

A New Method for Characterisation for the 5 DOF Spindle Volumetric Error Motions in Machine Tools

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1. Introduction

The accuracy performance of rotating spindle has been one of important key issues for the users and manufacturers of machine tools, and it has been widely acknowledged that there are 6 DOF (degree of freedom) error motions in the rotating spindle. The 6 DOF error motions are : two radial error motions, two tilt motions, one axial error motion, and one indexing error motions if required. Even though the 5 or 6 DOF spindle error motions are pretty well documented and procedured in many national and international standards, there have been needs or continued discussions for the performance characterisation for the spindle error motions, which can predict the real machining performance of machine tool spindles in more practical senses.

In this paper, a new method is proposed for characterizing the 3 dimensional performance of machine tool spindle, where two new terms of 3D error motions are introduced in addition to the existing 5 to 6 DOF spindle error motions: flatness error motion and cylindricity error motion. The flatness error motion of spindle can be calculated mathematically from the face motion of spindle in the rotating sensitive direction, which can predict the flatness tolerance of the machined. The cylindricity error motion also can be derived mathematically from the radial error motion in rotating sensitive direction along the axis of spindle movement, which can predict the cylindricity tolerance of the machined.

2. Spindle Error Motions

2.1 6 DOF spindle error motions

As mentioned in the introductory section, it has been widely acknowledged, e.g.[1], that a rotating spindle has 6 independant components, that is, degree of freedoms in error motions, and they are the radial error motions, tilt error motions, axial error motions, and the indexing error motion. A typical coordinate system for the spindle error motions is shown in fig.1, where the radial error motions, $X(\theta)$, $Y(\theta)$ are defined in the X, Y axis, respectively, and the axial error motion, $Z(\theta)$, in the Z axis. The rotary tilting motion can be defined in the X,Y axis, respectively, which are $\alpha(\theta)$, $\beta(\theta)$. The 6th component of spindle error motion is the indexing error motion of spindle, $\gamma(\theta)$, which does virtually little or no effects on the machining accuracy of machine tool. The angle, θ , is the angle of rotation of spindle as it revolves. The radial error motions, $X(\theta)$, $Y(\theta)$, are generally defined from the combination of the pure radial error motions defined at the reference location and the tilting error motions, which are

$$X(\theta) = X_0(\theta) + L \alpha(\theta) \quad (1)$$

$$Y(\theta) = Y_0(\theta) - L \beta(\theta) \quad (2)$$

where $X_0(\theta)$, $Y_0(\theta)$ are the pure radial error motions in the X,Y directions, respectively, and L is the offset distance between the two locations for the radial error motion observed.

2.2 3 dimensional spindle error motions proposed

In order to give more practical spindle performance explaining actual machining performance of machine tool spindles, two new error motions are proposed in this paper: cylindricity error motion and flatness error motion.

When the rotating spindle is machining workpieces such as in drilling processes, the machining accuracy is greatly influenced especially by the radial error motions of spindle, and in this case, a third radial error motion, $R(\theta)$, can be defined in view of rotating sensitive direction[1], which is,

$$R(\theta) = X(\theta) \cos \alpha(\theta) + Y(\theta) \sin \alpha(\theta) \quad (3)$$

where $R(\theta)$ simulates the actual radial error motion of spindle tool tip as it rotates.

As the practical machine tool spindle is going up and down with rotation, the concept of radial error motion in view of rotating sensitive direction can be expanded along the up and down spindle movement, which can be called as the cylindricity error motion. The cylindricity error motion, $C(\theta)$, can be derived mathematically by substituting eq(1),(2) into eq(3), that is,

$$C(\theta) = (X_0(\theta) + L \alpha(\theta)) \cos \alpha(\theta) + (Y_0(\theta) - L \beta(\theta)) \sin \alpha(\theta) \\ = X_0(\theta) \cos \alpha(\theta) + Y_0(\theta) \sin \alpha(\theta) + L(\alpha(\theta) \cos \alpha(\theta) - \beta(\theta) \sin \alpha(\theta)) \quad (4)$$

where the first two terms are the radial error motion in the rotating sensitive direction at the initial location, and the third and fourth terms indicate the variation of error motion along the cylindrical length, L. Eq(4) represents the error motion when the spindle machines cylindrical features, which can predict the cylindricity tolerance of machined cylinder when a radial fly cutter is equipped at the spindle.

For the better explanation on the practical performance of face machining of spindle, the flatness error motion can be introduced similarly.

When a spindle has the 5-6 DOF error motions, the accuracy of face machining is sensitively influenced by the axial error motion and the tilting error motions. When a face fly cutter is equipped at the distance r from the center of axis of rotation of spindle, the actual error motion of the cutter, F(), can be mathematically derived along the sensitive direction of face machining as the spindle rotates. That is,

$$F(\theta) = Z(\theta) + r(\alpha \sin \theta + \beta \cos \theta) \quad (5)$$

where Z() is the axial error motion of spindle, and (), () are the tilting error motions of spindle.

F() in Eq(5) can be called as the flatness error motion of spindle, as eq(5) simulates the flatness tolerance of the machined surface when the face fly cutter is equipped at the spindle. The first term in eq(5) indicates the axial error motion of spindle, and the next two terms are the variation of error motion along the distance from the spindle center.

3. Spindle Error Measurement/Performance Evaluation System

In this paper, the system of spindle error measurement and performance evaluation system has been implemented. Fig. 1 shows the measurement setup of the spindle error measurement/performance evaluation system, where 5 gap sensors (LION Precision) and two master balls are arranged for the measurement of the 5 DOF spindle error motions. The signals from the gap sensors are conditioned and amplified to feed to the PC via a high frequency A/D interface board, which enables the spindle error measurement to be performed in real time environment even when the spindle is rotating at about few thousands rpm. The spindle error evaluation is performed fairly quick such that eccentricity removal, FFT analysis, etc. In order to give very precise measurement result, the roundness error of the master balls are also calibrated using the well known reversal technology, then the measurement results are compensated.

Not only the 5 DOF error motions, but the 3D error motions such as the cylindricity error motion and the flatness error motion are also evaluated in the PC environment.

4. Practical application and conclusion

The developed system has been practically applied to a ultra precision CNC lathe for the performance check of the developed system. Fig.2 shows the measurement results of the X radial error motion typically, while fig.3 shows the FFT spectrum of the X radial error motion measured. The flatness error motion of the spindle is also evaluated as in fig.4, where the 3 dimensional flatness error pattern is graphically illustrated, giving the flatness error motion of 2.33um.. The cylindricity error motion is also evaluated as in fig.5, where the 3 dimensional cylindricity error pattern is graphically shown. The cylindricity error motions has been found as 1.33um for the 100mm length of spindle movement.

Therefore a new method for characterisation for the 3D spindle error motions are presented and implemented for practical application, and conclusions are as follows.

(1)A new method of spindle characterisation method has been proposed, enabling the 3D error motions such as the cylindricity error motion and the flatness error motion.

(2)The spindle performance measurement/evaluation system has been implemented around gap sensors, master balls, A/D interface board, and the measurement/analysis software in PC environment. From the practical application to a ultra precision lathe, the performance and efficiency of the developed system have been demonstrated.

References

- 1.Axis of Rotation, Methods for Specifying and Testing, ANSI/ASME B83.4, 1985

