論文の内容の要旨

Abstract of Dissertation

Title of Dissertation: Multi-Probe scanning method for calibrating high-precision micro-coordinate measuring machine

（走査型多点法による高精度三次元測定機の校正手法の研究）

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In recent times, miniaturization and modularization of microsystem technologies have attracted considerable attention as methods to improve the manufacture efficiencies of small size products with high accuracy. Further, as the result, it has become increasingly important to be able to perform three-dimensional (3D) measurements of nano and microstructures with uncertainties within 0.1 μm. Therefore, micro-CMMs equipped with special micro-probe systems for 3D metrology having high-aspect-ratio micro parts are currently being developed to satisfy the described requirements.

In order to develop a new high-precision micro-CMM (M-CMM) which is designed and built at the National Metrology Institute of Japan in the National Institute of Advanced Industrial Science and Technology (AIST), two significant factors should be considered. One is ensuring the high motion accuracy of each stage; the other is matching a proper probe system.

Firstly, our concern is how to improve the motion accuracy of each axis of the M-CMM platform. In order to satisfy the purpose of measurement uncertainty of 50-nm in a measuring volume of 30 × 30 × 10 mm (XYZ), a new high-precision calibration method should be developed. After calibration and compensation, each translational error should be less than 10 nm, and each rotational error should be less than 1 μrad. Therefore, we have proposed the targets of the dissertation as followings:

1. Measuring the motion errors of each stage
   a) If the stages of M-CMM have good respectabilities, we shall configure compensation table to improve the motion accuracy;
   b) If not, we shall perform the real-time measurement on the M-CMM.
2. An effective on-line measurement technique
3. Measuring multiple motion errors simultaneously

This dissertation details the development of a multi-probe scanning method (MPSM) designed to calibrate the motion accuracy of the M-CMM, and measure the profile line of the reference plane mirror simultaneously. The MPSM, referred to as a calibration system, comprising multiple laser interferometers and one autocollimator is suitable for online measurement that can be widely applied on different

platforms.

In Chapter 2, a new multi-probe scanning method (MPSM) is developed to measure multiple motion errors of moving stage, and profile line of reference plane mirror in nano-level accuracy. The principle and data processing technique of MPSM is addressed. The performance of MPSM is evaluated by simulating the measurement uncertainty of profile of reference plane mirror. How to choose the suitable configuration of MPSM has been discussed.

In Chapter 3, a new application of MPSM with the configuration of two laser interferometers and one autocollimator has been discussed. The simulation results of applying different intervals of displacement sensors show that the ratio of the standard deviation of the autocollimator to those of laser interferometers and the number of sampling points of the reference plane mirror are two important factors that affect the uncertainty value of the multi-probe measurement method. The results of pre-experiment A verify that the configuration of two laser interferometers and one autocollimator performs the multiple motion errors measurement extremely well and also measure the reference plane mirror profile with a small standard deviation of 10 nm.

In Chapter 4, a new application of MPSM with the configuration of three laser interferometers and one autocollimator has been performed to improve the lateral resolution of the measurement objects. The simulation results indicate that the average measurement uncertainty of the flat bar mirror profile increases almost continuously with increasing installation distances between the laser interferometers (D_1, D_2). The pre-experiment B results verify that the configuration of three laser interferometers and one autocollimator measure the multiple motion errors successfully with a high horizontal resolution. Moreover, the two standard deviations of the plane mirror profile is mainly fitting the simulated measurement uncertainty of 10 nm (2σ). In addition, the difference curves between the average value of ten profiles and each profile mainly lie within the simulated measurement uncertainty of ±10 nm ($\pm 2\sigma$). Comparing with the results measured by Zygo white light interferometer system, our measured data excluding some edge points showed agreement to within approximately 30 nm.

In Chapter 5, an analysis of the systematic errors in pre-experiment B has been addressed. Comparing our measurement result with the profile line measured by Zygo white light interferometer, there is some periodic variation in the range of 30 nm. Therefore, we discussed the two main impact factors which would cause the systematic errors in this Chapter. One is alignment error of optical elements; the other is the yaw error of the moving stage. From the estimation and simulation results, the yaw error of moving stage mainly affects systematic error, while random error mainly consists of measurement accuracy of laser interferometers. Therefore, reducing the yaw error of moving stage will decrease the systematic error.

In Chapter 6, optical devices of the MPSM have been designed and built on the M-CMM platform at AIST. Before performing the MPSM experiment on XY stage of the M-CMM, the stability of each sensor has been measured in the real environment. According to the stability tests of interferometers, we concluded that the top table of XY stage is vibrating in the range of several hundreds of nanometers because of the air input; and the measurement results of interferometers are affected from the vibration caused by the top table. Therefore, the single beam laser interferometer is unstable on the M-CMM platform. New displacement sensor will be applied in the future.

Finally, Chapter 7 summarizes the conclusions and contributions of this research, and gives recommendations for future work.

Throughout the whole dissertation, we can conclude the advantages of the MPSM as followings:

1. An effective on-line measurement technique;
2. Measuring multiple motion errors simultaneously;
3. Horizontal resolution can be set up / controlled;
4. Low cost without employing high-accuracy reference reflector;
5. Reconstructing profile line of reference bar mirror in nanometer accuracy.