Andrzej ZBROWSKI
Institute for Sustainable Technologies – National Research Institute, Radom
andrzej.zbrowski@itee.radom.pl

THE METHOD AND EQUIPMENT FOR PRECISION POSITIONING OF THE SCANNER IN AN ATOMIC FORCE MICROSCOPE

Key words

AFM microscope, scanner, initial approach, harmonic drive, eccentric mechanism.

Abstract

The article presents a method and equipment designed for an initial approach of a sample fixed at a table to a cantilever needle in the atomic force microscope. The presented solution is used in a microscope in which the scanning needle is positioned in the scanning head above the sample. Precise movement of the sample relative to the scanning needle is achieved by a piezoelectric tube. The solution described is designed for the initial approach of the piezoscanner tube with the sample attached under the cantilever needle. The final approach of the sample-needle system is done by manipulating the length of the piezotube. The solution of the initial approach uses an eccentric pushing mechanism with a harmonic drive and a stepper motor. The advantage of this solution is the quick motion of the effector while maintaining the high resolution and precision of positioning and elimination of backlash.

Introduction

In an atomic force microscope, it is very important to precisely position the tip of the scanner probe on the sample. Due to the small distance between the sample's surface and the tip, it is necessary to use a precise control system of the sample's position. This role is fulfilled by the piezoelectric scanner that, with electric potential applied to it, changes its geometry (elongates or shortens), according to the direction of the current applied (Fig. 1c). Operation of most scanners used in modern AFM microscopes utilises the reverse piezoelectric effect that makes piezoelectric materials change shape under electric fields. Before the piezoelectric scanner is turned on and the scanning procedure is performed, it is necessary to move the sample to the scanning tip close enough to begin the digitalisation of the sample's surface. This part of the procedure is important and difficult in the research methodology. An imprecise approach of the sample may result in damaging the scanning needle. The initial approach mechanism must enable position correction with resolution at no less than 0.0005 mm in both directions. The initial approach mechanism can be connected with the piezotube (Fig. 1b) or cantilever (Fig. 1a).

The most common solutions involve the initial approach of the scanner tube in atomic force microscopes by thread mechanisms (e.g. micrometric screw) or piezoelectric systems [1]. Solutions where scanner positioning is done in a parallel kinematic system with piezoelectric actuators are also developed. The downside of thread mechanisms used for linear movement of the scanner tube is the clearance in threading connection. Backlash is the biggest obstacle in precise positioning of the scanner tube during the initial approach of the sample fixed to the scanner table towards the scanning tip. The disadvantage of piezoelectric systems is a limited range of positioning and position loss during power shortage [3, 4].

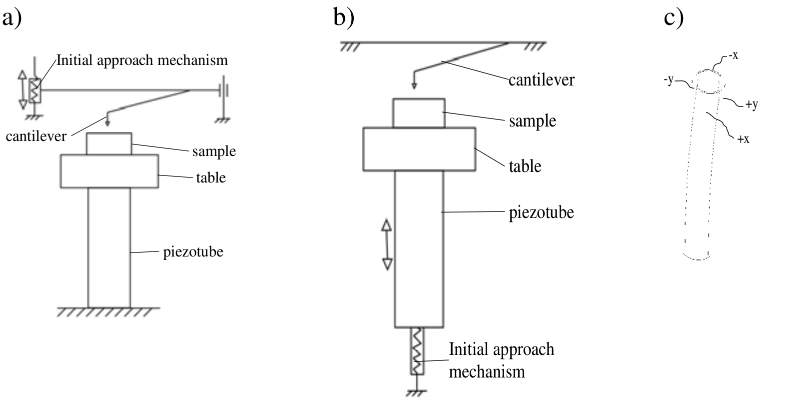

Fig. 1. Scanner diagram in AFM microscope: a) initial cantilever approach, b) initial piezotube approach c) piezotube deformation diagram

High requirements regarding positioning systems used in modern research and measurement equipment lead to a constant need to enhance their performance. Due to a precise character of the mechanisms, the solutions implemented are often unusual in the field of classical constructions field [5]. The mechatronisation of precise instruments, along with modern design methods, make more and more accurate levels of positioning possible. To achieve this, cam mechanisms with crown or peripheral cams are used [6]. Eccentric mechanisms allow high precision positioning while simplifying the kinematic chain [7] in precise laboratory tables used for sample exposition in research concerning contact angles and calculating surface energy of materials. The development of parallel kinematics is also connected with utilising eccentric systems in modular actuators of precise, multi-axis manipulators used in laboratory work [8].

1. Mathematical model

The developed system of mechanical initial approach uses eccentric pushing mechanism. In order to minimise friction in the mechanism, a ball bearing was installed on the circumference of the eccentricity. The positioning method allows moving the traverse beam via the rotating eccentric mechanism installed at motoreductor's shaft (Fig. 2). Adding a ball-bearing to the beam ensures one degree of freedom of the actuator's reciprocating movement.

a) b)

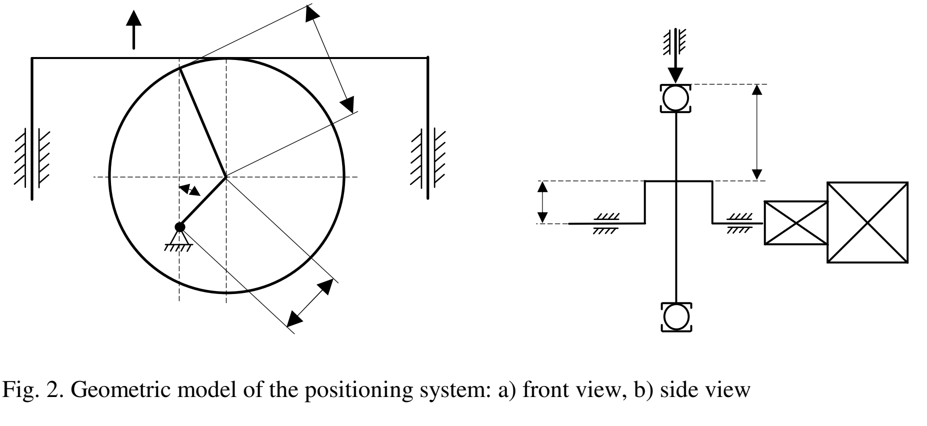

Fig. 2. Geometric model of the positioning system: a) front view, b) side view

Based on geometric relations indicated in Fig. 2, the equation of the mechanism's mathematical model, for any given angular position of eccentric shaft, can be described as follows:

$$H(\alpha) = e(1 - \cos(\alpha)) \quad (1)$$

where:

H – pusher's lift,
e – eccentricity value (6 mm),
α – angle of rotation of the eccentricity.

The solution used is characteristic for precise mechanics mechanisms. It is characterised by a short kinematic chain and a limited number of moving parts. Tension springs make it possible to cancel any backlash and dampen external vibrations. A single contact point between eccentricity and the pusher minimises friction and prevents hysteresis of positioning.

2. Simulation testing of the positioning parameters

In order to determine the characteristics of the positioning of the effector, a simulation testing of geometrical model has been conducted. The characteristic of the pusher's lift was determined as a function of the angle of rotation of the eccentricity installed on the motor's shaft.

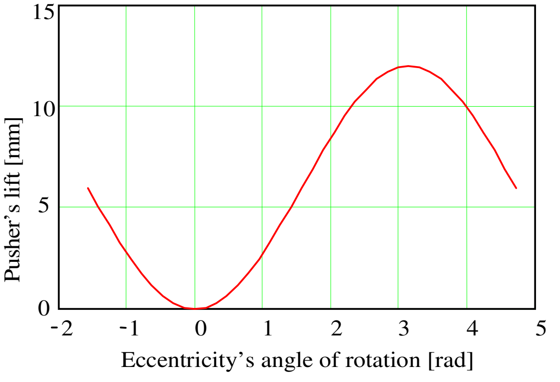

Fig. 3. The characteristic of the pusher's lift

Relative accuracy of the effector's positioning in micro-stepping control has been determined (Fig. 3). In this mode, the basic step has been divided into 8 micro-steps.

The pusher tip's slide positioning precision relative to the angle of rotation of the eccentricity can be defined as follows:

$$\Delta(\alpha) = \left| K(\alpha) - H(\alpha) \right| \quad (2)$$

where

$K(\alpha)$ – the lift of the pusher tip's slide after a single motor step.

$$K(\alpha) = e(1 - \cos(\alpha + \delta(\alpha))) \tag{3}$$

$\delta(\phi)$ – angular stroke of the propulsion unit

$$\delta(\phi) = \pi \cdot \frac{K \cdot S}{180^o \cdot G} \text{ [rad]} \tag{4}$$

where:

G – the ratio of the harmonic drive,
K = 1.8° – rotation angle in full-step control,
S = 1/8 – step division in micro-step control.

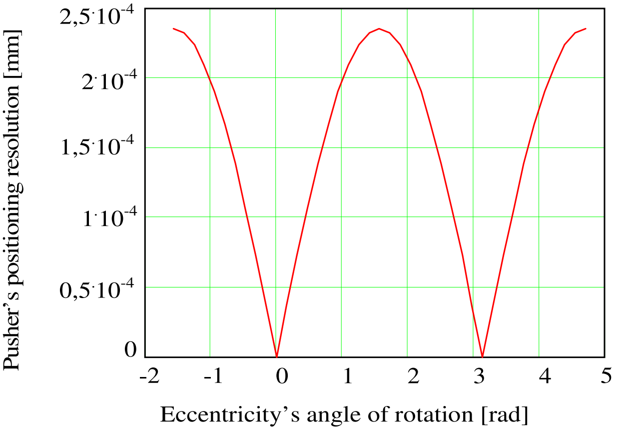

Fig. 4. The characteristic of the resolution of the pusher's positioning (using a 1/8 micro step)

3. 3D Model

The scanner has a modular structure. It consists of a motoreductor positioning the eccentricity's disc, traverse beam, piezoelectric scanner tube, and precise XY table.

In the designed 3D model of the motoreductor's mechanism, the eccentricity's disc with ball bearing and blade ring are installed on the transmission's output shaft. The blade ring cooperates with the traverse beam causing the movement of the scanner's piezotube. The roller bearings of the blade ring enable one to change the sliding friction between blade ring and traverse beam to rolling friction of the balls between the bearing's rings. Two miniature optical sensors were installed to detect terminal positions of the traverse beam (Fig. 5).

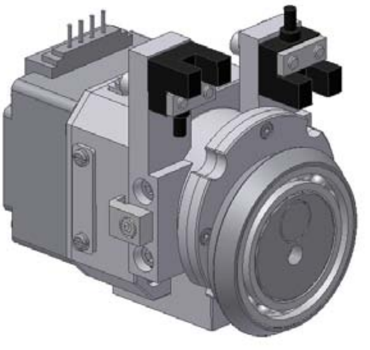

Fig. 5. Motoreductor module

A stepper motor with the resolution of 200 steps/revolution, cooperating with a miniature HFUC-11-100 harmonic drive with a 1:100 transmission was chosen as the propulsion unit. The reductor was designed using a miniature strain wave gear manufactured by Harmonic Drive (Fig. 6).

a)

b)

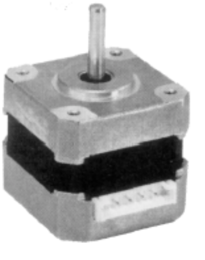

Fig. 6. Actuator components: a) miniature harmonic drive unit (Harmonic Drive), b) stepper motor (Elra)

Terminal positions of the effector were programmed in the top and bottom return position resulting from the angular position of the eccentricity. This means that the eccentricity's angle of rotation changes value between 0 and π rad.

The traverse beam module (Fig. 7) consists of a transverse beam lead by two pillars with linear bearings. In the traverse beam there is a slot that makes it possible to simultaneously base the replaceable segments of the piezotube. The lock of the eccentricity-pusher mechanism is a force lock utilising tension springs. The springs are enclosed in the traverse module at each end of a moving beam. Miniature linear ball bearings manufactured by Faulhaber were used in the traverse module.

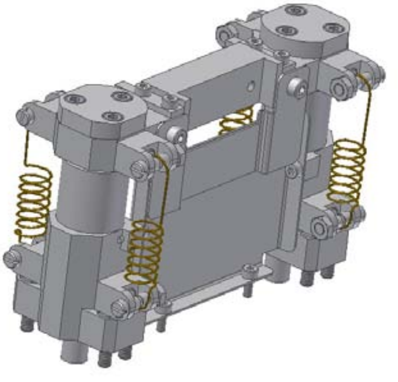

Fig. 7. Traverse module

Fig. 8. Piezoelectric tube module

Piezoelectric tube module is used to precisely position the tested material sample (Fig. 8). The tube is mounted on a foot, inside a sleeve acting as a mechanical shielding. The piezotube is equipped with a magnetic table for sample positioning. The module's handle enables one to install the segment as a detachable component of the scanner unit. Using a 1” tube, the scanning range in X and Y axes is 12 μm with the resolution of 0.3 nm and 2.5 μm with the resolution of 0.05 nm in the Z axis Using a 2”, the scanning range in X and Y axes is 50 μm with the resolution of 1 nm and 6 μm with the resolution of

0.1 nm in the Z axis [9]. The piezoelectric scanner's tube module can be equipped with tubes of varying lengths (1 and 2 inches). The module's replacement makes it possible to change the scanning range.

The motoreductor module with the piezoelectric and traverse modules that are installed at a common base plate (Fig. 9).

a) b)

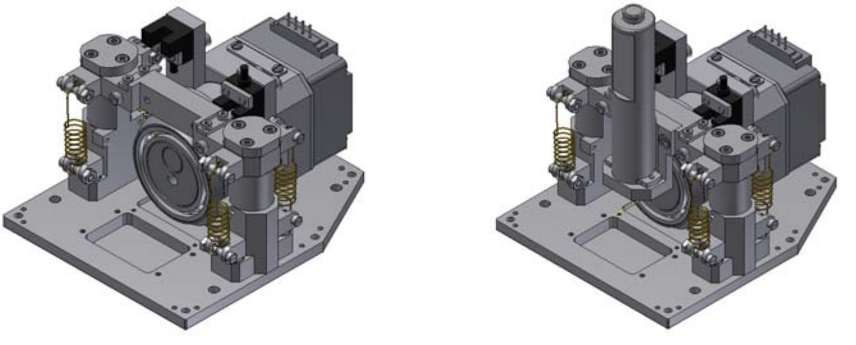

Fig. 9. The 3D model of the scanner in the atomic force microscope: a) the mechanism with no piezotube installed, b) the mechanism with the piezotube installed

A precise XY table with elements establishing the scanning head with cantilever is located on the scanner's body (Fig. 10). The XY table unit is used to position the microscope's head in relation to the tested sample. The table is installed in the top casing plate of the scanner. The table's wheels are positioned using miniature Mituyoto micrometric heads. Precise movement of the wheels is possible thanks to miniature INA linear cylinder bearings. The lock of the positioning mechanism uses tension springs. The table's construction ensures collision-free vertical movement of the piezoelectric tube module. The table's surface has openings to support the measuring head. On the table, there are lock-stop rails facilitating easy and clear installing of the AFM and STM modules.

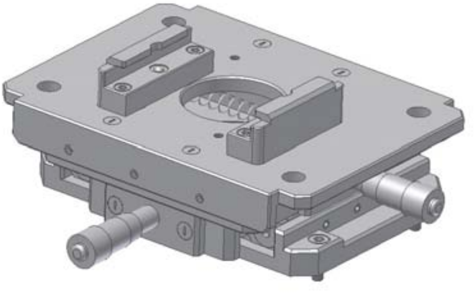

Fig. 10. X-Y table module

The regulation of the table with the micrometric screws enables one to guide the scanning tip over the examined area of the sample. An independent positioning unit installed in the head allows positioning the laser beam onto the cantilever tip.

4. Prototype

A device for precise approach of the piezoelectric tube (Fig. 11a) in an atomic force microscope is an element of the scanner unit (Fig. 11b), which is the base for the head with a laser beam projection system and a cantilever (Fig. 11c).

a) b) b)

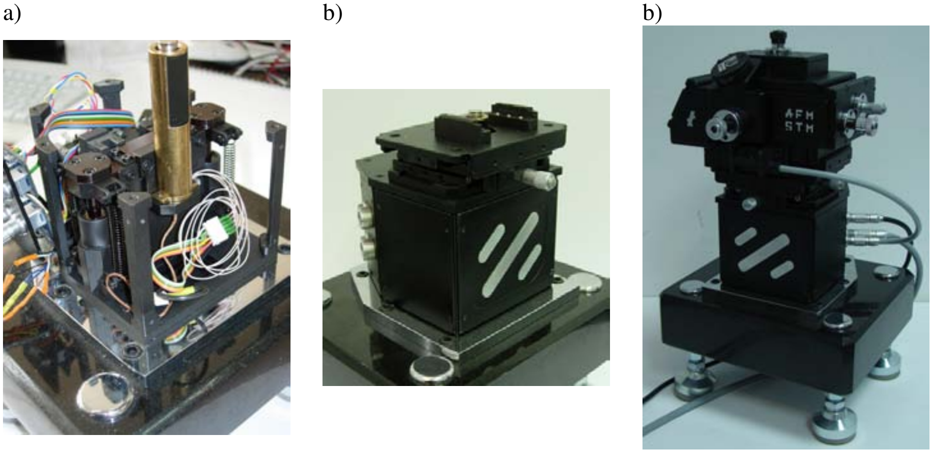

Fig. 11. The microscope's structure: a) precise initial approach module, b) scanner module, c) entire microscope with the AFM head installed on the scanner

In order to dampen any vibrations, the scanner unit was based on a thick granite slab with four elastomer dampeners.

Conclusions

One advantage of the presented solution is the lack of clearance, especially backlash, and a wide range of traverse beam's positioning, to which the element positioned can be attached, including the atomic force or tunnel microscope's scanner's tube. Eliminating clearance along with hysteresis associated with elasticity of the kinematic chain elements ensures immediate reaction and a change of the effector's position without delay or dynamic side effects.

A pushing eccentric mechanism with a force lock by means of a spring was used in the construction of the initial approach system. Utilising an actuator with an eccentric executing element introduces a sinusoid nonlinearity in the characteristic of the positioning. A rolling bearing based on the eccentricity enables one to change sliding friction between the blade and the traverse beam to rolling friction of the balls between the bearing's rings. Exploitation tests confirmed achieving assumed parameters. The positioning system in the micro-step control with a 1/8 step makes it possible to achieve a resolution no lower than 0.00025 mm in the entire 12 mm motion range. The mechanism does not demonstrate viscoelasticity and responds to each individual 1/8 micro-step impulse in forward and backward movements.

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Metoda i urządzenie do precyzyjnego pozycjonowania skanera w mikroskopie sił atomowych

Słowa kluczowe

Mikroskop AFM, skaner, wstępne zbliżanie, przekładnia falowa, mechanizm mimośrodowy.

Streszczenie

W artykule przedstawiono opracowaną metodę i urządzanie do wstępnego zbliżania próbki zamocowanej na stoliku do igły cantilevera w mikroskopie sił atomowych. Prezentowane rozwiązanie jest stosowane w mikroskopie, w którym igła skanująca znajduje się w głowicy nad badaną próbką. Dokładne przemieszczanie próbki względem igły, w czasie procesu skanowania zapewnia rurka piezoelektryczna. Przedstawione rozwiązanie jest przeznaczone do wstępnego zbliżania rurki piezoskanera z zamocowaną próbką pod igłę cantilevera. Ostateczne zbliżenie układu próbka–igła jest wykonywane poprzez zmianę długości piezorurki. Opracowane rozwiązanie układu zbliżania wstępnego wykorzystuje mimośrodowy mechanizm popychaczowy z przekładnią falową i silnikiem krokowym. Zaletą rozwiązania jest bardzo szybki ruch efektora przy zachowaniu wysokiej rozdzielczości i precyzji pozycjonowania oraz wyeliminowanie luzu nawrotnego.