研 究 速 報

A Linear Encoder Using a Crystal as a Reference

Yasuo HOSHI*, Takayoshi KAWAGISHI* and Hideki KAWAKATSU*

1. Introduction

A linear encoder based on a friction force microscope (FFM) is being investigated. This technique is useful for positioning control of the sample stage of a scanning probe microscope and in situ calibration of scanning distortion due to thermal drift. Figure 1 (a) shows the basic idea. A Crystal is attached on the moving part of the linear encoder and used as a scale reference. A displacement input is measured by the periodicity of the crystalline lattice that is observed by FFM. The moving part is supported by parallel leaf springs to assure the trueness of linear movement. A piezo element (*Pz*) is used for keeping an average of contact constant.

Typical signal detected from FFM is shown in the figure 1 (b). The torsion of the cantilever (θ_y) is plotted against the scanning voltage. An increasing slope in the figure indicates a stick of the tip to a period reflecting the crystal structure. A sharp decrease in torsion angle is observed when the tip jumps to the next 'stick-point'. Tip attitudes corresponding to the torsion signal are depicted at the head of the figure. A large stick of the tip is observed just after the change in the scanning direction. However, when the direction of displacement is constant, good regularity of the saw-toothed signal is observed. This 'stick-slip' motion of the FFM tip with atomic resolution was first reported in the case of observing graphite in ambient operation by Mate *et al.* in 1987.[1] Similar results have been reported on other materials.[2–7] Recently, Sasaki *et al.* reported theoretical simulations, which explain load dependence of FFM image patterns.[8,9] In most of these reports, only the load dependence of a stick-slip motion was discussed and there is little information about the velocity dependence. Mate *et al.* reported that the frictional force shows little dependence on the velocity over the range 4nm/s to 400nm/s. As known in the field of tribology, where the velocity exceeds severalμm/s, the velocity dependence is not negligible.[10–15] Analysis of atomic-scale stick-slip motion is difficult because it depends on

*Center for International Research on Micro-Mechatronics, Institute of Industrial Science, University of Tokyo

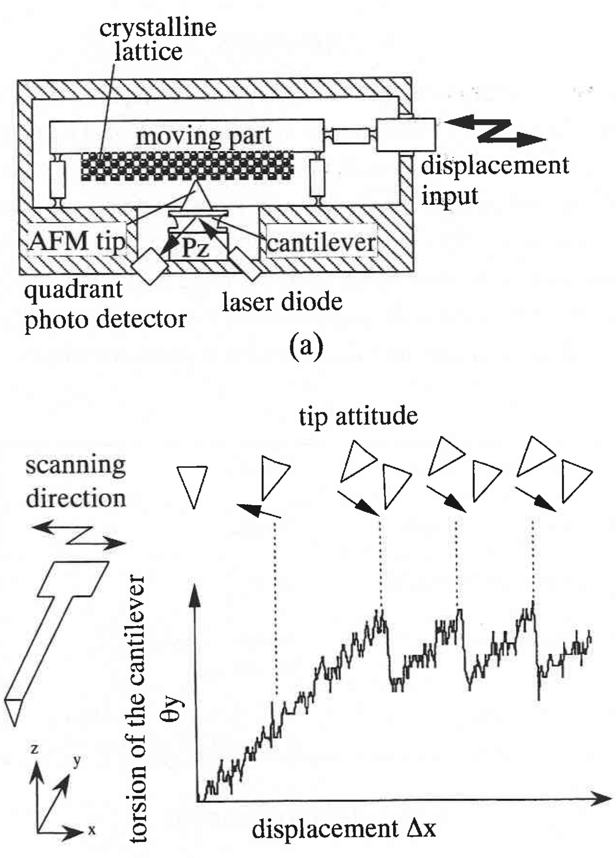

Fig. 1　(a) Schematic view of a linear encoder based on a friction force microscopy. (b) Regularity of a crystal observed by a friction force microscopy as a 'stick-slip' motion of the tip end. A big stick of the tip is observed just after the change in the scanning direction. Good regularity of the saw-toothed signal is observed.

many factors, for example, force control methods, structure and chemical characteristics of the crystal, cantilever characteristics, tip-crystal interface, and experimental atmosphere, etc. In most cases, average friction calculated from friction loop size was plotted against scanning speed.[11, 13] Teschke and Souza reported that scanning speed of 100nm/s provided the best resolution for mica immersed in water.[14] Persson gave a sliding dynamics model of lubricated surfaces.[15] The model expressed the translation from steady to stick-slip motion as a function of force and velocity. Sϕrensen *et al.* simulated an atomic-scale stick-slip of a Cu on a Cu surface, 12) which was confirmed by Bennewitz *et al.*[16]

We are now investigating the behavior of a friction microscope tip on a crystal. In this paper, mica and graphite were observed in ambient operation at tip velocities over 1μm/s to access the velocity dependence of FFM.

2. Experimental

Cleaved mica and highly oriented pyrolytic graphite (HOPG) were observed by a friction force microscope. A 200μm long and 20μm wide rectangular Si_3N_4 cantilever was used.[17] In all cases, the tip was brought into contact with the sample and very slow control of repulsive force was selected. A quadrant photo diode was used for the detection of the bending and torsion of the cantilever. The photodiode amplifier has a bandwidth of 800kHz (−3dB). All experiments were carried out at room temperature.

Table 1

Cantilever width	20μm
Cantilever length	200μm
Cantilever material	Si_3N_4
Atmosphere	Room temperature In ambient
Tip velocity	0.1 ~1.6μm/s for mica 0.1 ~23μm/s for HOPG

3. Results and Discussion

3.1 Velocity dependence of the behavior of the tip on mica

Figure 2 shows the tip velocity dependence of torsion of the cantilever on mica. At a tip velocity of less than 1μm/sec, a regular saw-toothed signal corresponding to atomic level stick-slip is observed as shown in Figs. 2 (a) and 2 (b). The pitch of the saw-toothed signal was about 0.5nm, which reflects the crystal

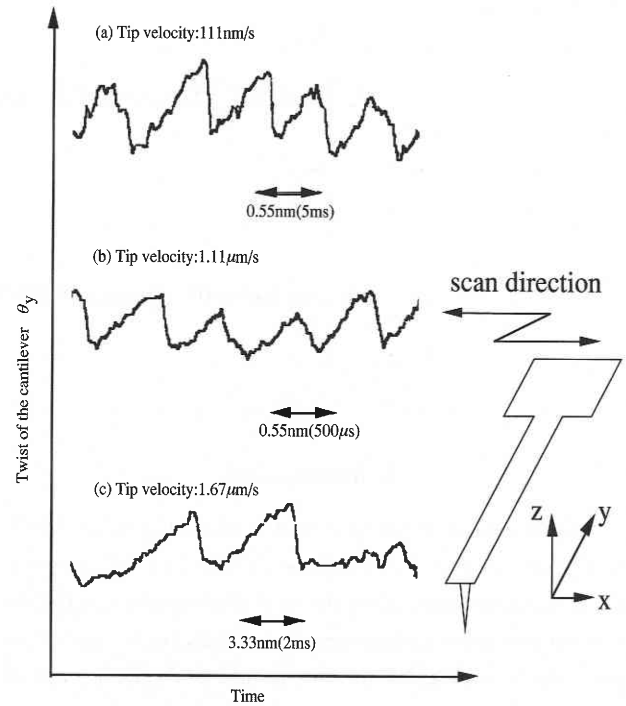

Fig. 2 Velocity dependence of a torsion signal in the cases of observing mica. The pitch of saw-toothed signal is about 0.5 nm corresponding to atomic periodicity of mica in cases where the tip velocity is (a) 0.55μm/s and (b) 1.1μm/s, and about 3 nm in the case where the tip velocity is (c) 1.6μm/s.

structure. At a tip velocity of over 1μm/sec, as shown in Fig. 2 (c), regularity of the signal became unstable. Sometimes no saw-toothed signal is observed. And even if there was a saw-toothed signal, the pitch of the saw-toothed signal was quite larger than that corresponding to the crystal structure. The tip jumps several stick-points at once when the tip velocity exceeds a certain value around 1μm/sec. No apparent difference of the maximum velocity without miscounting periodicity was observed for different loads ranging from 10nN to 100nN. Wear of mica became apparent at loads over 100nN.

In the case of observing mica, the tip-crystal interface seemed to act as a dominant factor for stick-slip motion. Because of the hydrophilic property of mica, water and other contamination are considered to gather around the tip-crystal interface and dump the vibration of the natural frequency of the cantilever for both bending and torsion direction.

3.2 Velocity dependence of the behavior of the tip on HOPG

Figure 3 shows the tip velocity dependence of torsion of the cantilever on HOPG. Clear regularity was detected at over

10μm/s. The difference from the case of observing mica is considered to be caused by hydrophilic/hydrophobic property of each crystal. A sinusoidal higher frequency signal corresponding to the natural frequency of the cantilever in the torsion direction was observed superposed on the saw-toothed signal.

The cantilever itself has a natural frequency of 22kHz in the bending direction. However, over 40,000 counts/s in Fig. 3 (c) is much higher than that frequency. Figure 4 explains a reason why the frequency of movement of the tip end exceeds the natural frequency of the cantilever. A peak at 22 kHz in freestanding condition was detected from the spectrum of the bending signal of the cantilever, as shown in Fig. 4 (b). However, the peak moved to about 95kHz after contacting the sample, as shown in Fig. 4 (e). The natural frequency in the torsion direction did not depend on the conditions and always stayed at around 417kHz.

Thus, this cantilever should be able to detect crystal periodicity at least at the frequency of lower than 95kHz, which corresponds to about 23μm/s in tip velocity. Figure 5 shows torsion signal, the spectrum of the bending signal and that of the torsion signal at tip velocities of 11μm/s and 23μm/s. In the case where the tip velocity was 11μm/s, crystal periodicity of about 47kHz was observed in the spectrum of torsion signal (Fig. 5 (c)). The periodicity did not appear in the spectrum of bending signal (Fig 5 (b)). A small hillock around 95kHz in Fig 5 (c) implies that there was interference between bending signal and torsion signal. At the tip velocity of 23.3μm/s, the periodicity was still observed in Fig 5 (d). However, the higher frequency signal corresponding to the natural frequency of the cantilever in the torsion direction started to mask the saw-toothed wave as the scanning velocity increased and the signal to noise ratio became worse. Sometimes the saw-toothed signal was not detected.

In the case of observing HOPG, damping effect of the tip-crystal interface is very small due to the hydrophobic property of graphite. What is worth noting is the fact that the slip velocity increased according to the scan velocity. Time period of slipping was always about tenth of that of sticking and no difference was observed on the saw-toothed pattern at the scan velocity of 0.1μm/s to 23μm/s. The slip velocity corresponding to the scan velocity of 23μm/s reaches at 230μm/s. The mechanical property of the cantilever is the limitation of atomic level FFM on graphite. Increase of the natural frequency of the cantilever is essential for tribological studies with atomic resolution. A nanometric cantilever with natural frequency up to 1GHz will allow observation up to 250mm/s.

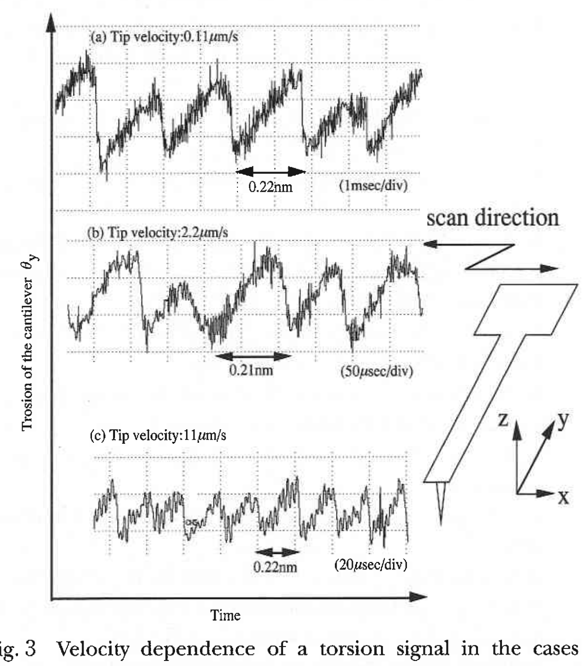

Fig. 3 Velocity dependence of a torsion signal in the cases of observing HOPG. The pitch of saw-toothed signal is about 0.2 nm corresponding to atomic periodicity of HOPG in all cases. A small wave at about 400 kHz in frequency is recognized clearly at tip velocity of (c) over 10μm/s.

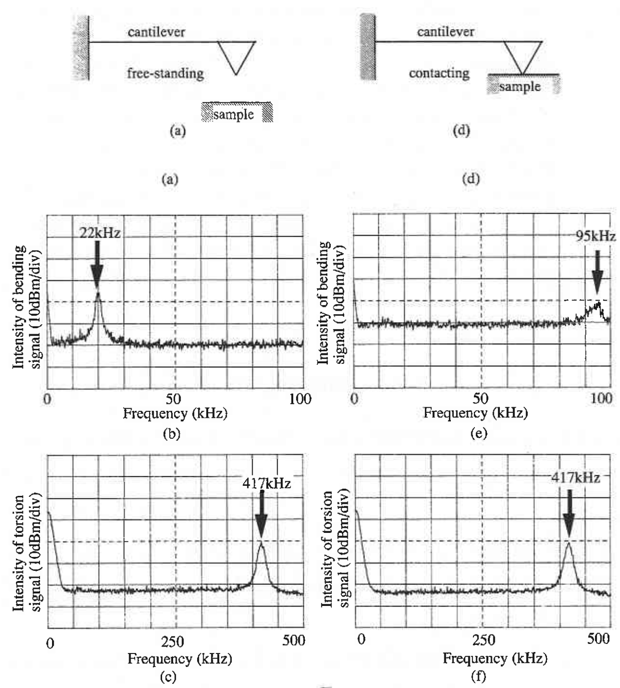

Fig 4 Frequency characteristics of the cantilever. A peak at 22 kHz in freestanding condition was detected from the spectrum of the bending signal of the cantilever ((b)). The peak moved to about 95 kHz after contacting a sample ((e)). The natural frequency in the torsion direction did not depend on the conditions and always stayed at around 417 kHz ((c), (f)).

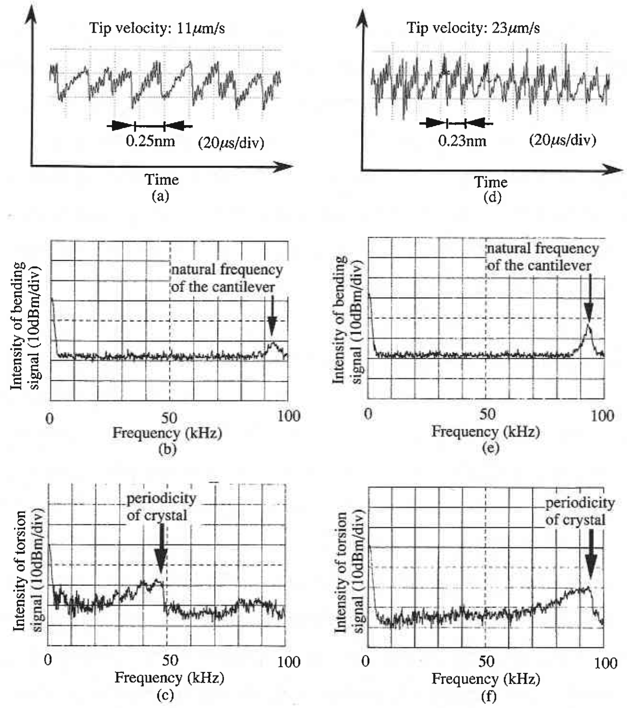

Fig. 5 Torsion signal, the spectrum of the bending signal and that of the torsion signal at tip velocities of 11μm/s and 23μm/s. In the case where the tip velocity was 11μm/s, crystal periodicity of about 47 kHz was observed in the spectrum of torsion signal ((c)). The periodicity did not appear in the spectrum of bending signal ((b)). A small hillock around 95 kHz in (c) implies that there was interference between bending signal and torsion signal. At the tip velocity of 23.3μm/s, the periodicity was still observed in (d). However, the higher frequency signal corresponding to the natural frequency of the cantilever in the torsion direction started to mask the saw-toothed wave as the scanning velocity increased and the signal to noise ratio became worse and sometimes the saw-toothed signal was not detected.

4 Conclusions

Cleaved mica and HOPG were observed with a friction force microscope in ambient operation. Obtained results are listed below.

(1) A regular saw-toothed signal corresponding to atomic level stick-slip was observed in each case at a tip velocity of less than 1μm/s.

(2) In the case of observing mica at a tip velocity of over 1μm/s, regularity of the signal became unstable.

(3) For HOPG, the mechanical property of the cantilever was the limitation. The difference is considered to be caused by the hydrophilic/hydrophobic property of each crystal.

(4) For a 200μm long and 20μm wide rectangular cantilever, 95kHz and 416kHz spectrums, corresponding to the natural frequency of the cantilever for deflection and torsion with the tip in contact, started to mask the stick-slip signal as the scanning velocity increased.

(5) The slip velocity increased according to the scan velocity and was always ten times larger than the scan velocity for the scan velocity from 0.1μm/s to 20μm/s. For example, for a 10μm/s of scan velocity, the slip velocity was 100μm/s.

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