Development of high precision Coordinate Measuring Machine - Uncertainty analysis of multi-probe method -

Tomohiko Takamura[1,#], Ping Yang[1], Satoru Takahashi[1], Kiyoshi Takamasu[1], Osamu Sato[2], Sonko Osawa[2] and Toshiyuki Takatsuji[2]

1 Department of Precision Engineering, The University of Tokyo, Tokyo 113-8656, Japan
2 National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki 305-8563, Japan
Corresponding author / takamura@nanolab.t.u-tokyo.ac.jp, TEL: +81-3-5841-6472

KEYWORDS : CMM, multi-probe method, laser interferometer, autocollimator, kinematic error

With the development of micro system technology, the demands for three-dimensional (3D) metrology in the mesoscopic range have been increased. To satisfy these requirements, A high precision Micro-CMM called M-CMM targeting 50nm uncertainty is under development. In order to improve the motion accuracy of each stage on the Micro-CMM, a multi-probe measurement system has been designed and established. The multi-probe scanning system is composed of three laser interferometers and one autocollimator. The autocollimator measures the yaw error of the moving stage, while three laser interferometers simultaneously probe the surface of a reference bar mirror which is fixed on top of the moving stage. The straightness motion error and the reference bar mirror profile are reconstructed by an application of simultaneous equation and least-squares methods.

From the experiment results, we conclude that the systematic error can't be ignored. We evaluate systematic error of nonlinear parameters such as the alignment errors and accuracy of the moving stage. To verify the systematic error, we add non linear parameter to the simulation program. The simulation result shows that yaw error affects systematic error, while random error consists mainly of laser interferometers' error.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

Y = measuring vector
A = jacobian matrix
X = parameter vector
S = weight matrix
$m_k(x)$ = the kth laser interferometer's output at x
$m_a(x)$ = the autocollimator's output at x
$f(x)$ = the profile of the bar mirror at x
$e_s(x)$ = the straightness error of the moving stage at x
$e_y(x)$ = the yaw error of the moving stage at x
u = the sensor offset constant

1. Introduction

1.1 Research background

As part of the trend toward miniaturization and modularization in microsystem technology, the requirements of measuring nano- and microstructures with 3D measurement uncertainty within the range of 0.1 µm have increased. However, conventional measuring methods cannot satisfy the requirements, because the measurement scales of conventional coordinate measuring machines (CMMs) are usually several tens of millimeters or more, which is not suitable for measuring small parts of submillimeter or even submicrometer order. In addition, the conventional CMMs lack the level of 3D measurement uncertainty and are not supplied with the proper probing systems in many applications [1]. Therefore, micro-CMMs with special micro-probe systems for 3D metrology with high-aspect-ratio micro parts are currently being developed to satisfy the described requirements. Some of the micro-CMMs are discussed, and there specifications are shown in Table 1. A novel high-precision micro-CMM called M-CMM has been developed, and a prototype has been built at the Advanced Industrial Science and Technology (AIST). We are aiming at a measurement uncertainty of 3D-coordinates of about 50 nm. To develop the motion accuracy of each stage of the M-CMM, we propose a multi-probe method and discuss its use for evaluating yaw and straightness motion errors.

Micro-CMMs	Range-XYZ[mm]	Uncertainty[nm]
Isara[2]	100×100×40	30
F25	100×100×100	Less than 100
M-NanoCoord[3]	200×200×100	200
M-CMM	160×160×100	Aim for 50

Table 1 Specification comparisons of micro-CMMs

1.2 Configuration of the M-CMM

The configuration of the M-CMM includes three main parts, the Z-axis, probe unit, and XY stage. Each axis has a linear motion stage system composed of air-bearing sliders, glass liner scale, moving table, driving motor and related parts. The linear motion stage systems have been applied successfully to precision measurement systems because the air bearings have no friction and the area averaging effect on the guide error provides high positioning accuracy and low traveling motion error. In addition, the linear scales feedback the position signal within the range of nanometer resolution.

There are three special specifications in the design of the M-CMM. First, the main structure of each axis is made of alumina ceramic that has high rigidity and a low coefficient of thermal expansion (CTE = 5.3 ppm/K), and the base plate of the M-CMM is made of granite of 5 ppm/K CTE. Therefore, the M-CMM has good performance in response to temperature changes, and the thermal deformation due to the driving heat and temperature changes can be significantly reduced.

Second, we divided the XYZ axis into two mechanical parts. One is the Z-axis, which was separately designed and built. The other is the XY-axis, which was stacked in two linear stages. The reason is that the sensitivity of the 3D contacting micro-probes in the Z-direction is usually lower than that in the XY plane because probing direction the length of the stylus has an effect in the horizontal. Therefore, the measurement uncertainty of the Z-axis is larger than that of XY-axis.

Third, the probe unit has a changeable connector by which the M-CMM can use different kinds of contacting probe systems and do the measurement with different levels of uncertainty.

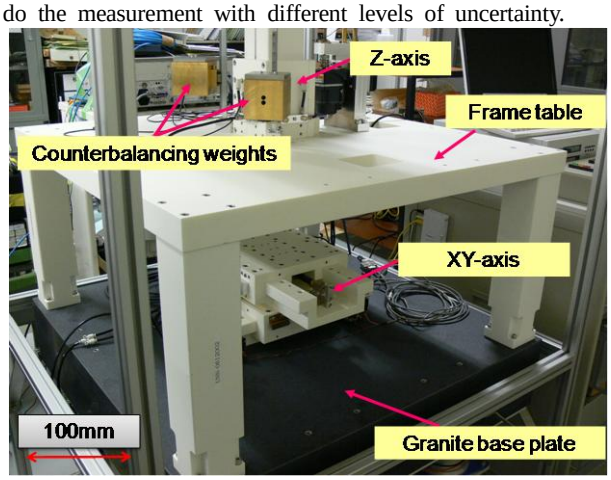


Fig. 1 Main Structure of M-CMM

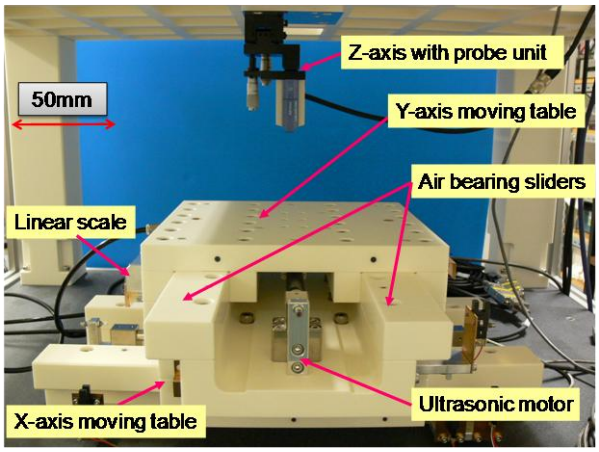


Fig. 2 Structure of XY stage and probe unit

2 Calibration of the M-CMM

2.1 DOF and Abbe error on the M-CMM

In a three-dimensional space, any positioning stage is considered to have six degrees of freedom (DOF): three translational errors and three rotational errors. Abbe errors are caused by the rotational errors of relative translations between the measurement object and probe device, and the offset between the reference and the measurement point. Often Abbe errors are the most important uncertainty sources in dimensional metrology applications aiming for measurement uncertainties of only a few nanometers [4]. For example, the Abbe error δ is approximately 10 nm of error based on a 10 mm moment arm H and a tilt of 1 μrad θ (Fig. 4). Therefore, the 6DOF of each stage on M-CMM is a very important factor in the development of high-precision micro-CMMs.

The motion accuracy values of the M-CMM without any compensation are shown in Table 3. For instance, the value of the Abbe error of the XY-axis can be in the range of micrometers. So the motion errors of the XY stage on the M-CMM should be measured and calibrated. The traditional calibration method using only a single sensor is up to the high accuracy of the reference mirror, because the motion errors are also present. To take this into account, an error separation technique employing several displacement probes was proposed and developed, and other applications using the multi-probe have been widely used in precision measurement [5, 6].In our measurement system, we use the multi-probe method to measure the yaw and straightness motion errors of each linear stage, and the profile of a standard mirror is also reconstructed by application of the simultaneous equation and least-squares methods [7-9].

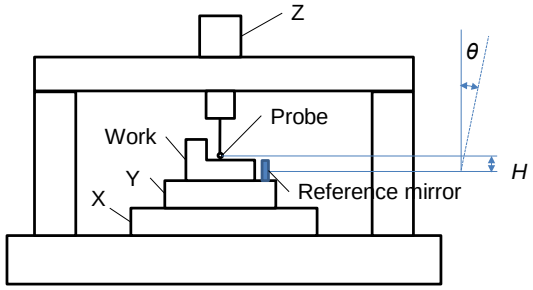


Fig. 3 Illustration of an Abbe error after compensation

Axis	Degree of freedom	Accuracy / range
X,Y	Straightness	Max: 0.5 μm / 160mm
X,Y	Tilting	Max: 8 μrad / 160 mm
Z	Straightness	Max: 0.3 μm / 100 mm
Z	Tilting	Max: 5 μrad / 100 mm

Table 3 Motion accuracy of M-CMM without compensation

2.2 The principle of the multi-probe method

In the measurement system, one autocollimator measures the yaw error of the stage, and multiple laser interferometers measure the profile of a bar mirror fixed on the top of the XY-axis. Unlike fixing the position sensors on a moving scanner, the laser interferometers are mounted stationary, as shown in Fig. 5 [15,16].

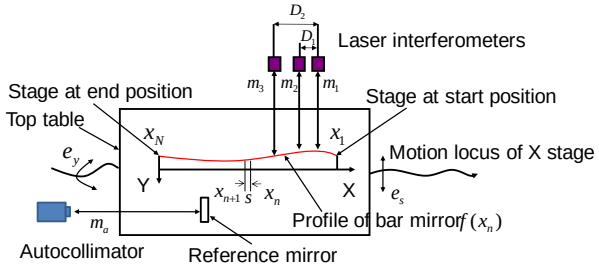


Fig. 4 Principle of the multi-probe method

When let the corresponding laser interferometers and autocollimator outputs be $m_k(x_n)$ and $m_a(x_n)$, the three probes system outputs can be expressed as follows:

$$\begin{aligned} m_1(x_n) &= f(x_n+0)+e_s(x_n)+0\cdot e_y(x_n)+u_1 \\ m_2(x_n) &= f(x_n+D_1)+e_s(x_n)+D_1\cdot e_y(x_n)+u_2 \\ m_3(x_n) &= f(x_n+D_2)+e_s(x_n)+D_2\cdot e_y(x_n)+u_3 \\ m_a(x_n) &= e_y(x_n)+u_a \\ n &= 1\ldots N_s \end{aligned} \quad (1)$$

where f(x_n) denotes the profile of the bar mirror, and $e_y(x_n)$ and $e_s(x_n)$ are the yaw and straightness motion errors of the moving stage. D_1 is the interval of the 2nd to the 1st laser interferometer, and D_2 is the interval of the 2th to the 1st laser interferometer. N_s = N - D_2 is the numbers of sampling points and N is

the sampling point of the bar mirror when s = 1 is the measu ring step distance of sampling points. u are the offsets of each probe.

Eq. (1) can be compactly written with matrix style expressions as follows:

$$\mathbf{Y} = \left[m_1\left(x_{1\ldots N_s}\right), m_2\left(x_{1\ldots N_s}\right), m_3\left(x_{1\ldots N_s}\right), m_a\left(x_{1\ldots N_s}\right)\right]^T$$

$$\mathbf{X} = \left[f\left(x_{1\ldots N-2}\right), e_s\left(x_{1\ldots N_s}\right), e_y\left(x_{1\ldots N_s}\right), c_1, c_2\right]^T \quad (2)$$

$$\mathbf{A} = \frac{\partial \mathbf{Y}}{\partial \mathbf{X}}$$

$$\mathbf{Y} = \mathbf{A}\mathbf{X}$$

where **Y** and **X** denote the measuring vector and parameter vect or involving the profile of bar mirror and the motion errors, res pectively. The jacobian matrix **A** is calculated from **Y** and **X**. T he offset constants c_1 and c_2 are differences of u.

In the analysis, the parameters are reconstructed by the weighte d least-squares methods using pseudo inverse matrix as follows:

$$\mathbf{S} = diag\left(\sigma^2_{m_1}\left(x_{1\ldots N_s}\right), \sigma^2_{m_2}\left(x_{1\ldots N_s}\right), \sigma^2_{m_3}\left(x_{1\ldots N_s}\right), \sigma^2_{m_a}\left(x_{1\ldots N_s}\right)\right) \quad (3)$$

$$\mathbf{X} = \left(\mathbf{A}^T\mathbf{S}^{-1}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{S}^{-1}\mathbf{Y}$$

This means that multi-probe method calculate the each paramete rs; the kinematic errors and the mirror profile, independently. Th e diagonal matrix **S** denotes the uncertainty of laser interferomet ers and autocollimator. The condition of solution existing is GC D(D_1, D_2)=s, and s may be smaller than the physical interval o f probes.

3. Pre-experiment of the three point method

3.1 Configuration of the pre-experiment

The pre-experiment of the multi-probe method is designed to measure the motion accuracy of an XY stage based on a steppe r motor system. In the pre-experiment, one autocollimator measu res the yaw error of the stage and three laser interferometers m easure the profile of a standard mirror fixed on the top of the XY stage. Fig. 5 shows the main setup of the pre-experiment, which is composed of optical refection devices, an XY stepper motor stage, laser interferometers, receivers, beam splitters, optic al refection mirrors, and an autocollimator. The optical refection devices that are fixed on the top of the XY stage consist of a bar mirror, a housing for the bar mirror, and a reference mirro r (mirror 6). (Fig. 6)

The pre-experiment was measured by three laser interferometers and one autocollimator at the same time. The laser interferomet ers probed the profile of the bar mirror and the autocollimator measured the yaw error of the XY stage by the reference mirro r 4 (Fig. 10). The valid size of the bar mirror was about 100 mm×30 mm with an accuracy of λ = 632.8 nm. The sampling l ength of the bar mirror was 101 mm. When the intervals of las er interferometers are D_1= 10 mm and D_2 = 11 mm, the sampli ng interval is s = 1 mm which is smaller than D. The number of sampling points on the bar mirror N is 101, and the number of sampling points on the stage N_s is 80.

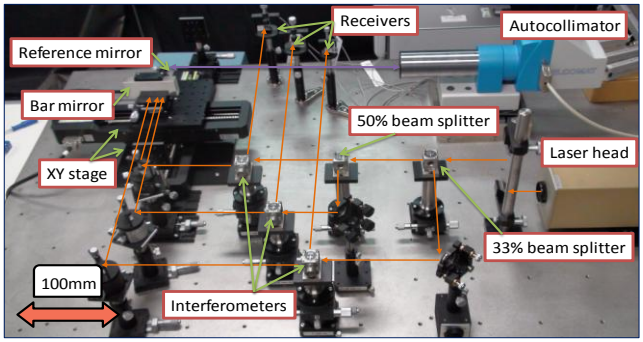


Fig. 5 Main set up of the pre-experiment

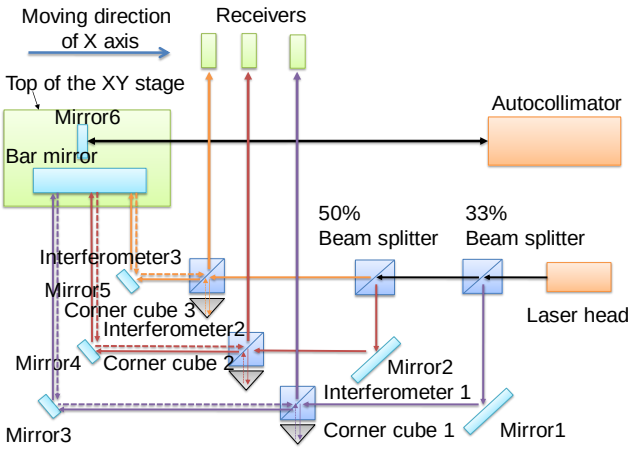


Fig. 6 Block chart of the pre-experiment

3.2 Results of the pre-experiment

During ten repetitions of the experiment, the yaw errors of the X-axis are presented in Fig. 7. The range of the yaw error is about 20 μrad. According to the application of the simultaneous equation and least-squares methods, the straightness errors of th e X-axis are showed in Fig. 8. The range of the straightness m otion error is about ±1 μm. The reconstructed profiles of the ba r mirror are shown in Fig. 9, and the repeatability is good. If we consider standard deviation of each sensor as σ_{m1} =σ_{m2} =σ_{m3} = 8 nm, and σ_{ma} = 0.4 μrad , the uncertainty of the multi-pro be method in the pre-experiment (±2σ) is 9 nm, as shown in Fi g. 10, and the profile standard deviation of the bar mirror calcu lated from the pre-experiment is compared with the theoretical u ncertainty of the multi-probe method. The Fig. 10 shows that th e standard deviation of the bar mirror profile is mainly in the r ange of ±2σ. The multi-probe method performs well in the real application.

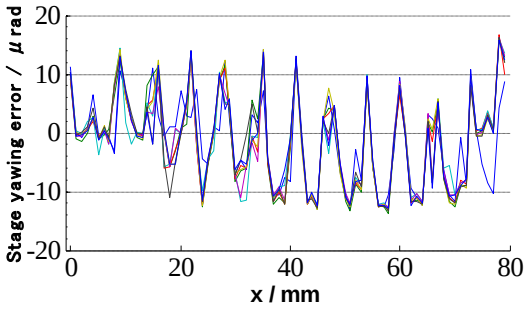


Fig. 7 Yaw error of moving stage

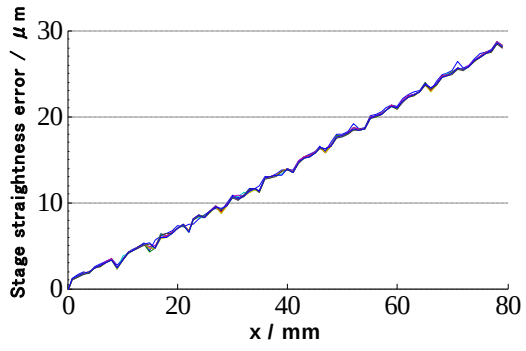


Fig. 8 Straightness error of moving stage

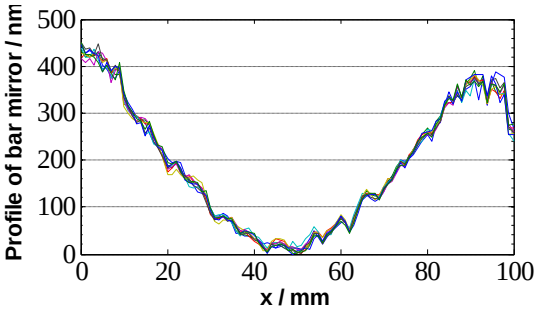


Fig. 9 Profile of bar mirror

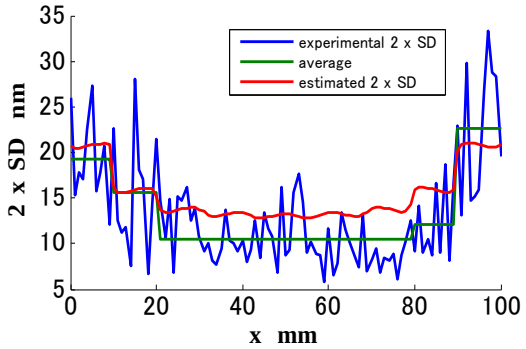


Fig. 10 Experimental and estimated uncertainty

4. Evaluation of the pre-experiment

4.1 Comparisons to the whitelight interferometer

To validate the results of the pre-experiment, we compared the results with that of the white light interferometer. The result of the pre-experiment is mean of 10 times measurement results. The results of the white light interferometer measurement are done by zygo's one before and after the pre-experiment. Because a result of the white light interferometer measurement is generally filtered, we applied the 5 points moving average filter to the results of pre-experiment too to compare.

As the white light interferometer measures the plain profile, we sliced the proper line profile to compare shown in Fig. 11 The result of comparisons is shown in Fig. 12 We conclude that they are equal because the doubled standard deviation of flat area; 9 nm is smaller than 10 nm.

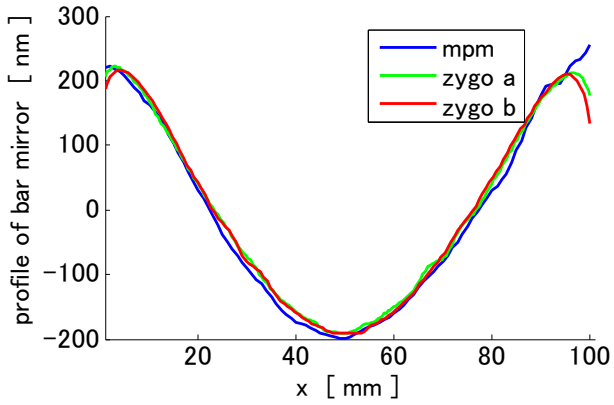


Fig. 11 The mirror profile of each measurement

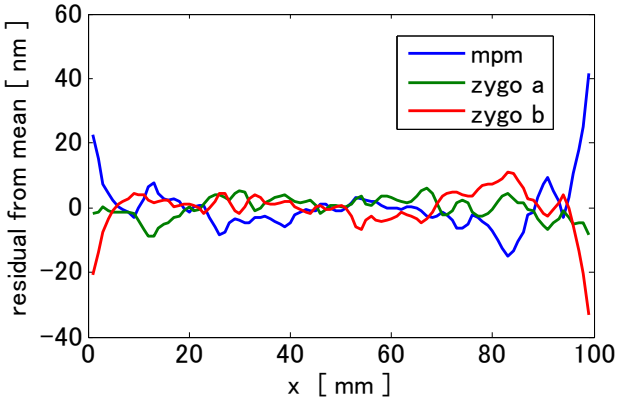


Fig. 12 Comparisons of the mirror profile

4.2 The difference between filtered and non filtered

While the filtered results of the pre-experiment correspond to that of the white light interferometer measurement, the non filtered results don't correspond. So we evaluate the effect of averaging filter on the condition that filtered result is enough precise. The difference between the mirror profile with MA filter and with no filter is shown in Fig. 13. Their uncertainty is 25 nm and show the repeatability while the measurement uncertainty is 11 nm. This means that the systematic error can't be ignored.

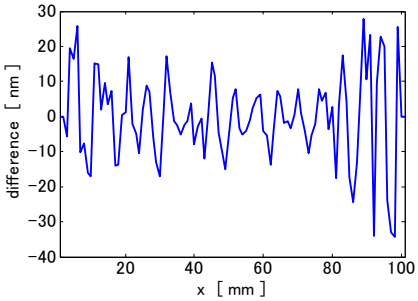


Fig. 13 Differences between filtered and non filtered

5. Estimation of the systematic errors

5.1 The change of the measuring vector

Because the systematic error can't be ignored, we estimated the effect of the systematic errors. At first, we discuss about the change of the measuring vector with non linear term. The non linear measuring vector can be expressed as follows:

$$m_k^{nl}(x_n) = f\left(x_n + D_k + \delta x_k(x_n)\right) + \delta x_k(x_n)\cdot e_y(x_n) + opd_k(\vartheta) + e_s(x_n) + u_k + D_k \cdot e_y(x_n)$$
$$m_a(x_n) = e_y(x_n) + u_a \quad (4)$$

where δx_k is positioning uncertainty of the kth probe and opd_k is the optical path difference of the kth probe.

As shown in Fig. 14 (a), δx_k can be expressed as follows:

$$\delta x_k(x_n) = eD_k + e_x(x_n) + D_k\left(\frac{1}{\cos\left(e_y(x_n)\right)} - 1\right) \quad (5)$$

where eD_k is the alignment error of the kth probe, e_x is moving stage's x positioning error and last term is probe interval changing from yaw error. We estimate that the standard deviation of eD_k is 100 μm as we align the probes with CCD, that of e_x is 20 μm from the moving stage's specification and last term is less than 1 nm from the result of pre-experiment. The total standard deviation of δx_k is 120 μm.

This positioning uncertainty affects to measuring vector. When we assume that e_y = 10μrad and f' = 5 nm, the difference caused by δx_k can be expressed as follows.

$$\delta x_k(x_n)\cdot e_y(x_n) \approx 1nm$$
$$f\left(x_n + D_k + \delta x_k(x_n)\right) = f'(x_n + D_k)\cdot \delta x_k(x_n) \approx 2nm$$

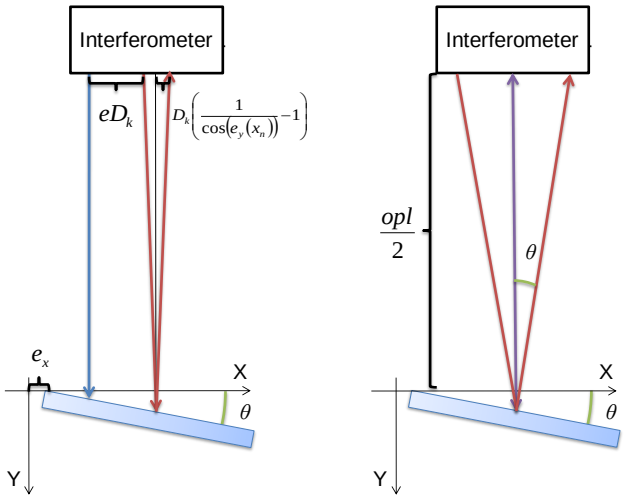
As shown in Fig. 14 (b), opd_k can be expressed as follows:

$$opd_k(\vartheta) = 2opl_k \cdot (\sec(\vartheta) - 1) = opl_k \cdot \vartheta^2 + o(\vartheta^4)$$
$$\vartheta^2 = (e_{yaw} + \varphi_{align})^2$$
$$= {\varphi_{align}}^2 + 2\varphi_{align} e_{yaw} + {e_{yaw}}^2 \quad (6)$$
$$= 2\varphi_{align} e_{yaw} + o(10^{-10}) + const$$

where opl_k is the optical path length of the kth probe which are 500 mm and θ is the angle between the optical path coordinate and the moving stage coordinate which consists with the moving stage's angle alignment error and the yaw error. We estimate that the angle alignment error is 500 μrad from the result of pre-experiment.

This optical path difference also affects to measuring vector. Because constant value stands for the trans offset, the difference caused by opd_k can be expressed as follows.

$$opd_k(e_{yaw}) = 2opl_k \varphi_{align} e_{yaw}$$
$$opd(e_{yaw}) \approx 2 \times 0.5 \times 500 \times 10^{-6} \times 10 \times 10^{-6} = 5\,\text{nm}$$



(a) δx_k (b) opd_k

Fig. 14 The effect of non linear terms

5.2 The change of the jacobian matrix

Secondly, we discuss about the change of the jacobian matrix with non linear terms. When we apply the Eq. (4), we should also apply the following equations:

$$\mathbf{A}^{nl} = \frac{\partial \mathbf{Y}^{nl}}{\partial \mathbf{X}}$$
$$= \frac{\partial}{\partial \mathbf{X}}\left(\left[m_1^{nl}(x_i), m_2^{nl}(x_i), m_3^{nl}(x_i), m_a(x_i)\right]\right) \quad (7)$$
$$\mathbf{X}^{nl} = \left(\mathbf{A}^{nl\mathrm{T}} \mathbf{S}^{-1} \mathbf{A}^{nl}\right)^{-1} \mathbf{A}^{nl\mathrm{T}} \mathbf{S}^{-1} \mathbf{Y}^{nl}$$

But we cannot solve analytically, because these equations are non linear polynomials. In the following simulations, we assume non linear parameters in the jacobian matrix as constant. This method cannot apply to the real measurement, but is enough for evaluate the effect of the change of the jacobian matrix as its act as linear polynomials.

6. Simulation with non linear parameters

6.1 The parameters of simulation

To evaluate the effect of non linear parameters, we performed some simulations. Because the purpose of the simulation is to reproduce the systematic error of the pre-experiment, most parameters are same to the pre-experiment's one. The bar mirror profile f is a convex sine curve whose height is 400 nm (Fig. 15) and the yaw error and the straightness error of the moving stage is mean of the results of the pre-experiment (Fig. 16).

Since the yaw error affects to the non linear terms, we define the uncertainty of the autocollimator as σ_{ma} = 0.5 μrad, besides the uncertainty of the laser interferometers as σ_{mk} = 0.01 nm to fasten the consequenceeee and not to make rankkkk. The sampling length of the bar mirror is 101 mm, the intervals of laser interferometers are D_1= 10 mm and D_2 = 11 mm, the sampling interval is s = 1 mm, the number of sampling points on the bar mirror N is 101 and the number of sampling points on the stage N_s is 80.

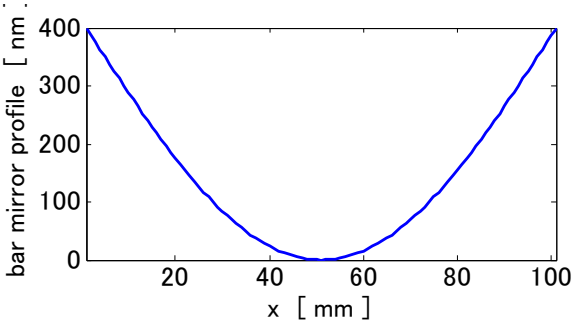


Fig. 15 Profile of bar mirror

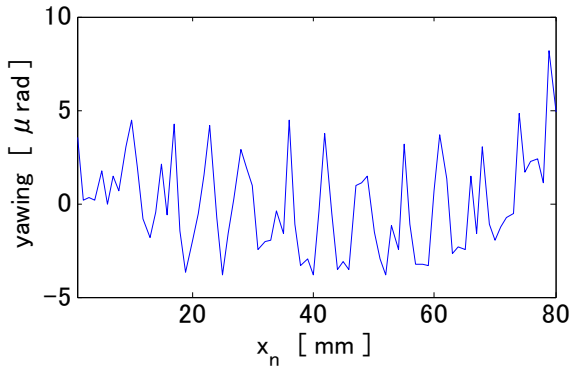


Fig. 16 Yaw error of moving stage

6.2 Effect of the measuring vector

We performed the simulations to evaluate the effect of the measuring vector difference. At first, we constructed the $\mathbf{Y}^{nl}$ from the parameters. Then we reconstructed the $\mathbf{X}^{nl}$ from $\mathbf{A}$ and $\mathbf{Y}^{nl}$. At last, we compared the 1000 times results mean of the reconstructed $\mathbf{X}^{nl}$ with the original $\mathbf{X}$. The non linear parameters are defined as followed:

1. Only the positioning uncertainty δx_k
   eD_k : 100 mm
   e_x : 20 mm
   φ_{align} : 0 mrad
   opl_k : 0 mm
2. Only the optical path difference opd_k
   eD_k : 0 mm
   e_x : 0 mm
   φ_{align} : 500 mrad
   opl_k : 500 mm
3. Both of them
   eD_k : 100 mm
   e_x : 20 mm
   φ_{align} : 500 mrad
   opl_k : 500 mm

The mean residual of the bar mirror profile is shown as Fig. 16. The results show that the systematic error on the parameter setting 1, 2, and 3 is 4 nm, 3 nm and 7 nm respectively.

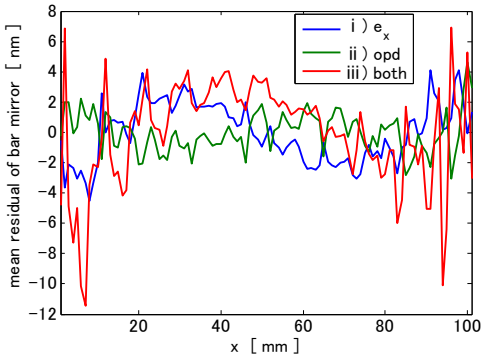


Fig. 16 The effect of non linear terms

6.3 Effect of the jacobian matrix

We performed the simulations to evaluate the effect of the jaco bian matrix difference. At first, we constructed the $\mathbf{Y}^{nl}$ from the parameters. Then we reconstructed the $\mathbf{X}^{nl}$ from $\mathbf{Y}$ and $\mathbf{A}^{nl}$. At last, we compared the 10000 times results mean of the reconst ructed $\mathbf{X}^{nl}$ with the original $\mathbf{X}$. The non linear parameters were same as that of 6.2(3). Because the results of $\mathbf{X}$ were unique fo r each non linear parameter settings, the results wouldn't conseq uenaat to average.

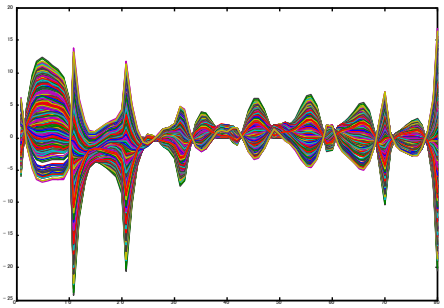


Fig. 17 The residual of the straightness error

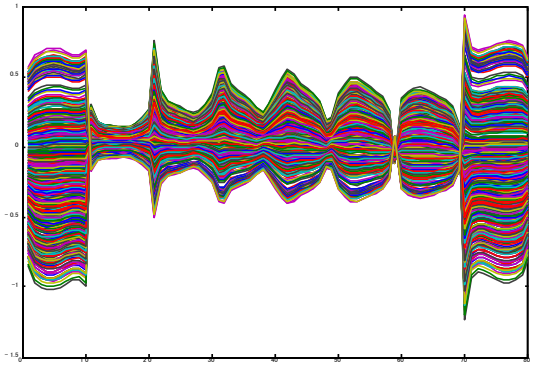


Fig. 18 The residual of the yaw error

7. Conclusion

To calibrate the motion error of the M-CMM, we devised a m ulti-probe method. At first, we used one autocollimator and thre e laser interferometers to measure the yaw and straightness error s of the stage, and the profile of the bar mirror could be calcul ated simultaneously, then compared the results of a pre-experime nt with that of a white light interferometer. Secondly, we discus sed about non linear parameters for estimating the systematic err or. At last, we perform a simulation with non linear parameters.

The conclusions of this study are summarized as follows:

1. The pre-experiment results showed that the uncertainty wit h no filter was 11 nm and that with MA filter was 6 nm, which was enough small to calibrate. The mirror profile measuring with a white light interferometer was equal to t he pre-experiment result with MA filter.
2. The difference between the mirror profile with MA filter a nd with no filter was 25 nm and showed the repeatability. This means that the systematic error can't be ignored.
3. The simulation with non linear measuring vector results sh owed that the average residual of mirror profile between o riginal and reconstructed was 7 nm (Table 4).
4. The simulation with non linear jacobian matrix results sho wed that the average residual of mirror profile between ori ginal and reconstructed was 10 nm (Table 4). In the real measurement, this effect as one set of differences, not as a verage of that.

The estimation and simulation result shows that yaw error affe cts systematic error, while random error consists mainly of laser interferometers' error. To improve the yaw error of moving sta ge will decrease the systematic error. Our future work is to appl y the M-CMM air bearing stage for achieving 2 nm systematic error and 6 nm random error, which is smaller than 10 nm.

The result of pre-experiment	25 nm
From the positioning uncertainty	4 nm
From the optical path difference	3 nm
From the jacobian matrix	10 nm
Total of the non linear terms effects	17 nm

Table 4 The systematic error estimation

ACKNOWLEDGEMENT

The present work was supported in part through the Global COE Prog ram, "Global Center of Excellence for Mechanical Systems Innovatio n," by the Ministry of Education, Culture, Sport, Science and Technol ogy.

REFERENCES

[1] Cao S, Brand U, Kleine-Besten T, HoffmannW H, Schwen ke, B¨utefisch S, and B¨uttgenbach S. Recent developments in dimensional metrology for microsystem components. M icrosyst. Technol. 2002;8; 3-6

[2] Vermeulen MMPA, Rosielle PCJN, and Schellekens PHJ. Design of a high-precision 3D-coordinate measuring machi ne. Annals of the CIRP1998; 47 (1); 447-450

[3] Mitutoyo, UMAP Vision System, Bulletin No. 1631.

[4] Bryan JP. The Abbe principle revisited: an updated interpre tation. Prec. Eng. 1979; 1; 129-32

[5] Whitehouse DJ. Some theoretical aspects of error separatio n techniques in surface metrology. J. of Phys. E: Sci. Instr um. 1976; 9; 531-536

[6] Gao W, Yokoyama J, Kojima H, and Kiyono S. Precision measurement of cylinder straightness using a scanning mult i-probe system. Prec. Eng. 2002; 26; 279-88

[7] Yang P, Shibata S, Takahashi S, Takamasu K, Sato O, Osa wa S, and Takatsuji T. Development of high precision Coo rdinate Measuring Machine (CMM) (1st report, Evaluation method of XY stage). JSPE autumn conference 2009, pp. 725-726

[8] Yang P, Shibata S, Takahashi S, Takamasu K, Sato O, Osa wa S, and Takatsuji T. Development of high precision Coo rdinate Measuring Machine (CMM) (2nd report, Pre-experi ment of multi-probe method for evaluating the XY stage). JSPE spring conference 2010, pp. 377-378

[9] Tomohiko Takamura, Ping Yang, Satoru Takahashi, Kiyoshi Takamasu, Osamu Sato, Sonko Osawa, Toshiyuki Takatsuj i, 2010, Development of high precision Coordinate Measuri ng Machine (CMM) (3rd report, Evaluation of the form of referential mirror and the kinematic error of stage by 3-pr obe method), 2010 JSPE autumn conference, pp.515-516