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# Influence of probe dynamic characteristics on the scanning speed for white light interference based AFM

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## ABSTRACT

The dynamic characteristics of an atomic force probe are important for rapid and accurate measurement in white light interference (WLI) based atomic force microscope (AFM). The tip of the probe will fly from the surface when its dynamic characteristics are poor, which will cause measurement error. Generally such tip flight can be avoided by reducing the scanning speed, which will decrease the error at the cost of measurement efficiency. In this paper, a dynamical model of atomic force probe is presented to analyze the causes of tip flight in the measurement process. A numerical simulation is performed on a typical sample surface to investigate the influence of profile, preloading and probe parameters on scanning speed. Experimental testing is conducted on a self-developed WLI based AFM, and the experimental results agree well with that of the theory. The maximum scanning speeds of the probe for a sample are tested under certain conditions. It is shown that for a certain probe, the tip flight occurs at the upwards points of the measured sample when the scanning speed exceeds the critical speed, which is constrained by the preloading.

## 1. Introduction

Atomic force microscope (AFM) plays an important role in the development of nanotechnology. The scanning speed and measurement accuracy of AFM are mostly related to the dynamic characteristics of the probe [1–3]. AFM has three measurement modes: contact mode, intermittent contact mode and non-contact mode, among which contact mode is the most widely used and the most efficient. In contact mode, there is vast amount of research concerning the dynamic response of AFM probe for general optical beam deflection (OBD) based AFM [4,5] The classical Hertzian contact model [6] assumed that the probe always keeps contact with the moving surface. The tip-sample model [7,8] indicated that the motion of the probe can be chaotic and the region in the space of physical parameters in which chaos exists was found. State feedback control is used to eliminate the possibility of chaos. Wang [9] has studied the effect of the cantilever slope on the sensitivity of the probe, showing that the angle between the cantilever and sample surface cannot be ignored, and the sensitivity decreases with the increase of the cantilever slope. The horizontal probe has the best sensitivity, by which samples can be measured with best results and minimal damage.

For WLI based AFM [10–12], white light interference is applied to detect probe deflection, which has a much larger measurement range and higher measurement efficiency than OBD based AFM in open-loop contact mode. As described by G.Binnig [13], AFM is a combination of scanning tunneling microscope (STM) and stylus profilometer. To some extent, the WLI based AFM is a miniature stylus profilometer, which has similar dynamic characteristics to a stylus profilometer during the measurement process. The main problem of such characteristics is the tip flight, which is a hot research topic in stylus profilometer. To improve measurement fidelity, Damir [14] studied the effects of stylus kinematics on tip flight without consideration of damping. Liu [15] developed an active damping control method to modify a stylus instrument and confirmed that the stylus instrument can obtain better working performance when the damping factor is in the region between 0.5 and 0.8, which matches the research results of Whitehouse [16,17]. Tian [18–20] built dynamic models and considered the Hertzian contact and nonlinear damping force to analyze the stylus flight problem. The works above have great significance for research on the tip flight of stylus profilometers.

To improve scanning speed and avoid tip flight in the measurement of WLI based AFM, this paper presents a dynamical model of the atomic force probe to analyze the causes of tip flight during measurement. Compared with the above models, this model combines the advantages of the OBD based AFM models and the stylus profilometer models. Due to the small measurement range of open-loop contact mode in OBD based AFM, there is no tip flight and the influence of scanning speed on

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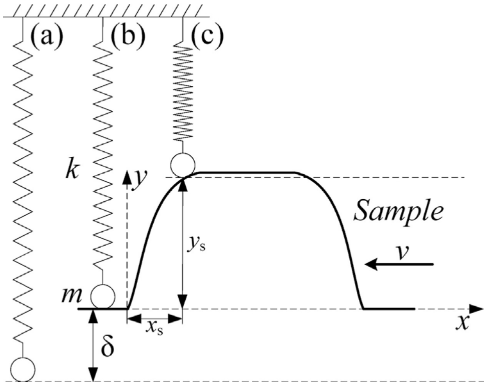

**Fig. 1.** The presented dynamic model of the probe during measurement.

actual measurement is not involved in the dynamic models. The stylus profilometer models consider the influence of scanning speed for tip flight, but WLI based AFM is fundamentally different from stylus profilometer. The measuring mechanism of the stylus is a rigid lever structure, while the atomic force probe is a flexible cantilever beam structure, thus the stylus profilometer models have much limitation for WLI based AFM. A numerical simulation was performed on a typical sample surface to investigate the influence of profile, preloading and probe parameters on scanning speed. Experimental testing was conducted on a self-developed WLI based AFM to verify theoretical results.

## 2. Dynamical model of atomic force probe

The atomic force probe used for WLI based AFM is a rectangular and elastic cantilever beam, which can be simplified as an equivalent mass-spring system. Fig. 1 shows the presented dynamic model of the probe during measurement. In the figure, $m$ is the equivalent mass and $v$ is the scanning speed. $k$ is the normal contact stiffness which is determined by the modal sensitivity $\beta$ and the free cantilever spring stiffness $k_0$ (without contacting the sample)[21]. Different states of the probe are displayed as (a), (b) and (c), respectively. In free state (a), the tip of the probe does not make contact with the sample and the cantilever of the probe has no deflection. In state (b), the tip of the probe makes contact with the sample and the deflection of the probe with preloading is $\delta$. In state (c), the probe scans a point ($x_s$, $y_s$) on the profile of the measured sample, and the deflection of the probe is $\delta + y_s$.

For measurement, the ideal situation is that the tip of the probe always makes contact with the sample and the tip moves up and down along the profile of the sample. Under these conditions, when the tip moves upwards or downwards, the friction force between the tip and the measured surface can be neglected for clarity, and the equation of tip motion can be expressed as follows:

$$\begin{cases} ma_\perp = F - k(\delta + y) - mg \\ a_\perp = \ddot{y} \end{cases} \tag{1}$$

where $a_\perp$ is the vertical acceleration of the tip, $\ddot{y}$ is the second derivative of the measured profile ($y = f(x)$). $F$ is the vertical reaction force between the tip and the measured surface.

Since tip flight does not occur, the velocity and the acceleration of tip motion are equal to the first derivative and second derivative of the measured profile, respectively. The relationship between the measured profile $y$ and the scanning speed $v$ can be expressed as:

$$\begin{cases} \dot{y} = \dot{x}f'(x) = vf'(x) = v_\perp \\ \ddot{y} = \dot{x}^2 f''(x) = v^2 f''(x) = a_\perp \end{cases} \tag{2}$$

where $v_\perp$ is the vertical speed of the tip, $\dot{y}$ is the first derivative of the measured profile ($y = f(x)$).

When the tip is out of contact with the measured surface, the separation occurs and the vertical reaction $F$ is reduced to zero. Assuming that the tip separates from the measured surface on the point ($x_s$, $y_s$), the conditions of separation can be derived from formula (1):

$$\begin{cases} ma_\perp = -k(\delta + y_s) - mg \\ 0 > a_\perp > \ddot{y} \end{cases} \tag{3}$$

As can be inferred from formula (3), separation will occur if the vertical acceleration of the tip is smaller in magnitude than second derivative of the measured profile and both of them are negative.

When the tip moves downwards and separation occurs, the vertical speed direction and acceleration direction of the tip are both downward, which will lead to separation only and no tip flight occurs. It is usually ignored due to the difficulty to obtain the actual profile. Thus tip flight may only occur when the tip moves upwards. When separation occurs, the vertical speed direction of the tip is upward and tip flight occurs, which makes apparent feature in the measurement results.

Suppose the path of the tip after separation is $h$, the equation of motion of the tip after separation is:

$$m\ddot{h} = -k(\delta + y_s) - kh - mg \tag{4}$$

The initial conditions of Eq. (4) are $h = 0$ and $\dot{h} = \dot{y}_s$ while $t = 0$. By solving Eq. (4) with initial condition, the path of the tip after separation is obtained as:

$$h = (\delta + y_s + \omega^{-2}g)\cos\omega t + w^{-1}vf'(x_s)\sin\omega t - (\delta + y_s + \omega^{-2}g) \tag{5}$$

where $\omega = \sqrt{k/m}$ is the natural frequency of the probe.

The maximum lift height of the probe after separation is determined by formula (5). The tip flight is associated with the profile of the measured sample, parameters of the probe, preloading and scanning speed.

## 3. Model based numerical analysis for tip flight

Since WLI based AFM is widely applied for grating measurement, a grating profile is established for model based numerical analysis about the influence of the profile, probe parameters and preloading on scanning speed, which is shown in Fig. 2.

According to the conditions under which tip flight occurs, tip flight may only occur while traveling upwards along the measured surface. The characteristics of the grating are periodic. The equation of the upwards profile of the grating can be expressed as:

$$y = al^{-2}[2l(x - nT + T) - (x - nT + T)^2] \tag{6}$$

where $a$ is the step height of the grating, $l$ is the width of the upwards of the grating, $T$ is the period width and $n$ is the number of periods.

According to formula (2), the variation velocity and acceleration of the measured surface can be obtained as:

$$\begin{cases} \dot{y} = al^{-2}v[2l - 2(x - nT + T)] \\ \ddot{y} = -2al^{-2}v^2 \end{cases} \tag{7}$$

It can be inferred from formula (7) that the second derivative of the measured profile is negative. Thus tip flight may occur. According to Eq. (3), the condition of tip flight occurring should satisfy the following equation:

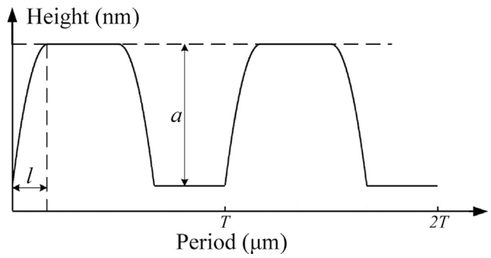

**Fig. 2.** The established profile of the grating.