Performance of High-Speed Precision Air-Bearing Spindle with Active Aerodynamic Bearing

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Abstract

A follow-up report of the high-speed air-bearing tool spindle with an active aerodynamic bearing proposed by the authors is presented. Instead of the conventional induction motor, a synchronous motor is built in the air-bearing spindle for improving the rotational accuracy of the spindle. By controlling the wedge angle of the aerodynamic bearing, the spindle vibration can be suppressed. Owing to the adoption of the synchronous motor, the amplitude of the spindle vibration can be suppressed to be 0.05μm at the rotational speed of 500Hz (30,000min^{-1}).

1 Introduction

Demand for the high-speed precision air-bearing tool spindle for ultraprecision machine tool is ever increasing. For suppressing the spindle vibration at higher rotational speed and improving the rotational accuracy of the spindle, 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 reported was as follows: the maximum controllable rotational speed was 500Hz (30,000min^{-1}), where the amplitude of the spindle vibration is about 0.1μm [2]. In the present paper, following improvements for the design of this active air-bearing spindle

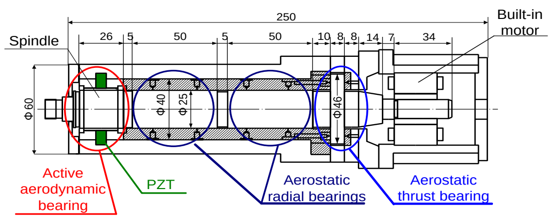


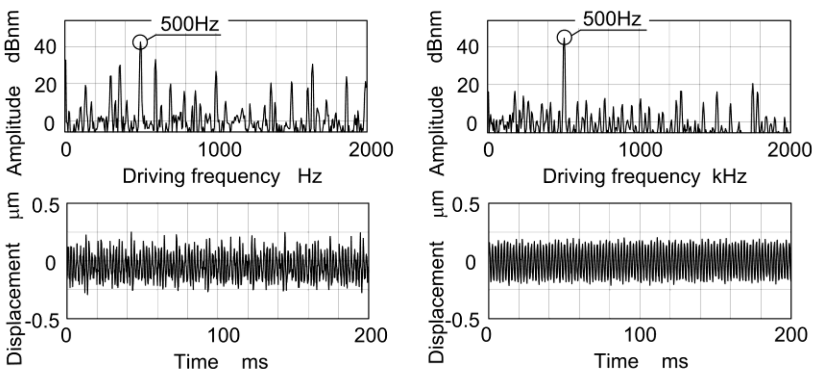
Figure 1: Hybrid air-bearing spindle employing aerostatic radial/thrust bearings and active aerodynamic radial bearing

are proposed: 1) for the weight saving of the spindle, the spindle is made of light weight new ceramics SIALON (sintered Si_3N_4-Al_2O_3, its density is about 40% of that of steel while its Young's modulus is higher than that of steel), and 2) instead of the conventional induction motor, a synchronous motor is built in the air-bearing spindle. The effect of these improvements on the performance of the active air-bearing spindle is discussed.

2 Effect of improvements on spindle vibration

The resonant frequency of the old steel spindle was about 1.6kHz and the amplitude of the spindle vibration grows rapidly to be larger than 5μm at the rotational speed of 900Hz. On the other hand, the resonant frequency of the light weight SIALON spindle is about 2.5kHz and the amplitude of the vibration is about 1μm at the rotational speed of 1kHz. Thus, the weight saving of the spindle is effective.

The induction motor is widely used as the built-in motor. For generating driving torque, however, the driving frequency is slightly higher than the rotational speed of the spindle. Consequently, the power spectrum of the spindle vibration has two peaks as shown in Figure 2 (a), and the spindle vibration shows beats. For reducing the beat of the spindle vibration, a synchronous motor is employed instead of the induction motor. The rotational speed of the spindle driven by the synchronous motor coincides with the driving frequency. As shown in Figure 2 (b), the beat of the spindle vibration can be decreased by the use of the synchronous motor.



(a) Induction motor (b) Synchronous motor

Figure 2: Effect of built-in motor selection on spindle vibration

3 Active control of the spindle vibration

Front view of the active aerodynamic radial bearing and its control system is shown in Figure 3. Fundamental shape of the bearing surface is a continuous circular. On the bearing surface, there are four elastic regions made by reducing the thickness of the bearing. Deformation of each elastic region, therefore the wedge angle is controlled by a piezoelectric actuator embedded behind the bearing surface.

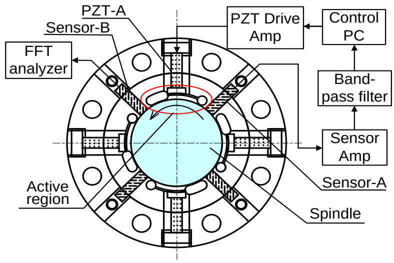


Figure 3: Feedback control system for active aerodynamic bearing

Figure 3 shows the control tactics when the spindle rotation is counterclockwise. According to the spindle vibration detected by a capacitance sensor-A, a microcomputer (PC) controls the deformation of the top elastic region on the aerodynamic bearing by using the piezoelectric actuator, PZT-A. The effect of the active control is evaluated by another capacitance sensor-B and displayed on a FFT analyzer. For the efficient control, the time lag of control system is tuned to be one-fourth of the cycle of the spindle rotation by using a band-pass filter.

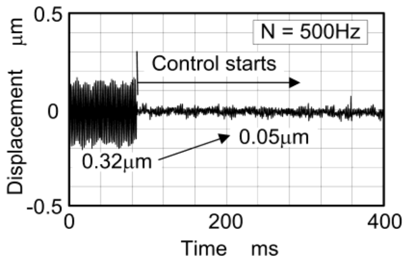


Figure 4: Start of active control

The effect of feedback control of the aerodynamic bearing on the spindle vibration at the rotational speed of 500Hz (30,000min^{-1}) is shown in Figure 4. Without control, the amplitude of the spindle vibration is larger than 0.3μm. When the active control starts, the amplitude rapidly decreases to 0.05μm. It was reported in the former euspen that the amplitude of vibration cannot be decreased to be less than 0.1μm [2]. Owing to the adoption of the synchronous motor, the effect of the active control is improved.

Figure 5 (a) shows the spindle vibration and its power spectrum without control. The amplitude is larger than 0.3μm, however, the vibration is almost simple sinusoidal wave and the power spectrum has only one outstanding line spectrum.

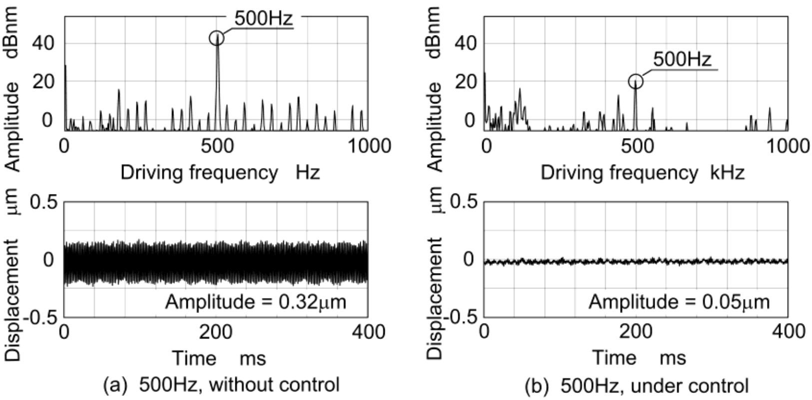


Figure 5: Effect of active control of aerodynamic bearing on spindle vibration

Therefore, the tuning of the control system is easy and the spindle vibration is effectively suppressed as shown in Figure 5 (b). The effect of the active control is summarized in Figure 6. When the rotational speed is larger than 200Hz, the spindle vibration is suppressed to be less than 0.1μm.

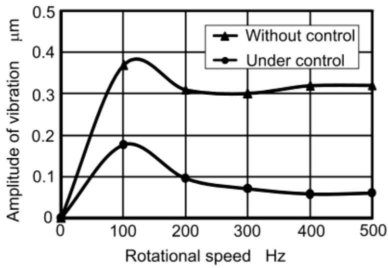


Figure 6: Summarized effect of active control on vibration

Summary

The adoption of the new ceramics SIALON and the synchronous motor are effective for improving the performance of the active air-bearing spindle. The amplitude of vibration is suppressed to be 0.05μm at the rotational speed of 500Hz.

References:

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