NANOMANIPULATION BASED ON AFM: PROBE CANTILEVER AND INTERACTIVE FORCES MODELING

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ABSTRACT

Nanomanipulation shows its powerful potential with its broad applications, and using AFM as a simple nanomanipulation tool becomes popular. This paper presents a cantilever model based on material mechanics and derives the relation of interactive forces and the cantilever defections which can be calculated on basis of the feedback from PSD. The effectiveness of a commercial AFM used both as an imaging and a nanomanipulation tool is proven with preliminary experiments.

Keywords: Nanomanipulation, AFM, Cantilever modeling

1. INTRODUCTION

Nano-science is the study of atoms, molecules, and objects whose size is on the nanometer scale (1~100nm). It aims at the ideal miniaturization of devices and machines down to atomic size and molecular size, and has been a hot topic as a promising high technology for this century. It is crucial to create new instruments and devices for nano manipulation. By precise control of atoms, molecules, or nano-scale objects, new sensors and man-made materials, terabyte capacity memories, micro scale robots/machines, DNA computers, quantum devices, micro scale distributed intelligence system devices with integrated sensors, actuators and communication tools, accurate medical tools etc., would be possible within the near future. However, for new nanotechnology products, there are still many challenges to be solved, and nanomanipulation, defined as the manipulation of nanometer size objects with a nanometer size end-effector with (sub)nanometer precision, is one of the important challenges of the nano world.

Nanomanipulation is an important "bottom-up" method to fabricate and assemble nanostructures, especially for the asymmetrical structures. It can also be used to repair or modify nanostructures built by other means. It has great potential for the nanotechnology. Nanomanipulation shows its powerful potential with its broad applications, and using AFM as a simple nanomanipulation tool becomes popular.

Nanomanipulation based on AFM in ambient conditions was initiated by Samuelson's group [1]. From then on, using AFM as a simple nanomanipulation tool becomes popular, such as works reported in [2], [3], [4], and [5]. As a nanomanipulator in the system, the AFM probe cantilever and nano interactive forces modeling work was reported by Xi et al. [5]. After considering the cantilever tip selection in [6], we will show a cantilever model based on material mechanics, and derive the relation of interactive forces and the cantilever defections which can be calculated on basis of the feedback from PSD, differs from the previous work in [5] just presented the relationship of the nano interactive forces.

Based on a commercial AFM—CSPM4000 (Benyuan Nano-Instruments Ltd., China), a feasible nano pushing strategy is proposed as Fig. 1. The system setup is shown in Fig. 2. The AFM cantilever which is used as nanomanipulator is analyzed and modeled. The interactive forces during the manipulation process are modeled. Preliminary experiments are carried out to prove the effectiveness of the system.

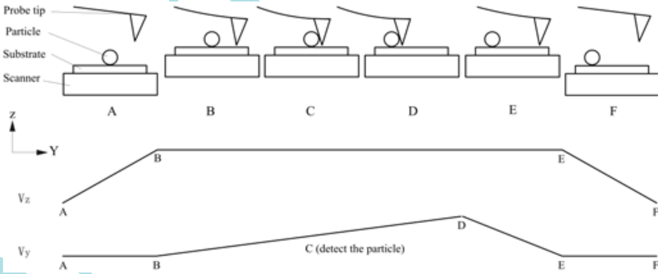

Fig. 1 Nano pushing strategy.

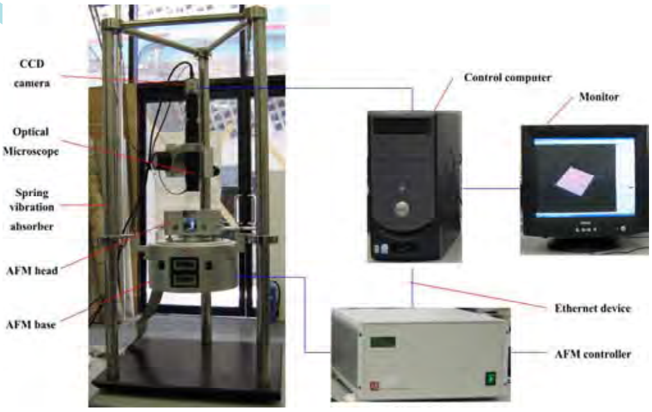

Fig. 2 System setup.

2. CANTILEVER MODELING

2.1 The Hooke's law

The AFM acquires information about a surface because of the cantilever beam mechanical deflections which are detected by an optical system as shown in Fig. 3. Normally, cantilever is a beam in the form of a rectangular (see Fig. 4) having length l, thickness t ($t<<l$) and width w ($w<<l$). The probe's tip interacts with the surface. During nano manipulation with AFM probe, the cantilever-tip will subject to various kinds of nano

forces such as Van del Walls force, capillary force, electrostatic force, contact repulsive force, frictional force etc.. The force acting on the probe has sometimes not only vertical but also horizontal components. Therefore, the cantilever tip can deflect not only along the *z*-axis but in other directions: *x* and *y*. Let's call the vertical component F_z the normal force, and both the longitudinal component F_y and the transverse component F_x as the lateral forces (see Fig. 3).

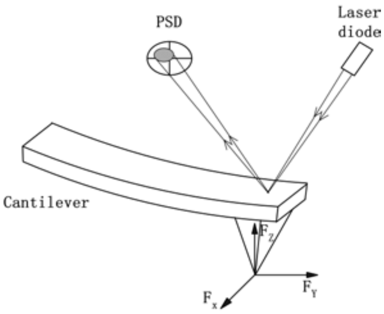

Fig. 3 Cantilever deflections measurement using PSD.

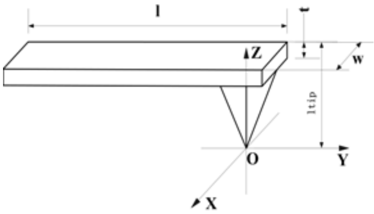

Fig. 4 Rectangular cantilever with a tip.

Consider that the tip deflection vector $\boldsymbol{\zeta}$ (having components ζ_x, ζ_y, and ζ_z) is linearly dependent on the applied force in accordance with the Hooke's law:

$$\boldsymbol{\zeta} = \boldsymbol{CF} \tag{1}$$

The constant of proportionality is the second rank tensor $\boldsymbol{C}$ which we call the inverse stiffness tensor. It contains all the information about elastic properties of the cantilever. For the sake of clarity, we write the formula as a matrix expression:

$$\begin{pmatrix} \zeta_x \\ \zeta_y \\ \zeta_z \end{pmatrix} = \begin{pmatrix} c_{xx} & c_{xy} & c_{xz} \\ c_{yx} & c_{yy} & c_{yz} \\ c_{zx} & c_{zy} & c_{zz} \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \tag{2}$$

Notice that the optical system detects not tip deflection but inclination of the cantilever top surface near its free end. Two angles are measured: deflection of the normal from vertical in the *Oyz* plane (angle α, see Fig. 5 and Fig. 6) and in the orthogonal direction – in the plane *Oxz* (angle β, see Fig. 7).

Instead of equation (2), we can write for the mathematical convenience the matrix expression relating angles α and β directly with force $\boldsymbol{F}$ components.

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \boldsymbol{BF} = \begin{pmatrix} b_{\alpha x} & b_{\alpha y} & b_{\alpha z} \\ b_{\beta x} & b_{\beta y} & b_{\beta z} \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \tag{3}$$

2.2 Cantilever deflection of x, y, z types

Let us consider the magnitude and direction of the deformation arising from the vertical force F_z, the longitudinal force F_y, and the transverse force F_x, respectively. Solution to these problems will allow us to find components of the tensor $\boldsymbol{C}$ one by one.

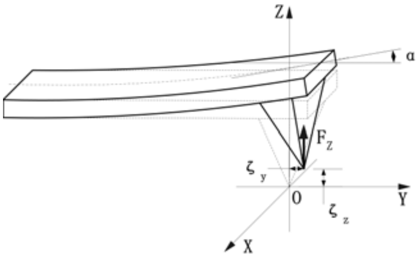

Fig. 5 Vertical deflection of the z-type.

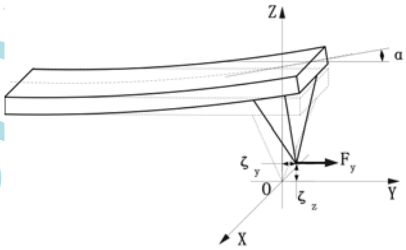

Fig. 6 Vertical deflection of the y-type.

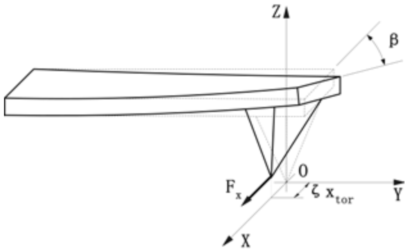

Fig. 7 Torsion.

2.3 Cantilever model

Let us write the obtained components of inverse stiffness tensor $\boldsymbol{C}$ into the representative matrix for mathematical convenience as:

$$\mathbf{C} = c\begin{pmatrix} \dfrac{2l_{tip}{}^2}{l^2} + \dfrac{t^2}{w^2} & 0 & 0 \\ 0 & \dfrac{3l_{tip}{}^2}{l^2} & \dfrac{3l_{tip}}{2l} \\ 0 & \dfrac{3l_{tip}}{2l} & 1 \end{pmatrix}. \tag{4}$$

Where the quantity c characterizes cantilever compliance which is reciprocal of the stiffness k. And the relation between angles α and β directly with the force $\boldsymbol{F}$ is obtained as:

$$\begin{pmatrix}\alpha \\ \beta\end{pmatrix} = \frac{1}{k}\begin{pmatrix} 0 & \frac{3l_{tip}}{l^2} & \frac{3}{2l} \\ \frac{2l_{tip}}{l^2} & 0 & 0 \end{pmatrix}\begin{pmatrix}F_x \\ F_y \\ F_z\end{pmatrix}. \tag{5}$$

Substitute expression (4) into (1), we have the cantilever model as:

$$\begin{pmatrix}\zeta_x \\ \zeta_y \\ \zeta_z\end{pmatrix} = \frac{1}{k}\begin{pmatrix} \frac{2l_{tip}{}^2}{l^2} + \frac{t^2}{w^2} & 0 & 0 \\ 0 & \frac{3l_{tip}{}^2}{l^2} & \frac{3l_{tip}}{2l} \\ 0 & \frac{3l_{tip}}{2l} & 1 \end{pmatrix}\begin{pmatrix}F_x \\ F_y \\ F_z\end{pmatrix}. \tag{6}$$

3. MODELING THE NANO FORCE ACTING ON CANTILEVER TIP

Till now, we have the relationship of cantilever deflections and tip-substrate interactive forces. To convert the measured nm deflection into nN interactive force, we must calibrate the AFM scanner, since it is made from piezo ceramics which has intrinsic characteristics such as nonlinearity and hysteresis.

In order to protect the sharp tip of the cantilever, a gentle approach is used to calibrate the scanner. Namely, using z-axis calibration gratings comprising a one-dimensional array of rectangular steps with a calibrated height, move the probe horizontally from the above to the bottom of steps with vertical force feedback off, the cantilever deflection will be the height of the step. With this method, Benyuan Nano-Instruments Ltd. calibrates the system with 1μm scanner, and provides system constants with the device.

The outputs of the PSD are two signal differences S_v and S_h, which reflect the cantilever vertical deflection ζ_z and twisting deflection β respectively. Then the nanometer value of ζ_z and β are computed from the below equations

$$\varsigma(t) = k_v S_v \tag{7}$$

$$\beta = k_h S_h \tag{8}$$

Where k_v and k_h are system constants which are calibrated as 706nm/V and 0.00565rad/V by Benyuan Nano-Instruments Ltd.. S_v is vertical signal output and S_h is horizontal signal output of PSD.

Therefore, using the laser interferometry deflection measurement system, ζ_z and β can be measured as:

$$\zeta_z = \frac{1}{k}\left(\frac{3l_{tip}}{2l}F_y + F_z\right) = K_v S_v \tag{9}$$

$$\beta = \frac{2l_{tip}}{kl^2}F_x = K_h S_h \tag{10}$$

Due to the component of ***C***, $c_{zy} \neq 0$, the lateral force of F_y has also effect on ζ_z. When the AFM uses constant force mode, the change of the normal force is negligible during the pushing operation. Thus the change in F_y and F_x can be computed as:

$$\Delta F_y = \frac{2lk}{3l_{tip}}\Delta\zeta_z \tag{11}$$

$$\Delta F_x = \frac{2l_{tip}{}^2}{kl^2}\Delta\beta. \tag{12}$$

This means that the longitudinal F_x and transverse F_y force components corresponding to the applied pushing load can be observed from the cantilever deflection ζ_z and β directly.

From expression (6), the 3D force models can be obtained on basis of the PSD signals S_h, S_v:

$$F_x = \frac{2l_{tip}{}^2}{kl^2}\beta = \frac{2l_{tip}{}^2}{kl^2}K_h S_h \tag{13}$$

$$\frac{3l_{tip}}{2l}F_y + F_z = k\zeta_z = kK_v S_v. \tag{14}$$

4. PRELIMILARY EXPERIMENTS

In this section, preliminary experiments are presented. It is shown that the CSPM4000 can work as both an imaging tool and a simple nanomanipulation tool.

4.1 Nano topography

Sample: Mica

Mica was selected as the substrate for nano pushing due to its smooth surface which we could validate in the consequent topography. The largest height difference in the topography is smaller than 0.4nm. In addition, clear topography of the mica molecular demonstrates the accuracy of the system.

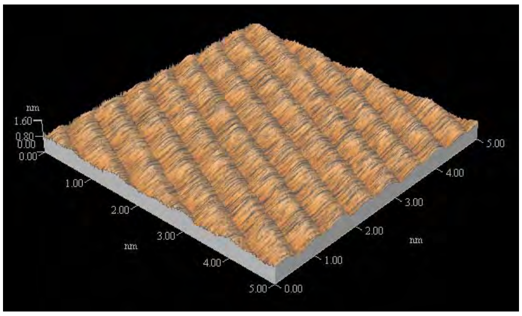

Fig. 8 Mica topology.

4.2 Nano imprint

Substrate: Polycarbonate

We used the back surface of a common CD plate as substrate. At the beginning, the cantilever was brought to contact with the substrate. Then the system worked under the following program which controlled the cantilever's deflection, the scanner's control voltages, and the scanner's motion speed.

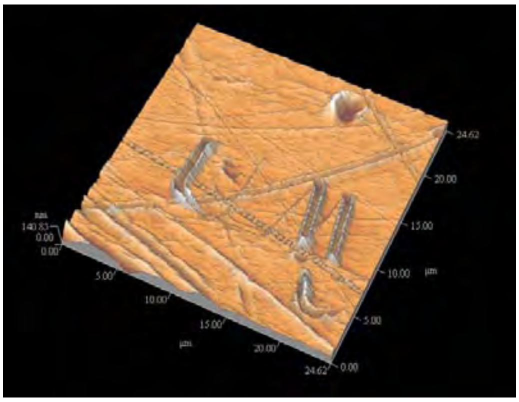

Fig. 9 Imprint UM.

4.3 Nano pattern

Substrate: hydrogen passivated single crystalline silicon

The CSPM4000 could add a pulse voltage between a conductive tip and the substrate, and oxidized the substrate surface selectively to form a pattern defined by user. The badge of University of Macau (UM) was pretreated and sent to the controller as input. The patterned surface is scanned and result is shown in Fig. 10.

In addition, the result also show that the silicon can be selected as the nanomanipulation substrate as its smooth surface. The largest height difference is around 2nm.

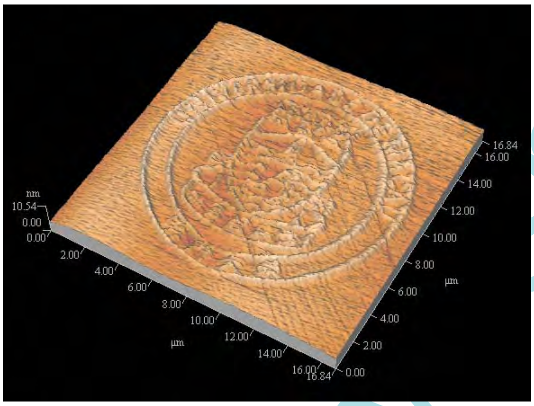

Fig. 10 Nano pattern of badge of UM.

4.4 Nano pushing

In nano pushing experiment, the cantilever can be used as detective sensor to detect whether it contacts with substrate or separates with substrate as shown in Fig. 11. In the curves, both the deflection and separation are represented in voltage, the blue lines represent approach, and red lines represent retraction. The blue line curve denotes the contact mode, while the red curve line represents the separation mode.

5. CONCLUSIONS

In this paper, a nanomanipulation system based on AFM is built, a feasible manipulation strategy is proposed, and the AFM cantilever used as a nanomanipulator is modeled. The interactive forces during the manipulation process are modeled. And preliminary experiments are carried out to prove the effectiveness of the system. The modeling and the experiments have also enhanced the understanding of the interatomic forces at the nano scale during nano assembly and nano particle manipulation.

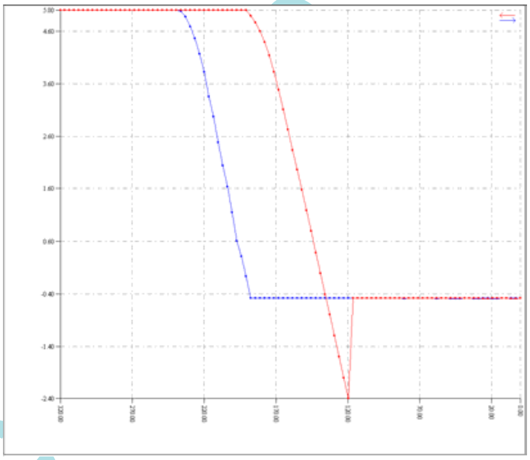

Fig. 11 Cantilever works as a detective sensor.

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