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Theoretical and experimental investigation of spindle axial drift and its effect on surface topography in ultra-precision diamond turning

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A R T I C L E I N F O

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A B S T R A C T

In ultra-precision diamond turning (UPDT), the spindle axial drift directly affects the machining accuracy. Due to the difficulty of measuring the spindle drift during the machining process, the spindle axial drift was rarely studied. In this paper, an experimental method is used to prove and measure the existence of the spindle axial drift at the machining process, and the influence of spindle drift error on the machined surface is further studied. A mechanical model of the spindle system is considering the mass eccentricity, and the dynamic behavior of the spindle in working conditions are simulated with the mathematical model. Periodicity whirl of the spindle is found in the simulation, which is verified by the end face turning experiments. Then, the influence of the spindle vibration on surface topography is discussed, considering the spindle rotation speed and its dynamic balance. Meanwhile, the vibration frequencies induced by the spindle rotation are detected by the signal analyzer, and the detected frequency has been found to agree well with the experimental wave period of the workpiece surface (WS). This study is quite meaningful for deeply understanding the influence rule of spindle unbalanced error from the viewpoint of machined surface and vibration frequency. The research results are useful for the spindle error control and machined surface error prediction.

1. Introduction

Ultra-precision diamond turning (UPDT) is widely utilized to fabricate high precision rotational symmetric components, such as plane, spherical, and aspheric surface. In UPDT, the aerostatic bearing spindle (ABS) is the key component, which has significant influence on the machined surface quality. In order to obtain high quality of workpiece surface (WS), the spindle should be balanced dynamically to achieve a good performance. Due to the manufacturing and assembly error of the spindle system, the spindle has eccentricity inevitable, and an unbalance mass will be generated. In the spindle system, the internal vibration source is mainly caused by the centrifugal inertia force generated by the unbalanced mass which is derived from machining errors and installation errors of the rotating parts. This centrifugal force has the characteristic of periodic variation, and as the exciting force acts on the spindle, the rotating parts of the spindle system are forced to vibration. Moreover, the unbalanced spindle rotation can cause spindle drift and machine vibration, which affects the topography of the machined surface. Therefore, analysis of unbalanced spindle has great significance for understanding the spindle performance and improving the machining quality.

In the earlier works, numerous researchers have considered dynamic behaviors of the ABS, containing the vibration modeling of spindle systems, the spindle rotation error and so on. The spindle unbalance is a critical factor attributing to error motions of the ABS in UPDT, which eventually leads to a structured error called "spindle star" that appeared as straight concentric spokes radiating out from the center of the part [1]. Huang et al. [2] established a dynamics model of the ABS to characterize the dynamic behavior with consideration of the unbalance effects. Gaber and Hashemi [3] established a vibration modeling of spindle systems based on a calibrated dynamic stiffness matrix method to predict the vibration characteristics of spindle systems. Zhang et al. [4] and Sun et al. [5] proposed that spindle vibration had great influence on machining precision of high precision optical components. Mathematical solutions for an ABS were derived to explore natural mechanisms of spindle vibration. Thus, the potential benefits were applied for the prediction and optimization of the spindle vibration. The ABS vibration played the major part in many factors that influence the surface topographies, and the defects observed on the surface [6,7]. Chen et al. [8] directly addressed the relationship between the original frequency content of the different dynamic error of the machine tool and of the machining process, and the resulting

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spatial frequency content of the machined surface. It was experimentally verified in the case of ultra-precision flycutting, where the dynamic error of the machine tool focused on the spindle error [9]. Some scholars also studied the spindle error induced dynamic errors at different rotation speeds [10,11]. The dynamic behaviors of ABS were proposed well and in depth. It can be found in the available research on machine errors [12] that the spindle rotation error is still insufficient, although it is quite important for the machining case with surface requirements of frequency domain error. Besides, little attention has been paid to the effects of the spindle-error-induced vibration on surface topography in UPDT, and the spindle tilting vibration has not been well studied, although the effects of spindle error motions on the machining accuracy have been widely studied. Furthermore, the imbalance and drift vibration of the spindle affecting on surface topography are rarely considered in the experimental process. Some scholars [13–15] have studied the radial vibration of the spindle, and the available research result has lots of positive significance for the spindle error identification and characterization, but little attention has been paid to the axial vibration of the ultra-precision aerostatic spindle, especially for which in the ultra-precision turning, which is the focus of this paper. In the ultra-precision machining process, the axial direction of the spindle is the sensitive direction of the plane processing and so on. In order to improve the WS quality, the axial vibration of spindle should be studied in depth.

In this article, the axial vibration of spindle and the axis average line of the ABS are investigated both theoretically and experimentally, and the spindle drift in the machining process is studied. Moreover, the machining process of the ultra-precision machine tools is simulated, and the performance of ultra-precision spindle system is experimentally verified. Because the frequency of the spindle vibration signal is an important information to study the dynamics of the spindle rotor, the frequency error of the ultra-precision spindle in an ultra-precision turning is measured. This study would be very helpful for the deep understanding the relationship between the frequency of spindle errors and machined surface.

2. Modeling simulation system

2.1. Drift motions

The axis position of the rotating spindle changes with time, and this phenomenon is called spindle drift. The drifts of the spindle axis have three forms as shown in Fig. 1, including the axial Fig. 1(a), radial Fig. 1(b) and tilting Fig. 1(c) motions. In Fig. 1, O-O indicates the ideal position of the spindle axis, and O′-O′ denotes the actual position of the spindle axis with drift. In the ideal condition, the spindle rotation has only one degree of freedom. However, there is no such ideal rotary motion [16,17]. As a result of the manufacturing and installing errors of the spindle system, the spindle would have drifts. Actually, when the spindle rotates, there are three forms of the drift existing simultaneously, and they couple with each other.

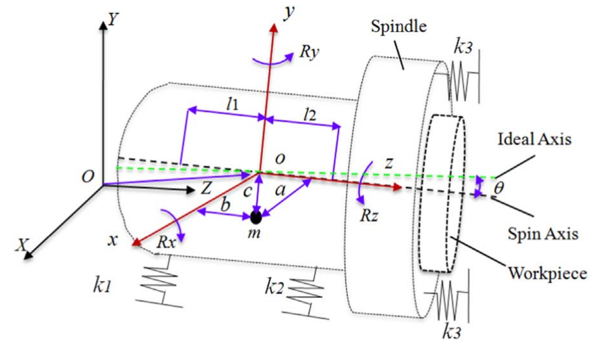

Fig. 2. The spindle system with regard to the reference coordinate frame *o(xyz)* moving in the inertial coordinate frame *O(XYZ)*.

2.2. Mechanical model of ABS

In order to study the drift motions of spindle, the spindle system is simplified, and the mechanical model is shown in Fig. 2. The spindle rotor is fixed with a reference system *o (xyz)*, moving in the inertial coordinate system *O (XYZ)*. *O (XYZ)* is fixed in the *X* feed system (shown in Fig. 6). *X, Y* and *Z* represent the feed direction, the cutting direction and the axial direction corresponding to the initial spindle axis, respectively. Therefore, its motions can be described by the rotations of *o (xyz)* around the *x, y* and *z*-axis at the angles (R_x,R_y and R_z) in *O (XYZ)* and by the translations of *o (xyz)* along the *X*, *Y* and *Z*-axis at the displacements (*x*, *y* and *z*, respectively) in *O (XYZ)*.R_z is equal to ωt (ω is spindle speed and t is time). m and k stand for the rotor eccentric mass and stiffness respectively.

When the spindle is not eccentric, the position of geometric center is concentric with the bearing center and is defined as the origin *o*; *xoz* plane is defined as a rotating cross-section in Fig. 2. Supposing that the eccentric mass is m, the distance between the eccentric mass m and the center point *o* is c, the distance between the eccentric mass m and the axis line is a, and the vertical distance between eccentric masses m and the center point *o* is b. Due to the presence of the unbalance amount ma, the spindle axis rotates around the bearing center, generating a whirl. Since the eccentric mass m is small, the center position of gravity is still regarded as the point *o*. The motion equations, which are the translation and rotating around the center of gravity *o* along *x*, *z* axis, are established as Eqs. (1)–(5) respectively [18]. The influence of the damping effect of the aerostatic spindle can be neglected.

$$\begin{pmatrix} M & 0 \\ 0 & I \end{pmatrix}\begin{Bmatrix} \ddot{Z} \\ \ddot{\theta} \end{Bmatrix} + \begin{pmatrix} k & 0 \\ 0 & k_e \end{pmatrix}\begin{Bmatrix} Z \\ \theta \end{Bmatrix} = \begin{Bmatrix} 1 \\ -b \end{Bmatrix} ma\omega^2 e^{j\omega t} \tag{1}$$

Where I denotes the rotational inertia of the spindle, M denotes the weight of the spindle, $Z = x + jz$, $k = k_1 + k_2$ and $k_e = k_1 l_1^2 + k_2 l_2^2$.

The solution of Eq. (1) is:

$$Z = \frac{ma\lambda^2}{M\sqrt{(1-\lambda^2)^2 + (2\zeta\lambda)^2}} e^{-j\phi} \tag{2}$$

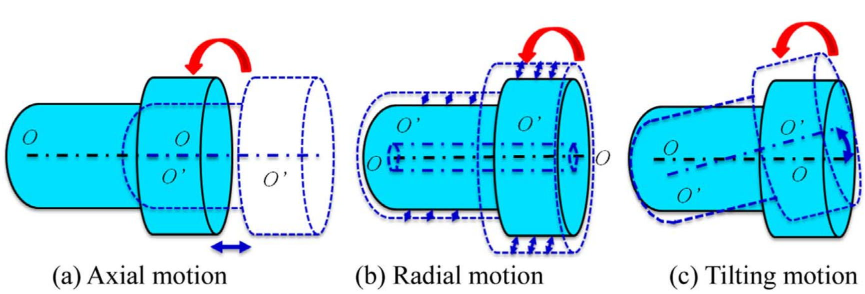

Fig. 1. Schematic diagram of the spindle axis with drift motions.