Development of Hybrid Magnetic Spindle —Synchronous Control with Rotation—

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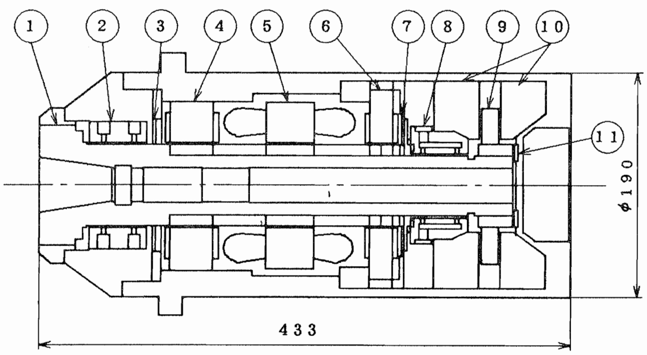
Abstract: This report concerned with the hybrid magnetic spindle, which consists of air bearings and magnetic bearings. This is developed to use as the main spindle of machining center. In this report, to eliminate the influence the of unbalance, a synchronous control with rotation is used in addition to PID control. This control system consists of the DSP and analog circuits. As a result, it is clarified that with the synchronous control, the whirling amplitude of spindle can be smaller and the higher rotating speed is attained.

1 Introduction

The authors have been developed a hybrid magnetic spindle system, which consists of 5-axis controlled magnetic bearings and radial hydrostatic air bearings. In the former report[1], the properties of PID controlled system, in which the analog control circuits were used, were investigated and the advantages of this system were clarified. However, when the unbalance of the test spindle became very large, this spindle system couldn't pass the critical speed. In order to lessen the effect of the unbalance, a synchronous control system is applied to the system. Although there are some reports on the complex synchronous control system[2, 3], a quite simple feedback control method is used in our control system. That is, to let the phase of control force leads to 90 degree from that of whirling vibration. From our previous investigations of this spindle, it can be assumee that the shaft is a rigid body and there is little gyroscopic effect. Therefore, this synchronous control system isn't so unreasonable. The controller feedbacks only the first order component that is synchronous with shaft rotation, in order to reject higher order oscillation. In this report, the performances of this system are examined.



1 : Hollow Shaft	7 : Rear Sensor
2 : Front Air Bearing	8 : Rear Air Bearing
3 : Front Sensor	9 : Rotor Disk
4 : Front Magnetic Bearing	10 : Axial Magnetic Bearing
5 : Induction Motor	11 : Axial Sensor
6 : Rear Magnetic Bearing	

Figure 1: Hybrid Magnetic Spindle

2 Experimental Rig

2.1 Spindle and Measuring System

Figure 1 shows the hybrid magnetic bearing system. This system was designed for main spindle of machining center and consists of two hydrostatic radial bearings (2, 8), 5-axis controlled magnetic bearing system(4, 6, 10), 5.5 kW built-in induction motor (5) and a hollow shaft (1). The diameter of the shaft is about 68 mm and the weight is about 9 kg. The cylindrical casing of this spindle is about 433mm length and 190 mm diameter. The air bearings are supplied 8 kgf/mm^2 air pressure by a compressor. The displacements of shaft are measured by gap sensors (3, 7, 11). In order to detect the rotational angle of shaft, 16 small reflectors are attached radially on the top plain of the shaft. An

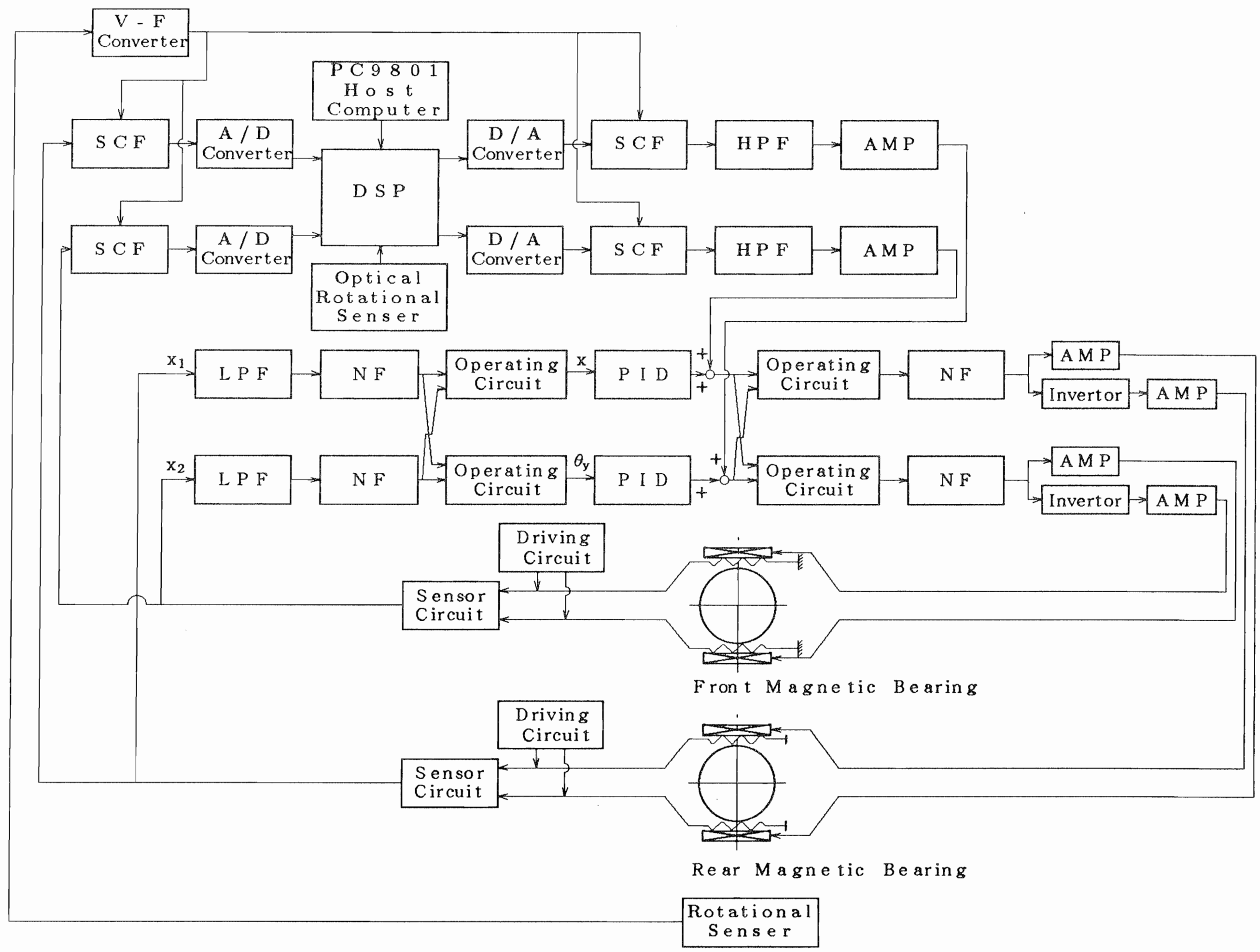


Figure 2: Control Circuit

optical sensor detects the reflections and generates sampling clock pulses.

2.2 Control System

If a resonance occurs, it may be lessened by feedback the differential signal of the vibration. However, as the mechanical or the electrical runout exists, the differential signal is very noisy and it causes other higher order resonances. The main resonance is occurred by unbalance and this unbalance force has the same frequency as that of the rotation of shaft. Therefore, if only the synchronous component, that has the same frequency as rotation, is feedbacked, the amplitude might be lessen without other excitations.

According to this concept, the following control circuits of radial bearings were made. It is shown in fig.2.

The main circuits of magnetic bearing system are analog PID control circuits. The synchronous control circuits are the upper part of this figure. These circuits are realized by a digital signal processor (DSP:TMS320C30) and analog circuits. The rotational angle of the spindle is detected by optical rotational sensor that generates 16 pulses per one revolution. This number 16 is decided from the limit frequency of optical sensor. Since the limit frequency is 10 kHz, this system can follow to about 37500 rpm.

The pulse is used as sampling trigger of A/D conversion. Once a pulse is generated, the DSP gets the displacement data from the displacement sensors and A/D converters. Using these data, it calculates the displacement of gravitational center and the inclination of the shaft. DSP memorizes these values and calculates the first order sine and cosine coefficients from the last 16 data by the Fourier transform. After that, it generates the stepwise sine waves that result in the force that leads 90 degrees to the displacement waves. This phase lead can be change by DSP program easily.

However, these stepwise waves still cause the higher order excitation because of their discontinuity. Therefore, these waves pass the low pass filters to be pure sin waves. As the rotational speed of this spindle may vary in wide range, the low pass filters must not have a fixed cut off frequency. The cut off frequency of these filters must be controlled proportionally to rotational speed of shaft.

We use the switched capacitor filters (SCF) to realize this. The SCF changes the cut off frequency proportionally to external clock. The frequency of this clock is 100 or 50 times of the cut off frequency. If the number of rotational pulses is more than 100 per one revolution, it is very convenient to use the SCF. Unfortunately, we cannot use the rotational pulse as clock of the SCF. Therefore, we make the clock from the monitor voltage of rotational speed using V/F converter. Later, the signals pass high pass filters to avoid DC offset errors, since the SCF has a large offset. These filters are needed not to lessen the integral feedback effect of PID controller, too. Then the signals go through the amplifiers and are added to the parallel and conical control signal inputs.

3 Experimental Results

The largest synchronous feedback levels are decided not to saturate the control signal by tuning the circuits and DSP program. We define the synchronous feedback level as the percentage of this largest level.

First, we discuss no synchronous controlled case (synchronous feedback level is 0%). Figure 3 shows the amplitudes at front and rear sensor of the hybrid magnetic spindle. In this system, the rotational speed can be raised until the amplitude is over $35\mu m$. Therefore, zero amplitude of higher rotational speed means that the spindle couldn't pass a critical speed. In this case, the highest rotational speed is 16200 rpm. At higher rotational speed, rear amplitude is larger than front one, and the difference of the amplitudes became large as the rotational speed increases.

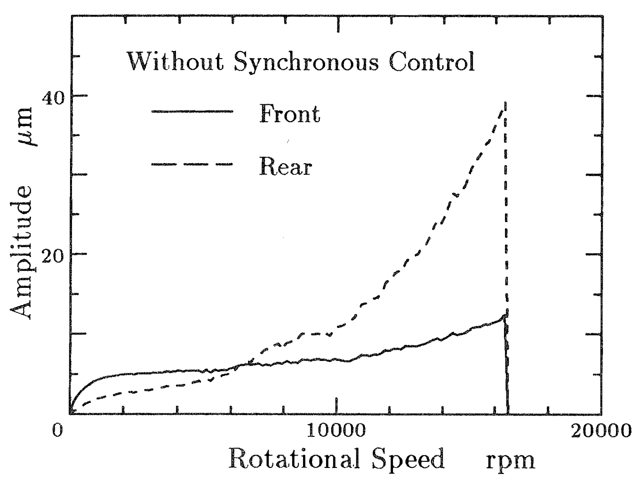


Figure 3: Whirling Amplitude of the Spindle without Synchronous Control

Figures 4, 5 and 6 show the effects of parallel feedback (feedback of the displacement of the gravitational center) at 20%, 50% and 80% respectively. Comparing 20% and 50% case with no synchronous control case, it is clear that the synchronous parallel feedback control is effective to lessen the amplitude (above 10000 rpm) and to achieve higher rotational speed (17600 rpm and 18000 rpm). In the 80% case, there is a big resonant peak at 8000 rpm, and shaft can reach to 18500 rpm.

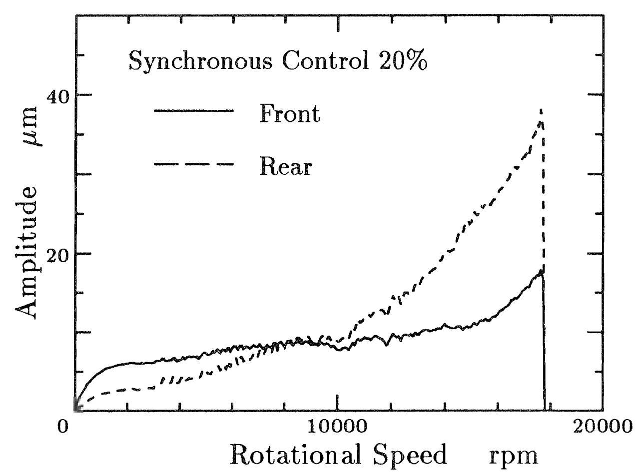


Figure 4: Whirling Amplitude of the Spindle with Synchronous Control (Output Level : 20%)

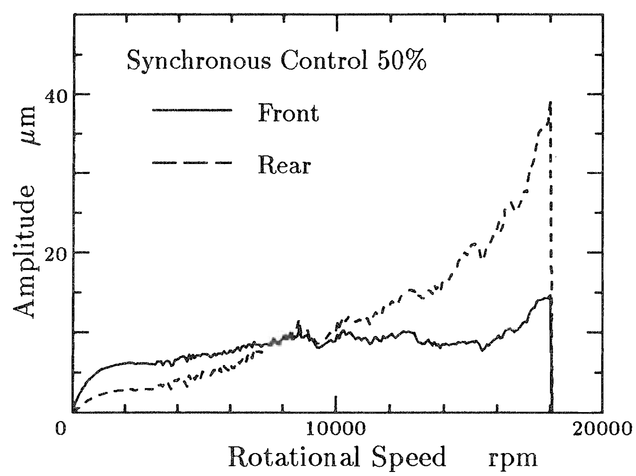


Figure 5: Whirling Amplitude of the Spindle with Synchronous Control (Output Level : 50%)

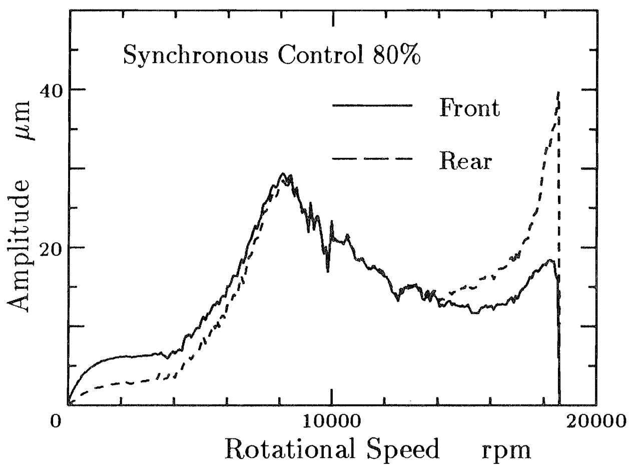


Figure 6: Whirling Amplitude of the Spindle with Synchronous Control (Output Level : 80%)

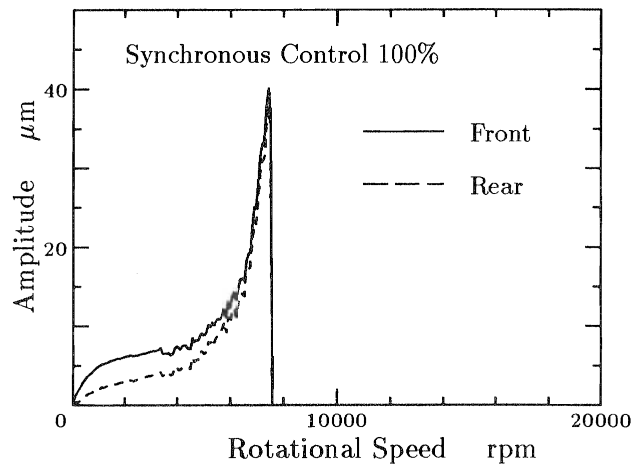


Figure 7: Whirling Amplitude of the Spindle with Synchronous Control (Output Level : 100%)

Figure 7 is the 100% case, the lower frequency peak is very large, so the spindle is stopped at 7400 rpm. The reason of this low frequency resonance is the phase disturbance by the high-pass filter. As the result, 50% is the most preferable level of this system.

On the other hand, the conical feedback (feedback of the inclination of the shaft) was tried, but there was no remarkable effect on the amplitude. This reason is considered as that in this system the dynamic unbalance is large compared with the static unbalance and the dynamic unbalance can not be cancelled by 100% conical feedback at all.

4 Conclusion

The hybrid magnetic spindle with the synchronous control with shaft rotation was developed. The whirling amplitudes of the spindle were examined by the rotating experiments. As a result, though the feedback is based on very simple idea, it is clarified that this synchronous control system is effective to lessen the whirling amplitude and to attain higher rotational speed. However, too much feedback causes another low frequency peak, and the conical feedback control is not effective in this system.

References

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