Abbe error compensation for a micro/nano CMM with a coplanar stage

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Abstract: A micro/nano Coordinate Measuring Machine (CMM) with a stroke of 20 mm × 20 mm × 10 mm has been developed by our group. The “Pagoda structure” with Chinese style is adopted, which has fine mechanical stability. The base of the micro/nano CMM is made of granite to achieve high thermal stability. The stages are driven by piezoelectric motors with a resolution of 1 nm in three directions. The displacements of the stages in horizontal directions are detected by homemade Michelson interferometers. The optical axes of the two interferometers are consistent with their slide way of the coplanar stages respectively, which can reduce the Abbe errors in X and Y axes as much as possible. Semiconductor laser diodes are used as the light source of the interferometers due to low-cost and small size. A linear diffraction grating interferometer (LDGI) has also been developed to detect the displacement in Z direction. After subdivision, the measuring resolution can reach nanometer scale. The micro/nano CMM is compatible with different types of probes. A model of Abbe error and its compensation method are proposed in this paper. Experimental results show that the positioning errors were reduced from 435 nm to 91 nm and from 426 nm to 151 nm via Abbe error compensation method. The flatness of a 0-grade gauge block was tested by the micro/nano CMM, the repeatability of 44 nm (K=2) was achieved.

1. Introduction
With the rapid development of ultra-precision manufacturing technology, Micro-Electro-Mechanical Systems (MEMS), various miniature components have been manufactured. In order to measure these small components with complex geometrical features, ultra-precision micro/nano-CMMs are required. The resolution of the micro/nano CMM needs to reach 1 nm, the accuracy should also reach nanometer scales. Several micro/nano CMMs have been developed by other institutions or universities around the world, such as: (a) The micro-CMM with a stroke of 50 mm × 50 mm × 50 mm developed by NPL (National Physical Lab.), its resolution can reach 0.31 nm in three directions and the uncertainty is 50–100 nm. This CMM has been used in industrial fields [1-2]; (b) The CMM with a stroke of 25 mm × 40 mm × 25 mm developed by PTB (Physikalisch-Technische Bundesanstalt), its repeatability can reach 10 nm and the uncertainty is 100 nm [3-5]; (c) The X/Y/Z nano stage developed by SIOS corporation, whose displacement is detected by fiber laser interferometer, it has a
linear resolution of 0.1 nm while the stroke is 25 mm × 25 mm × 5 mm [6].

Both Taiwan University and our University have developed a micro/nano CMM with a coplanar X/Y stage. The stage is driven by two piezoelectric motors and the displacements in X/Y directions are detected by homemade Michelson interferometers. The design of coplanar X/Y stage conforms to the Abbe free principle. However, Abbe error in Z direction still exists. The performance of our micro/nano CMM can be improved by compensating the Abbe error in Z direction.

Abbe error compensation method is proposed and some experiments are conducted in this study. The effectiveness of the method has been verified. The measurement performance of the micro/nano CMM has also verified initially through testing a flatness of a gauge block.

2. Structure and sensors of the micro/nano CMM

2.1. Mechanical structure and Z-spindle

Figure 1 shows the structure of the micro/nano CMM. The base of the CMM and the moving stage is made of granite and invar respectively. The structure adopts the pagoda type with Chinese style, which has very good rigidity and symmetry. The Z-spindle with the probe is suspended from the top of the machine and only have the freedom in vertical. The two-dimensional X/Y stage is placed under the Z-spindle. A linear diffraction grating interferometer (LDGI) is used to measure the displacement in Z direction [7], while the horizontal displacements are detected by two homemade miniaturized Michelson interferometers.

![Figure 1. Micro/nano CMM.](image)

(a) schematic diagram; (b) photography.

2.2. Coplanar stage and miniaturized Michelson interferometer

The two slide ways of the X/Y motion stage are coplanar in horizontal plane. This design conforms to the Abbe principle which can improve measurement accuracy. Figure 2 shows the structure of the coplanar stage. The base of the stage is made of invar which has good thermal stability. Two piezoelectric motors with a resolution of 1 nm are used to drive the stage.

The displacements in X/Y directions are detected by two homemade miniaturized Michelson interferometers with low-cost and good integration. The Michelson interferometer using a semiconductor laser diode has a resolution of 1 nm by electronic and software subdivision method.

2.3. Angle measurement module based on autocollimator

The X/Y stage usually generate pitch and yaw angle errors when doing a linear motion. Since an Abbe offset still exists in Z direction, Abbe error need to be detected and compensated. An angle measurement module based on autocollimator is used to measure the pitch and yaw errors in real time during the stage movement. Figure 3 shows the principle of angle sensor [8]. A laser beam passes through the polarizing beam splitter, then reflected by the measuring mirror. The reflected beam will
pass through a focusing lens and project on the surface of the quadrant photo detector (QPD). The pitch and yaw angles can be detected by applying appropriate resistances to QPD and signal processing circuit.

![Co-planar X/Y stage](image)

**Figure 2.** Co-planar X/Y stage.

![Principle of the 2D angle sensor](image)

**Figure 3.** Principle of the 2D angle sensor.

2.4. Contact scanning probe

The probe can greatly affect the measuring accuracy of the micro/nano CMM. A contact scanning probe with nano-scale resolution has been developed by our group [9]. Figure 4 shows the photo of the probe.

The 3D displacements of the probe tip are transferred into a displacement in Z direction or two-dimensional angle of a plane mirror adhering to the upper surface of an elastic mechanism. A Michelson interferometer is used to detect the mirror’s displacement in Z direction. An autocollimator is used to detect the angles of the mirror and the probe has a resolution of 1 nm, a stroke of 40 μm×40 μm×20 μm (X×Y×Z) and a repeatability of 30 nm in each direction.
3. Abbe error compensating model

According to the Abbe principle, the positioning errors of the X/Y stage can be calculated by the Abbe offset \((L)\) and the angle error \((\theta)\). It can be expressed by the following equation [10]:

\[
\delta = L \times \theta
\]  

(1)

The contact point and the Abbe offset are shown in figure 5.

![Figure 4. Photo the contact scanning probe.](image)

![Figure 5. Abbe offset of the micro/nano CMM.](image)

The Abbe error in three directions can be expressed by:

\[
\begin{bmatrix}
\delta_x \\
\delta_y \\
\delta_z
\end{bmatrix}
= \begin{bmatrix}
0 & \theta_z & \theta_y \\
\theta_z & 0 & \theta_x \\
\theta_y & \theta_x & 0
\end{bmatrix}
\begin{bmatrix}
\Delta L_x \\
\Delta L_y \\
\Delta L_z
\end{bmatrix}
\]  

(2)

where \(\delta_x, \delta_y, \delta_z\) are the Abbe error in each direction, \(\theta_x, \theta_y, \theta_z\) are the angles in each axis and \(\Delta L_x, \Delta L_y, \Delta L_z\) are the Abbe offset in each direction. In this equation, \(\theta\) can be precisely obtained by the 2D angle sensors. However, it is quite difficult to measure \(\Delta L\) accurately, a calculation method using “Least Square Method” has been proposed to solve this problem. The displacements of the stage in each direction can be measured by the Michelson interferometers integrated in the CMM and reference.
interferometers at the same time, then the positioning errors \((\delta_x, \delta_y, \delta_z)\) of the CMM can be obtained. At the same time, \(\theta_x, \theta_y, \theta_z\) can be detected by an angle sensor. Therefore, the Abbe offsets \((\Delta L_x, \Delta L_y, \Delta L_z)\) can be calculated by Eq. 2 using “Least Square Method”.

4. Experiments

4.1. Abbe error compensation

Each of the three linear stages of a CMM has three angle degrees of freedom. Angle error and Abbe offset always exist. In order to obtain the Abbe errors, both the angle errors and the Abbe offset need to be measured. However, no proper angle sensor can be used to measure the angle errors of the Z stage currently due to the limited space. Therefore, we have only finished the Abbe error compensation in X and Y axes.

Two SIOS laser interferometers (SP2000) were used as references. The X/Y stage moved at an interval of 1 mm from 0 to 10 mm. The displacement motions of the stage measured by the integrated interferometers and SIOS interferometers and the angles of the stage were recorded. Then, both the Abbe error and Abbe offset \((\Delta L_x=1.520 \text{ mm}, \Delta L_y=0.017 \text{ mm})\) can be obtained. Figures 6 and 7 show the positioning errors of the X/Y stage with and without compensating the Abbe error. From figures 6 and 7, we can see that the positioning errors in X and Y directions have been reduced from 435 nm to 91 nm and from 426 nm to 151 nm respectively after compensating the Abbe error.

**Figure 6.** Comparison of results before and after Abbe error compensation (X position).

**Figure 7.** Comparison of results before and after Abbe error compensation (Y position).
4.2. Flatness test

In order to verify the performance of the micro/nano CMM, the flatness of a 0-grade gauge block was tested. The coordinate data of the six points shown in figure 8 were measured by the CMM, a plane equation was fitted in accordance with the principle of “Least Square Method”. The measurement precision of flatness mainly depends on the measurement precision of Z coordinate. The Abbe offset of Z-axis stage is 120 mm and the angular motion is within ±15 arcsec by calibration. The Abbe error in Z direction is less than 2.5 nm. Therefore, it is so small that can be ignored. Therefore, the flatness of the gauge block can be obtained. The results are shown in table 1, the repeatability is 44 nm (K=2).

![Figure 8. The gauge block and the flatness measurement path.](image)

| Times | Flatness (μm) |
|-------|---------------|
| 1     | 0.387         |
| 2     | 0.370         |
| 3     | 0.430         |
| 4     | 0.380         |
| 5     | 0.371         |
| Average | 0.388         |
| Standard deviation | 0.022 |

Table 1. The measurement results of flatness.

5. Conclusions

On the basis of a micro/nano CMM developed by our group, Abbe error compensation method is introduced and verified. In comparison with a SIOS interferometer (SP2000), experimental results validated the effectiveness of the method. The repeatability of the flatness measurement can reach 44 nm (K=2). Much more works to promote the performance of the CMM still need to be carried out in future.

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