Research on error correction methods for a novel Nano-CMM

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Abstract: A new type Nano-CMM which has 50× 50× 50mm measuring range is introduced, which is suitable for the micro and thin-wall devices measurement. The structure layout of it is based on the "331" construction principles, it can effectively eliminate the impact of Abbe error on the machine and reduce the guide errors on the measurement results, so it cost less. The article also analyzes the single axis measurement errors which have great influence on the CMM, establishes the error compensation model correspondingly and obtain synthetic errors by measurement. Finally, the sampling data of each error are separated, interpolated and compensated to get each axis's measurement errors in arbitrary position of measuring range.

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NOMENCLATURE

O_i(i=0,1,2) Coordinate system of Z stage in different position

v_L(v=x、y、z) Laser's output

1. Introduction

Microsystems (MEMS) is one of the symbol of modern science and technology. High-accuracy detection of MEMS devices is needed to ensure the quality and accuracy of Microsystems. When the size of the objects is in the centimeter-level and tolerances below the micron-level, traditional coordinate measuring machine will no longer be able to meet the measurement requirements. This requires the development of three-dimensional measuring instruments which has smaller measuring range and higher precision. Therefore, in recent years, the development of small Nano-measuring machine has become a hot research field of modern test technology. Countries around the world invest heavily in research, such as the UK National Physical Laboratory (National Physical Laboratory) have designed a small three-dimensional measuring machine SCMM[1], which is mainly for three-dimensional measurement of micro-devices; Eindhoven university developed a high-precision measuring machine 3D-CMM[2], which layout laser and the probe to meet Abbe principle; The molecular measuring machine[3] of NIST; And the Nano-CMM designed by National Institute of Metrology in China, etc. In order to develop high-precision Nano-measuring machine, number of effective technological measures should be taken. Above all, we must analysis the error factors affecting the measurement precision completely. But the improving accuracy of key parts would cost much. So the methods which both improve accuracy and reduce cost, which is reasonable layout and low-cost error correction technology, will be a particular concern.

2. Innovative Design consideration of Nano-CMM

2.1 The key factors that affect the CMM

Mechanical design for precision instrument is intended to achieve a high position and measuring accuracy (Teague and Evans in 1989)[4]. Also to achieve a small positioning and measurement uncertainty, that is: High repeatability, Low geometric calibration uncertainty, High predictability of the machine response to the main error sources ("design for predictability"). Germany's E. Abbe published the design principles of measuring instrument in 1890, He thought the line of the standard length (standard line) should be collinear with the line of the measured length (measured line) in the length measurement process. This principle is only applicable to one-dimensional measuring instruments, at present there is no scientific design principles for three-dimensional measuring instruments. According to the composition of Nano-CMM, we can get the following number of key factors affecting the measurement accuracy.

(1) Reasonable layout the instrument structure system, it is necessary to ensure the stability of the overall structure, but also has some environmental adaptability. As the Abbe error would bring a first order linear error to the measurement, it has great influence on

measurement result. The Abbe error compensation depends on the accurate measurement of the angle error and Abbe arm. When the Abbe arm is longer, the accuracy of Abbe error separation is difficult to reach the nanometer level. Therefore, a reasonable layout is needed to decrease or eliminate Abbe arm, and .minimize the impact of systematic errors.

(2) The performance of probe should adapt to the overall measurement precision of the instrument, including the sensitivity, repeatability, minimum force and the anisotropy. And rational arrangement of the probe is needed to achieve the best match between the probe system and measurement system.

(3) Make sure the accuracy of single-axis displacement measuring device meets these targets such as high resolution, stability, repeatability, etc. And the measurement system should be isolated from outside influences as possible.

(4) It is impossible to achieve nanometer measurement accuracy by assembling and regulating. Error sources of measuring machine must be analyzed in detail, and the main error must be separated by high precision instruments. Some error suitable for modeling can be compensated by a separate test. Modeling the error model plays a key role in the error compensating, and the stability and repeatability of the measurement system is also very important.

The above key errors factors affect on the overall accuracy of the measuring machine are not in the same degree. In order to improve the final accuracy effective measures should be taken to the main factors. Among them, the measuring machine's structure and layout have greater impacts on the overall measurement accuracy, so the structure system should be properly arranged firstly.

2.2 The structure and distribution of a novel measuring machine

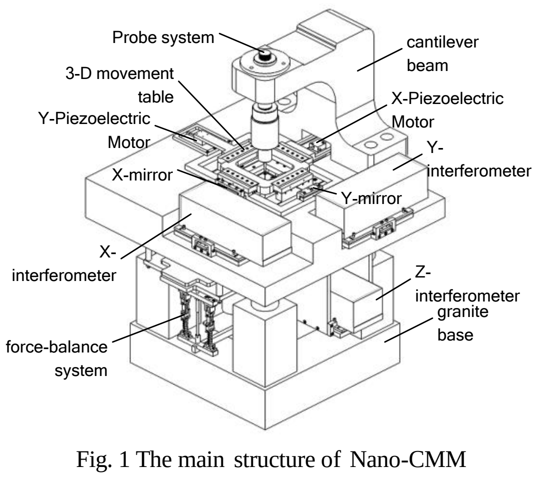

Fig. 1 The main structure of Nano-CMM

The structure of Nano-CMM is shown in figure 1, which is composed by a granite base, a cantilever with a probe, a laser interferometer with three-axes, a metal reflecting plane with three axes, a piezoelectric ceramic driving system with three-axes, a three-dimension working table and a force balance system. The base and the cantilever equipped with the probe[5] are granite which is the main frame of measuring machine. The moving range of three-dimension movement table is 50×50×50mm. Lapping metal reflecting planes are respectively fixed on the outboard of the working table to detect the displacement of each direction. In order to effectively avoid the structural deformation caused by temperature change and minimize the influence of thermal error, the whole measuring machine is placed in an independent vibration isolation thermostat with constant temperature and humidity and thermostat's temperature control accuracy can be below 0.05℃.

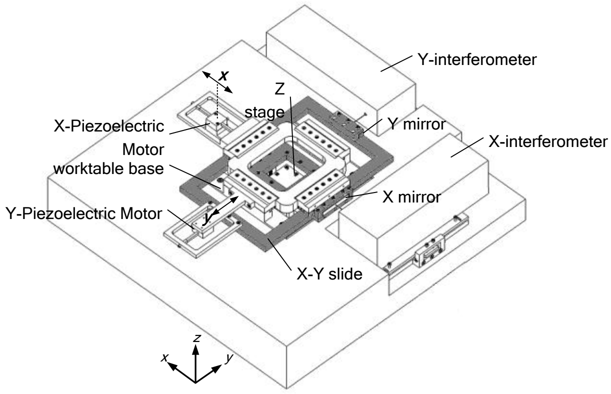

Fig. 2 Design of coplanar moving platform

The distribution of measuring machine's structure follows the "331" [6] principle: Three measuring line intersect to one point; X、Y plane of guide overlap with measuring plane; The intersection point of three measuring lines is on the measuring plane. And as shown in figure 2, slide table of X-Y direction is designed in the form of mutual nesting to ensure X and Y guide rails are in the same height, and ensure the planes of X, Y guide overlap with measuring plane. Z-direction working table with a reflecting plane fixed on its base is nested in X-Y sliding table individually and can rise and fall unrestrainedly. After the adjustment of laser and 3-dimension movement table, adjust the height of probe system to enable probe's center is on the intersection point of laser's three axes. This type of distribution can eliminate the influence of Abbe error from principle and lower effect that rails' movement errors bring to working table. The elaborate discussion of "331" principle is shown in No.6 reference document.

3. Error analysis of measuring machine and error building of an individual axis

There are many factors can influence measuring machine's precision. Except the measurement environment, the main errors are caused by the imperfection of measuring machine's mechanical structure which is called structural errors or geometrical errors. Besides the measurement errors of the laser interferometer system, the main errors sources are the flatness yaws and out-of-squareness of the three metal reflectors, the motion error of Z axis. In addition, three measuring line not intersect to one point or X、Y guide plane not overlap with measuring plane will cause errors Δs to measurement results. The affection of it is the same as Abbe errors. (Δq: angle error of guide)

Δq / Δs	1″	2″	5″
0.5mm	2.5nm	5nm	12.5nm
1.0mm	5nm	10nm	25nm
2mm	10nm	20nm	50nm

Table 1 The affection of not intersect to one point and not overlap with measuring plane to measurement

In addition, single axis's cosine error can be caused because of the included angle between the direction of measuring light beam and rails. Cosine error's can be expressed as $l(1-\cos q)$, when the measurement range is $l=50mm$ and the included angle is 1′, the cosine error is 2nm which can be eliminated by set-up.

3.1 Measurement error analysis of XY axis

According to "331" principle, one-dimension measurement has no first order error (Abbe error). While the measurement is in 2-dimension or 3-dimension, guide's movement errors and parallelism errors of other axis's metal reflecting plane between with the direction of guide. will influence the measurement results.

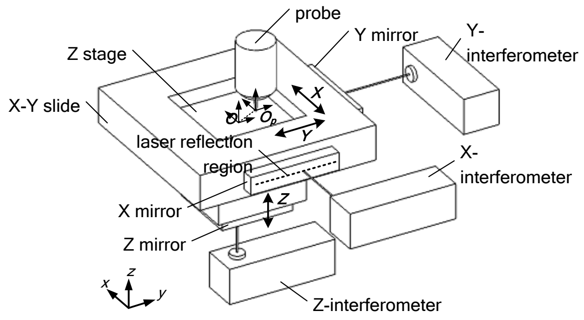

Fig. 3 Design of coplanar moving platform

Simplified model of measuring machine is shown in Figure 3. X, Y direction laser reflecting mirror are separately fixed on each side of X-Y sliding table, Z direction laser reflecting mirror is fixed on the base plate of Z working table. The measuring machine is simplified as a base, an X-Y sliding table and a Z stage, and measuring machine's 3 dimension movement is decomposed into a 2-dimension movement in X-Y plane and a Z direction movement. For expressing the coordinate transformation relation between probe and Z stage, two coordinate system are built: Z stage coordinate system O_i(i=0,1,2) and probe coordinate system O_p. Because probe's relative position to base is immobile, probe coordinate system is the same with machine coordinate system. At the beginning, the both coordinate machine (O_0 and O_p) are enclosing, probe coordinate system's X direction and working table's X direction are enclosing. What we need to obtain is probe's coordinate under Z stage coordinate system O_i.

Take measuring machine's X direction for example (AS is shown in Fig. 4). After X-Y slide table move distance x_L from O_0 to O_1 along X direction, X axis's yaw angle error is $\varepsilon_z(x_L)$, straightness error of Y direction is $\delta_y(x_L)$, parallelism error between Y reflecting plane and X movement direction is $f_y(x_L)$, these errors would cause a extra output of Y laser:

$$\delta_y(x) + x_L \cdot tan(\varepsilon_x(z)) \quad f_y(x_L).$$

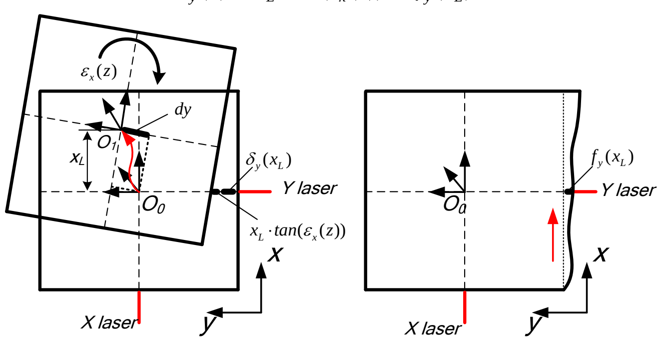

Fig. 4 The measurement error of y axis

The stage move form O_0 to O_1, angular movement error $\varepsilon_z(x_L)$ and straightness error $\delta_y(x_L)$ can cause additional displacement $\delta_y(x) + x_L\ tan(\varepsilon_x(z))$. At the same time, the coordinate's values of O_0 (the center of probe) under the world coordinates also produce a change dy. The calculation shows that they can offset each other.

As a result, when moves along X direction, measuring machine's measurement error of y direction is only y reflecting plane's parallelism error $f_y(x_L)$. For acquiring y reflecting plane's straightness error, take y-direction laser beam as standard, drive measuring machine move along X-direction, and record y laser's output Δy_L. Measurement error compensation model of y direction F_y could be shown as following:

$$\begin{aligned} F_y &= f(x_L, \Delta y, \delta_y, \varepsilon_z) \\ &= \Delta y_L - \delta_y(x_L) - x_L\ tan(\varepsilon_z(x_L)) \end{aligned} \tag{1}$$

X direction measurement error can be analyzed by the same method. When measuring machine is moving along y direction, the structural errors that would influence measuring machine's X direction positioning precision are yaw angle $\varepsilon_z(y_L)$ of Y axis, straightness error $\delta_x(y_L)$ of X direction and perpendicular error θ_{xy} between X axis an Y axis, The model of X direction positioning error F_x is

$$\begin{aligned} F_x &= f(y_L, \Delta x, \delta_x, \varepsilon_z, \theta_{xy}) \\ &= \Delta x_L - \delta_x(y_L) - y_L \cdot tan(\varepsilon_z(y_L)) \quad y_L\ tan(\theta_{xy}) \end{aligned} \tag{2}$$

3.2 Measurement error analysis of Z axis

Measuring machine's Z axis is different from X axis and Y axis. When Z axis moves individually, only Z laser has output change. Besides Z axis positioning error, there are 5 errors[7]: 2 straightness errors、 3 angular movement errors and 2 spatial perpendicular errors between X axis and Y axis. Without the error of laser, when measuring machine moves in X-Y plane, Z direction errors just caused by parallelism error $f_z(x_L, y_L)$ between Z reflecting plane and X-Y measuring plane(shown as figure 5). When measuring machine moves along Z direction, Z reflecting plane's spatial position and attitude will change, Z reflecting plane's pitch angle $\varepsilon_x(z_L)$ and yaw angle $\varepsilon_y(z_L)$ will make parallelism errors of Z reflecting plane changing. So it's complicated to build Z axis error model, the following steps are adapted:

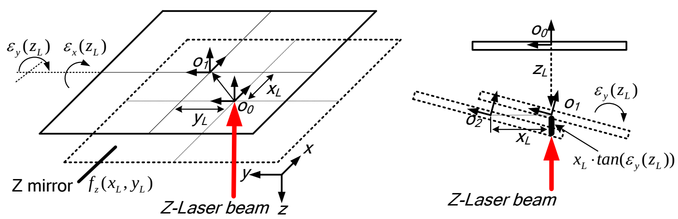

Fig. 5 The measurement error of z axis

(1) Take Z laser as reference, keep Z axis still at zero, drive measuring machine move on X-Y plane, and get Z laser's output $\Delta z_L(x_L, y_L)_0$ at different position of X-Y plane.

(2) Drive measuring machine return to zero on X-Y plane, then drive Z axis to n uniformly-spaced position, Z laser's output $z_L(i)(i = 0 \sim n)$ are working table's actual displacement on Z direction without consideration of cosine error. Then repeat step 1 , get Z laser's outputs $\Delta z_L(x_L, y_L)_i (i = 0 \sim n)$ of the series positions. These outputs contain parallelism error of Z reflecting plane, angular movement errors and actual displacement $z_L(i)(i = 0 \sim n)$, which is a comprehensive error.

Each layer's error compensation model of Z direction positional error $F_z(i)$ can be obtained by use laser's output of each layer minus laser's output at zero point of this layer.

$$F_z(i) = \Delta z_i(x_L, y_L) - z_L(i)(i = 1 \sim n) \tag{3}$$

(4) After finishing the above three steps, measuring machine's 2-dimension error model on Z direction could be gained. Then each layer's 2-dimension error can be acquired by using appropriate interpolating function. After that, measuring machine's Z direction positional error in the whole measurement space can be calculated by 3-dimension interpolation.

4. Three-axis measurement error model based on spline function

4.1 Cubic spline interpolation method

Each axis's measurement error of the Nano-measuring machine needed to be checked according to above analysis. The measurement data $D_i (i = 0 \sim N)$ of the errors are discrete points, so D_i should be interpolated calculation in order to obtain the errors at any position in the travel range. Compared to other interpolation functions, spline interpolation function has the following characteristics: (1) It is piecewise, low polynomial and has better smoothness. (2) Only need to provide the function's values at interpolation nodes and derivatives information of the N boundary nodes (N is the time of interpolating polynomial) [8]. Spline interpolation function has a broad and important application in the project because of cubic spline interpolation functions has a lower frequency and higher order of smoothness. Cubic spline interpolation function can be expressed as:

$$S(x) = M_j \frac{(x_{j+1} - x)^3}{6h_j} + M_{j+1} \frac{(x - x_j)^3}{6h_j}$$

$$+ \left(y_j - \frac{M_j h_j^2}{6} \right) \frac{x_{j+1} - x}{h_j} + \left(y_{j+1} - \frac{M_{j+1} h_j^2}{6} \right) \frac{x - x_j}{h_j}$$

x_j is the sampling location, y_j is a function value of the corresponding position, h_j is the sampling interval, Mj is the bending moment, j=0~N.

For one-dimensional data F_x、F_y can be directly calculated through cubic spline interpolation function, then we can obtain one-dimensional interpolation function. While the measurement errors of Z-axis are related to the three axes, the output value (x_L, y_L, z_L) of the lasers need to be calculated by the cubic spline interpolation three times. The specific interpolation method as follows:

(1) For the two-dimensional error array $F_Z(i)(i = 0 \sim n)$ of each Z layer, the data in each group of x direction were calculated by cubic spline interpolation firstly, which can obtain a set of one dimensional interpolation function group $f_Z(x, i)(i = 0 \sim n)$.

(2) Then calculate the value of $(x_0, y_0)_i (i = 0 \sim n)$ in each measurement plane. Firstly, substitute x_0 into the one-dimensional interpolation function group in this layer, obtained a one-dimensional data group $f_Z(x_0, i)(i = 0 \sim n)$ along y direction; Then one-dimensional interpolation function $f_Z(x_0, y)$ will be obtained by cubic spline interpolation calculation. Finally, Two-dimensional interpolation results $f(x_0, y_0)_i (i = 0 \sim n)$ in the point of (x_0, y_0) acquired when y_0 is substituted.

(3) The results of the two-dimensional interpolation of each layer can be calculated through one-dimensional interpolation in z-axis. Ultimately, one-dimensional interpolations function $f_Z(x_0, y_0, z)$ in z-axis is obtained. The final three-dimensional interpolation results can be got substituted by the z_0 axis.

4.2 The result of interpolation

Take the separation process of the y-axis's measurement error as an example; the measurement error of the Y laser is compensated. Measured range is 50mm, the sampling spacing is 5mm, 4 sets of data measured in one direction and all the values in starting position are cleared. Table 2 shows the compensation results of the y-axis measurement errors according to equation (1).

x_L /mm	Dy_L /um	$d_y(x_L)$ /um	$d_y(x_L)$ /arc sec	result /um
0	0.0	0.0	0.0	0
5	0.26	-0.34	1.1	-0.097
10	-2.45	-0.73	6.1	-3.252
15	-1.3	-0.79	6.7	-2.230
20	-0.01	-0.66	7.3	-0.880
25	0.5	-0.56	8.3	-0.354
30	-0.6	-0.59	11.5	-1.601
35	-0.2	-0.58	13	-1.321
40	0.9	-0.56	13.3	-0.347
45	3.6	-0.42	11.8	2.358
50	2.57	-0.14	14.7	1.497

Table 2 Compensation results of Y-axis measurement errors

Two-dimensional cubic spline interpolation results of reflecting surface in Z direction when Z=0(Shown in Fig. 6).

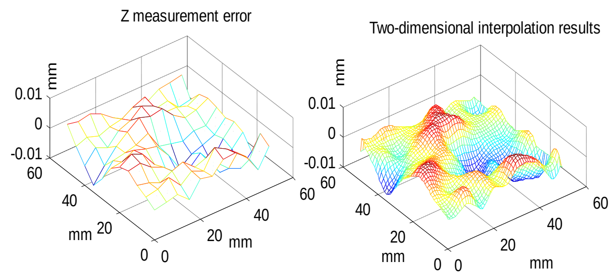

Fig.6 Two-dimensional interpolation results of Z error (Z=0)

5. Conclusions

The Nano-CMM based on "331" design principle is introduced. This specific layout of the machine make it achieves near "zero" Abbe errors. In addition, the article also analyses the errors which affect the measuring machine accuracy mainly, and measurement error compensation model is established for each axis. One dimensional and three dimensional interpolation calculations are made for the sampling data of each axis's errors using cubic spline function, then the values of each axis's measurement error at any position within the range are obtained. This will have some significance on the development of the micro-Nano Coordinate Measuring Machine.

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