A High-speed Atomic Force Microscope for Precision Measurement of Microstructured Surfaces

Yuguo Cui[1,#], Yoshikazu Arai[1], Takemi Asai[1], BinFeng Ju[1] and Wei Gao[1]

1 Nano-Metrology and Control Laboratory, Research Center for Precision Nanosystems Department of Nanomechanics, Tohoku University, 6-6-01, Aramaki Aza Aoba, Aoba-ku, Sendai, Miygi, 980-8579, JAPAN

Corresponding Author / E-mail: cuiyuguo@nano.mech.tohoku.ac.jp, TEL: +81-22-795-6953, FAX: +81-22-795-6953

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This paper describes a contact atomic force microscope (AFM) that can be used for high-speed precision measurements of microstructured surfaces. The AFM is composed of an air-bearing X stage, an air-bearing spindle with the axis of rotation in the Z direction, and an AFM probe unit. The traversing distance and maximum speed of the X stage are 300 mm and 400 mm/s, respectively. The spindle has the ability to hold a sample in a vacuum chuck with a maximum diameter of 130 mm and has a maximum rotation speed of 300 rpm. The bandwidth of the AFM probe unit in an open loop control circuit is more than 40 kHz. To achieve precision measurements of microstructured surfaces with slopes, a scanning strategy combining constant height measurements with a slope compensation technique is proposed. In this scanning strategy, the Z direction PZT actuator of the AFM probe unit is employed to compensate for the slope of the sample surface while the microstructures are scanned by the AFM probe at a constant height. The precision of such a scanning strategy is demonstrated by obtaining profile measurements of a microstructure surface at a series of scanning speeds ranging from 0.1 to 20.0 mm/s.

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1. Introduction

Many micro-optic products contain microstructured surfaces with profiles that are greater than several millimeters.[1,2] High-speed and precision measurements of such surfaces are important tasks for the purpose of quality control. An atomic force microscope (AFM) is commonly used to measure three-dimensional profiles of microfeatures,[3~5] but an AFM offers limited throughput because its imaging speed is slow and its imaging area is small.[2,6]

The following approaches have been used to increase the image acquisition speed of microstructured surfaces.

(1) Using a constant height mode.[7] The constant height mode is a type of contact scanning that can increase the scanning speed without feedback control of the Z direction PZT actuator of the AFM probe-unit. However, it is only used to image flat microstructured surfaces with careful slope adjustments. Any unintended contact between the AFM probe tip and the sample can damage both the probe tip and the sample surface.[8]

(2) Using high-frequency PZT-scanners. Egawa *et al.*[9] introduced high-frequency PZT segments to the scanner to improve the dynamic performance.

(3) Using small cantilevers or integrating actuators on the cantilever to reduce the moving mass. Walters *et al.*[10] and Schaffer *et al.*[11] used small cantilevers with very high resonant frequencies to obtain fast images of biopolymers using a tapping mode. Sulchek *et al.*[12] and Rogers *et al.*[13] succeeded in fabricating integrated piezoelectric bimorph actuators onto cantilevers to increase the imaging speed.

(4) Using cantilever arrays. Minne *et al.*[14] worked on cantilever arrays with integrated PZT actuators that directly controlled the force through the cantilever and provided parallel imaging.[6,14] This approach requires specially designed cantilevers.[8]

(5) Using modern model-based control algorithms to compensate for the dynamic behavior of the AFM system. Researchers have applied open loop control[15] or feedback control[8,9] to speed up the scanning system. Model-based feedback controllers have also been implemented to increase the bandwidth of the AFM in the Z direction.[16]

Although the approaches using PZT scanners effectively improve the imaging speed, they cannot be used to measure profiles over large areas of microstructured surfaces because of the limited scanning range of the PZT scanner.

This paper describes a large-area AFM system that consists of an air-bearing X stage, an air spindle, and an AFM probe unit. This system is different from conventional AFM systems employing PZT scanners and can be used to extend the measurement area. A scanning strategy that combines constant height measurements with a slope compensation technique is proposed to achieve high-speed precision measurements of microstructured surfaces.

2. The AFM system

Figure 1 shows the setup of our AFM system for high-speed precision measurements. The AFM is composed of an air-bearing X stage, an air spindle, a manual Z stage, and an AFM probe unit. The X stage and air spindle are used to scan sample surfaces in the XY plane. A linear encoder and rotary encoder are used to provide precision positioning of the X stage and air spindle, respectively. The X stage can traverse over a distance of 300 mm with a speed up to 400 mm/s. The spindle, which has a rotating speed of 300 rpm, can hold a sample in a vacuum chuck with a maximum diameter of 130 mm. Tables 1 and 2 give the performance details of the X stage and the spindle, respectively.

Multiple scanning patterns can be generated by combining the motions of the X stage and the spindle, including linear scanning in the X direction, concentric scanning about the Z axis, and spiral scanning.[17] The silicon cantilever in the AFM probe unit is actuated by a Z direction PZT actuator (Z-PZT actuator), which is used to adjust the Z position of the cantilever tip to place it in the repulsive area of the atomic force. The actuator is also used to provide servo control of the cantilever when measuring using a constant force, and to compensate for the slope of the sample when measuring using a constant height. The movement of the Z-PZT actuator is measured by a linear encoder with a resolution of 1 nm.[18] A manual Z stage is employed for coarse adjustments of the AFM probe unit.

The commercial silicon cantilever is embedded with a piezoresistive sensor to sense the deformation of the cantilever due to the atomic force. Figure 2 shows a SEM image of the cantilever tip. The tip radius is less than 20 nm. Table 3 gives the detailed parameters of the probe unit.

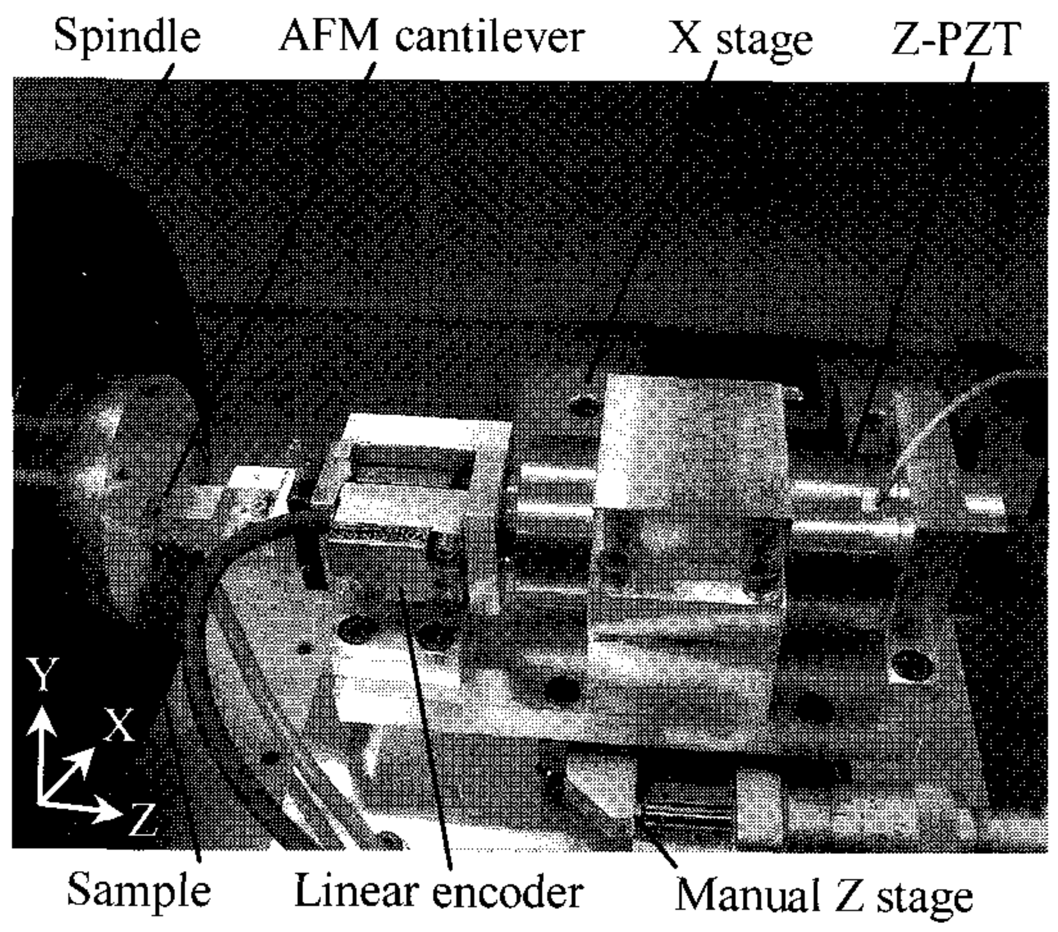


Fig. 1 AFM system setup

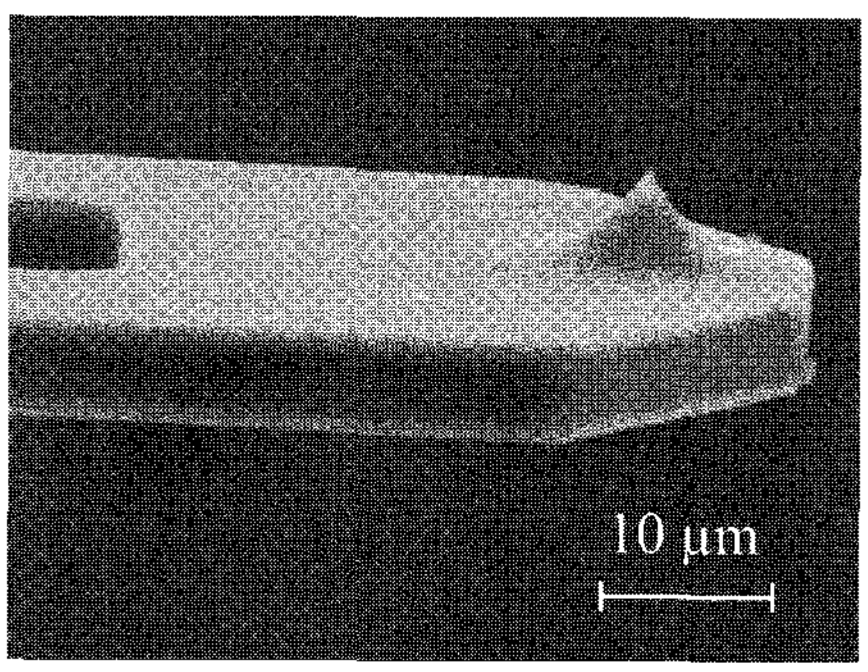


Fig. 2 Cantilever used for the measurements

3. High-speed slope compensation scanning strategy

Most microstructures have small amplitudes that can be directly measured by an AFM running in the constant height mode, resulting in high-speed scanning. However, even if the microstructures are generated on a flat substrate, a slope can occur when mounting the sample on the spindle due to assembling errors of the spindle and parallelism errors between the top and back surfaces of the sample. The slope must be compensated for when measuring over large areas because the height measurement range of an AFM running in the constant height mode is limited to 1 or 2 μm. We used the Z-PZT actuator of the AFM probe unit to provide the slope compensation.

Table 1 X stage specifications

Manufacturer	NTN
Model	F3
Stroke	300 mm
Maximum speed	400 mm/s
Resolution	Approx. 0.28 nm
Absolute positional accuracy	0.5 μm/300 mm
Repetitive positional accuracy	2 nm

Table 2 Specifications of the air spindle

Manufacturer	NTN
Model	SP
Diameter	130 mm
Rotation speed	0–300 r/min
Resolution	Approx. 0.00857 arc seconds
Absolute positional accuracy	40 arc seconds/360°
Repetitive positional accuracy	0.1 arc seconds

Table 3 Specifications of the piezo-resistive cantilever

Manufacturer		Seiko Instruments
Model		PRC400 Contact
Lever	Length	400 μm
	Width	50 μm
	Thickness	5 μm
	Resonance frequency	>40 kHz
	Quality factor	100–160
Tip	Radius	<20 nm
	Height	>5 μm
Sensor	Resistance	500–650 Ω
	Sensitivity	0.5×10^{-5} (ΔR/R)/nm

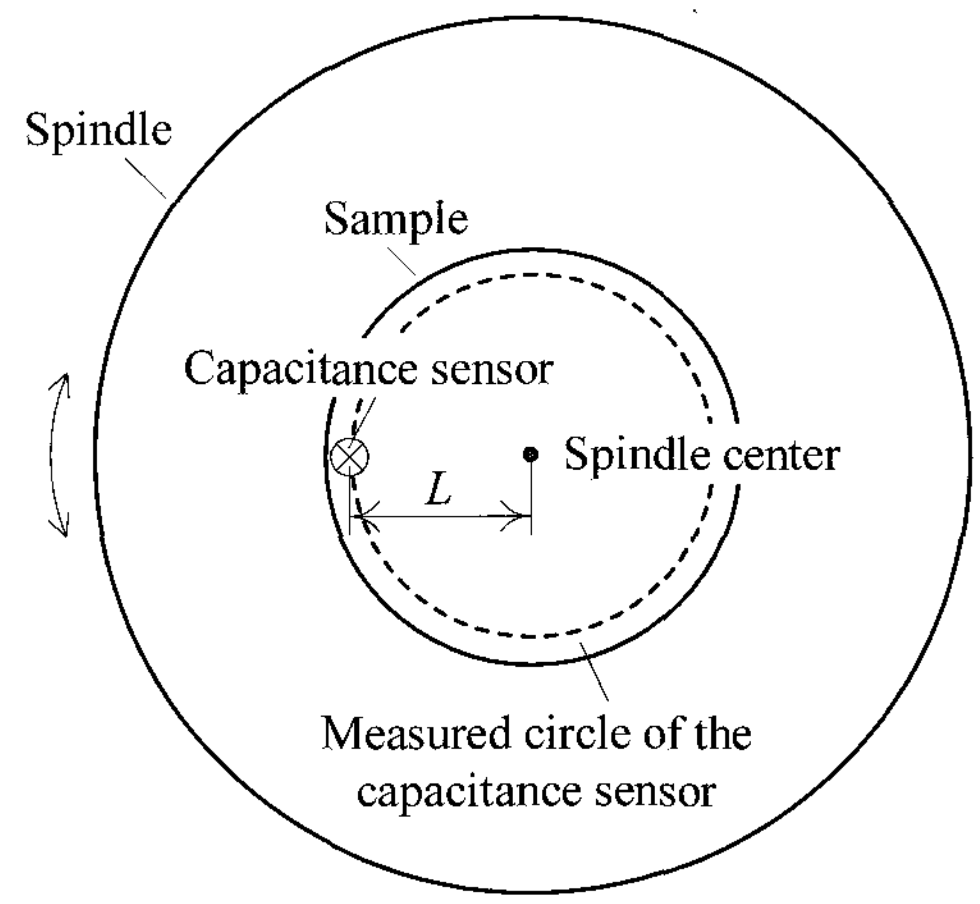


Fig. 3 Measuring the slope on the surface of a sample

As shown in Fig. 3, the slope of the sample surface is measured with a capacitance displacement sensor by rotating the sample through 360°. Assuming that the position of the capacitance sensor with respect to the spindle center is L, which is the radius of the measurement circle of the capacitance sensor, the height variation along the Z axis caused by the sample slope can be derived from a polynomial curve-fit expressed as

$$z = a_0 + a_1\theta + a_2\theta^2 + \cdots a_n\theta^n, \quad 0 \le \theta \le 360 \tag{1}$$

where z is the height variation along the axis direction; θ is the rotated angle of the spindle; $a_0, a_1, a_2, \ldots, a_n$ are the coefficients of the polynomial; and n is the order of the polynomial.

Table 4 Coefficients of the curve-fit polynomial

a_0	a_1	a_2	a_3	a_4
0.016718	1.161×10^{-4}	2.753×10^{-4}	-4.952×10^{-6}	7.914×10^{-8}
a_5	a_6	a_7	a_8	a_9
-7.116×10^{-10}	3.462×10^{-12}	-9.428×10^{-15}	1.371×10^{-17}	-8.355×10^{-21}

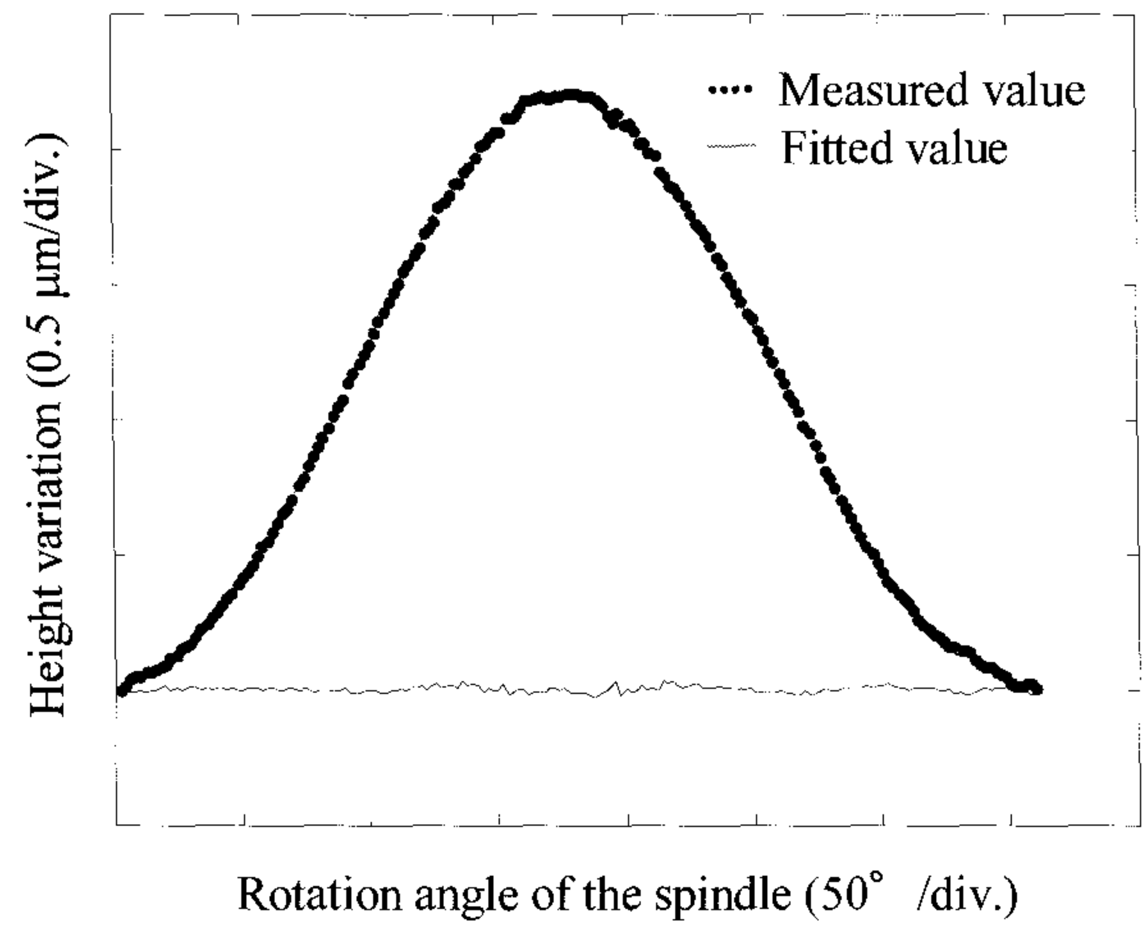


Fig. 4 Measured and curve-fitted results of the slope of the sample

We set the radius L to 20 mm and used the least squares method with an orthogonal algebraic polynomial base function to curve-fit the measured data. The order of the polynomial was set to 9. The resulting coefficients are listed in Table 4. Figure 4 shows the measured and curve-fitted results. The height variation caused by the slope of the sample was approximately 2.2 μm, and the maximum residual error was approximately ±0.03 μm.

The slope compensation data over the entire scanning area were then calculated based on the curve-fit. The results are shown in Fig. 5. In Fig. 5(a), Line 1-1 is the initial measurement position for the slope of the sample and Line 2-2 is the measurement position when the sample is rotated at an angle τ. The height variation Δz caused by the slope of the sample along scanning line CD at the position of Line 2-2 can be evaluated based on the relationship shown in Fig. 5(b). Assuming that the heights z_A and z_B of points A and B, which are located on the measurement circle of the capacitance sensor in Fig. 3, can be calculated based on Eq. (1) as

$$z_B = a_0 + a_1\tau + a_2\tau^2 + \cdots a_9\tau^9 \tag{2}$$

$$z_A = a_0 + a_1(\tau+\pi) + a_2(\tau+\pi)^2 + \cdots a_9(\tau+\pi)^9, \tag{3}$$

the Δz for the slope compensation can be evaluated from

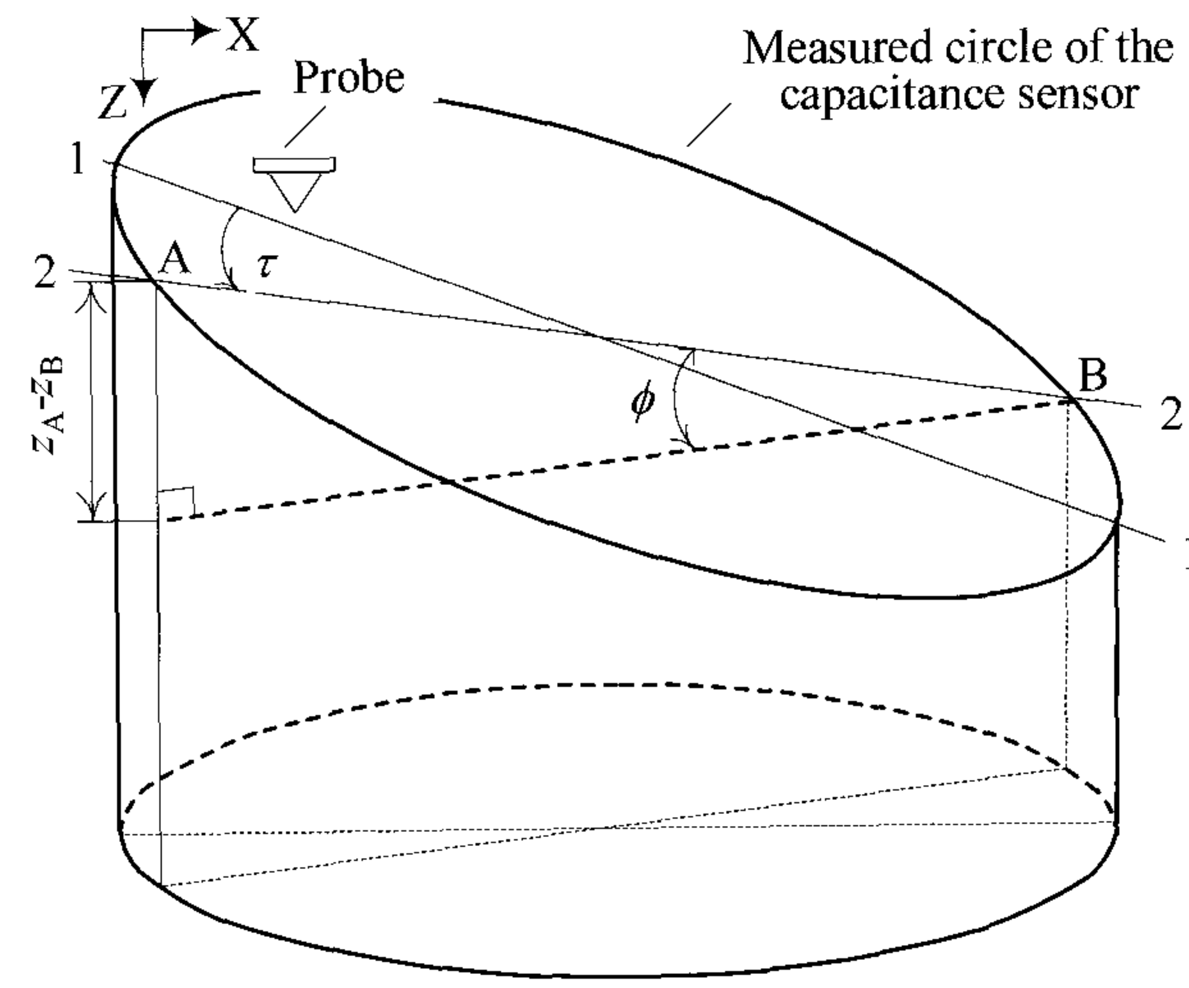
$$\Delta z = (z_A - z_B)\Delta l / 2L, \tag{4}$$

where Δl is the length of CD and L is the radius of the measurement circle of the capacitance sensor in Fig. 3.

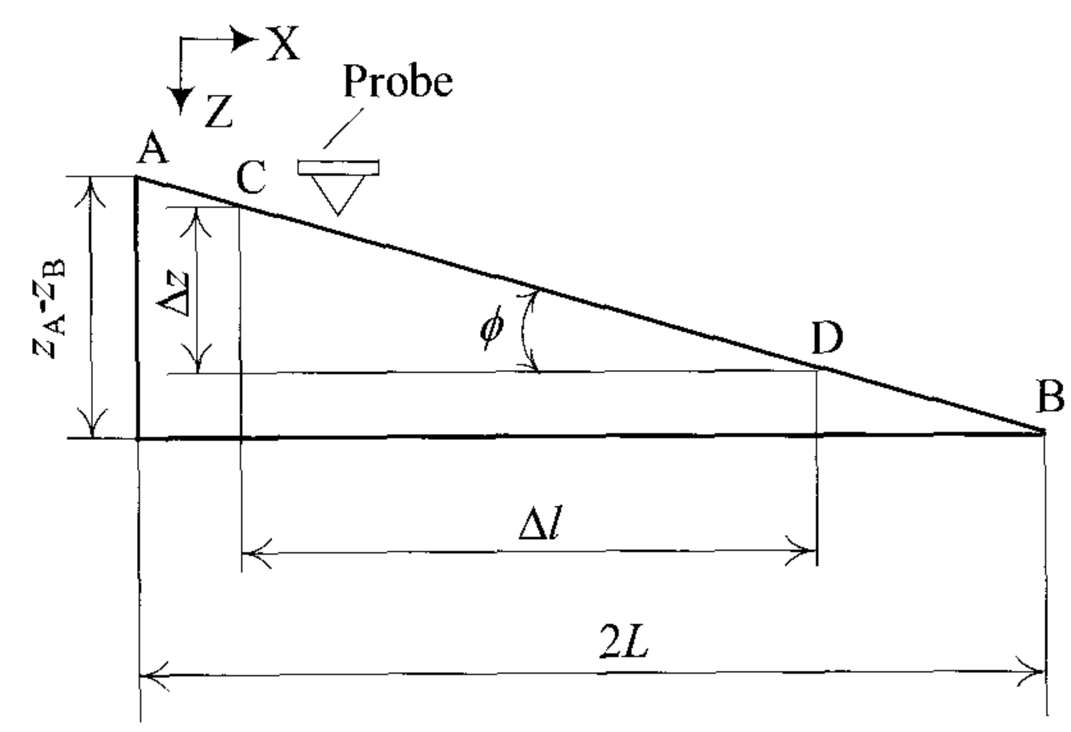
During scanning, the Z-PZT actuator in the AFM probe unit is used to compensate for the slope of the sample based on the value of Δz so that the surface microstructures can be measured at a relatively high speed using our AFM running in the constant height mode.

4. Experimental results

Figure 6 shows the setup used to measure the dynamic performance of the cantilever with open loop and closed loop control systems, and Fig. 7 gives the measurement results. The bandwidth of the cantilever with the open loop control was greater than 40 kHz, and only depended on the bandwidth of the cantilever and the electronics of the piezoresistive sensor, allowing high-speed scanning. However, the cutoff frequency of the cantilever with the closed loop control was approximately 50 Hz (Fig. 7(b)), which was mostly limited by the electronics of the feedback controller. Comparing the results shown in Fig. 7(a) and (b), the possible measurement speed of the AFM running in the constant-height mode, which works using open loop control, was 800 times greater than that running in the constant-force mode, which works using closed-loop control.



(a) Schematic view of a sample with a sloped surface



(b) Geometrical simplification

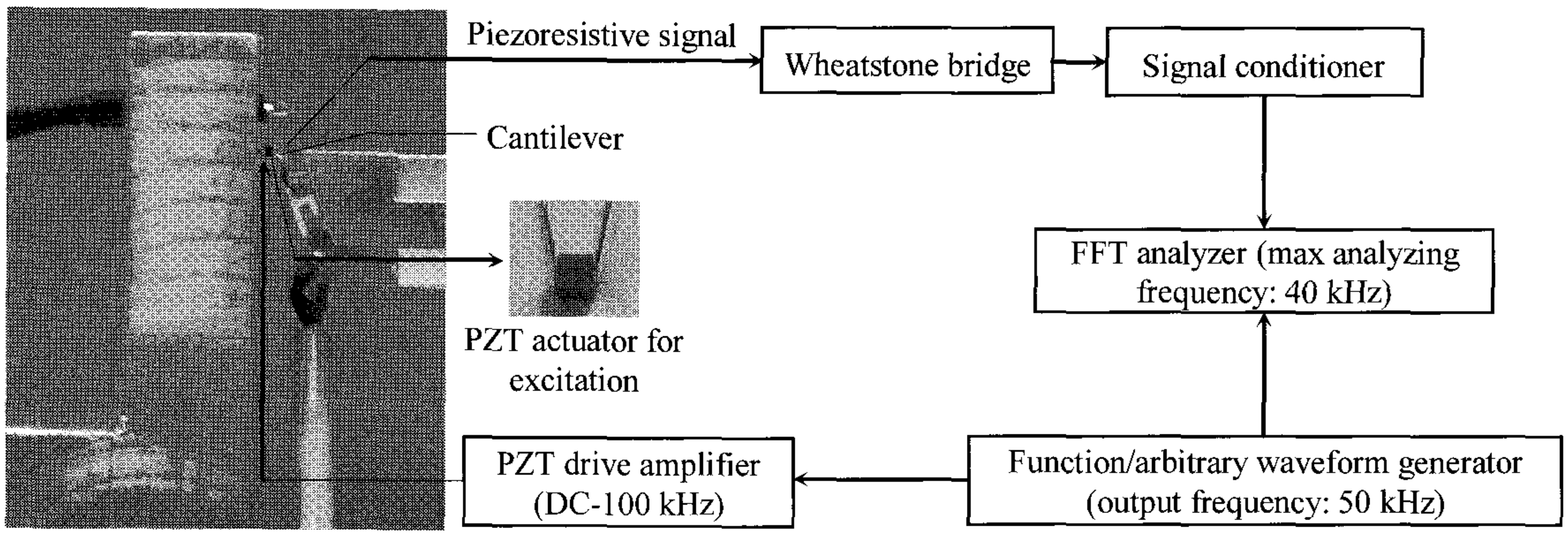
Fig. 5 Calculating the data for the slope compensation

We used our AFM to measure a microstructure sample consisting of a sinusoidal wave with an amplitude of 0.5 μm and a wavelength of 150.0 μm. The microstructures were fabricated by diamond turning.[1] For simplicity, only the X stage was employed during this test. The scanning distance was 4.5 mm, and the scanning speeds were 0.1, 0.5, 1.0, 5.0, 10.0, 15.0, and 20.0 mm/s. The measurements were performed using a constant force or a constant height with and without slope compensation.

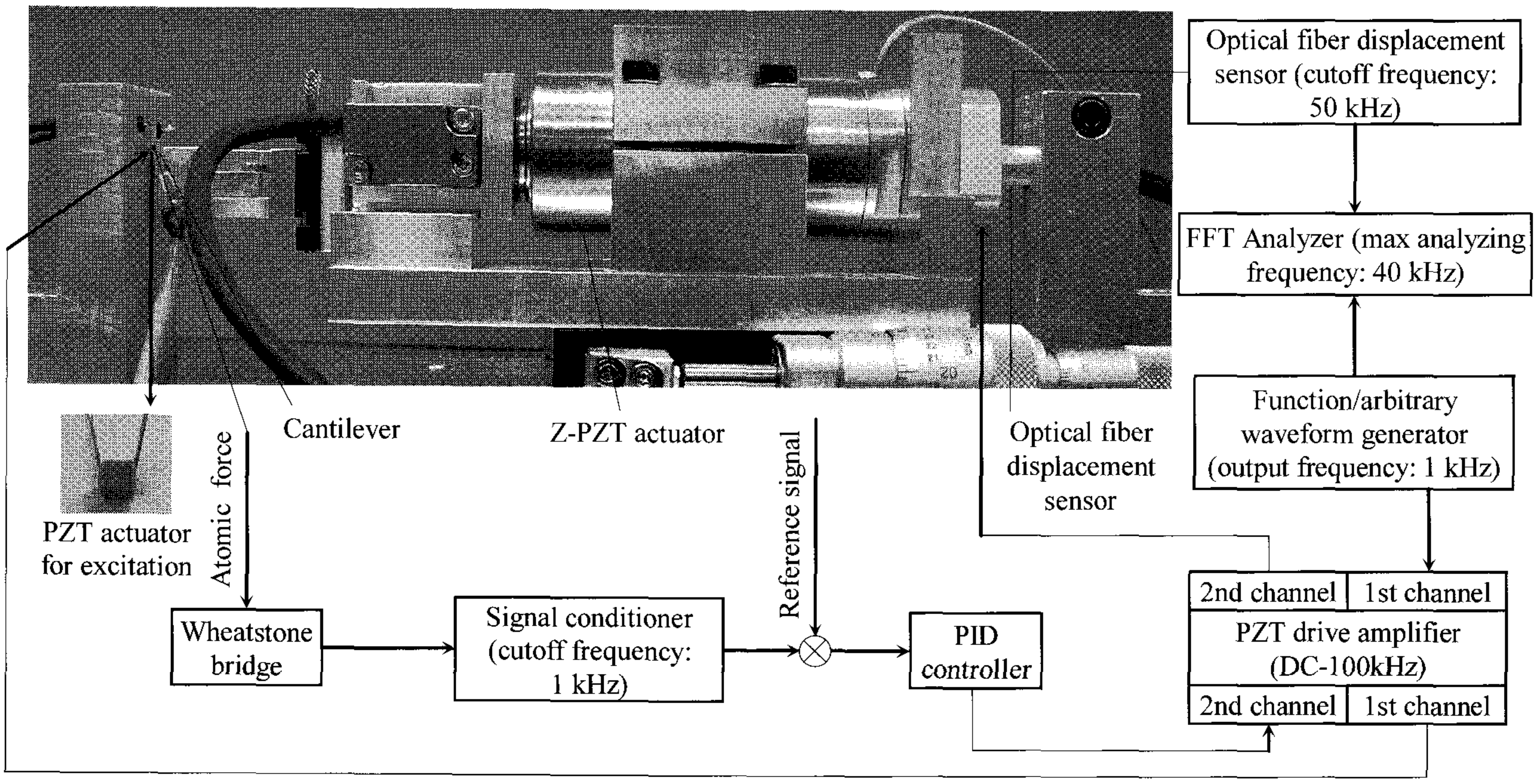
Figure 8 shows the AFM results obtained using a constant height without slope compensation. The slope affected the results. The maximum height variation of the slope was approximately 0.5 μm. Parts of the surface were not measured correctly because the measurement range of the AFM in the Z direction was not sufficient to cover the slope.

Figure 9 shows the AFM results obtained using a constant force based on PID feedback. The slope was covered by the feedback control when the scanning speeds were slow. However, when the scanning speed was greater than 10.0 mm/s, the measured profile of the microstructures started to contain distortions due to the limited bandwidth of the feedback control.

Figure 10 shows the AFM results obtained using a constant height with slope compensation. No slopes were observed in the measured results. The measured profile of the microstructure was detected well at different scanning speeds, which demonstrates the feasibility of using our scanning strategy.

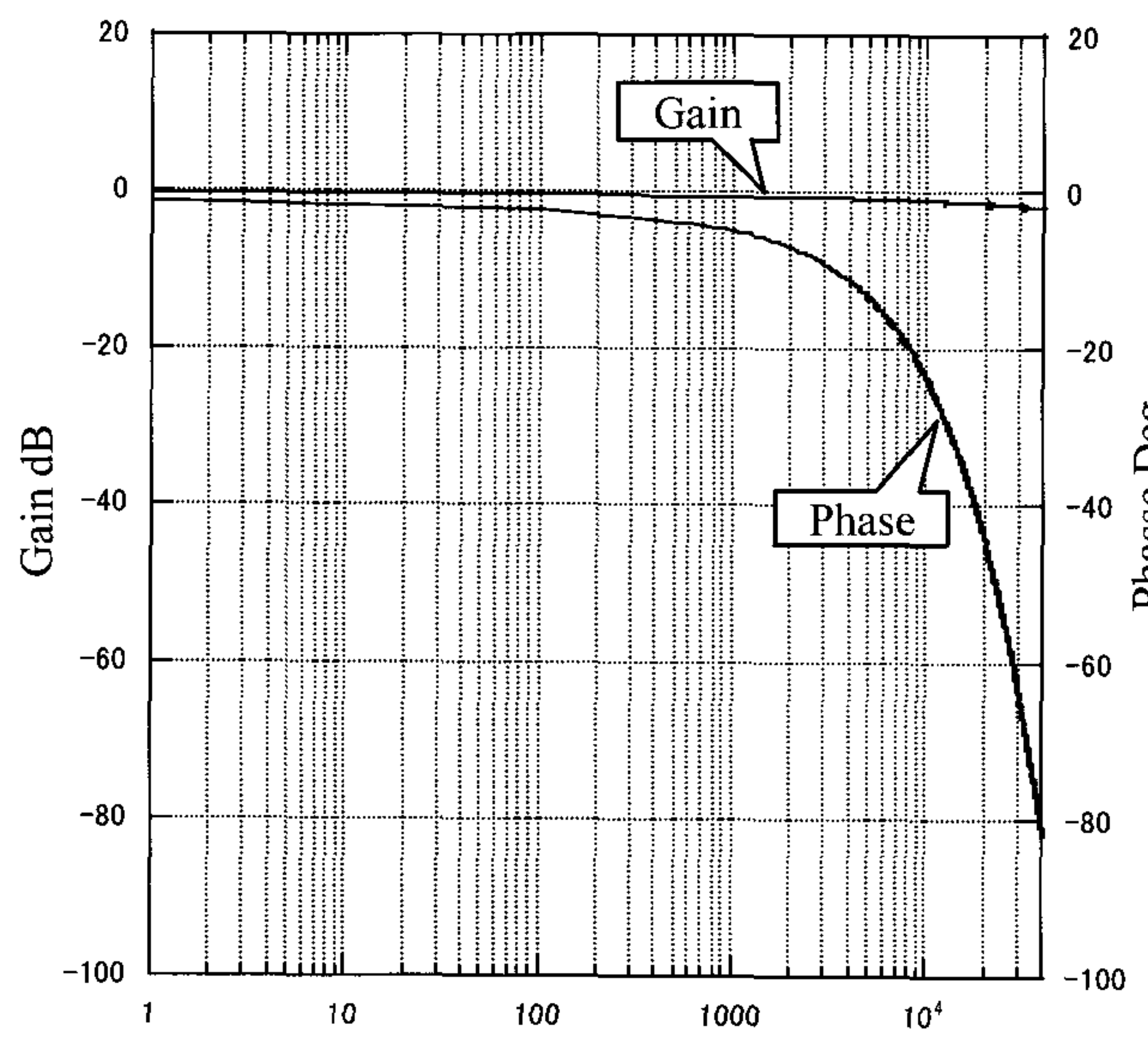


(a) Open loop control

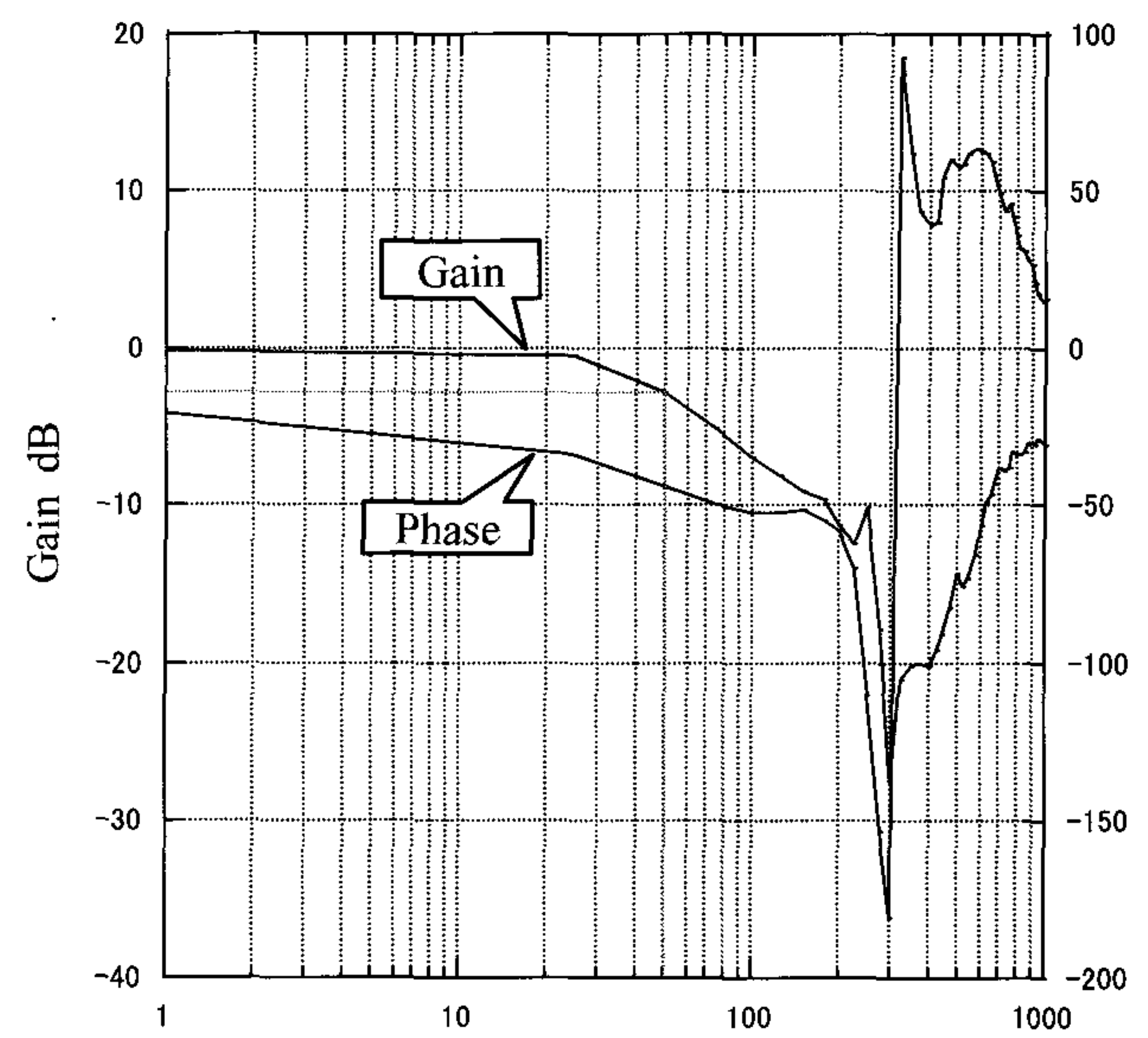


(b) Closed loop control

Fig. 6 Setup to measure the dynamic performance of the cantilever



(a) Open loop



(b) Closed loop

Fig. 7 Dynamic performance of the cantilever

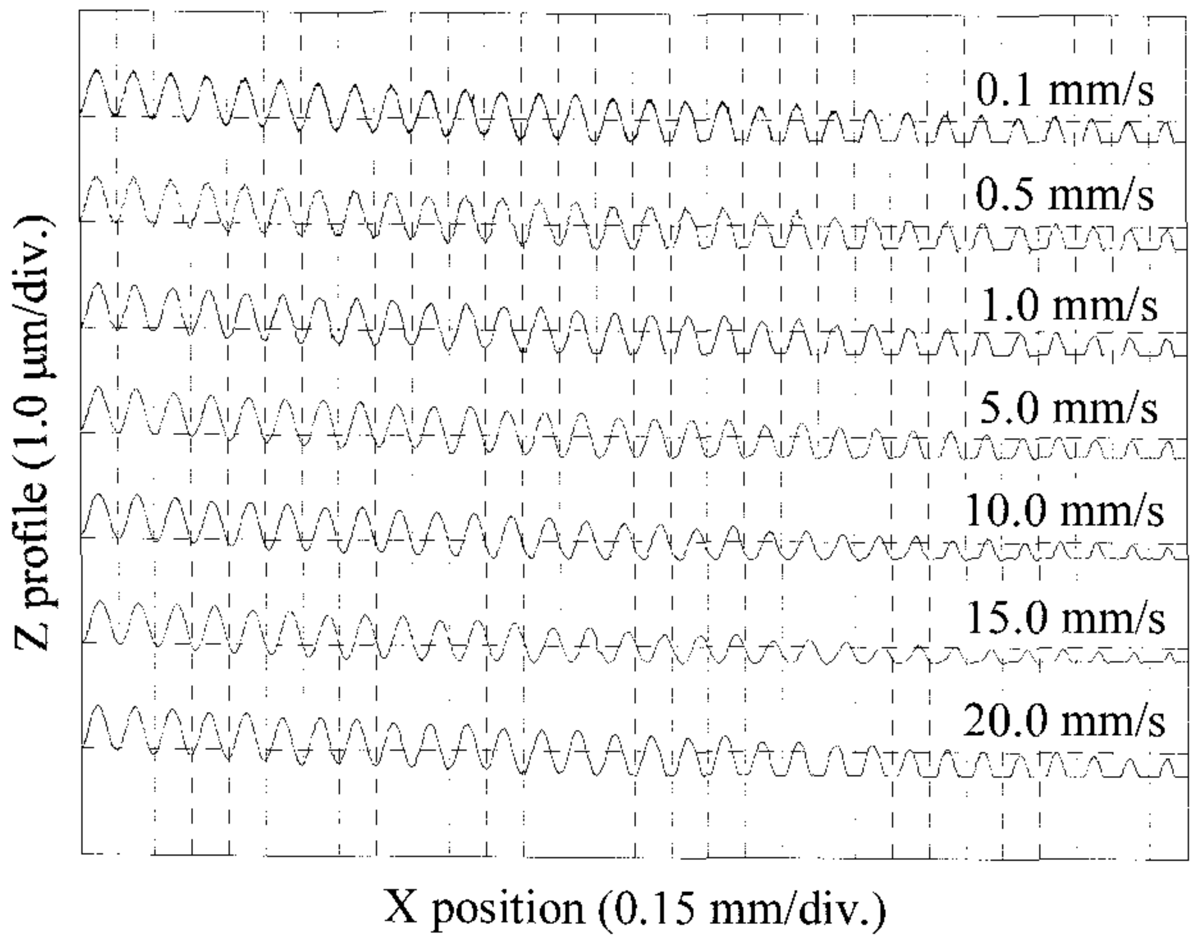


Fig. 8 Measured profile of the microstructured surface using a constant height without slope compensation

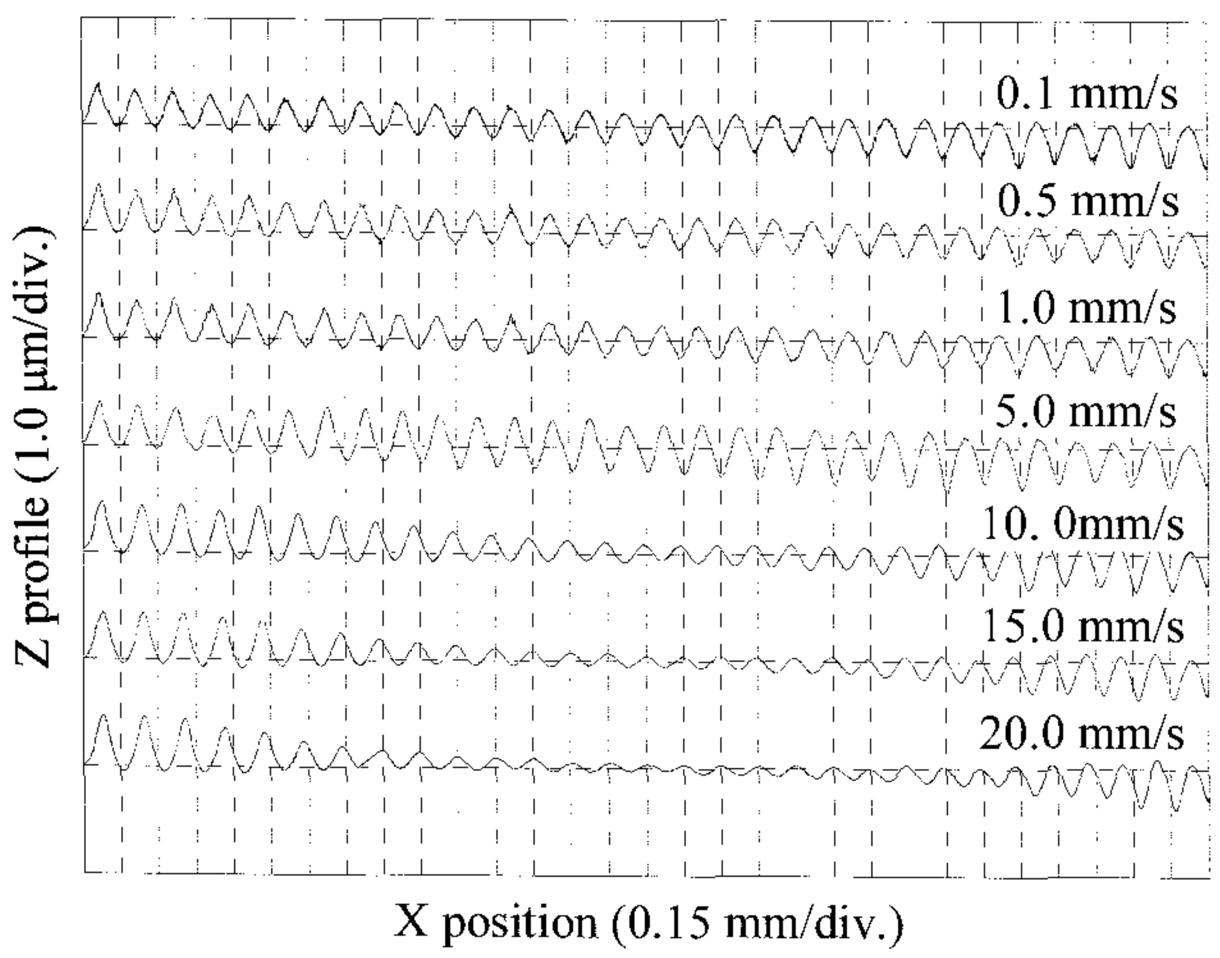


Fig. 9 Measured profile of the microstructured surface using a constant force

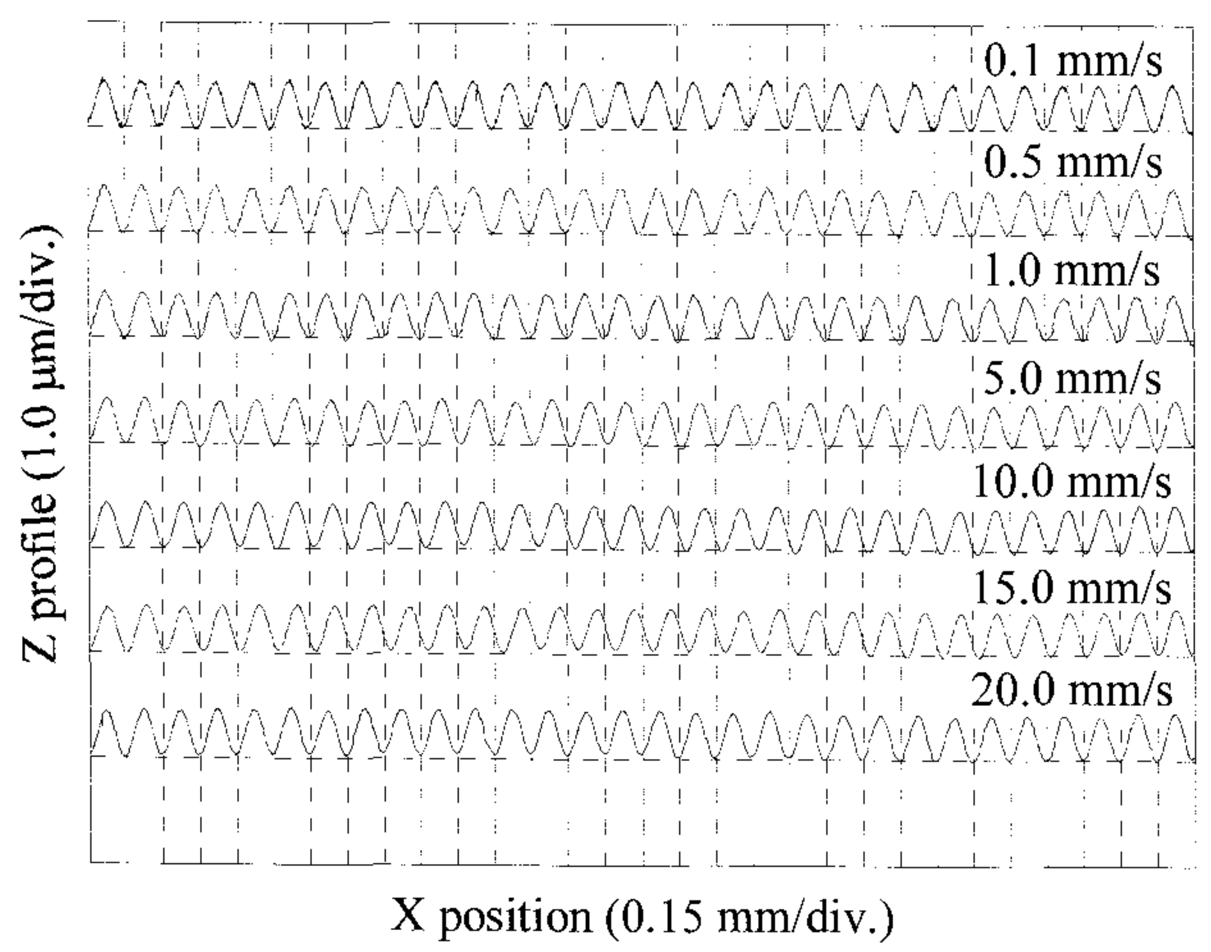


Fig. 10 Measured profile of the microstructured surface using a const ant height with slope compensation

5. Conclusions

A new AFM system consisting of an air-bearing X stage, an air spindle, and an AFM probe unit was developed. A scanning strategy was proposed that combined a constant measurement height with compensation of the slope of the sample to attain high-speed precision measurements. The slope compensation was implemented using the Z-PZT actuator in the AFM probe unit based on data measured with a capacitance sensor.

Profile measurement tests using a microstructured surface with a sinusoidal wave were carried out using different scanning modes. The results demonstrated that the new scanning strategy was more suitable for high-speed precision measures of microstructured surfaces than conventional constant height or constant force scanning techniques.

Only linear scanning tests along the X axis were performed in this study. Tests over a larger area that require driving both the X stage and the air spindle will be performed in the near future.

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