Development of AFM Based on Nano Positioning Stage

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***Abstract*—A single PZT (piezoelectric) tube is generally used in atomic force microscope (AFM) as its scanner. But due to the kinematic coupling of the single tube during its bending motion, there usually exist two kinds of structure errors: vertical cross coupling error and scanning size error which affect the precision of nano observation and manipulation. In this paper, a new AFM with nano positioning stage as its scanner is developed. The stage has three PZT actuators and can move in three directions with high precision without kinematic coupling, thus the two structure errors are eliminated effectively in the new AFM. Some development results are presented and the experimental results validate the performance of the AFM.**

Keywords-AFM; kinematic coupling; nano positioning stage; AFM force curve

I. INTRODUCTION

AFM has experienced great development as a tool for nano observation and manipulation since it was firstly invented [1~3]. The scanner of most AFM is a single PZT tube which moves either the AFM probe or the sample during scanning [4~6]. However, due to the kinematic coupling of the scanner caused by its bending motion, there usually exist two kinds of structure errors: vertical cross coupling error and scanning size error [7~8]. The vertical cross coupling error refers to the arising of an additional vertical motion when the scanner moves in horizontal direction. The scanning size error exists in the sample scanning AFM and refers to the varying of actual scanning size with the thickness of the sample. These two errors affect the precision of nano observation and manipulation. In this paper, a new AFM without kinematic coupling is developed. In the AFM a nano positioning stage instead of a single tube is used as its scanner. The stage can move in three directions with nanometer order precision without coupling, therefore, the vertical cross coupling error and scanning size error are eliminated effectively. The new AFM improves the precision of nano observation and manipulation greatly. Here we present the principle and implementation of the AFM.

II. DEVELOPMENT OF NANO POSITIONING STAGE

The main body in our new developed AFM is the nano positioning stage. Its moving precision affects the whole performance of the AFM. To implement nanometer order positioning and accurate scanning motion of the AFM, the positioning stage need to be developed firstly.

A. Principle of Nano Positioning Stage

Generally, the scanning mode of AFM includes tip-scanning mode and sample-scanning mode. Here, the AFM we developed takes the sample-scanning mode, i.e., the nano stage actuates the sample during scanning motion while the AFM tip keeps fixed. The basic structure of the AFM is shown in Fig. 1. A laser is designed to shoot on the back of the cantilever of AFM probe and is reflected to a position sensitive detector (PSD). In scanning mode, the nano stage actuates the sample to perform scanning motion. During the scanning the AFM tip moves up and down along the sample surface, which makes the cantilever bend or twist. So the reflected laser spot moves slightly on the PSD and makes the outputs of PSD change. From the changed PSD outputs we can get the height information of the surface and then form the image of the surface.

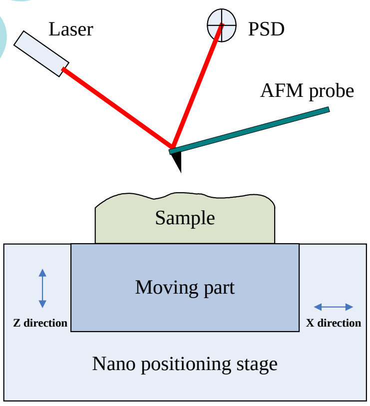

Fig. 1. Basic structure of the AFM.

The nano stage in our AFM system has three separate PZT actuators. The actuators' cooperating motions make the moving part of the nano stage move in three directions without coupling. The working principle of the stage is as this: the motion commands are sent to the nano stage controller, then the controller turns the commands to voltage and adds it to each actuator to control their elongation or retraction. The actuators are controlled in close loop by the stage controller according to their positions, which are got through capacitive sensors, to insure the stage's moving precision. The stage can move in various modes such as line, curve and scanning motions with nanometer order precision, and enables the AFM developed on it to scan and manipulate with high precision.

B. Implement of Scanning Motion of the Nano Stage

The scanning motion of the stage is implemented by

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controlling the motions of the X and Y actuators cooperatively as shown in Fig. 2. Firstly the X actuator elongates evenly while the Y actuator keeps still. Secondly, when the X actuator elongates the destined length the Y actuator elongates for a short length and keeps there. Meanwhile, the X actuator retracts to its original position. When the course is performed circularly the scanning motion is implemented.

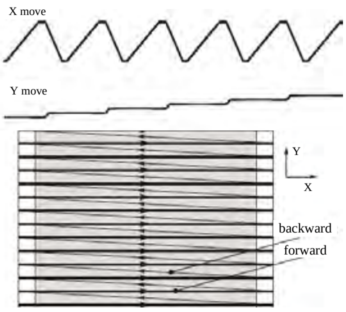
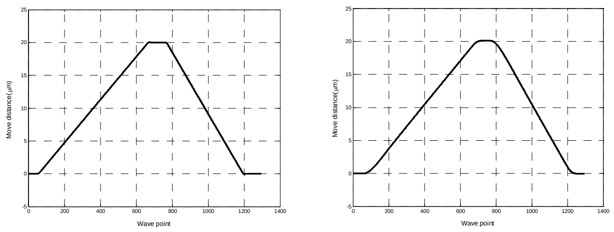


Fig. 2. Scanning motion of the stage implemented by the cooperating motions of the X and Y actuators.

The moving velocity of the stage can be set by command. But when the stage moves at high speed there will generate residual error. Fig. 3 shows the movement of X actuator at low and high speed respectively. The horizontal axis in the figure refers to the wave point of the actuator and vertical axis refers to the moving distance. The velocity of the actuator in Fig. 3(a) and (b) are 10μm/s and 80μm/s respectively. In Fig. 3(a) the moving track is the same as theoretical track, but there is a little lag in Fig. 3(b) which is caused by the PZT's nonlinearity and the controller's limited dynamic performance. To eliminate the residual error we can record the error during several initialization periods and then compensate for it in the next periods. After the compensation the error is reduced almost to zero.



(a) (b)

Fig. 3. Moving track of the actuator at low and high speed: (a) moving at low speed (b) moving at high speed.

III. DEVELOPMENT OF AFM BASED ON NANO STAGE

Based on the nano positioning stage and combined with others equipments we developed a new AFM without kinematic coupling. With different control schemes we realized the constant height and constant force scanning mode. We also measured the AFM force curve and studied the impact of nano forces to AFM tip. Finally the high quality scanning function of the AFM was realized.

A. Structure and Control Scheme of the AFM

Our homemade AFM system consists of laser, quad position sensitive detector (PSD), AFM probe, nano positioning stage, nano stage controller, micron equipment, micron equipment controller, microscope, charge coupled device (CCD) camera and correlative circuitries. The system's structure is shown in Fig. 4. In the system, the micron equipment is used to rise up and approach to the AFM tip roughly. Then the nano positioning stage is controlled to realize the accurate approach and perform scanning motion.

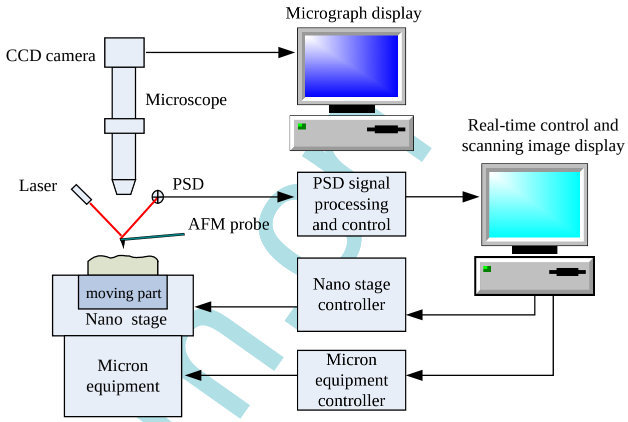


Fig. 4. Structure of the AFM system based on nano positioning stage.

To insure the control commands be performed in real-time, WinCE real-time OS is used in the PC which controls the stage. To get the PSD signal we devised relative signal processing circuits. After processing there are two PSD signal outputs corresponding to the normal and lateral position of the laser spot on the PSD, which are obtained as follows:

$$S_n = \frac{(A+B)-(C+D)}{A+B+C+D} \tag{1}$$

$$S_l = \frac{(A+C)-(B+D)}{A+B+C+D} \tag{2}$$

where *A*, *B*, *C* and *D* are the four signals of the quad PSD.

At present we have implemented the constant height and constant force scanning modes of the AFM. The constant height mode refers to the scanning that the distance between the end of the AFM cantilever and the sample surface keeps fixed during scanning. The constant force mode refers to the scanning that the force between the AFM tip and the sample surface are kept at a pre-set reference force by regulating the distance between the tip and the surface continually. Constant height mode enables fast scan times but is only suited to very flat samples. Whereas in constant force mode the tip moves up and down along the surface of the sample with a constant force, so the topography of the surface can be got with high resolution.

There are different control schemes for constant height and force modes. In constant height mode, the nano stage controller controls the stage to perform circular scanning motion, and meanwhile the PSD signal outputs characterize the profile of the surface. By recording the PSD data at every sampling point the topography can be formed finally. The control scheme is shown in Fig. 5.

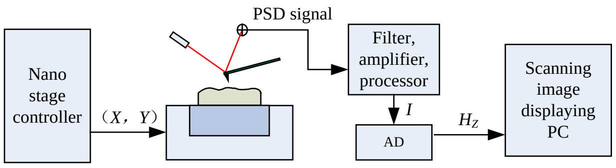


Fig. 5. Control scheme for constant height scanning mode.

In constant force mode, there is a feedback control besides the scanning motion control. The feedback control is the kernel part of constant force mode. It is used to regulate the rise and descent of the nano stage continually according to the changes of PSD outputs to maintain the force between the tip and sample constant as shown in Fig. 6. The specific control course is as this: first of all, the AFM tip contacts the sample surface slightly where can be determined through AFM force curve (introduced later). The PSD at this point is recorded as the reference signal I_{ref} and is regarded as the intensity of pre-set reference force between the tip and the sample surface.

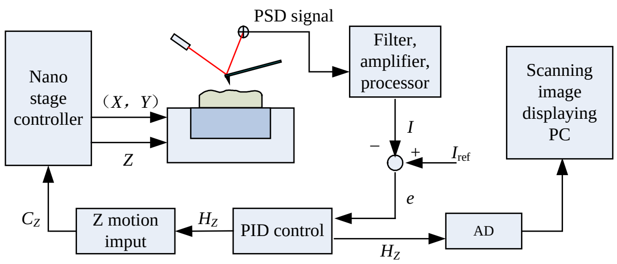


Fig. 6. Control scheme for constant force scanning mode.

The input of the PID control is the deflection of PSD denoted as e and the output is *Hz* which is sent to the controller to move the stage in *Z* direction. During scanning the nano stage is controlled by PID feedback control to move up and down continually according to *Hz* to make the changed PSD signal return to its original reference signal I_{ref}. By doing so, the force between the tip and sample is maintained constant. During scanning the *Hz* signal is recorded at each sample point, thus the topography of the sample can be formed later.

In the development we noticed that two factors affected the quality of scanning image greatly: laser and various disturbances (vibration and electric noises). On one hand the laser spot, reflected on the PSD as the only signal source for measure and control, its quality, shape and size all affect the PSD signal, thus the quality of the scanning image is affected too. So the choice for proper laser is an important factor for the implement of high quality AFM. On the other hand various disturbance signals also affect the quality of PSD signal. Because the AFM tip is very sensitive to small disturbance, any vibration such as loud speaking and heavy walking will make big variation of PSD signal. So we put the main part of the AFM system in a capsule and the capsule on an air floated platform to eliminate the effect of vibration from air and ground. In addition to the vibration, electrical source and circuits may generate electrical noises which are adverse to the PSD signal. By screening and grounding the electrical source and relative circuits, the noises can be reduced greatly. After the processing above the new AFM reaches a so ideal level of exploring as to characterize nanometer order topography of the sample surface.

B. Studies of the Positioning of AFM Tip for Proper Pre-set Reference Force

The proper pre-set reference force is very important for imaging in the constant force mode. If the pre-set reference force between the tip and the surface is too strong the tip may be hurt by the sample; if it is too weak the tip will not be sensitive to the topography. So how to control the position of the tip relative to the sample surface to keep a proper constant force is an important problem.

In nano environment, the sample has great attraction to the AFM tip. The attraction consists of van der Waals force, capillary force and electrostatic force [9]. To understand the interaction between AFM tip and sample, and explore the tip's proper position, we measured the AFM force curve just as shown in Fig. 7. The force curve reveals the changing interaction between the tip and sample surface during the tip's

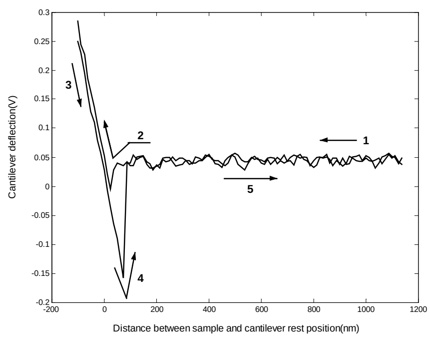


Fig. 7. AFM force curve.

approaching and retracting courses relative to the sample surface. The courses are denoted as 1 to 5, and are explained as below: 1. The nano stage rises up and makes the sample lying on it approach the AFM tip. 2. When the gap between the tip and the sample reaches tens of nanometers the tip is suddenly attracted to contact the sample surface due to the long range attraction of the sample [10]. In this case, the cantilever of the AFM bends downward to the sample surface. When the nano stage rises furthermore, the cantilever will bend upward gradually by the contact repulse force of the sample. 3. The sample retracting from the tip by the descending of the stage, meanwhile, the tip still contacts the sample surface by the strong attraction. 4. When the retracting distance goes beyond the bounds of the attraction, the tip pulls away suddenly from the surface completely. 5. The nano stage returns to its original position. From the experimental study we find the tip is most sensitive to the topography when the tip just contacts the sample surface, where can be ascertained from the jump-to-contact signal of the force curve. By positioning the AFM tip at this point before scanning the proper pre-set reference force is set, thus a high quality AFM scanning image can be obtained in the later scanning.

IV. Experiments and Performance Testing

With our homemade AFM we made a serial scanning experiments. In the AFM system, the nano positioning stage (Physik Instrumente Co., Ger., mode E-710.3CD) is used as the scanner. The maximum scanning area of our AFM is 100μm×100μm with accuracy 1nm; the moving range in *Z* direction is 20μm with accuracy 0.1nm. The highest scan speed is 12.5mm/s and the highest moving speed in *Z* direction is 10mm/s. The hardware setup of our homemade AFM is shown in Fig. 8.

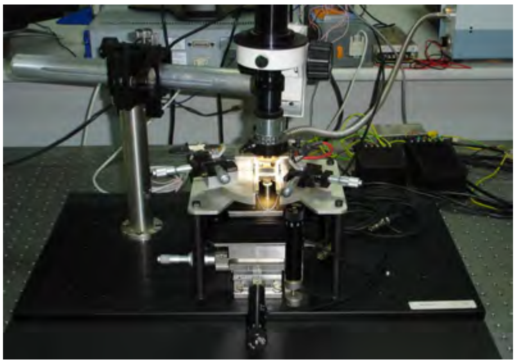


Fig. 8. The hardware setup of the AFM.

With the AFM we scanned the standard grating whose step height is 20nm and pitch 3μm (MikroMasch Co., USA, mode TGZ01). Fig. 9 is the scanning image of the grating, and the scanning range is 15μm. The profile of the grating can be seen clearly from the figure. The 20nm height step corresponds to about 0.2V PSD signal change, which verifies the quality of the PSD and relative processing circuits. Furthermore, the scanning data validates that our new AFM can distinguish the height of nanometer order in the *Z* direction.

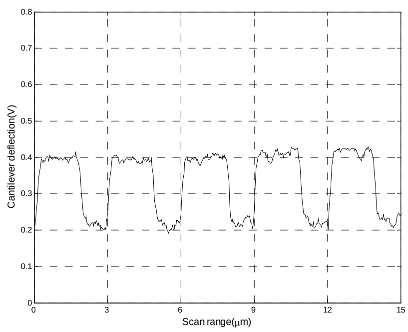


Fig. 9. Profile of the standard grating.

To test whether our new AFM had eliminated the kinematic coupling we did the experiments of scanning the standard grating with different thickness. If the AFM has kenematic coupling in the horizontal and vertical moving direction, the actual scanning size will vary with the thickness of the sample [7~8]. As a contrast for performance test, we compared the experimental results with that got from a single tube mode AFM (Benyuan Co., Ch., mode CSPM2000). The scanning image is shown in Fig. 10. Fig. 10(a) and (b) are the scanning images from our new AFM with scanning area 15μm×15μm, and Fig. 10(c) and (d) are from the single tube mode AFM with scanning area 30μm×30μm [7]. In Fig. 10(a) the thickness of the sample is 2mm, and after increasing the thickness to 10mm the scanning image is shown in Fig. 10(b). Taking the grating whose pitch is 3μm as a measuring standard, we measured that the scanning range in Fig. 10(b) was still 15μm, which did not vary with the changed thickness of the sample. Fig. 10(c) and (d) are from single tube AFM and the thickness of sample is 2mm and 10mm as well. From the figure we can observe that the step numbers in Fig. 10(d) is one more than that in Fig. 10(c). Through measuring, we found the actual scanning range in Fig. 10(d) was 4.1μm longer than that in Fig. 10(c), which was caused by the kinematic coupling of the single tube scanner. This case did not exist in our new AFM in the experiments. Therefore it validates that our AFM has eliminated the kinematic coupling effectively, and the cross coupling error and scanning size error caused by the kinematic coupling are eliminated accordingly.

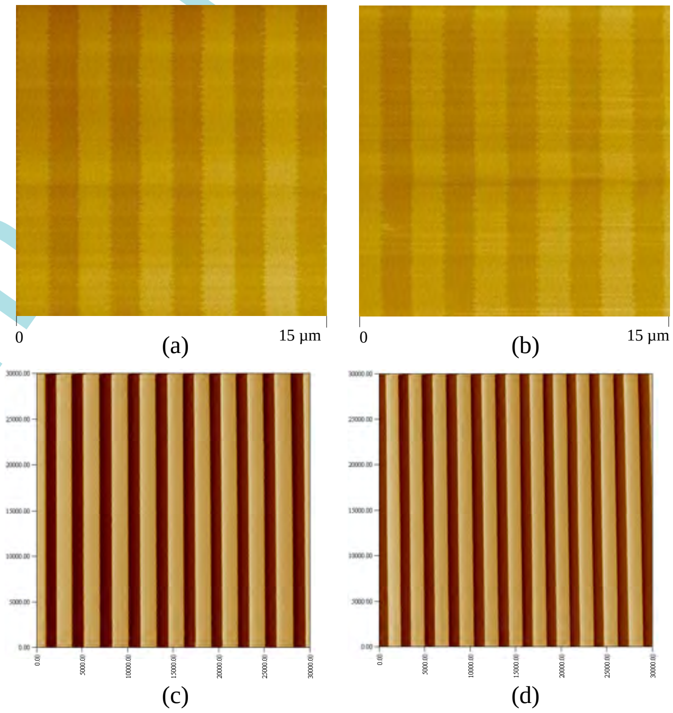


Fig. 10. Performance test: comparison between the homemade AFM and the single tube AFM.

V. Conclustion

A new AFM with nano positioning stage as its scanner is developed in this paper. The nano stage has three PZT actuators and can move in three directions without coupling. So the kinematic coupling due to the bending motion of single tube scanner is eliminated effectively. As a result, the cross coupling error and scanning size error caused by the kinematic coupling are eliminated radically. The new AFM improves the precision of nano observation and manipulation greatly. At present the AFM is still under development, we will integrate more scanning modes into it and consummate the function of nanomanipulation in the next work to provide a nano observation and manipulation platform with high performance for further exploring the nano world.

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