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Automatic Tuning of PI Controller for Atomic Force Microscope Based on Relay with Hysteresis

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***Abstract*—An atomic force microscope (AFM) usually employs proportional-integral (PI) control strategy to sustain a constant cantilever deflection. However, it is well known that the tuning of PI parameters is a tedious and complicated procedure, especially for those unfamiliar with control theory. In this paper, we employ and implement relay controller to automate the tuning procedure for contact-mode AFM PI controller during different scanning speed operations based on relay with hysteresis. Experimental results show that this approach offers system with satisfactory step response with typical settling time of about 2 ms. Moreover, better sample topography image can be obtained after auto-tuning the control gains during different scanning speed.**

I. Introduction

Since the invention of the atomic force microscope (AFM), it has become the most powerful tool in such fields as nano-technology, surface, material , biology and so on [1, 2]. Although lots of efforts and improvements have been made to enhance the performance of AFM system [3-7], there are still many primary limitations which hinder its further application. One of them is that AFMs are more difficult to use than other microscopes such as optical and electron microscopes. Usually, before operation begins, AFMs need to be set up manually and the controller parameters need to be well adjusted according to different situations. A common commercial AFMs controller block diagram is shown in Fig 1. In Z direction the system consists of voltage amplifier, piezo-scanner, cantilever, photo-diode and the controller which usually employs a standard proportional-integral (PI) algorithm. Several model based robust controllers are explored and applied to achieve faster scanning speed, and those controller parameters are synthesized. However, weighting functions used to design such controllers are even more difficult to handle than PI parameters because the performance of resulting controllers depends heavily on weighting functions [8, 9]. Besides, those advanced controllers are still not available for most of common AFM users.

For standard PI controller, it is important to choose proper control gains for different samples, cantilevers, piezo-actuators and scanning speed so that superior performance can be achieved. Especially for different scanning speed, with the increasing of scanning speed, the error (deflection) will usually increase as a subsequence. As indicated by experimental experience, the proper PI parameters for low scanning speed may result in oscillations of the system during high speed operation. Those oscillations bring damage to the cantilever and fragile samples like biological cells and proteins. Based on this observation, a semi-automatic tuning method of PID gains for AFM by utilizing PID notch filter design is proposed in [10]; however, those effects such as scanning speed are not addressed.

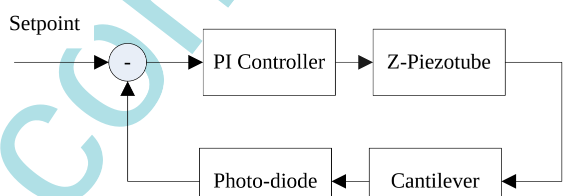

Fig. 1 Block diagram of AFM controller in Z-direction.

In this paper, an automatic tuning method based on relay is proposed and implemented for a commercial AFM. Specifically, a relay controller is implemented on RTLinux platform and the signal is fed into AFM through signal access module. Ultimate period and gain of the system are extracted in relay test; then plant information is used to design PI parameters based on Ziegler-Nichols formulas. Besides, a scaling factor is proposed to relate the PI parameters with scanning speed. Different factors such as piezo-tube, cantilever and scanning speed on PI parameters are discussed and analyzed. Experimental results show that this method can achieve satisfactory step response with settling time of 2 ms; moreover, better sample topography image can be obtained after retuning the control gains during high speed operation comparing to that with proper gains for low speed operation.

II. Method of Auto Tuning Based on Relay

There are two basic methods to tune the PID loop for control systems: Ziegler-Nichols method and relay method [11]. However, for AFM system, the Ziegler-Nichols method which utilizes P control to drive the system to critical point is not applicable because there are some disadvantages of this method: 1) the system is driven to critical point which means that the cantilever is vibrating on the sample with much viscous forces; 2) it is almost impossible to automate the tuning procedure for AFM system because it requires to keep increasing the P gain until oscillations happen. Hence we

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employ the relay based feedback identification scheme[12] proposed by Astrom *et al.* which is still widely used by industrial auto-tuning controllers because relay based tuning method is much easier to automate the procedure.

Relay based auto-tuning method has been presented and thoroughly investigated in literature [13, 14]. For the relay based auto-tuning system designed in this paper, its basic system structure is shown in Fig.2. The system outputs a limit cycle if it has a phase lag of at least π. Driven by the relay controller a limit cycle with ultimate period T_c will be generated. With ultimate period and gain, the PID controller is designed according to Ziegler-Nichols formula. To avoid disturbance or measurement noise which is quite common for micro/nano system, a set point hysteresis is added during the relay test which will also add constant phase lag to the output.

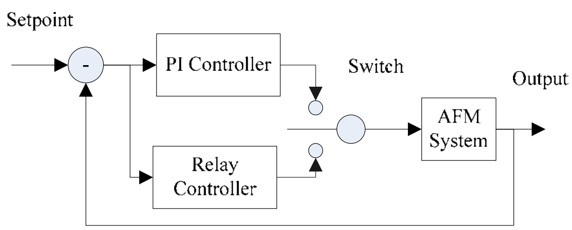

Fig.2 Relay based auto-tuning

III. Calculation of PI Parameters

A. Calculation of Critical gain and period

The describing function of relay with hysteresis is

$$N = \frac{4d}{\pi A} \angle -\sin^{-1}\left(\frac{\varepsilon}{A}\right) \tag{1}$$

where d, A and ε is relay amplitude, output amplitude and width of relay hysteresis, respectively.

During relay test, only two characteristic parameters can be identified. Therefore an AFM model is adopted consisting of integral time and delay as follows

$$G(s) = \frac{1}{Ts} e^{-\tau s} \tag{2}$$

The critical gain (K_c) and period (T_c) with respect to AFM system's integral constant T and delay τ can be calculated from

$$\begin{aligned} &\arg G\left(j\frac{2\pi}{T_c}\right) = -\pi \\ &K_c = \frac{1}{\left|G\left(j\frac{2\pi}{T_c}\right)\right|} \end{aligned} \tag{3}$$

Thus after simple calculation we can obtain

$$\begin{aligned} T_c &= 4\tau \\ K_c &= \frac{\pi T}{2\tau} \end{aligned} \tag{4}$$

From the relay test, the oscillation period T_e can be obtained. However, due to the presence of hysteresis, the period T_e is slightly different from T_c. The criterion for stable limit cycle during relay test is

$$\begin{aligned} &\frac{4d}{\pi A}\left|G\left(j\frac{2\pi}{T_e}\right)\right| = 1 \\ &-\arcsin\frac{\varepsilon}{A} + \arg G\left(j\frac{2\pi}{T_e}\right) = -\pi \end{aligned} \tag{5}$$

From (2) and (5), the following relation is obtained

$$\begin{aligned} T &= \frac{4d}{\pi A} \times \frac{T_e}{2\pi} \\ \tau &= \frac{\pi - 2\varphi}{\pi} T_e \\ \varphi &= \angle -\sin^{-1}\left(\frac{\varepsilon}{A}\right) \end{aligned} \tag{6}$$

From (4) and (6), the relation between K_c T_c and experimental data is obtained as follows

$$\begin{aligned} K_c &= \frac{4d}{\pi A} \times \frac{\pi}{\pi - 2\varphi} \\ T_c &= \frac{\pi - 2\varphi}{\pi} T_e \end{aligned} \tag{7}$$

B. Gains and Margin Specification

Assuming the PI controller is of the following form

$$H(s) = K_p\left(1 + \frac{1}{\tau_i s}\right) \tag{8}$$

where K_p is the proportional gain and τ_i is the integral time constant. For typical PI settings, Ziegler-Nichols formula is given as follows

$$\begin{aligned} K_p &= 0.45 K_c \\ \tau_i &= T_c / 1.2 \end{aligned} \tag{9}$$

With the settings of (8), the Ziegler-Nichols formula can be interpreted as finding parameters such that the point where Nyquist curve intersects the negative axis is moved to -0.45-0.086j. During AFM imaging, PI parameters vary within a batch for different scanning speed. With the increasing of scanning speed, the error (deflection) may be increased too; thus the appropriate PI parameters for low scanning speed may result in oscillations of the system during high speed operation.

To address this problem, a scaling factor $\alpha (0 \le \alpha \le 1)$ is introduced. For common AFM systems, the scanning speed is in the range of 1Hz to 10Hz. Then a linear full mapping is constructed from the scanning speed to α. Instead of moving the critical point to -0.45-0.086j, the new desired point is $re^{i(\pi-\theta)}$ where θ is the phase lag and r is the distance from the critical point and its new position in Nyquist curve. According to generalize Ziegler-Nichols formula, the PI settings are

$$\begin{aligned} K_p &= r K_c \cos\theta \\ \tau_i &= T_c / 2\pi \tan\theta \end{aligned} \tag{10}$$

It's quite obvious that (9) is the special case of (10) with $\theta = 0.19$ and $r = 0.46$. To adjust the PI gains according to different scanning speed, following empirical relation is adopted

$$\begin{aligned} \theta &= 0.19 + 0.07\alpha \\ r &= 0.46 \times (1 - 0.74\alpha) \end{aligned} \tag{11}$$

When the scanning speed is 1Hz, i.e $\alpha = 0$, (10) is equivalent to (9); When the scanning speed is increased to 10 Hz, the control gains will be dropped to 1/4 of the former value.

C. *Other considerations*

In our system, the controller is implemented on Digital Signal Processor (DSP) with control period of 20μs. The integral parameter needs to multiply the sampling period. Besides, there is a scaling factor between the interface parameters and the real values. Both of those two considerations will be taken into account.

IV. IMPLEMENTATION

A. *System Setup*

The whole system setup is shown in Fig. 3. All experiments are performed on an AFM system produced by Benyuan Nano-Instruments. The measurement setup for acquiring input and output data is shown in Fig. 1. A target PC equipped with DAQ card (ADLink) is developed to obtain the photo-diode output data, for which the RTLinux operating system is adopted to ensure real-time data-collecting. The AD/DA resolution is 16 bits, which ensures nano-resolution for a piezo-tube of a range of several tens of micrometers. The relay feedback controller is implemented using C programming language. The typical sampling time is 50μs. Before operation begins, the PI control loop is disabled by setting their parameters to zero; after relay test the appropriate PI parameters are obtained, then the system is switched back to PI control loop.

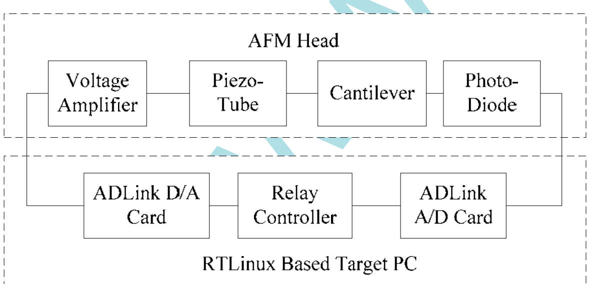

Fig. 3 Relay feedback test system setup.

During the relay test, two set points are chosen to form the hysteresis. The relay output is properly chosen such that the cantilever deflection is in the linear range.

B. *Ultimate Period Detection*

Theoretically, the oscillation period is the period of plant output. However, when a limit cycle is generated, the relay switch period is almost equal to the oscillation period. Therefore, it is straightforward that we can use the relay switch period to replace the oscillation period since the control output is much easier to obtain. Experimental result shows that this is a convenient way to detect the oscillation period (see Fig.4).

C. *Amplitude Detection*

After obtaining the oscillation period, the amplitude detection is carried out from next period. To attenuate the measurement noise, the oscillation output is integrated over five consecutive periods. Approximating the limit cycle with sinusoid wave, the amplitude can be determined as

$$A = \left(\frac{4}{5T_e}\int_0^{5T_e} y^2(t)dt\right)^{1/2} \tag{12}$$

D. *Auto-tuning*

After the relay test, these experimental data will be recorded in the AFM console PC and the relay feedback is switched back to PI control. When the scanning speed is changed, the PI parameters will be recalculated automatically according to (10).

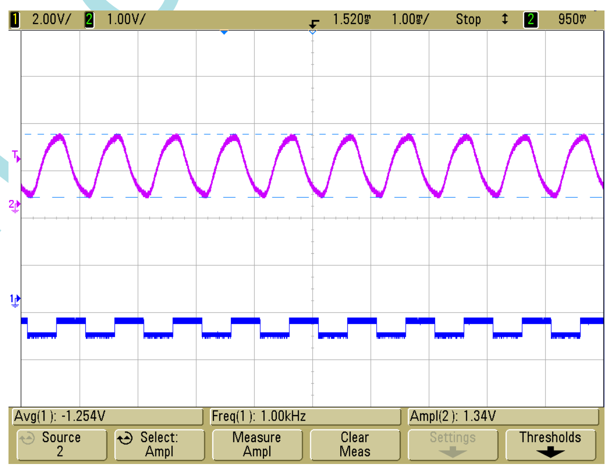

Fig. 4 A typical relay with hysteresis test on AFM system. Relay output is in blue line (lower); deflection output is in purple line (upper).

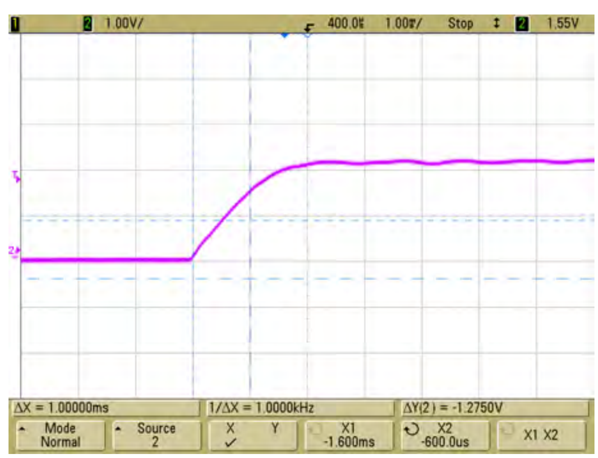

Fig.5 A typical set point step response of the system after auto-tuning.

TABLE 1
RELAY TEST WITH DIFFERENT PIEZO-TUBES

Symbol	Tube 1	Tube 2
d	10v	20v
A	1.3v	0.55v
ε	0.2	0.1v
T	1ms	610us

Tube 1 is with nominal sensitivity of 9.7nm/v; tube 2 with that of 1.7nm/v. The cantilever is not changed during the relay test

TABLE 2
RELAY TEST WITH DIFFERENT CANTILEVERS

Symbol	Cantilever A	Cantilever B
d	10v	3v
A	1.3v	1.4v
ε	0.2	0.2v
T	1ms	650us

Cantilever A with nominal length of 290um; while cantilever B with that of 110um. The piezo-tube is not changed during the relay test

V. EXPERIMENTAL RESULTS AND ANALYSIS

A typical oscillation experiment is shown in Fig.4. The control output is in blue while the cantilever deflection is in purple. The oscillation frequency for relay output and the deflection are almost identical except a phase shift which is induced by the relay hysteresis. A tuned step setpoint response is shown in Fig.5. The settling time is about 2 ms without oscillations which is very typical for common AFM systems.

To explore various factors such as piezo-tubes, cantilevers and scanning speed on PI parameters, extensive experiments are performed and those factors are analyzed in the following sections.

A. Piezo-tube on PI parameters

Usually, different piezo-tubes may have various dynamical behavior and sensitivity. Therefore, the PI parameters may vary for about an order of ten. Table 1 compares the experiment parameters using relay test examining two different piezo-tubes. Tube 1 with relatively large scale has slow dynamical response comparing with that of the smaller piezo-tube. Besides, tube 1 generates much larger output because its sensitivity is almost 6 times that of tube 2. Hence, the relay test can identify the dynamics of piezo-tube and their static gains.

Fig. 6 Cantilever deflection with different length.

B. Cantilever on PI parameters

Cantilever is usually of high natural frequency (10-300 kHz) which is much faster than piezo-tube in the control loop. Table 2 compares the different cantilevers during the relay test (both are with tube 1). Small cantilever (B) is more compact and of faster response time. Besides, the amplitude is larger than that of big cantilever. This is because during relay test, the cantilever is in contact with the sample. The cantilever deflection angle will be much larger for small cantilever to reach the same amount of piezo-tube extension (Fig.6). This, in turn, will lead to large photo-diode output because the photo-diode output is proportional to the bending angle of cantilever. Therefore, the cantilever effect can also be identified by using relay test and proper PI parameters can be chosen according to (10).

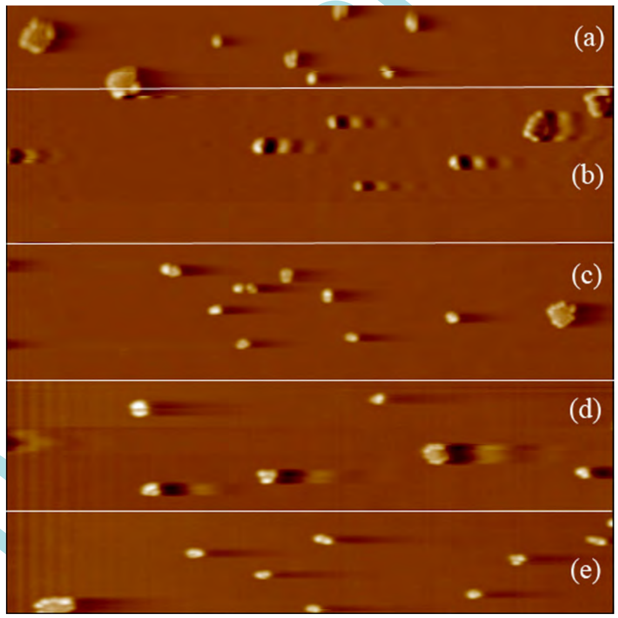

Fig. 7 SiO_2 on mica surface (scan size 10550 nm). (a) scanning speed 3Hz with appropriate PI parameters (b) scanning speed 5 Hz without changing PI parameters (c) scanning speed 5 HZ after tuning parameters (d) 10 Hz without changing PI parameters (e)10 Hz after tuning parameters

C. Scanning speed on PI parameters

To explore the scanning speed factor, SiO_2 nano-particle on mica surface is consecutively imaged at different speed (shown in Fig.7). In (a), the speed is 3 Hz, and the PI parameters is tuned according to Ziegler-Nichols formula. Then the speed is increased to 5 Hz with the same PI parameters (shown in (b)); when the tip is across the nano-particle, the control error will increase due to the scanning speed. The proper PI parameters that tune the loop well for 3 Hz result in oscillations which form the shadow after the real particles. After retuning the PI parameters, the particle shadow is largely attenuated. In (d), the speed is increased to 10 Hz, and particle shadow happens again. After retuning, oscillations are well handled. The periodical noise in the (d) and (e) is largely from the structural vibration of X-Y piezo-tube which is not able to be handled by the Z-control loop.

To further demonstrate the effect of scanning speed on PI parameters, the same area is scanned with increasing speed

TABLE 3
PI PARAMETERS FOR SCANNING

Image	K_p	τ_i
(a),(c),(e)	17.0	0.88
(b)	14.14	0.82
(d)	11.35	0.76
(f)	4.37	0.65

(Fig.8). In (a), (c) and (e) the PI parameters that tune the loop well at 1HZ are chosen according to (8); however, with the increasing of the speed those parameters yield oscillations when scanning across the nano-particles. After retuning, (b), (d) and (f) give much better image quality. The PI parameters for each scan are listed in table 3. With the increasing of speed, the PI parameters need to be reduced to attenuate those oscillations.

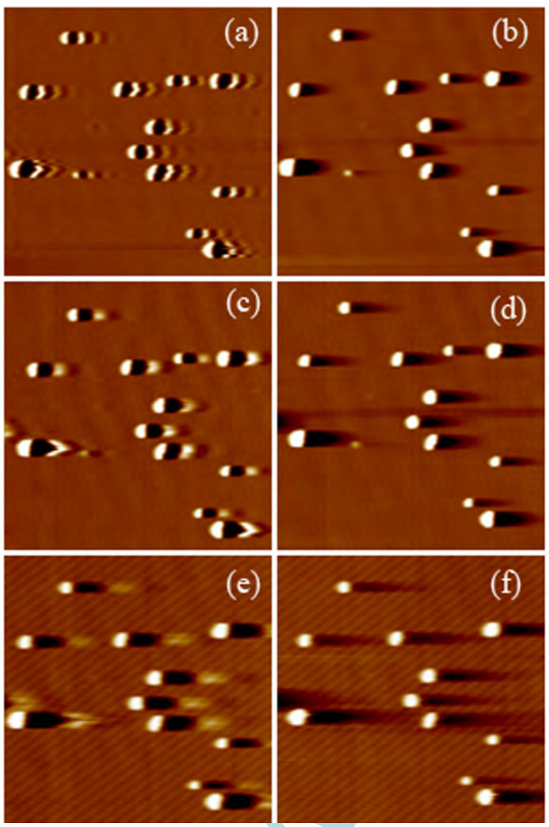

Fig. 8 SiO_2 on mica surface (scan size 4500nm). (a) and (b) scanning speed 3Hz ; (c) and (d) scanning speed 5 Hz; (e) and (f) scanning speed 10 Hz. The parameters used for scanning are listed in table 3.

VI. CONCLUSION

Automatic tuning simplifies the operation procedure for common AFM users. As discussed in this paper, the relay based tuning method is able to account for different piezo-tubes and cantilevers because their dynamics and static gains have been identified in the relay test. For different scanning speeds, the scaling factor can be used to adjust the controller parameters properly. This method is effective in various situations for AFM systems. However, the sample and set point factors are not discussed in this paper. Future work will take those factors into account.

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