ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2011, Vol. 75, No. 1, pp. 9–11. © Allerton Press, Inc., 2011.
Original Russian Text © I.M. Malovichko, A.Yu. Ostashenko, S.I. Leesment, 2011, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2011, Vol. 75, No. 1, pp. 14–17.

A Phase Compensating Inverse-Dynamics Method for High-Speed AFM Imaging

I. M. Malovichko[a, b], A. Yu. Ostashenko[a], and S. I. Leesment[a]

[a] *NT-MDT Co. Building 100, Zelenograd, Moscow, 124482 Russia*
[b] *Moscow Institute of Physics and Technology, Dolgoprudny, 141700 Russia*
e-mail: ivantuss88@ya.ru

Abstract—We examine the problem of the low velocity of AFM scanning and suggest a method to increase scanning velocity considerably. Our method exceeds existing analogous methods and allows us to examine damageable samples. Corresponding experimental results are presented.

DOI: 10.3103/S1062873811010175

INTRODUCTION

Increasing the scanning velocity of AFM is an important task in scanning probe microscopy (SPM), now in great demand in biology, microelectronics, and other fields. Investigated objects often change, move, and are often easily destroyed. During the investigation of similar samples by means of SPM, an important condition for successful results is increasing the scanning speed. At the same time, the force of the probe on the sample must not increase. The aim of the work is to solve this problem.

WELL-KNOWN METHODS FOR INCREASING THE SCANNING VELOCITY OF AFM

There are many methods that allow us to deal with image distortions caused by delays in the feedback circuit and with the resonances of the z-scanner, e.g., image reconstruction (which uses a mismatch error signal [1]), and predictive control [2, 3].

In the first method, the mismatch error signal is recorded in addition to the voltage signal on the z-scanner during the scanning process. By adding the mismatch error signal multiplied by a normalization factor to the signal voltage on the z-scanner, we can improve the obtained image (especially in areas of sharp changes in height). The main drawback of this method is that the form of the control signal remains unchanged. The overall effect is achieved by the subsequent treatment of the data received during a normal scan. As a result, the force on the sample increases unduly with an increase in the scanning sweep frequency.

Predictive control involves the formation process of the signal that controls the z-scanner. A so-called predictive control signal is added to the output signal of the SPM feedback circuit. The predictive control signal equals the signal voltage applied to the z-scanner when moving from the previous scanning line. A memory block is used to store the control signal array applied in moving from the previous scanning line (Fig. 1). The feedback thus processes only the change in the relief of the line, compared to the relief of the previous line. Our method is based on predictive control.

Figure 1 shows a block diagram of the predictive control method.

Line-by-Line Feedback Support

It is possible to improve predictive control by using the mismatch error signal recorded at the previous line. Arrays of the values of the control signal and mismatch error signal are stored in two memory blocks (Fig. 2) and used when moving to the next scan line. In this case, the predictive control signal is formed as the sum of the control signal and the correction provided by the presence of the mismatch error. Correction is in the form of a mismatch error signal multiplied by the

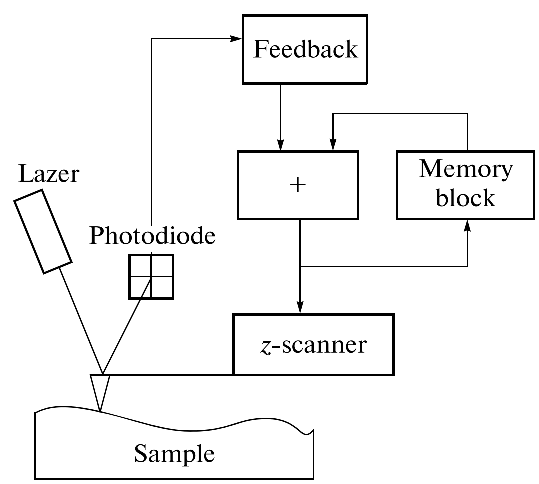

Fig. 1. Basic diagram of predictive control method.

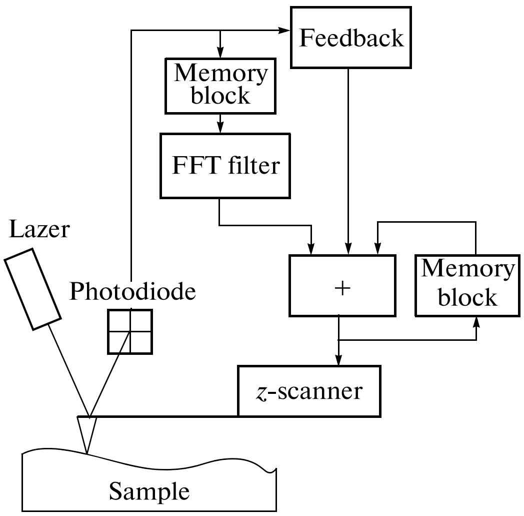

Fig. 2. Basic diagram of improved predictive control method.

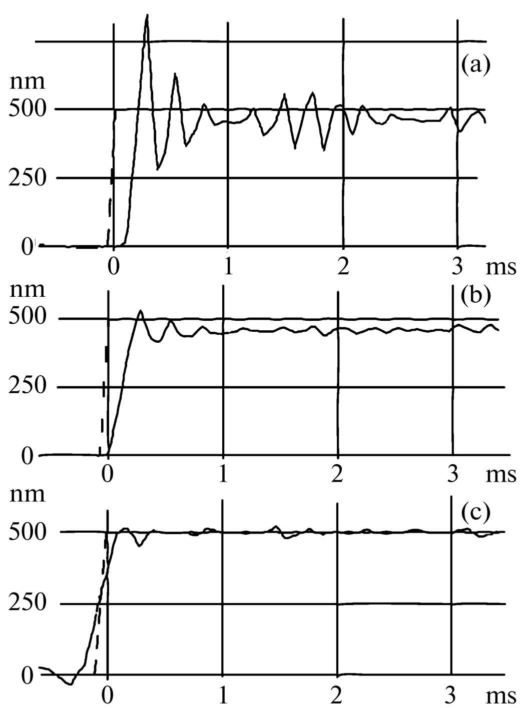

Fig. 3. Applying the results of the inverse frequency characteristic method. The dashed line represents the control signal; the solid line shows the scanner's response to a control signal (a) without filtering of the control signal, (b) with the usual filtering, and (c) with FFT filtration.

normalization factor. The correction of the control signal by means of the mismatch error signal allows the tracking of relief changes from line to line. In essence, this ensures line-by-line feedback support.

This approach allows us to use the algorithms that process the arrays of voltage on the z-scanner and the mismatch error signal obtained in the previous scan line for the formation of the control signal. One example of such an algorithm is the implementation of the phase-compensating method of inverse dynamics described below.

IMPLEMENTATION OF THE PHASE-COMPENSATING METHOD OF INVERSE DYNAMICS

The line-by-line feedback support can be improved by applying inverse dynamics implemented as a frequency filter [4, 5]. The essence of this method is to improve the frequency characteristics of the filter–scanner by adding a frequency filter to the control circuit of the scanner. Once we begin using an array of mismatch error signals for the formation of predictive control signal, it becomes possible to use a fast Fourier transform (FFT) filter [6] as a frequency filter. An FFT filter works as follows: the Fourier transform of the input array is multiplied elementwise by an array that specifies the frequency characteristic of the FFT filter, and the result is subjected to an inverse Fourier transform. Each time before moving on to the next scan line, the array of the mismatch error signal stored in the memory block is filtered (Fig. 2). The use of such a filter for inverse dynamics offers advantages over that of conventional difference filters. The well-known method of inverse dynamics, implemented as a difference filter included in the regular feedback circuit, allows us to improve only the amplitude and frequency characteristics (AFCs) of the filter–scanner system, while the phase–frequency characteristics (PFCs) are not improved and even grow worse [7]. Use of the FFT filter allows us to arbitrarily change not only the AFCs but the PFCs of the filter–scanner system as well. This property of the FFT filter is reflected in the name of the phase-compensating method of inverse dynamics.

Figure 2 shows a block diagram for implementing the phase-compensating method of inverse dynamics.

EXPERIMENTAL

Our method was applied on an Ntegra Prima scanning AFM (NT-MDT, Zelenograd) using the accompanying software.

The efficiency of the FFT filter using is illustrated in the Fig. 3. When the probe of the microscope malfunctioned, a control signal of rectangular shape was sent to the filter–scanner system and the response of the mismatch error signal was recorded. We can see that the delay in the response virtually disappeared as a result, and overcontrol was reduced considerably.

Thanks to the phase-compensating method of inverse dynamics, we can substantially improve the scanning velocity without a noticeable increase in the force on the sample. A series of measurements with different methods of z-scanner control were performed. A TGZ2 gauge lattice with the following characteristics was chosen as the test sample: a lattice in the

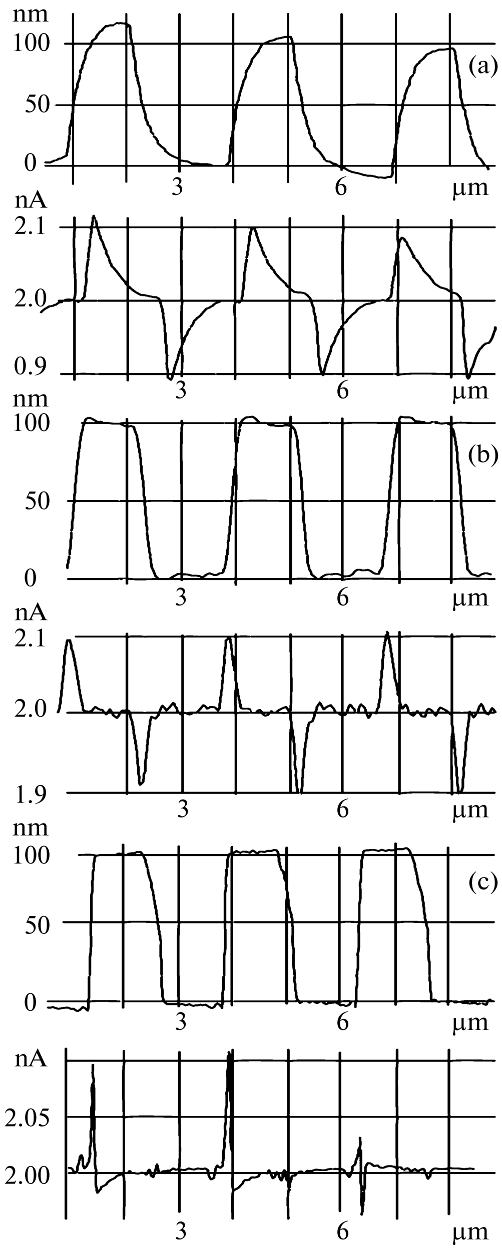

Fig. 4. Relief and mismatch error signal obtained by the scanning of the TGZ2 lattice: (a) the usual scan (scan velocity, 5 Hz); (b) predictive control method (scan velocity, 10 Hz); (c) phase-compensating method of inverse dynamics (scan velocity, 15 Hz).

form of longitudinal rectangular steps 108.5 nm in height and a 3 μm period made of silicon dioxide. The lattice was oriented such that the fast scan axis was perpendicular to the steps. Figure 4 shows the relief and the mismatch error signal obtained by the scanning of the TGZ2 gauge lattice using three different methods of scanning control. We can estimate the probe force on the sample by the value of the mismatch error signal. Figure 4 shows that the peaks on the curve of the mismatch error signal become lower and substantially shorter in time, while the fronts of the lattice step relief become steeper. In the usual method of scanning and in scanning by predictive control with sweep frequencies of 5 and 10Hz, respectively, we observe considerable front blurring of the relief of lattice steps and an unacceptable increase in the magnitude of the force on the sample. The relief obtained by phase-compensating method of inverse dynamics was recorded at the highest scanning frequency sweep of 15 Hz. The shape of this relief describes the real shape of the lattice quite well, and the value of the mismatch error spread indicates acceptable probe impact on the sample. In general, the performed series of measurements demonstrates the workability and effectiveness of the proposed method.

CONCLUSIONS

We have shown through measurements that the application of our method allows us to increase the scanning velocity of AFM by several times over that of the conventional method of predictive control. The approach of maintaining line-by-line feedback can serve as the basis for efficient algorithms of control signal formation (as was shown by the example of the phase-compensating method of inverse dynamics).

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