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Investigation the gas film in micro scale induced error on the performance of the aerostatic spindle in ultra-precision machining

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The objective of this work is to study the influence of error induced by gas film in micro-scale on the static and dynamic behavior of a shaft supported by the aerostatic bearings. The static and dynamic balance models of the aerostatic bearing are presented by the calculated stiffness and damping in micro scale. The static simulation shows that the deformation of aerostatic spindle system in micro scale is decreased. For the dynamic behavior, both the stiffness and damping in axial and radial directions are increased in micro scale. The experiments of the stiffness and rotation error of the spindle show that the deflection of the shaft resulting from the calculating parameters in the micro scale is very close to the deviation of the spindle system. The frequency information in transient analysis is similar to the actual test, and they are also higher than the results from the traditional case without considering micro factor. Therefore, it can be concluded that the value considering micro factor is closer to the actual work case of the aerostatic spindle system. These can provide theoretical basis for the design and machining process of machine tools.

1. Introduction

The performance of a machine tool is evaluated by the machining accuracy, which is critical for machined components, such as guideway and spindle. And its properties are closely related to the accuracy of the machined workpieces. Many scholars investigated the machining accuracy factors and the corresponding elimination methods. The machining accuracy factors have been studied including motion errors, cutting force induced deformations, position and assembly errors of machine tool components, and deformation errors caused by thermal errors [1–3].

Aerostatic spindle is increasingly used in precision and ultra-precision machining due to the high movement precision, low friction coefficient and friction torque, clean and cold working conditions, etc. And it is also worth mentioning that the clearance of the gas flow in the aerostatic bearing of the spindle is extremely narrow that is belonged to the micro scale (1 μm~1 mm--micro scale, >1 mm--macro scale). In micro scale, the specific phenomenon of gas will occur such as compressibility, velocity slip, viscosity variation of the gas film. Accordingly, the performance of the aerostatic spindle will be different from the one in macro scale. Therefore, these specific effects are defined as mirco factor and its effects on the spindle system is researched in this paper.

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Considerable research related to factor in micro scale and dynamic behavior of the aerostatic spindles has been published. Morini et al. [4] studied the influence of micro factor on friction factor and pointed out that the micro factor caused the decrease of the Knudsen number and the friction factor of cross section. Khadem et al. [5] simulated the roughness of flow wall directly to explore the influence of micro factor and compressibility. Kauehpour et al. [6] studied the different effect of the compressibility and the micro factor of different gas by Using two-dimensional micro pipe flow and heat transfer model, and made a comparison and verification. Shamshiri et al. [7] studied the influence of Knudsen number on fluid velocity in slip zone. Tang et ai. [8] researched the influence of micro factor on the fluid in micro channel through experiments. Giulio et al. [9] numerically analyzed the influence of micro factor on the pressure drop in micro channel.

Erturkd et al. [10] applied coupling analysis of frequency response function and cantilever beam model to the study of dynamic characteristics of machine tool spindle, and the results between frequency analysis and finite element analysis were compared and verified. Ahmadi et al. [11] introduced the elastic support transformation method to predict the machine tool dynamic performance with different cutting tools, and tool-holder joint interface characteristics are included in the model by considering a distributed elastic interface layer between the holder-spindle and the tool shank part. The changes of the distributed interface layer in normal contact pressure along the joint interface were taken into account and compared to the lumped joint model, and experiments are conducted to demonstrate the efficiency of proposed model finally. Kolluru and Axinute [12] studied the coupling influence of dynamic response between tool and workpiece, and the difference of dynamic response was recognized by extracting the frequency domain and time domain of acceleration signal in the process of machining. Gagnol et al. [13] identified the modal of cutting tool units of the spindle in high speed machining, and a stable industrial sensor device with recognition program was developed. Finally the measurement results were compared with the finite element simulation results. Apart from this, the spindle error is studied in different ways. Chen et al. [14] established the error measurement for the ultra-precision aerostatic spindle in a flycutting machine tool The dynamic and multi-direction errors of the spindle are real-time measured under different rotation speeds. Then the cause of the main synchronous and asynchronous errors is analyzed and indicated. In [15], Chen et al. gave a method for obtaining the frequency spectrum of the machined surface error in radial directions. Besides a method to influence the number of spatial frequency components of the surface error in radial directions and to predict and control their magnitude is put forward. Liang et al. [16] used Monte Carlo method to analyze the volumetric error of machine tool from multi-perspective. And it is proven to be an effective tool to obtain the probabilistic distribution characteristics of positional error in arbitrary point and moving path in the workspace. Ji et al. [17] studied the important factors which influence the magnetic abrasive polishing. Then some tentative experiments are carried out to study its polishing effect. Liu et al. [18] used the fluid–structure interaction method to obtain the actual clearance changes of the hydrostatic bearing. The dynamic and thermal performances of the machine tool are analyzed considering the effect of hydrostatic bearings. In [19], the effects of motor rotor eccentricity on surface topography in ultra-precision processes are analyzed. An electromagnetic–mechanical method is used to study the coupling effects between the motor rotor and the aerostatic spindle. It is found that motor rotor eccentricity has a significant influence on the spindle vibration, which dramatically reduces the processing quality. Gao et al. [20] investigated the computational design and analysis of aerostatic journal bearings at ultra-high speed spindles particularly in light of the nonlinear compressible Reynolds equation and the associated computational analysis and algorithms using the finite element method-based Galerkin weighted residual method. Zhang et al. [21] developed a five-degree-of-freedom dynamic model for an aerostatic bearing spindle to describe its dynamic responses, involving translational motions and tilting motions, and to analyze the effects on surface topography of the spindle vibration under different cutting processes in UPDT. In [22], a novel active non-contact journal bearing based on squeeze film levitation is presented. Theoretical models to calculate load carrying forces induced by squeeze film ultrasonic levitation are studied and validated by experimental results. Active control of the spindle center position is achieved with positioning accuracy of the spindle center in the range of 100 nm.

However, for the above researches, most have been dedicated to analyze the behavior of the bearing under the traditional condition, little to the micro factor in micro scale, and the influence of the micro factor on the dynamic characteristics of the spindle in the machining process were seldom studied. In this paper, unbalance models of the coupled spindle shaft and aerostatic bearings in static and dynamic are presented. The deflection and the transient analysis of the aerostatic spindle under micro factor are deduced. The actual stiffness in axial direction and the radial rotation error of the shaft are measured. It shows that they are very close to the simulation results of the spindle system. Similarly the results of modal and harmonic experiment are close to the actual work case of the aerostatic spindle system.

2. Aerostatic spindle-bearing system

2.1. The structure of the aerostatic spindle system

The spindle is contacted with the turning tool of a vertical machining lathe, and it includes bearings in radial (journal bearing) and axial (thrust bearing) directions. The structure is shown in Fig. 1. Considering the spindle actual working conditions and calculate easily, the spindle is modeled through a three-dimensional solid unit which can consider the factor of cross-sectional shape. Therefore, it meets the actual situation in terms of constraints. The aerostatic air is pressurized to the bearing with a compressor, then a thin film is formed between the spindle shaft and the bearing. And in the three-dimensional model, the gas film of the bearing in radial and axial is denoted by a series of the springs.