HARDWARE AND SOFTWARE CORRECTION METHOD OF PIEZO SCANNER NONLINEARITY IN SCANNING MICROSCOPE

Key words
Scanning microscope, piezo scanner, the piezo scanner nonlinearity correction.

Abstract
An inherent feature of the piezo scanner in scanning probe microscopy is their time-varying nonlinear. This results in a distortion of images and a difficulty of the measurements that require adequate control of the current position of the cantilever with respect to the sample surface. This paper presents methods of correcting a nonlinear piezo scanner. The advantages and disadvantages of each solution are pointed out, and the developed hardware and software correction methods are described. The correction is performed by a digital system made up of high-speed analogue-to-digital converters and a FPGA programmable system in which the correction algorithms are implemented. These algorithms determine, on the basis of actual measurement data, a set of correction factors for different areas and scanning speed. This set can be modified during each scanning process. This method of hardware and software use does not slow down scanning speed, and it maintains high resolution measurements.
**Introduction**

The scanning microscopy element responsible for collecting data from a specific point on the sample given by the researcher in the area of responsibility is the piezo scanner. In most SPM systems piezoceramic tubes with deposited electrodes are used to actuate the sample displacement (Fig. 1) [1, 2, 3]. By bringing to each scanning electrode voltages, it is possible to move the unattached tube in three directions x, y, and z.

The main problem is the nonlinearity of the piezoceramic tube. This element is characterized by hysteresis, nonlinearity spontaneous, which is the result of a slow investigation into the full swing and is in the process of aging. It is extremely difficult to describe these properties theoretically, because they depend on many factors, such as temperature, humidity, scanning speed, the mass of the sample, characteristics of electronic equipment, and the interplay of individual quadrants on each other.

![Scheme piezo scanner tube](image1)

![Surface topography of the test](image2)

Fig. 1. Scheme piezo scanner tube (a) [4] and the surface topography of the visible characteristic of the test due to the nonlinearity of the element bend scan (b)

The result of these phenomena is the distortion of images (Fig. 1b) and the necessity of introducing nonlinearity correction piezo scanner systems, particularly in cases of the need for accurate measurements of length and measurement modes that require compensation of the surface topography of the sample and the cantilever positioning in a specific point on the surface of the sample.

1. **Nonlinearity correction methods of piezo scanner**

The scanning microscopes typically use three methods for the nonlinearity correction [5, 6, 7]:
− Correction by introducing the inverse model,
− Correction by introducing a feedback, and
− Software correction.

The first step for the correction by introducing the inverse model is to find the inverse function of the scanner response to stimulation of linear \( H(s) \). The computer system gathers measurement data from the well-known reference grid. A table of coefficients is determined by matching the collected data to the size of the reference grid. On this basis, the function \( H(s) \) is found. After this process, the system can compensate the nonlinearity by adjusting the voltage applied to the scanner, as the inverse function \( H(s) \).

More complex algorithms include theoretical (mathematical) models of the nonlinear scanner, which is used to calculate the value of the voltage being applied to the electrodes of the scanning tube. Due to the change of parameters of the piezoceramic tube at a given time, performing control using the inverse of the calculated model theory does not lead to satisfactory results.

An alternative way of correcting nonlinear deflection of the piezo scanner is the introduction of feedback in the X and Y axes \([8]\). In this case, the voltage generated by the precision measurement circuit is compared to the deflection current, respectively scaled reference voltage, which is produced in the scanning voltage generator circuit. The error signal formed by comparing the voltage in the comparator is fed to the PID controller, which controls the high voltage amplifier circuits X, and Y (Fig. 2).

![Fig. 2. Deflection control circuit diagram of piezo tube using PID control loop](image-url)

However, this approach is not without drawbacks. Too little gain in the feedback loop causes under compensation adjustment. This effect is minimized by reducing the scan speed or by increasing the loop gain \([9]\). Bigger gain in the feedback loop results in both higher gain noise generated by the deflection...
measurement system, which in turn moves the scanning voltage and consequently the greater the swing sound of tubes, worsening the resolution of the microscope [10]. Figure 3 shows the effect of the control loop. There is better linearity and disadvantages compared to the blur of the contours of the image (a) obtained from the disabled loop feedback.

Fig. 3. Images obtained without the feedback loop (a), and the operating system of the coupling (b) [12]

Another method of correction is the correction using the software. This method uses a special calibration grid. The system of the microscope collects, in the form of a matrix, the data obtained during the scanning of known characteristics. With the so obtained coefficients matrix, images collected during the test session may be subject to correction. Software solutions are simple and cheap, but their disadvantage is the limited degree of nonlinearity compensation of the scanner (Fig. 4). The effectiveness of this method depends on the speed and direction of the scan and the scan position relative to the centre of the tube for maximum scanning area [11]. As a result, correction works fine for scanning conditions that were set during calibration.

Fig. 4. Software correction of scanner nonlinearity
Whenever the measurement conditions are changed, the system should be re-calibrated. In systems with only this kind of correction, the real behaviour may be different from the linear up to 10% [1]. For small scanning ranges, this difference is often transparent to the operator.

2. Hardware and software correction

The above described methods have disadvantages which can be avoided by the use of a digital system, performing the “hardware and software correction.”

Fig. 5. Hardware and software scanner nonlinearity correction

In the developed method (Fig. 5), the first step is to determine the correction factors based on data from the measurement of the actual deflection scanner. They are stored in the computer's memory, converted, and then the computer displays the corrected topographic image. Coefficients obtained in this way are used to correct the deflection in the next scanning process.

The resulting set of coefficients for the different areas of the scan rate is modified as required for each scanning process. Therefore, this device becomes a self-compensating system, and this method does not reduce the scanning speed (using parallel computing hardware solutions) and retains high-resolution measurements. The digital system, which implements the above correction method, was built on the basis of fast 100MHz, 16-bit A/D converters and programmable system Virtex series FPGA from Xilinx. The right FPGA algorithms were implemented in the system.

A deflection sensor inductive element in the form of a small coil-like solid aluminium element mounted on the end of the scanning tube is used (Fig. 6).

The formation of eddy currents resulting from a loss of energy from the coil reduces the voltage across the element. Since the data read from the sensors can be distorted deflection and thermal noise, before their analysis, they must be filtered.
The measurement of signals is conducted by means of a bridge method. The measurement coils are supplied from the generator stabilized with a quartz resonator with the working frequency of 800 kHz. The signal of the imbalance of the bridge is first inputted to the differential amplifier, and then to the low-pass Butterworth filter with a cut-off frequency of 1.5 kHz. The final stage is the system of the amplifier and the shifts of the levels. The presented measurement system enables the measurement of the deflection of the piezo tube with an accuracy of 50 nm.

The designed deflection correction system of the piezo scanner includes filtering algorithms – averaging and dominant. Averaging the arithmetic mean is calculated from a series of piezo tube deflection readings. The data indicating a deflection of less than the previous position and those indicating abnormal growth are adjusted. In the case of dominant values, they are usually present in the series of data read from the sensors swing, which allows the purification of the random noise data.
The developed nonlinearity correction circuit of the piezoelectric tube is built into the microscope TERRA AFM [13]. The use in the microscope fast A/D converters, both in the loop and in the displacement detection module piezo scanner, allows one to reduce the impact of non-linear piezo tube deflection from the applied voltage by making readings until the measured values of the actual item scanning element. In this way, it is possible to almost completely eliminate the effects of both nonlinearity and hysteresis of the piezo scanner’s data obtained in a single measurement line (Fig. 7).

When the user selects the scan, and determines the number of measurement points as well as the speed and direction of movement piezo scanner, voltage values are calculated for the D/A converters that are responsible for setting the size and position of the initial gain in the track piezo scanner X and Y. Then the frequency of D/A converters is calculated. In addition, the controller module sends information to the module position correction and the detection of piezo scanner about the number of read points and the corresponding standard deflection of the piezo scanner. When the sensor indicates the position of the swing in which the reading of the measurement channels is done, a signal is transmitted to the module feedback loop that forces the read data from the active channels through the A/D converters. These data is placed in a FIFO (First In, First Out), and then, at the end of movement along the line of measurement, it is transmitted to the controller, where it is then transmitted to the PC, which is responsible for the acquisition of images. Depending on the size of the test area, it is possible to control the gain of the position sensor, which allows for increased accuracy.

During the runtime of the algorithm of the control position of the piezo tube, the selection of clock frequency converters D/A is also necessary in order to ensure a smooth and steady increase in tensions on the cover of the piezo tube, which is responsible for the deflection. The start of moving the tube along the “fast line measurement” (X), only after ensuring that the actual deflection of the tube in the direction of “free” axis (Y), is equal to the theoretical deflection, corresponding to smoothing the distribution of consecutive lines measured at intervals specified by the user in the selection of the study area and resolution. Additionally, while moving in the direction of the line piezo scanner measurement (X), the monitoring of the deflection along the Y axis prove to be incorrect if the level of the cover tube voltage is correct.

An important functional feature of the microscope is the ability to select and zoom in on those parts of the sample with the currently displayed area. The essence of this process lies in the fact that the portion selected for magnification actually meets the scanning area again. The confirmation of this fact, which in turn proves the correctness of the correction, is a sequence of successive scans presented in Fig. 8.
Summary

The nonlinearity scanning microscope scanning of a piezo tube is usually corrected by the introduction of a reverse model, by introducing a feedback loop in the track X and Y, or software. The main disadvantage of the inverse model is the difficulty in determining the answer clearly. The use of feedback decreases the scanning speed or generates additional noise, which reduces the resolution. The software correction has, in turn, a limited ability to compensate for nonlinearities and requires calibration with the model after each change of scanning conditions.

The developed hardware and software correction method does not reduce the scanning speed and maintains high resolution measurements. This method creates, using the results of the actual measurements, a set of coefficients for the different speeds and scan areas. This set is modified as necessary during each scanning process, making automatic corrections for the piezo scanner deflection.

This method of correction improves the accuracy of the representation of objects, especially in the X and Y axes. This allows the introduction of advanced microscopy AFM modes, such as magnetic mod or lithography, requiring actual control of the relative positions of the sample surface and the scanning tube.
References

Sprzętowo-programowa metoda Korekcji nieliniowości piezoskanera w mikroskopie skaningowym

Słowa kluczowe
Mikroskop skaningowy, piezoskaner, korekcja nieliniowości piezoskanera.

Streszczenie