A STUDY ON ACTIVE MAGNETIC BEARINGS FOR MACHINE TOOL'S HIGH SPEED SPINDLE

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ABSTRACT

This paper describes a high-speed spindle with five-degree-of-freedom active magnetic bearings. High efficient magnetic bearings of this spindle provide non-contact, no rubbing and permanent life suspension. The spindle is ϕ 49.1 mm in diameter and 268-mm long. The position and attitude of the center of mass of the spindle is controlled by a centralized PID compensator making use of DSP. Thus, the control bandwidth of this magnetic bearing is about 250 Hz. An exclusive controller and an amplifier for the spindle rotation enable to control its rotation speed. Moreover, it takes only 10 seconds. to power the maximum rotation up to 70,000 r/min. and to stop, and the motor of the spindle is powerful enough to 11 kW at maximum.

INTRODUCTION

Recent industrial machine tools require the High Speed Cutting (HSC) technology. Compared with the conventional cutting process, the HSC provides many advantages:

- Drastic improvement in production time, cutting volume and surface quality of workpiece,
- Lower cutting force,
- Longer life of tools.

One of the effective solutions of HSC is the application of magnetic bearing system to the machine tool spindles.

The Active Magnetic Bearings (AMB) are superior to the mechanical one in terms of high speed, friction, vibration, and diameter of the rotational axis. Therefore, AMB has the advantage that the stiffness of the machine which is attached the tools to can be high, and the high precision and stable cutting process can be obtained for a long time. Furthermore, AMB is superior to the air bearing for the high-speed spindle in terms of suspension stiffness, load volume, and bearing clearance.

However, the machine tool is one of the most difficult fields to apply AMB. The high stiffness of the magnetic bearing, in short, the high response of the control system is demanded because of the various frequencies of the cutting load and high energy. Furthermore, it is difficult to solve this problem because the contact state between tools and workpieces always changes, in other words, the contact stiffness always varies and the vibration system is complex.

This paper describes the design specifications, the design method, and the characteristic estimate results of AMB for machine tool's high speed spindle, and so on. This AMB system consists of two radial and one axial magnetic bearings, and controls the spindle's five-degree-of-freedom (5-DOF). A built-in AC servomotor with spindle speed feedback controls remaining 1-DOF. Using a prototype of the AMB spindle, high-speed rotation up to maximum 70,000 r/min. is accomplished. Some experimental results of HSC show that this AMB spindle has sufficiently high performance.

MECHANICAL DESIGN

The specification of our AMB spindle unit is shown in **TABLE 1**. This spindle has two radial bearing and one axial bearing. Their maximum load capacities are 500 N (front), 250 N (rear), and 600 N (axial). These AMBs enable the maximum rotation speed of 70,000 r/min., which was difficult to realize with the conventional ball bearings. It takes only 10 seconds for the acceleration and deceleration time. The low noise rotation was materialized at the 70,000-r/min. constant operation and during the time of the acceleration and deceleration.

Also, the tool holder HSK-32E of 2-face restraint type provides the tool fixing to this spindle.

TABLE 1: Specification of AMB Spindle

Item		Specification
Rotational speed		Max. 70,000 r/min.
Recommended rotational speed range		20,000-70,000 r/min.
Spindle motor	Max. power	11 kW (peak) 7.5 kW (continuous)
	Main circuit	Sinusoidal wave PWM inverter
	Controller	Pulse generator speed feedback Digital closed-loop control Vector control
Max. load for magnetic bearings	Front	500 N
	Rear	250 N
	Axial	600 N
Tool clamping mechanism		HSK-32E

The outline structure of this AMB spindle is shown in **FIGURE 1**. The outside diameters of the radial and axial bearings are ϕ 49.1 mm and ϕ 91.1 mm, respectively, and the spindle length is 268 mm. The AMB consists of the front and rear radial bearing and axial bearing, and controls the five degrees of freedom (X, Y, Z-axes position, and X, Y-axis attitudes) except the axial rotation. The spindle and AMB is protected even in the case that the abnormality occurred in the magnetic bearings, because the clearance at each magnetic bearings is only 0.5 mm and the clearance at the touch down bearings is 0.2 mm. Since a pulse generator is attached in the spindle back, the spindle is controlled its rotational speed by build-in AC spindle motor.

The spindles for the machine tools require high natural bending frequency, because the bending mode may exert influence on the accuracy of the cutting face of workpiece. Therefore, the mode frequency should be designed to be as high as possible.

The mechanism (i.e. a draw bar and plate springs etc.) to hold the cutting tool is usually inserted to the inside of the spindle. Accordingly, the calculated value and the measured one do not often agree with each other in modeling the simple beam structure. Then a natural bending frequency of the spindle was simulated, by using the algorithm, which models the spindle with two-beam structure and expanded transfer matrix method, to consider the tool system part in our company. Considering the control stiffness of the magnetic bearings and the gyroscopic momentum, a natural frequency of the first bending mode of this spindle itself was calculated to be 1.4 kHz (84,000 r/min.). The first and the second bending modes are illustrated in **FIGURE 2**.

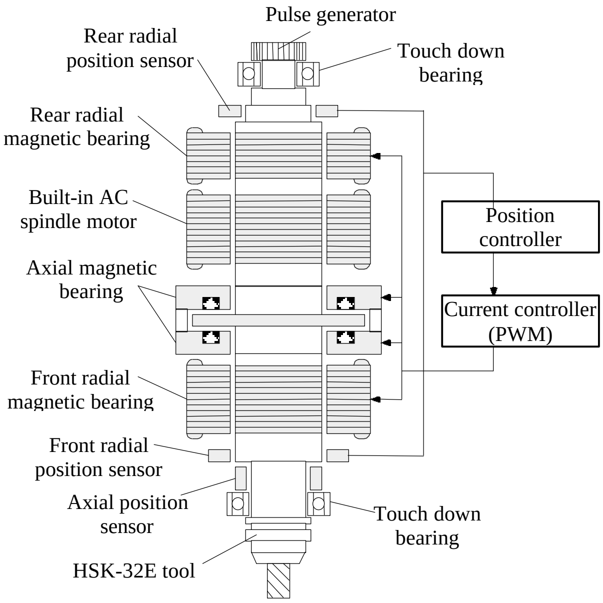

FIGURE 1: System structure of AMB spindle (Omitting the spindle motor controller)

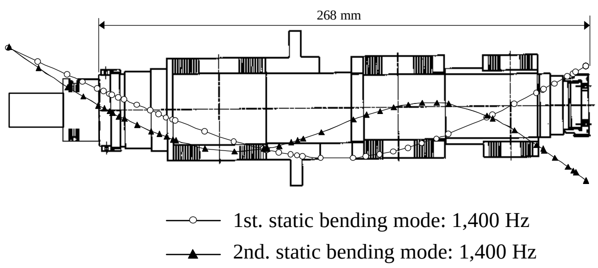

FIGURE 2: Bending modes of spindle

AMB CONTROLLER DESIGN

The spindle on the machine tool should be supported with stiffness enough to accomplish the high accuracy HSC. Hence, the spindle requires the AMB controller to provide all of sufficient high gain and satisfactory damping. Moreover, the controller must stabilize the bending modes of the spindle, because the higher spindle rotational speed gets closer to their resonance frequencies.

The AMB controller consists of fundamental five sections as shown in **TABLE 2**.

TABLE 2: AMB Controller

Section	Note
Displacement detection	5 pairs of gap sensors for 5-DOF (eddy current type)
Rotor position / attitude calculation	Coordinate transformation #1
PID compensator	For each 5 axes Centralized PID
Control force / torque calculation	Coordinate transformation #2
Power amplifier and force / torque generation	5 pairs of electromagnets and 10-axis amplifiers with bandwidth 4 kHz, max. 20 A

All pair of the gap sensors face each other, so that the changes of sensor characteristics, due to the environmental temperature variation for an example, are canceled automatically. The compensator is of conventional PID type. In this PID section, there are also several filters (notch and/or active damping etc.), automatic balancing compensator and gyroscopic effect compensator. Moreover, in order to improve the control stability, the current-force relationship of each pair of the electromagnets is linearized by bias current addition, estimated gap multiplication and square root calculation concerning the current command. This linearization procedure is expressed in Eq.(1).

$$i_{REF} = \sqrt{i_{COM} + i_{BIAS}} \times g_{EST} \qquad (1)$$

where

i_{REF} = final current command,
i_{COM} = initial current command,
i_{BIAS} = bias current command,
g_{EST} = estimated gap at electromagnet.

The actual force generated by a pair of electromagnets is written in Eq.(2).

$$f = \frac{\mu_0 N^2 S}{4}\left(\frac{i_A^2}{g_A^2} - \frac{i_B^2}{g_B^2}\right) \qquad (2)$$

Therefore, if the estimated gap is equal to the real gap, by substituting the Eq.(1) into Eq.(2), one can obtain the linear relationship between the force-command and the actual force:

$$f = \frac{\mu_0 N^2 S}{4}\left(i_{COMA} - i_{COMB}\right) \qquad (3)$$

Accordingly, the position and attitude of the tool edge is controllable with thorough stability, and the bending modes of the spindle are suppressed adequately.

The AMB controller electronics has a Digital Signal Processor (DSP) and A/D D/A parts. The DSP executes all of these calculation processes, and enables flexible modification of the AMB parameters. Moreover, a communication line of the AMB controller provides real-time monitoring of control variables.

The target performance of the AMB control is roughly:

- 300-Hz control bandwidth with appropriate damping
- 20 kHz sampling (using TMS320C50)
- Stable and still suspension up to 70,000 r/min.

PERFORMANCE OF AMB SPINDLE

In this section, we describe the results of several performance tests, and confirm each characteristic of this AMB spindle unit.

Measurement of Frequency Response

First of all, in order to grasp the control performance of AMB, the open loop transfer functions about each degree of freedom of the spindle were measured. The vibration signal was given to DSP via A/D converter. The spindle was equipped with the tool holder named HSK-32E (end milling tool with ϕ 8-2 sheets) at the spindle edge. The measured transfer functions are shown in **FIGURE 3**. This figure indicates that the crossover frequencies of a radial and axial axis are 250 Hz and 150 Hz, respectively, and the AMB has the adequate dumping characteristics at the crossover frequency of AMB.

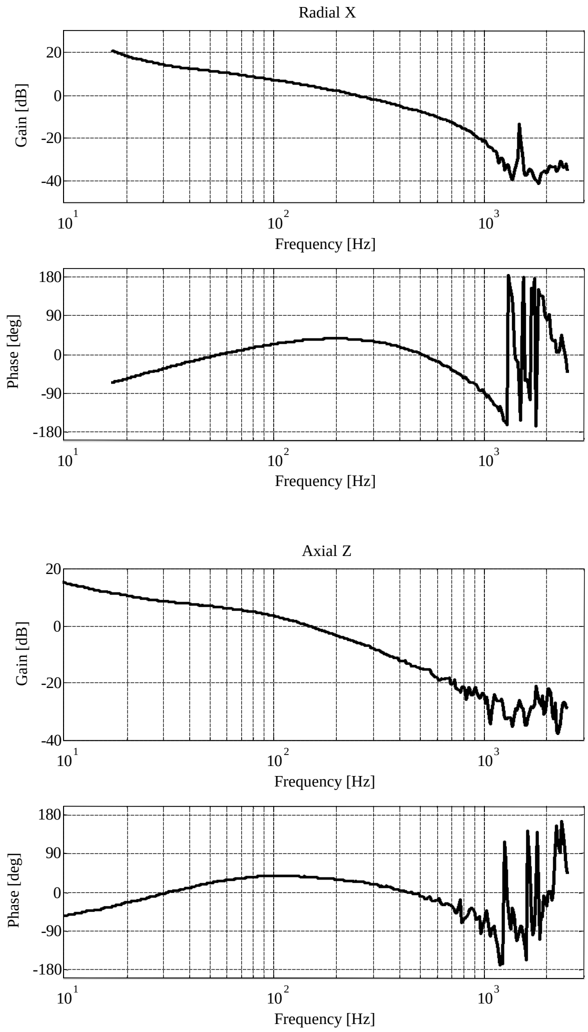

FIGURE 3: Open-loop transfer function of AMB (upper: radial, lower: axial)

Measurement of Dynamic Stiffness

Dynamic stiffness at the tool edge position is most important, because the cutting force and other strange force act on the spindle edge directly, when the machine tool's spindle is cutting the workpiece. The measurement result of the dynamic stiffness at the cutting tool attached position of the spindle is shown in **FIGURE 4**. The measurement was done by: (1) giving force to tool edge by impact hammer, (2) measuring force and spindle position, by accelerometer and non-contact displacement sensor at tool edge, and (3) processing data with FFT analyzer.

Although the minimum dynamic stiffness is about 1,800 N/mm, the usable rotational range of this spindle is more than 20,000 r/min. Therefore, the stiffness goes higher up to 100,000 N/mm at 70,000 r/min. for example. Because a required stiffness value is about 10,000 N/mm in the general end-mill cutting of aluminum, this spindle has sufficient stiffness. Moreover, a natural frequency of the first bending mode of the spindle is 1.4 kHz (84,000 r/min.), and we can obtain that this value agree with the simulated value very much.

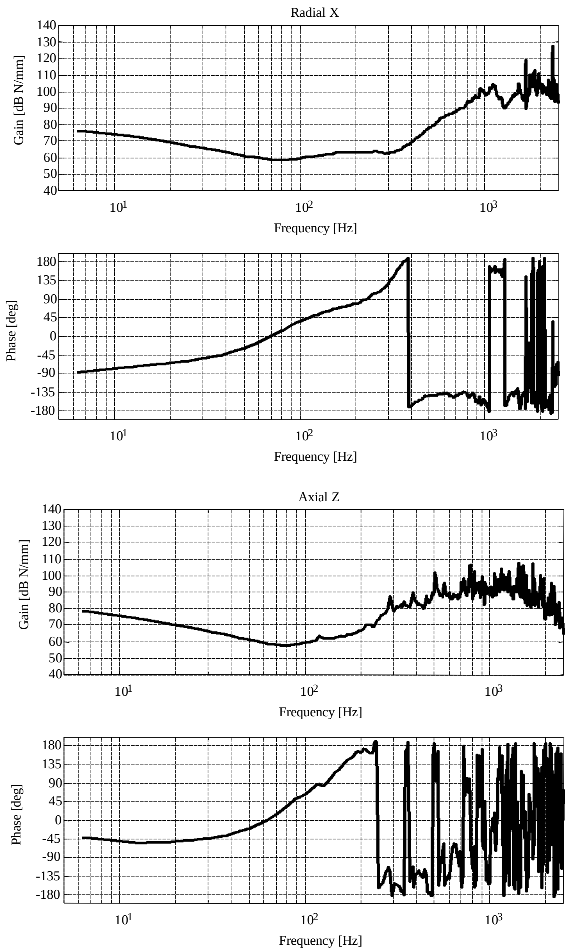

FIGURE 4: Dynamic stiffness at tool edge (upper: radial, lower: axial)

A Test of Spindle at Non-load Turn

Next, the turn test with non-load to the spindle was carried out. In this case, the weight of the spindle acts on the bearing (axial direction), and the radial load and positional load do not act on. A Lissajous' figure of the tool edge at 70,000 r/min. is shown in **FIGURE 5**. The vibration consists of mainly the turn basis component (effect of the spindle rotor imbalance), and its amplitude is 3 μm at the front and 3 μm at the rear.

Furthermore, the repeatability of the spindle path and the vibration characteristic is good.

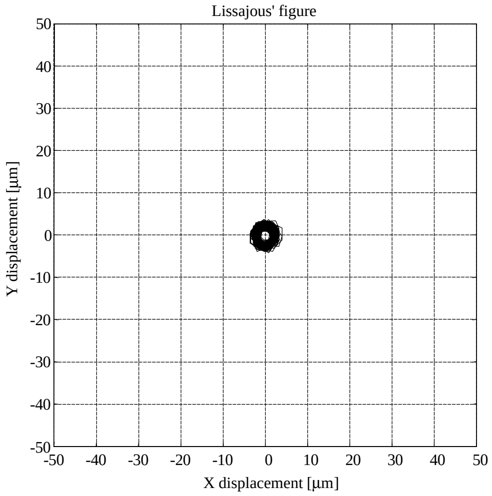

FIGURE 5: Lissajous' figure of spindle vibration

Cutting Test

To grasp the real cutting ability of this AMB spindle, we installed the spindle unit to the standard vertical machining center machine and carried out the cutting test. The cutting condition is shown in **TABLE 3** and **FIGURE 6**. The spindle rotation was set to 50,000 r/min. because of the speed characteristics and the life of the cutting tool. The picture of the cut workpiece is shown in **FIGURE 7**. It was made sure that the condition of the cut plane was fine and the stable high speed cutting was realized.

At this cutting test, we could cut with the maximum depth (8 mm) to the radial direction and the operation of the magnetic bearing was stable at any time. Furthermore, the cutting force changed from AMB current was about 100N at the case that the cutting depth to the radial direction was 2mm.

TABLE 3: Cutting conditions

Item	Setting
Spindle rotational speed [r/min.]	50,000
Cutting speed [m/min]	1,257
Cutting depth [mm]	6
Feed rate [m/min.]	5
Tool diameter [mm]	ϕ 8 (2 edges)
Cutting material	Aluminum

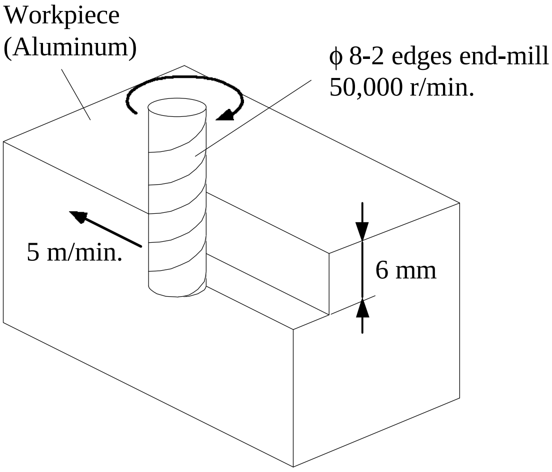

FIGURE 6: Cutting view

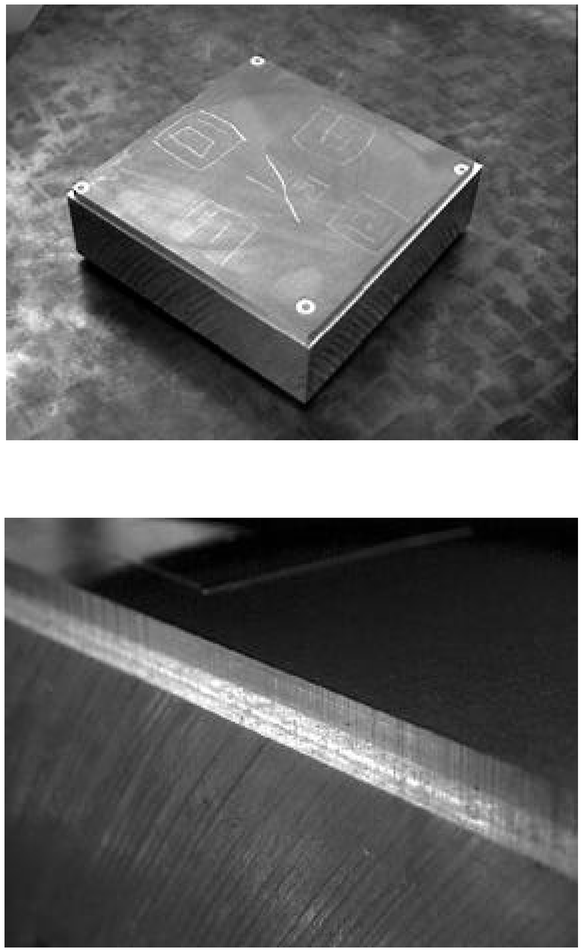

FIGURE 7: Picture of the cut workpiece

SUMMARY

We developed the high speed spindle with Active Magnetic Bearings (AMB) for the machine tools to realize High Speed Cutting (HSC). At first, we described about the mechanical design of AMB. In the field of the spindle for the machine tools, a natural bending frequency of the spindle effects on the accuracy of the cutting plane. Therefore, the natural frequency of the spindle is needed to be as high as possible. The spindle we developed realized the high stiffness of 1,400 Hz at first bending mode. Secondly, we described about the AMB controller design. The remarkable point of this AMB controller is the linearized current-force relationship of each pair of the electromagnets in order to realize the high-gain magnetic bearing. This linearization was accomplished by bias current addition, estimated gap multiplication, and square root calculation concerning the current command. Thirdly, we reported some test results to make sure the characteristics of this spindle. It is made sure that the crossover frequencies of a radial and axial axis are 250 Hz and 150 Hz, respectively, and that the AMB has adequate dumping at these frequencies. Additionally, we realized the stable high-speed rotation of the spindle with very small vibration amplitude. Furthermore, we made sure that the spindle has the stable cutting ability in the end-mill cutting of the aluminum.

In the future, we will improve the mechanical and control systems for the higher cutting accuracy under the condition of the high-speed cutting and the cutting load changes.

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