

# A PRECISION ACTIVE AEROSTATIC SPINDLE WITH AN AXIAL POSITIONING ACTUATOR

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## 1. Introduction

Many types of miniaturized machine tools have been developed for machining micro mechanical parts and to save energy, space and resources [1-3]. The next targets for the miniaturized machine tools will be multi-axis and ultra-precision machining. Conventional multi-axis machine tools are constructed from several stacked one-degree-of-freedom (one-DOF) positioning mechanisms to realize multi-degrees-of-freedom motion [4]. The stacked positioning mechanism is not suitable for miniaturization or ultra-precision motion control, due to the cumulative effect of the space occupied by several one-DOF positioning mechanisms and non-collocation of actuators with displacement feedback sensors.

In ordinary vertical milling machines, a two-DOF motion table and a spindle moving in the vertical direction are normally realized by assembling several one-DOF motion tables, consisting of lead screws, one-DOF linear guideways, servomotors and rotary encoders. The larger the number of the stacked one-DOF positioning mechanism becomes, the larger the actuators that are required to move the mass of the other DOF motion mechanisms. Furthermore, the mass centers of the positioning tables or the spindle and the locations of the displacement sensors are not collocated. Such non-collocations can cause motion and machining errors.

One solution for realizing an ultra-precision and miniaturized machine tooling is to develop a multiple-degrees-of-freedom-controlled positioning mechanism

without stacking several one-degrees-of freedom-positioning mechanism, thus only one mass is directly moved multi-directionally by several actuators.

Our research group is developing a compact nano-machine tool (high-precision vertical milling machine) featuring nano-positioning resolution that can be placed on a normal-sized desk. The compact nano-machine tool consists of a novel X-Y- $\Theta$  motion table system, in which the square table is levitated with compressed air and is directly driven by six voice coil motors with three-axis laser feedback [5], and an aerostatic spindle integrated with an axial positioning actuator and an air motor, in which the ordinary precision spindle and the stacked one-DOF positioning mechanisms are not required.

This paper reports on the design and fabrication of a precision aerostatic spindle integrated with axial positioning actuator, precision measurement system and an air motor. The dynamic characteristics of the spindle have been evaluated.

## 2. Active Aerostatic Spindle

The principle of the proposed spindle is shown in Fig. 1. The main spindle is supported by two radial air bearings, placed at the both ends of the spindle housing. The aerostatic bearings not only support the radial motion of the main spindle, but they also work as a linear guideway in the axial direction of the spindle. As a result of the averaging effect of compressed air

in gaps between the main spindle and air bearings, the main spindle can rotate precisely and slide in the axial direction without restriction and friction. Thus a one-DOF table system to move the spindle in the axial direction can be omitted.

The main spindle is moved and positioned in the axial direction by utilizing the Lorentz force between a permanent magnet in the main spindle and air-core coils in the spindle housing. The Lorentz force, in proportion to the value of the current in the coil, acts in the axial direction. The reaction force against the Lorentz force moves the main spindle in the axial direction. Such a driving mechanism is as same as that in voice coil motors, except the spindle can also precisely rotate. The advantage of the air-core coil is the freedom from an unbalanced pull which would be generated in the radial direction between electromagnets and steel cores and having longer stroke than the electromagnets, while the draw-back is the small driving force in the axial direction, compared with that obtainable from electromagnets having steel cores. However, the small driving force may not be a major drawback for micro machining, because this operation does not require much axial force.

Feedback control is necessary in order to control the position of the main spindle in the axial direction. To measure the axial displacement of the main spindle with a laser interferometer system, a plane mirror is precisely attached at the end of the main spindle, in order to minimize the inclination of the mirror to the rotational axis. Abbe's principle and the collocation of the sensor and actuator are satisfied in this spindle system.

An air turbine is used to rotate the main spindle, being light and compact, and able to apply rotating torque while the spindle is moving in the axial direction. Furthermore the air turbine drive not only generates less

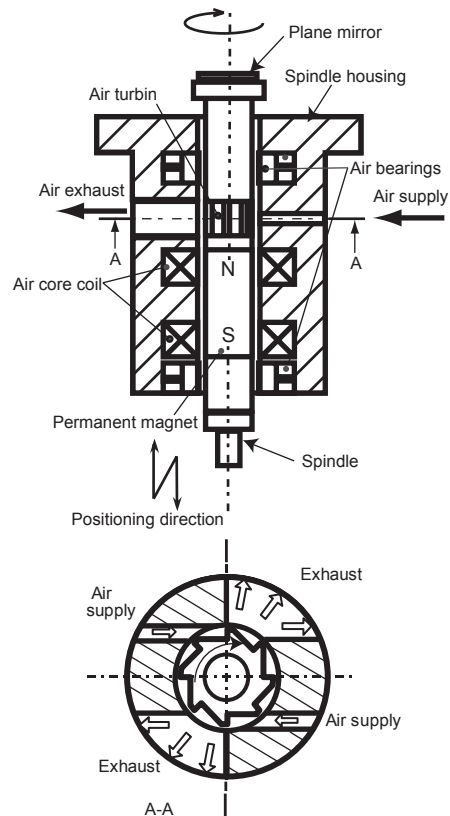
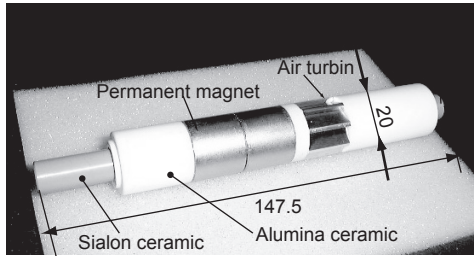


Fig. 1 Principle of an aerostatic spindle with an axial positioning actuator

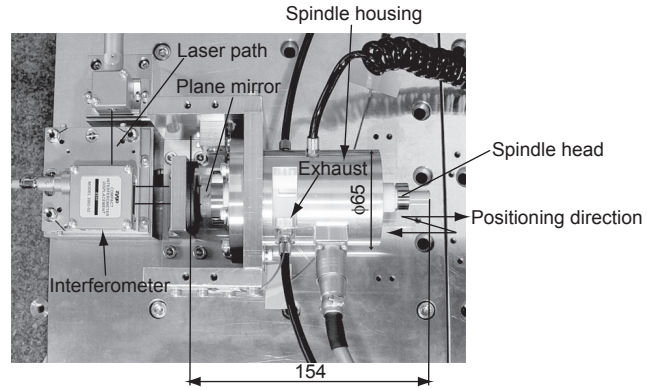
disturbance force interfering with the axial magnetic actuator, but also is expected to have the effect of cooling the coils in the spindle housing due to adiabatic expansion of the air. Thus, thermal expansion of the spindle can be suppressed. The air turbine has eight blades and the turbine stator has two nozzles, placed symmetrically with respect to the rotational center to cancel the radial forces.

### 3. Fabrication

Figure 2(a) shows a fabricated main spindle. The length and diameter of the main spindle without the plane mirror are 147.5mm and 20mm respectively, and its weight, including a plane mirror, is 0.26 kg. The shaft core and the sleeves working as the air bearing rotor are made of SIALON (Si-Al-O-N) and alumina (Al<sub>2</sub>O<sub>3</sub>)



(a) Main spindle



(b) Assembled spindle

Fig. 2 Test spindle

ceramic, respectively. SIALON is a ceramic with a large fracture resistance. The sleeves were precisely machined to attain concentricity of the order of sub-micrometer after being glued to the shaft core. The average air gap between the sleeves and air bearings in the spindle housing is  $3\mu\text{m}$ . The measured stiffnesses of the air bearings at tool and plane mirror sides are  $25\text{N}/\mu\text{m}$  and  $50\text{N}/\mu\text{m}$ , respectively, while supplying compressed air at  $0.5\text{MPa}$  at  $1.7\text{NL}/\text{min}$ .

The cylindrical permanent magnet, made from  $\text{Nd}_2\text{Fe}_{14}\text{B}$ , was glued to the shaft core, and was axially-magnetized after assembling and grinding the shaft. The air turbine, which is made of duralumin, was fixed to the shaft core using a shrink fit. The plane mirror for the laser interferometer measurement, with an effective diameter of  $12\text{mm}$ , was precisely attached at the end of the shaft. The flatness of the plane mirror is  $2.53\text{nm rms}$ .

In the spindle housing as shown in figure 2(b), a pair of coils, each comprising 357-turns, were placed and connected in series so that they generate magnetic flux in opposition. The coil current is supplied by a current-controlled amplifier. The actuator generates a driving force with  $4.0\text{ N/Ampere}$ .

The spindle is designed to have a  $10\text{mm}$  positioning range in the axial direction. The displacement signal from a compact laser interferometer measuring system (Zygo Corp., ZMI 501), with the highest

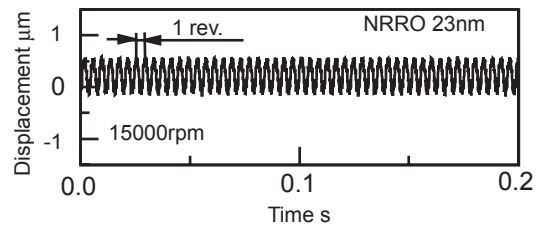


Fig. 3 Radial displacement at 15,000 rpm

resolution of  $1.24\text{ nm}$ , with maximum velocity of  $28.4\text{ mm/s}$ , provided a feedback signal. The position signal is input to a counter at  $25\text{MHz}$  and used in a DSP board to calculate a control signal with a sampling period of  $33\text{ kHz}$ . Precisely machined balance rings, which also act as sensor targets to evaluate the rotational accuracy, were attached at both ends of the spindle. The roundness of side surface of the balance rings is  $0.11\mu\text{m}$ .

#### 4. Positioning Test

The main spindle can be magnetically supported in the axial direction and can rotate at over  $15,000\text{ rpm}$ , using the air motor turbine. The radial displacement of the main spindle was measured at the tool side using a capacitance type displacement sensor. The NRRO in the radial direction was about  $23\text{nm}$ , as evaluated from the variation of positive displacement peak in the radial direction at  $15,000\text{rpm}$ .

Figure 4 shows the  $1\mu\text{m}$  step response of the main spindle in the axial direction while the spindle

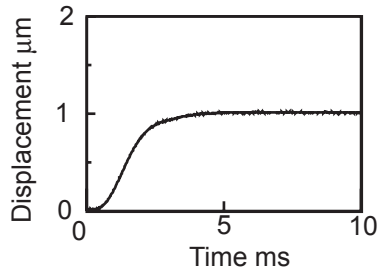


Fig. 4 Step response of 1  $\mu\text{m}$

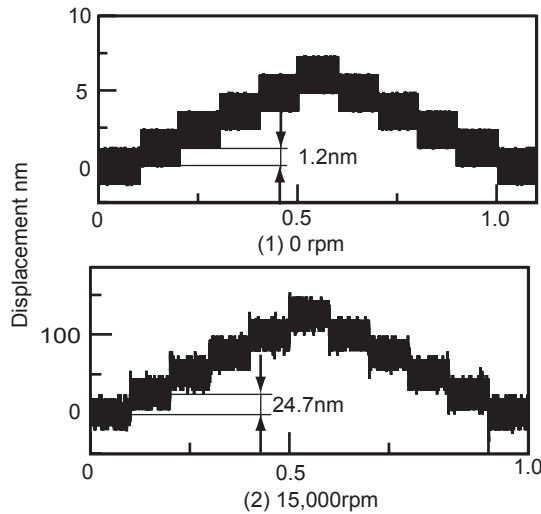


Fig. 5 Positioning resolution

was not rotating. Using the feedback signal from the high precision laser interferometer measurement system and feedforward compensation of the inverse transfer function of the closed loop system, both high speed and no overshoot response were attained. Long stroke positioning of  $\pm 5$  mm was also verified.

Figure 5 indicates the positioning resolution in the axial direction with/without rotation. The positioning resolution decreases from 1.2 nm at 0 rpm to 24.7 nm at 15,000 rpm due to disturbing force of the air turbine. To improve the positioning resolution at a high speed, the bandwidth of the closed system needs to be extended.

The temperature rise on the spindle housing was measured while the spindle was rotating or stationary, as shown in Fig. 6. These data show the cooling effect of the air turbine.

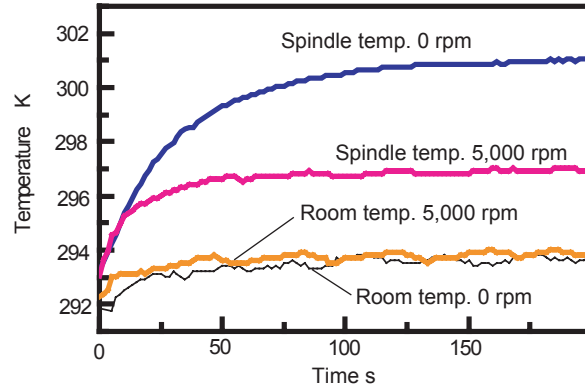


Fig.6 Temperature rise on the housing

## 5. Conclusions

A precision active aerostatic spindle with an axial positioning actuator was proposed and tested in order to realize a compact nano-machine tool. The spindle could rotate at over 15,000 rpm and had a positioning range and a resolution of  $\pm 5$  mm and 24.7 nm, respectively, at 15,000 rpm. Future work will involve multi-axis and micro milling machining using the X-Y- $\Theta$  table system and this spindle. This research was supported by an Industrial Technology Research Grant Program in '02 from NEDO of Japan. The authors gratefully acknowledge the contribution of Dr. M. Fukuda of NTT for fabrication of the experimental spindle.

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