New nano-contouring measurement techniques for a nano-stage

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Abstract

Among the most commonly used contouring measurement methods, no measuring techniques have been available with nanometer resolution except for the grating encoder measurement system. Although the grating encoder measurement system can reach the resolution of nanometers for nano-contouring, its resolution and accuracy of measurement are limited by the manufacturing accuracy of the size of the grating etching, the size of the light-spot and the pitch of the grating. When the contouring radius is less than the pitch of the grating, the grating encoder system does not work. So, no measuring instrument could simultaneously measure the nano-stage contouring error. In this paper, three new nano-contouring measurement techniques for a nano-stage have been successfully developed by employing laser interferometers, corner cubes and some developed fixture. By specified light path arrangements, three different setting-ups are described in this paper. The measuring resolution of these techniques is 10 nm. Contouring tests with a very small radius were carried out. A 500 nm radius contouring test result was given. Since the techniques are simple, it is very easy to set up and to carry out the tests, compared to other systems. Also, the setting-up error can be ignored when the contouring radius is small. A Heidenhain measuring system was employed to verify these three new techniques. Good verification results were obtained to prove these systems.

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1. Introduction

Currently, contouring measurement technology can largely be divided into contact measurement methods and non-contact methods. The contact measurement method is exemplified by Ziegert et al. who advocated the Laser Ball Bar system (LBB) on the basis of the laser interferometer [1,2]. In 1982, Bryan employed the testing method of the Telescoping Magnetic Ball Bar (TMBB), which used a magnetic double ball bar with an LVDT inside to measure the errors of circular movements [3]. Using the circular comparison method, Knapp’s system fastened the standard disk to the machine to be measured [4,5]. Burdek and Park and Jywe, considering the shortcomings of Bryan’s TMBB method and Knapp’s circular determination method, improved the software and hardware measurement system and developed a set of ‘COUNTISURE’ machines using a dynamic circular measurement analysis system [6,7], allowing the machine tools dynamic precision test to meet the testing specifications of ISO230. Dönmez employed the laser interferometer to measure the errors of relative positions to make compensations so as to improve the precision of the machine tool [8,9]. In 1989 [10], Sommargren suggested using a pair of laser interferometers for measuring the second positioning error of a wafer stage and the error of the first deflection angle. Then in 1993 [11], Nakamura proposed a new method where four interferometers and one corner tube reflector were used to measure the 3D coordinate positions of the microscopic scanning stage. However, it was limited to measurements with little travel. Lee et al. [12] also used two laser interferometers to measure the errors of wafer stages and used an angle measurement interferometer to measure the deflection angle error. Jywe et al. [13] developed a double axis online two-degrees-of-freedom measurement system, whose system architecture utilized a planar encoder. In 1988, Zhang et al. [14] published a method that used direct measurement of displacement to obtain 21 error elements, and stressed that this method could improve the accuracy of measurement.
and reduce the use of instruments. In 2004, Jywe [15] offered a multi-function error measurement system that utilized three sets of four-quadrant meter photo sensors to measure the five-degrees-of-freedom errors of numerical machine tools at one time. Ni et al. [16,17] presented a measurement system of multiple degrees-of-freedom in 1992 and 1995 for measuring the geometric errors of a Coordinate Measurement Machine, which utilized four four-quadrant meter photo sensors to measure the five-degrees-of-freedom error, other than positioning errors. In 1994, Shimizu et al. [18] also presented a measurement system which utilized three four-quadrant photo sensors and one interferometer for measuring the six-degrees-of-freedom errors at the same time. The above methods [1–18] can be employed only for micro-meter resolution contouring tests.

For nano-contouring measurement, the method currently available is the HEIDENHAIN measurement system [19]. However, the disadvantages of the system can be listed as followed. (1) Although the grating encoder measurement system can reach the resolution of nanometers for nano-contouring, its resolution and accuracy of measurement are limited by the manufacturing accuracy of the size of the grating etching, the size of the light-spot and the pitch of the grating. (2) When the contouring radius is less than the pitch of the grating, the grating system does not work.

2. Description of the system architecture

The nano-contouring measurement method presented in this paper mainly uses the characteristics of high accuracy and high stability of the laser interferometer in conjunction with a different method of lens arrangements to achieve the goal of multiple axes measurements. The measuring methods developed in this paper can be divided into three architectures, which are shown in Figs. 2–4, respectively. The first measuring architecture is named a 1L2RH; the second is a 1L2RV; and the third is a 2L0RV (1L2RH: one laser head and two external receivers horizontally, 1L2RV: one laser head and two external receivers vertically, 2L0RV: one laser head and no external receivers vertically).

In this paper, a He–Ne laser is used to measure the stage contouring. When the nano-stage was contoured, the projected position of the light source was moved along the reflector, as shown in Fig. 1. The contouring radius is limited by the working range of the two reflectors since each projected light must be reflected back to parallel the related receiver.

2.1. Nano-contouring measurement architecture 1 (1L2RH)

Nano-contouring measurement method 1 is shown in Fig. 2. It mainly uses a He–Ne laser (HP5519A) to let its light source be split by the beam splitter first, then measures the movement of the nano-stage in the X and Y-axis. In this paper, measurement and analysis are mainly made for circular contouring, with the optical measure paths shown in Fig. 2. The He–Ne emits a laser beam, which splits into two rays of light after going through a semi-reflector. One of the laser beams shoots directly into the beam splitter in one axial direction and measures the error in the other axis. At the end, the two laser light sources receive the signal storage of the X and Y-axis via the two receivers, then a computer is used to process the signals for the two pieces of information.

2.2. Nano-contouring measurement architecture 2 (1L2RV)

Nano-contouring measurement method 2 is shown in Fig. 3. It is mainly characterized by placing the beam splitter on the stage to be measured, but not using the commonly used method whereby the deflector is placed on the stage to be measured. As for its measurement method, a He–Ne laser (HP5519A) first lets its light source be split by the beam splitter, then measures the movement conditions of the nano-stage against the X and Y-axis, respectively. However, in this paper, measurement and analysis are mainly made for circular contouring, with optical measure paths shown in...
of the nano-stage made known, but also the extent of displacement and interference of the X or Y-axis may be measured simultaneously.

3. Analysis of uncertainties

In this paper, error sources that affect the experiment results can be divided into inherent errors, environmental errors and setting-up. Of these, the inherent errors of the measuring system can be reduced through system instrument calibration, while environmental errors can be reduced by means of environmental compensation or tests in a dust-free room. As for setting-up errors, the uncertainties that need to be taken into consideration are more complicated. The effect of setting-up errors will be described as followed.

3.1. Setting-up errors for nano-circular contour test

In this architecture, since it is necessary to set up lens systems, laser light source and receivers against different axial directions, it is likely that dead path errors and cosine errors may take place due to improper set up. Dead path is caused mainly because there is unnecessary fluctuation in the laser beam path, so dead-path errors may be reduced by bringing the laser head as close as possible to the measurement point. Cosine error is the linear error caused by the non-parallelism between the laser beam path and moving axis. When an angle \(\theta\) is included between the laser beam and measurement axis, then cosine error signals may be produced, with error forms of each axis shown as follows:

- \(X\) there are no pitch errors or yaw errors in the \(X\)-axial direction of the laser interferometer such as types 1–4
- \(X_p\) there are pitch errors in the \(X\)-axial direction of the laser interferometer such as types 5–8
- \(X_y\) there are yaw errors in the \(X\)-axial direction of the laser interferometer such as types 9–12
- \(X_pX_y\) there are pitch errors and yaw errors in the \(X\)-axial direction of the laser interferometer such as types 4, 8, 12 and 16
- \(Y\) there are no pitch errors or yaw errors in the \(X\)-axial direction and \(Y\)-axial direction of the laser interferometer such as types 1, 5, 9 and 13
- \(Y_p\) there are pitch errors in the \(Y\)-axial direction of the laser interferometer such as types 2, 6, 10 and 14
- \(Y_y\) there are yaw errors in the \(Y\)-axial direction of the laser interferometer such as types 3, 7, 11 and 15
- \(Y_pY_y\) there are pitch errors and yaw errors in the \(Y\)-axial direction of the laser interferometer such as types 4, 8, 12 and 16

\(\theta_p\) pitch error angle of tilt
\(\theta_y\) yaw error angle of tilt
4. The experiment results

The contouring measurement experiment described in this paper mainly used the nano-stage (NPS XY-100A) designed by QI, and made measurement and analysis in conjunction with the nano-scale double axis contouring measurement system; at the same time the grating encoder was also used as the verifying tool for the measurement system. In the experiment, a small piece of optical plate was placed on the nano-stage so that it became a fixed motion mechanism. When the stage moved, the optical plate also followed the move. In this way the contouring signals of the laser interferometer and the signals of the grating encoder could be obtained at the same time for comparison and analysis. Compensation and control were made by comparing the signal differences of the two. In this paper, a circle with a radius of 40 µm is used as the comparison and analysis graph of the measurement results.
4.1. The experimental results of the 1L2RH

Circular radius 500 nm, clockwise
Circular radius 500 nm, counterclockwise
Circular radius 40 μm, clockwise
Circular radius 40 μm, counterclockwise

4.1.1. Discussion of the results

The amount of circular errors of the stage itself when the nano-stage is at different circular radii can be seen clearly from Figs. 5–8. The repeatability is high when the stage is moving clockwise and low when the stage is moving counterclockwise. It can also be seen from Figs. 5 and 6 when the nano-stage is making circular motion. Its starting and ending points are unable to return to the start point. This is possibly for the following reasons: (1) There are some problems with the controller of the nano-stage itself when making feedback compensation so that the nano-stage is slow to respond as the stage makes circular motion. (2) Another possible reason is environmental factors—when the HP laser interferometer causes value...
drift during the process of measurement so that the laser interferometer value itself still contains the error signal of the amount of drift as the nano-stage returns to the original point, making it impossible for the starting and ending point of the circular signal to form a circle. (3) When the piezoactuator pushes the stage, the piezoceramic has hysteresis by itself, making it impossible for the starting point to coincide with the ending point.

Figs. 7 and 8 show the results obtain by the proposed method and the HEIDENHAIN measurement system. They coincide with each other. Moreover, the performance of the stage can be verified, as such, it can be seen that this nano-scale double-axis contouring measurement system method can indeed be applied to contouring measurement.

4.2. The experimental results of the 1L2RV

The biggest difference between the second kind of double axis contouring measurement method and the first kind of measurement method is that the beam splitter of the stage can be verified, as such, it can be seen that this nano-scale double-axis contouring measurement system method can indeed be applied to contouring measurement.


Fig. 13. Clockwise four times.

Fig. 14. Counterclockwise four times.

Fig. 15. Comparison of the results of the 2L0RV measurement system signal and the HEIDENHAIN system signal.

Fig. 16. Comparison of the results of the 2L0RV measurement system signal and the HEIDENHAIN system signal.
method 2 is placed in a different position. As with the general measurement method, the reflector is placed on the objects to be measured in order to obtain just a small amount of displacement. However, in this architecture, the beam splitter is placed on the objects to be measured to measure the circular signals of the double axis using different methods of placing the lens system. In comparing the signal results of the laser interferometer and grating encoder, it can be found that in cases of a rotation angle error between the signals, the signal which yaws can be corrected by comparing the angle difference of the two signals so as to eliminate cosine errors.

Circular radius 500 nm, clockwise
Circular radius 500 nm, counterclockwise
Circular radius 40 μm, clockwise
Circular radius 40 μm, counterclockwise

4.2.1. Discussion of results

In the second measurement architecture method in this paper, the results of measured circular errors are shown in Figs. 9–12. From the above measurement results, it can be seen that the measurement method employed in the architecture is feasible and suitable for measuring the contouring performance of the stage.

4.3. The experimental results of the 2L0RV

The practical architecture of the third kind of double axis contouring measurement method given in this paper involves double lasers which are mainly used to make double axis contouring measurements. The beam splitter is placed on the objects to be measured, and by observing the signal results of the laser interferometer and grating encoder, it can be found that in the case of rotation angle errors between the two signals, the signal which yaws can be corrected by comparing the angle difference of the two signals so as to eliminate cosine errors.

Circular radius 500 nm, clockwise
Circular radius 500 nm, counterclockwise
Circular radius 40 μm, clockwise
Circular radius 40 μm, counterclockwise

4.3.1. Discussion of result

In the third measurement architecture method in this paper, the circular error results are shown in Figs. 13–16. The measurement results of the above graphics show that the signals in architecture 3 have the same problems as those generated by architecture 1 and architecture 2.

5. Conclusion

In this paper, three kinds of nano-contouring measurement system were successfully developed by using different methods of optical lens arrangement to achieve the goal of multiple axes measurements. The three kinds of nano-contouring measurement methods were developed by the different setting ups of the optical lens systems. The hardware and software were integrated and described in the paper. The experimental work was carried out to verify these methods successfully. The setting-up can be executed easily in 30 min and a contouring test can be carried out in 10 min with a resolution of 10 nm and with an uncertainty of 15 nm in a contouring radius range from 50 nm to 5 mm.

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