Active Control of High-Speed Precision Air-Bearing Spindle

H. Mizumoto[1], Y. Yabuta[1], S. Arii[1], Y.Tazoe[2], K. Atoji[2], T. Hirose[2]
[1]*Tottori University, Koyama, Tottori, JAPAN*
[2]*Nachi-Fujikoshi, Nachi-Fujikoshi, Namerikawa, Toyama, JAPAN*

mizu@ike.tottori-u.ac.jp

Abstract

A follow-up report of the high speed air-bearing tool spindle with an active aerodynamic bearing proposed by the authors is presented. For improving the performance of the prototype air-bearing spindle, following improvements in the designing are proposed: (1) decrease in the spindle weight by using new ceramics, (2) increase in the area of wedge region on the bearing surface of the active aerodynamic bearing and (3) increase in the power of the piezoelectric actuator for the active control. The effects of these improvements on the performance of the active air-bearing spindle are discussed.

1 Introduction

Recently, small diameter of end-mills and grinding wheels are often used in the ultraprecision machining, then the demand for a high speed tool spindle with low vibration is ever increasing. For suppressing the spindle vibration at higher rotational speed, we have proposed a hybrid air-bearing spindle shown in Figure 1; an active aerodynamic bearing is incorporated into the top of an air-bearing spindle supported by ordinary aerostatic thrust and radial bearings [1]. The performance of the prototype active air-bearing spindle showed that the maximum controllable rotational speed was 500Hz

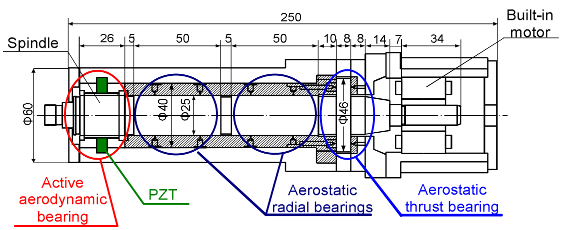

Figure 1: Hybrid air-bearing spindle employing aerostatic radial /thrust bearings and active aerodynamic radial bearing

(30,000min^{-1}). In the present paper, several improvements for the design of the air-bearing spindle are proposed.

Table 1: Characteristic table for spindle materials

material	Sialon	Inver
code	S110	EXEO-S10
composition	Si_3N_4-Al_2O_3	63Fe-32Ni-5Co
density g/cm^3	3.24	8.15
Young's modulus Gpa	290	137
linear expansion coefficient 10^{-6}/K	1.6	0.1
heat conductivity W/m K	21	13

2 Weight saving of the spindle

First improvement is the weight saving of the spindle for increasing the resonant frequency. Instead inver for the prototype spindle, improved spindle is made of light weight new ceramics SIALON (sintered Si_3N_4-Al_2O_3). The comparison of the characteristics of both materials is shown in Table 1. The density of SIALON is about 40% of that of inver. As the result, the total weight of the ceramic spindle is 422g, while the inver spindle is 960g. The bearing surface of the ceramic spindle is chromium plated and ground, then assembled.

Owing to the low resonant frequency of the inver spindle (about 1.6kHz), the spindle vibration of the prototype growed rapidly to a dangerous level (larger than 5μm) at the rotational speed of 900Hz. The resonant frequency of the ceramic spindle is improved to be 3.6kHz and the spindle rotation is stabilized. Figure 2 shows the Lissajous figure of the ceramic spindle at the rotational speed of 1000Hz. The amplitude of the vibration is about 1μm and the NRRO (non-repeatable run out) is 0.2μm.

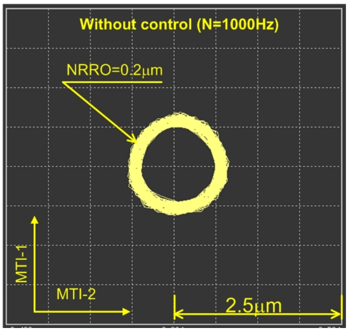

Figure 2: Lissajous figure of spindle vibration at 1000Hz

3 Improvement in design of active aerodynamic bearing

Second improvement is the increase in the area of wedge region of the active aerodynamic bearing for increasing its load carrying capacity. The elastc region for the active control on the bearing surface is extended by about 2.5mm (30%) in the circumferential direction.

It was shown in the last report that the load carrying capacity of the active aerodynamic bearing did not increase as expected. This is because the lack in the power of the piezoelectric actuator deforming the elastic region on the bearing surface. Then, the third improvement is the increase in the power output of the piezoelectric actuator. In Figure 3, the actuators for the prototype air-bearing spindle (left) and for the improved air-bearing spindle spindle (right) are shown in Figure 3, and the comparison of the characteristics of these actuators are shown in Table 2. The actuator for the improved design (AE0505D08) is about four times larger than the old version in its power; three actuators are incorporated into each elastic region of the improved active aerodynamic bearing.

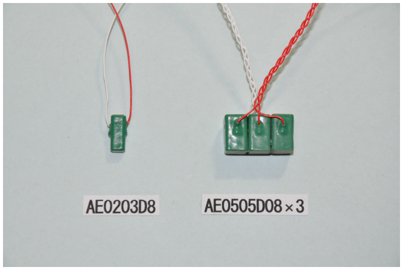

Figure 3: Piezoelectric actuators incorporated into active aerodynamic radial bearing (left: for prototype right: for improved design)

Table 2: Characteristics of piezoelectric actuators

code	AE0505D8	AE0203D8
Max. expansion at 150V μm	9.1	9.1
Max. force N	850	200
Resonant frequency kHz	138	138
Capacitance μF	0.75	0.18

4 Active control of spindle

Figure 4 shows the strokes of the active control of the prototype spindle. The strokes increase as the rotational speed increases, however, they shows the maximum at the rotational speed of 400Hz, where the strokes are about 0.2-0.4μm. In the higher rotational speed, the

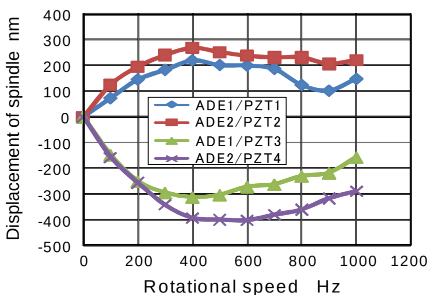

Figure 4: Strokes of prototype spindle (ADE1 shows the vertical stroke controlled by PZT 1, 3 and ADE2 shows the horizontal stroke controlled by PZT 2, 4.)

strokes are saturated or slightly decrease. The strokes of the improved air-bearing spindle shown in Figure 5 are twice as large as those of the prototype, however the saturation of the stroke is also observed.

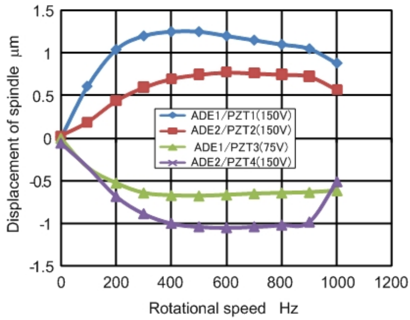

Figure 5: Strokes of improved spindle with high-power PZT

The effect of the active control on the spindle vibration in the improved air-bearing spindle is shown in Figure 6. Up to the rotational speed of 700Hz, the amplitude of the spindle vibration falls to one-half by the active control.

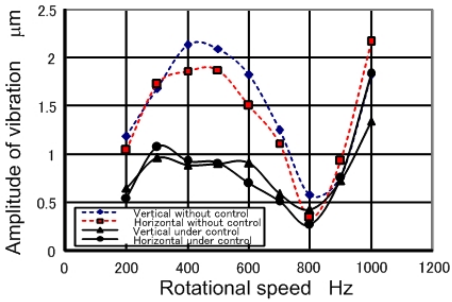

Figure 6: Effect of active control on spindle vibration (broken lines indicate amplitudes without control and solid lines indicate amplitudes under control)

5 Summary

The results of the experiments show that the improvements in the material and the design are effective for improving the performance of the air-bearing spindle. The maximum controllable rotational speed was 700Hz (42,000min^{-1}). However, the effect of the active control is not sufficient for the final goal of our research to suppress the spindle vibration less than 0.1µm at the rotational speed of 2kHz (120,000min^{-1}).

References:

[1] H. Mizumoto, et al., “A High-speed Air Spindle employing Active Aerodynamic Bearing System,” Proc. of 10th Anniversary International Conference of the euspen, Vol.1 (2008) pp.394-397.

[2] H. Mizumoto, et al., “An Active Aerodynamic Bearing for Ultraprecisio Machining,” Proc. of 10th International Conference of the euspen, Vol.1 (2010) pp.300-303.