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MONITORING AND ACTUATING FUNCTION OF THE INTERNAL GRINDING SPINDLE WITH MAGNETIC BEARING

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Abstract

Ultra-high speed (180,000rpm) internal grinding spindle with active magnetic bearing (AMB) was manufactured slightly modified from our licensor's original model. Grinding accuracy with AMB spindle was confirmed better than with conventional ball bearing spindle,thanks to the vibration-free AMB operation. Beside the accuracy,using shaft location sensor signal and bearing control current, the moments of the grinding wheel touches against the work piece and against the dresser diamond are detected. The force adaptive control was performed using bearing current monitoring and shaft retreat motion with AMB as an actuator. These functions decrease grinding idle time and improve grinding quality.

1. Introduction

The machine tool shaft speed has further been advanced to improve processing efficiency. The machine tools with adaptive control and a self-diagnosis function have been developed to maintain high-accuracy processing for a long time. An active magnetic bearing spindle (AMB) can be an effective element to realize these functions.

The electromagnet and sensor which are the elements of the magnetic bearing provides various information related to processing phenomena. Further, the utilization of the actuating function which is the essential function of the electromagnet enables the improvement of the processing accuracy and the reduction of the processing time.

Presently, the mainstream bearing for the wheel spindle for an internal grinding machine is a rolling bearing but the vibration due to the rolling motion mechanism and due to the unbalance of the rotor limits the processing accuracy. The magnetic bearing, however, generates only very low vibrations even at a high speed revolution because of its being non-contact bearing and its automatic balance function[1]. From this viewpoint, the magnetic bearing has excellent characteristics as the spindle bearing for machine tools.

The following describes the experiment results on the monitoring and actuating function of the five-axis control type magnetic bearing spindle.

2. Structure of five-axis control type magnetic bearing spindle

Figure 1 shows its structure. It is composed of a radial electromagnet, axial electromagnet and displacement sensor corresponding to that. The revolution drive is made by a built-in high frequency motor. The air gap at the bearing portion is 200 µm on its radius. A auxiliary bearing is mounted on both end of the shaft to protect the magnetic bearing when power failure . The air gap of the auxiliary bearing shall be half of the magnetic bearing gap and it is designed so that the auxiliary bearing will not touch the rotor at its normal operation.

3. Monitoring function

One of the characteristics of the active magnetic bearing (AMB) is a monitoring function. Observing the output of the built-in displacement sensor used for control and the control current of the electromagnet enables to know what is happening the processing phenomena (grinding force, tool abrasion, etc.). The monitoring function when the AMB spindle is used in the internal grinding machine is described below.

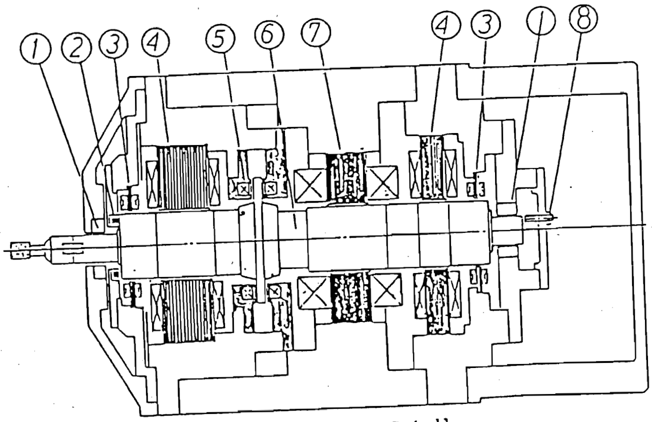

Figure 1 The Structure of The Spindle

3.1 Gap elimination

For the purpose of reducing the idle time in processing and preventing a work piece damage from collision with grinding wheel , gap elimination is employed. Detecting the touch of the work piece with the wheel, the controller of the mechanical system changes the feed from quick approach to rough grinding speed. When the control current of the electromagnet reaches a preset value, it is fed back to the infeed system of the machine to change the feed speed. The results of this experiment are described in Item 5.

3.2 Truing force

In order to maintain the grindability of the wheel , a truing operation with a sharp diamond dresser is carried out. If the diamond dresser becomes dull, the surface of the grinding wheel which has been trued loses grindability. This lower grindability wheel increases the grinding force. The increase of the grinding force increases the elastic deformation in the tool system, the work piece and its holding system and decreases the processing accuracy. Therefore, it is important for maintaining the stable processing accuracy to obtain the information on the sharpness of the diamond dresser.

Figure 2 shows the examples of the truing force monitored by the AMB control current in the cases where the sharpness of a single-point diamond dresser was changed. In these experiment examples a force as minute as 0.1 N could be measured.

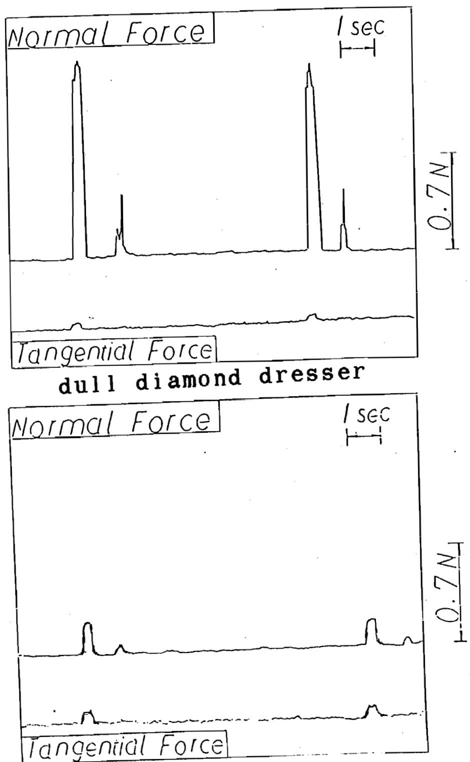

Figure 2 Truing force

3.3 Grinding force monitoring

We can detect the bearing force by monitoring the current of the bearing coil. In principle, the force applied on the AMB is proportional to the squared value of the coil current if the bearing gap is kept constant.

Before monitoring, we confirmed that the relation between the coil current and the bearing force was within 5% from linearity, in the 20 N force range.

In Figure 3, the upper chart was obtained from the input power signal of the driving motor. Each peak shows the power consumption of a work piece.

Simultaneously obtained with power, the charts at the middle and bottom show the coil current of the bearing located in the infeed direction of the grinding wheel and the bearing at right angles to the infeed. The middle and the bottom chart therefore show two components; normal grinding forces and grinding forces tangential to the wheel.

From Figure 3, we can see that the bearing current chart picks up very sharply, quickly reaches its peak, then varies around the peak with some repetitive motions. These motions correspond to the grinding process explained in the table below.

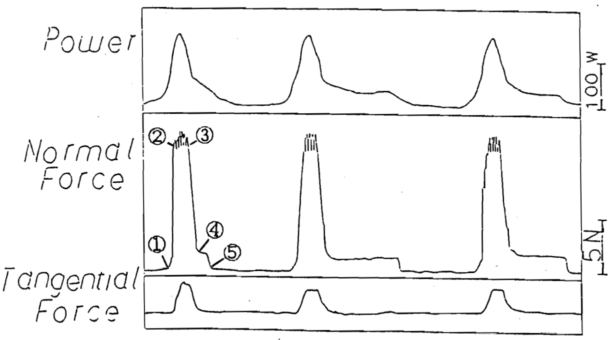

Figure 3 Grinding force

Thus, the bearing current monitoring is a much better method for watching the grinding process than is motor power monitoring. The reason is that the AMB system reacts very quickly to the load. For instance, current response to the load is in the order of ms and the AMB system's control bandwidth is close to 1 kHz in the case of this spindle. However, the motor power monitor cannot detect the transient energy exhaustion of the rotor's spin at the early stage of wheel contact against the work piece.

From the viewpoint of the grinding process monitoring, the bearing current represents force variation faithfully and tells us what happens during grinding operation better than power monitoring does.

Spot Number in Figure-3	Situation	Grinding Process
~ ①	Non-Contact Wheel to Work	Air Cut (Quick Approach to the Work Piece)
①	Initial Contact	Start of Grinding
① ~ ②	Transient State	Pile Up Accumulation (note 1)
② ~ ③	Steady State (Periodical Variation)	Rough Grinding (note 2) (Synchronized with Wheel Oscilation)
③ ~ ④	Transient State	Rough to Finish (Accumiulation Decrement)
④ ~ ⑤	Steady State	Finish Grinding (note 3)
⑤	Release Contact	Wheel Retreate
Note 1 : Accumulation = Radial unground amount (Infeed - Removed) ≒ Elastic Deformation		
Note 2 : Stock is removed efficiently		
Note 3 : Surface Smoothing Process		

Table Situation and Grinding Process

To confirm the detection sensitivity of the force on the bearing by the coil current, a wheel Truing force was applied by a single-point diamond tool and the depth of the Truing cut was 0.01 mm.
Under this condition, 1.5 N normal force was measured, and 0.1 N sensitivity can be seen in Figure 2.

3.4 Rotor behavior motion

Against the grinding force, the wheel spindle deflects and the shaft rotating center moves dynamically. This dynamic shaft movement is observed through the shaft location sensor signal.

Figure 4, (a) and (b), shows the spectrum of the sensor signal. The frequency of the highest peak is the spindle's rotation frequency, this peak means that the rotor is rotating around its inertial axis without vibration due to imbalance, as described before.

Figure 4(a) was obtained at the rough grinding stage. On higher side of the frequency of rotation, several small peaks can be seen on the bending resonance and harmonics of the shaft rotation frequency. On the lower frequency side of the shaft rotation, there are some levels of component but on unspecified frequencies.

These lower frequency components are probably caused by remaining geometric error of the work piece being ground, and these levels diminish gradually until the end of the grinding process.
Figure 4(b) shows the spectrum of the fine grinding process. We can see that there are fewer lower frequency components and no resonance frequency.

Thus, shaft behavior tells us in real time what is happening in the grinding process. We can see whether shape error on the work piece is being corrected and whether there is any grinding chatter.

4. Actuator function

4.1 High-speed respondency

Figure 5 shows the Lissajous' figure of the radial sensor output whenthe rotor spindle is excited by inputting a sinusoidal wave signal to the control circuit of the radial electromagnet. The right side shows the Lissajous' figure at a normal revolution and the left side shows that at 100-Hz excitation. These experiment results show that the rotor shaft can be moved at a high speed with a basic revolution accuracy maintained.

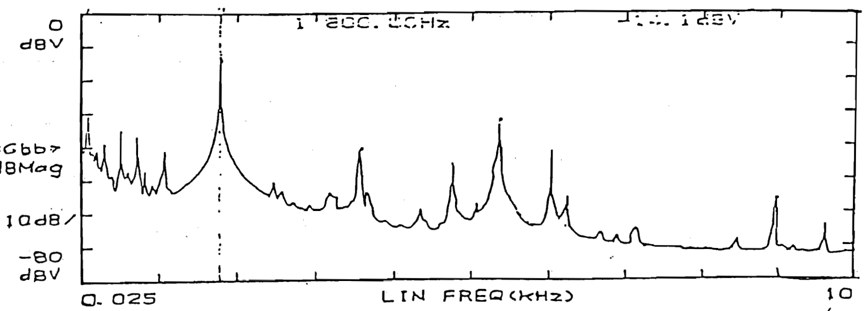

Figure 4 (a) Shaft Motion Spectrum at Rough Grinding (Example)

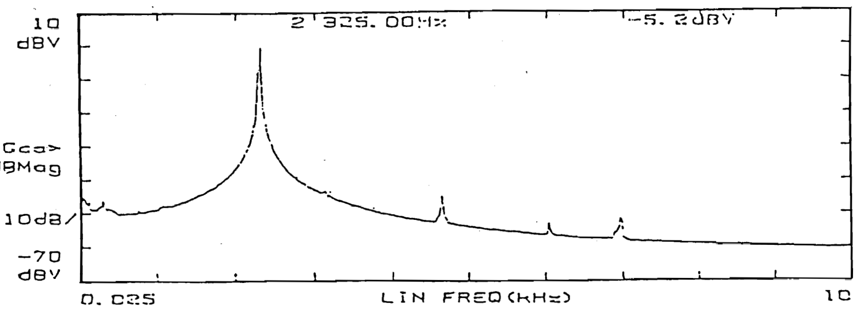

Figure 4 (b) Shaft Motion Spectrum at Finish Grinding

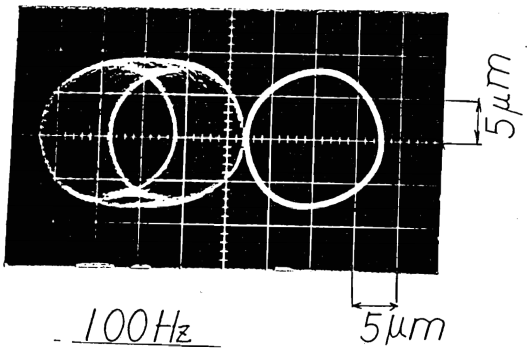

Figure 5 Lissajous'figure

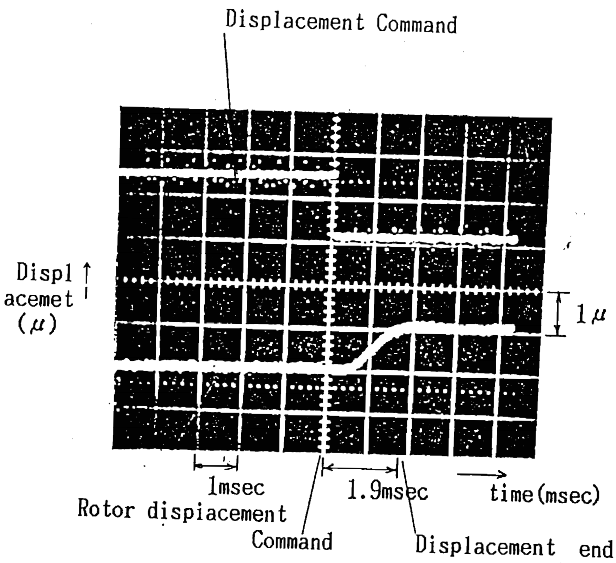

Figure 6 Rotor Displacement Respondency

Figure 6 shows the experiment data on a step response.

4.2 Retreat motion

For improving the efficiency of the grinding process with the internal grinding machine by reducing idle time, the infeed table is retracted in the opposite direction temporarily between the rough grinding process. The idle time can be reduced by changing the large grinding force at the time of rough grinding to the small one as quickly as possible.

Usually, the infeed table with a system in which a hydraulic drive or servomotor is combined with a ball screw. The response delay of the hydraulic pressure or motor, which is scores tens of m sec., can be reduced to several m sec. by displacing the rotor of the magnetic bearing spindle.

Moreover, the response delay of the wheel disengagement with work piece at grinding finish greatly affects the dimension and accuracy of a work piece. In the same way, the displacement of the grinding spindle rotor at the time of grinding finish enables to lessen the disengagement delay and to stabilize the dimension and accuracy. This function is very important to a machine which is used for mass production.

5. Constant grinding force control

Constant grinding force control is a kind of adaptive control constraint . It decreases and stabilizes the deviation of the processing accuracy due to the change of the sharpness of the wheel by controlling the feed speed so that the grinding force may be constant. As a result, the idle time caused by the grinding stock removal variation is minimized and the efficiency is improved.

Figure 7 shows the block diagram of the constant grinding force control. The feed speed is controlled so that the control current of the electromagnet during the grinding processing may be a preset value.

Figure 8 shows the example of the experiment on the constant grinding force control. The position of the infeed table, dimension of a work piece and two components of the grinding force (Fn, Ft) are shown there.

The gap elimination and the retreat motion which displaces the rotor shaft at a point where the rough grinding speed is changed into the fine grinding are carried out there by utilizing the output signal of the electromagnet control current.

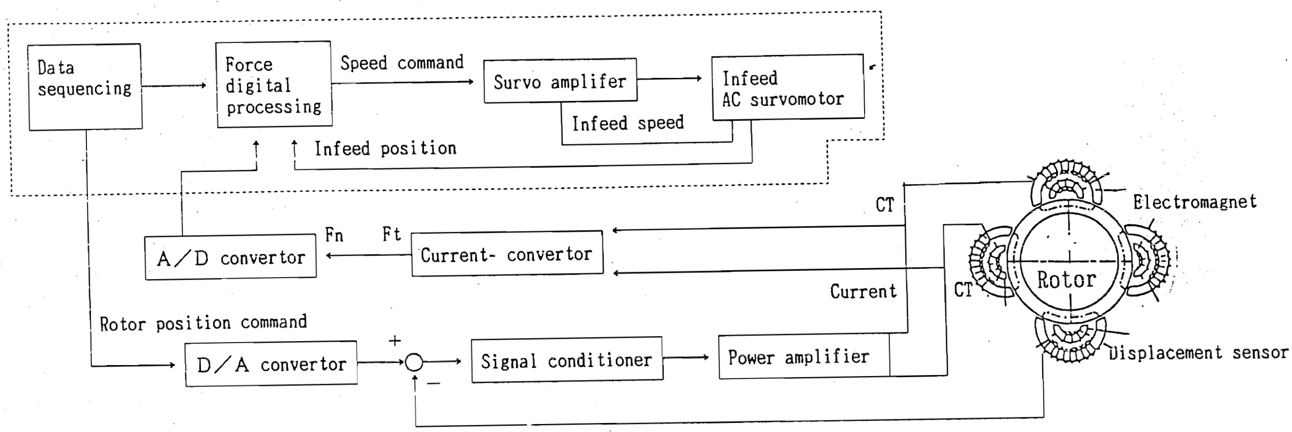

Fig 7. Block Diagram of Constant Force Control

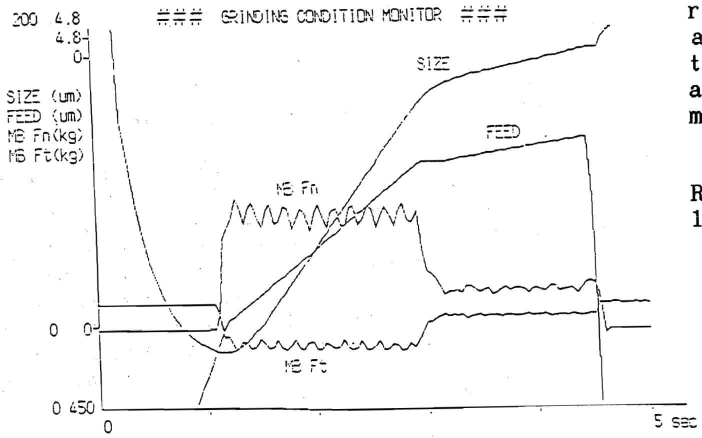

Figure 8 Grinding condition monitor

6. Conclusion

We confirmed the effectiveness of the monitoring and actuating functions in the experiment in which the active magnetic bearing was applied to the grinding wheel spindle for the internal grinding machine.

Because the AMB spindle functions as a high-speed and high-accuracy actuator and can make infeed motions after moving the rotor shaft which is revolving parallel or slantingly, it has a good chance of realizing a cylindricity or roundness control of a work piece easily.

Moreover, we are quite confident of that it will become an effective element in realizing an intelligent machine enabling adaptive control, tool life anticipation, processing quality stabilization and failure prediction based on the monitored processing conditions.

Reference

1) French patent 2 336 602