THE MANUFACTURING TECHNOLOGY OF AN ULTRA-PRECISION AEROSTATIC SPINDLE SYSTEM

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Abstract

The paper presents a newly–developed aerostatic work spindle applied in the Nanosys-300 system, an aspheric optical surfaces ultra-precision machining system. In addition, the corresponding technical parameters and the technical measures adopted in the process of manufacturing are also investigated. The theoretical study and the practical application show that the concerned aerostatic spindle satisfies the design requirements and can be applied in the practical ultra-precision production.

1 General Introduction

As is well known that the work spindle of an ultra-precision machining system supports directly the work-piece or the cutting tools, therefore its motion accuracy (radial, axial and angular motion accuracy) will inevitably affect the accuracy of the work-piece machined. As a matter of fact, the work spindle is the most important component of an ultra-precision machining system, by whose accuracy and performance, we can evaluate, to a certain extent, the overall accuracy of an ultra-precision machining system. The motion accuracy and vibration performance of a spindle depends upon the bearings utilized. The precise ball bearings are employed in machining system in the earlier days, the corresponding form accuracy and the surface finish of the work-piece machined was approximately 1μm and Ra 0.04 ~ 0.02μm respectively. The machining system on such principle has the disadvantages of high cost of production and limited, relatively low motion accuracy. Later people considered replacing it by a brand-new fluid hydrostatic bearing of higher stiffness and motion accuracy. However,it still has the following disadvantages:

1) It is difficult to control the temperature of the working fluid. The thermal deformation due to the temperature growth will influence the motion accuracy of the spindle.

2) The air tends to mix into the working fluid and suspending in the fluid in the form of minute foam, thus reducing the stiffness and the dynamic performance of the spindle.

On the basis of the mentioned reasons, the aerostatic spindle began to be employed in the ultra-precision machining system in the 1960s for such advantages as low friction, insensitiveness to the temperature and the cleanliness, high motion accuracy, smooth rotation and low temperature growth. In spite of the disadvantages of relatively low stiffness or load capacity, it can still be widely used in the small-sized or medium–sized ultra-precision machining systems where the lower cutting

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force is required. The reason why the aerostatic bearing has the good motion accuracy (much better than the accuracy of the composed parts itself) is the "averaging" effect of the pressure film of the spindle. For example, the motion accuracy of the spindle can be up to 1/15 ~ 1/20 of the roundness of the shaft and the sleeve. The Japanese researchers have revealed that we can obtain the 10nm motion accuracy when the roundness of the shaft and the sleeve is between 0.15 ~ 0.2μm, and the aerostatic spindle of the highest motion accuracy ever made is 8nm till now through the FFT test. In addition, the aerostatic spindle has the advantages such as good dynamic property, long precision life, less vibration, good stiffness/load capacity adaptability to the practical operating condition.

Up to now, the technical barrier of high accuracy, high speed and high stiffness aerostatic spindle has not been removed completely yet. The aerostatic spindle of high accuracy (0.05 ~ 0.1μm), high speed (100 ~ 3,000rpm), high stiffness and high load capacity (45~55Kg) for the Nanosys-300 system is still a real technical challenge.

By making full use of the latest research and development achievements of the specialized aerostatic spindle manufacturers in the world, with the help of many years of rich experience in the development of aerostatic spindle, we have carried out the successful research on the aerostatic spindle.

2. Technical Parameters

Speed range: 100 ~ 3,000 rpm
Operating air pressure: 0.6 MPa
Axial motion error: < 0.05 ~ 0.1 μm
Radial motion error: < 0.05 ~ 0.1 μm
The accuracy of the machined work-piece:
Form accuracy: < 0.3 ~ 0.5 μm
Surface finish: Ra0.01 μm (typical work-piece)

3. Technical Measures

The structural patterns of the aerostatic bearing can usually be divided into three types: cylindrical radial journal bearing (hereinafter called journal bearing) with planar axial thrust bearing (hereinafter called thrust bearing), double hemispheres(radial and axial bearing), sphere(radial and axial bearing) with journal bearing, etc., In this research, we adopted the first design, namely journal bearing with thrust bearing, for the purpose of simplicity in structure. However, the disadvantage of the structure is that it demands relatively complicated manufacturing technology including good perpendicularity of the journal and thrust bearing, high manufacturing accuracy of the shaft and the sleeve, and excellent uniformity of the air supply orifice restrictors because the uniformity of the air flow through the orifice restrictors will surely affect the uniformity of the air flow in the close clearance between the shaft and the sleeve, and affect the motion accuracy of the spindle eventually. The uniformity of the air flow through the orifice restrictors depends upon the damping feature, the quantity, the distribution of the orifice restrictors, the roundness, the cylindricality and the surface finish of the concerned spindle parts, etc..(For detailed construction, please refer to the Fig. 1)

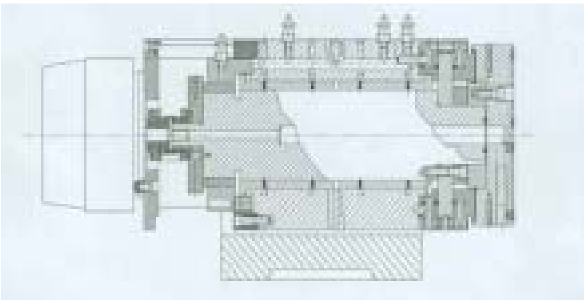


Fig.1. The Schematic Diagram of the Aerostatic Spindle

For the aerostatic spindle in the Nanosys-300 system, the two thrust plates of the thrust bearing, being an integrated one rather than two separated ones, are arranged directly in the front of the aerostatic spindle, meanwhile their operating areas have been enlarged properly. This kind of structure can not only minimize the vacuum chuck on the nose of the spindle drifting forward when the temperature of the spindle rises, which leading to the machining error, but it can also prevent alteration of the axial clearance of the thrust bearing. Besides, the application of the increased area thrust bearing can maximize effectively the stiffness of the spindle, ensuring its motion accuracy accordingly.

The coaxial non-contacting clearance seal, at the rear of the housing of the spindle, is applied to transfer the vacuum to the vacuum chuck on the nose of the spindle, thus avoiding the accidental connecting of the high pressure system and the low pressure system, and the jamming and the disturbing of the high pressure system. Thanks to the introduction of the non-contacting clearance seal, the non-linear factor is reduced in the spindle system and thus the motion accuracy is increased.

The spindle housing is designed to mount to the base frame at the spindle centerline to prevent the centerline height from rising as the spindle warms up at elevated speed. The bolts which fix the spindle in place are arranged carefully so that the spindle housing will expand axially from a point in line with the thrust bearing.

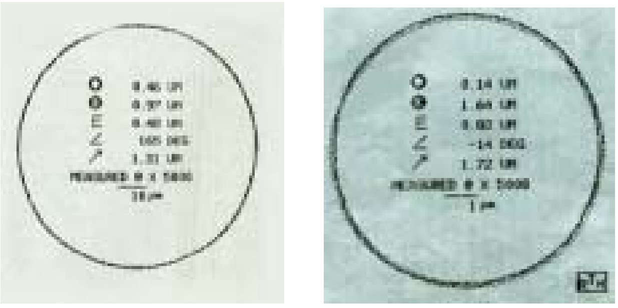
The clearance of the thrust bearing is 7~ 8 μm, the journal bearing 8~9 μm. The orifice restrictors are employed, the orifice restrictors of the journal bearing are arranged symmetrically to the centerline as follows: Φ 0.15mm, 4row×12pcs./row=48 pcs., the orifice restrictors of the thrust bearing as follows: Φ 0.15mm, 1row×12pcs. /row=12 pcs..

Because the diameter of the orifice restrictor is pretty small, the requirement to the air supply is accordingly rigorous. The pressure air from the air compressor must be firstly dried and purified, then be separated from the oil mist, to guarantee that the pressure air for the spindle system is dry(in case any components rust) and clean (in case any orifice restrictors jam).

The structure and geometric dimensions of the air cavity have a great influence upon the performance of the spindle. If the volume of the air cavity is too big, the so -called "pneumatic hammer" phenomenon will occur, resulting in the instability of the spindle; if too small, the stiffness of the spindle will be weakened. In this research, the "—" shaped air cavity of triangle section is applied, the opening of the air cavity is 0.25mm wide, and the depth 0.15mm.

Both the shaft and the sleeve are made of excellent metal material. To avoid any accidental damage of the two coupling components---the shaft and the sleeve, two different metals are selected: the harden material of the shaft is the stainless steel 9Cr18, whose hardness after the heat treatment is HRC 58- 62, the softer material of the sleeve is QSn65-0.1. The material and the hardness of the thrust bearing is the same as that of the journal bearing.

To achieve the desired design accuracy, a systematic study is conducted on the manufacturing technology of the ultra-precision aerostatic spindle system, and a series of concerned technical measures are carried out successfully in the process of the spindle manufacturing, they are as follows: 1) The specially designed aerostatic journal bearing is used to bear the floating boring rod when machining the bore of the sleeve, the rotation movement of the borer shaft is transmitted to the floating boring rod through the heart carrier, the motion and the machining accuracy of the floating boring rod, being independent of the accuracy of the borer itself, is determined by that of the two aerostatic journal bearing used. The technical measure taken here has ensured that the machining and the operating condition of the spindle is absolutely the same, accordingly ensuring the machining accuracy of the spindle system. 2) Concerning the machining of the outside diameter of the spindle shaft, apart from the study on the material decision and the heat treatment, the structural pattern of the center hole and its grinding technology is also improved. Furthermore, the grinding technology of the outside diameter is innovated. With all the necessary technical measures, the roundness of the spindle sleeve achieved is 0.46 ~ 0.48 μm, the spindle shaft, 0.14 ~ 0. 21 μ m. (For details, please refer to the Fig. 2)



a) The Spindle Sleeve b)The Spindle Shaft

Fig.2. The Roundness Test Results of the Aerostatic Spindle Sleeve

The way in which the spindle is driven will naturally affect the accuracy of the ultra-precision machining system. At present, there are three main ways used to drive the spindle, they are as follows: 1) AC/DC electrical motor with the belt transmission, the step-less speed control is feasible. 2) coaxial electrical motor. 3) AC/DC electrical motor with the flexible couplings transmission. In the Nanosys-300 system, the Mavilor AC brushless servo motor MA-10 is applied, which has the advantages of higher moment stiffness, less disturbing moment and less thermal effect, the step-less speed control is also feasible. With the thermal isolation effect of the flexible coupling, there is no need for any other refrigeration measures. The AC motor has been carefully dynamic balanced. When the motor is installed, the centerline of the motor and the spindle should be in alignment, and a flexible couplings is applied to eliminate the vibration and the motion error resulting from the installation error of the motor to improve the accuracy of the spindle, the comprehensive motion accuracy of the spindle system can be up to 0.05 μ m.

In the course of the design, the structural and the thermal symmetry of the related components should be also fully considered. All the rotational parts of the spindle should be dynamic balanced strictly(there are two dynamic balance adjustment mechanisms in the front and the rear of the spindle), the accuracy of the balance can be up to 0.05 μ m.

4. Conclusions

Based on all the necessary test results, it is believed that the performance of the aerostatic spindle system has fully satisfied the design requirements, and it can be widely applied in the practical ultra-precision production. The test results are as follows:

Table.1. The Test Results of the Aerostatic Spindle

The items tested	The design value	The achieved value
The speed range	100 ~1,000/3,000rpm	100 ~3,000rpm
The load capacity	45Kg	53Kg
The swing diameter	300mm	320mm
The motion accuracy*	0.05 ~ 0.1μm*	0.07μm*

*The specification of the motion accuracy test of the aerostatic spindle system:

The instruments applied in the test: the Form Measuring System FMS 4210 by FAG, the motion accuracy of the shaft is 0.02μm.

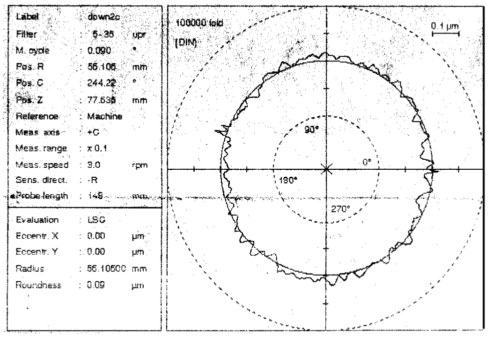


Fig. 3. The Test Results of the Aerostatic Spindle

The ways in which the test is performed: we have machined a cylindrical work-piece with the Nanosys-300 system to measure the roundness of the corresponding work-piece to reflect indirectly the motion accuracy of the aerostatic spindle of the system (the other errors of the system are also included, although the achieved value is a bit greater, yet between 0.05 ~ 0.1μm).

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