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Real-time scan speed control of the atomic force microscopy for reducing imaging time based on sample topography

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ABSTRACT

Here, a novel method, real-time scan speed control for raster scan amplitude modulation atomic force microscopes (AM-AFMs), is proposed. In general, the imaging rate is set to a fixed value before the experiment, which is determined by the feedback control calculations on each imaging point. Many efforts have been made to increase the AFM imaging rate, including using the cantilever with high eigenfrequency, employing new scan methods, and optimizing other mechanical components. The proposed real-time control method adjusts the scan speed linearly according to the error of every imaging point, which is mainly determined by the sample topography. Through setting residence time on each imaging point reasonably, the performance of AM-AFMs can be fully exploited while the scanner vibration is avoided when scan speed changes. Experiments and simulations are performed to demonstrate this control algorithm. This method would increase the imaging rate for samples with strongly fluctuant topography up to about 3 times without sacrificing any image quality, especially in large-scale and high-resolution imaging, in the meanwhile, it reduces the professional requirements for AM-AFM operators. Since the control strategy employs a linear algorithm to calculate the scanning speed based on the error signal, the proposed method avoids the frequent switching of the scanning speed between the high speed and the low speed. And it is easier to implement because there is no need to modify the original hardware of the AFM for its application.

1. Introduction

The atomic force microscope (AFM) has been a powerful tool for obtaining the nano-characteristics of materials and cell biology since it was invented in 1986 (Binnig et al., 1986). However, the normal AFM needs several minutes to acquire the topographic information of samples (Fleming et al., 2010). The slow imaging rate limits its application in dynamical observation of living cells (Schitter et al., 2004), chemical reaction (Ichii et al., 2014), physical process (Fantner et al., 2006), and large-range surface inspection (Borionetti et al., 2004) within desired time.

The working principle of the AFM is based on the interaction force between the probe and the sample surface, and it is a kind of mechanical scan (Picco et al., 2007). That is to say, fast imaging rate requires fast motion of the sample or the probe. In recent years, many attempts have been developed to increase the imaging rate. They can be roughly divided into two types: optimization of components and new scan methods. In the first approach, the hardware including the cantilever, the scanner and the electronic system is improved to meet the demands for the fast imaging (Fantner et al., 2006; Herfst et al., 2015; Bozchalooi and Youcef-Toumi, 2014). Fantner et al. (2006) improved the performance of AFM components to record 30 frames per second at 150 × 150 pixels as early as 2006. However, due to its complexity implementation and the current industrial level, there is almost no breakthrough in fast-speed AFMs until now.

In the second approach, which is more generally adopted recently, new scan methods including optimized control methods are proposed to increase the scan speed. Yong et al. (2010) introduced a cycloid scan method to promote the scan rate to 156.25 Hz. Schitter et al. (2007) designed a scanner for a fast-speed AFM whose scan rate is up to 20 kHz. However there are special requirements for the controllers and the scanners, which limit wide-spread applications of these methods. Practically, the closed-loop feedback control (e.g. PID control) is utilized for maintaining the distance between the probe and the sample

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constant in the *Z*-direction, and the performance of the controller affects the quality of images greatly. However, the PID control will decrease the scan speed because it spends prolonged time to maintain the probe-sample distance constant. To accelerate the imaging rate, Zhou et al. (2010) built a high-speed AFM without Z-direction feedback control, and its scan rate is approximately 1.5 kHz. Nevertheless, the obtained image is serious distorted and loses fine structures of samples. Many advanced control methods, such as iterative learning control (Wu et al., 2008; Fang et al., 2014) and robust control (Wu and Zou, 2009), have been proposed to improve the imaging rate. Unfortunately, they do not make great improvements and they make the controller more complex.

Next, adaptive scan controls have been applied to the standard AFMs. Ren and Zou (2014) adjusted set-point value dynamically to increase the imaging rate up to 30 folds by introducing iterative feedforward control, but it is only effective for samples with strong stiffness imaged by contact-mode AFM and needs a continuous tip-sample contact which is difficult to achieve at the edge of decline. Ahmad et al. (2014) and Wang et al. (2015) respectively presented an easier technique upon control error to improve the imaging rate of the amplitude modulation atomic force microscopy (AM-AFM). However, the introduction of sharp scan speed variations between the high speed and the slow speed will lead to noticeable vibrations of piezoelectric scanner because of the excessive acceleration or deceleration. This phenomenon can be observed where the mechanical resonance of the piezoelectric scanner is excited when a fast triangular waveform is applied in high-speed raster scan (Croft et al., 2000; Mahmood et al., 2011; Rana et al., 2014). Therefore, the algorithm will give wrong error value, and the scan speed will stay low even in flat area after the speed switch. Here, a control strategy employing a linear algorithm to calculate the scanning speed based on the error signal is proposed to solve the problem. Compared with the Ahmad et al.'s method, the method avoids frequent switching of the scanning speed between the high speed and the low speed. In comparison with the Wang et al.'s method, the proposed method is easier to implement because there is no need to modify the original hardware of the AFM for its application.

In the present study, we have developed a simple, reliable, and rapid real-time scan speed control method for AM-AFMs. This method can increase the imaging speed of AM-AFMs and further improve the image quality while the vibrations of piezoelectric scanner can be avoided during scan speed change. The structure diagram of the real-time scan speed control AM-AFM is depicted in Fig. 1. In our method, the scan speed is changed linearly according to the error of every imaging point under the premise of guaranteeing the quality of image. That is to say, the imaging time is determined by the AFM itself according to the sample, and the exact scan speed does not need to be set by operators. Adjusting the scan speed based on the tracking error properly can optimize the imaging process of the AFM to reduce the imaging time without any image quality sacrificed. The simulations and experiments show that the real-time scan speed control method would achieve the ideal tracking and take advantages of the hardware performance of AFMs. Furthermore, it will reduce professional requirements for AFM operators, avoid probe crash and protect the sample effectively.

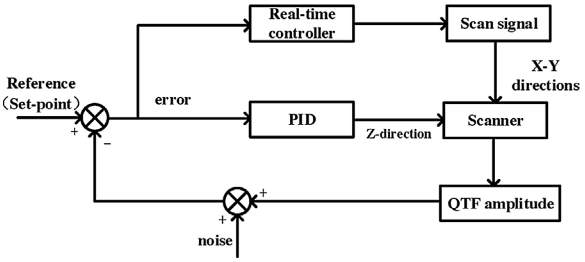

Fig. 1. The structure diagram of the real-time scan speed control AFM.

2. Formulation of the problem

Generally, the imaging rate is limited by the speed of the feedback controller that maintains a constant tapping amplitude for an AM-AFM (Sulchek et al., 2002). In order to achieve good imaging performance, the normal AFM is designed to scan at a constant speed, which is relatively easy to implement. The constant speed should be carefully set to balance the imaging rate and the imaging performance. When the scan speed increases, the average time that a probe stays on a single point decreases. For an AM-AFM, assuming that the probe tracks a smooth sample and the tracking error is negligible, the maximum scan speed v_{m1} is determined by the *Z*-direction resolution of the AFM and the bandwidth of the feedback system, which can be expressed as Ando et al. (2008)

$$v_{\mathrm{m1}} = f_{\mathrm{bw}} \cdot \Delta z, \tag{1}$$

where Δz is the resolution in the *Z*-direction, and f_{bw} is the bandwidth of the feedback system. When the probe scans upon a sample with fluctuant topography, the maximum scan speed must be less than v_{m2} (Sulchek et al., 2002)

$$v_{\mathrm{m2}} = \frac{(a_{\mathrm{free}} - a_{\mathrm{set}})[1 - \exp(-w_0 T/2Q)]\tan(\alpha)}{T}, \tag{2}$$

where a_{free} is the air-free amplitude of the cantilever, a_{set} is the set-point amplitude, w_0 is the air-free resonance frequency of the cantilever, Q is the effective quality factor of the cantilever, T is the oscillation cycle, and α is the cone of the probe. Eqs. (1) and (2) give the fastest scan speeds of AFMs in the smooth area and strongly fluctuant area, respectively. This means that AM-AFMs can scan different areas with variable speeds to shorten the imaging time without any sacrifice of image quality. Therefore, for a smooth area where the control error is small, increasing scan speed below v_{m1} would not lead to degradation of the imaging performance. For a strong fluctuant area where the error may be large, AFM needs to slow down to ensure the image quality. In this case, the scan speed is no more than v_{m2}.

To further study the influence of scan speed on different imaging area, we image a one-dimensional standard grating at different scan speeds. In Fig. 2, different imaging speeds are conducted and the imaging results at the scan lines (red horizontal lines) are compared in Fig. 2(e). The topography of the one-dimensional standard grating can be divided into two areas, one is the edge of a step which will cause a large tracking error, and another is the flat part of a step which leads to a small tracking error. In Fig. 2(e), different scan speeds lead to different performances in these two areas. In the flat part, there is no significant difference of imaging results, which means that a faster scan speed can be applied. However, when scanning the edge of the step, as the scan speed increases, the image quality is significantly decreased. Since different areas needs different scan speeds, imaging samples at a constant rate will result in a waste of time, especially upon a large sample. Therefore, it needs a speed adjustment mechanism to determine the scan speed dynamically according to the error.

3. Principle of the real-time scan speed method

From Section 2 we know that it is difficult to keep tracking a sample with different fluctuant topography well at a constant high speed. Therefore, it is required to balance the imaging rate and the image quality when imaging is performed by the normal AFM, which needs professional operation. This balance operation requires expert experience, thus it limits the wide application and promotion of AFMs. In order to characterize the sample as accurate as possible, the scan speed of the normal AFM is set according to the most fluctuant area, while it will be a great waste of time resources for the smooth area. To overcome this shortage, a real-time scan speed controller is presented to adjust the scan speed, as presented in Fig. 3. The actual scan speed could be set automatically according to the initial control error on every