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New control methodology of microcantilevers in atomic force microscopy

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ABSTRACT

We apply an external feedback control technique to vibrating microcantilevers in atomic force microscopy. Here we have no difficulty in getting information on periodic orbits required for application of the external feedback control unlike controlling chaos since stable orbits are used as reference ones. This approach enables us not only to control vibrations of the cantilevers but also to measure the sample surfaces (surface topographies) simultaneously. The efficiency and validity of our approach is demonstrated by numerical simulations and a theoretical analysis with the assistance of numerical computations.

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1. Introduction

Atomic force microscopy (AFM) [1–3] with tapping (or intermittent contact) mode operation has been widely used in nanometer-scale characterization of material surfaces, especially for soft materials such as polymers, DNA molecules and proteins (see [4–7] and references therein). In the standard AFM, a microcantilever tip is excited at a frequency near the primary resonance and the sample surface is imaged while the tip–surface distance is controlled so that the oscillation amplitude is kept at a fixed value.

Several nonlinear phenomena exhibited by microcantilevers in AFM have also been numerically, experimentally and theoretically revealed. One of the characteristic and interesting motions is "bistable" behavior occurring near the sample surfaces. Hence, the microcantilevers exhibit hysteretic responses when the driving frequency is swept up and down through the primary resonance (see [4,8] and references therein). Moreover, several bifurcations and chaotic motions were numerically and/or experimentally observed [9,10] and theoretically analyzed [11–17]. In particular, an agreement between experimental measurements and numerical computations for a mathematical model in which the tip–surface interaction is represented by the van der Waals and Derjaguin–Muller–Toporov (DMT) [18] forces is impressive [9,10].

On the other hand, chaos control has attracted much attention in the past two decades and several techniques for controlling chaotic dynamical systems have been developed [19–21]. Among others, Pyragas [22] proposed two effective control methods for continuous chaotic dynamical systems: *external* and *delayed feedback control techniques*. In particular, the delayed feedback control requires no knowledge of unstable periodic orbits to be stabilized except their periods and has been applied experimentally to many mechanical, electric, chemical and biological problems [20,21,23]. In contrast, the external feedback control requires precise information on unstable periodic orbits, so that it has been experimentally applied to real systems only in very limited cases [24].

In this Letter, we apply the external feedback control technique to vibrating microcantilevers in AFM. Here we have no difficulty in getting information on periodic orbits required for application of the external feedback control unlike controlling chaos since stable orbits are used as reference ones. This approach enables us not only to control vibrations of the cantilevers but also to measure the sample surfaces (surface topographies) simultaneously. The efficiency and validity of our approach is demonstrated by numerical simulations and a theoretical analysis with the assistance of numerical computations. The mathematical model used here is a slightly improved version of [9,10] and the same as the one in [13,14].

2. Mathematical model

Fig. 1 shows our mathematical model for a vibrating microcantilever in atomic microscopy. Here the length is non-dimensionalized by the tip–sample separation Δ when the cantilever is not excited and no tip–sample interaction occurs, while the time is non-dimensionalized by the first mode frequency of the cantilever. The cantilever base is excited by a dither piezoelectric actuator with a constant amplitude γ and constant frequency ω around a distance z from a reference position, so that

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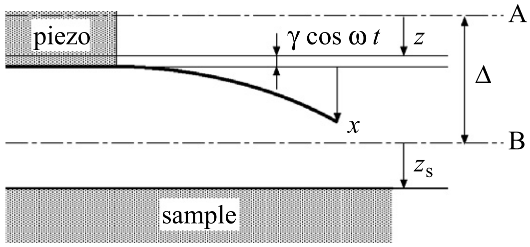

Fig. 1. Cantilever configuration. Lines A and B represent the reference positions of the microcantilever and sample surface, respectively. The variables and constants except Δ are non-dimensionalized.

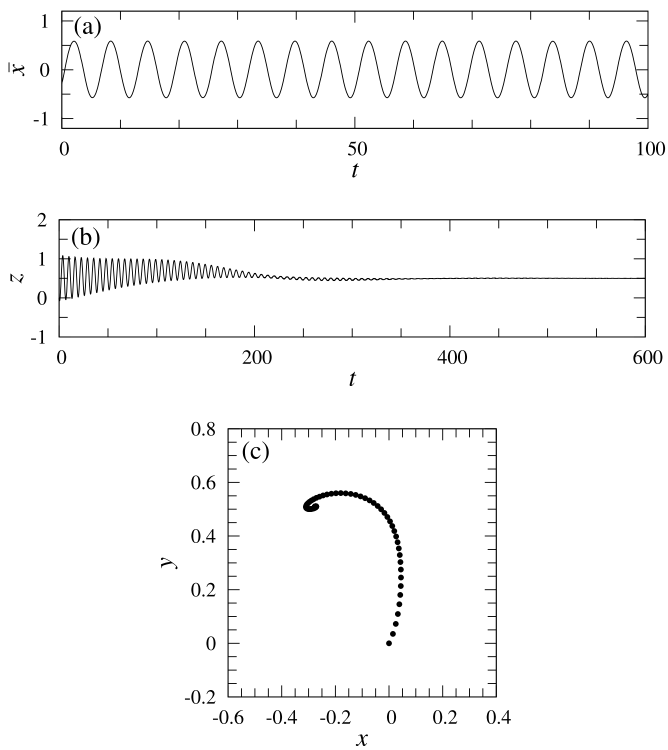

Fig. 2. Numerical simulation results for $\delta = 0.03$, $\gamma = 0.02$, $\kappa = 1$, $z_s = 0.5$, $\alpha = 4.4 \times 10^{-3}$, $\beta = 107$, $a = 0.076$ and $\omega = 1$: (a) Reference periodic response $\bar{x}(t)$; (b) center of the cantilever base oscillation $z(t)$; (c) Poincaré plots.

its displacement is given by $\gamma \cos \omega t + z$. Note that z does not represent the cantilever deflection. We assume the van der Waals and DMT forces between a sphere (tip apex) and a flat surface (sample) for the tip–sample interaction in tapping mode AFM as in [4,9,10,13,14]. Approximating the beam deflection by the first mode of the associated linear problem and applying the Galerkin method, we obtain a mathematical model for the microcantilever,

$$\ddot{x} + \delta\dot{x} + x + f(1 - x - z + z_s) = \gamma \cos \omega t,$$

or as a first-order system

$$\dot{x} = y, \qquad \dot{y} = -x - \delta y - f(1 - x - z + z_s) + \gamma \cos \omega t, \tag{1}$$

where z_s is the displacement of the sample surface from a reference position and

$$f(x) = \begin{cases} -\frac{\alpha}{x^2} & \text{for } x > a; \\ \beta(a - x)^{3/2} - \frac{\alpha}{a^2} & \text{for } x \leqslant a \end{cases} \tag{2}$$

with α, β constants. Here δ and a, respectively, represent the damping constant and non-dimensionalized intermolecular distance. See [13] for the details on the model (1). When $x < a$ in (2), the tapping mode operation occurs.

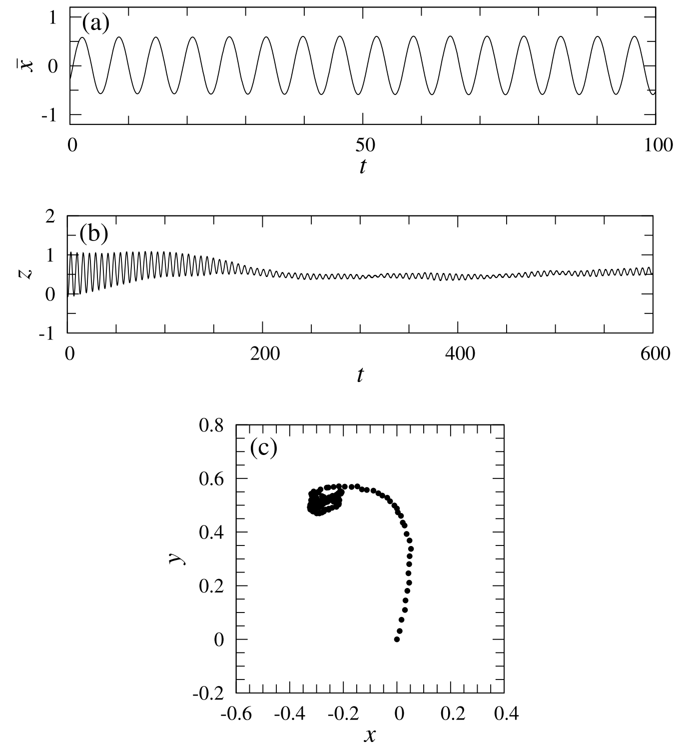

Fig. 3. Numerical simulation results under the influence of white noise with intensity of 0.01: (a) $\bar{x}(t)$; (b) $z(t)$; (c) Poincaré plots. The other parameter values are the same as in Fig. 2.

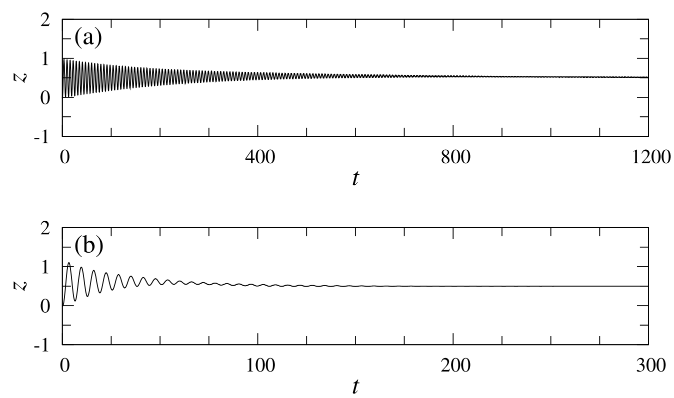

Fig. 4. Numerical simulation results for the center of the cantilever base oscillation, $z(t)$, for $\kappa = 1$, $z_s = 0.5$ and $\omega = 1$: (a) $\alpha = 5.5 \times 10^{-4}$, $\beta = 152$, $\delta = 0.01$, $\gamma = 0.005$ and $a = 0.038$; (b) $\alpha = 4.4 \times 10^{-3}$, $\beta = 107$, $\delta = 0.1$, $\gamma = 0.06$ and $a = 0.076$.

The reader may think that this model is too simple, especially because only one vibrational mode of the beam is used. However, such a model is widely used in studying microcantilevers of AFM and enables us to succeed in understanding their dynamics [4,6]. Recall the impressive agreement between experimental measurements and numerical computations for a similar model [9,10].

3. External feedback control

Now we describe our control approach for the microcantilever. We first obtain a periodic response of the cantilever tip as a reference one when the center of the cantilever base oscillation and the sample surface are at the reference positions, i.e., $z = z_s = 0$. This is an easy task unlike the chaos control case since the periodic orbit is stable. Here we do not require that the sample surface position is known. Let $\bar{x}(t)$ denote the reference response. If the

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