Instrumentation Science and Technology, 41:394–405, 2013

ISSN: 1073-9149 print/1525-6030 online
DOI: 10.1080/10739149.2012.757740

A PRACTICAL DYNAMIC IMAGING METHOD FOR FAST-SCANNING ATOMIC FORCE MICROSCOPY

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□ *For atomic force microscopy (AFM), fast scanning usually results in low imaging resolution, which leads to inaccurate sample topography reconstruction. Based on the analysis for the experimental step-response of AFM, a practical dynamic imaging method is proposed in this article to enhance measurement performance under fast scanning speed. Specifically, the experimental step-response is employed to obtain the transient displacement of the piezo-actuator in the Z-axis, which is then utilized, together with the control error, to calculate the topography of the detected sample surface. As no model is required to enable this algorithm, it presents such advantages as easy implementation and reliable imaging results. Some experimental results are included to demonstrate the superior performance of the proposed imaging method.*

Keywords atomic force microscopy (AFM), dynamic imaging method, fast scanning tasks, piezo-actuator, step-response

INTRODUCTION

The invention of an atomic force microscopy (AFM)[1] brings a great revolution in the field of nano-science and nano-technology.[2] Compared with other nano-imaging instruments, AFM can measure various types of samples under different environments, such as ultra-high vacuum (UHV), air, and liquid.

In an AFM system, a sample is scanned with a very sharp tip mounted on the free end of a micro-cantilever. The tip-sample interaction force is regulated to remain constant in a feedback loop. During the scanning process, the control input exerted on the piezo-actuator and the output from

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the laser detector are analyzed to reconstruct the topography of the sample surface. For an AFM system, imaging resolution and scanning speed[3,4] are the foremost topics that current researchers focus on. Specifically, to supervise some chemical or biological processes on-line,[5] high scanning speed is needed without much compromise on imaging resolution. Unfortunately, at present, nano-resolution can be obtained only under comparatively low scanning speed. Based on this fact, many efforts have been devoted to improving the scanning speed without sacrificing image accuracy. In general, there are three main approaches: (1) adopting a piezo-actuator with high resonant frequency for three-axis positioning, so that to enhance scanning speed by shortening response time;[6–8] (2) employing a scanner consisting of an array of cantilevers to operate in a parallel fashion[9,10] to fasten the scanning process; and (3) proposing more effective control strategies[11–16] or imaging methods[17–20] to fulfill high speed scanning and high resolution topography reconstruction. The methods of (1) and (2) are related to the modification of hardware, which unavoidably increase the cost and complexity of AFM systems, and are thus hard to implement. Based on this observation, this paper aims to design an advanced imaging method to obtain more accurate reconstruction of sample surface for fast scanning tasks.

As shown in Schitter et al.,[17] the dynamic characteristics of the piezo-actuator are the main limitations on the scanning speed/resolution of an AFM. Generally, the current imaging method usually does not consider about the dynamic characteristics of the piezo-actuator, it tries to image the topography in a static manner which will be stated later. In such a manner, accurate topography reconstruction can be only obtained for low-speed scanning tasks when the positioning control in the Z-axis is good enough so that the cantilever tip follows well with the topography of the detected sample surface. However, as the scanning speed increases, the situation becomes more and more dire, since the piezo-actuator can no longer reach steady-state at most scanning points. Due to this reason, if the dynamic characteristics of the piezo-actuator are still ignored, the obtained topography will be seriously distorted from the real sample surface.

Based on the drawbacks of current Atomic Force Microscopy (AFM) systems, the topic of how to propose suitable imaging method to obtain more accurate topography reconstruction under fast scanning speed has recently become one of the research focuses for an AFM. Among the reported results, the dynamic character of piezo-actuator is firstly considered in the interesting imaging method designed in Schitter et al.[17] In Han and Chung'[18] a topography reconstruction strategy is designed which considers the creep effect of piezo-actuator in the Z-axis. In Salapaka et al.,[19] a robust control based observer is designed for the topography reconstruction. In Kuiper et al.,[20] a robust control strategy in feedback loop is designed, together with some imaging method, to obtain reliable image under the effect of detection noise and model uncertainties. It should be pointed out that the forementioned methods usually utilize the model of the piezo-actuator to enhance imaging performance, yet it is practically difficult to obtain an accurate model for such a nonlinear system as an AFM. Besides, the identified model, as an approximator for the behavior of the piezo-actuator, loses many high-frequency characteristics of the piezo-actuator, which then decreases the accuracy of imaging results. Based on this observation, a practical convenient dynamic method is proposed in this article, which directly utilizes the experimental step-response characteristics of the piezo-actuator, instead of an identified transfer function, to enable reliable imaging under fast scanning speed. Compared with currently existing methods, the proposed approach is much easier to implement, and it achieves accurate topography reconstruction even in fast-scanning tasks, which is convincingly supported by numerous experimental results.

The remainder of this article is organized as follows. In the next section, the current static imaging method is described, whose flaw is vividly analyzed. Subsequently, the proposed experimental step-response based dynamic imaging method is introduced in detail and some experimental results for calibration gratings and biological specimen are provided to demonstrate the performance of the proposed imaging method. Then following is concluded.

STATIC IMAGING METHOD AND ITS DRAWBACKS

Contact mode and tapping mode[21] are the commonly utilized scanning ways of an AFM. For the brevity of description, only contact mode is considered to design the novel dynamic imaging method, yet most of the discussions are also valid for a tapping mode AFM, and it is not of much difficulty to extend the proposed imaging method to other scanning modes.

In the contact mode, the relationship between the probe and the detected sample is shown in Figure 1. During the scanning process, the

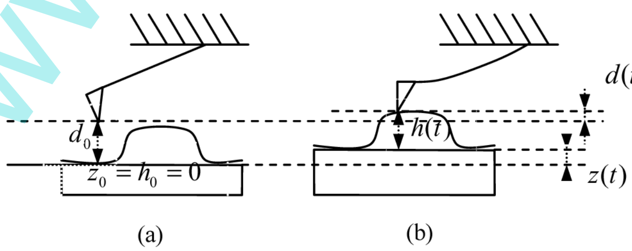

FIGURE 1 The relationship between the probe and the detected sample (a) before the scanning (b) during the scanning process.

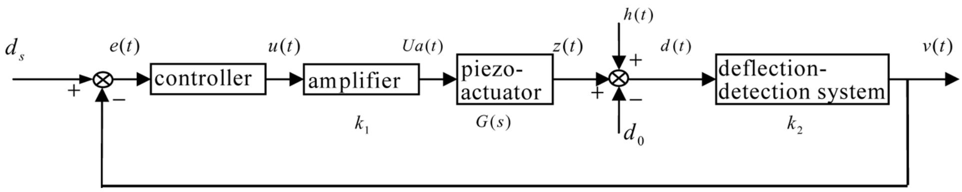

FIGURE 2 Signal flow graph of the AFM system on the Z-axis.

X, Y, Z displacements of the sample are all provided by the piezo-actuator attached with the base where the sample is put on. Figure 1a shows the situation when the probe has been driven sufficiently near the sample for the scanning, with d_0 denoting the initial separation from the probe to the sample surface. For brevity, the initial displacement of the piezo-actuator in the Z-axis and the height of the sample surface are both assumed to be 0 as $z_0 = 0$, $h_0 = 0$. Figure 1b describes the relationship at some scanning moment t with the displacement of the piezo-actuator denoted as $z(t)$, the height of surface as $h(t)$, and the deflection of the probe as $d(t)$.

Figure 2 shows the signal flow graph of the AFM system in the Z-axis, where $G(s)$ is the dynamic characteristic of the piezo-actuator, $u(t)$ is the control input calculated from the controller, $U_a(t)$ is the amplified control signal exerted on the scanner, $v(t)$ is the feedback signal from the laser detector, and $e(t)$ is the control error between the setpoint and the feedback signal. The signals of $z(t)$, $h(t)$, $d(t)$ are defined the same as those in Figure 1. It is a generally known fact that the response of the piezo-actuator is far slower than that of the power amplifier and the deflection-detection system, thus the dynamic behavior of the piezo-actuator is the bottleneck for fast scanning. Due to this reason, the dynamics of the amplifier and the deflection-detection system are ignored and they are regarded as static components, whose gains, denoted as k_1 and k_2 respectively,[17] can be measured through experiments.

From Figure 2, the following equation can be obtained:

$$d_s - k_2(z(t) + h(t) - d_0) = e(t), \tag{1}$$

where d_s is the setpoint for the control. Based on the operating principle of the AFM, the topography of the sample can be obtained as:

$$h(t) = -(z(t) + e(t)/k_2) + d_0 + d_s/k_2. \tag{2}$$

Furthermore, as $d_0 + d_s/k_2$ is a constant, and it does not affect the relative fluctuation of the sample surface, it is removed from the expression and the following formula is usually adopted to calculate the sample surface topography:

$$\hat{h}(t) = -(z(t) + e(t)/k_2). \tag{3}$$

Unfortunately, the displacement of the piezo-actuator $z(t)$ cannot be detected directly, and it needs to be obtained from other signals. In the current static imaging method, the dynamics of the piezo-actuator is completely ignored, and the displacement $z(t)$ is approximated as follows:

$$z(t) \ = k_1 k_s u(t), \tag{4}$$

where k_s is the static gain of the piezo-actuator, which can be obtained through experimental studies by the following steps:[22] with the feedback turned on, a calibration grating is scanned slowly enough to ensure that the piezo-actuator will reach steady-state in almost each scanning point, then the static gain k_s can be calculated from the relationship between the control input and the nominal height of the grating.

After substituting (4) into (3), the static imaging method calculates the sample topography as follows:

$$\begin{aligned}\hat{h}(t) &= -(k_1 k_s u(t) + e(t)/k_2) \\ &= k_1 k_s(-u(t) - e(t)/(k_1 k_2 k_s))\end{aligned}. \tag{5}$$

It can be seen from the previous analysis that the performance of the static imaging method largely depends on the accuracy of Equation (4). For slow-speed scanning, the piezo-actuator reaches steady-state for most scanning points, thus Equation (4) is satisfied, and the obtained results from static imaging method provide an accurate reconstruction for the sample topography. However, for fast scanning, the piezo-actuator can not reach steady-state, thus its displacement $z(t)$ cannot be accurately described as $k_1 k_s u(t)$ any longer, for this reason, the topography cannot be well reconstructed through the static imaging method.

EXPERIMENTAL STEP-RESPONSE BASED DYNAMIC IMAGING METHOD

According to the analysis, it is preferred to use the displacement $z(t)$ to reconstruct the topography rather than the control input $u(t)$. Therefore, model based method is the main approach to obtain the displacement $z(t)$.

However, model identification for the piezo-actuator is a complicated task, for which high frequency dynamics is usually ignored, which finally degrades the quality of the reconstruction for the topography.

When considering the short-range extension/contraction behavior along the Z-axis, the piezo-actuator can be approximated as a linear element, whose displacement can be regarded as the comprehensive effect of the control inputs in a sufficiently long interval. From signal analysis theory, we know that the step-response of a linear system can be used to calculate the corresponding output by convolving it with the control inputs, and it successfully avoids the shortage of losing high frequency dynamics when employing identified models. Therefore, the experimental step-response of the piezo-actuator is utilized as the dynamic characteristics to calculate its displacement. To obtain the experimental step-response of the piezo-actuator, a step input $U_a(t)$ is exerted on the actuator and the output signal $v(t)$is then detected in an open loop. Considering the internal/external disturbances and measurement noise, numerous repetitive trials have been implemented to collect enough data and the average response from $U_a(t)$ to $z(t)$ is obtained after some analysis, with the resulting curve plotted in Figure 3. The experimental step-response is compared with the step-response of the identified model in Zhou et al.,[22] a transfer function. It can be seen that the high-frequency dynamics is inevitably neglected in the identified model, which degrades the performance of topography reconstruction, while the dynamics is preserved integrally in the experimental step-response. Then the experimental step-response is sampled and denoted as $s(n\Delta)$ where Δ is the sampling interval, $n \in \{1, 2, 3, \ldots, N\}$ with N being the number of total samples.

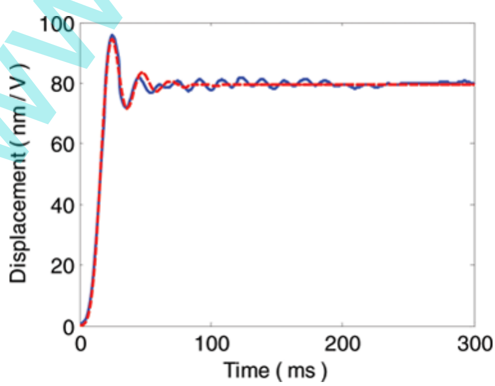

FIGURE 3 Experimental step-response (blue solid) and the step-response of the identified model (red dashed) for the piezo-actuator. (color figure available online.)

Therefore, the transient displacement can be obtained by convolving the experimental step-response with the control inputs as follows:

$$z(n\Delta)=\begin{cases}\sum_{i=1}^{n}k_1(u(i\Delta)-u((i-1)\Delta))\cdot s((n+1-i)\Delta) & n\le N\\ k_1\cdot u((n+1-N)\Delta)\cdot s(N\Delta) & \\ +\sum_{i=2}^{N}k_1(u((n+i-N)\Delta)-u((n+i-N-1)\Delta)) & n>N\\ \cdot s((N+1-i)\Delta) & \end{cases}, \tag{6}$$

where the initial condition u(0)is set as: u(0) = 0. z($n\Delta$) and u($n\Delta$) stand for z(t)and, u(t) respectively, at the n-th sampling instant. Therefore, Equation (3) for surface topography reconstruction can be modified as:

$$\hat{h}(n\Delta)=\begin{cases}-\sum_{i=1}^{n}k_1(u(i\Delta)-u((i-1)\Delta))\cdot s((n+1-i)\Delta)-e(i\Delta)/k_2 & n\le N\\ -k_1\cdot u((n+1-N)\Delta)\cdot s(N\Delta) & \\ -\sum_{i=2}^{N}k_1(u((n+i-N)\Delta)-u((n+i-N-1)\Delta)) & n>N\\ \cdot s((N+1-i)\Delta)-e(i\Delta)/k_2 & \end{cases}, \tag{7}$$

where $\hat{h}$(nΔ) and e($i\Delta$) stand for $\hat{h}$(t) and e(t) at the n-th and i-th sampling instant, respectively. Subsequently, the surface topography can be calculated from the control input u($i\Delta$), control error e($i\Delta$), and recorded experimental step-response sequence of s($i\Delta$).

The change of cantilever or sample will bring some uncertainties into the AFM system. It mainly affects the deflection-detection gain k_2. However, as k_2 is measured from the force-distance curve before each experiment, this uncertainty will not degrade the performance of the proposed imaging method. Furthermore, the step-response dynamics of the piezo-actuator is always stable enough, which implies that the proposed imaging method is sufficiently robust for topography reconstruction.

The advantage of this experimental step-response based dynamic imaging method is that it avoids the complicated process of modeling the practical system and overcomes the shortage of losing high-frequency dynamics when identified models are employed.

EXPERIMENTS AND APPLICATIONS

To demonstrate the performance of the proposed dynamic imaging method, some experiments are conducted on an AFM system which is composed of a commercial AFM apparatus (CSPM4000, Being-Nano Inc., P.R. China), high-performance cantilevers (CSC21/Cr-Au, μ Masch Inc., USA), and a self-developed RT-Linux based real-time control platform, with the control period set as 50 μs, equivalent to a wide control bandwidth of 20 kHz. The feedback control law is selected as the commonly utilized proportional-integral (PI) controller with well-tuned parameters.

Firstly, a calibration grating (μ Masch Inc., USA) with nominal height of 84 nm ± 1.5 nm and period of 3 μm is selected as the sample. It is scanned at the speed of 10 Hz, 25 Hz, and 50 Hz line frequency, respectively, with the scanning scope set as 10 μm × 10 μm, and the image resolution as 200 × 200 pixels. Under different scanning frequencies, one-line topography is plotted in Figure 4, respectively, with the corresponding control input $u(t)$ provided in Figure 5. The topography obtained from the proposed dynamic imaging method is obviously in accordance with the actual calibration grating. It successfully avoids the overshoot-like distortion presented in the results from current static imaging method, and the calculated floor height is around the nominal 84 nm. Even for fast scanning, when the control input in Figure 5c can no longer follow well with the sample surface profile, the obtained image still provides a decent description for the topography of the grating. Figure 6 shows the obtained image from the scanning task of 50 Hz line frequency. To enable comparison, Figures 6a and 6b provide the results of the proposed dynamic imaging method and the current static imaging method, respectively. As clearly demonstrated from Figure 6, the proposed dynamic method achieves superior performance over current methods.

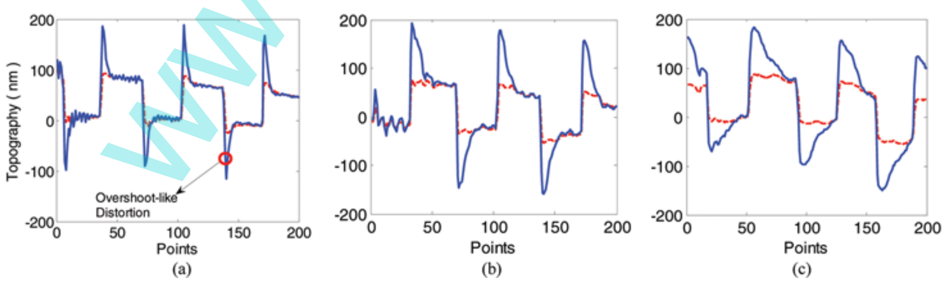

FIGURE 4 One-line topography reconstruction for calibration grating by static imaging method (blue solid) and dynamic imaging method proposed in this article (red dashed): (a) 10 Hz, (b) 25 Hz, and (c) 50 Hz. (color figure available online.)

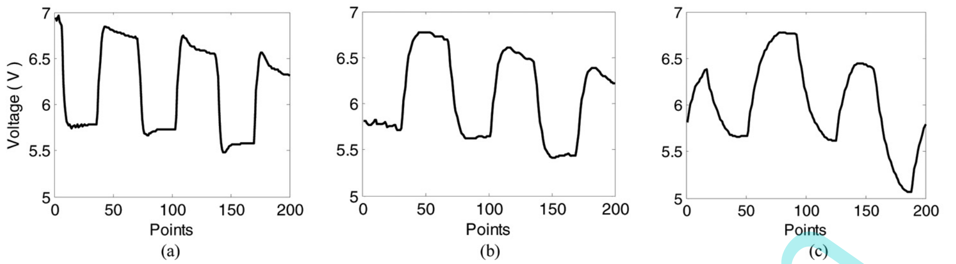

FIGURE 5 One-line control input voltage corresponding to the cases in Figure 4: (a) 10 Hz, (b) 25 Hz, and (c) 50 Hz.

The proposed imaging method is further employed to scan a biological specimen of *E. Coli* bacillus in air. The scanning scope is still set as 10 µm × 10 µm, and the image resolution is 200 × 200 pixels. In Figure 7, the specimen is scanned at the speed of 5 Hz. As analyzed before, the results of static and dynamic imaging methods are almost identical at low scanning speed. Both Figures 7a and 7b can be regarded as the true topography of the specimen surface. The specimen is then scanned at the high speed of 50 Hz to see the difference. As shown in Figure 8, the results obtained from the two imaging methods are obviously different. It can be seen that the result of dynamic imaging method is much more similar to the true topography plotted in Figure 7, while the result in Figure 8b has been distorted seriously.

According to the working principle of the dynamic imaging method, it will be effective as long as the experimental step-response is reliable. All the

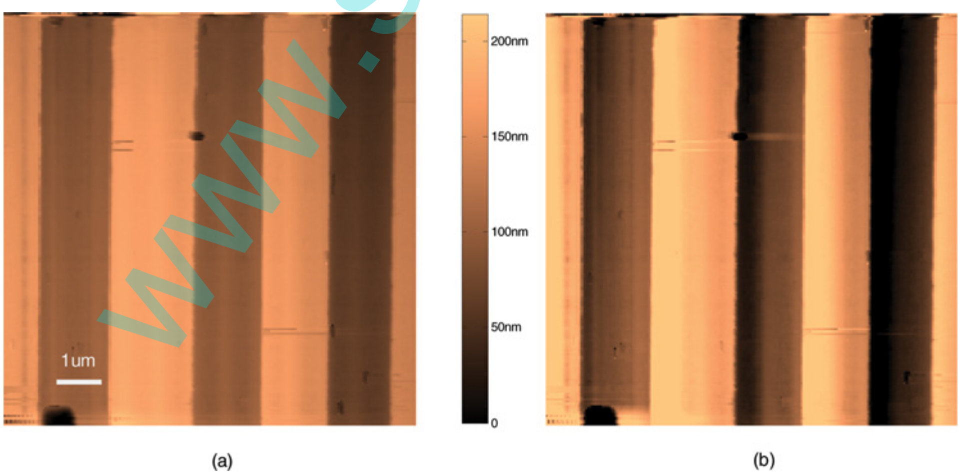

FIGURE 6 50 Hz scanned image of calibration grating: (a) dynamic imaging method and (b) static imaging method. (color figure available online.)

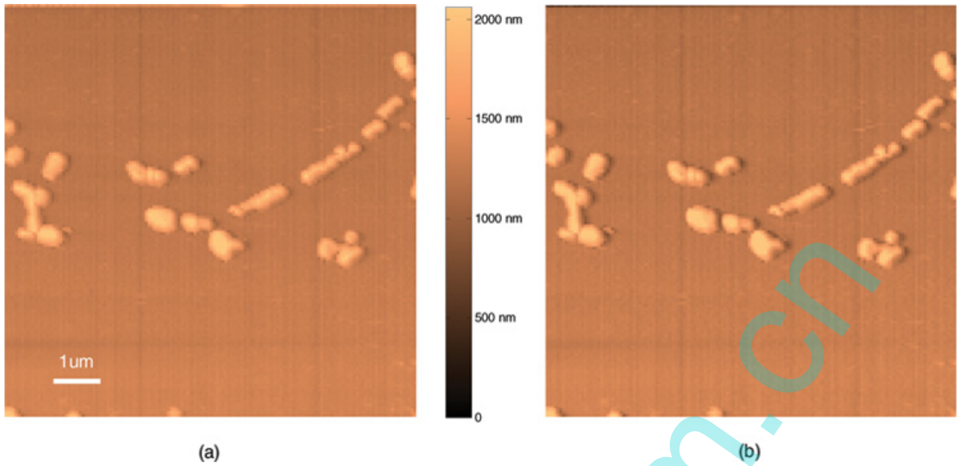

FIGURE 7 5 Hz scanned image of *E. Coli* bacillus specimen: (a) dynamic imaging method and (b) static imaging method. (color figure available online.)

experimental results shown in this article are conducted in air ambient. If conducted in the liquid circumstance, the resonant frequency, and damping coefficient of the piezo-actuator will be changed, and the experimental step-response will be different accordingly, yet it is still available and reliable for the implementation of the proposed practical dynamic imaging method. In this sense, it is not difficult to apply the proposed dynamic imaging method to the scanning tasks in liquid environment.

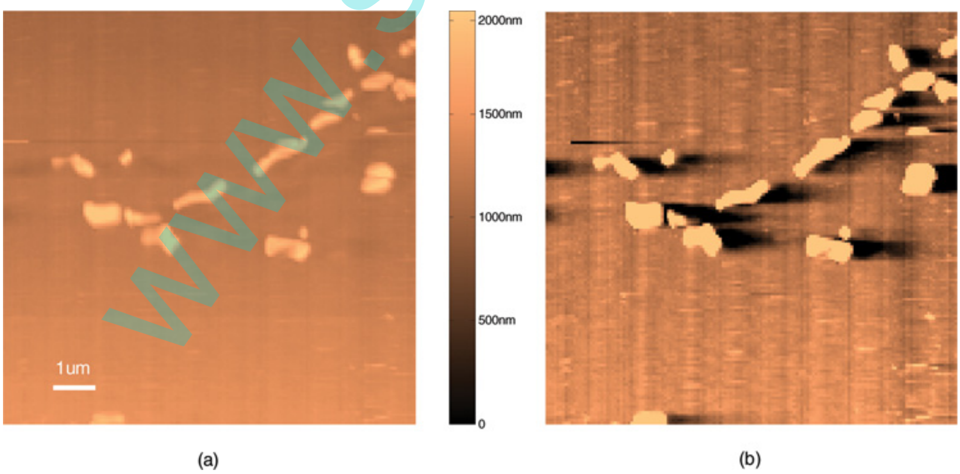

FIGURE 8 50 Hz scanned image of *E. Coli* bacillus specimen: (a) dynamic imaging method and (b) static imaging method. (color figure available online.)

CONCLUSIONS

In this article, a practical experimental step-response based dynamic imaging method is proposed for AFM to enhance its imaging performance for fast scanning tasks. That is, the experimental step-response is utilized for the description of the dynamic characteristics of the piezo-actuator. The transient displacement of the actuator is obtained from the step-response, which is then combined with the control error to reconstruct the topography of a sample. The efficacy of the proposed experimental step-response based dynamic imaging method is firstly verified by the experimental results of scanning a calibration grating. After that, the proposed dynamic method is utilized to scan a biological specimen of *E. Coli* bacillus, and the obtained results further indicate that the designed method provides very accurate description for the actual topography of sample surface, even for high-speed scanning tasks.

ACKNOWLEDGMENTS

This work was supported by the Special Fund for Basic Research on Scientific Instruments of the Chinese National Natural Science Foundation (61127006).

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