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Investigation on the position drift of the axis average line of the aerostatic bearing spindle in ultra-precision diamond turning

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ABSTRACT

To evaluate the performance of the spindle, many techniques have been proposed to measure the spindle error motion. However, few studies have focused on the investigation of the position drift of the axis average line (AAL). In the present study, the AAL of the aerostatic bearing spindle is investigated both theoretically and experimentally. An error model is developed to analyze the errors which contribute to the error of depth of cut in slow tool servo assisted turning. Moreover, an experiment of microstructure fabrication is conducted to investigate the amplitude error of microstructures along both axial and radial direction of the cylindrical workpiece. The effects of spindle error motion, spindle unbalance induced eccentricity, thermal error and position drift of AAL are analyzed. The results indicates that the position drift of AAL varies significantly in terms of the variation of the spindle speed due to the hydrodynamic effect, and the relation between the drift and the spindle speed is nonlinear.

1. Introduction

With the increasing demand of artificial components with ultra-precision accuracy and ultra-smooth surface roughness in modern industries, the ultra-precision single point diamond turning (SPDT) technique has been extensively adopted to generate these components, and accordingly popularize their applications in a variety of fields, including optical and photonic systems, telecommunications, aerospace, and biomedicine systems. With the SPDT, the spindle of machine tool is a critical component to guarantee the machining accuracy. Due to the properties of low friction, low heat generation and simple structure, aerostatic bearing spindles are widely employed in ultra-precision machine tools [1–3].

To estimate and control the quality of machined components, it is very important to evaluate performances of the spindle of machine tool before machining. The spindle error motion which is the most common item to be evaluated is usually evaluated by non-contact sensors targeting an artifact attached to the spindle rotor [4]. For instance, Gao et al. developed an angular three-point method which utilizes 2D slope sensors [5]. This method can simultaneously measure the spindle radial and angular error motions as well as the out-of-roundness of the artifact. Fujimaki and Mitsui utilized an auto-collimation to develop an optical system for measuring the radial error motion of a miniature ultra-high-speed spindle [6]. Anandan and Ozdoganlar presented a laser Doppler vibrometry-based methodology to measure the axial and radial spindle error motions of a miniature ultra-high-speed spindle at high spindle speed [7]. The obtained measurement data consists of both the spindle error motions and the form error of the artifact. Thus, to separate the spindle error motions from the form error of the artifacts, three classical error techniques have been proposed, including the reversal, multi-step and multi-probe methods [6–12]. The reversal technique is extensively utilized to separate the form error of the artifact from the spindle error motion [10,13]. This method needs two rounds of measurements to separate the two errors by rotating both the artifact and the probe with an angle of 180° around the spindle axis between the two rounds of measurements. Theoretically, reversal technique can entirely separate the two errors. Multi-step and multi-probe techniques are alternative methods to the reversal technique. In multi-step technique, the probe remains stationary during the measurement, whereas the artifact is indexed through equal angles [9,14]. Multi-probe technique simultaneously utilizes three or more probes to target the artifact. In general, all the three methods are capable of measuring the spindle error motions with a measurement uncertainty of sub-nanometer level.

As discussed in Ref. [15], the spindle error motion is defined as a relative motion between the spindle axis and the corresponding axis average line (AAL) in the reference frame. The AAL should remain stationary during the measurement of spindle error motion at a given spindle speed. However, position of this AAL can

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drift in an unpredicted way due to thermal, air flow instability and external disturbances. With respect to the aerostatic bearing spindle used in ultra-precision machine tool, the thermal effect has relatively small effects on the position drift under good cooling conditions. Instead, because of the hydrodynamic effect of the aerostatic bearing, the position of the AAL can drift away from the center of the bearing stator, and this can lead to significant drifts of the AAL position [16–19].

In ultra-precision machining, the position drift of the AAL of the spindle axis is commonly in the range of several hundreds of nanometers, which may significantly deteriorate the form error of the machine components. However, few studies have been reported on this issue. Thus, the present study will give a detail discussion on the position drift of the AAL induced by the hydrodynamic effects and its influences on the generation of the microstructures on the roller surfaces.

2. Theoretical analysis

In terms of the spindle error motions, two critical concepts should be introduced before the analysis, namely the axis of rotation (AOR) and axis average line (AAL) [15]. The AOR is a line fixed on the rotor and vertical to the cross-sectional plane of the rotor, and also the rotor rotates around it. The AAL is defined as the spatial mean location of the AORs over many revolutions in the reference frame.

2.1. AAL drift due to hydrodynamic effect

For the air bearing, either aerostatic or hydrodynamic journal bearings, the air film thickness along the circumferential direction is not homogeneous [16–19]. Therefore, the equilibrium position of the rotor is not at the center of the bearing as shown in Fig. 1. In general, the air film thickness is determined by the centricity e and the attitude angle φ at steady state, which can be expressed by:

$$\bar{h}(\theta,\ \bar{z}) = 1 + \varepsilon\ \cos(\theta - \varphi) \tag{1}$$

where $\bar{h} = (h/c)$, and h and c denote the local film thickness and the radial clearance of bearing respectively; eccentricity ratio $\varepsilon = e/c$; $\bar{z} = \left(z/(L/2)\right)$, and z and L are the axial coordinate and length of bearing; θ is the angular coordinate.

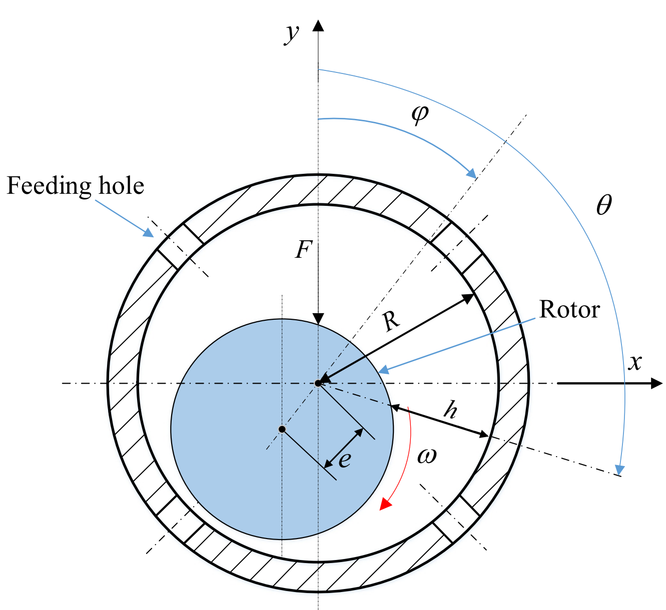

Fig. 1. Schematic of the aerostatic bearing.

The distribution of the corresponding pressure along the circumferential direction under the applied load F is governed by the non-dimensional Reynolds equation [16]:

$$\frac{\partial}{\partial\theta}\left[\bar{h}^3\frac{\partial\bar{P}^2}{\partial\theta}\right] + \left(\frac{D}{L}\right)^2\frac{\partial}{\partial\bar{z}}\left[\bar{h}^3\frac{\partial\bar{P}^2}{\partial\bar{z}}\right] = 2\Lambda\frac{\partial}{\partial\theta}\left[\bar{P}\bar{h}\right] \tag{2}$$

where $\bar{P} = (P/P_s)$, P is the pressure at the feeding hole, and P_s is the supply pressure; $\Lambda = \left(6\mu\omega/\left(P_s(c/R)^2\right)\right)$, μ is the dynamic viscosity of lubricant, and ω and R denote the spindle speed and the radius of bearing respectively; $D = 2R$ is the diameter of bearing.

For a specific spindle error motion test, the AAL is stationary in the reference frame and the axis of rotation has a motion relative to AAL shown in Fig. 2. The relative motion is then defined as the spindle error motion. Nonetheless, position of the AAL may vary with respect to different working conditions, including different spindle speeds and different surrounding temperatures. For the aerostatic bearing spindle, the spindle speed is a critical factor to determine the equilibrium position of the rotor shown in Fig. 1. Different spindle speeds may lead to changes of the equilibrium positions of the rotor, and accordingly, lead to the position drift of the AAL of the rotor.

2.2. Error model

In slow slide servo (S^3) assisted freeform surface turning, there are usually two machining steps. The first step is to machine a rough surface with a relatively high spindle speed and feed rate per revolution to serve as the reference. Then, this rough surface will be subjected to the S^3 based finish machining with relatively low spindle speed. The low speed is jointly caused by the servo operation of the spindle rotation and the much higher angular sampling ratio, which is required to guarantee the low interpolation error [20]. Fig. 3 shows a S^3 machining on a roller surface. After rough turning of the roller surface, microstructures can then be fabricated on it on basis of the cylinder surface obtained in the first step rough turning. The relative distances between the AAL and the tip of the diamond tool in rough and S^3 machining are denoted as d_1 and d_2, respectively. Ideally, the AAL remains unchanged for the two machining processes, namely:

$$d_1 = d_2 = \left|x_t - x_{O_s}\right| \tag{3}$$

where the x_t and x_{O_s} are the X-axis coordinates of the cutter tip P_t and the intersection point O_s of AAL and OXY plane. Actually, the AAL will change with respect to different spindle speeds, and this effect lead to the change of the relative distance between the tip of the diamond tool and the AAL. Thus, the actual distance is expressed as:

$$d_2 = \left|x_t - x_{O_s'}\right| \tag{4}$$

where $x_{O_s'}$ is the coordinate of the new intersection point O_s' of AAL and OXY plane due to position drift of AAL. The relative position drift of the AAL between different spindle speeds is denoted as d_e and can be expressed by:

$$d_e = \left|x_{O_s} - x_{O_s'}\right| = \left|e_1 \cdot \sin\ \varphi_1 - e_2 \cdot \sin\ \varphi_2\right| \tag{5}$$

where e_1, e_2 are the eccentricities of the rotor of the aerostatic bearing during the rough and S^3 turning, respectively. φ_1 and φ_2 are the corresponding attitude angle (as defined in Fig. 1) during rough and S^3 turning.

During machining, a variety of motion errors of the machine tool may contribute to the form accuracy of the generated