APPLYING FEEDBACK CONTROL IN ATOMIC FORCE MICROSCOPY

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ABSTRACT

The aims of the presented paper are to make a concise state-of-art of the most commonly used feedback loops for the AFM control. Moreover, to propose a feedback control loops in order to minimize the effect of the thermal noise on the weak forces measurements and improve manipulation abilities of the AMF.

1 STATE OF ART

Stringent demand to probe and fabricate systems of ever-shrinking sizes demands an ever-increasing performance of instruments like atomic force microscopes (AFM). A typical AFM consists of a micro-cantilever with a sharp tip, a sample positioning system, a detection system and a control system.

The actual commercial AFM are using standard PI(D) controller to position the micro-cantilever tip at a desired distance from the sample. There is still a need for studies showing the optimal way of tuning these controllers in order to achieve high closed-loop performances of the positioning. Choosing other controller structures, more suitable to deal with the compromise robustness/performance can be also a solution.

Moreover, new type of measures with AFM (like small interaction forces), which are very challenging for experimental physics, call for new studies of the appropriate control schemes.

2 AFM DESCRIPTION

Atomic Force Microscopy (AFM) is one example of Scanning Force Microscopes, and is capable of measuring the interaction force between the sample and a sharp tip mounted on the end of a weak cantilever (fig. 1).

Two main modes of operating the AFM are used: static detection mode and dynamic detection mode, often called taping mode. In static detection mode, the interaction force is determined by measuring the static deflection of the cantilever and is able to detect displacement on atomic scale resolution. In dynamic detection mode, the cantilever is mechanically driven, usually at its resonant frequency, with an amplitude no larger than 100 nm. Resonance frequency shifts occur if the cantilever is approaching the surface of the sample. Further description of this technique will be provided in the next chapter. This technique is used to measure weak forces like van der Waals force for example. The cantilever driver is usually a piezo-electric element but many experiments have been done with electrostatic drivers, too.

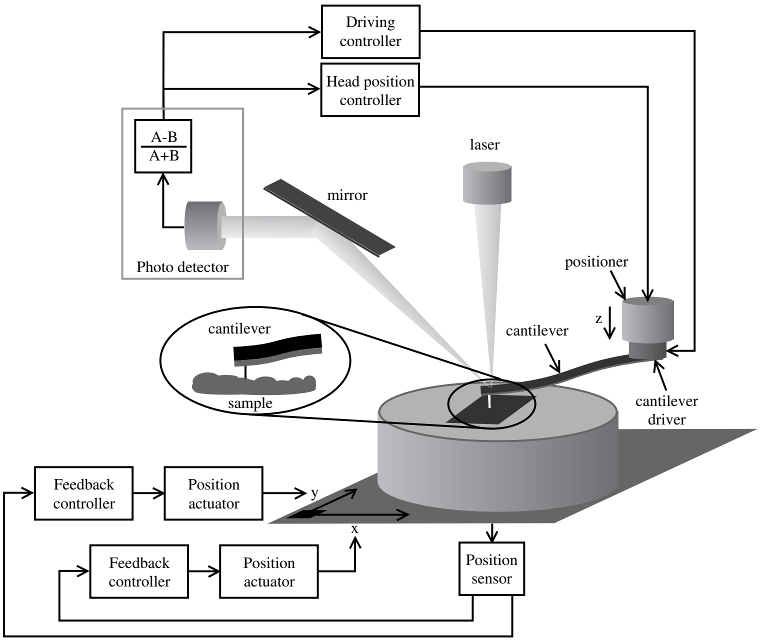

Figure 1: Schema of the AFM

Accuracy in measuring the cantilever displacement is very important for reaching good resolution of AFM. Many techniques have been developed for this measurement based on different principles including capacitive and optical techniques (as the interferometry, optical beam deflection and laser diode feed back detection). Each technique has specific advantages and disadvantages. A widely used method by many manufacturers of AFM is the optical beam deflection technique shown in fig. 1. Its function is based on sensitive photodetector which is able to detect very small laser beam displacement. Photodiode receiving reflected laser beam from the cantilever is divided into two sections A and B. Due to the macroscopic length of reflected light path, any deflection cause a magnified displacement of the reflected laser spot on the photodiode. The relative amplitudes of the signals from the two segments of the photodiode change in response to the motion of the spot. The difference signal (A-B) is very sensitive to cantilever deflection.

3 FEEDBACK CONTROL IN AFM

Modern AFM includes many feedback loops to control different blocks of this complicated instrument. Some of the most exciting and still widely open areas in AFM feed back control are:

3.1 LOOP CONTROLLING POSITION OF AFM STAGE IN X-Y AXES

Many experiments have been done with different techniques on how to move the stage with very high precision and speed. Over many years most of the AFM manufacturers and scientists prefer piezo-electric actuators. These devices offer fine position capabilities reaching sub-Angstrom resolution and high-speed manipulation. Piezo electric actuators have disadvantages such as nonlinear properties, which become worse with the increasing need for fast movement given by actuators. This illustrate the need for better and more accurate models describing the piezo element and taking part of feedback control systems.

Surface physicists have been using AFM mainly for scanning purposes in the past. Recently, AFM is being used in many different fields of biology, medicine, material science, nano-manipulation and nano-lithography. This movement involves improve accuracy and explores possibilities to use AFM as a manipulator instead of a scanner. The difference between these two approaches is displayed in fig 2. The left part is simple movement across the sample in the straight lines, scanning. On the other side is shown movement that is required to manipulate little object on the surface. Cantilever has to reach desired position then approach the surface and do movement which is not necessarily straight but it could be of any shape.

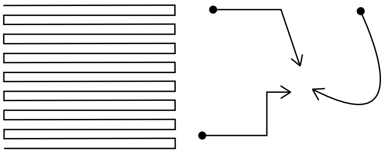

Figure 2: Scanning approach on the left, manipulation approach on the right.

With the increasing accuracy of the piezo actuator, the problem of measuring the distance on a smaller scale is becoming apparent. Most of the position sensors are experiencing problems with exceedingly high levels of electric and thermal noise, which lower the resolution.

Now a day feedback control loops for x and y axes have to be able to do very complex movements with very high speeds, instead of dragging the cantilever across the sample in straight lines. This area is now open to new techniques and ideas on how to control nonlinearities of the systems coming from piezo hysteresis to achieve desired performance. The figure 3 displays possible feedback control loops that could improve resolution.

3.2 LOOP CONTROLLING POSITION OF AFM HEAD IN Z AXE AND CANTILEVER EXCITATION

Surface is measured by a very small cantilever (usually not larger than 100 microns) and is capable of detecting displacements of the tip corresponding to tenths of an Angstrom. The cantilever is usually vibrating at its resonance frequency with amplitude no larger then hundreds of nanometers. Harmonic movement of the cantilever is driven by the piezoelec-

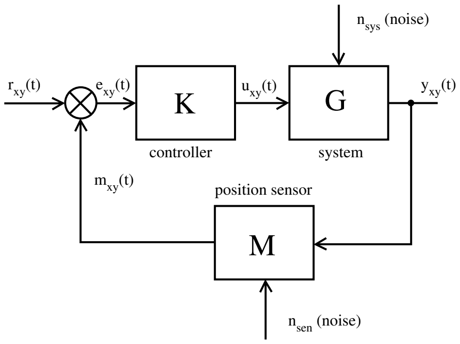

Figure 3: Feedback control loop utilizable to control position of the sample mounted on the stage of the AFM.

tric element, which is the fixed end of the attached cantilever. Two control loops are needed for proper function of AFM.

Modern cantilevers are designed and manufactured weak enough not to destroy the surface of the measured sample. A very weak cantilever is sensitive to thermal excitation that appears in the system as the largest source of noise. Thermal noise significantly affects sensitivity and limits resolution improvement. Fig. 4 displays the amplitude spectrum measured on the cantilever without any artificial excitation. The spectrum shows little excitation across all frequencies and at the resonance frequency of the cantilever, a large peak generated by thermal noise exciting the cantilever is visible. Some techniques already exist on how to improve sensitivity by eliminating the thermal noise of the cantilever. One of interesting techniques that has been introduced is Noise Squeezing.

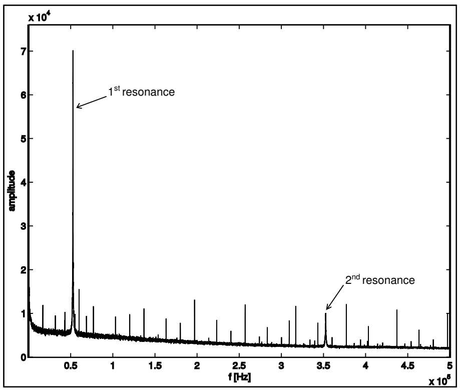

Figure 4: Frequency spectrum of a freely vibrating cantilever driven by the thermal noise (Brownian Motion). The spectrum displays just first resonation frequency and it has been measured at the NanoTec AFM.

The cantilever is of course exposed to many another noises such as electrostatic, electromagnetic and air turbulences. Eliminating the influence of these noises is possible by appropriate mechanical and electrical construction of the AFM.

It is very reasonable to believe that by applying a certain feedback control loop, could eliminate the noise and increase the sensitivity of the instrument. The scanning force microscopes are usually controlled by simple proportional-integral regulators which are not able to give the best possible results. The figure 5 shows control loops improving sensitivity of the AFM. The regulators used it these loops need to be designed by robust control techniques.

Control system consists of two parts: positioning loop and driving loop. Positioning loop is working at lower frequencies and its duty is to keep the head in constant distance from sample surface. It provides simultaneous measuring of the surface without loosing any information. This distance is in the scanning force microscopy usually called "set point" and ensures that the cantilever is vibrating at its maximum harmonic deflection without hard taping at the surface. The driving loop is operating at the higher frequencies and is keeping the cantilever excited at its resonant frequency despite contact (van der Waal interaction) with the surface of the sample. This is usually done by piezoelectric element harmonically vibrating at desired frequency with very small amplitude.

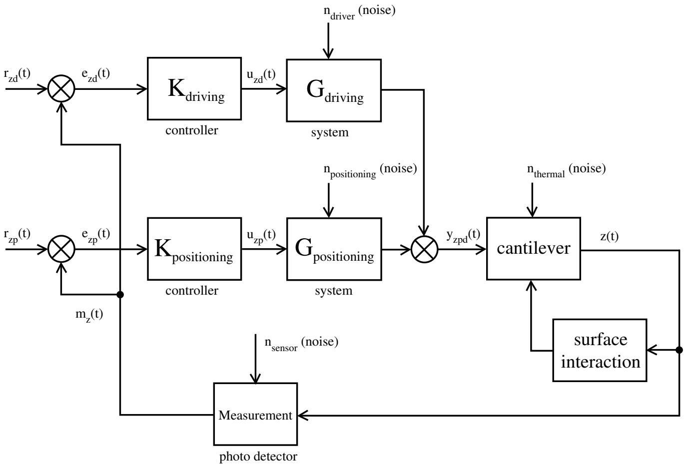

Figure 5: Feedback control loops of the head positioning and the cantilever driving.

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