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Development of Noise Measurements. Part 6. Opposing Method in Stepless Shifting Regulation

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Abstract: It is considered the hydraulic technique and studied nanoobject stepless shifting means along the Z-axis with the working liquid monomolecular layer thickness order error. Systematic multiplicative error elimination is obtained by means of the opposing method usage when calibrating. *Copyright © 2013 IFSA.*

Keywords: Nanoshift, Shift stepless control along the *Z*-axis, Relative error, Opposing method of error minimization, Calibration.

1. Introduction

Accuracy and stability problems of *3-D* positioning are considered to be principal in the nanotechnology. Authors [1] employ a combination of simulation techniques to model three different physical properties of the dopant atom, accessible in an experiment, and then use this information to triangulate the dopant position to ±2.5 nm in two directions and ± 15 nm in the third direction.

Today there are *3-D* positioning precise means of nanomachines, shift mechanism in atomic-force microscopes (later AFM) and familiar to them means. To reduce the scanner positioning error along the axes *X* and *Y* the AFM is preliminarily calibrated by the lateral standard. The calibration consists in standard surface measurement with the help of AFM and further usage of obtained length unit as a standard [2].

It is more complicated to calibrate along the axis *Z*. Paper [3] focuses on the on the design and calibration of an elastically guided vertical axis that will be applied in a small high precision 3D Coordinate Measuring Machine aiming a volumetric uncertainty of 25 nm. In the metrology part of this paper the calibration methods to determine the linearity as well as motion straightness and axis rotation errors were discussed. Finally first calibration results of *Z*-axis show nanometer repeatability of the probing point over the 4 mm stroke of this axis. The causes of the short-term variations with a bandwidth of about ± 10 nm are under investigation. Error compensation may reduce the residual error of the probing point to the nanometer level.

So a step standard [4] is used for calibration with next calculation – by the calibration results – calibration coefficient C_z. To detect scanner nonlinearities the calibration measurements are carried out by the means of different height step standards set, in other words by the multivalued measure producing of which is very complicated. At the same time own calibration coefficient $C_z(h)$ is calculated for every standard, and calibration

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coefficients for interim height standards will be calculated by the linear interpolation. For instance, the key features of standards TGZ set of NT-MDT firm are given in the Table 1 [5].

Table 1. Standard TGZ features as multivalued height measure.

Material	Silicium
Standard size	5×5×0.5 mm^3
Certificated area size	Central part 3×3 mm^2
Structure type	One-dimensional right-angled structure
Period	3.0 μm
Height	TGZ1 19±1 nm TGZ2 104±1.5 nm TGZ3 540±2 nm

A number of additional requirements appear during the preparation to the calibration on the multivalued step standard:

- Standard lateral positioning – in horizontal plane the structure must be located in the centre of controlled range;
- The structure must be located at angle of 90^0 to the measurement direction;
- Measurement speed is chosen so to provide the minimal distortion of structure fronts;
- Gauge range must exceed in 4 times the step width (to provide the measurement data sufficient quantity).

After calibration measurements providing the next stage is the step height estimation, for instance, in accordance with the method of ISO 5436 [4]. Here, the step height calibration artefact is a machined block of steel. It automatically detects the steps and calculates the step height or groove depth according to the mentioned standard. In this case the average step height is evaluated to 572 nm. All samples values of which exceed the threshold level are accepted as high level, and others – as low one. In this case the noise problem is neglected under this method usage that is not always acceptable, for instance, at step height small values. The step height h is calculated as the difference between high level and basic plane level.

To create Z-shift realization means the mentioned method is not enough as well as the thickness special measure usage: monomolecular layer coating, multilayer film etc. The main shortcomings of the mentioned means are gradation positioning, some measure quantity necessity, calibration process complication and its significant duration and cost.

2. Work Goal

The work goal is stepless highly precise nanoshift hydraulic technique development and positioning means along the axis Z-elaboration (within 2 nm) of the nanomachine or other device, for instance AFM contact assembly.

3. Theoretical and Practical Basis of Hydraulic Unit Creation for Nanosized Objects Shift Along the Z-axis

During the creation of hydraulic positioning unit along the axis Z of the nanomachine with providing stepless shift and position control possibility along this axis it is proposed to use hydraulic potential. To this purpose U-shaped hydraulic construction is proposed with ends of larger (D = 200 mm) and smaller (d = 0.3 mm) diameter. Diameters ratio is equal: $\frac{D}{d} = 20.0\,mm / 0.3\,mm = 66.66$. In the case of liquid level shift control in the narrow end with error ± 2.5 μm it is appeared the possibility to provide stepless and quite accurate level displacement in the wide end. This is the object of this study.

Hydraulic positioning is based on the laws of liquid motion and balance. The main part of hydraulic unit consists of two hermetic cylinders of different diameters connected by the interim diameter tube. The space in cylinders is partly filled of liquid (generally with distilled water, alcohol etc.). The height set levels of liquid column in every cylinder are fixed as zero levels. Spontaneous or enforced liquid level shift, for instance, in the small diameter tube or end, is detected by means of micrometer head (Fig. 1).

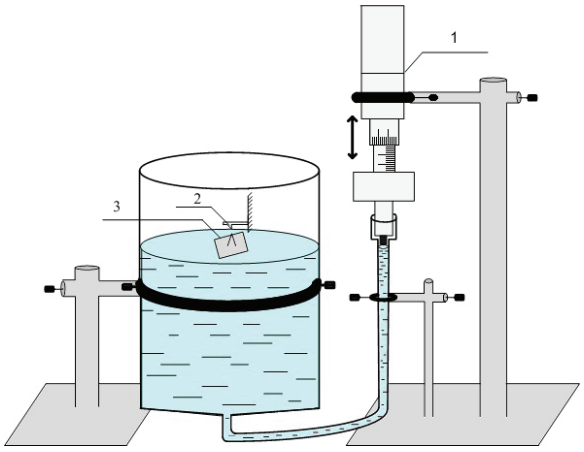

Fig. 1. The unit of nanosized objects hydraulic positioning: 1 - shift micrometer head; 2 – cantilever; 3 – float with mounted research nanoobject.

3.1. Measurement Operation

In the motionless fixed tube its pivot sinks by the shift micrometer head pressing hydraulic liquid to the

wide cylinder. Consequently the liquid level is increased in this end – on Δh_1. It results to weak but appreciable liquid level increase in the wide end. In accordance with joined vessels law the level increases on ΔH_1 in the wide end. Floating plate mounted in this wide end lifts the same as the studied nanoobject mounted on it.

In this case the condition of liquid quantity invariability under pouring from one end to another one can be described by the next formula: $\frac{\pi}{4} D^2 \Delta H = \frac{\pi}{4} d^2 \Delta h$. If we use $A = \frac{D^2}{d^2}$ as constant for this unit construction then with mentioned above ends diameters $A = \frac{D^2}{d^2} = \frac{400}{0.09} = 4444.4$. So we have got the formula specifying the level drops changes in wide (ΔH_1) and narrow (Δh_1) device ends.

$$\Delta H_1 = \frac{\Delta h_1}{A} \tag{1}$$

Accordingly with error approach principles [6] the relative errors of liquid level change in both device ends are linked between each other by the formula getting from (1):

$$\delta(\Delta H_1) = \delta(\Delta h_1) + \delta A\,, \tag{2}$$

where $\delta(\Delta h_1)$ is the device relative error specified by the inaccuracy of the drop level measurement by the micrometer head; δA is the device relative error specified by the inaccuracy of constant value A which can reach significant values and, even, change during the experiment. Let's consider consequently these two error components and abilities to decrease or/and eliminate them.

The first error component is determined by the following way. So far as liquid level measurement drop in the narrow end is 5 μm then the device measurement step is 1 ΔH determined by the formula (1) in the wide end is 5.0 μm / 4444.4 = 1.1 nm. Micrometer head absolute error in accordance with passport is ± 2.5 μm. Its value included to the result of the level shift in the wide end is ± 0.55 nm. Hereby the absolute measurement error of the liquid shift level in the wide end is specified by the micrometer head inaccuracy.

The step measurement refinement result with value error is equal to 1.10 + 0.55 nm. Otherwise the relative measurement error of hydraulic shift on 1.1 nm specified by the micrometer head capabilities is estimated as + 50 %. In the case of liquid level shift control in the narrow end with error ± 1.0 μm it seems possible to reach the relative measurement error of hydraulic shift ±20 %.

Hereinafter the unknown second component of the device error – the relative error of constant A value determination.

3.2. Metrological Experience of the Error Measurement Systematic Component Minimization

The error correction possibilities analysis enables to divide the absolute aggregate measurement error into three components: a) an additive error Δ_α which is independent from the value of measured quantity X and is also called zero error; b) the error Δ_{non} from the characteristic nonlinearity; c) the multiplicative error $\Delta_m = \delta_m X$ which is proportional to X and is called the sensitivity error.

The additive component can be easily detected if X=0. To detect nonlinear error component it should be used multivalued measures or scale converters. The multiplicative component can be detected under presence of the measure or the scale converter.

Relative multiplicative error δ_m can be eliminated by the means of the single-channel unregulated measure by the way of the measurement device verification if the X_0 value is known (in our case - Δh_0) and next division and multiplication.

For measurement accuracy improvement and multiplicative component minimization can be used the opposing method [7]. The method point consists in that the measured quantity H_X is compared twice with regulated measure - $H_{N1}; H_{N2}$; besides that before the second measurement it is rearranged with the measure. Consequently this quantity value with the eliminated measurement error multiplicative component can be gained:

$$H_X = \sqrt{H_{N1} H_{N2}}$$

3.3. Hydraulic Device Calibration

There is a real operation realizing before or after the measurement operation and is assigned to eliminate mentioned above multiplicative error component. In the current case it is assigned to decrease or/and eliminate the second component (in the formula "2") of the shifted liquid level relative error determination in the wide device end, in other words to set accurately Z-coordinate in the nanomachine.

The calibration operation (Fig. 2) is on principle inverse to the measurement operation.

The liquid level in the wide end is changed with the help of plunger connected at this time to micrometer head. After the liquid balance setting in two ends the liquid level shift in the narrow end is measured by the means of the Vernier-caliper gauge. Simultaneously the micrometer head is moved to the wide device end. It provides the plunger shift and liquid level on value that meets the level shift in the narrow end during the measurement. So $\Delta h_1 = \Delta H_2 = 5$ μm.

In this case the mentioned shift when the constant A value is equal to 4444.4 specifies the

liquid level shift in the narrow device end on $\Delta h_2 = A\,\Delta H_2 = 4444.4 \times 5 = 22.2$ mm. Under this, device constant A is determined from:

$$A = \frac{\Delta h_2}{\Delta H_2} \tag{4}$$

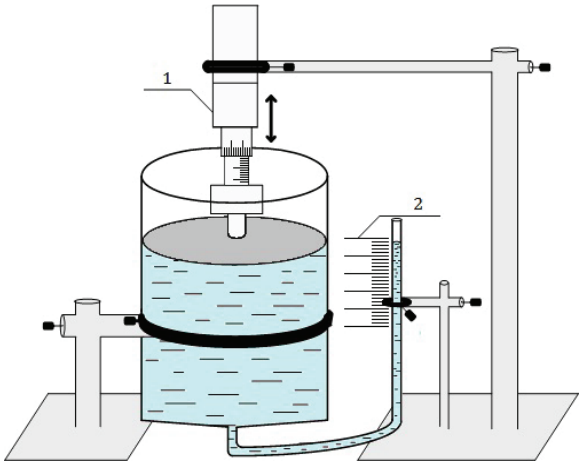

Fig. 2. Unit calibration for hydraulic positioning: 1- micrometer head; 2 – control linear scale of the liquid level shift.

Having placed (4) into (1) liquid column height desired change in the wider end can be found:

$$\Delta H_X = \Delta H_1 = \frac{\Delta h_1}{\Delta h_2}\Delta H_2 = \frac{\left(\Delta h_1\right)^2}{\Delta h_2} \tag{5}$$

Column height change ΔH_x numerical value assessment gives 5^2 μm^2/22.2 mm = 0.0011 μm = 1.1 nm. The error component is absent here that is specified by the device constant A unknown value. But completely known components of relative measurement error of the liquid level displacement appear. The next formula describes it. Aggregate relative error of the liquid level change measurement in the wide device end can be obtained by the differentiating (5):

$$\delta(\Delta H_X) = \delta\left[\frac{\left(\Delta h_1\right)^2}{\Delta h_2}\right] = 2\delta\left(\Delta h_1\right) + \delta\left(\Delta h_2\right) \tag{6}$$

Under the condition of the micrometer head double usage when level measurement is conducted with relative error ± 50 %, the aggregate relative error of before specified new liquid level in the wide end exceeds slightly ± 100 % (± 40 % in the case of liquid level shift control in the narrow end with error ± 1.0 μm). By the way the second component in (6) – insignificant (substantial level shift can be measured quite precisely with relative error not more than ± 2 %).

In the conditions of the studied nanoobject height single fixing so far as the unknown ideal fixing result it is more correctly to work not within the error approach but on the basis of the uncertainty approach. Accordingly with last one [9], [6] the height fixing result is more correctly to write in the form of readout result with established expended standard uncertainty of type A that is in our case $\pm\ 102/\sqrt{3}\ (42/\sqrt{3}) = \pm\ 58.89\ (24.25)$ %.

The calibration obtained results enable to reach efficiency in Z-axis shift control in the nanomachine. To this purpose the calibrated unit with concrete determined ration of two ends areas is used by appointment as described in the Fig. 1. If the average atoms size of liquid is approximately equal to ≈ 3Å = 0,3 nm then current device enables to set the liquid level and nanoobject mounted on the floating platform with absolute error which is slightly more than atoms size.

At the same time the work [8] gives close values of water film estimated thicknesses pretermitting the accuracy issue of their regulation and setting. For instance, thickness of a liquid layer seems to be of order 10 Å at the temperatures up to 3-4 K below the melting point of ice. To determine the thickness at temperatures closer to the melting point, larger simulation cells and more accurate estimates of the melting point are needed. The thickness of a liquid layers determined in this work seems to be of the same order of magnitude as determined by Bluhm *et al.* [10] from photoelectron microscopy.

Thanks to the wide device end and layer-by-layer filling of the liquid this hydraulic positioning method provides the required contact of cantilever and studied nanoobject mounted on floating platform.

During the study of cantilever Z-axis regulating capabilities or shift of the floating platform relative to it by the height with the help of mentioned above it is able to find the next one. Under accurate settings of very small Z-axis values the movable means elements (hydraulic liquid molecules) determine the noise device features. Perhaps, in future it should be taken into account the viscosity fluctuating deviations. They may be specified, for instance, by the temperature deviations from optimal regime, the diversions from the horizontality, the non-discrete character of the every layer filling and some other factors. They determine the noise threshold and limit the device sensitivity.

4. Conclusions

1. Nanotechnology further progress is impossible without methods and means development of nanosamples and sensitive elements stepless reciprocal shift along the Z-axis, for instance, probes and cantilevers that guarantee of tunnel and other phenomena studies that demand exceptional shift accuracy.

2. Hydraulic method and reciprocal shift means of the nanoobject and cantilever enable with the error

of working liquid monomolecular layer thickness order to provide their stepless shift along the *Z*-axis.

3. Simultaneously the systematic multiplicative component of aggregate error is eliminated by the opposing method of error minimization usage in the course of the calibration – standard method of the current error component elimination in the metrology. Therefore noise threshold is displaced in the direction of nanosizes and, as result, *Z*-axis accuracy setting is improved.

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