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A Multi-probe Measurement Method to Evaluate the Yaw and Straightness Errors of XY Stage on High Precision CMM

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Abstract. To develop a high precision Micro Coordinate Measuring Machine (Micro-CMM), it is important to evaluate an X-Y stage on the Micro-CMM. A precision multi-probe measurement system has been designed and developed for simultaneously measuring the yaw and straightness errors of the X-Y stage. In the system, an autocollimator measures the yaw error of the stage, and two laser interferometers measure the profile of a standard mirror which is fixed on the X-Y stage. The straightness error is reconstructed by the application of simultaneous equation and least-squares methods, and the uncertainty associated with the multi-probe method is simulated. When the interval of the laser interferometers equals 10 mm, the standard deviation of multi-probe method using the high accuracy autocollimator and the laser interferometers is about 10 nm. The simulation results satisfy our purpose for the uncertainty of 50 nm, and practical considerations are discussed.

Introduction

As micro-systems have been developed continuously, the demands for higher measurement accuracy have increased in the field of dimensional metrology. Conventional measuring methods restrict the possibilities for three-dimensional measurements on small size products with nanometer accuracy. Conventional coordinate measuring machines (CMMs) lack the level of measurement uncertainty and do not supply with the proper probing systems in many applications [1]. The micro-CMMs are currently developed with special micro-probe systems in decades. 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 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 for the uncertainty of M-CMM is 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

Configuration of the M-CMM

The structure of the M-CMM includes three main components: Z-axis, probe unit, and XY-axis. The whole stage is made of alumina ceramic of 7ppm CTE (coefficient of thermal expansion), and the base plate is made of granite of 5ppm CTE. Therefore, the thermal deformation dues to the driving heat and temperature changes can be significantly reduced.

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

The XY-axis is a stacking-type mechanism made by two linear stages that composed of air bearing sliders, ultrasonic motors, moving stages, etc., as shown in Fig. 2. Each axis motion is actuated by a ultrasonic motor and its motion is detected by a linear scale mounted on the moving stage.

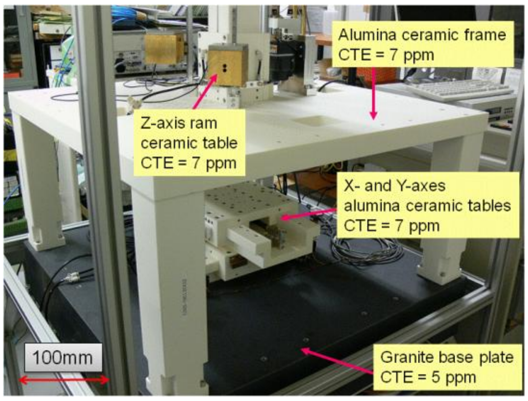

Fig. 1 Main Structure of M-CMM

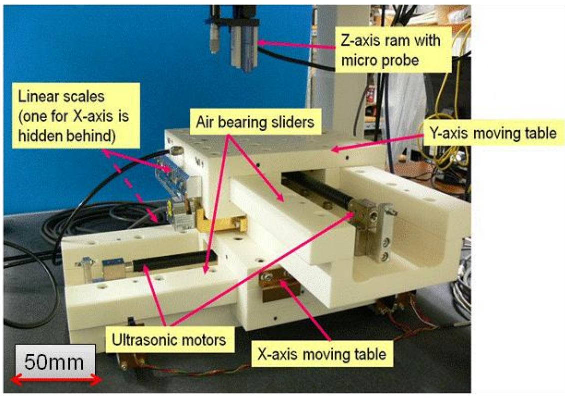

Fig. 2 Structure of XY stage and probe unit

Calibration of M-CMM

In order to develop the high motion accuracy of M-CMM, the Abbé error of the XY stage on M-CMM should be considered and calibrated. Because the Abbé error is high and the motion accuracy of each stage is made in the range of micrometers. To improve the Abbé error in vertical direction of the motion accuracy, it is important to measure the straightness and the yaw errors of each moving stage on the M-CMM. The multi-probe method has been proposed for this purpose [4][5].

In the multi-probe system, one autocollimator measures the yaw error of the stage, and two laser interferometers measure the profile of a bar mirror which is fixed on the XY stage. 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 $m_1(n)$, $m_2(n)$, $m_a(n)$ and, these can be expressed as

$$\begin{cases} m_1(n) = f(x_n) + e_s(n) + 0 \cdot e_y(n) + u_1 + b_0, \\ m_2(n) = f(x_n + D) + e_s(n) + D \cdot e_y(n) + u_2 + b_0, \quad n = 1 \ldots N_s \\ m_a(n) = e_y(n) + u_a, \end{cases} \tag{1}$$

where D is an interval of the laser interferometers, N is the data number of the bar mirror, N_s is the sampling 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 and u_a are the offset of each probe, and b_0 is an unknown 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, and the uncertainty associated with the multi-probe method is simulated.

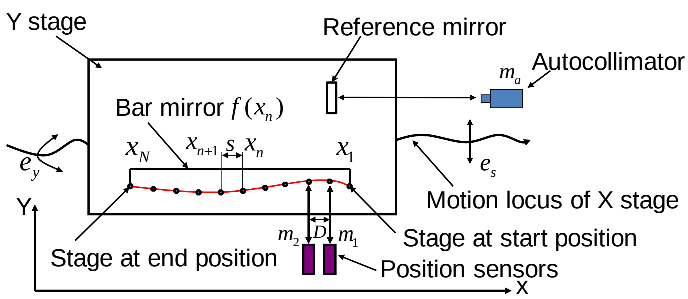

Fig. 3 Principle of the multi-probe method

Simulation of M-CMM

The multi-probe method was evaluated theoretically by computer simulation. The profile of bar mirror $f(x_n)$ is predefined, and the straighntness 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 $D = s$ = 10 mm and the measuring step distance is the same as the interval of the probes, the standard deviation of each probe is considered as σ_{m1} = 1.2 nm, σ_{m2} = 1.2 nm, σ_{ma} = 0.5 μrad, 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 result value of the standard deviation σ is about 5 nm (Fig. 4). The multi-probe measurement method is found to have a good performance in measuring the straightness profile and the yaw error with low standard deviation.

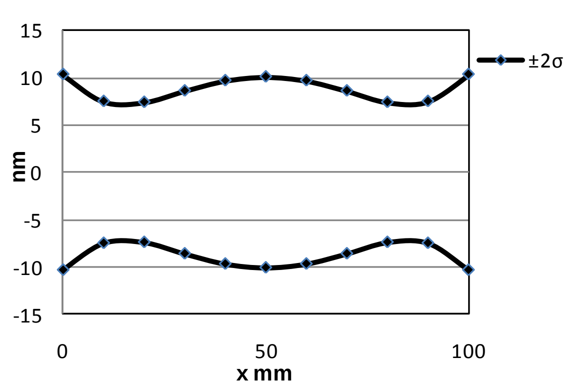

Fig. 4 Standard deviation of multi-probe method

Configuration of the pre-experiment

In the paper, pre-experiment of multi-probe method is designed for evaluating the XY stage based on a stepper motor system. In the pre-experiment, one autocollimator measures the yaw error of the stage, and two 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 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 (Fig. 6). The size of bar mirror is about 110mm×40mm. The pre-experiment is measured by the bar mirror with the accuracy of λ. Two laser interferometers probe the profile of the bar mirror and one autocollimator measure the yaw error of the XY stage by the reference mirror. 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).

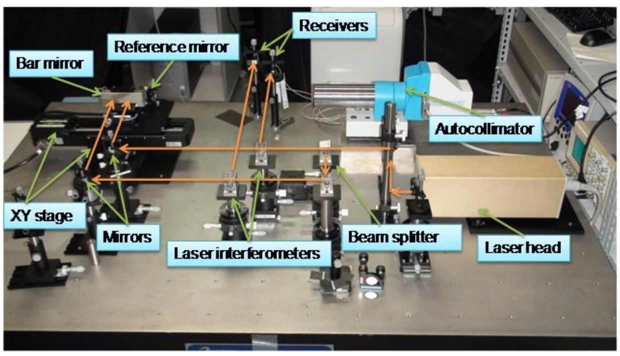

Fig. 5 Main set up of the pre-experiment

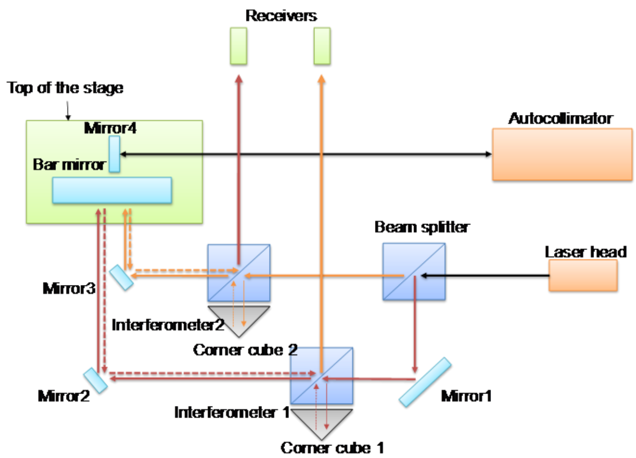

Fig. 6 Block chart of the pre-experiment

Results of pre-experiment

The pre-experiment was measured by two laser interferometers and one autocollimator. The sampling length of bar mirror equals 100 mm. The number of sampling points is limited by the arrangement of the two laser interferometers. When the interval of laser interferometers and the moving distance of each point is $D = s$ =10 mm, the sampling points is only 10. And the standard deviation of each sensor in the real enviroment is considered as $\sigma_{m1} = 10$ nm , $\sigma_{m2} = 10$ nm , $\sigma_{ma} = 0.5$ μrad .

The yaw and straightness errors of X axis are presented in Fig. 7 and Fig. 8. During times of experiment, the average value of the reconstructed profile of bar mirror is show in Fig. 9. The standard deviation (σ_0) calculated by the theoretical simulation is about 12 nm as showed in Fig. 10. Comparing with the standard deviation (σ_P) from the pre-experiment, σ_P is about 10 nm which is mainly in the range of the σ_0.

The reason that 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 effecting 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.

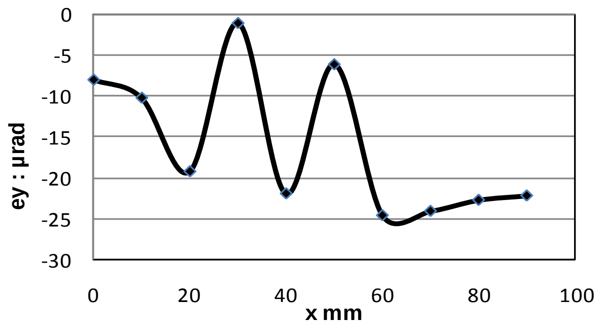

Fig. 7 Yaw error

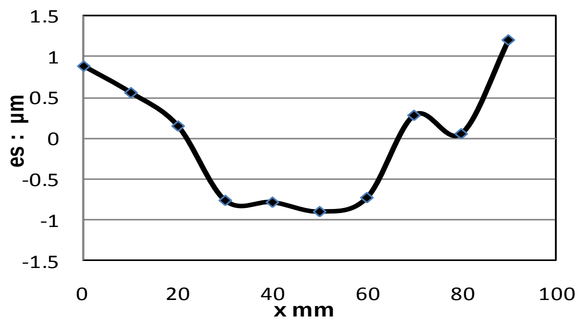

Fig. 8 Straightness error

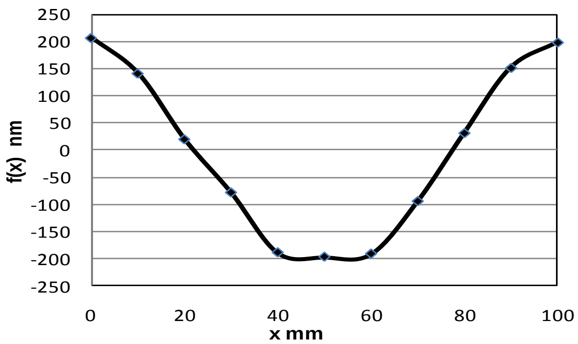

Fig. 9 Profile of bar mirror

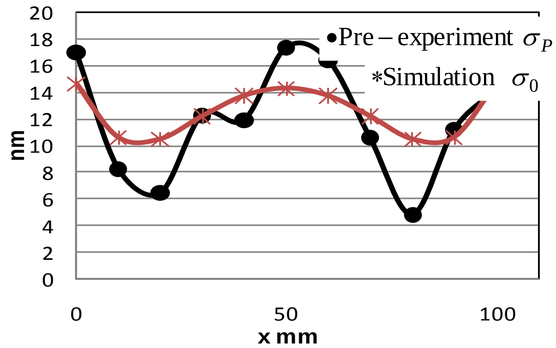

Fig. 10 Standard deviation of the pre-experiment comparing with the simulation

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 lateral measurement is limited by two laser interferometers. In order to improve this disadvantage, a new method of three laser interferometers and one autocollimator has been proposed and new pre-experiment has been designed. We are going to do the new pre-experiment in the near future and compare with the results from this paper.

Acknowledgements

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6. References

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