Controlling chaos in dynamic-mode atomic force microscope

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Abstract

We successfully demonstrated the first experimental stabilization of irregular and non-periodic cantilever oscillation in the amplitude modulation atomic force microscopy using the time-delayed feedback control. A perturbation to cantilever excitation force stabilized an unstable periodic orbit associated with nonlinear cantilever dynamics. Instead of the typical piezoelectric excitation, the magnetic excitation was used for directly applying control force to the cantilever. The control force also suppressed the cantilever's occasional bouncing motions that caused artifacts on a surface image.

Key words: controlling chaos, atomic force microscopy, time-delayed feedback control, cantilever
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1. Introduction

Science and engineering at the nanoscale are of great importance nowadays [1]. The scanning probe microscopy (SPM) has been a powerful tool for direct access into the nanoscale [2]. Among the members of SPM family, the atomic force microscopy (AFM) [3] has been significantly developed for more than two decades [4]. In particular, the dynamic-mode AFM, distinguished from the operating-modes of the AFM [5, 6], has been very important in its ability to achieve the true atomic and molecular resolution in various samples, including semiconducting [7, 8, 9] and biological samples even in liquids [10, 11, 12]. In addition, versatile applications of the dynamic-mode AFM are remarkable in profiling of surface properties [13, 14, 15] and manipulation of single atoms [16].

On the other hand, extensive studies have focused on nonlinear cantilever dynamics especially in the amplitude modulation AFM (AM-AFM) because of its close relation to imaging characteristics [17, 18, 19, 20, 21]. The AM-AFM, in fact, exhibits various nonlinear phenomena including bistability [22, 21], bifurcation [23, 24], chaotic oscillations [25, 26], which nonlinear scientists have focused on for half a century [27]. Actually, the existing techniques for analysis of nonlinear systems have been applied to some problems in the nonlinear cantilever dynamics [17, 18, 19, 20, 21, 25, 26, 28, 29, 30] such as the application of Melnikov method [31, 32]. It should be emphasized that the cantilever dynamics is directly connected to the resolution of images [26] and scanning rate of the AM-AFM [33]. Control strategy is thus effective for significantly improving and accelerating the surface imaging [34].

In this Letter, we present the application of the time-delayed feedback control to AM-AFM. The time-delayed feedback control is a well-known chaos control method to stabilize unstable periodic orbits embedded in chaotic attractors in the field of nonlinear dynamics [35, 36]. Some of the authors have already confirmed its ability by numerical simulation [34]. We here show the first experimental success of stabilization of cantilever oscillation by time-delayed feedback control.

The Letter is organized as follows. Section 2 summarizes the principle of AM-AFM. In Sec. 3, we introduce experimental results on nonlinear cantilever oscillation based on the previous literatures. Section 4 describes the time-delayed feedback control proposed by Pyragas [35]. In Sec. 5, we address the implementation of the time-delayed feedback controller to an actual AM-AFM. Section 6 experimentally shows the stabilization of cantilever oscillation using our controller.

2. Amplitude modulation atomic force microscopy

The principle of the dynamic-mode AFM is based on the detection of force interaction between two nanosized objects separated in less than several nanometers (See, Fig. 1) [3]. Even though the force interaction is so tiny, typically ranging from piconewton to nanonewton, it is detected using a microcantilever having a very sharp tip at the free end. When the oscillating tip is brought close to a sample surface, the shift of the cantilever resonance frequency is induced [5, 6]. One of the ways to measure the interaction force is to excite the cantilever by a sinusoidal

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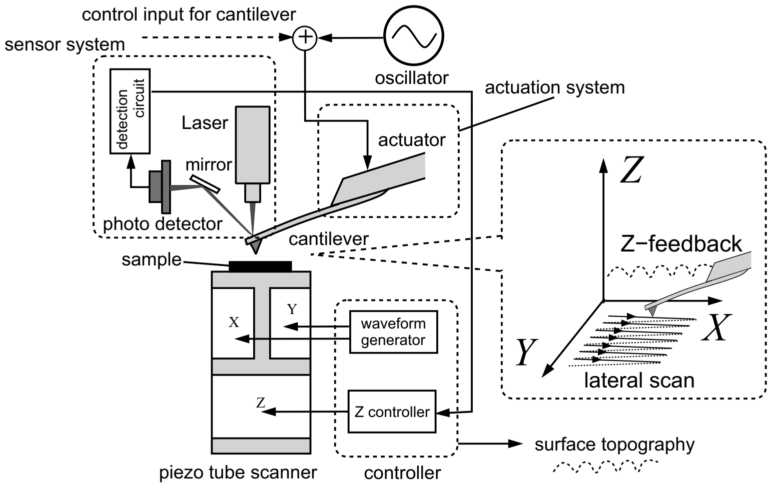


Figure 1: The principle of amplitude modulation atomic force microscopy. A cantilever with a sharp tip is excited by a sinusoidal external force. The tip is placed close to a sample surface and then the surface is laterally scanned by the tip. The amplitude shift due to sample asperity is compensated by a feedback controller so that the tip-sample distance (z-direction) is kept constant. The asperity is reconstructed from the feedback signal.

external force close to its mechanical resonance. The resonance frequency shift caused by a force then modulates the amplitude of periodic oscillation [5]. Since the force is governed by the tip-sample distance, the raster scan of a surface asperity by the tip results in the amplitude modulation. The asperity of a scanned surface is, conversely, reconstructed from the modulated amplitude. In the actual operation, the tip-sample distance is regulated at a specified reference amplitude, called *set point*, during the raster scan using a feedback technology. Instead of the modulated amplitude, the recorded feedback signal to a nanopositioning device, such as a tube scanner, is used for reconstruction of the topography image. This is the basic operation of AM-AFM that is one of the major operating modes in air and liquid environments [5, 37].

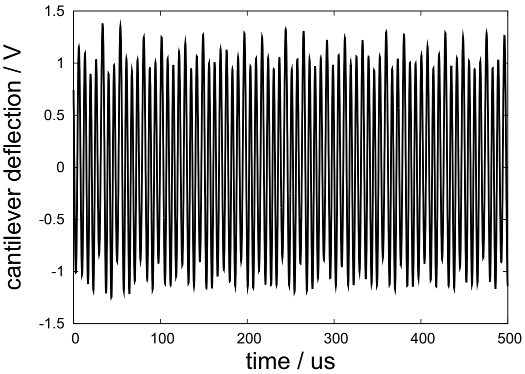
3. Nonlinear cantilever dynamics

An equation of motion for a cantilever can be obtained as a partial differential equation using Euler-Bernoulli theory [28]. The equation is then reduced to an ordinary differential equation with one degree of freedom, when a particular oscillation mode of interest, typically the first mode, is considered under control:

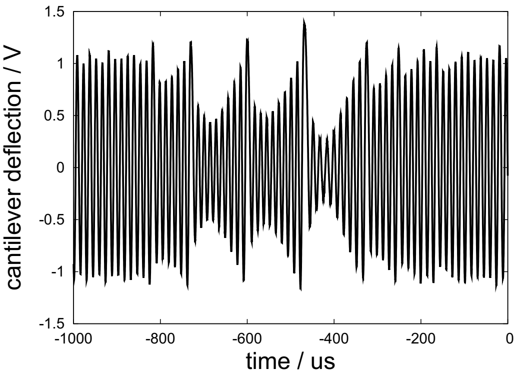
$$\ddot{x} = -\omega_0^2 x - \frac{\omega_0}{Q}\dot{x} + f(Z) + A\cos\omega t + \eta(t) + u(t), \qquad (1)$$

where x denotes deflection of cantilever. ω_0 and Q are resonance frequency and quality factor of the mode under consideration. For the first-mode, the resonance frequency typically ranges from 20 kHz to 300 kHz. Q is a few hundreds in the ambient condition. The cantilever is excited by external sinusoidal force with amplitude A. The excitation angular frequency ω is close to the resonance ω_0. $\eta(t)$ denotes the thermal noise. $u(t)$ is the control force for stabilization of cantilever oscillation, as described in Sec. 4. $f(Z)$ is the tip-sample interaction force depending on the tip-sample distance Z. $f(Z)$ is often described based on such as the Lennard-Jones potential [28, 32] and DMT (Derjaguin-Muller-Toporov) theory [18].

The free oscillation is observed, when the tip is sufficiently far from the surface. On the other hand, Hu *et.al* and Jamitzky *et.al* have recently reported that chaotic oscillation possibly occurs especially when the cantilever tip is located close to the surface [25, 26]. With reference to their experimental results [25, 26], we performed an experiment on nonlinear cantilever dynamics. Figure 2 shows examples of the nonlinear oscillation in the AM-AFM. The sample was highly oriented pyrolytic graphite (HOPG) in air. The cantilever had a small spring constant (Agilent Technologies, MAC lever Type I: nominal spring constant 0.6 N/m, resonance frequency 75 kHz) and the amplitude of free oscillation was roughly estimated as several tens of nanometer. As will be described later in detail, the cantilever has a magnetic coat for applying the magnetic excitation method [38]. As shown in Fig. 2(a), the oscillation became irregular and non-periodic after approach of the tip to the surface. The set point of amplitude was about 80 percents decrease to the free oscillation. Although the behavior was caused by a deterministic nature, the resolution of image is decreased due to fluctuation of oscillation amplitude, as pointed out by Hu and Raman [26]. Another oscillation state was also observed as shown in Fig. 2(b). The oscillation was kept periodic in almost all time; however, the periodic oscillation was occasionally broken by a bouncing motion. It is natural to expect that artifacts may appear in the image due to a sudden change of the oscillation amplitude.



(a) chaotic



(b) occasional bouncing

Figure 2: Nonlinear cantilever oscillation observed in amplitude modulation atomic force microscopy. (a) chaotic oscillation (b) occasional bouncing motion. Nominal spring constant and resonance frequency of cantilever used in experiment was 0.6 N/m and 75 kHz. The sample was graphite in air and the cantilever was excited with a large amplitude. The free amplitude was roughly estimated as several tens of nanometer.

4. Time-delayed feedback control

We here demonstrate the suppression of these irregular oscillation and maintain the periodic oscillation using the time-delayed feedback control. The time-delayed feedback control has been successfully applied to various experimental systems [39, 40, 41, 42, 43]. In particular, the magnetoelastic beam [42] has a similar dynamical structure with a cantilever of the AM-AFM. As proposed by Pyragas, a continuous control input $u(t)$ for stabilization of a chaotic oscillation is given by the error between the current output and the retarded one [35]. Based on the previous numerical results [34] with reference to the chaos control of magnetoelastic beam [42], the velocity $\dot{x}$ is here employed to stabilize the cantilever oscillation:

$$u = K[\dot{x}(t-\tau) - \dot{x}(t)]. \tag{2}$$

τ denotes delay time precisely adjusted to the period of an unstable periodic orbit that one intends to stabilize. In the case of the AM-AFM, the delay time should be equal to the period of the excitation force. The target orbit is an unstable periodic orbit with the period equal to the excitation force. K is the feedback gain that governs the stability of the target unstable periodic orbit. The control input should converge to a noise level once the stabilization is achieved. It is worth noting that no parameter of a cantilever is modified after the stabilization is achieved. The stability of a target orbit is eventually maintained by only a small perturbation force to the sinusoidal excitation force. The noninvasive control method is significant for the dynamic-mode AFM, because the stabilized orbit should depend on just the pure tip-sample interaction. This is an essential difference from the Q-control that has caused a controversy on the effects of feedback control to measurement [44].

The features of the control method allow us to implement it without identifying parameters of each cantilever. Spring constants of commercial cantilevers are given as nominal values, which is often largely different from the exact value. Only the excitation frequency of AM-AFM has to be known to adjust the delay time. The excitation frequency is close to the resonance, which is easily measured in the standard setup. Although the resonance frequency of a cantilever usually ranges from 20 kHz to 300 kHz, as previously mentioned, the control method is feasible to high frequency oscillation [40]. The control law is so simple that any complicated online calculation with digital equipment is not needed to implement the control method.

5. Implementation of control

We built a time-delayed feedback controller and implemented it to a commercial AFM (Seiko Instruments, SPA-300 / NanoNavi Station), as shown in Fig. 4. The controller consists of a differentiator, digital delay line, and differential amplifier. The digital delay line is constructed using a high speed analog-to-digital (A/D) converter (Texas Instruments, ADS807), two first-in-first-out (FIFO) memories (Seiko NPC, SM5837A), and a digital-to-analog (D/A) converter (Texas Instruments DAC902). A signal approximately proportional to the velocity of oscillation $\dot{x}$ is obtained by the differentiator using an operational amplifier (OPAMP). The signal from differentiator is stored in the FIFO memories as digital data through A/D converter with 12 bit resolution. The data stay in the memories for specified clock cycles and are then withdrawn as the retarded signal through the D/A converter. The delay time is adjusted in the range from 1.725 μs to 104.075 μs, which covers the resonance frequency of cantilevers from 10 kHz to 570 kHz. The clock frequency is 40 MHz and the resolution of the adjustment of the delay time is ±12.5 ns, which achieves, for example, the accuracy around 0.1 % for a cantilever resonance of 100 kHz. The signal approximating $u(t)$ of Eq. (2) is finally obtained by an elementary amplifier using an OPAMP.

In order to apply the time-delayed feedback control, the control input to the cantilever should be applied ideally shown in Eq. (1). However, in the standard AFM, the

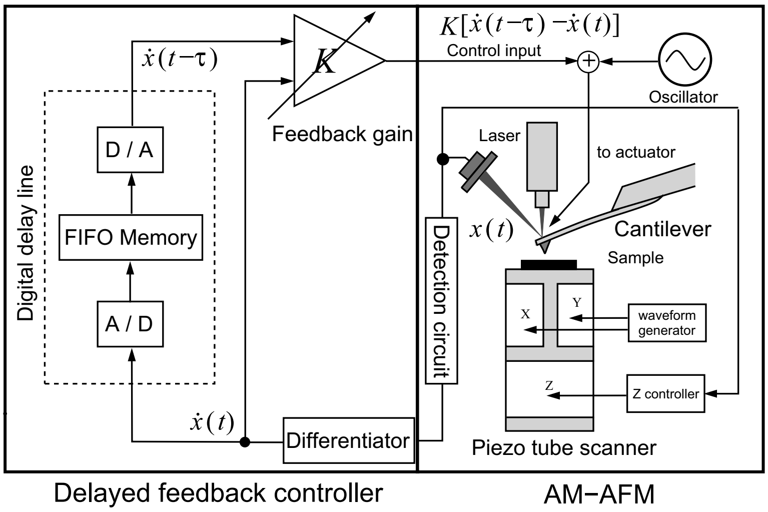
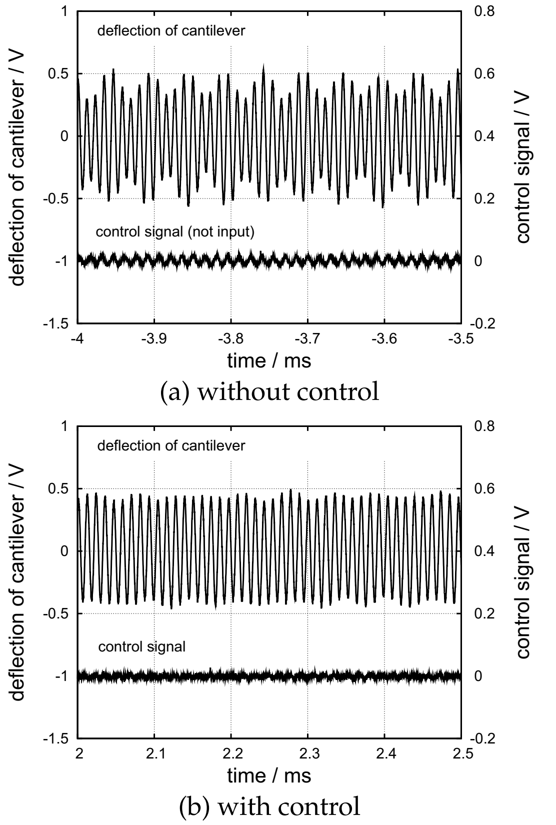


Figure 4: Implementation of time-delayed feedback control to amplitude modulation atomic force microscopy. The retarded signal is generated by a digital delay line, which consists of an A/D converter, two FIFO memories, and D/A converter. Signal from differentiator is approximately proportional to velocity of cantilever oscillation. We used a cantilever with magnetic coat for directly applying the control force to cantilever. The bandwidth of a home-built deflection sensor is about 1.5 MHz.



(a) without control

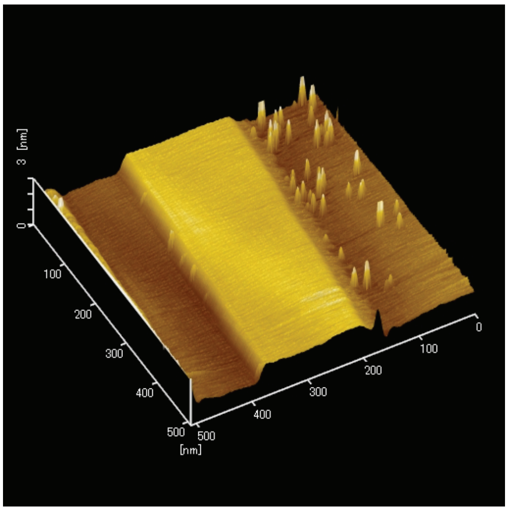
(b) with control

Figure 3: Stabilization of cantilever oscillation. (a) An irregular and non-periodic oscillation observed when control was not activated. (b) A periodic oscillation recovered by time-delayed feedback control. The control force converged to noise level. The irregular oscillation and periodic one were repeatable by turning control on and off, respectively. The sample was a polyimide film. The free amplitude was roughly several tens of nanometer.

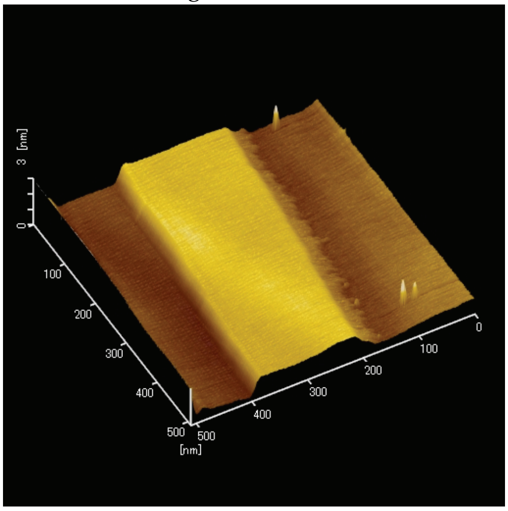
cantilever is excited by a dither piezo attached to the cantilever support. The force generated by the piezoelectric element is propagated toward the cantilever through a mechanical contact and the cantilever support. The transfer characteristics then becomes so complicated that no one can expect that the control force appropriately acts on the cantilever tip as in Eq. (1), where the transfer characteristics is ideally neglected. We therefore employed the magnetic excitation method that is able to directly actuate the cantilever [38]. In our setup, a small solenoid coil (inductance: 68 μH) was placed beneath a sample stage for excitation of a cantilever with magnetic coat. The coil was driven by a voltage-to-current converter, which was constructed with a wide-band and high output current OPAMP (Analog Devices, AD811). It should be mentioned that additional phase delay in the feedback loop should be reduced for better control performance. The developed voltage-to-current converter has a bandwidth around 300 kHz. A home-built low-noise and wideband deflection sensor with 1.5 MHz bandwidth [12] is also employed to decrease phase delay in the feedback loop. Using this setup, we confirmed the cantilever was excited with sufficiently large amplitude for the AM-AFM. The implementation of controller enables us to investigate the ability of the time-delayed feedback control experimentally.

6. Stabilization of cantilever oscillation

An experimental result is shown in Fig. 3. The sample was a polyimide film and scanned by a magnetically coated cantilever previously mentioned. As shown in Fig. 3(a), an irregular and non-periodic oscillation was observed in the close proximity of the sample surface. In



(a) image without control



(b) image with control

Figure 5: Comparison of images of graphite. (a) An image obtained without control force. There were many artifacts due to the occasional bouncing cantilever motion. (b) An image of the same area under control force. Only few artifacts were observed as results of suppression of bouncing motion by time-delayed feedback control.

contrast, after the control was activated, the stabilization of the oscillation was achieved, shown in Fig. 3(b). The oscillation became periodic and, simultaneously, the oscillating components of the control input were eliminated almost. Only the small fluctuation remained in the control input. The fluctuation seemed to be intrinsic noise, because its amplitude hardly changed regardless of whether the control was switched on or off. The main source of noise is the cantilever's Brownian motion, which is significant especially in AM-AFM operating at room temperature. It was also confirmed that the irregular oscillation were recovered if the control was turned off again. It is worth noting that no phase jump occurred in the cantilever oscillation whether the control was turned on or off. This implies that the control force did not make dynamical transition to another stable periodic orbit, which typically has a different phase in the AM-AFM [19, 20, 21, 28]. These facts showed that an unstable periodic orbit was successfully stabilized by adding small perturbation to the excitation force.

7. Conclusion

In this Letter, we demonstrated the first experimental stabilization of cantilever oscillation using time-delayed feedback control, previously confirmed only numerically by some of the authors [34]. The small perturbation to the excitation force successfully eliminated irregular and non-periodic oscillation by stabilizing an unstable periodic orbit associated with nonlinear cantilever dynamics. The stabilization is effective for keeping the resolution of image that is reduced by the irregular oscillation. We also showed that the control force is also useful for suppression of the occasional bouncing cantilever motion, which results in the greatly reduced artifacts on the image. For the feedback control of cantilever oscillation, the direct actuation of the cantilever is needed and we employed the magnetic excitation method. Our controller is a still prototype and the control performance is limited at the present stage. The performance will be improved by optimizing control parameters and insertion of appropriate filters for rejecting the effects of higher frequency components. Nevertheless, this is the first implementation of the chaos control method to the actual AFM. The stabilized periodic oscillation remains the pure dynamics of the original system. The controlled dynamics should be a probe for detecting the nonlinear force interaction at the nanoscale.

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