International Journal of the Korean Society of Precision Engineering Vol 2, No. 2. July 2001.

A New Calibration Method of Atomic Force Microscopy

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ABSTRACT

This paper presents an in situ self-calibration method to correct the Z-directional distortion of AFM(Atomic Force Microscopy). Principle of the method, results of simulation and experiment are presented that is mainly introduced from the non-linear motion of the servo PZT of the AFM. In this method, the derivative of the calibration curve function of the PZT actuator is calculated from the profile measurement data, which are obtained from two measurements with a small Z-direction shift (The present paper introduces data processing technique that can realize in situ self-calibration through evaluating the inverse function of the calibration curve). Simulation results showed that the Z-directional distortion can be calibrated with the accuracy that is approximately twice of the Z-directional resolution of the calibrated AFM. Calibration of a commercial AFM is carried out in the experiment. Effectiveness of the proposed self-calibration method has been confirmed by the simulations experimental results.

KeyWords : Calibration, Atomic Force Microscopy, PZT actuator, Z-directional distortion

1. Introduction

Almost all Atomic Force Microscopes (AFM) employ piezo-electric elements (PZT) as their servo and scanning actuators. Although PZTs have atomic displacement resolution and fast frequency response, they also possess some undesirable properties such as hysteresis and nonlinear motion[1][2], which cause three-dimensional distortion of AFM images. This problem becomes serious when large samples are observed by AFM. As a consequence, calibration and compensation are necessary for both XY scanning actuators in the X-Y plane of the surface and the servo actuator in the Z-direction.

Several methods have been proposed for this purpose. The software compensation method pre-calibrates PZTs using a displacement probe, and carries out compensation of the SPM image based on the calibration data[3]. This is the most popular method of calibrating XY scanning actuators which generally demonstrate fixed movement patterns. However, this method is very complicated and difficult to obtain a sufficient effect for the Z-directional compensation because movement of the servo-actuator is irregular. The direct-monitoring method[3][4][5], which detects movement of the PZT directly by optical or capacitance-type displacement probes, can perform real-time XY-compensation. However, Z-directional compensation is also difficult using this method due to the large space requirements for installing a displacement probe to monitor the movement of the servo-actuator. This will influence the compactness and rigidity of the AFM structure. In addition, the accuracy of both the software compensation method and the direct-monitoring method depends on that of the displacement probe. However, very few displacement probes with atomic resolution are commercially available. To overcome such problems in Z-directional compensation. Kiyono et al. proposed a new external-monitoring method[6] in which the same voltage signal used to control the servo actuator is applied to another reference PZT actuator, the displacement of which is monitored by a displacement sensor. Because PZT actuators of the same type have almost the same characteristics, the displacement of the servo actuator should be estimated accurately based on the displacement of the reference actuator. As a result, the Z-directional distortion caused by the linearity error of the servo actuator of SPM can be corrected. A new in situ self-calibration method has also been proposed[7].

This method can obtain the correct calibration curve of the servo PZT and the correct profile curve using only the profile measurement data with a converging data processing technique. Both methods have been experimentally confirmed to be effective for Z-directional compensation[8]. Self-calibration can be realized because no accurate calibration references are necessary. Thus, the in situ self-calibration method is more accurate and easier to be applied than conventional compensation methods. The present paper introduces another data processing technique that can realize in situ self-calibration through evaluating the inverse function of the calibration curve. The effectiveness of the new method is confirmed both through computer simulation and experiment.

2. Principle

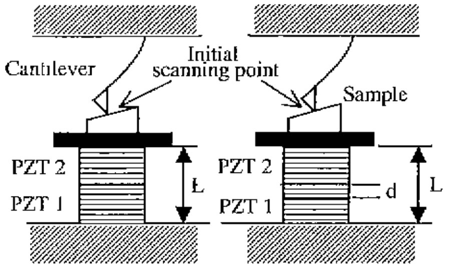
Figure 1 shows the principle of the in situ self-calibration method. PZT1 is the calibration target, which is a servo actuator of the AFM. Another PZT actuator (PZT2) which can be used to adjust the position of the cantilever relative to the sample is placed in series in the AFM. In the in situ self-calibration method, the sample is scanned twice with a constant small shift d in the Z-direction to obtain two profile measurement data sets g1(x) and g2(x)(Figure 2). The small shift d is determined by PZT2. In each scanning (Figure 1(a)), a constant voltage is applied to PZT2 while scanning. A set of voltage signals V1i of PZT1, which corresponds to the profile data, can be obtained. Before the start of the second scanning(Figure 1(b)), the voltage applied to PZT2 is changed so that PZT2 extends a distance of d. The profile is scanned again while the state of PZT2 is maintained, and another set of voltage signals V2i of PZT1 can be obtained.

As shown in Figure 3, the calibration curve f(z) of PZT1 can be expressed as follows:

$$h=f(z)=kz+g(z), \qquad (1)$$

where, g(z) is the linearity error and k is the mean sensitivity. Expressing the output at zi by mi, the inverse function of f(z) can be given by

$$hi=mi, \qquad (2)$$



(a) 1st measurement (b) 2nd measurement

Fig. 1 Principle of the In-situ self calibration method

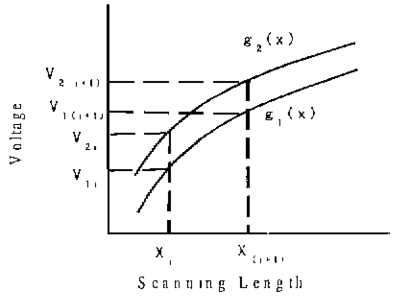


Fig. 2 Output data of the two surface profile measurement

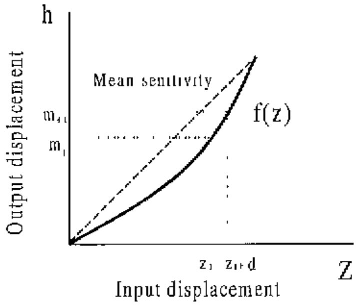


Fig. 3(a) Calibration curve f(z) of PZT1.

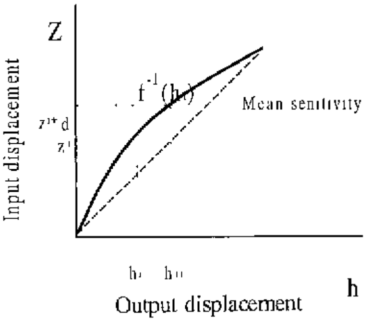


Fig. 3(b) Inverse function of calibration curve.

$$f^{-1}(h_i)=(1/k)h_i-b(h_i). \qquad (3)$$

Expressing the output at z_i+d by m_{+i}, the derivative of $b(h)$ at the discrete i-th sampling point can be expressed as(from Figure 3(b)):

$$b'(h_i)=(1/k)-d/(m_{+i}-m_i). \qquad (4)$$

Assuming that d can be evaluated accurately from the mean value of $(m_{+i}-m_i)$, $b'(h_i)$ can be also accurately defined. As a result, $f^{-1}(h_i)$, and then $f(z)$, can be accurately calculated. Compared to the previously proposed method which requires a converging process of approximated $g'(z)$[7][8], the present calculation technique is simpler while maintaining the same accuracy.

3. Simulation

Figure 4 shows one of the results of computer simulations. A profile with line up and down slope was used as the sample. Considering that the calibration curve of the PZT maks a hysteresis loop when this profile is measured from left and right ends continuously, the upward and downward slopes are evaluated separately. The sample was scanned twice with a constant small shift d (d=25nm) in the Z-direction to get two profile sampled data sets. Each sampled data set included the real profile and the error caused by the nonlinear error of the PZT. The maximum nonlinear error of the PZT was set to be 10nm[6]. Assume that the resolution of the AFM was kept to be 0.1nm, and random errors with a maximum value of 0.1nm were also added to the sampled data. Then the two sampled data sets were used to evaluate the profile by the proposed self-calibration method. The real profile and the error, which is defined as the difference between the evaluated profile and the real profile, are plotted in Figure 4. It can be seen that the given profile was evaluated with an accuracy of approximately 0.2nm. Without the correction through the self-calibration, the error becomes larger than 10nm in the maximum value. g1(x) and g2(x) in Figure 2 may have different mean sensitivities because the mean sensitivity of the calibration curve of a PZT changes according to the starting point of the hysteresis loop[6]. The influence of variation in sensitivity caused by the shift d was then investigated. The sample consisted of the upward slope of the profile surface in Figure 4. The leftside vertical axis shows the maximum error of the evaluated profile height due to variation in sensitivity. The relationship between d and the variation in mean sensitivity [6] is also plotted in Figure 5. The error of the evaluated profile height increased with d. Selecting d less than 0.15㎛ allow the profile to be evaluated with an error of less than 0.2%.

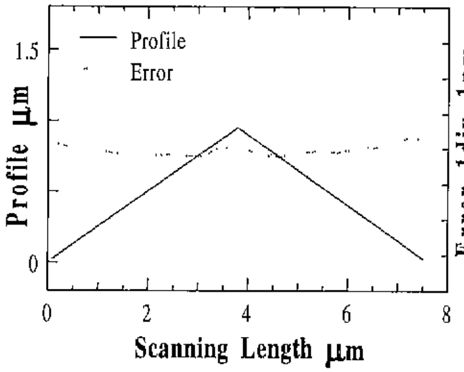


Fig. 4 Simulation result 1(Profile calibration).

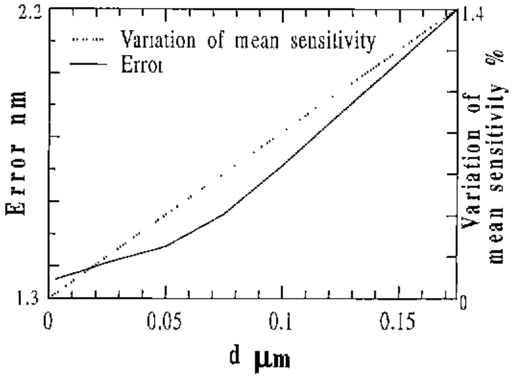


Fig. 5 Simulation result 2 (Influence of the variation of mean sensitivity).

Figure 6 shows the results with repeatability errors. Because the positioning error of the scanning stage in the developed AFM greatly affects the repeatability of the profile measurements, random positioning errors were introduced in the simulation. It can be seen that the residual error of the compensated result increases with the repeatability error of the profile measurements. The residual error was approximately 2nm when the repeatability error of the profile was 1nm. This is becaus

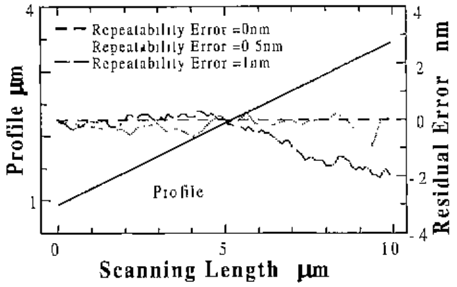


Fig. 6 Simulation result 3 (Repeatability Error).

d, which is supposed to be constant, changes at each point. It should be pointed out that the residual error can also be significantly reduced using the in situ self-calibration method. In the case of using the tube PZT as the scanning stage, which has high positioning accuracy, the compensation can be expected to be with sub-nanometer accuracy.

4. Experiment

4.1 Experimental apparatus

Figure 7 shows the experimental setup for calibrating a commercially available AFM. A PZT(PZT2) to generate the constant shift d was inserted between the sample and AFM 3-Dimension scanning stage. d was set to be 25nm in the experiments. PZT1 on the dimensional scanning stage which is the servo actuator of the AFM represented the calibration target. The present study examined two samples and their compensation. Sample 1 was a flat surfaced silicon, and Sample 2 is a spherical stainless precision ball.

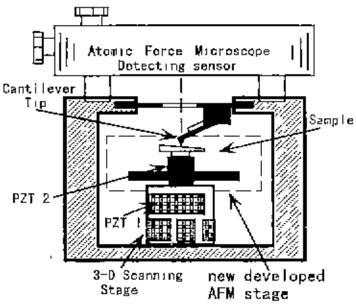


Fig. 7 Experimental Setup(Commercially available AFM)

Figure 8 shows the scanning sequence of the AFM cantilever. The profile of each scanning line was compensated separately

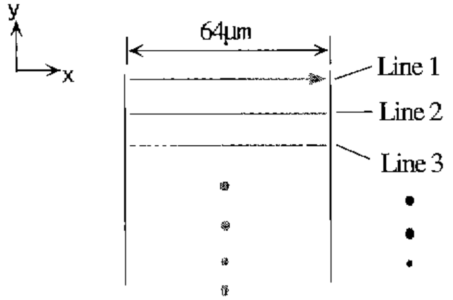


Fig. 8 Scanning sequence of the AFM cantilever

4.2 Experimental results

Figure 9 shows the compensated profile of Sample 1 obtained using the in-situ self-calibration method. The difference between the uncompensated and the compensated profile was approximately 15nm, which is approximately 3% of the profile height. Figure 10 shows the corresponding calibration results for the servo PZT. Figures 11 and 12 show the difference between the results of various scanning lines. Figure 11 shows the difference between the calibration results of the servo PZT, and Figure 12 shows that between the compensation results of the profile. The difference between the calibration curves of the PZT shown in Figure 11 is less than 2nm, and that between profiles shown in Figure 12 is large than 20nm. Therefore, the calibration curve of the servo PZT does not change even when the profiles differ among the various scanning lines. Thus, the new in situ self-calibration method appears to be an effective means of compensation. Figure 13 shows the repeatability error of the in situ self-calibration method. Examination of the difference between the compensation results of two repeated scannings of the same line revealed a repeatability error of approximately 5nm.

Figure 14 shows the comparison between the new in situ self-calibration method and the conventional software compensation method. The difference was less than 5nm. Figure 15 shows the three-dimensional compensation result of sample 1. A remarkable difference between uncompensated and compensated profile can be seen in this figure. The maximum compensated amount was approximately 30nm. Figure 16 shows the compensated result of Sample 2 The difference between the uncompensated and compensated profiles was approximately 50nm. Thus, the new in situ self-calibration method appears to be reliable and effective.

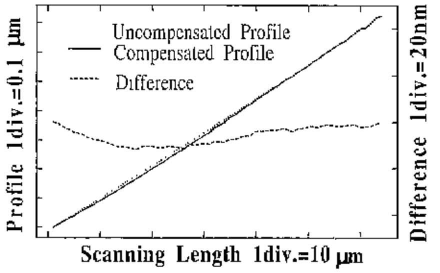


Fig. 9 Calibration result of sample 1

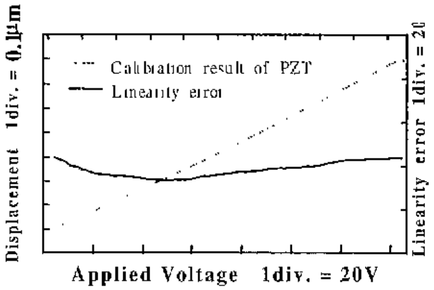


Fig. 10 Calibration result of PZT.

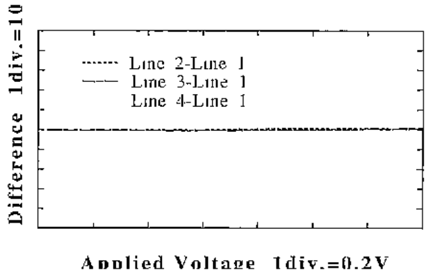


Fig. 11 Compensation results of PZT.

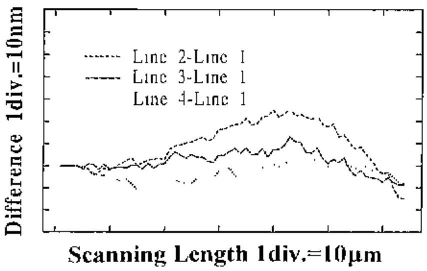


Fig. 12 Compensation results of profile

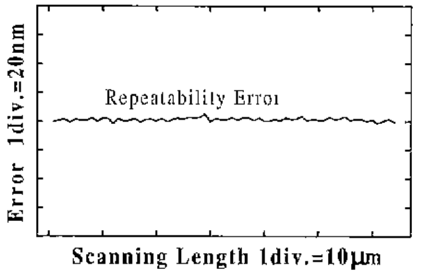


Fig. 13 Repeatability error of the in situ self-calibration.

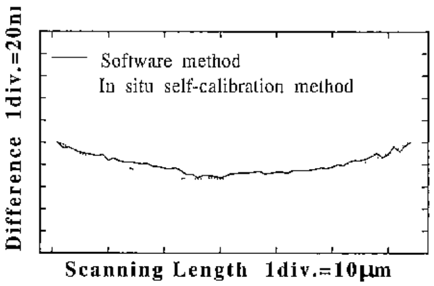


Fig. 14 Comparison of the results by two methods : in-situ self-calibration method and software method.

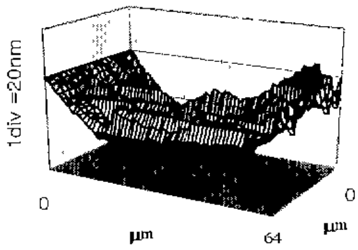


Fig. 15 Three-dimensional compensation amount of flat surface.

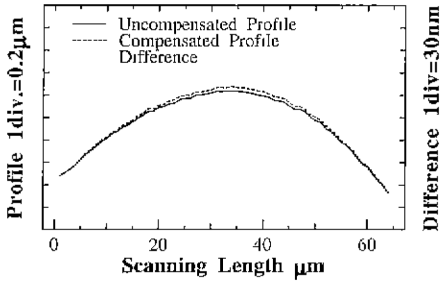


Fig. 16 Calibration result (spherical surface).

5. Conclusions

Based on the present results:

(1) An in situ self-calibration method has been proposed to compensate the linearity error of the PZT actuator without removing it from the AFM. Only profile data are used in this method. The effectiveness of the method, as well as the influence of the repeatability of the profile data on the compensation accuracy, has been confirmed by computer simulations.

(2) The new data processing technique can realize in situ self-calibration through evaluating the inverse function of the calibration curve.

(3) Simulation results demonstrated that the accuracy of the in situ self-calibration method is approximately twice that of the Z-directional resolution of the AFM.

(4) The effectiveness of the proposed method was confirmed by experimental calibration of a commercially available AFM.

Acknowledgement

This study was funded by a grant-in-aid for Scientific Research from the Ministry of Education of Japan. The author would also like to thank Prof. Kiyono of Tohoku University for the support..

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