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On automating atomic force microscopes: An adaptive control approach

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Abstract

In this paper, modeling and experimental results are given to reveal the structure of atomic force microscope (AFM) dynamics and uncertainties which are strongly impacted by the user's choice of scan and controller parameters. A robust adaptive controller is designed to eliminate the need for the user to manually tune controller gains for different sample cantilever combinations and compensate for uncertainties arising from the user choice of different scan parameters. The performance of the designed adaptive controller is studied in simulation and verified through experiments. A substantial reduction in contact force can be achieved with the adaptive controller in comparison with an integral controller.

Keywords: Atomic force microscope (AFM); Adaptive control; Model

1. Introduction

Atomic force microscope (AFM) (Binning, Quate, & Gerber, 1986) has been a key enabling tool in nano-sciences and nanotechnology. AFM has been used in numerous fields and applications including nano-manipulation (Sitti, 2003), imaging and dissection of DNA (Hansma, 1992), measuring nano-scale friction and adhesion (Homola, Israelachvili, Gee, & McGuiggan, 1989), studies of micro-mechanics of single molecules (Fisher, Marszalek, Oberhauser, Carrion-Vazquez, & Fernandez, 1999), and investigation of nanotribology and nanomechanics of MEMS devices (Bhushan, 1996).

The performance of AFM relies strongly on its dynamic response and hence its control system. Several authors (Schitter, Allgöwer, & Stemmer, 2004; Sebastian, Salapaka, & Cleveland, 2003) have used linear robust control strategies to control AFM dynamics. In Szuchi, Qingze, and Devasia (2004), iterative control was used to compensate for coupling dynamic effects in AFM.

The dynamics of AFM is strongly influenced by the user's choice of cantilever, sample properties, environment, and scan and controller parameters. As a result, the AFM exhibits large level of uncertainties. Ultimately, the objective is to be able to automatically select scan parameters such as rate (or speed), force set-point, and controller parameters in order to consistently achieve a *good* image. Characteristics of achieving a good image include probe and sample remain in contact during scanning and the set-point error is maintained small at all times. In addition, the control signal which is used to create the sample image should be free from mode oscillations. More so, high-frequency noise level in the image signal should not be amplified by feedback. Consequently, system uncertainties should be compensated for.

This paper presents initial work on automatically selecting scan and controller parameters in order to consistently achieve a *good* image. The approach is to improve the performance of AFM in the presence of large uncertainties by utilizing robust adaptive control to avoid manual tuning of controller parameters. In addition, guidelines for selecting scan parameters are provided. In contrast to a fixed robust control approach, adaptive control can handle a larger range of parametric uncertainties

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without leading to a conservative design or to the worst case feedback instability.

The contributions of this paper are as follows: it reviews earlier work (El-Rifai & Youcef-Toumi, 2000, 2001, 2002) on modeling of AFM dynamics and builds on it to identify an appropriate plant structure for adaptive control. A robust adaptive control based on results in the literature (Krstic, Kanellakopoulos, & Kokotovic, 1995; Xu & Yao, 1999; Yao & Tomizuka, 1997) is designed and tailored to the AFM dynamics and practical implementation. In addition, user specified scan parameters are tied with control design and guidelines are given for scan parameter selection. Moreover, a practical method for uncertainty modeling and identification of range of uncertain parameters for use in the robust adaptive control design is provided. Finally, both simulation and experimental results are presented to demonstrate the performance of the adaptive control.

The paper is organized as follows. Section 2 describes the AFM and its operation. Probe sample interactions are discussed in Section 2.1. In Section 2.2 a model for in-contact dynamics of AFM is briefly presented. In addition, sources of uncertainties and their impact on dynamics are discussed along with supporting experimental data. A discussion on scan parameter selection and AFM performance in presented in Section 3. Section 4 presents a robust adaptive output control algorithm. The adaptive controller is applied to AFM feedback system in Section 5. In addition, discussion on estimating bounds on uncertain parameters is given and both simulation and experimental results are presented and discussed. Finally, summary and concluding remarks are given in Section 6.

2. Atomic force microscope

An AFM, Fig. 1, has three main components, namely, a scanner, a cantilever with a sharp probe, and a cantilever deflection sensor composed of a laser source and a position sensitive diode (PSD). The scanner, typically a piezoelectric tube, provides three-dimensional motion of the probe relative to the sample. A piezo amplifier is used to provide the high-voltage needed for driving the piezoelectric scanner. Information on sample topography or local properties is obtained based on probe–sample interactions. One of the main operating modes of AFM is contact mode. In this mode, the probe presses against a sample exerting a vertical force proportional to the cantilever deflection. The probe is then dragged against the sample along each scan line in a raster fashion. The angle at the cantilever's free-end is measured and fed back. During scanning, a control system is used to maintain a constant angle by adjusting the vertical deflection of the piezoelectric scanner. Changes in the deflection of the scanner are taken as measure of sample topography.

The performance of AFM is strongly influenced by the user's choice of scan and controller parameters. Fig. 2(a) shows some of the effects of scanning speed and controller

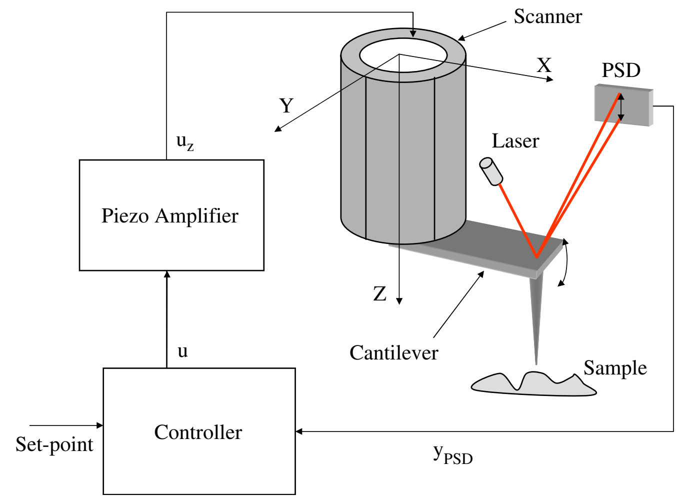

Fig. 1. Schematic of the main components of an AFM.

gains on the image of a calibration step. Higher gains result in oscillations as the cantilever falls along the right edge of the step, with peaks indicating momentary loss of contact between the probe and the sample. However, the higher gains improve tracking as the sharp left edge of the step is resolved more accurately. On the other hand, choosing a small contact force set-point reduces contact deformation and friction; however, it reduces stability of the contact. As seen in Fig. 2(b), the image generated with a small contact force has erroneous height information due to loss of contact between the probe and the sample.

In pursuit of consistently achieving an accurate and artifact free image the AFM dynamics need to be understood. Moreover, sources of uncertainties and their effects on the dynamics need to be identified. This will be discussed in the following two subsections.

2.1. Probe–sample interaction

The probe–sample interaction force is a nonlinear function that depends on probe–sample separation, geometry, operating environment, and probe and sample material properties. A model for the contact interaction force based on the work of Maugis was presented in El-Rifai and Youcef-Toumi (2000). Out of contact van der Waals forces are assumed. A nondimensional composite force–separation curve was generated using the model and is shown in Fig. 3(a). The model can predict an instability that has been observed in quasi-static experiments. This quasi-static instability, as seen in the experimental results of Fig. 3(b), occurs when an approaching/receding probe jumps in/out of contact (pull-in/pull-off points), with the sample surface corresponding to a sudden jump in the contact area. The actual point of instability on the force–separation curve will depend on the stiffness of the cantilever k_c as shown in Fig. 3(a). The cantilever stiffness is estimated from Fig. 3(b) as the slope of the line just after the pull-off point. It can be seen from both figures that the