A new rotational error measurement method for precision spindle based on the registration analysis of motion topography

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A new precision spindle rotational error measurement method based on the registration analysis of motion topography is proposed. The surface topography of the test sample on the platform rotating by a precision spindle is measured and data registration image motion analysis is carried out. The radial and axial rotation error data of the precision spindle can be obtained simultaneously. Series of works are carried out including the rotating error modeling, fabrication of the test sample with special microstructures, image registration method selecting and parameters seeking, and so on. The precision spindle rotating errors test experimental system with nano-accuracy is established using the Atomic Force Microscope (AFM) probe as a sensor. A rotational error measurement test is performed and the feasibility of this method is verified. The method and the corresponding experimental system in our work are expected to provide a new way of testing the rotating error of high-precision spindles with features of simple principle and wide applicability.

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1. Introduction

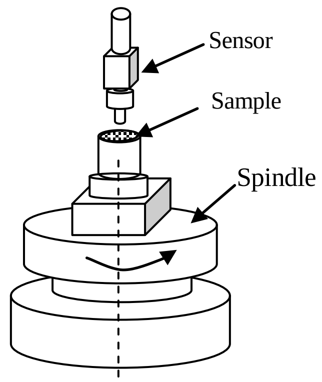
The precision rotary spindle is the key component of precision machine tools and test equipment. With the development of the ultra-precision machining and nano-technology, the precision level of mechanical parts and measurement instruments are demanded increasingly, particularly in high-precision rotary parts, such as ultra-precision machine tool spindles, test rotary stage, the laser gyroscope rotor, roundness standards and so on. The manufacturing allowable errors of these parts are typically from a few nanometers to several tens of nanometers. So the detection and further improving the rotation accuracy of precision spindle which is the core component of precision roundness measurement instrument becomes a challenging subject.

In general, the rotational error of precision spindle can be roughly divided into two basic forms: rotary axial drifting and radial rotational error (including radial run-out and angular swing). At present, the measurement methods of precision spindle rotational error mainly include static measurement, dynamic multi-probe method and multiple location method, and so on. Among them, the static measurement method assumes that the standard circular profile for the ideal, so that, the measurement error is spindle error; dynamic multi-probes method and multiple location method are measured on the same circular contour using multiple probes or multiple rotation, the high-precision spindle error data is obtained though the error separation of the spindle rotational error and the circular profile of the test parts. But the disadvantage of these two methods is that there is methodic error of harmonic restraint, the further data processing and analysis correction are needed. In general, these measurements either require very high-precision cylindrical standard profile as a standard device, or require a relatively sophisticated measurement devices or sophisticated adjustment process, the measurement goals are also focused on the radial rotation error of the spindle.

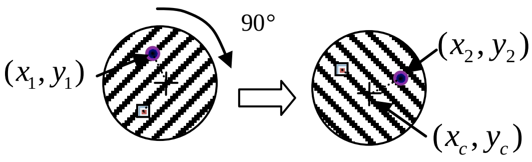
If high-precision sensor is adopted to capture for the surface topography of sample rotating with the spindle and analysis the rotary center of this topography (i.e., registration analysis of the motion topography), then this idea is expected to achieve the measurement simultaneously both precision spindle radial error data and the axial error data on condition that unnecessarily expensive standard cylindrical contours and complex test system and test process. So it may become a new method of testing the rotating error of high-precision spindles with features of simple principle and wide applicability. Based on this principle, we use atomic force microscope (AFM) as a measurement sensor to achieve nanometer accuracy measurement of precision spindle error in the article. In Section 2 of the article we introduce the basic principles of measurement; in Section 3 we describe experimental setup and experimental process; in Section 4 we describe the experimental results and the process of measurement data; and we discuss the conclusions in Section 5.

2. Measuring principle

The measurement principle based on the registration analysis of motion topography of precision spindle error is proposed in Fig. 1 a), it is comprised by the measurement sensors, precision spindle and the flat sample with some feature microstructure. The flat sample is fixed on the precision spindle platform (near the center of rotation) and rotated with the spindle in the circumference of 360°. A series of surface topography data is obtained by measurement sensors aligned the rotation center of the flat sample and measuring the surface topography from different angles, as shown in Fig. 1 b). Since during the spindle rotation, the sample surface only rotate around a coordinate point (the center of rotation) in spatial position, the sensor captures essentially the same area of the sample surface. The precision spindle rotational error is obtained by analyzing the change of measurement result of this region in space.



a) Experimental system setup



b) Rotation of the surface topography

Fig.1 Schematic diagram of the measurement principle

Next, we discuss the registration analysis method of the motion topography. In Fig. 1b), we only consider the model of simple two-dimensional rigid body movement (i.e., only considering radial rotating error). Supposing that the spindle stop in a certain position, there is a feature point (x_1, y_1) on the surface of the flat sample; turn the spindle to a known angle θ, this feature point changes to (x_2, y_2), set the rotation center at (x_c, y_c), then

$$\begin{cases} x_2 - x_c = (x_1 - x_c)\cos\theta + (y_1 - y_c)\sin\theta \\ y_2 - y_c = -(x_1 - x_c)\sin\theta + (y_1 - y_c)\cos\theta \end{cases} \tag{1}$$

Organize above equation into matrix form, then

$$A \cdot \begin{pmatrix} x_c \\ y_c \end{pmatrix} = B \tag{2}$$

Where $A = \begin{bmatrix} \sin\theta & 1-\cos\theta \\ 1-\cos\theta & -\sin\theta \end{bmatrix}$, $B = \begin{bmatrix} y_2 + x_1\sin\theta - y_1\cos\theta \\ x_2 - y_1\sin\theta - x_1\cos\theta \end{bmatrix}$.

So

$$\begin{pmatrix} x_c \\ y_c \end{pmatrix} = A^{-1} \bullet B \tag{3}$$

By formula (3), the rotation center coordinate can be solved by calculating position change of the feature point during the rotation. The precision spindle turning around the entire circumference, the motion position variation of the rotation center forms the spindle radial rotary error. From the above analysis, we can know that the measurement accuracy of the rotational error depends on the sensor capabilities, and it relates to the resolution both in horizontal direction(X, Y direction) and vertical direction (Z direction). If the measure sensor can only measure the two-dimensional image, this method can only measure the spindle radial rotation error. And if the sensor can measure three-dimensional microstructure topography, obtained the three-dimensional data, it may get the radial and axial rotation error data of the precision spindle simultaneously. In order to achieve rotation error measurement of precision spindle with nano-accuracy, AFM is used as a measurement sensor in the article witch can be achieved nanometer measurement resolution in both horizontal and vertical direction and obtains three-dimensional surface topography data. As a preliminary exploratory study, this approach only measures the radial rotating error of the precision spindle; further research work will be carried out in the future.

3. Measurement Procedure

3.1 Experimental apparatus

Photo of the measuring apparatus is shown in Fig.2. The sensor of measuring apparatus uses the Q-Port-type atomic force microscope, made by Ambios Company of U.S. The maximum measuring ranges of this AFM are 80, 80, 17μm in X, Y and Z direction respectively, the resolution of X and Y direction are 1nm, and the resolution of Z direction is 0.1nm.

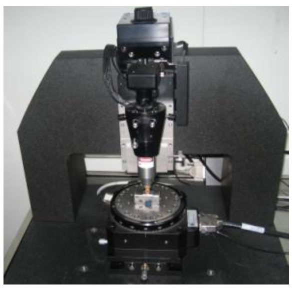


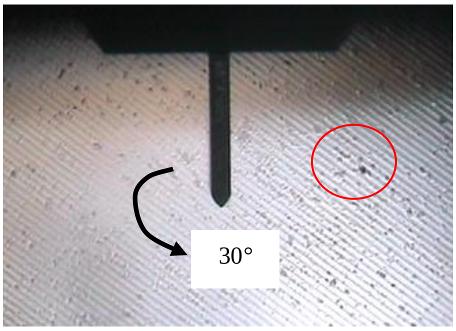
Fig.2 Photo of measuring apparatus

The tested precision spindle is an air-bearing rotary stage, ABRS-150MP type, made by Aerotech Inc., U.S. Its rotary radial error is less than the 250nm by factory calibration. The measurement experiment used a flat aluminum sample obtained using ultra-precision turning. In order to adjust the position of the AFM and the air-bearing rotary stage, the rotary stage and samples are installed in two-dimensional XY linear stages, the minimum displacement of these two stages are less than 1μm.

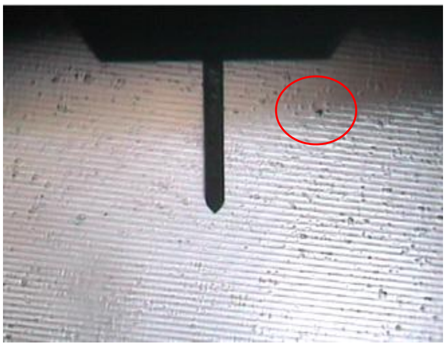
3.2 Aligning the sample

Before the measurement experiment, the position adjustment of the sample is a very important work. On the one hand, the aim of this work is to adjust the flat sample, move some certainly micro-structure feature to the center of rotation (in general, there are some micro defects on the surface of the samples by ultra-precision machining, these micro defects can be used as feature points); On the other hand, this work will make the rotation center of the sample (ie precision spindle center) in the measurement region of AFM, which is actually a very difficult task.

In this paper, a successive adjustment method is used: firstly, start s the tested precision spindle, the sample will rotate in the optical vie w field of the AFM, move the precision spindle approximately so that the rotary center of the sample is in the observation view field; Seco ndly, stop the spindle at some position, and capture an optical image o f the sample surface at this angle (as shown in Fig. 3 a) below), select one or a number of feature points in the image, then rotate the spindle to another position (e.g. rotating the spindle by 30 °), re-capture a sample surface optical image, and find the feature points of t he rotated position (as shown in Fig. 3 b) below), the rotation center o f these two image can be solved by Formula (3) in Sect. 2.



a) Before rotate



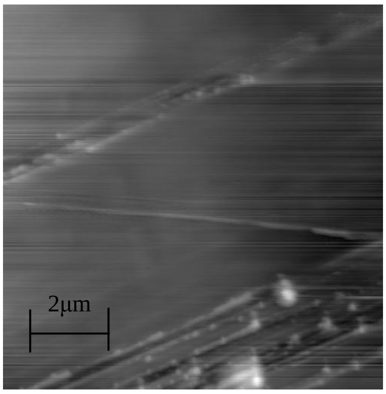
b) After rotate a 30°

Fig.3 Optical image of the sample surface at the different position

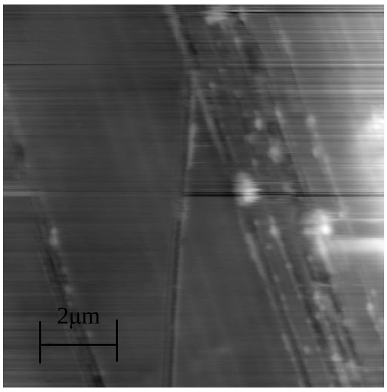
Next, move the spindle so that this rotation center coincides exactly with the AFM probe position; through these adjustments (possibly several times), the rotary center of the sample has been located under the AFM probe (the rotary center can be scanned by AFM), and finally, the AFM probe approach to the sample surface, and scan two AFM images at two angle positions of the spindle circumference with a large scope. Further the rotation center of the sample can be accurately calculated though these two AFM images using Formula (3), accordingly so that offset the AFM probe to this position, and in the subsequent experiments we can test in a small range.

3.3 Experiment procedure

When the aligning work mentioned above is completed, the experiment of rotational error measurement can be carried out. In this paper we only measure some experiments at the equidistant angle of circumference. Firstly the tested precision spindle is rotated to its 0 ° position (Origin position), then the AFM starts scanning in contact mode, the typical measurement range 10 * 10μm, the scanning frequency is 2Hz, 500 * 500 sampling points, and collect the first AFM image; Secondly, the spindle is rotated 10° relatively every time, the AFM image series are obtained by scanning the surface topography of the sample at the different angle position one by one, until the completion of the whole circumference measurement experiments. The typical AFM images of the experiment procedure is shown in Fig. 4, where in Fig. 4 a) is the surface topography image when the spindle at the initial 0 ° position, and Fig. 4 b) is its at the 90° position(the number ten in the total of 36 images).



a) First image at 0 degree



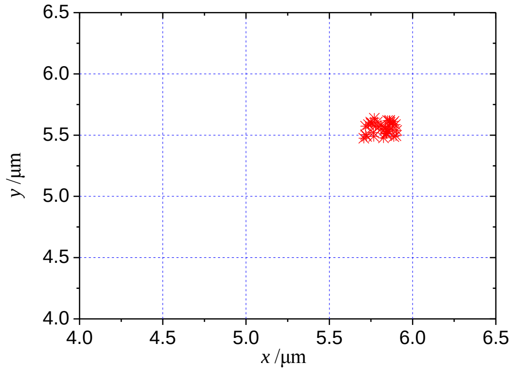
b) Image at 90 degrees

Fig.4 AFM topography images of the sample

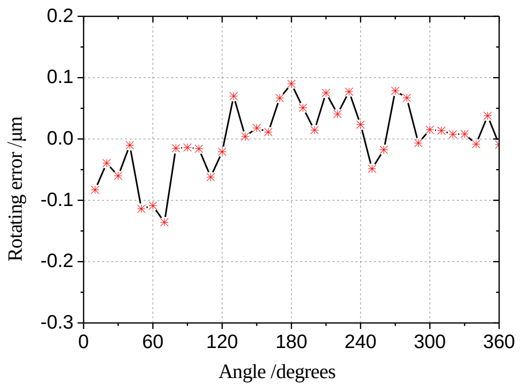
4. Rotational error analysis

As mentioned above, a total of 36 AFM images are obtained with 10° intervals. The rotational error curve of the precise spindle can be determined by analysis the location of the rotary center of these images. In order to facilitate automated processing of measurement data image, the original images obtained by AFM is firstly pretreated preprocessed, including flattening the image (remove the tendency), median filtering and Sobel edge detection algorithm. The edge information of the image topography characteristics is extracted. It can be seen from Fig. 4, the data image has a pattern of micro-structure look like a 'Z', after the edge extraction processing, can be fitted to three straight features. Next, the registration analysis of these three line features is carried out, and by formula (3) we can calculate the average rotary center of each location, and then obtain the rotary instantaneous center trajectory as shown in Fig. 5 a).

We expand the data along the circumferential direction, and then i t becomes a curve as shown in Fig. 5 b). This curve is the spindle rota tion error curve measured by this method. Evaluation by the least squ are circularity method we can obtain the radial rotating error of this sp indle is about 231 nm.



a) The trace of instantaneous rotating center



b) Circular curve of rotating error

Fig.5 Experimental rotating error curve of the test spindle

5. Conclusions

In order to solve the measurement problem of precision spindle rotational error with nano-accuracy, this paper proposes a new method based on the measurement of flat sample surface topography and the registration analysis of these motion topographies to obtain the radial rotational error. An experimental system is established using AFM probe as a sensor. For a typical high-precision spindle, we carry out a preliminary measurement experiment, and obtain its radial rotating error data curve. Next, we will further design typical micro-structure of samples and study the simultaneous calculation of radial and axial rotation error related work.

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