A THREE LASER INTERFEROMETERS AND ONE AUTOCOLLIMATOR SYSTEM FOR MEASURING THE YAW AND STRAIGHTNESS ERRORS OF A XY STAGE ON HIGH PRECISION CMM

Ping YANG[1], Shusaku SHIBATA[1], Tomohiko TAKAMURA[1], Satoru TAKAHASHI[1], Kiyoshi TAKAMASU[1], Osamu SATO[2], Sonko OSAWA[2], Toshiyuki TAKATSUJI[2]

1 Department of Precision Engineering, The University of Tokyo, Tokyo 113-8656, Japan, yangping@nanolab.t.u-tokyo.ac.jp

2 National Institute of Advanced Industrial Science and Technology, Ibaraki 305-8563, Japan

Abstract:

To develop a high precision micro coordinate measuring machine (Micro-CMM), it is important to evaluate motion accuracy of each stage on the Micro-CMM. A three laser interferometers and one autocollimator system has been designed and established. In the system, the autocollimator measures the yaw error of the stage, and three laser interferometers simultaneously measure the profile of a standard mirror which is fixed on the top of a X-Y stage. The straightness error is reconstructed by the application of simultaneous equation and least-squares methods. With the different intervals of laser interferometers, the results of the standard deviation of multi-probe method are being discussed.

Keywords: Multi-probe method, Micro-CMM, Yaw error, Straightness error, X-Y stage

1. INTRODUCTION

With the development of microsystem technology, the demands for three-dimensional (3D) metrology on microsystem components have been increased. However, conventional measuring methods can not satisfy the requirements of 3D measurements of microscale features at nanometer resolution. Because, conventional coordinate measuring machines (CMMs) lack the level of measurement uncertainty and do not supply with the proper probing systems in many applications [1]. Therefore, the micro-CMMs are currently developed with special micro-probe systems for 3D metrology with high-aspect-ratio micro parts in decades. Some of the micro-CMMs are discussed in the following projects.

Isara is commercial small CMM which is now available from IBS Precision Engineering. Its design is a metrology frame with thermal shielding on which three laser sources are mounted and a moving product table [2]. F25 micro-CMM is another commercial product available from Carl Zeiss. The National Physical Laboratory (NPL) is currently carrying out research into reducing the size of the probing sphere to allow measurement of even smaller structures. VSL is studying the traceability of the F25. The Physikalisch-Technische Bundesanstalt (PTB) works together with Carl Zeiss that are researching on the field of 3D micrometrology. M-NanoCoord designed by Mitutoyo is a flexible 3D vision measuring machine using the UMAP switching probe system [3]. The specifications of these products are showed in the Table 1.

A novel high precision micro-CMM called M-CMM has been developed, and a prototype has been settled up at the Advanced Industrial Science and Technology (AIST). And we are aiming at a measurement uncertainty of 3D-coordinates of about 50nm.

Table 1: Specification comparison of micro-CMMs

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

2. CONFIGURATION OF THE M-CMM

The configuration of the M-CMM includes three main parts: Z-axis, probe unit, and X-Y axis. The main structure of each axis is made of alumina ceramic that CTE (coefficient of thermal expansion) is about 7ppm, and the base plate of M-CMM is made of granite of 5ppm CTE. Therefore, the each axis has the good performance with the effect of temperature changes, and the thermal deformation dues to the driving heat and temperature changes can be significantly reduced.

The Z-axis is embedded in the center of a table frame which is built on the base plate, as show in Fig. 1. The motion system in Z-axis is composed of a counterbalancing weight, air bearing sliders, an AC servomotor, and etc. The Z-stage moves separately so that the Z-axis performs better static stiffness than the traditional types of CMM. The probe unit that has a changeable connector is mounted on the Z-axis, as shown in Fig. 2. Therefore, the M-CMM can do the measurement with the different probing systems that contain Renishaw TP200 and Mitutoyo UMAP103 to achieve different level of the 3D uncertainty.

The X-Y axis is a stacking-type mechanism made by two linear stages that are composed of air bearing sliders, ultrasonic motors, moving stages, linear scales and etc., as shown in Fig. 2. Each stage of X-Y axis is drive by the ultrasonic motor and its movement is detected by the linear scale which is mounted on side of the moving stage.

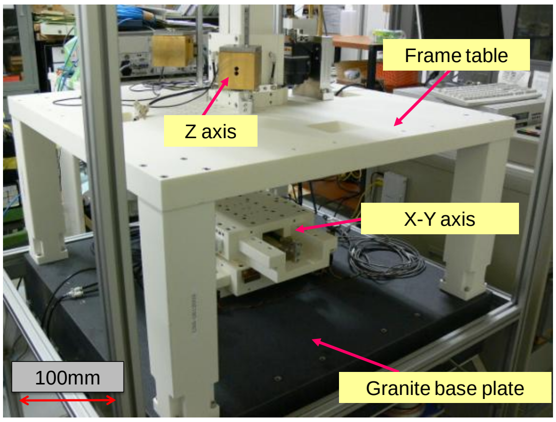

Fig. 1: Main Structure of M-CMM

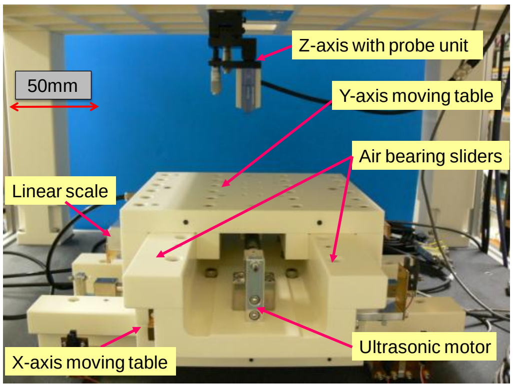

Fig. 2: Structure of XY stage and probe unit

3. CALIBRATION AND MULTI-PROBE METHOD

The motion accuracy of M-CMM is a very important factor in the development of high precision micro-CMMs. Because of the Abbé error is created by the motion accuracy of each stage. The motion accuracy values of M-CMM without any compensation are showed in the Table 2. For instance, the Abbé error of X-Y axis can be in the range of micrometers. So the Abbé error of the XY stage on M-CMM should be calibrated and compensated. To reduce the Abbé error in vertical direction, it is important to measure the straightness and the yaw errors of each moving stage of the X-Y axis. The multi-probe method has been proposed for this purpose [4][5].

Table 2: Motion accuracy of M-CMM without 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

In our multi-probe measurement system, one autocollimator measures the yaw error of the stage, and three laser interferometers measure the profile of a bar mirror which is fixed on the top of X-Y axis. Unlike fixing the position sensors on a moving scanner, the laser interferometers are mounted stationary, as show in the Fig. 3. Let the corresponding probe outputs be $m_1(n)$, $m_2(n)$, $m_3(n)$ and $m_a(n)$, these can be expressed as

$$\begin{cases} m_1(n) = f(x_n+0)+e_s(n)+0\cdot e_y(n)+u_1+b_0, \\ m_2(n) = f(x_n+D_1)+e_s(n)+D_1\cdot e_y(n)+u_2+b_0, n=1...N, \\ m_3(n) = f(x_n+D_2)+e_s(n)+D_2\cdot e_y(n)+u_3+b_0, \\ m_a(n) = e_y(n)+u_4, \end{cases} \quad (1)$$

where D_1 and D_2 are the intervals of the laser interferometers, s is the measuring step distance of the stage, n is the data number over the entire scanning length, $e_s(n)$ and $e_y(n)$ are the straightness and yaw errors of the moving stage, u_1 , u_2 , u_3 and u_a are the offset of each probe, and b_0 is an unknown fixed parameter. The $e_y(n)$ is measured by the autocollimator, and the $e_s(n)$ is reconstructed by the application of simultaneous equations (Eq. 1) and least-squares methods. The uncertainty of the multi-probe method is simulated.

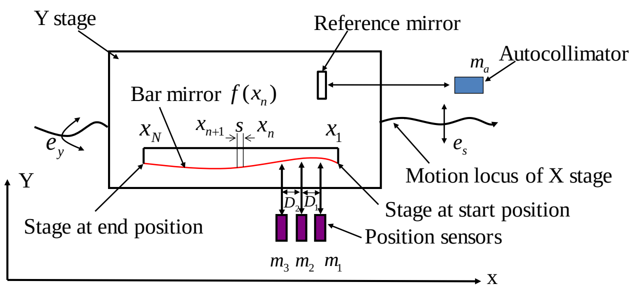

Fig. 3 Principle of the multi-probe method

4. SIMULATION

The multi-probe method was evaluated theoretically by computer simulation. In the simulation program, the profile of bar mirror $f(x_n)$ is predefined, and the straightness error $e_s(n)$ and the yaw error $e_y(n)$ is the random number from the initialization. Each sampling point of $f(x_n)$ is picked up by the predefined function. When $D_1 = 10\ mm$, $D_2 = 11\ mm$, and $s = 1\ mm$ that the difference value of D_1 and D_2 is the same as the measuring step distance, and the offset of each probe is considered as 0, the equations from (Eq. 1) can be simplified. The sampling length of bar mirror equals 100 mm. The resolution of laser interferometer (model 10705A, made by Agilent) is about 1.2 nm. The accuracy of autocollimator is ±0.1 arc-sec (about 0.5μrad) over any 20 arc-sec range (model Elcomat 3000, made by Moller-Wedel Optical). Therefore, we considered the standard deviation of each probe is considered as $\sigma_{m1} = 1.2$ nm, $\sigma_{m2} = 1.2$ nm, $\sigma_{m3} = 1.2$ nm, and $\sigma_{ma} = 0.5$ μrad . The simulation result of the uncertainty value ±2σ is about ±10 nm (Fig. 4).

The simulation result shows that the multi-probe measurement method is found to have a good performance in measuring the straightness profile and the yaw error with small standard deviation. And we also have designed and set up pre-experiment for verifying the multi-probe method in the real application.

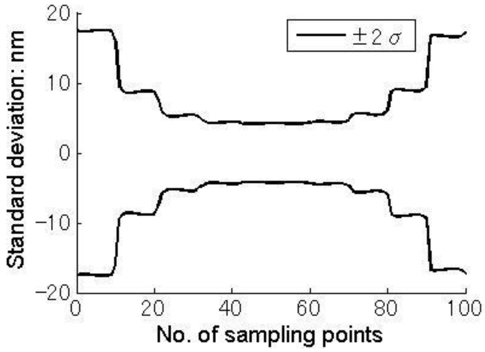

Fig. 4 Uncertainty of multi-probe method

5. CONFIGURATION OF THE PRE-EXPERIMENT

The pre-experiment of multi-probe method is designed for measuring the motion accuracy of a XY stage based on a stepper motor system. In the pre-experiment, one autocollimator measures the yaw error of the stage, and three laser interferometers measure the profile of a standard mirror which is fixed on the top of the XY stage. Fig. 5 shows the main set up of the pre-experiment. This pre-experiment is composed of optical refection devices, a XY stepper motors stage, laser interferometers, receivers, beam splitters, optical refection mirrors and an autocollimator. The optical refection devices which are fixed on the top of the XY stage consist of a bar mirror, a fixing part and a reference mirror (mirror 6). (Fig. 6)

The pre-experiment was measured by three laser interferometers and one autocollimator at the same time. Three laser interferometers probe the profile of the bar mirror and one autocollimator measure the yaw error of the XY stage by the reference mirror6 (Fig. 6). The moving direction of X axis is from left to right as the Fig. 6 showed. The valid size of bar mirror is about 100mm×30mm with the accuracy of λ. The sampling length of bar mirror equals 100 mm. When $D_1 = 10\,mm$, $D_2 = 11\,mm$, and $s = 1\,mm$ that the difference value of D_1 and D_2 is the same as the measuring step distance s, and the offset of each probe is considered as zero. The moving distance of X axis is 79 mm

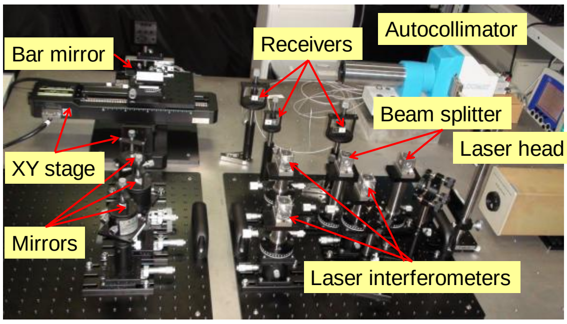

Fig. 5 Main set up of the pre-experiment

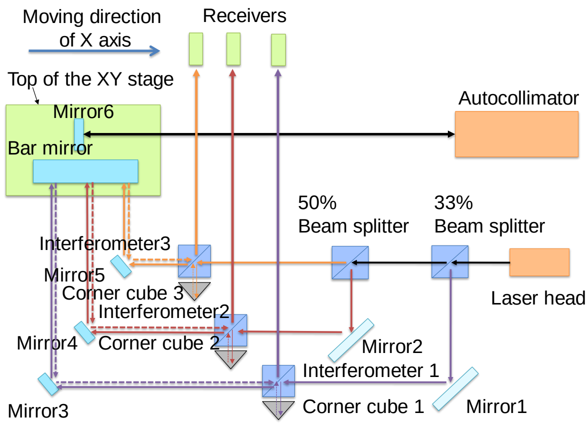

Fig. 6 Block chart of the pre-experiment

6. RESULTS OF PRE-EXPERIMENT

In order to verify the standard deviation of each sensor in the real environment, we have measured the stability of laser interferometers and the autocollimator that are showed as Fig. 7 and Fig. 8. So the standard deviations of laser interferometers and the autocollimator are considered as $\sigma_{m1} = 10$ nm , $\sigma_{m2} = 10$ nm , $\sigma_{m3} = 10$ nm , and $\sigma_{ma} = 0.5$ μrad in the pre-experiment.

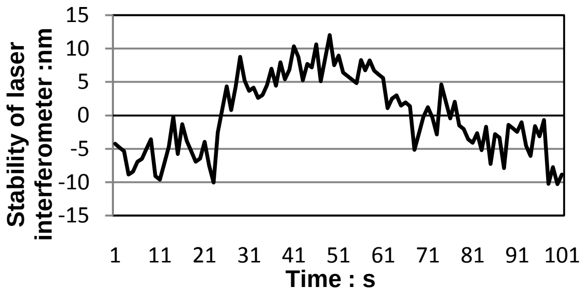

Fig. 7 Stability of laser interferometer

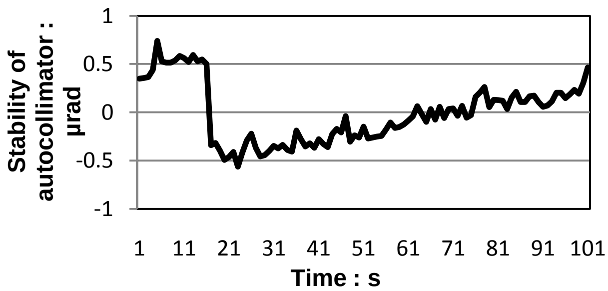

Fig. 8 Stability of autocollimator

During nine times of experiment, the yaw errors of X axis are presented in Fig. 9. According to the application of simultaneous equation and least-squares methods, the straightness errors of X axis are showed in Fig. 10. And the reconstructed profiles of bar mirror are showed in Fig. 11. The uncertainty ($\pm 2\sigma$) simulated by the theoretical parameter is about ±10 nm as showed in Fig. 4. However, the uncertainty of multi-probe method in the pre-experiment

(±2σ') is about ±25nm as showed in Fig. 12. And the profile standard deviation of bar mirror that is calculated by the nine times pre-experiment is compared with the uncertainty of multi-probe method. The Fig. 12 showed that the profile standard deviation of bar mirror is mainly in the range of the ±2σ'.

The reason that the 2σ' is 15nm bigger than the 2σ, because the deviation value of the laser interferometer in the pre-experiment is about 10 times worse than the theoretical value is being considered. There are two main factors affect the deviation value of the laser interferometer. One is the set up of the optical device and the other is the impact from the measurement enviroment, such as air refractometry, vibration and so on. And these factors will be more considered in the next experiment.

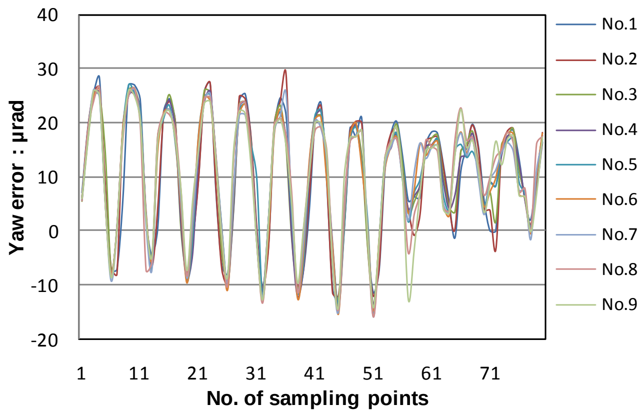

Fig. 9 Yaw error

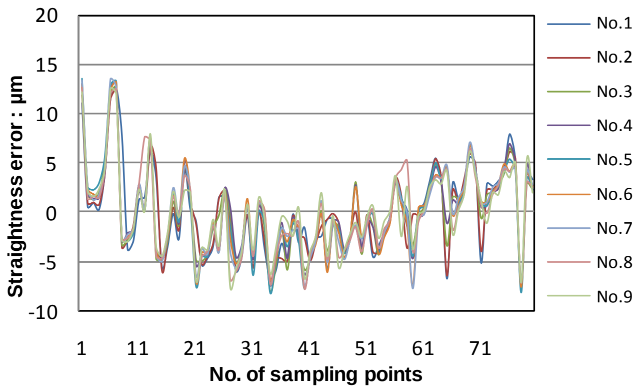

Fig. 10 Straightness error

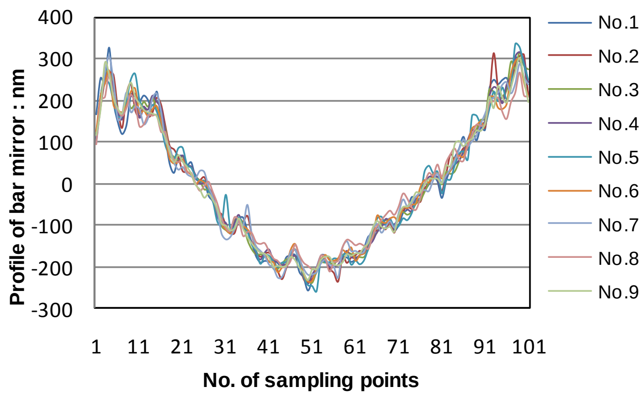

Fig. 11 Profile of bar mirror

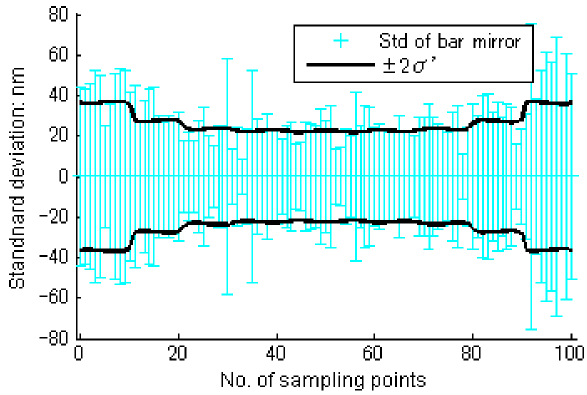

Fig. 12 Profile standard deviation of bar mirror comparing with the uncertainty of multi-probe method

7. CONCLUSIONS

The multi-probe measurement method is found to have a good performance in measuring the straightness and the yaw errors. But the resolution of laser interferometer in the pre-experiment is worse than the theoretical value. The influencing factors are being considered. And we are going to do the new pre-experiment in the near future and do the improvement.

ACKNOWLEDGEMENTS

The present work was supported in part through the Global COE Program, "Global Center of Excellence for Mechanical Systems Innovation," by the Ministry of Education, Culture, Sport, Science and Technology.

REFERENCES

[1] S. Cao, U. Brand, T. Kleine-Besten, H. HoffmannW, Schwenke, S. B¨utefisch and S. B¨uttgenbach, " Recent developments in dimensional metrology for microsystem components", *Microsyst. Technol.* 8, pp. 3-6, 2002.

[2] M.M.P.A. Vermeulen, , P.C.J.N. Rosielle , Schellekens, and P.H.J, "Design of a high-precision 3D-coordinate measuring machine", Annals of the CIRP, 47 (1), pp. 447-450, 1998.

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

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

[5] P. Yang, S. Shibata, S. Takahashi, K. Takamasu, O. Sato, S. Osawa and T. Takatsuji, "Development of high precision Coordinate Measuring Machine (CMM) (2nd report, Pre-experiment of multi-probe method for evaluating the XY stage)", 2010 JSPE spring conference, pp.377-378, 2010.