Control and Estimation Techniques for High-Bandwidth
Dynamic Mode Atomic Force Microscopy

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Acknowledgments

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or 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 University’s Digital Repository, subject to the provisions of the Copyright Act 1968.

Kai Karvinen
March, 2014
Statement of Collaboration

I hereby certify that the work embodied in this thesis has been done in collaboration with other researchers. I have included as part of the thesis a statement clearly outlining the extent of collaboration, with whom and under what auspices.

- In Chapter 5, the formulation of the tip-sample force estimation algorithm was performed in collaboration with A/Prof. Kaushik Mahata (of the University of Newcastle). The new insights into the modeling of the microcantilever in dynamic mode atomic force microscopy were proposed in collaboration with Mr. Michael Ruppert (of the University of Newcastle).

Kai Karvinen  
March, 2014
Patents and Publications

The research performed throughout the duration of my candidature has resulted in an Australian patent and the following peer-reviewed conference and journal papers.

Patents


Journal Articles


Conference Papers


Abstract

The atomic force microscope is possibly one of the greatest scientific inventions of the twentieth century. Owing to its ability to non-invasively image a range of surfaces with sub-nanometer resolution, the atomic force microscope is found in laboratories across the world. For the past 25 years it has also been the focus of significant research interest. This research outlines several control and estimation techniques, which are compatible with next generation atomic force microscopes, that are designed to enable high-speed and multifrequency imaging.

The first section proposes the application of a novel high-bandwidth controller implementation, namely the modulated-demodulated controller, to the $Q$ control of an atomic force microscope microcantilever. A mathematical analysis highlights that modulated-demodulated controllers are linear time invariant. Furthermore, the modulated-demodulated control architecture can be configured to produce both positive position feedback and resonant controllers. The usefulness of these fixed structure controllers becomes evident in the context of negative imaginary systems theory, which can be utilized to ensure robust stability of the closed-loop system – a clear advantage over alternative $Q$ control techniques. Mathematical models have also been presented to enable the analysis of more complex modulated-demodulated controllers. The modulated-demodulated controller is verified experimentally on a microcantilever and AFM images are presented. One significant advantage of this technique is the reduction of the bandwidth requirements of the baseband controller which simplifies the controller implementation. Modulated-demodulated control appears to be well suited to the control of high-frequency resonant dynamics and may find additional applications in high-frequency MEMS and applied optics.

The second section outlines two novel high-bandwidth amplitude estimation techniques, including the invention of the high-bandwidth lock-in amplifier and the proposal of a high-speed discrete Kalman filter approach. These techniques are designed to improve the performance of dynamic mode AFM imaging techniques which rely on amplitude estimation in the feedback loop by significantly increasing the bandwidth of the estimation technique. Furthermore, both techniques are robust against noise and harmonics making them suitable for multifrequency atomic force microscopy. Experimental verification highlights fast amplitude estimation in several oscillation cycles – a significant improvement over conventional techniques.
Finally, new insights into the modeling of a microcantilever in dynamic mode atomic force microscopy are outlined. Using these results, a novel tip-sample force estimation technique is proposed and experimentally verified. Assuming that the tip-sample force takes the form of an impulse train, the estimation problem can be formulated using a Kalman filter. The technique potentially offers significant improvements in the bandwidth of the z-axis control loop through high-bandwidth tip-sample force estimation, which eliminates the requirement for amplitude demodulation and the dependence of the imaging bandwidth on microcantilever transients. The estimation technique is numerically robust and converges quickly. Previous improvements to z-axis control in dynamic mode atomic force microscopy have focused on the development of model-based controllers. Still limited by the microcantilever dynamics and amplitude demodulation technique, these controllers require accurate models of the nanopositioner; nonlinearities such as creep and hysteresis complicate the design of these controllers. The proposed technique is potentially advantageous as it only requires accurate knowledge of the microcantilever.

The application of systems and control theory has, to date, revolutionized the capabilities of the atomic force microscope. The techniques outlined and implemented as part of this research serve to further enhance the performance of an instrument, which has a vital role in the scientific world.
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