&= \frac{\beta\omega_n^2(s^2 + 2\zeta_c\omega_n s + \omega_n^2)}{s^4 + \varphi s^3 + \gamma s^2 + \psi s + \omega_n^4}, \tag{3.7}
\end{aligned}$$

where $\varphi = 2\zeta\omega_n + 2\zeta_c\omega_n$, $\gamma = 2\omega_n^2 + 4\zeta\zeta_c\omega_n^2 + \beta\omega_n^2\alpha$, and $\psi = 2\zeta\omega_n^3 + 2\zeta_c\omega_n^3$.

Through the technique of pole placement the values of α and ζ_c may be determined to place the poles of $T(s)$ in locations of the complex plane to obtain the desired cantilever Q factor. Once the controller is initially tuned the operator may adjust the cantilever Q factor by simply varying α . Increasing α results in a decrease in Q and reducing α results in an increase in Q .

3.4 Stability Analysis of the Closed-Loop System With a Resonant Controller

To analyze the closed-loop stability of $T(s)$, when α and ζ_c are set to decrease the cantilever Q factor (α and ζ_c are both positive), the control loop is viewed in a positive feedback context by multiplying $K(s)$ by -1 as shown in Fig. 3.3. If $\bar{K}(s) = -K(s)$ then

$$j \left[\bar{K}(j\omega) - \bar{K}^*(j\omega) \right] = \frac{4\alpha\zeta_c\omega_n\omega^3}{(\omega_n^2 - \omega^2)^2 + (2\zeta_c\omega_n\omega)^2} \tag{3.8}$$

is greater than 0 for all $\omega > 0$. $-K(s)$ is therefore strictly negative imaginary as it is stable and satisfies condition (3.2).

As both of the transfer functions in the positive feedback loop of Fig. 3.3 are strictly negative imaginary the closed-loop transfer function $T(s)$ is guaranteed to be stable in the presence of the unmodeled dynamics of $G(s)$ if the DC loop gain is less than one, *i.e.*

$$G(0)(-K(0)) < 1, \tag{3.9}$$

which holds true for $G(s)$ and $-K(s)$.

The negative imaginary systems approach can not be used when increasing the cantilever Q factor. $-K(s)$ is not negative imaginary in this case because α is negative. As mentioned previously the poles of the first cantilever resonance will remain the dominant poles when the cantilever Q factor is increased. The poles of the first cantilever mode must therefore be placed carefully to ensure sufficient stability margins.

3.5 Controller Implementation

The controller $K(s)$ may be implemented using standard analog components such as operational amplifiers and passive components, a Digital Signal Processor (DSP) or a Field Programmable Analog Array (FPAA) [121].

3.5.1 Field Programmable Analog Array

FPAAs [121] use a programmable array of switched capacitor operational amplifier circuits to implement analog transfer functions [122]. FPAAs have an advantage over DSP based devices in that there are no quantization or sampling rate issues due to the analog nature of the device. The only limitation is the capacitor switching frequency which is 16 MHz for the Anadigm AN221E04 FPAA [123] used in this work which allows for a very high control bandwidth. The high resonance frequency of the cantilevers used in tapping mode limits the number of DSP options for controller implementation due to the high sampling rate required.

The AN220E04 FPAA used in this control implementation has many Configurable Analog Modules (CAMs) which may be configured in the FPAA to implement transfer functions via the Anadigm Designer2 PC interface software [123]. The PC interface software allows for the controller parameters to be easily modified in real time to accommodate for changing cantilever parameters and environmental conditions. The

ease in which control parameters may be changed gives the FPAA implementation an advantage over implementation with standard analog components.

The AN221E04 FPAA inputs and outputs are 0 to 4 V differential signals referenced to 2 V. The use of differential signals reduces the amount of noise processed by the device. To convert and scale the ground referenced single ended signals used by the AFM an interface circuit was developed. A description of this interface circuit is given in Appendix A. The FPAA and interface circuitry occupy a small footprint, which is an advantage when integrating the controller into an existing commercial AFM system.

3.6 The DMAPS Piezoelectric Self Actuated AFM Micro-cantilever

Piezoelectrically actuated AFM micro-cantilevers were developed to replace the bulky piezoelectric stack actuator used for cantilever oscillation when operating in tapping mode. They have also been used for Z axis actuation in some cases [31]. Piezoelectrically actuated micro-cantilevers are also becoming increasingly popular for sensing temperature, humidity, noise and the mass concentration of chemical and biological substances [124].

The micro-cantilever used in this work is the (Dimension Micro-actuated Silicon Probe) DMAPS AFM probe from Bruker AFM Probes [125]. A schematic of the DMAPS micro-cantilever is shown in Fig. 3.7. This device consists of a silicon cantilever which has a length of 120 μm and a width of 55 μm with a thin layer of piezoelectric ZnO material deposited on the bottom surface. A magnified view of the cantilever showing the relative dimensions is given in Fig. 3.8. A probe tip which has a height of 15-20 μm and a tip radius of approximately 10 nm is found on the underside of the cantilever.

The most common piezoelectric material used in micro-cantilever applications is

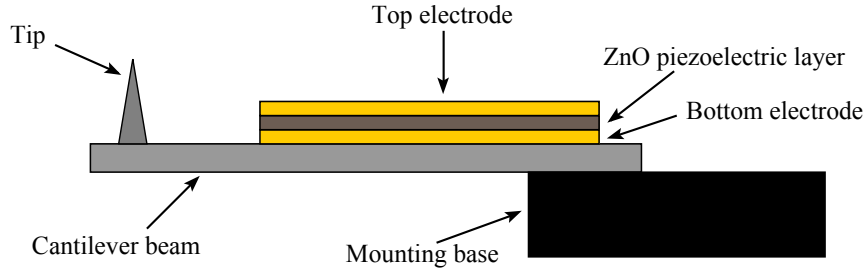


Figure 3.7: Schematic of the DMAPS micro-cantilever. A side view showing the main elements of the device.

zinc-oxide (ZnO). ZnO has a lower electromechanical coupling coefficient than lead zirconate titanate (PZT). However, the process of depositing ZnO onto micro-electro-mechanical devices such as micro-cantilevers is simpler and more cost effective than the process for PZT.

A layer of titanium gold (Ti/Au) is bonded above and below the ZnO layer acting as electrodes. Applying a voltage to the electrodes causes the piezoelectric layer to expand or contract, depending on the polarity of the voltage, resulting in flexure of the cantilever. A sinusoidal voltage is applied to the electrodes to oscillate the cantilever tip when operating in tapping mode. The breakdown voltage defined by the manufacturer is 6 V RMS. Exceeding this voltage may cause irreversible damage to the device.

The cantilever comes mounted to a ceramic base which contains gold pads that are wire bonded to the electrodes enclosing the ZnO piezoelectric. A photograph of the cantilever mounted to the base is shown in Fig. 3.9.

A frequency response of the first two resonance modes of the DMAPS micro-cantilever was obtained using a Polytec MSA 400 Microsystem Analyser. The response is shown in Fig. 3.10. The first cantilever mode occurs at 53 kHz and the second cantilever mode occurs at 239 kHz. As the characteristics of each individual cantilever vary due to manufacturing tolerances and environmental conditions, a frequency response is obtained for each individual cantilever used in the various

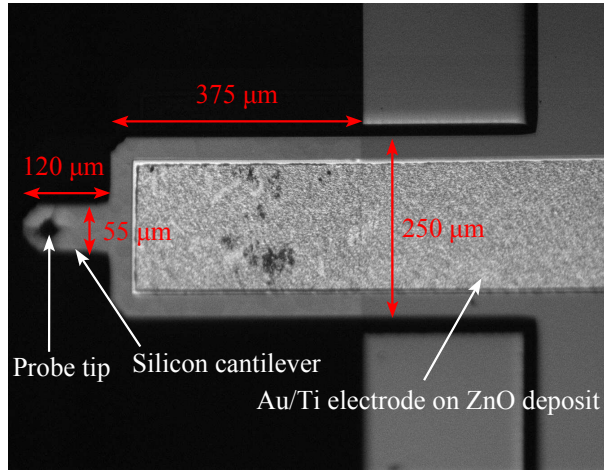


Figure 3.8: Magnified image of the DMAPS micro-cantilever.

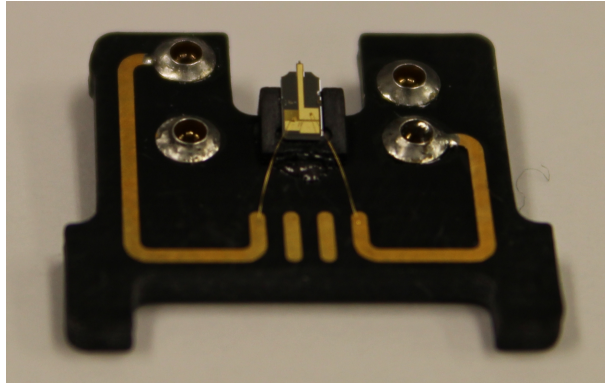


Figure 3.9: Photograph of the DMAPS micro-cantilever.

experiments throughout this thesis.

The three-dimensional modal shapes of the DMAPS micro-cantilever were obtained by defining a number of points on the micro-cantilever surface to be scanned with the MSA-400 Microsystem Analyser. The laser beam was scanned to each individual measurement point to obtain the three-dimensional mode shapes of the cantilever shown in Fig. 3.11. Along with the first two cantilever modes, which were identified in Fig. 3.10, the first torsional mode was observed. This torsional mode was not observed in the frequency response of Fig. 3.10 as the point on the tip where

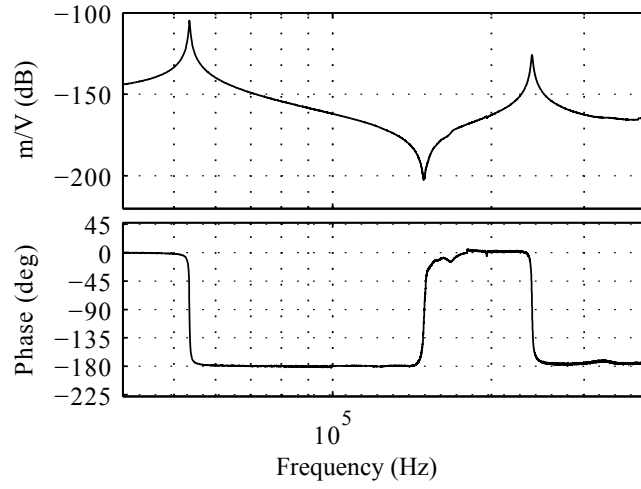


Figure 3.10: Frequency response of the first two resonance modes of the DMAPS micro-cantilever.

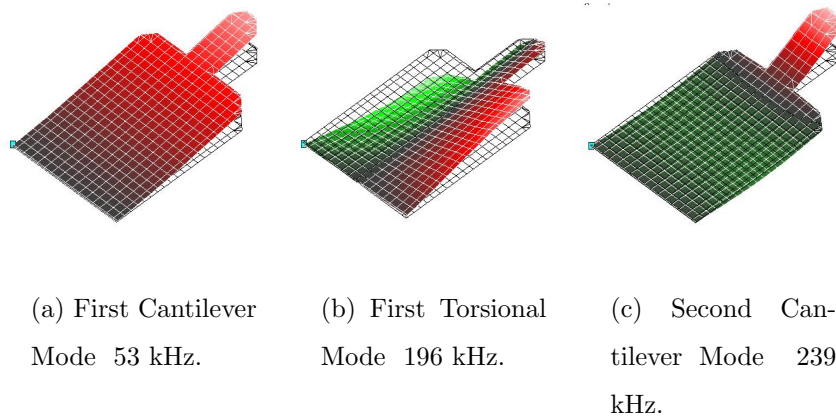


Figure 3.11: DMAPS micro-cantilever three-dimensional mode shapes.

the laser was focused is relatively static in this mode.

3.7 Pole Placement Optimization Technique for Obtaining a Desired Cantilever Q Factor

3.7.1 Reducing the Effective Cantilever Q Factor

For a second order system it is relatively easy to place the closed-loop poles to achieve a desired Q factor. The real part of the poles in the complex plane should be placed at

$$\Re(p_i) = -\frac{\omega_n}{2Q}, \quad (3.10)$$

where $\Re(p_i)$ is the real part of the i^{th} pole of the transfer function.

The closed-loop transfer function $T(s)$ is a fourth order transfer function with a pair of complex conjugate zeros. Analytically determining the effective Q factor of a higher order system such as $T(s)$ could be a tedious task. If the real part of all four poles of $T(s)$ are placed in the same location along the real axis of the complex plane the frequency response of the closed-loop system may be approximated by a second order system. In this case the approximate location of the poles of $T(s)$ along the real axis of the complex plane in relation to the effective Q factor Q^* is

$$\Re(p_i) = -\frac{\omega_n}{Q^*}. \quad (3.11)$$

A pole placement optimization technique was used in this work to place the poles of $T(s)$ at desired locations along the real axis of the complex plane to obtain a desired effective Q factor according to the relationship shown in (3.11). Only the desired real part of the poles of $T(s)$ is specified in the optimization rather than the exact location of the poles.

The resonant controller $K(s)$ has two parameters (α and ζ_c) which may be adjusted to place the poles of $T(s)$ at desired locations to obtain a desired cantilever quality factor Q_{des} .

The cost function

$$J(\alpha, \zeta_c) = \sum_{i=1}^4 (\Re(p_i^{act} - p_i^{des}))^2, \quad (3.12)$$

minimizes the absolute distance between the desired position of the poles of $T(s)$ along the real axis of the complex plane ($\Re(p_i^{des})$) and the actual position of the poles of $T(s)$ along the real axis ($\Re(p_i^{act})$). As $T(s)$ has four poles, the sum of the absolute distance for each of the four poles is used.

The Matlab function `fminsearch` uses the Nelder–Mead algorithm [126] to determine the unconstrained minimum of a given cost function and the values of the variables which produce this minimum. `fminsearch`($J(\alpha, \zeta_c)$) returns the values of α and ζ_c for which $J(\alpha, \zeta_c)$ is a minimum. As a result the poles of $T(s)$ will be placed as close as possible to the desired pole locations in order to achieve the desired cantilever Q factor.

A frequency response of $G(s)$ for the DMAPS micro-cantilever used in this experimental work was obtained using a Stanford Research Systems SRS780 dynamic signal analyzer. A 1 V periodic chirp signal was applied to the cantilever and the voltage output from the AFM photodiode sensor was recorded. The AFM used in this work is the NTEGRA AFM manufactured by NT-MDT [127]. The measured frequency response of $G(s)$ is shown in Fig. 3.12. The transfer function

$$G(s) = \frac{1.12 \times 10^9}{s^2 + 1976s + 1.245 \times 10^{11}} \quad (3.13)$$

was obtained from the frequency response of Fig. 3.12 through system identification. From (3.13) the values for $\omega_n = 2\pi \times 56150$ rad/sec and $Q = 178.6$ were obtained for the cantilever. Q_{des} was chosen to be 40, which gives a significant reduction in the cantilever Q factor while retaining sufficient force sensitivity.

The real part of the open-loop poles is $\Re(p_i^{ol}) = \frac{\omega_n}{2Q} = -988$. The desired real part of the closed-loop poles is $\Re(p_i^{des}) = \frac{\omega_n}{Q_{des}} = -8820$.

The pole placement optimization technique described above was used to place all four poles of $T(s)$ at $\Re(p_i^{des})$. Using this technique the optimal values for α and ζ_c

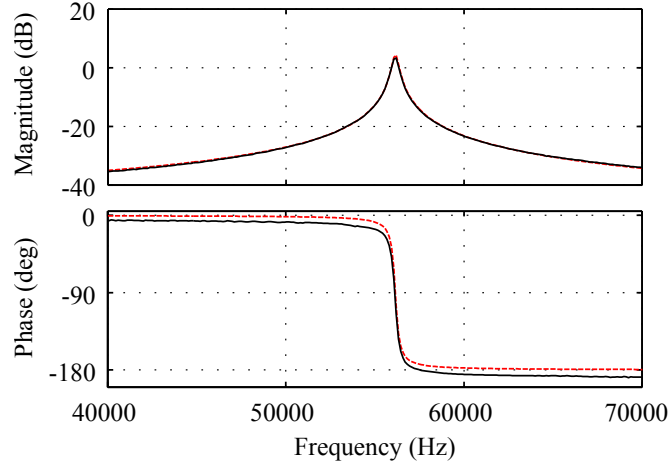


Figure 3.12: Frequency response of the DMAPS micro-cantilever's first resonance mode (—) and fitted model (- -).

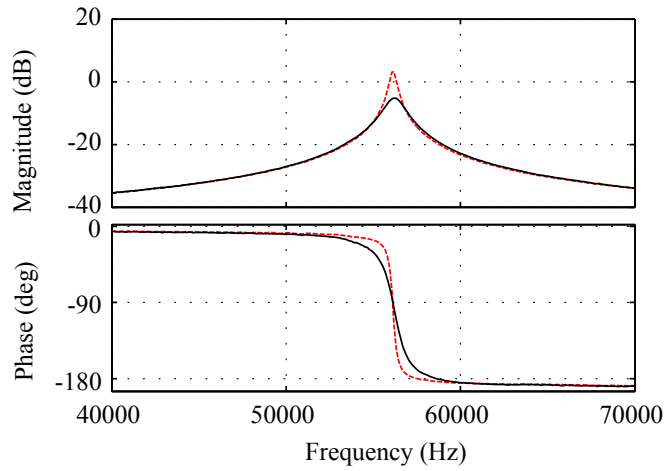


Figure 3.13: Frequency response of the DMAPS micro-cantilever in open-loop (- -), with a Q factor of 178.6, and closed-loop (—) with an effective Q factor of 37.5.

were found to be $\alpha = 0.2190$ and $\zeta_c = 0.0472$.

The controller was implemented in the FPAA with the parameters determined above for a desired Q factor of 40. The measured closed-loop frequency response of $T(s)$ along with the measured open-loop frequency response are shown in Fig. 3.13 and a pole zero map showing the open and closed-loop pole locations is shown in Fig. 3.14. The closed-loop pole locations in the real axis are very close to the desired poles

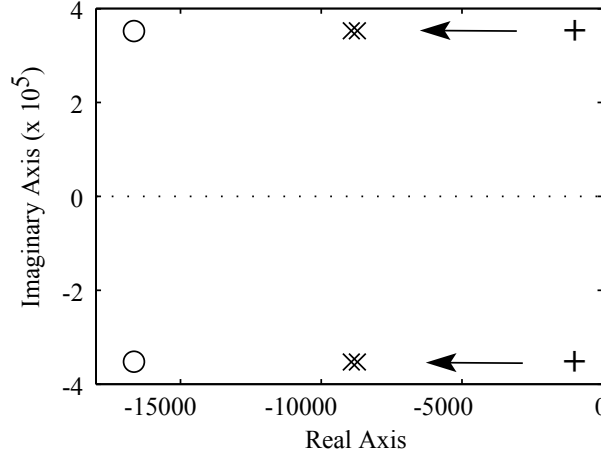


Figure 3.14: The open-loop pole (+) locations and closed-loop pole (x) and zero (o) locations of the DMAP micro-cantilever with resonant control Q factor reduction.

of $\Re(p_i^{des}) = -8820$.

The effective Q factor of the closed-loop system was determined from the frequency response of $T(s)$, shown in Fig. 3.13, by measuring the resonance frequency f_r and the half power bandwidth Δf_{-3dB} . The effective cantilever Q factor is

$$Q^* \cong \frac{f_r}{\Delta f_{-3dB}}. \quad (3.14)$$

The effective Q factor measured from the frequency response of $T(s)$ in Fig. 3.13 using this method was 37.5.

3.7.2 Increasing the Effective Cantilever Q Factor

When increasing the cantilever Q factor it is not possible to place all four poles of $T(s)$ at the desired locations close to the $j\omega$ axis, as the cost function of (3.12) does not converge under feedback control with a controller structure of (3.6). It is only possible to place two of the poles of $T(s)$ at the desired locations. As these two poles will be the dominant poles of the closed-loop transfer function the closed-loop transfer function may be approximated by a second order model and the location of the dominant poles along the real axis is determined by (3.10).

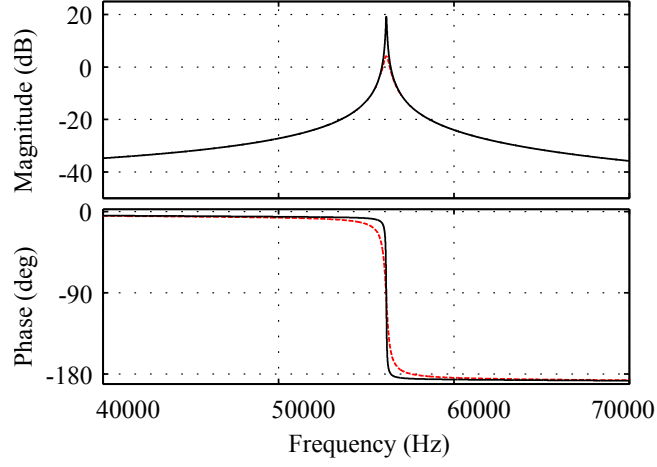


Figure 3.15: Frequency response of the DMAPS micro-cantilever in open-loop (- -), with a Q factor of 178.6, and closed-loop (—) with an effective Q factor of 990.

The cost function is modified to

$$J(\alpha, \zeta_c) = \sum_{i=1}^2 \left(\Re(p_i^{act} - p_i^{des}) \right)^2, \quad (3.15)$$

where the absolute distance between the desired position of two of the poles of $T(s)$ and the actual position of the poles of $T(s)$ along the real axis is minimized.

The pole placement technique was used to increase the cantilever Q factor from $Q = 178.6$ to $Q_{des} = 1000$, where $\Re(p_i^{des})$ is now -176.4. The values obtained for α and ζ_c using this technique place the remaining two poles of $T(s)$ deep into the left half of the complex plane. The optimal values for α and ζ_c were found to be $\alpha = -0.8441$ and $\zeta_c = 0.8263$.

The open and closed-loop frequency responses are shown in Fig. 3.15 and a pole zero map showing the open and closed-loop pole locations is shown in Fig. 3.16. Note that only two of the closed-loop poles are shown in the closed-loop pole zero map. The remaining two closed-loop poles are deep in the left half plane at $-292000 \pm j198000$. Therefore, these poles may be ignored. The poles shown on the pole zero map are at $-176 \pm j353000$. The effective cantilever Q factor of $T(s)$ was measured at 990 from the frequency response of Fig. 3.15.

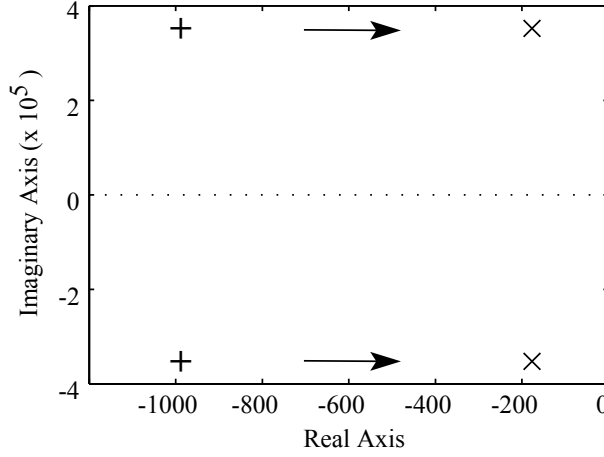


Figure 3.16: The open-loop pole (+) locations and closed-loop pole (x) locations of the DMAPS micro-cantilever with resonant control Q factor enhancement. Note that there is another pair of complex poles located at $-292000 \pm j198000$ in closed-loop.

3.7.3 Modification of the Effective Cantilever Q Factor

After Initial Pole Placement

After the values of α and ζ_c have been set it is easy to modify the effective Q factor. From (2.10) it can be seen that the effective Q factor depends on the gain of the velocity feedback. This gain is the value of $K(s)$ at ω_n which is proportional to α . Increasing α will reduce the effective cantilever Q factor, and decreasing α will enhance the effective cantilever Q factor.

3.8 AFM Imaging With the Resonant Control Technique

To demonstrate the effectiveness of the resonant controller and the benefits of reducing the cantilever Q factor, images of a NT-MDT TGZ1 [127] calibration grating were obtained with and without the resonant controller. The grating consists of a periodic step formed from silicon dioxide with a period of $3 \pm 0.05 \mu\text{m}$ and step height

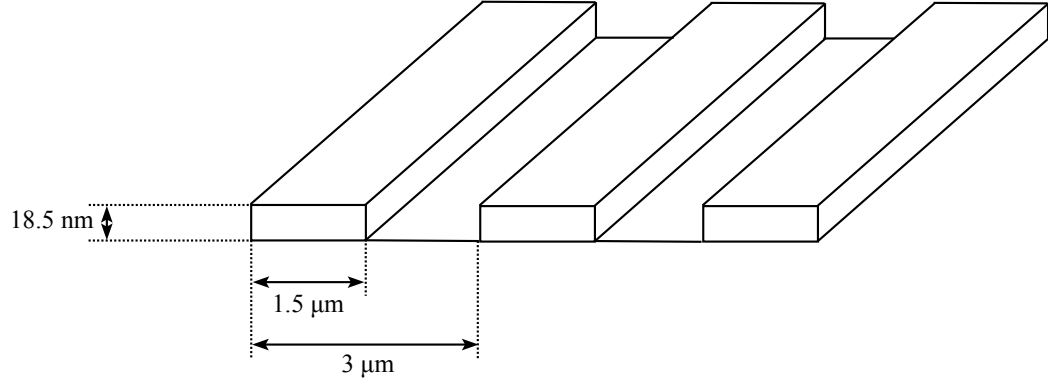
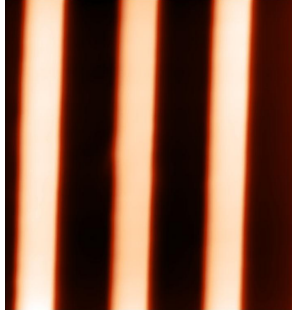


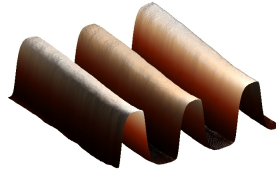
Figure 3.17: Diagram showing the relevant dimensions of the NT-MDT TGZ1 calibration grating.

of 18.5 ± 1 nm as shown in Fig. 3.17.

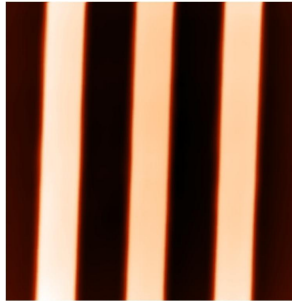
Scans were obtained on a $10 \mu\text{m} \times 10 \mu\text{m}$ section of the calibration grating at a scan speed of $20 \mu\text{m/s}$. Images were obtained with no Q control ($Q=178.6$) and with the resonant controller applied to reduce the cantilever Q factor to $Q=37.5$. The Z axis feedback controller gain (K_Z) was increased until the loop became unstable. K_Z was then reduced slightly to ensure loop stability. The maximum value of K_Z obtainable when the resonant controller was applied was 7 times the gain obtainable without the controller. The images obtained with and without the resonant controller are shown in Fig. 3.18. A cross section of the three-dimensional images is shown in Fig. 3.19. It can be seen from these images that the increase in feedback gain significantly reduced the artifacts in the image obtained. This demonstrates that using resonant control to reduce the effective cantilever Q factor can significantly improve the Z axis feedback bandwidth which improves image quality at high scan speeds.



(a) 2D image without resonant control.



(b) 3D image without resonant control.



(c) 2D image with resonant control.



(d) 3D image with resonant control.

Figure 3.18: Images of the NT-MDT TGZ1 calibration grating obtained at a scan speed of $20 \mu\text{m/s}$. In each case the maximum value of K_Z , which ensured loop stability, was used. The use of resonant control to reduce the cantilever Q factor increased the cantilever response speed which allowed a higher feedback gain to be used and consequently reduced image distortion.

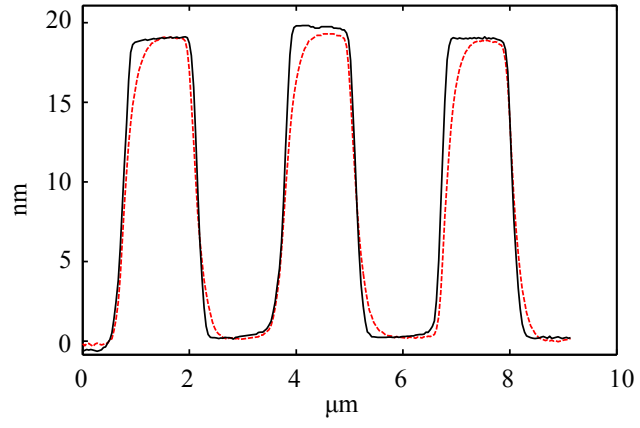


Figure 3.19: Cross section of the NT-MDT TGZ1 sample topography obtained with (—) and without (- -) resonant control.

Chapter 4

Sensorless Reduction of Cantilever Q Factor With Passive Piezoelectric Shunt Control

In Chapter 3 active Q control using a resonant controller was introduced as a new technique to modify the Q factor of an AFM micro-cantilever. This control technique has an advantage over the time delay method of velocity estimation commonly used in active Q control in that there are no spill-over effects from the control action, ensuring stability of higher order modes. Like conventional methods of active Q control the resonant control technique uses an optical sensor in the feedback loop.

The optical deflection sensing technique used to measure cantilever tip displacement in most commercial AFMs introduces a significant amount of noise into the deflection measurement. In addition to electronic noise, two other forms of noise are introduced by the optical sensor. The first form of noise introduced by the optical sensor is due to stray beams of light reflecting off the sample surface and back into the photodiode sensor [128]. The second form of noise is due to light reflecting back from the cantilever and the sample into the laser source [128]. Imaging in a liquid

environment is particularly problematic due to reflection and refraction of the laser beam at the interface between air and water.

Other problems with the optical deflection sensing technique include the time taken to align the laser beam and the size of the sensor. The task of aligning the laser beam must be completed every time that the cantilever is changed. This can be a tedious and time consuming task. The optical sensor occupies a relatively large amount of space. Reducing the size of the sensor is an advantage for applications which use an array of cantilevers [129–131] and to reduce the size of the AFM [130]. One application of the AFM where a reduction in instrument size is a benefit is in the investigation of matter on interplanetary explorations [132].

In this chapter passive piezoelectric shunt control is introduced as an alternative technique for reducing the Q factor of a self actuated piezoelectric AFM micro-cantilever. This technique removes the optical sensor from the Q control feedback loop to reduce sensor artifacts in the loop. If the cantilever displacement can be measured with the piezoelectric transducer [40, 48, 49] it would be possible to remove the optical sensor from the AFM altogether, overcoming the limitations of the optical sensing technique mentioned above.

The passive piezoelectric shunt controller has a similar control structure to the resonant controller. The similarities between passive piezoelectric shunt control and resonant control are discussed in detail in [133]. Like the resonant controller the closed-loop stability of the passive piezoelectric shunt controller may be proven using the negative imaginary systems theory.

Passive piezoelectric shunt control may not be applicable in all situations as the reduction of the cantilever Q factor is limited by the properties of the actuator and it may not be feasible to use a self actuated piezoelectric micro-cantilever in some AFMs.

When an increase in the cantilever Q factor is desired a passive impedance can not be used, as energy must be added to the system to increase the cantilever Q factor.

For this reason an active impedance must be used. This is demonstrated in Chapter 5.

4.1 The Piezoelectric Effect

The piezoelectric effect is the property exhibited by crystals and certain ceramic materials that generate electrical charge in response to a mechanical strain (compressing or stretching the material). Conversely, when a voltage is applied across the piezoelectric material, a mechanical stress is generated [134]. This effect naturally occurs in crystals such as quartz, Rochelle salt and tourmaline. The behaviour of these materials is weak compared to man made ceramics such as barium titanate, PZT and ZnO [135].

As detailed in [136] each molecule of a crystal has a polarization. One end is positively charged and the other end is negatively charged. This is termed a dipole. A crystalline material contains electric dipoles arranged in random directions. A crystalline deformation occurs along the axis in which each dipole is aligned when an electric field is present. When an electric field is applied to the material the response of the dipoles cancels one another out due to this random alignment, leading to zero average deformation of the crystal. When the dipoles of the material are permanently aligned (this process is termed poling) a physical response may be observed when an electric field is applied to the material, or an electric field is produced when the material is strained.

The Curie temperature T_c of a piezoelectric material is the temperature above which the material becomes depolarized. T_c is greater than 300°C for many materials. The poling process involves heating the material to just below its Curie temperature and then applying a strong DC electric field, which forces the dipoles in the crystal to line up and face in the same direction [134]. The element becomes elongated and permanently polarized in the direction of the applied field after the field is removed.

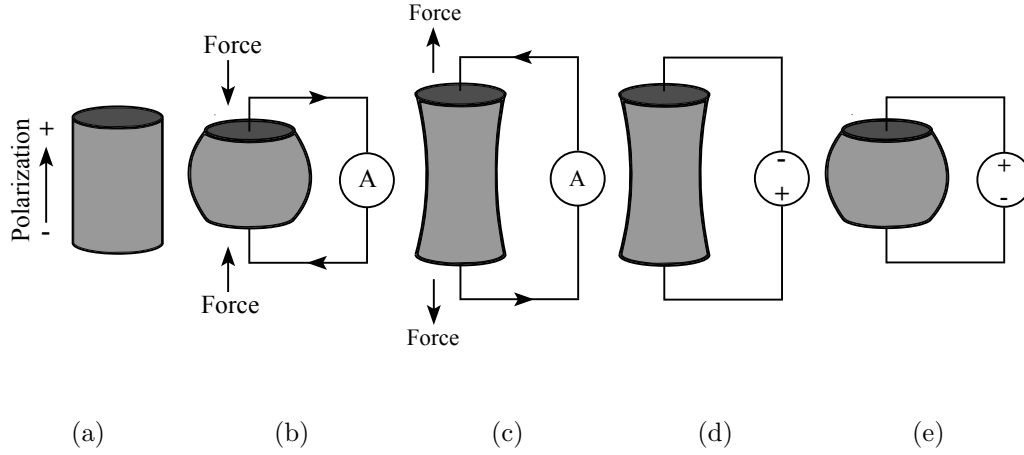


Figure 4.1: Response of a piezoelectric transducer to an applied force and an applied voltage. The transducer with no applied stimulus is shown in (a). The response to an applied force is shown in (b) and (c). The response to an applied voltage is shown in (d) and (e).

A more thorough explanation of the poling process is given in [134].

Compression along the direction of polarization or tension perpendicular to the direction of polarization generates a voltage of the same polarity as the polarizing voltage [134], as shown in Fig. 4.1(b). Tension along the direction of polarization or compression perpendicular to the direction of polarization generates a voltage opposite in polarity to the polarizing voltage [134], as shown in Fig. 4.1(c). If a voltage with an opposite polarity to the poling voltage is applied to the piezoelectric element, the element will lengthen and the width will become narrower as shown in Fig. 4.1(d). If a voltage with the same polarity to the polarizing voltage is applied to the piezoelectric element, the element will shorten and the width will become wider as shown in Fig. 4.1(e).

A piezoelectric material may be used as a sensor or an actuator or a combination of the two. When used as a sensor, strain is measured by observing the voltage generated by the material. When used as an actuator strain is generated by applying a voltage to the material. Piezoelectric materials work well as high resolution sensors

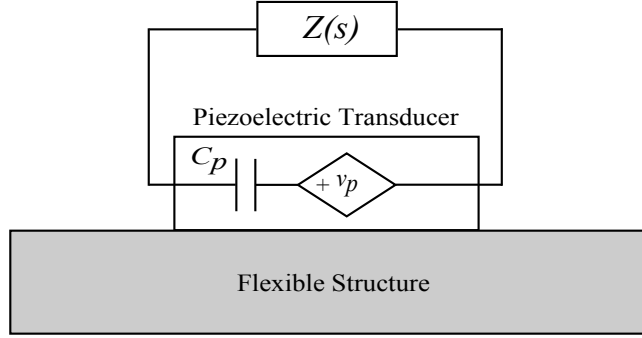


Figure 4.2: Piezoelectric shunt control of a flexible structure. A piezoelectric transducer is bonded to the structure and an electrical impedance $Z(s)$ is attached to its electrodes. The dynamics of the electrical circuit influence the mechanical dynamics of the structure.

and actuators in nanoscale systems due to the large voltages produced by a small displacement and the small displacements resulting from a large voltage.

4.2 Piezoelectric Shunt Control of Flexible Structures

The efficiency at which piezoelectric materials transform mechanical energy into electrical energy and vice versa has led to their use in damping undesired vibration in flexible structures such as snowboards [137], automobile bodies [138], flexible space structures [139,140], and aircraft [141,142]. Piezoelectric shunt control involves bonding a piezoelectric transducer to a structure and connecting an electrical impedance to its terminals [133] as shown in Fig. 4.2. Piezoelectric shunt control was first introduced by Forward [143] with an experimental demonstration of the technique. An analytical description of piezoelectric shunt control was later presented by Hagood and von Flowtow [144] in which the shunt circuit is shown to be analogous to a mechanical proof mass damper.

Piezoelectric shunt control has been used to increase the bandwidth of AFM scan-

ners by damping the first resonant mode of the scanner. This was demonstrated in [145] and [146] with a piezoelectric tube scanner and in [147] with a piezoelectric stack actuated flexure based scanner.

4.3 Passive Piezoelectric Shunt Control of a Self Actuated Piezoelectric AFM Micro-cantilever

The self actuated piezoelectric AFM micro-cantilever used in this work is described in Chapter 3 Section 3.6. The piezoelectric transducer bonded to the cantilever may be modeled as a strain dependent voltage source v_p in series with a capacitance C_p [148]. When a shunt impedance $Z(s)$, consisting of a resistor R and an inductor L , is placed in series with the driving voltage source v_s an LRC circuit is obtained, as shown in Fig. 4.3. Tuning the electrical resonance of the LRC circuit to the mechanical resonance of the cantilever ensures that the electrical dynamics of the circuit interact with the mechanical dynamics of the cantilever. The damped electrical resonance acts to increase the mechanical damping of the cantilever, *i.e.* a reduction in the Q factor. Varying the value of R in the circuit modifies the amount of electrical damping; therefore the probe Q factor may be tuned by varying the value of R in the circuit.

4.3.1 System Modeling

The piezoelectric cantilever may be modeled by the system G , as shown in Fig. 4.4, where w is a disturbance strain on the cantilever due to a change in the sample topography, d is the displacement of the cantilever tip, v is the voltage across the piezoelectric transducer terminals and q is the charge generated by the piezoelectric transducer. The electrical and mechanical system depicted in Fig. 4.3 may be represented by the block diagram in Fig. 4.5, where v_z is the voltage across the shunt

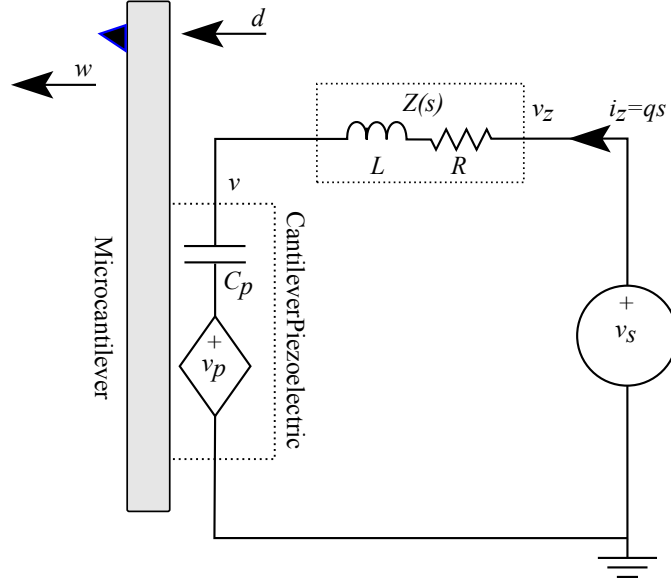


Figure 4.3: Piezoelectric shunt control applied to a self actuating piezoelectric microcantilever. The impedance $Z(s)$ is placed in series with the oscillation voltage source v_s to create an LRC circuit. The dynamics of this LRC circuit influence the mechanical dynamics of the cantilever.

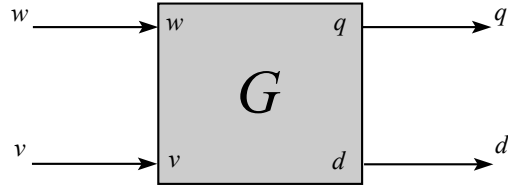


Figure 4.4: Piezoelectric cantilever model describing the tip displacement d and generated charge q in response to an applied voltage v and disturbance w .

impedance, α is the piezoelectric voltage to displacement coefficient ($\alpha = \frac{v_p}{d}$), d_w is the initial displacement due to a sample perturbation, $G_{dv}(s)$ is the transfer function from $v(s)$ to $d(s)$, and $G_{dw}(s)$ is the transfer function from $w(s)$ to $d_w(s)$. In the standard second order transfer function form:

$$G_{dv}(s) = \frac{d(s)}{v(s)} = \frac{\beta_v \omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2}, \quad (4.1)$$

and

$$G_{dw}(s) = \frac{d_w(s)}{w(s)} = \frac{\beta_w \omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2}, \quad (4.2)$$

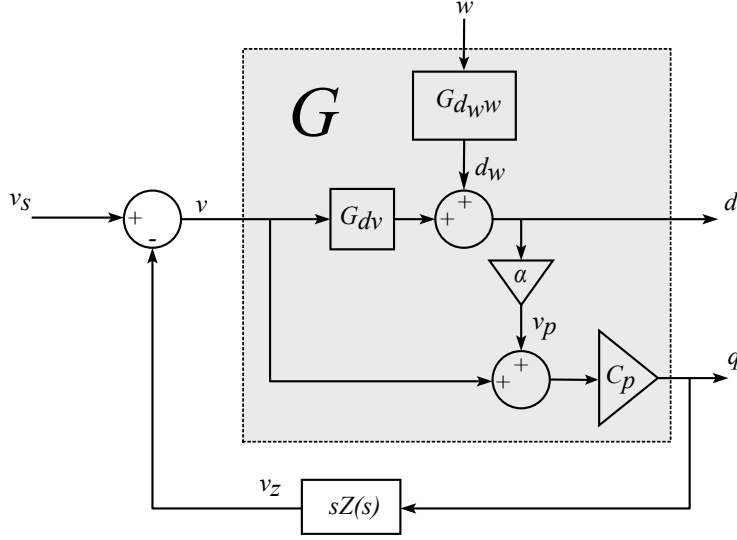


Figure 4.5: Block diagram of the piezoelectric shunt control system. The cantilever is represented by the system G which has two inputs (the terminal voltage v and a disturbance strain w) and two outputs (the charge generated by the piezoelectric transducer q and the cantilever tip displacement d).

where β_v and β_w are the steady state gains of $G_{dv}(s)$ and $G_{dww}(s)$ respectively.

4.3.1.1 Modeling the transfer function from actuating voltage to tip displacement

From the block diagram of Fig. 4.5 the transfer function from v_s to v may be derived as

$$G_{vv_s}(s) = \frac{v(s)}{v_s(s)} = \frac{1}{1 + sZ(s)G_{qv}(s)}, \quad (4.3)$$

where $G_{qv}(s)$ is the transfer function from $v(s)$ to $q(s)$ represented by

$$G_{qv}(s) = \frac{q(s)}{v(s)} = \alpha C_p G_{dv} + C_p. \quad (4.4)$$

Substituting (4.4) into (4.3) the transfer function from $v_s(s)$ to $v(s)$ is derived as

$$G_{vv_s}(s) = \frac{1}{1 + \frac{sZ(s)C_p \alpha G_{dv}}{1 + sZ(s)C_p}}. \quad (4.5)$$

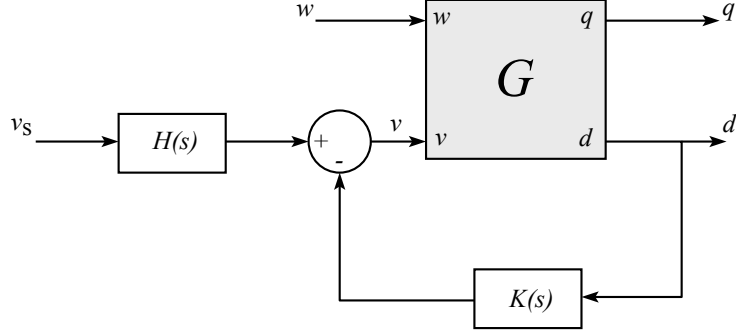


Figure 4.6: Equivalent feedback system from v_s to d . The filter $H(s)$ in the feed forward path is due to the electrical dynamics of the shunt impedance.

To simplify (4.5) let

$$H(s) = \frac{1}{1 + sZ(s)C_p} \quad (4.6)$$

and

$$K(s) = \frac{sZ(s)C_p\alpha}{1 + sZ(s)C_p}, \quad (4.7)$$

then

$$G_{vv_s}(s) = \frac{H(s)}{1 + K(s)G_{dv}(s)}. \quad (4.8)$$

The transfer function from v_s to d , when the shunt is applied, is now found to be

$$G_{dv_s}(s) = G_{vv_s}(s)G_{dv}(s) = \frac{H(s)G_{dv}(s)}{1 + K(s)G_{dv}(s)}. \quad (4.9)$$

G_{dv_s} may be viewed as a negative feedback loop with a filter $H(s)$ (which is due to the electrical dynamics of the shunt impedance) in the feed-forward path as shown in Fig. 4.6. $H(s)$ adds a filter in the cantilever transfer function from v_s to d . For accurate tracking of the driving signal it must be pre-filtered by $H^{-1}(s)$ to compensate for $H(s)$. When operating in tapping mode the driving signal is a single frequency sinusoid. The effect of $H(s)$ on this signal is a modification of magnitude and phase. The change in magnitude can easily be compensated for by varying the amplitude of the drive signal. The change in phase will not affect the operation of the device so there is no need to compensate for this.

4.3.1.2 Modeling the transfer function from a perturbation in sample topography to tip displacement

To obtain the transfer function from a perturbation in sample topography to tip displacement, $v_s(s)$ is first set to zero. From Fig. 4.5 it is observed that

$$v = -v_z(s), \quad (4.10)$$

and

$$v_z(s) = sq(s)Z(s), \quad (4.11)$$

where $q(s)$ is given by

$$q(s) = -v_z(s)C_p - v_z(s)\alpha C_p G_{dv}(s) + d_w(s)\alpha C_p. \quad (4.12)$$

Substituting (4.12) into (4.11) gives

$$v_z(s) = [-v_z(s)C_p - v_z(s)\alpha C_p G_{dv}(s) + d_w(s)\alpha C_p] sZ(s). \quad (4.13)$$

Substituting (4.10) into (4.13) results in the transfer function

$$\begin{aligned} G_{vd_w}(s) &= \frac{v(s)}{d_w(s)} \\ &= \frac{-\alpha s Z(s) C_p}{1 + s Z(s) C_p + \alpha s Z(s) C_p G_{dv}(s)}. \end{aligned} \quad (4.14)$$

From Fig. 4.5 it is observed that

$$d(s) = G_{vd_w}(s)G_{dv}(s)d_w(s) + d_w(s). \quad (4.15)$$

Substituting (4.14) into (4.15) results in the transfer function

$$\begin{aligned} G_{dd_w}(s) = \frac{d(s)}{d_w(s)} &= \frac{1}{1 + \frac{\alpha s Z(s) C_p G_{dv}(s)}{1 + s Z(s) C_p}} \\ &= \frac{1}{1 + K(s)G_{dv}(s)}. \end{aligned} \quad (4.16)$$

Combining (4.16) and (4.2) results in the transfer function

$$\begin{aligned} G_{dw}(s) &= G_{dd_w}(s)G_{d_w w}(s) \\ &= \frac{G_{d_w w}(s)}{1 + K(s)G_{dv}(s)}. \end{aligned} \quad (4.17)$$

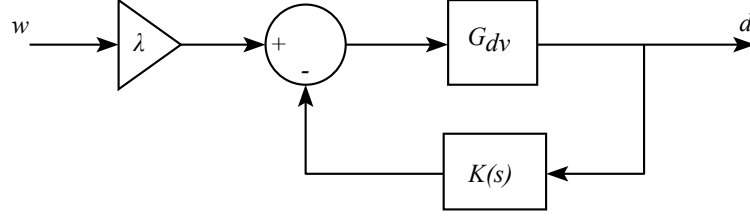


Figure 4.7: Feedback interpretation of the transfer function from a disturbance w to cantilever tip displacement d . $G_{dv}(s)$ is the transfer function from the piezoelectric terminal voltage v to cantilever tip displacement d . The controller $K(s)$ is a function of the shunt impedance $Z(s)$.

Note that the transfer function $G_{dw}(s)$ has the same poles as $G_{dv}(s)$. The only difference being the steady state gain β_w . The transfer function $G_{dw}(s)$ may be written as

$$G_{dw}(s) = \frac{\lambda G_{dv}(s)}{1 + K(s)G_{dv}(s)}, \quad (4.18)$$

as shown in Fig. 4.7, where $\lambda = \frac{\beta_w}{\beta_v}$. Therefore, it can be seen that the transfer function from a perturbation in the sample topography to tip displacement may be viewed as a negative feedback system. The controller $K(s)$ may be designed using standard feedback control techniques, allowing the poles of $G_{dw}(s)$ to be placed according to the desired performance objectives.

Note that the transfer function of the controller is

$$K(s) = \frac{\alpha s \left(s + \frac{R}{L} \right)}{s^2 + \frac{R}{L}s + \frac{1}{C_p L}}. \quad (4.19)$$

A frequency response of the controller resulting from the passive shunt impedance designed in Section 4.5 is shown in Fig. 4.8. This is a bandpass filter with a phase lead of $\frac{\pi}{2}$ at the resonance frequency (f_r). If f_r is tuned to the oscillation frequency of the cantilever the controller is effectively estimating the cantilever tip velocity and applying a gain, similar to the active Q controller described in Chapter 2 Section 2.3.3. The gain and bandwidth of control may be tuned by varying the parameters R and L .

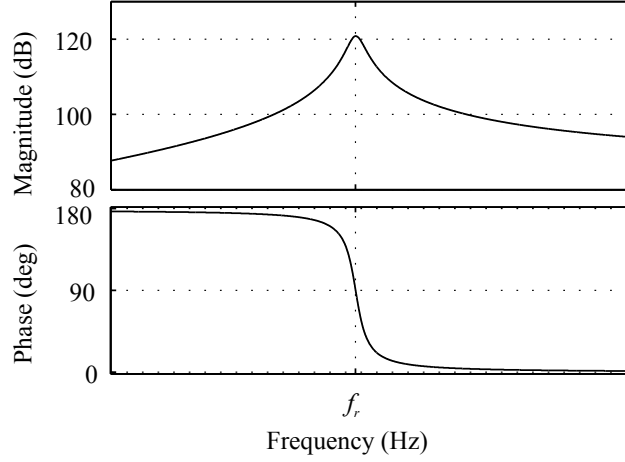


Figure 4.8: Frequency response of the controller resulting from the passive shunt impedance designed in Section 4.5. As the input signal is sinusoidal this controller therefore approximates a differentiator at the resonance frequency of the filter.

4.4 Closed-Loop Stability Analysis of the Passive Piezoelectric Shunt Controller

The closed-loop stability of the passive piezoelectric shunt controller in the presence of unmodeled cantilever dynamics may be analyzed using the theory of negative imaginary systems outlined in Chapter 3 Section 3.2. This theory states that two negative imaginary systems arranged in a positive feedback loop have guaranteed closed-loop stability in the presence of unmodeled higher order dynamics if two conditions are satisfied. These two conditions are:

- at least one of the systems is strictly negative imaginary; and
- the DC loop gain is less than one.

To analyze the closed-loop stability of the system, when the passive shunt controller is applied, the control loop is viewed in a positive feedback context by multi-

plying $K(s)$ by -1 as shown in Fig. 3.3. If $\overline{K}(s) = -K(s)$ then

$$j \left[\overline{K}(j\omega) - \overline{K}^*(j\omega) \right] = \frac{4\alpha \frac{R}{L} \omega^3 + 2\alpha \frac{R}{C_p^2 L^3} \omega}{\left(\frac{1}{(C_p L)^2} - \omega^2 \right)^2 + \left(\frac{R}{L} \omega \right)^2} \quad (4.20)$$

is greater than 0 for all $\omega > 0$. $-K(s)$ is therefore strictly negative imaginary as it is stable and satisfies condition (3.2).

As both of the transfer functions in the positive feedback loop are strictly negative imaginary the closed-loop transfer function will be guaranteed stable in the presence of the unmodeled dynamics of $G(s)$ if the DC loop gain is less than one, *i.e.*

$$G(0)(-K(0)) < 1, \quad (4.21)$$

which holds true for $G(s)$ and $-K(s)$.

4.5 System Model Parameters Obtained From Experimental Results

To determine optimal values of L and R for the desired cantilever Q factor, mathematical models of $G_{dv}(s)$ and $K(s)$ must be obtained and analyzed. A frequency response of $G_{dv}(s)$, for the DMAPS micro-cantilever used in this experimental work, was obtained with a Microscope Scanning Laser Doppler Vibrometer (Polytec MSV 400). The cantilever was excited by applying a pseudo random signal, and the resulting tip displacement measured. The frequency response of $G_{dv}(s)$ is shown in Fig. 4.9. The mathematical model of $G_{dv}(s)$ obtained by system identification is

$$G_{dv}(s) = \frac{1915}{s^2 + 1150s + 1.133 \times 10^{11}}, \quad (4.22)$$

and is also shown in Fig. 4.9.

Note from (4.7) that α and C_p are properties of the cantilever and must be determined in order to design $K(s)$. C_p was measured at 23.4 pF using an Agilent E4980A *LCR* meter.

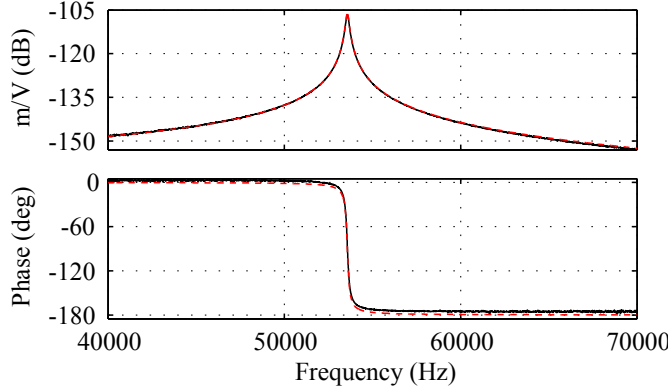


Figure 4.9: Frequency response of the DMAPS micro-cantilever's first resonance mode (---) and fitted model (—).

4.5.1 Determination of α by Measuring the Cantilever Impedance

Rearranging (4.4) results in the transfer function

$$Z_p(s) = \frac{v(s)}{i(s)} = \frac{v(s)}{sq(s)} = \frac{1}{sG_{qv}(s)} = \frac{1}{\alpha C_p G_{dv}s + C_p s}. \quad (4.23)$$

The only unknown in (4.23) is α which was determined by measuring the cantilever impedance and obtaining a transfer function of the impedance from this measurement.

A frequency response of the cantilever impedance was obtained by applying a swept sine current to the cantilever terminals and measuring the resulting voltage at the terminals using the circuit shown in Fig. 4.10. The impedance of the cantilever is measured by applying a swept sine input voltage v_{in} . This causes a current $i_p = \frac{v_{in}}{50k}$ to flow through the piezoelectric transducer. The impedance is measured by taking the frequency response of $\frac{v(s)}{i_p(s)}$ as shown in Fig. 4.11.

Note that the phase of the impedance off resonance is slightly higher than the expected -90 degrees. This is due to dielectric losses in the piezoelectric transducer (see Chapter 5 Section 5.1.1). The inclusion of these losses in the cantilever model results in a marginal increase in the damping obtained with passive piezoelectric shunt control. To simplify the calculations involved in determining the shunt impedance

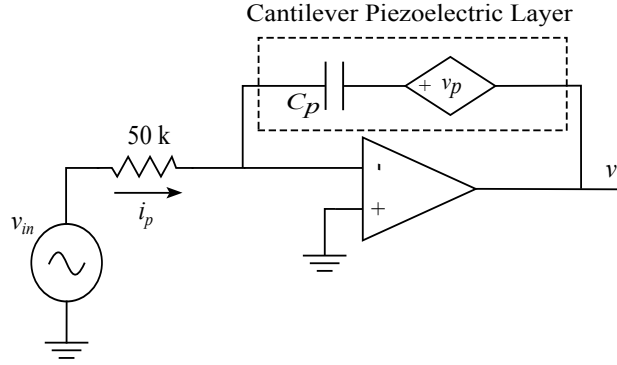


Figure 4.10: Circuit used to measure the cantilever impedance. A swept sine current is applied to the cantilever piezoelectric layer and the resulting terminal voltage is measured.

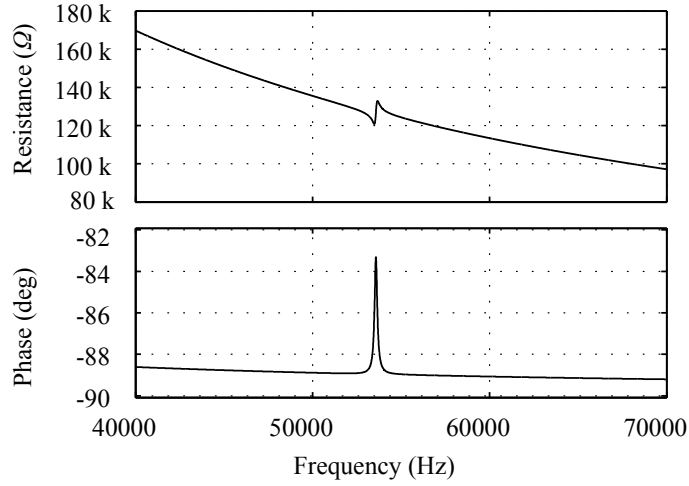


Figure 4.11: Frequency response of the DMASP micro-cantilever electrical impedance.

parameters the dielectric losses have not been included in the cantilever impedance model. In Chapter 5 piezoelectric shunt control is used to increase the cantilever Q factor. It was found that when increasing the cantilever Q factor with piezoelectric shunt control the dielectric losses must be accounted for.

Neglecting dielectric losses, the transfer function obtained from Fig. 4.10 is

$$Z_p(s) = \frac{4.271 \times 10^{10} s^2 + 4.912 \times 10^{13} s + 4.840 \times 10^{21}}{s^3 + 1150 s^2 + 1.133 \times 10^{11} s}. \quad (4.24)$$

Equating 4.23 and 4.24 gives a value of $\alpha \approx 2 \times 10^4$ V/m.

4.6 Determination of Shunt Impedance Parameters to Obtain the Maximum Reduction in Cantilever Q Factor

The amount of cantilever Q factor reduction obtainable when passive piezoelectric shunt control is applied is limited by the properties of the piezoelectric transducer. The following steps were taken to analytically find the control parameters which would result in the maximum reduction in cantilever Q factor.

4.6.1 Inductance

For a series LCR circuit the undamped resonance frequency is given by

$$\omega_r = 2\pi f_r = 1/\sqrt{LC_p}. \quad (4.25)$$

From the frequency response shown in Fig. 4.9 it can be seen that the resonance frequency f_r of the first mode occurs at 53580 Hz. Note that the resonance frequency will shift from f_r to a slightly lower value f_d , when the shunt circuit is connected, as the damping of the cantilever is altered. This will alter the required value of L . As the cantilever Q factor is significantly high it may be assumed that $f_d \approx f_r$, therefore the change in L will be insignificant. Substituting the values for f_r and C_p into (4.25) gives a value for L of 376.90 mH.

4.6.2 Resistance

The H_2 norm of the transfer function $G_{dw}(s)$ was used to determine the lowest Q factor which can be obtained with the DMAP micro-cantilever using passive piezoelectric shunt control. The H_2 norm of a system represents the variance of the output given a white-noise input. When the H_2 norm of the system is minimized the system damping is at a maximum since the area under the magnitude curve of

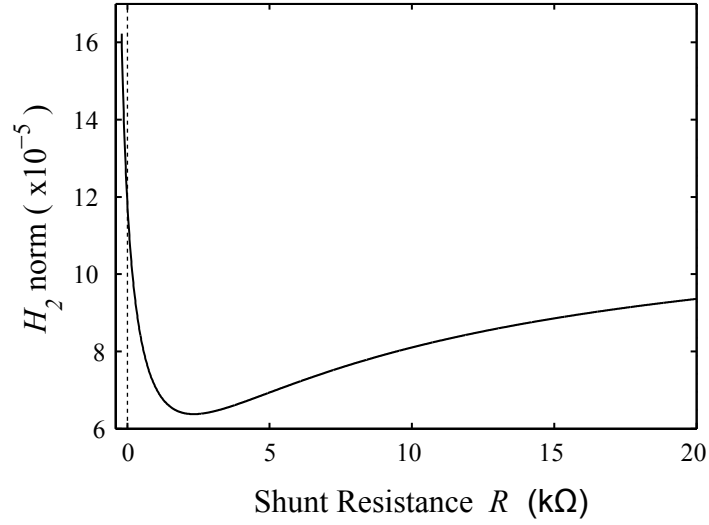


Figure 4.12: H_2 norm of G_{dw} vs. R . By minimizing the H_2 norm of G_{dw} the maximum reduction of the cantilever Q factor is achieved.

the frequency response is minimized. The H_2 norm of $G_{dw}(s)$ was obtained using the command `norm` in Matlab. A plot of the H_2 norm of $G_{dw}(s)$ for a varying resistance (-200 to 20000 kΩ) is shown in Fig. 4.12. From the plot it can be seen that the value of R which minimizes the H_2 norm is $R=2335 \Omega$. Using this value of R in the shunt impedance will give the minimal Q factor obtainable using passive piezoelectric shunt control with the DMAPS micro-cantilever.

It may also be noted from Fig. 4.12 that a negative resistance results in an increase in the H_2 norm of $G_{dw}(s)$. This indicates that the use of a negative resistance in the shunt impedance may increase the cantilever Q factor. This is investigated in Chapter 5.

4.7 Synthetic Impedance

C_p and α vary from cantilever to cantilever due to manufacturing tolerances and material imperfections. The resonance modes of the cantilever may change with environmental conditions (for example temperature, humidity and air pressure). The

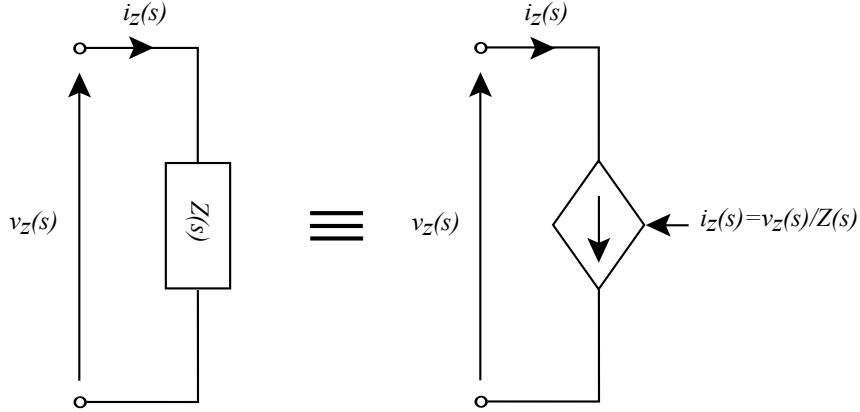


Figure 4.13: An arbitrary terminal impedance $Z(s)$ implemented by a synthetic impedance. The terminal voltage is measured and a current source applies an appropriate current to mimic the voltage to current relationship of the impedance.

required L and R necessary to obtain a desired cantilever Q factor will therefore vary from cantilever to cantilever and with changes in environmental conditions. Implementing the shunt impedance synthetically allows for fine tuning of the values of L and R .

An arbitrary impedance $Z(s)$ may be implemented synthetically [149] by measuring the terminal voltage $v_z(s)$ and controlling the terminal current $i_z(s)$ according to the relationship $\frac{v_z(s)}{i_z(s)} = Z(s)$ or $i_z(s) = v_z(s)Y(s)$ (where $Y(s) = \frac{1}{Z(s)}$) as shown in Fig. 4.13.

By letting

$$F_Y(s) = RY(s) = \frac{R}{Ls + R}, \quad (4.26)$$

the circuit of Fig. 4.14 is equivalent to the shunt impedance circuit shown in Fig. 4.3.

From Fig. 4.14 it is observed that

$$F_Y(s) = \frac{v_{out}(s)}{v_z(s)} = \frac{R}{Ls + R} \quad (4.27)$$

and

$$i_z(s) = \frac{v_{out}(s)}{R}. \quad (4.28)$$

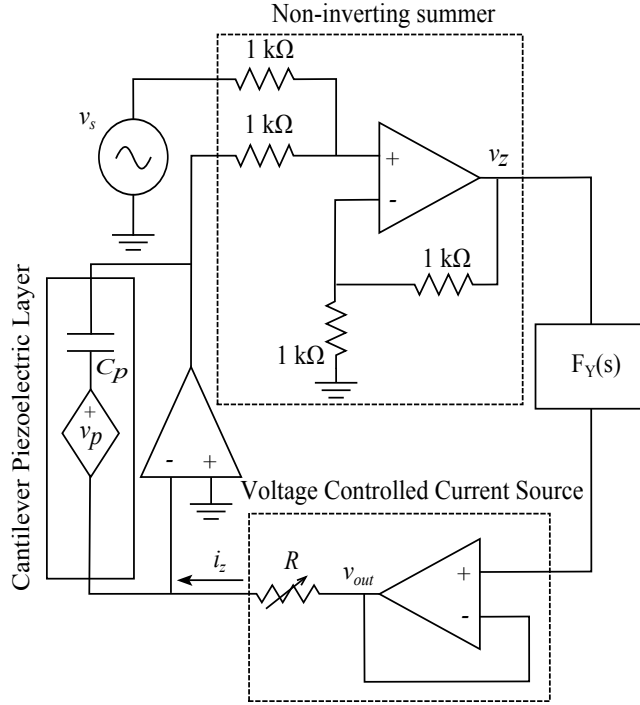


Figure 4.14: Piezoelectric shunt control circuit implemented with a synthetic impedance.

The resulting impedance is now found to be

$$Z(s) = \frac{v_z(s)}{i_z(s)} = \frac{v_z(s)R}{v_{out}(s)} = Ls + R. \quad (4.29)$$

The filter $F_Y(s)$ may be implemented with a simple first order RC filter as shown in Fig. 4.15. From Fig. 4.15 it is observed that

$$F_Y(s) = \frac{v_{out}(s)}{v_z(s)} = \frac{1}{R_f C_f s + 1}, \quad (4.30)$$

which may be written as

$$F_Y(s) = \frac{R}{RR_f C_f s + R} = \frac{R}{Ls + R}, \quad (4.31)$$

where

$$L = RR_f C_f. \quad (4.32)$$

By varying R and R_f , using potentiometers, the values of L and R may be modified accordingly.

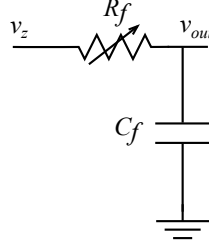


Figure 4.15: Admittance filter $F_Y(s)$ implemented with an RC low pass filter.

The operational amplifiers used to implement the circuit of Fig. 4.14 are Linear Technology LT1468 operational amplifiers [150]. This operational amplifier was chosen due to its high gain bandwidth product (90 MHz) and its low input bias current (10 nA).

4.8 Experimental Demonstration

The frequency response of $G_{dw}(s)$ is a measure of the effectiveness of the passive piezoelectric shunt controller to alter the cantilever's dynamics. Ideally this would be measured by exciting a piezoelectric actuator placed underneath the cantilever mounting base and observing the frequency response of the vibrations. It is difficult to obtain these measurements as the cantilever mounting adds additional dynamics to the system and it is difficult to find an actuator with resonant modes which are higher than those of the cantilever to ensure that these resonances do not affect the measured response.

Due to the difficulties encountered when obtaining the frequency response of the transfer function $G_{dw}(s)$, $G_{dv_s}(s)$ was used as a performance indicator.

Equation (4.9) shows that $G_{dv_s}(s) = \frac{H(s)G_{dv}(s)}{1+K(s)G_{dv}(s)}$ and (4.18) shows that $G_{dw}(s) = \frac{\lambda G_{dv}(s)}{1+K(s)G_{dv}(s)}$. Equating (4.9) and (4.18) gives

$$G_{dw}(s) = \lambda H^{-1}(s)G_{dv_s}(s), \quad (4.33)$$

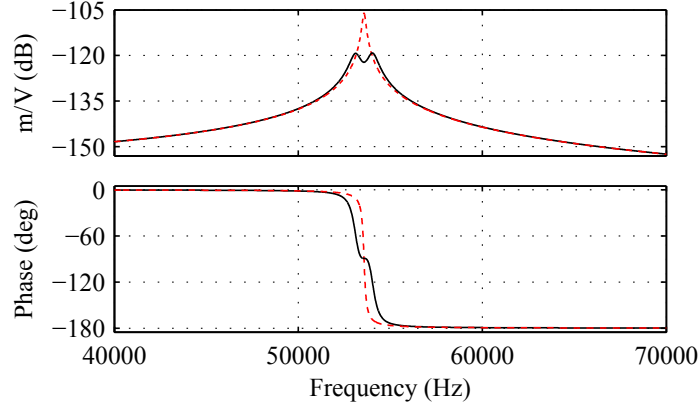


Figure 4.16: Frequency response of $G_{dv_s}(s)$ with the cantilever in open-loop (—) and $H^{-1}(s)G_{dv_s}(s)$ with the cantilever in closed-loop (—). A reduction of 13 dB in the resonance peak can be observed.

where

$$H^{-1}(s) = 1 + sZC_p = s^2 + \frac{Rs}{L} + \frac{1}{LC_p}. \quad (4.34)$$

Therefore, to test the effectiveness of the shunt controlled system on $G_{dw}(s)$ it is sufficient to test $H^{-1}(s)G_{dv_s}(s)$. Note that the gain λ will have no effect on the closed-loop poles of the system and therefore may be ignored.

The synthetic impedance consisting of a non-inverting summer, a voltage controlled current source and a passive RC filter, as shown in Fig. 4.14, was used to implement $Z(s)$. The filter $H^{-1}(s)$ is non-causal. It may be approximated physically by adding fast poles into the transfer function. However, it is not necessary to do this. The frequency response of $G_{dv_s}(s)$ was obtained with the Polytec MSV 400 then filtered afterward using Matlab to obtain $H^{-1}(s)G_{dv_s}(s)$.

Fig. 4.16 shows the frequency response plot of $G_{dv_s}(s)$ with the cantilever in open-loop and $H^{-1}(s)G_{dv_s}(s)$ with the cantilever in closed-loop. A 13-dB reduction of the resonance peak is observed from open-loop to closed-loop. Fig. 4.17 shows the open and closed-loop pole locations of the cantilever. It is clear from this figure that the introduction of the shunt impedance has significantly shifted the poles of the cantilever further into the left half plane, increasing the damping of the cantilever.

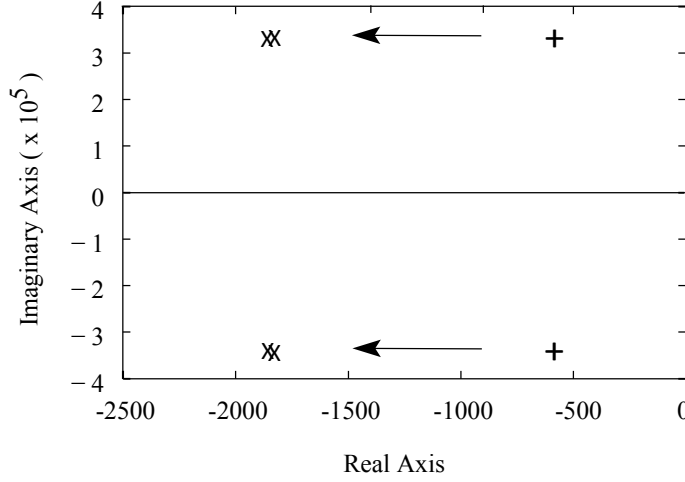
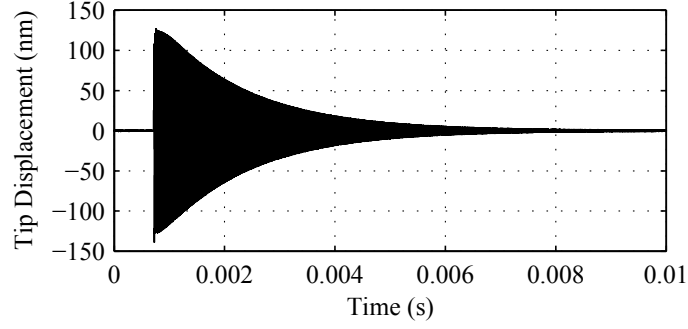


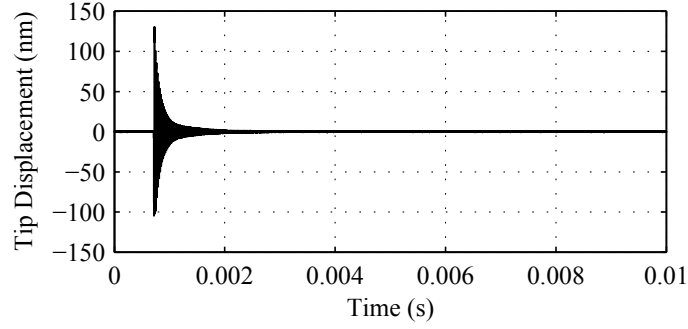
Figure 4.17: The open (+), and closed-loop (x) pole locations of the passive piezo-electric shunt controlled cantilever.

A step response of the cantilever was also obtained to demonstrate the effect of the passive piezoelectric shunt control circuit on the transient response of the cantilever. A 2.6 V amplitude step signal was applied to the cantilever and the resulting displacement was measured with the Polytec MSV 400. The response of $G_{dv_s}(s)$ to a step of 2.6 V with the cantilever in open-loop is shown in Fig. 4.18(a). It was possible to apply a pre-filtered step signal to the shunt circuit using an Agilent 33220A arbitrary waveform generator [151]. The step signal was pre-filtered by $H^{-1}(s)$ in Matlab then applied to the arbitrary waveform generator before being applied to the circuit. The pre-filtered step of amplitude 2.6 V was applied to the cantilever and shunt impedance to obtain the step response of $H^{-1}(s)G_{dv_s}(s)$ with the cantilever in closed-loop as shown in Fig. 4.18(b). It can be seen that the addition of the shunt impedance has reduced the settling time from 9 ms to 2 ms. This reduction in transient settling of 7 ms means that the cantilever will respond much faster to changes in the sample topography.

The effective Q factor of the cantilever probe may be estimated from an analysis of the step response. Note that the exponential decay rate is approximately $\sigma = \frac{\omega_n}{2Q}$. The exponential decay rate may be defined as the time taken for the step response to



(a) Step response of $G_{dv_s}(s)$ without piezoelectric shunt control.



(b) Step response of $H^{-1}(s)G_{dv_s}(s)$ with piezoelectric shunt control.

Figure 4.18: Step response of the DMAP micro-cantilever with and without passive piezoelectric shunt control.

decay to 36.79% of its peak amplitude. ω_n is measured from the frequency response of Fig. 4.16 and σ is measured from the step responses of Fig. 4.18(a) and Fig. 4.18(b). The effective Q factor with the cantilever in open and closed-loop can now be calculated from $Q = \frac{\omega_n}{2\sigma}$. A reduction in the effective Q factor from 297.6 in open-loop to 35.5 in closed-loop was observed.

4.9 AFM Imaging With the Passive Piezoelectric Shunt Control Technique

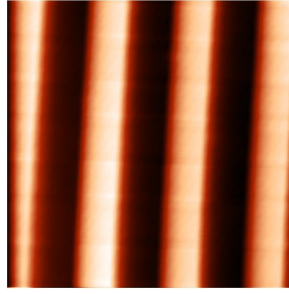
Images of the NT-MDT TGZ1 calibration grating, described in Chapter 3 Section 3.8, were obtained with the NT-MDT NTEGRA AFM [127] which was instrumented with the DMAP micro-cantilever.

Scans were obtained with the damped and undamped cantilever on a $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$ section of the calibration grating at a scan speed of $20\text{ }\mu\text{m/s}$. The Z axis feedback controller gain (K_Z) was increased until the loop became unstable. K_Z was then reduced slightly to ensure loop stability. The maximum value of K_Z obtainable using the undamped cantilever was 0.02 compared to a value of 0.2 using the damped cantilever. This increase in feedback gain by a factor of 10 significantly reduced the distortion of the image obtained, as shown in Fig. 4.19. A cross section of the three-dimensional images is shown in Fig. 4.20. This demonstrates that reduction of the cantilever Q factor using passive piezoelectric shunt control can significantly improve the Z axis feedback bandwidth to reduce image artifacts at high scan speeds.

Note that the image artifacts in the scans obtained in this experiment with no Q control are worse than the artifacts in the scans obtained with no Q control in Chapter 3 Section 3.8. This is because the cantilever used in this experiment has a higher natural Q factor.

4.10 Obtaining a Desired Cantilever Q Factor

Note that unlike the resonant control method of velocity estimation for active Q control described in Chapter 3 the passive piezoelectric shunt control technique has a limitation in the amount of damping attainable due to limitations of the transducer and the passive nature of the impedance used. In most applications the reduction



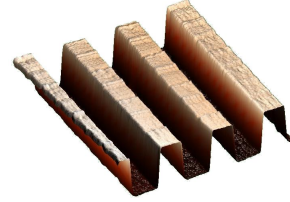
(a) 2D image without shunt control.



(b) 3D image without shunt control.



(c) 2D image with shunt control.



(d) 3D image with shunt control.

Figure 4.19: Images of the NT-MDT TGZ1 calibration grating obtained at a scan speed of $20 \mu\text{m/s}$. In each case the maximum value of K_Z , which ensured loop stability, was used. The use of passive piezoelectric shunt control to reduce the Q factor of the cantilever increased the cantilever response speed allowing a higher feedback gain and consequently, reduced image distortion.

in Q factor attainable with passive piezoelectric shunt control is sufficient as the cantilever Q factor must remain high enough to provide sufficient force sensitivity. If further reductions in Q factor are desired then it may be necessary to design an active impedance [152].

The pole placement optimization technique such as the one described in Chapter 3 may be used to obtain the desired cantilever Q factor. This may, however, be a tedious process for the operator. It may be noted that the cantilever Q factor may

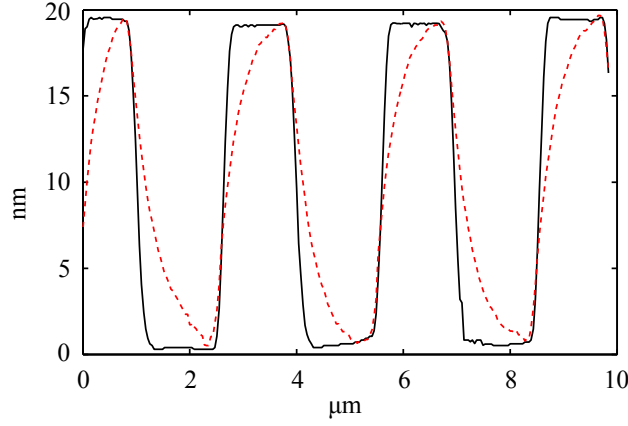


Figure 4.20: Cross section of the NT-MDT TGZ1 calibration grating image from Fig. 4.19(b) and 4.19(d). The scan obtained with passive piezoelectric shunt control (—) contained less artifacts in the image than the scan obtained without passive piezoelectric shunt control (- -).

be tuned by variation of the resistance in the shunt impedance. From Fig. 4.12 it can be seen that varying the value of R leads to a variation of the H_2 norm of the system. As the H_2 norm is reduced the effective cantilever Q factor will decrease. Therefore, a variation of R will lead to a variation of the cantilever Q factor. Most AFMs operating in tapping mode will have a means of displaying the cantilever frequency response for tuning scan parameters such as the operating frequency. This frequency response may be used to estimate the cantilever Q factor when tuning R .

Chapter 5

Sensorless Enhancement of Cantilever Q Factor With Active Piezoelectric Shunt Control

In Chapter 4 passive piezoelectric shunt control was applied to a piezoelectrically actuated AFM micro-cantilever to reduce the Q factor of the cantilever, resulting in reduced image artifacts when imaging a hard sample surface in air at high scan speeds. The advantage of this technique over conventional methods of Q control is that the optical sensor is removed from the Q control feedback loop reducing sensor noise.

For many imaging applications increasing the cantilever force sensitivity and reducing tip-sample force may be a higher priority than increasing the scan speed. Increasing the cantilever Q factor results in increased force sensitivity and reduced tip-sample force when imaging in tapping mode, which is beneficial when imaging samples with fine features, soft samples and samples in a fluid environment. The influence of the cantilever Q factor on force sensitivity and tip-sample force is described in Chapter 1 Sections 1.3.7 and 1.3.8.

Passive piezoelectric shunt control can not be used in applications where an increase in the cantilever Q factor is desired to increase force sensitivity and reduce tip-sample force. To increase the cantilever Q factor using piezoelectric shunt control energy must be added to the system. This requires the design of an active impedance in the piezoelectric shunt control framework. In Chapter 4 Section 4.6.2 the H_2 norm of the closed-loop piezoelectric shunt control system was obtained for varying resistances in the shunt impedance. An increase in the H_2 norm of the closed-loop piezoelectric shunt control system results in an increase in the effective cantilever Q factor. For negative resistances it was observed that the H_2 norm increased, indicating that the use of a negative resistance in the shunt impedance may be used to increase the cantilever Q factor.

The concept of using active piezoelectric shunt control to increase the Q factor of a cantilever has recently been demonstrated by Zhao *et al.* [153]. Their experiments were conducted on a large cantilever ($0.043 \text{ m} \times 0.433 \text{ m}$) with a resonance frequency of 91.7 Hz. An inductance and a negative resistance were connected to the terminals of a piezoelectric transducer which was bonded to the cantilever surface. To test the influence of the electrical impedance on the cantilever dynamics a separate piezoelectric transducer bonded to the cantilever was used for actuation.

In this work the technique of active piezoelectric shunt control is applied to a self actuated piezoelectric AFM micro-cantilever with a resonance frequency of approximately 50 kHz. The piezoelectric layer on the surface of the cantilever is used to simultaneously oscillate the cantilever and modify its dynamics in a way that enhances the Q factor.

5.1 Active Piezoelectric Shunt Control System Modeling

5.1.1 Piezoelectric Transducer Electrical Model

The AFM micro-cantilever chosen to demonstrate the concept of active piezoelectric shunt control in this work is the DMAPS micro-cantilever described in Chapter 3 Section 3.6.

When analyzing piezoelectric shunt systems the piezoelectric transducer is typically modeled electrically as a strain dependent voltage source v_p in series with a capacitance C_p [133]. This model was used to analyze the passive piezoelectric shunt control system designed to reduce the Q factor of the cantilever in Chapter 4.

Initial experiments with active piezoelectric shunt control of the DMAPS micro-cantilever for Q factor enhancement indicated that the v_p in series with C_p model does not work well for this application. The experimental results did not match the values calculated for the shunt impedance parameters. This issue was also observed by Zhao *et al.* [153] in their experimental work. Zhao *et al.* [153] concluded that the mismatch between expected results and experimental results was due to electrical energy losses (dielectric losses) which may be modeled as a resistance R_p in parallel with C_p and v_p .

The frequency response of the DMAPS micro-cantilever electrical impedance was measured in [154], [155] and [156], where significant electrical energy losses in the ZnO piezoelectric transducer were observed.

When the cantilever is modeled electrically as a resistance R_p in parallel with C_p and v_p the transfer function from a voltage $v(s)$ applied to the transducer terminals to the charge $q(s)$ generated at the terminals is represented by

$$G_{qv}(s) = \frac{q(s)}{v(s)} = \alpha C_p G_{dv}(s) + C_p + \frac{1}{R_p s}, \quad (5.1)$$

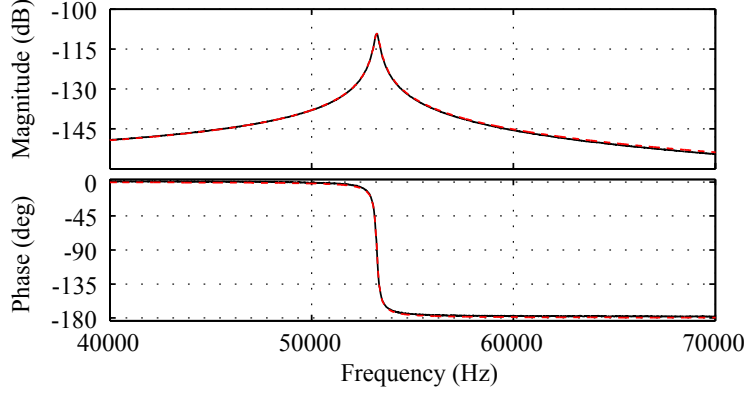


Figure 5.1: Frequency response of the DMASP micro-cantilever's first resonance mode (- -) and fitted model (—).

where $G_{dv}(s)$ is the transfer function from $v(s)$ to the cantilever tip displacement $d(s)$ given by (4.1) and α is the piezoelectric voltage-displacement coefficient ($\alpha = \frac{v_p}{d}$).

The impedance of the piezoelectric transducer may now be derived as

$$Z_p(s) = \frac{v(s)}{i(s)} = \frac{v(s)}{s q(s)} = \frac{1}{s G_{qv}(s)} = \frac{1}{\alpha C_p G_{dv}(s) s + C_p s + \frac{1}{R_p}}. \quad (5.2)$$

The values for C_p and R_p were measured using an Agilent E4980A *LCR* meter. C_p was measured to be 28.5 pF and R_p was found to be 6.7 M Ω .

The frequency response of $G_{dv}(s)$, for the DMASP micro-cantilever used in this work, was obtained by applying a pseudo random signal to the cantilever electrodes and measuring the resulting tip displacement with a Microscope Scanning Laser Doppler Vibrometer (Polytec MSV 400). The frequency response of $G_{dv}(s)$ is shown in Fig. 5.1. The mathematical model of $G_{dv}(s)$ obtained by system identification is

$$G_{dv}(s) = \frac{2126}{s^2 + 1472s + 1.119 \times 10^{11}}, \quad (5.3)$$

and is also shown in Fig. 5.1.

The frequency response, shown in Fig. 5.2, of the cantilever impedance was obtained by applying the method described in Chapter 4 Section 4.5.1. The transfer function obtained from this frequency response is

$$Z_p(s) = \frac{s^2 + 1472s + 1.119 \times 10^{11}}{2.85 \times 10^{11}s^3 + 1.912 \times 10^7s^2 + 3.191s + 1.67 \times 10^4}. \quad (5.4)$$

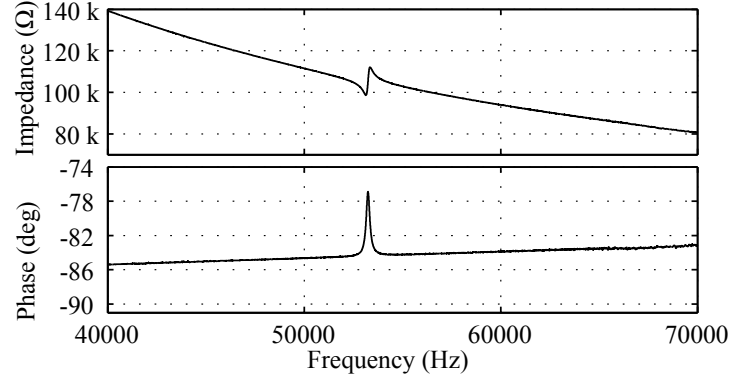


Figure 5.2: Frequency response of the DMAPS micro-cantilever electrical impedance.

Equating (5.2) and (5.4) gives a value of $\alpha \approx 4 \times 10^4$ V/m.

A schematic of the micro-cantilever with the attached shunt impedance is shown in Fig. 5.3. For the electrical dynamics to have a sufficient influence on the mechanical dynamics of the cantilever the resonance frequency ω_e created by the electrical circuit must be tuned close to the mechanical resonance ω_r of the cantilever. The inductance tuning ratio is defined as

$$\delta = \frac{\omega_e}{\omega_r}. \quad (5.5)$$

For the circuit shown in Fig. 5.3 ω_e is given by

$$\omega_e = \sqrt{\frac{1}{LC_p} - \frac{1}{(R_p C_p)^2}}. \quad (5.6)$$

The necessary inductance may be found by tuning δ close to 1.

5.1.2 Electromechanical Modeling of the Piezoelectric Shunt System

The piezoelectric shunt control system depicted in Fig. 5.3 may be modeled by the block diagram of Fig. 5.4. In this representation the cantilever is modeled as the system G . The system G has been modified from the system shown in the block diagram of Fig. 4.5 to include the resistance R_P in the model. Here, v_s is the applied

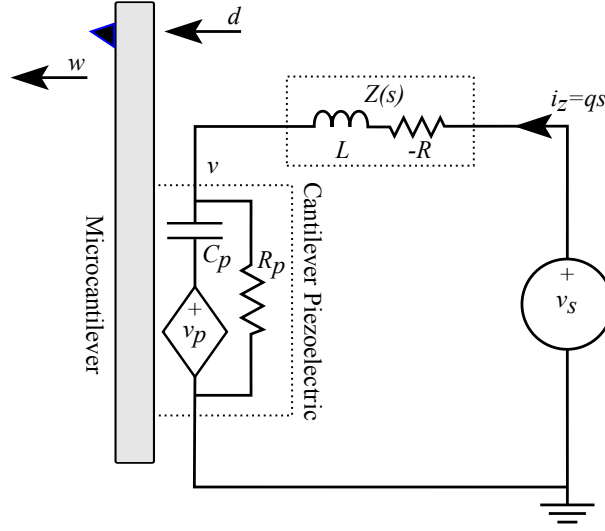


Figure 5.3: Piezoelectric shunt control applied to a self actuating piezoelectric microcantilever. The impedance $Z(s)$ is placed in series with the oscillation voltage source v_s to create a resonant circuit. The dynamics of this electrical circuit influence the mechanical dynamics of the cantilever. Note that R_p has been included in the cantilever model.

voltage, v_z is the voltage across the shunt impedance, w is a disturbance strain on the cantilever due to interactions with the sample (changes in topography), d_w is the initial tip displacement due to a disturbance, and $G_{d_w w}(s)$ is the transfer function from $w(s)$ to $d_w(s)$. $G_{d_w w}(s)$ may be modeled as

$$G_{d_w w}(s) = \frac{d_w(s)}{w(s)} = \frac{\beta_w \omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2}, \quad (5.7)$$

where β_w is the steady state gain of $G_{d_w w}(s)$.

5.1.3 Modeling the Transfer Function From Actuating Voltage to Tip Displacement

From the block diagram of Fig. 5.4 the transfer function from v_s to v may be derived as

$$G_{vv_s}(s) = \frac{v(s)}{v_s(s)} = \frac{1}{1 + sZ(s)G_{qv}(s)}. \quad (5.8)$$

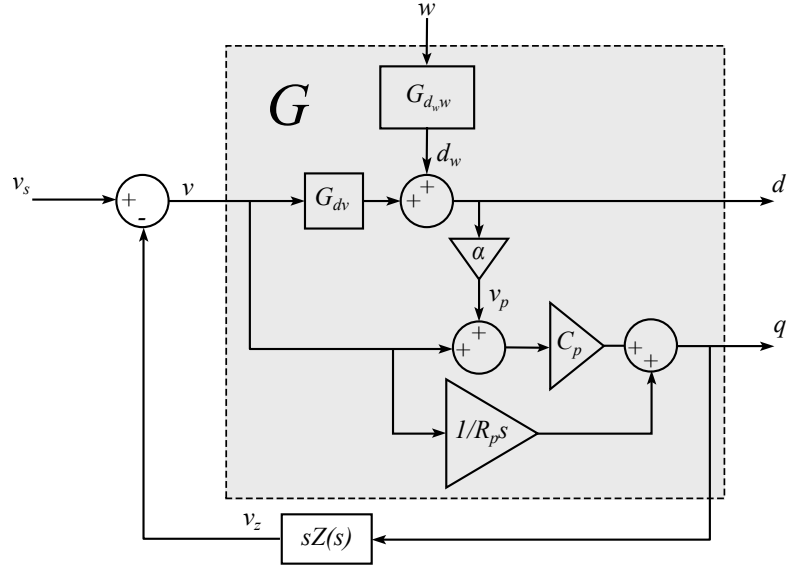


Figure 5.4: Block diagram of the piezoelectric shunt control system (including R_p in the model). The cantilever is represented by the system G which has two inputs (the terminal voltage v and a disturbance strain w) and two outputs (the charge generated by the piezoelectric transducer q and the cantilever tip displacement d).

Substituting (5.1) into (5.8) gives

$$G_{vv_s}(s) = \frac{\frac{1}{1+sZ(s)\left(C_p+\frac{1}{R_p s}\right)}}{1+\frac{sZ(s)C_p\alpha G_{dv}(s)}{1+sZ(s)\left(C_p+\frac{1}{R_p s}\right)}}. \quad (5.9)$$

Let

$$H(s) = \frac{1}{1+sZ(s)\left(C_p+\frac{1}{R_p s}\right)} \quad (5.10)$$

and

$$K(s) = \frac{sZ(s)C_p\alpha}{1+sZ(s)\left(C_p+\frac{1}{R_p s}\right)}, \quad (5.11)$$

then

$$G_{vv_s}(s) = \frac{H(s)}{1+K(s)G_{dv}(s)}. \quad (5.12)$$

The transfer function from $v_s(s)$ to $d(s)$, when the shunt impedance is connected, is now found to be

$$G_{dv_s}(s) = G_{vv_s}(s)G_{dv}(s) = \frac{H(s)G_{dv}(s)}{1 + K(s)G_{dv}(s)}. \quad (5.13)$$

G_{dv_s} may be viewed as a negative feedback loop with a filter $H(s)$ in the feed forward path. $H(s)$ causes a distortion in the cantilever transfer function from $v_s(s)$ to $d(s)$.

When imaging in tapping mode the oscillation voltage is a sinusoidal signal. The filter $H(s)$ results in a modification in the magnitude and phase of this signal. The modification of phase does not affect the performance of the device and the modification in the magnitude may be accommodated for by varying the amplitude of the input signal.

5.1.4 Modeling the Transfer Function From Sample Topography to Tip Displacement

To obtain the transfer function from $w(s)$ to $d(s)$, $v_s(s)$ is first set to zero. From Fig. 5.4 it is observed that

$$v(s) = -v_z(s) \quad (5.14)$$

and

$$v_z(s) = sq(s)Z(s), \quad (5.15)$$

where $q(s)$ is given by

$$q(s) = -v_z(s)C_p - v_z(s)\alpha C_p G_{dv}(s) - \frac{v_z(s)}{R_p s} + d_w(s)\alpha C_p. \quad (5.16)$$

Substituting (5.16) into (5.15) gives

$$v_z(s) = (-v_z(s)C_p - v_z(s)\alpha C_p G_{dv}(s) - \frac{v_z(s)}{R_p s} + d_w(s)\alpha C_p)sZ(s). \quad (5.17)$$

Substituting (5.14) into (5.17) results in the transfer function

$$G_{vd_w}(s) = \frac{v(s)}{d_w(s)} = \frac{-\alpha s Z(s) C_p}{1 + s Z(s) \left(C_p + \frac{1}{R_p s} \right) + \alpha s Z(s) C_p G_{dv}(s)}. \quad (5.18)$$

From Fig. 5.4 it is observed that

$$d(s) = G_{vdw}(s)G_{dv}(s)d_w(s) + d_w(s). \quad (5.19)$$

Substituting (5.18) into (5.19) results in the transfer function

$$G_{ddw}(s) = \frac{d(s)}{d_w(s)} = \frac{1}{1 + \frac{\alpha s Z(s) C_p G_{dv}(s)}{1 + s Z(s) \left(C_p + \frac{1}{R_p s} \right)}} = \frac{1}{1 + K(s) G_{dv}(s)}. \quad (5.20)$$

Combining (5.20) and (5.7) results in the transfer function

$$G_{dw}(s) = G_{ddw}(s)G_{dvw}(s) = \frac{G_{dvw}(s)}{1 + K(s)G_{dv}(s)}. \quad (5.21)$$

$G_{dvw}(s)$ has the same poles as $G_{dv}(s)$, the only difference being the steady state gain β_w . The transfer function $G_{dw}(s)$ may be written as

$$G_{dw}(s) = \frac{\lambda G_{dv}(s)}{1 + K(s)G_{dv}(s)}, \quad (5.22)$$

where $\lambda = \frac{\beta_w}{\beta_v}$. In this form $G_{dw}(s)$ may be viewed as a negative feedback loop. The closed loop poles may be placed in the s plane by design of the feedback controller $K(s)$ to obtain the desired cantilever Q factor.

5.2 Synthetic Impedance

An active impedance such as $Ls - R$ can not be implemented using passive components. A synthetic impedance was designed to implement the impedance and to allow for fine tuning of the values of R and L . The synthetic impedance design is based on the schematic shown in Fig. 4.14. A full description of its design is given in Chapter 4 Section 4.7.

To implement an impedance $Ls - R$, the admittance filter used in the synthetic impedance circuit must be of the form

$$F_Y(s) = RY(s) = \frac{R}{Ls - R}. \quad (5.23)$$

A block diagram implementation of $F_Y(s)$ is shown in Fig. 5.5.

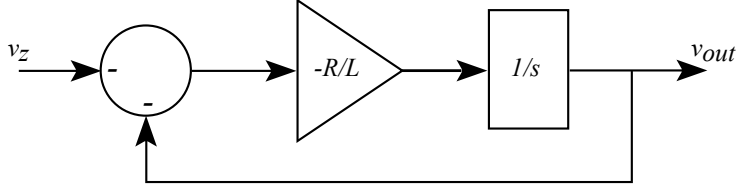


Figure 5.5: Admittance filter $F_Y(s)$. The transfer function of the filter is $F_Y(s) = RY(s) = \frac{R}{Ls - R}$.

From Figures 4.14 and 5.5 it is observed that

$$\frac{v_{out}(s)}{v_z(s)} = F_Y(s) = \frac{R}{Ls - R} \quad (5.24)$$

and

$$i_z(s) = \frac{v_{out}(s)}{R}. \quad (5.25)$$

The resulting impedance is now found to be

$$Z(s) = \frac{v_z(s)}{i_z(s)} = \frac{v_z(s)R}{v_{out}(s)} = Ls - R. \quad (5.26)$$

By varying R and the gain $\left(\frac{R}{L}\right)$ of the integrator in the filter $F_Y(s)$ the values of L and R may be modified accordingly.

The filter $F_Y(s)$ may be implemented using a DSP device, a FPAA or operational amplifiers. For the experimental demonstrations performed in this work the filter $F_Y(s)$ was implemented using operational amplifiers. The operational amplifier chosen for this application is the Linear Technology LT1468 operational amplifier [150].

A schematic of the piezoelectric micro-cantilever attached to the synthetic impedance, with $F_Y(s)$ implemented with operational amplifiers, is shown in Fig. 5.6. The non-inverting summer, shown in Fig. 4.14, which adds the oscillation voltage v_s to the cantilever terminal voltage is incorporated into the admittance filter circuit to reduce the number of operational amplifiers required in the circuit. In this implementation the value of the inductance is determined by $L = RR_I C$.

This synthetic impedance may be modified easily, as shown in Fig. 5.7, to allow for a wide range of cantilever Q factors. By switching between a gain of -1 and 1

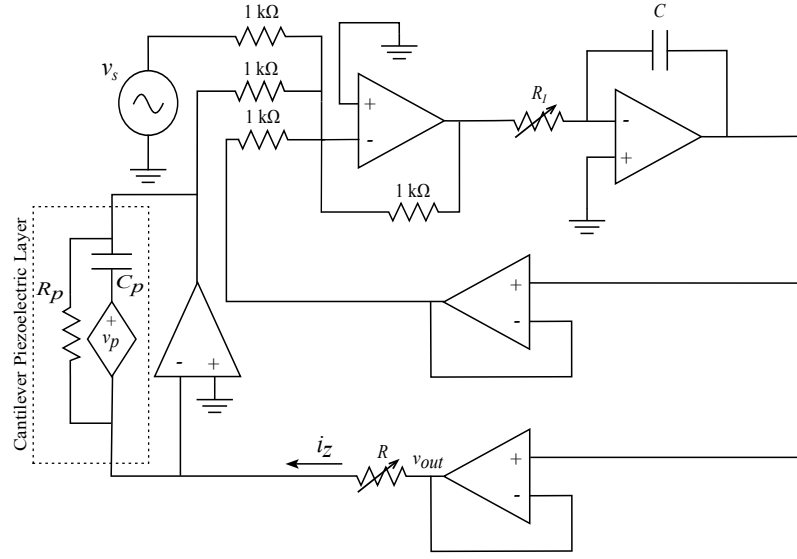


Figure 5.6: Piezoelectric shunt control circuit implemented with a synthetic impedance. The synthetic impedance is based on the design illustrated in Fig. 4.14. The admittance filter $F_Y(s)$ is implemented with operational amplifiers. The non-inverting summer, shown Fig. 4.14, which adds the oscillation voltage v_s to the cantilever terminal voltage is incorporated into the admittance filter circuit to reduce the number of operational amplifiers required in the circuit.

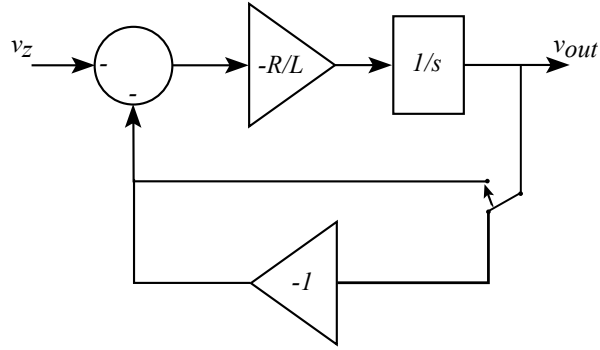


Figure 5.7: Admittance filter $F_Y(s)$. A switch has been placed in the feedback loop to allow the user to switch between positive and negative resistances enabling the cantilever Q factor to be reduced or increased as needed.

in the feedback branch of the admittance filter $F_Y(s)$ the value of R may be made positive or negative respectively. This means that the cantilever Q factor may be increased or decreased to suit any imaging environment and sample type.

Any method of increasing the cantilever Q factor will result in the poles of the system being shifted closer to the $j\omega$ axis of the complex plane, bringing the system closer to instability. If the cantilever becomes unstable there is a risk of cantilever and/or sample damage. When using the synthetic impedance to implement $Z(s)$ the power supply voltage of the operational amplifier to which the cantilever is connected to may be limited. This ensures that the amplitude of the cantilever oscillations do not exceed a value that could damage the cantilever or sample if the system becomes unstable.

5.3 Experimental Demonstration

5.3.1 Determination of Shunt Impedance Parameters to Increase the Cantilever Q Factor

5.3.1.1 Inductance

For the electrical dynamics of the shunt circuit to have a significant influence on the mechanical dynamics of the cantilever, the electrical resonance frequency f_e must be tuned close to the open-loop cantilever resonance frequency f_r . For an initial demonstration of the active piezoelectric shunt control technique this is achieved by setting $f_e = f_r$ ($\delta = 1$). f_r was measured from the frequency response shown in Fig. 5.1 to be 53234 Hz, therefore f_e was tuned to 53234 Hz. The necessary inductance is calculated by substituting the values for f_e , C_p and R_p into (5.6). The value for L was found to be 313.56 mH.

5.3.1.2 Resistance

The characteristic equation (A_{CL}) of $G_{dw}(s)$ is $1 + K(s)G_{dv}$. A root locus of $G_{dw}(s)$ was obtained by rearranging A_{CL} into the form

$$A_{CL} = 1 + R \frac{\psi s^3 + \psi 2\zeta \omega_n s^2 + \psi \omega_n^2 s + C_p \alpha \beta_v \omega_n^2 s}{L\psi s^4 + L\psi 2\zeta \omega_n s^3 + \gamma s^2 + 2\zeta \omega_n s + \omega_n^2}, \quad (5.27)$$

where $\psi = C_p + \frac{1}{R_p s}$ and $\gamma = 1 + L\psi \omega_n^2 + LC_p \alpha \beta_v \omega_n^2$.

The root locus when δ is tuned to 1, for $R \in [-\infty, 0]$, is shown in Fig. 5.8(a). A zoomed in view of the upper left quadrant of the root locus is shown in Fig. 5.8(b). As R is reduced, the poles of $G_{dw}(s)$ shift toward the right of the complex plane, increasing the Q factor of the cantilever. The cantilever reaches a point of instability when the poles cross the imaginary axis. The value of R , when this occurs, may be determined by conducting a Routh-Hurwitz stability analysis on A_{CL} . The value of R which causes system instability, when δ is tuned to 1, is -3250Ω . A slightly higher value of resistance (-3150Ω) was chosen to ensure stability of the cantilever.

5.3.2 Cantilever Frequency Response

The force sensitivity and tip-sample force of the AFM operating in tapping mode are dependent on the dynamics of $G_{dw}(s)$. To measure the frequency response of $G_{dw}(s)$ a piezoelectric actuator is placed underneath the cantilever mounting base with an excitation signal applied to the actuator. Difficulties were encountered with this method due to the additional dynamics added to the system by the cantilever mounting base and the piezoelectric actuator.

An alternative method of measuring the frequency response of $G_{dw}(s)$, when the active piezoelectric shunt controller is implemented, is to apply a filtered excitation signal to the cantilever electrodes. Equating (5.13) and (5.22) gives

$$G_{dw}(s) = \lambda H^{-1}(s) G_{dv_s}(s). \quad (5.28)$$

$G_{dw}(s)$ is therefore equivalent to $H^{-1}(s) G_{dv_s}(s)$ multiplied by a gain λ . The poles of

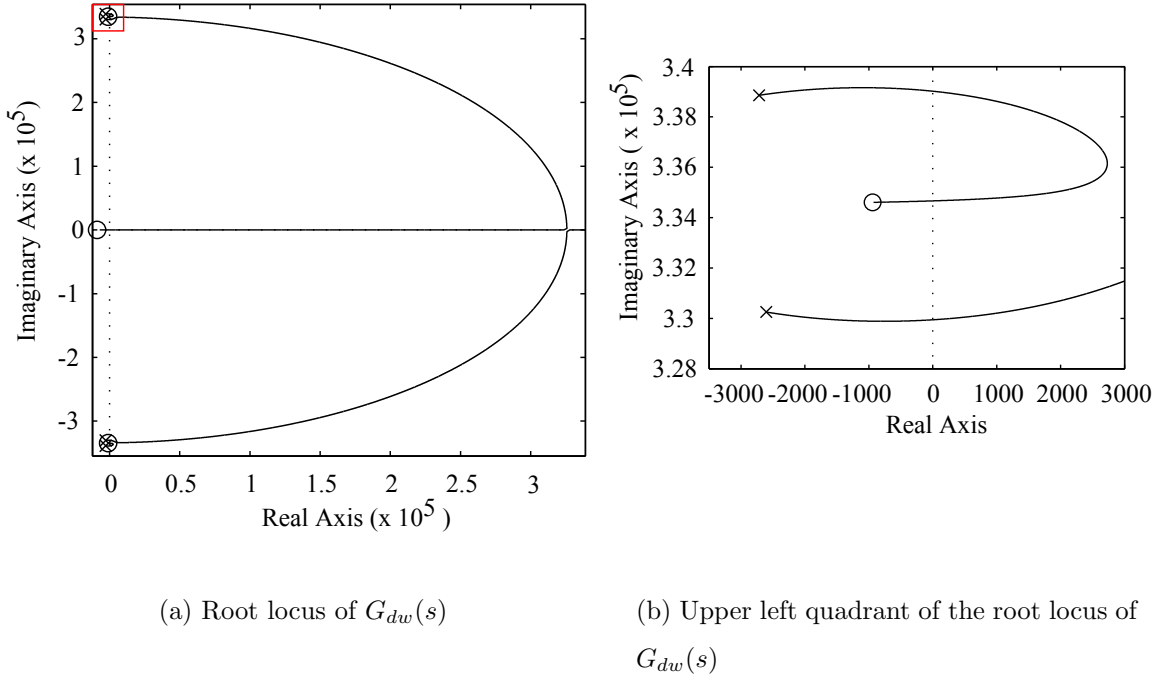


Figure 5.8: Root locus of $G_{dw}(s)$ when $\delta = 1$ ($R \in [-\infty, 0]$)

the system are not affected by the gain λ . λ may therefore be disregarded and the frequency response of $H^{-1}(s)G_{dvs}(s)$ used to determine the Q factor of $G_{dw}(s)$. The filter $H^{-1}(s)$ is non-causal. $H^{-1}(s)$ may be approximated physically by adding fast poles into the transfer function. The approach taken in this work was to obtain the frequency response of $H^{-1}(s)G_{dvs}(s)$ by filtering the frequency response of $G_{dvs}(s)$ with $H^{-1}(s)$ afterward using Matlab.

The active shunt impedance containing a negative resistance of $-3150 \, \Omega$ and an inductance of $313.56 \, \text{mH}$ was applied to the DMAP micro-cantilever. The frequency response plot of $H^{-1}(s)G_{dvs}(s)$ for this system is shown in Fig. 5.9. The Q factor of the left resonance peak was measured to be 2165 with the right peak having a Q factor of 767. The cantilever Q factor with no applied shunt impedance was measured to be 178. Using the left resonance peak of the shunt controlled cantilever for tapping mode imaging would result in an increase of the effective cantilever Q factor by over

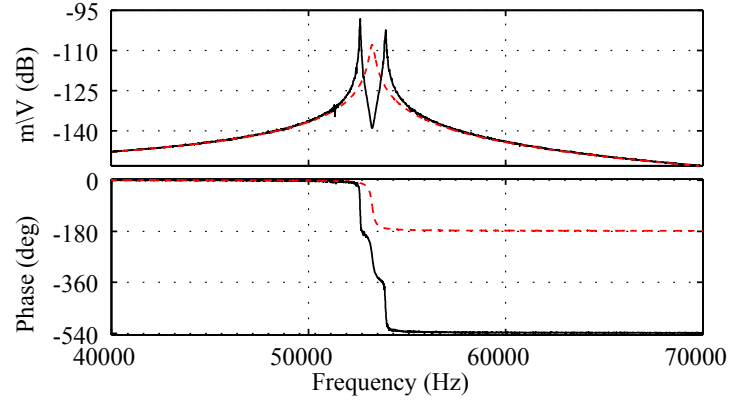


Figure 5.9: Frequency response of $G_{dv_s}(s)$ with no shunt impedance (---) and $H^{-1}(s)G_{dv_s}(s)$ with a shunt impedance consisting of an inductance of 313.56 mH and a negative resistance of -3150Ω (—).

12 times.

5.4 AFM Imaging With the Active Piezoelectric Shunt Control Technique

To test the efficacy of the active piezoelectric shunt controller images of a sample with fine features were acquired with an NT-MDT NTEGRA AFM [127]. The sample chosen to demonstrate this technique consisted of clusters of gold nanoparticles sputtered on a silicon wafer, which is commercially available from Nanosurf Instruments [157]. The features found on this sample were less than 6 nm high which is ideal for testing the effect of increasing the cantilever Q factor on image quality.

A $350 \text{ nm} \times 350 \text{ nm}$ section of the sample was scanned with no cantilever Q factor enhancement at a scan speed of $1 \mu\text{m/s}$. The image obtained is shown in Fig. 5.11(a). The active piezoelectric shunt controller was then placed in the tip oscillation circuit and the cantilever Q factor tuned by varying L and R . The amount of Q enhancement required to improve the quality of the image was determined experimentally. It was found that a Q factor of 410 gave the greatest improvement in image quality.

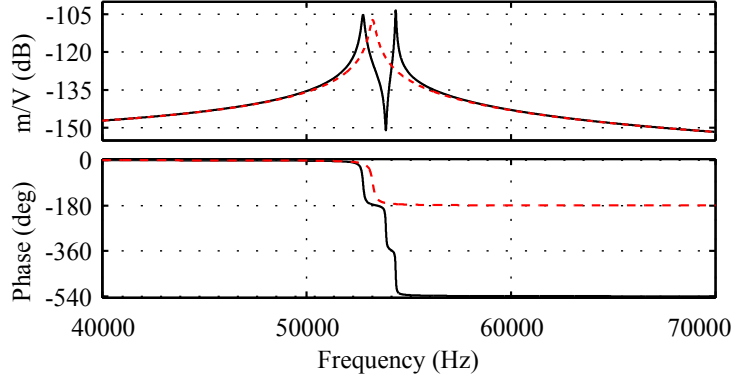


Figure 5.10: Frequency response of $G_{dv_s}(s)$ with no active piezoelectric shunt control (---) and $H^{-1}(s)G_{dv_s}(s)$ with a shunt impedance consisting of an inductance of 306.10 mH and a negative resistance of -2450Ω (—).

Increasing the Q factor further lead to significant oscillations appearing in the image due to low Z axis feedback loop stability margins. The shunt impedance parameters of $L = 306.10$ mH and $R = -2450 \Omega$ were required to increase the Q factor from 178 to 410. A frequency response of $G_{dv_s}(s)$ with no shunt impedance and $H^{-1}(s)G_{dv_s}(s)$ with the shunt impedance is shown in Fig. 5.10. The resonance peak on the left was used for imaging. The image obtained is shown in Fig. 5.11(b).

Comparing the images of Fig. 5.11(a) and Fig. 5.11(b) it can be seen that the sample features in the image obtained using active piezoelectric shunt control to enhance the cantilever Q factor are higher, giving a sharper image contrast.

5.5 Active Piezoelectric Shunt Control for Other Micro-cantilever Sensing Applications

Piezoelectric micro-cantilevers are used as sensors in applications such as measuring air pressure [155], temperature [158], humidity [159] and the concentration of chemical and biological substances [160–162]. A cantilever's resonance frequency changes with air pressure, temperature and humidity. By coating one surface of the

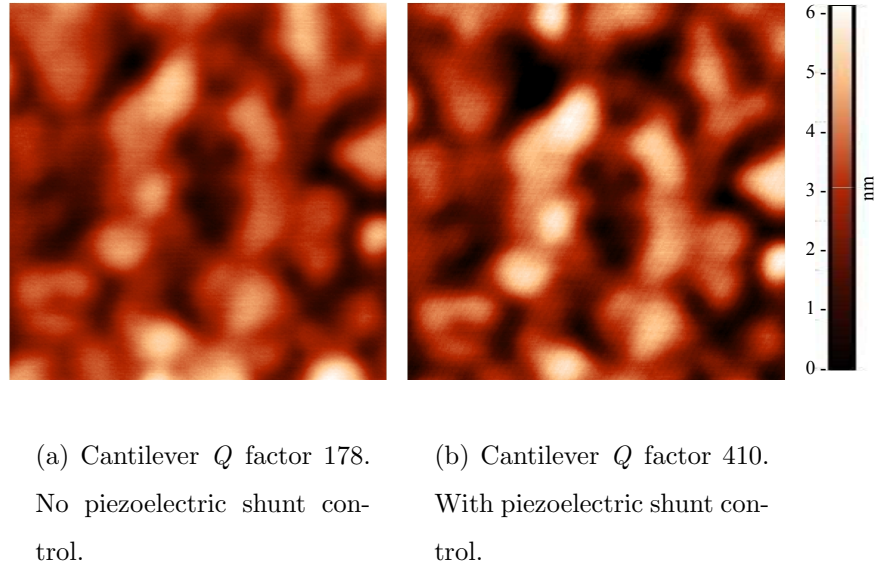


Figure 5.11: Images of the gold cluster sample obtained at a scan speed of $1 \mu\text{m/s}$ with and without enhancement of the cantilever Q factor. The scan area is $350 \text{ nm} \times 350 \text{ nm}$.

cantilever with a substance which adsorbs the chemical or biological substance being measured, changes in concentration of the substance change the mass and surface stress of the cantilever resulting in a shift in resonance frequency which is measured by observing variations in the amplitude, phase or frequency of the oscillating cantilever. In these micro-cantilever sensing applications a very high cantilever Q factor is desirable for maximum measurement sensitivity.

Active Q control has been applied to chemical and biological sensors in a liquid environment [163]. This technique is effective in increasing the sensitivity of the sensor. However, the instrumentation involved is large, expensive and not practical when large quantities of sensors are needed. Active piezoelectric shunt control is particularly attractive in these applications due to the compact size of the instrumentation and the reduction of sensor noise in the feedback loop.

The active piezoelectric shunt control technique is capable of producing increases in the cantilever Q factor to the high values desirable in the above mentioned sensing

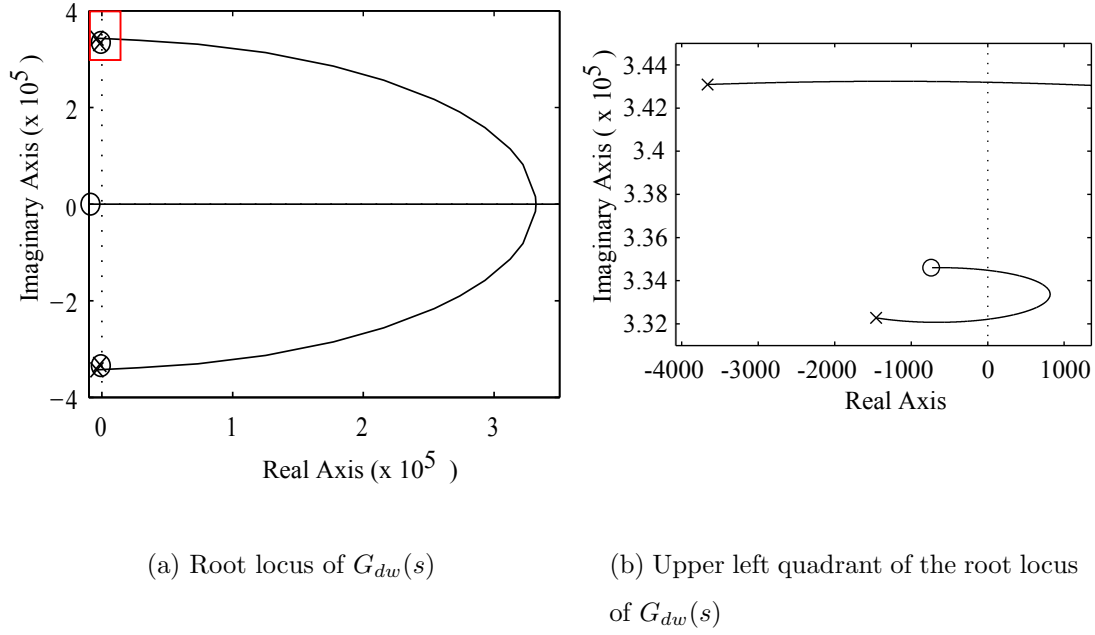


Figure 5.12: Root locus of $G_{dw}(s)$ when $\delta = 1.0187$ ($R \in [-\infty, 0]$)

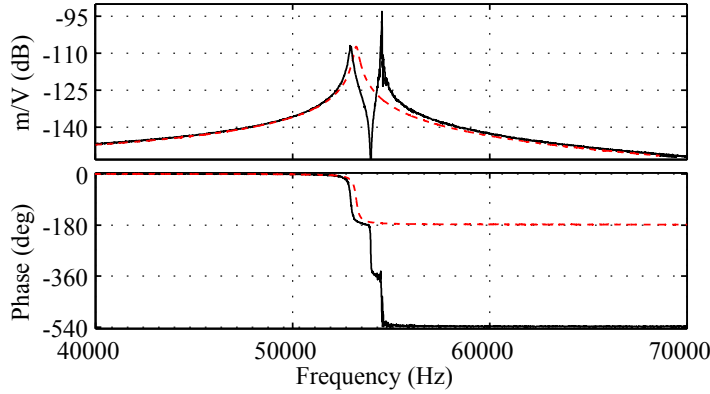


Figure 5.13: Frequency response of $G_{dv_s}(s)$ with no active piezoelectric shunt control (---) and $H^{-1}(s)G_{dv_s}(s)$ with a shunt impedance consisting of an inductance of 302.13 mH and a negative resistance of -2800Ω (—).

applications. By tuning the value of δ slightly higher than 1 it is possible to obtain further increases in the cantilever Q factor using active piezoelectric shunt control. L was reduced to 302.13 mH, shifting the electrical resonance to 54231 Hz ($\delta=1.0187$). This modifies the root locus, as shown by Fig. 5.12(a) and the zoomed in view of

the upper left quadrant, which is shown in Fig. 5.12(b). The resistance at which the system becomes unstable is now -2820Ω . R was set to -2790Ω to obtain the frequency response of Fig. 5.13. The Q factor of the second resonance peak has increased to 5123. This is an increase in cantilever Q factor of over 28 times that of the original cantilever Q factor.

Chapter 6

A Switched Gain Resonant Controller to Minimize Image Artifacts Due to Probe Loss

In most imaging applications it is desirable to have a high scan speed with minimal tip-sample force. Minimizing tip-sample force reduces the likelihood of tip and/or sample damage and deformation of soft samples. The trade-off between increasing scan speed and minimizing tip-sample force was described in Chapter 2 Section 2.5.

Tip-sample force may be reduced by decreasing the spring constant or increasing the Q factor of the cantilever. Modifying either of these parameters in this manner will have the undesirable effect of reducing the maximum scan speed obtainable. If scan speed is important another method of minimizing tip-sample force is to reduce the difference between A_{set} and A_0 .

Increasing A_{set} is also beneficial on upward sloping features of the sample as it reduces the chance of the Z axis feedback loop error signal saturating. The drawback of setting A_{set} close to A_0 is that the Z axis feedback loop error signal may saturate when the probe detaches from the sample on steep downward sloping features. Sat-

uration of the Z axis feedback loop error signal prolongs the time that the probe is detached from the sample. While the probe is detached from the sample the sample topography signal is erroneous, causing artifacts in the image. The area of the image affected by these artifacts will increase as the scan speed increases.

The techniques developed by other researchers to minimize probe loss have been highlighted in Chapter 2 Section 2.5.2. All of these techniques use some form of switched controller which detects if the probe has detached from the sample. When probe loss is detected the control parameters are switched to either reduce the scan speed, increase the Z axis feedback controller gain or increase the Z axis feedback error signal. Reducing the scan speed when probe loss occurs reduces the area of the sample affected by probe loss. Increasing the Z axis controller gain or increasing the magnitude of the error signal when probe loss occurs will increase the speed at which the Z axis actuator can bring the sample back into contact with the probe tip.

In this chapter a new method of minimizing probe loss is presented using a resonant controller with a switchable gain. The switched gain resonant controller is based on the control philosophy of increasing the Z axis feedback error signal, when probe loss is detected, to increase the feedback response speed.

6.1 Control Philosophy

When probe loss occurs the maximum possible value of the Z axis feedback error signal is $e_{max} = |A_{set} - A_0|$. Increasing A_0 in the region of probe loss will increase e_{max} . This will have the effect of increasing the speed at which the Z axis actuator brings the sample back into contact with the probe, reducing artifacts appearing in the image due to probe loss.

A_0 is proportional to the cantilever Q factor. Therefore, increasing the cantilever Q factor is a means of increasing e_{max} when probe loss is detected.

Increasing the cantilever Q factor will have the detrimental effect of reducing the

bandwidth of the Z axis feedback loop which will decrease the stability margins of the loop. As the tip is not in contact with the sample there are no disturbances to induce instability in the Z axis feedback loop. Increasing the cantilever Q factor will not result in loop instability as long as the cantilever Q factor is quickly returned to its on-sample value when the sample approaches the probe tip.

6.2 Switched Gain Resonant Controller

In Chapter 3 the resonant controller was introduced as a new method of modifying the Q factor of an AFM micro-cantilever. The resonant controller is preferred over other methods of Q control in that it eliminates amplification of high frequency noise and ensures that unmodeled cantilever dynamics are not excited by the control action. The transfer function of the resonant controller presented in Chapter 3 to modify the effective cantilever Q factor is

$$K(s) = \frac{\alpha s^2}{s^2 + 2\zeta_c \omega_* s + \omega_*^2}, \quad (6.1)$$

where α and ζ_c are parameters which determine the gain at the frequency of interest ($\omega_* = \omega_n$) and the bandwidth of control. Once α and ζ_c have been set to achieve a particular cantilever Q factor, the Q factor may be modified by adjusting the value of α . The effective cantilever Q factor is reduced by increasing α or enhanced by decreasing α .

The switched gain resonant controller replaces $K(s)$ in the active Q control feedback loop of Fig. 3.4. The controller detects probe loss by comparing $A(t)$ to a threshold value of the cantilever oscillation amplitude A_{thresh} and modifies the cantilever Q factor between a low value and a high value depending whether the tip is on or off-sample.

The Anadigm AN220E04 FPAA used to implement the resonant controller in Chapter 3 was used to implement the switched gain resonant controller in this work. Refer to Chapter 3 Section 3.5.1 for a description of the AN220E04 FPAA. The FPAA

interface circuitry, consisting of electronics to convert the single ended signals from the AFM to differential signals used by the FPAA as well as a summer for the feedback loop is detailed in Appendix A.

6.2.1 Switch Implementation

The Anadigm AN220E04 FPAA has many Configurable Analog Modules (CAMs) which may be configured using the Anadigm Designer2 interface software [123]. One such CAM is a comparator with a switchable gain which is used in the implementation of the switched gain resonant controller. The comparator, shown in Fig. 6.1, selects the input to be passed through the gain stage according to the level of the input control signal $V_{control}$. There are two possibilities for the value of the CAM output voltage V_{out} :

$$V_{out} = G_1 V_{input1} \quad \text{if} \quad V_{control} < V_{ref} \quad (6.2)$$

and

$$V_{out} = G_2 V_{input2} \quad \text{if} \quad V_{control} \geq V_{ref}. \quad (6.3)$$

G_1 and G_2 are configurable gains and V_{ref} is a configurable reference voltage.

In this application the value of V_{ref} is set to equal the threshold value of cantilever deflection amplitude A_{thresh} . $V_{control}$ is connected to the demodulated value of cantilever deflection $A(t)$.

The switched gain resonant controller which uses the comparator with switchable inputs CAM to reduce error saturation is shown in Fig. 6.2. Note that the comparator, shown in the green shaded section, differs slightly from that shown in Fig. 6.1. This is because V_{input1} and V_{input2} are connected together. Therefore it is only the gain which is switched, not the inputs. There are two modes of operation:

$$v_{out} = K(s)G_1 \quad \text{if} \quad A(t) < A_{thresh} \quad (6.4)$$

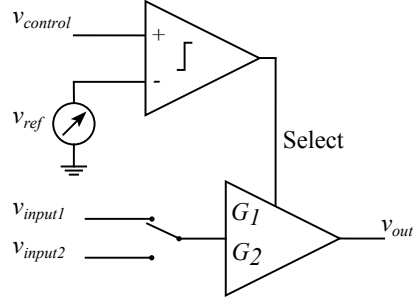


Figure 6.1: Anadigm comparator with a switchable input CAM.

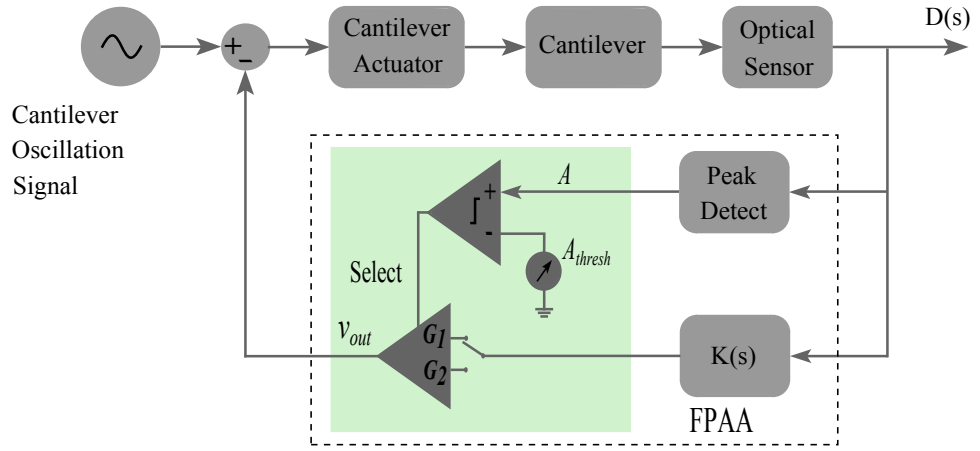


Figure 6.2: Switched gain resonant control feedback loop used to minimize probe loss. The blocks inside the dotted line are implemented in a FPAA.

and

$$v_{out} = K(s)G_2 \quad \text{if} \quad A(t) \geq A_{thresh}, \quad (6.5)$$

where $K(s)$ is given in (6.1).

The parameters of $K(s)$ are set to obtain the desired on-sample cantilever Q factor. As this is the desired on-sample cantilever Q factor G_1 is set to 1. The desired on-sample Q factor should be set at a low enough value for a wide Z axis feedback loop bandwidth but high enough to give sufficient force sensitivity.

The off-sample cantilever Q factor is dependent on the value of G_2 . $K(s)$ is multiplied by G_2 when $A(t) > A_{thresh}$. G_2 must therefore be set to a value less than

1 to increase the cantilever Q factor when probe loss is detected.

6.2.2 Amplitude Demodulation

As the switched gain resonant controller uses the value of $A(t)$ to determine when the probe has detached from the sample it is important that $A(t)$ be measured accurately in as short a time as possible.

The most common methods used to demodulate the cantilever deflection signal such as the RMS to DC converter or lock-in amplifier typically take approximately 10 oscillation cycles to acquire an accurate measure of the oscillation amplitude [89]. This delay in measuring $A(t)$ may be significant when trying to minimize probe loss.

For a cantilever with a resonance frequency of 55 kHz a delay of up to $\approx 180 \mu\text{s}$ would be expected to obtain an accurate measure of $A(t)$. At a scan rate of $40 \mu\text{m/s}$, 7.2 nm of the sample would have been scanned laterally in this time.

Ando *et al.* [92] developed a much faster method of amplitude detection using sample and hold circuits, and a low pass filter to detect the peak of the sine wave and hold that value for a predefined time. This method enables accurate demodulation in up to half an oscillation cycle.

The peak detect CAM available in the Anadigm FPAA works in a similar manner to the demodulator developed by Ando *et al.*. This CAM allows accurate measurements of $A(t)$ in less than one oscillation cycle. For the same cantilever with a resonance frequency of 55 kHz the demodulation delay is less than $\approx 18 \mu\text{s}$. At a scan rate of $40 \mu\text{m/s}$, 0.72 nm of the sample would have been scanned laterally in this time.

Rather than using the demodulated displacement signal from the AFM to measure $A(t)$ for threshold amplitude detection a peak detect demodulator was implemented in the FPAA. The advantages of this are:

- there are less input signals to connect to the controller making it easier to install

in an existing AFM; and

- it allows for faster detection of probe loss.

6.3 Experimental Demonstration

To demonstrate the improvements to scan speed and image reliability, when the switched gain resonant controller is employed in the AFM, experiments were conducted comparing images obtained with and without the controller.

The experiments were conducted with an NT-MDT NTEGRA AFM [127]. The NTEGRA AFM was fitted with a DMAPS piezoelectric self actuating AFM micro-cantilever. For a detailed description of the DMAPS micro-cantilever refer to Chapter 3 Section 3.6. Images were obtained when the cantilever Q factor is dynamically modified by the switched gain resonant controller and when the cantilever Q factor is set at a predefined value using active Q control.

The NT-MDT TGZ1 periodic step calibration grating, described in Chapter 3 Section 3.8, was used in this experiment as a test sample. The periodic step grating is ideal to test for probe loss as the sample shape and dimensions are known and it provides a worst case scenario for probe loss. Step features such as these would be found on electronic devices such as integrated circuits. Characterization of such electronic devices is an application of the AFM where a high scan speed is important to increase productivity. Images were obtained on a $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$ section of the calibration grating at a scan speed of $40\text{ }\mu\text{m/s}$. The free air cantilever oscillation amplitude A_0 was set to 53 nm with $A_{set} = 47\text{ nm}$, *i.e.* 89% of A_0 . The Z axis feedback controller gain K_Z was increased until the loop became unstable. K_Z was then reduced slightly to ensure sufficient stability margins in the feedback loop. The same K_Z was used for all scans.

The Q factor of the cantilever with no active Q control applied was measured to be 185. For the switched gain resonant controller the on-sample Q factor was

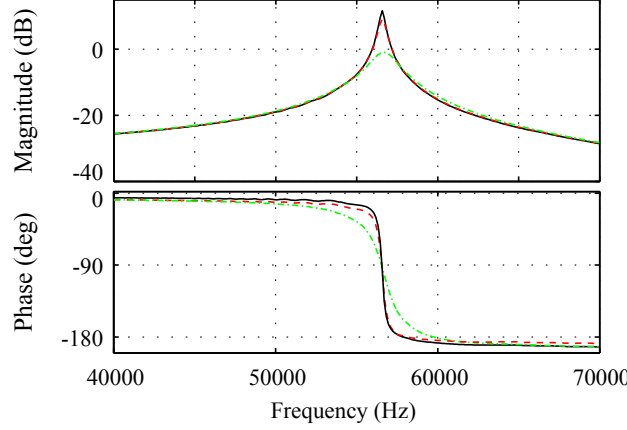


Figure 6.3: Frequency response of the DMAPS micro-cantilever. Natural Frequency response, $f_r = 56700$ Hz and $Q = 185$ (—). Frequency response with resonant active Q control, $Q = 50$ (- · -). Frequency response when probe is off-sample, $Q = 165$ (- -).

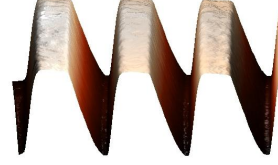
set to 50 and the off-sample Q factor set to 165. Therefore, when the off-sample condition is detected the cantilever oscillation amplitude will increase by a factor of 3.3. This larger oscillation amplitude results in a magnification of the maximum error sent to the feedback controller by a factor of 21.3. A frequency response showing the cantilever response with no Q control and with the Q factor reduced to 50 and 165 is shown in Fig. 6.3. A_{thresh} was set to 51.5 nm *i.e.* 97% of A_0 . To show the efficacy of the switched controller, scans obtained using active Q control (without switching) with the Q factor set to 50 (which is the same as the on-sample Q factor used with the switched controller) were used as a comparison.

The resulting images obtained using only active Q control and using the switched gain resonant controller are shown in Fig. 6.4. A cross section of the images obtained is shown in Fig. 6.5. Significant probe loss can be observed in the image obtained using active Q control. This imaging artifact, caused by probe loss, is significantly reduced in the image obtained with the switched controller. The Z axis feedback loop error signal for the same cross section is shown in Fig. 6.6. Saturation of the error signal can be clearly seen in the image obtained with only active Q control.

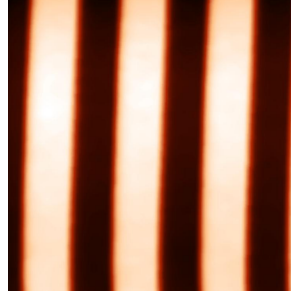
It should be noted that a reduction in probe loss duration was observed in images



(a) 2D image with active Q control.



(b) 3D image with active Q control.



(c) 2D image with switched gain resonant controller.



(d) 3D image with switched gain resonant controller.

Figure 6.4: Images of the NT-MDT TGZ1 calibration grating obtained at a scan speed of $40 \mu\text{m/s}$. The use of the switched gain resonant controller resulted in significant reduction of probe loss as can be seen by the sharper downslope in the image.

obtained when the Q factor was reduced to 50 compared to images obtained with the unmodified Q factor of 185. With the same scan speed and a cantilever Q factor of 185 the maximum set-point obtainable was 65% of A_0 . When A_{set} was increased to higher than 65% of A_0 the cantilever would completely detach from the sample and a flat image would be produced. This is because the higher cantilever Q factor reduced the stability margins of the Z axis feedback loop requiring a lower value of K_Z to avoid loop instability. The lower value for K_Z reduces the speed at which the Z axis

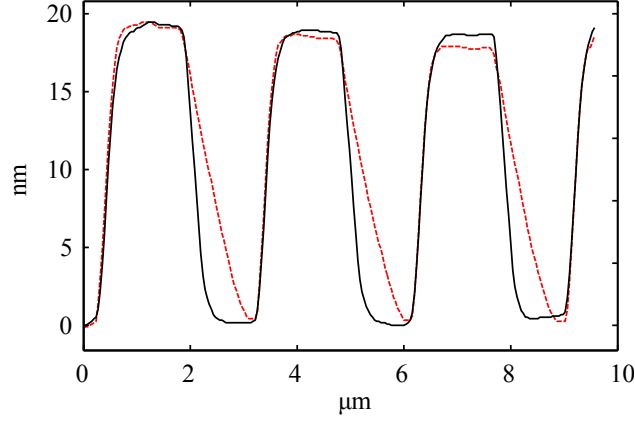


Figure 6.5: Cross section of the NT-MDT TGZ1 calibration grating image from Fig. 6.4(b) and 6.4(d). The scan obtained with active Q control (—) is clearly affected by probe loss when the step drops away. This area of probe loss is significantly reduced when the switched gain resonant controller is used (—).

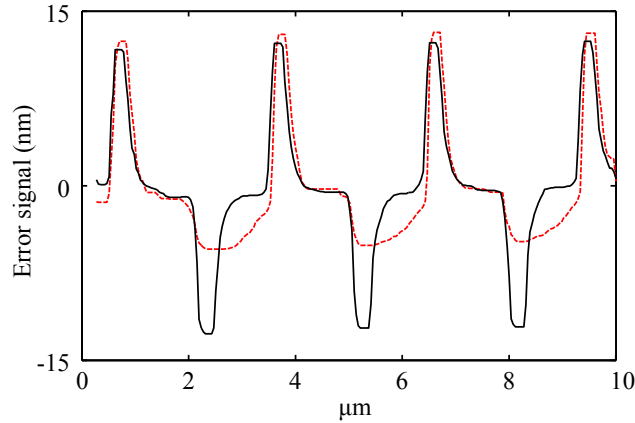


Figure 6.6: Z axis feedback error signal, taken from the NT-MDT TGZ1 calibration grating image in Fig. 6.4(b) and 6.4(d). Moments after the sample topography drops in height the error signal obtained using active Q control (—) is clearly smaller than the error signal obtained using the switched gain resonant controller (—).

actuator can bring the sample back into contact with the probe tip. Note that this sample has a large step drop. If a sample with smaller features was to be scanned at a lower scan speed then a higher set-point would be obtainable. If the Q factor had been reduced lower than 50 with active Q control the probe loss observed in Fig. 6.5 would be reduced. However this may have detrimental effects such as reduced image

resolution and increased tip-sample forces.

There is the possibility that switching between the two controller gains may lead to system instability. No such issues were observed when conducting the above experiments. Future research will investigate the conditions for which the switched system is guaranteed to be asymptotically stable.

Chapter 7

Summary and Conclusion

In this thesis new techniques for controlling the Q factor of an AFM micro-cantilever have been presented, with the aim of increasing the scan speed and image quality when imaging in tapping mode. The following is a summary of the work presented in this thesis, highlighting the contributions and results achieved.

An introduction to the AFM was provided in Chapter 1 highlighting some of its many applications and giving an overview of its principle of operation. The three main AFM imaging modes were described and the advantages/disadvantages of operating in each mode were discussed. Tapping mode has become the most widely used AFM imaging mode as the lateral forces between the probe and sample are significantly reduced when operating in this mode. The remainder of the chapter focused on the tapping mode of operation, as the work of this thesis is based on the performance of the AFM operating in tapping mode.

The cantilever Q factor was shown to be the main factor which determines the force sensitivity of the instrument operating in tapping mode. Factors which influence the tip-sample force while scanning were shown to be the set-point oscillation amplitude, the cantilever Q factor and spring constant.

In Chapter 2 the need for increased scan speeds, while minimizing image artifacts,

when operating in tapping mode was discussed and highlighted as the main motivation for this research. The limitations to increasing the scan speed of the AFM operating in tapping mode are the bandwidth of the scanner in the lateral axes and the bandwidth of the Z axis feedback loop, with the latter being the main limitation. Factors which affect the bandwidth of the Z axis feedback loop are the bandwidth of the cantilever in cascade with the demodulator, the time taken to demodulate the cantilever tip oscillation amplitude and the bandwidth of the Z axis actuator. The bandwidth of the cantilever in cascade with the demodulator, which is dependent on the cantilever Q factor, is the major restriction on the bandwidth of the Z axis feedback loop. Reducing the cantilever Q factor increases the Z axis feedback loop bandwidth allowing for faster scan speeds.

The method of active Q control used in commercial AFMs to modify the cantilever Q factor is based on velocity feedback of the cantilever tip displacement. Tip velocity is typically estimated by applying a phase shift of 90 degrees to the displacement signal with a time delay circuit. The higher order modes of the cantilever are affected by the control action of the time delay controller and this may reduce the performance of the control system or cause the cantilever to become unstable when the cantilever Q factor is reduced. This problem was detailed in Chapter 3 and the resonant controller was introduced as a solution.

Like the time delay controller, the resonant controller estimates the cantilever tip velocity by phase shifting the measured cantilever displacement signal by 90 degrees at the cantilever oscillation frequency. The main advantage of using the resonant controller, when reducing the cantilever Q factor to improve the image quality at high scan speeds, is that it guarantees closed-loop stability in the presence of unmodeled higher order cantilever dynamics. It was shown that the controller may also be used to increase the cantilever Q factor if increased force sensitivity and reduced tapping forces are desired.

By implementing the controller with a FPAA it has been demonstrated that the

control system may be designed to be simple, compact and straightforward to tune. Initial tuning may be achieved through a pole placement technique, then the cantilever Q factor may be adjusted by varying the controller gain.

The efficacy of the resonant controller was demonstrated by reducing the effective cantilever Q factor with the controller and imaging a calibration grating with the AFM. A significant reduction in imaging artifacts when imaging at high scan speeds was observed when reducing the cantilever Q factor, as expected.

Passive piezoelectric shunt control was introduced in Chapter 4 as a new method of reducing the Q factor of a piezoelectric self actuated AFM micro-cantilever. By placing a passive impedance consisting of an inductance and a resistance in the cantilever oscillation circuit a resonant LRC circuit is obtained. By tuning this damped electrical resonance to the mechanical dynamics of the micro-cantilever a significant reduction in the effective cantilever Q factor is achieved.

Like the resonant controller, this control technique has guaranteed stability in the presence of unmodeled higher order cantilever modes, giving it an advantage over the traditional time delay velocity estimation method of active Q control. Another advantage of using passive piezoelectric shunt control to reduce the cantilever Q factor is that it removes the need for an optical sensor in the Q control feedback loop, which results in a reduction in sensor noise. If this method of active Q control is used in conjunction with alternative methods of measuring the cantilever displacement which work by measuring the current through the piezoelectric transducer bonded to the cantilever, the optical sensor may be removed from the instrument altogether. Removing the optical sensor is not only an advantage for reducing sensor noise, it allows for a reduction in the size of the AFM which is a benefit in many applications.

It was shown that the transfer function from a disturbance, due to variations in sample topography, to tip displacement is equivalent to a negative feedback system when a shunt impedance is added to the cantilever oscillation circuit. When viewing the system in a negative feedback context the controller is a function of the shunt

impedance. This allows the use of standard control design techniques to determine the required shunt impedance for the desired performance objectives.

To allow for fine tuning of the control parameters a synthetic impedance, which mimics the voltage to current relationship of the desired impedance, was designed. The use of a synthetic impedance also allows for the design of more advanced controllers which may not be possible with passive components.

A reduction in cantilever Q factor from 297.6 to 35.5 was achieved using this technique on a commercially available piezoelectrically actuated AFM micro-cantilever, resulting in a significant improvement in image quality at high scan speeds. There is a limit on how far the Q factor of the cantilever may be minimized using a passive shunt impedance. The use of an active impedance may allow further reductions in the Q factor of the cantilever.

In many imaging applications high force sensitivity and reduced tip-sample force may be a higher priority than increased scan speeds. In such cases it is desirable to increase the cantilever Q factor. To increase the cantilever Q factor energy must be added to the system. It is not possible to do this in the piezoelectric shunt control framework when using a passive impedance. In Chapter 5 active piezoelectric shunt control was introduced as a new method of increasing the Q factor of a piezoelectrically actuated AFM micro-cantilever. An impedance consisting of an inductance and a negative resistance was designed using a synthetic impedance. AFM images of a sample with very fine features were obtained with the cantilever Q factor enhanced by active piezoelectric shunt control to demonstrate the resulting improvement in image quality.

The active piezoelectric shunt control technique is also useful in other cantilever sensing applications such as sensing of temperature, humidity and gas pressure where high cantilever Q factors are desired to improve sensitivity. The reduction of sensor noise, low cost and small footprint of this controller makes it desirable in these applications.

In most imaging applications it is desirable to minimize tip-sample force. By setting the desired cantilever oscillation amplitude very close to the free air oscillation amplitude tip-sample forces are minimized and tracking is improved in upward sloping regions of the sample. However, this high set-point has a detrimental effect of increasing the likelihood of error signal saturation occurring in sharp downward sloping regions of the sample. When the probe reaches a sharp drop in the sample topography it is likely that the Z axis feedback control loop error signal will saturate, as the set-point oscillation amplitude is set so close to the free air amplitude. This will lead to a slow response of the feedback controller to the change in sample topography, producing artifacts in the image obtained.

A switched gain resonant controller was presented in Chapter 6 as a new method of minimizing the effects of error signal saturation on the image obtained. While the cantilever is in contact with the sample the controller reduces the cantilever Q factor to increase the stability margins of the Z axis feedback control loop, which allows for higher scan speeds. When the probe loses contact with the sample, after a sharp drop in sample topography is encountered, the switched gain resonant controller increases the cantilever Q factor which in turn increases the free air oscillation amplitude of the cantilever resulting in a larger error signal sent to the Z axis feedback controller. This reduces the time that the probe is not in contact with the sample resulting in a reduction of image artifacts. The benefits of a high oscillation amplitude set-point are therefore maintained while reducing the effects of probe loss. Increased imaging speeds with minimal image artifacts have been demonstrated using this control technique.

When implementing the switched gain resonant controller it takes some trial and error to determine the optimal values for the cantilever oscillation amplitude set-point, the Q factor switching threshold amplitude, the on-sample Q factor and the off-sample Q factor. Future research will look at automating the selection process of the above parameters, through an optimization process, to achieve increased scan speeds

with minimal image artifacts and tip-sample force. Factors which would need to be considered are the cantilever properties, the sample type, the imaging environment and the height of the sample features.

The applications and scientific discoveries which have been achieved so far with the AFM offer a glimpse into its capabilities. However, there is still a long way to go until the AFM reaches its full potential.

The development of new control techniques combined with those developed in this thesis will have an important role in the future development of this instrument, which is playing a key role in many fields of research. Further advancement of the AFMs capability will require a multidisciplinary approach combining the expertise of researchers in the fields of physics, materials science, mechanical engineering and electrical engineering. However, the control systems engineer will have a pivotal role in the challenge of increasing the imaging speed of this device while maintaining minimal image artifacts and avoiding damage to the sample.

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Appendix A

Field Programmable Analog Array Interface Circuit

The AN221E04 FPAA inputs and outputs are 0 to 4 V differential signals referenced to 2 V. The use of differential signals reduces the amount of noise processed by the device. To convert and scale the ground referenced single ended signals used by the AFM an interface circuit was developed, as shown in Fig. A.1. An operational amplifier with a high gain bandwidth product is required for this circuit due to the high resonance frequency of the cantilever. The Linear Technology LT1468 operational amplifier [150] chosen for this application has a gain bandwidth product of 90 MHz.

The signal from the AFM optical displacement sensor is in the range of -10 to 10 V. This signal is scaled to -2 to 2 V by the block labeled *A* in Fig. A.1. The output of this block is then converted to a differential signal and the reference shifted from 0 V to 2 V by the block labeled *B* to produce a 0 to 4 V differential signal referenced to 2 V which is compatible with the FPAA inputs. The output of the FPAA is a 0 to 4 V differential signal referenced to 2 V. This signal is converted to a single ended signal referenced to ground by the block labeled *C*. The block labeled *D* is the summer for

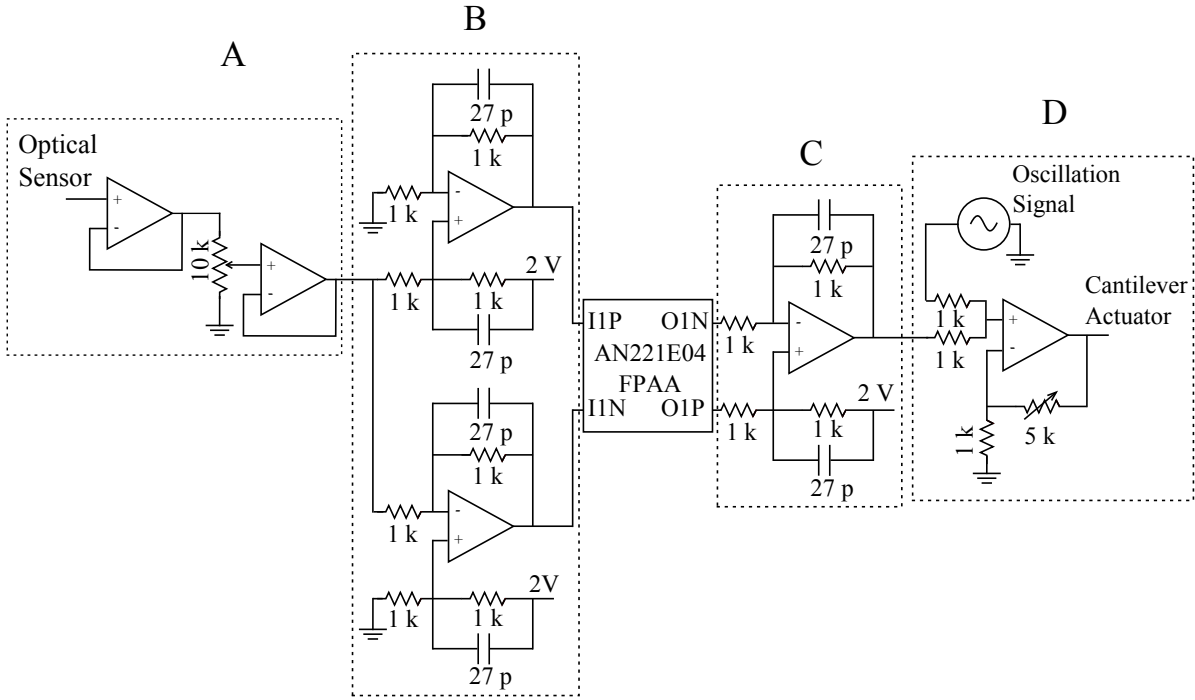


Figure A.1: Schematic of the FPAA interface circuit. Note that this schematic also includes the summer used in the Q control feedback loop. The function of each block (A-D) is detailed in Section A.

the feedback loop. It also has the function of amplifying the signal dependent on the gain of the controller configured in the FPAA.