

PRECISION RADIAL MAGNETIC BEARING

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Introduction

Conventional air bearings of a high rotational accuracy have been widely used in precision machines. However the rotational accuracy of the air bearings decreases due to the unbalance force at a high speed and the disturbance force because of their low stiffness and damping. On the contrary, magnetic bearings can compensate motion errors caused by the unbalance and disturbance forces because of their active motion control capability. Moreover magnetic bearings are free from friction so that they are candidates for high accurate and high-speed bearings in the future. A precision magnetic stage and linear guides having positioning resolutions of several ten nanometers have been presented [1-2]. However there have been no magnetic bearings of nanometer rotational accuracy.

The goal of this research is to realize a magnetic bearing which has rotational accuracy of several nanometers at 10,000 rpm. As the first step, this paper discusses a precision radial magnetic bearing (PRMB) in which radial two-degree-of-freedom motions of the spindle are precisely controlled.

Precision Radial Magnetic Bearing

An experimental radial magnetic bearing is designed and constructed, as shown in Figures 1 and 2. The spindle motions in the X and Y directions are controlled by eight electromagnets. To support the other degrees of freedom of the spindle motion, thrust air bearings are used. The electromagnets are comprised of E-core laminations of Ni-Fe alloy and coils of 25 turns. The nominal air gap between the spindle and the electromagnets is 0.2 mm. The saturation current to the coil with which the flux density of the core as well as the electromagnetic force saturates is 10 A. The possible moving range of

the spindle is between -100 and 100 μm which is restricted by touch-down bearings and measurement range of capacitance displacement sensors.

The spindle consists of one steel shaft with a flange as a sensor target, two Ni-Fe lamination rings facing electromagnets and one rotor of an induction motor. The mechanical surfaces of the spindle and electromagnets are finished precisely to prevent the magnetic disturbance force which is caused by variation of the magnetic reluctance due to gap errors between the electromagnets and the spindle. The maximum diameter of the spindle is 80 mm and its mass is 3.29 kg. The roundness of the sensor target is 30 nm. The spindle can be alternatively driven by the induction motor or compressed air. The displacements of the spindle in the X and Y directions are measured by two capacitance displacement sensors

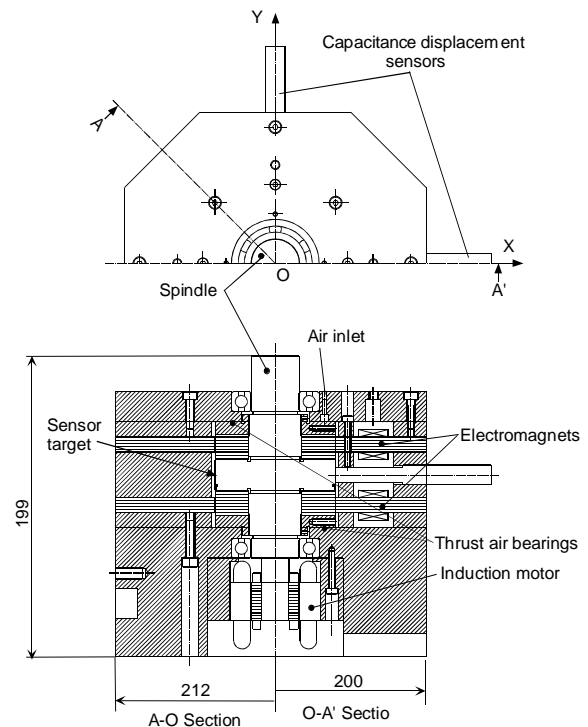


Figure 1: PRMB configuration

(ADE, Microsense 5130, 0.2 mm measuring range). The resolutions of the sensors are about 15 nm including signal acquisition and processing systems.

Control Scheme

A pair of electromagnets is necessary to generate a bidirectional force. In Figure 3, the electromagnetic force F to an object is predominantly controlled by two currents i_a and i_b . Because there is a infinite number of combination of i_a and i_b to generate a certain force, how to determine the currents must be discussed.

One of simple solutions is to work only one actuator of the two shown in Figure 4 (zero bias control). The primary advantage of this control is that the heat generation of the actuators can be minimized. On the contrary, the drawbacks are zero-force slew rate at zero coil current [3], and nonlinear relationship between the current and the force. Although the latter can be overcome by feedback linearization [4], the zero-force slew rate can not be compensated. The zero-force slew rate is undesirable for precise motion control because the electromagnets do not produce control forces when the currents are around zero.

The other solution is to work both coils simultaneously such that $i_a = i_0 + i$ and $i_b = i_0 - i$, where i_0 is a fixed bias current and i is a command current (bias current control). This control scheme is widely used in the conventional magnetic bearings because they have lin-

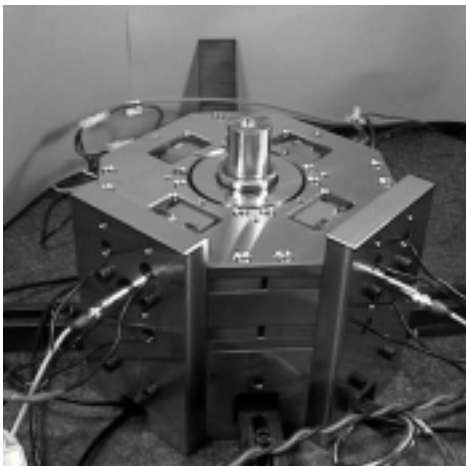


Figure 2: The prototype PRMB without upper thrust air bearings

earity to the command current i without additional linearization and the force slew rate does not become to zero unless i_0 is zero. To generate the maximum force within the linear range of the command current and force with the push-pull scheme, i_0 should be the half of the saturation current. Such a large bias current generates a large amount of heat.

To overcome the zero-force slew rate and the heat generation, this paper proposes the partial bias control as shown in Figure 5. While the command current is within $\pm i_0$, the drive currents such that $i_a = i_0 + i$ and $i_b = i_0 - i$ are applied to the coils. On the contrary, the command current exceeds $\pm i_0$, one of the drive currents is made to zero.

Figure 6 shows the block diagram of the control system. The positioning controller consists of a states feed-

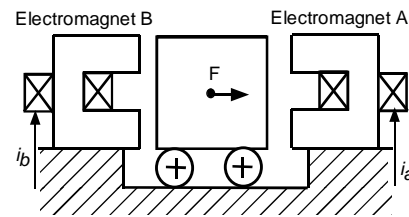


Figure 3: 1- DOF motion control using a pair of electromagnets

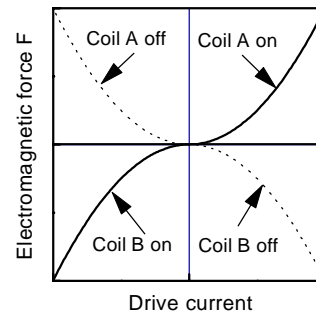


Figure 4: Zero bias control

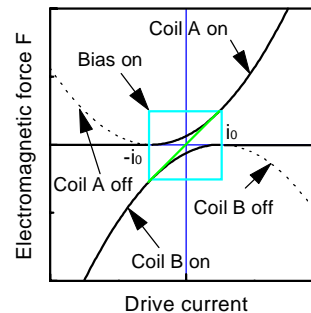


Figure 5: Partial bias control

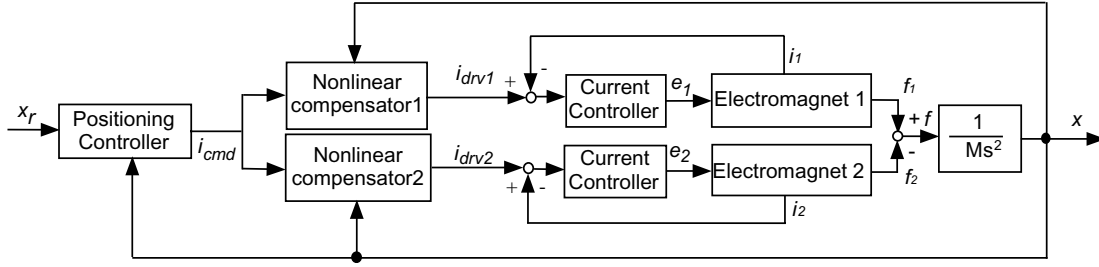


Figure 6 : Block diagram of the PRMB system

back controller and an observer. To decrease a time constant of the electromagnets, current feedback loops are used. Nonlinear compensators using the gap information linearize the relationship between the command current and the control force. Thus the zero-force slew rate and the nonlinearity of the actuators can be overcome by the partial bias control and the nonlinear compensator. Furthermore, the heat generation of the partial bias control can be made much smaller than that of the bias control when a smaller i_o is used..

The PRMB is controlled by a DSP, 16 bit A/D and 14 bit D/A converters at 10 KHz sampling. The gain of the capacitance displacement sensor is 10 nm/mV. The positioning controller works so as to keep the gap constant. Strictly speaking, the measured gap does not indicate an real rotational accuracy because the profile errors of the sensor target is included in the displacement sensor outputs.

Experimental Results

Positioning and rotational accuracies of the spindle using the zero bias and the partial bias control ($i_{max}=10A$, $i_o=1A$) are compared with the same positioning and current feedback controllers. Figure 7 shows positioning resolutions using the zero bias and the partial bias control. In the X and Y directions, the positioning resolutions of the zero bias control are 40 nm. By the partial bias control, 20 nm positioning resolutions approximately as same as noise levels of the displacement sensors are achieved.

Figure 8 shows runouts of the rotational spindle using the zero bias and the partial bias control. A standard deviation σ is calculated using runout e during one turn of the spindle. The runout e is calculated by a following

equation,

$$e = \sqrt{x^2 + y^2} \quad (1)$$

where x and y are displacement sensor outputs. The 3σ of the partial bias control at 500 rpm is under 10 nm. The repeatable runouts are shown at 1500 rpm. The runouts of the spindle gradually increase by the unbalance force as the spindle speed increases shown in Figure 9. The rotational accuracies of the partial bias control are better than those of the zero bias control.

Conclusions

As the first step to realize a precision magnetic bearing, a radial magnetic bearing was designed and constructed. The higher positioning resolutions and rotational accuracies than those of conventional magnetic bearings [5] were attained. The spindle using the partial bias control had 20 nm positioning resolutions in the X and Y directions at 0 rpm and 8.97 nm (3σ) rotational accuracy at 500 rpm. It is proved that the partial bias

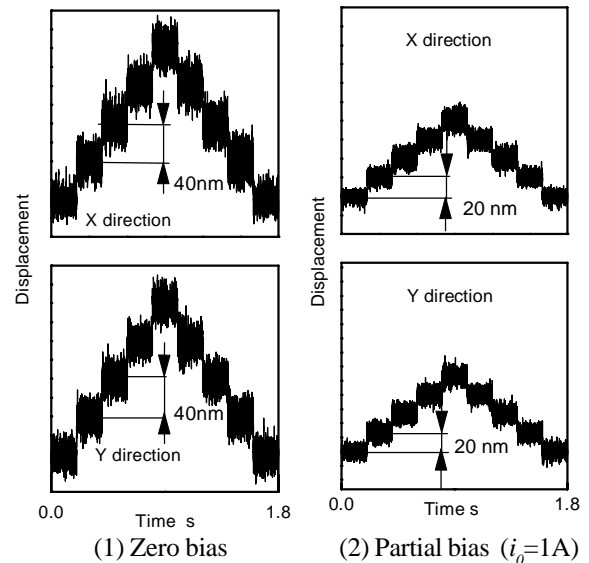
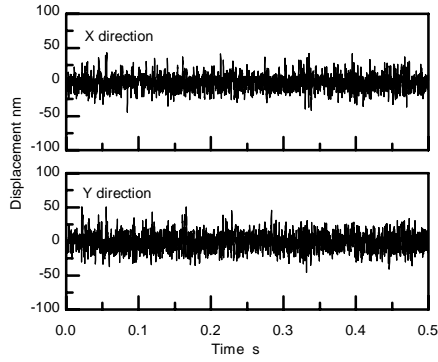
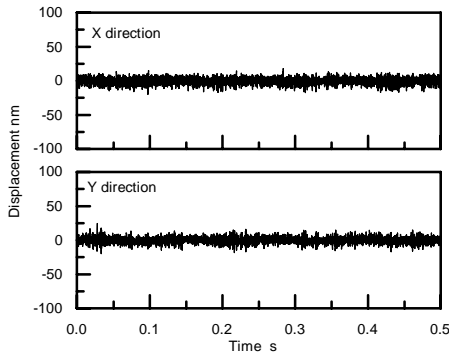


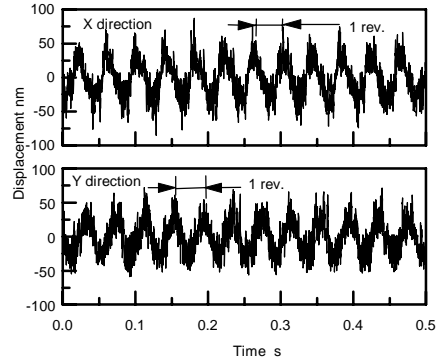
Figure 7 : Positioning resolutions at 0 rpm



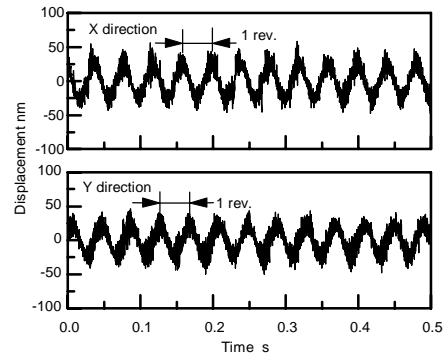
(1-1) Zero bias (500 rpm, $3\sigma=24.7$ nm)



(2-1) Partial bias ($i_0=1$ A, 500 rpm, $3\sigma=8.97$ nm)



(1-2) Zero bias (1500 rpm, $3\sigma=35.7$ nm)



(2-2) Partial bias ($i_0=1$ A, 1500 rpm, $3\sigma=23.4$ nm)

Figure 8 : Runouts at 500 and 1500 rpm

control is more suitable for improving positioning resolutions and rotational accuracies than the zero bias control.

The future works are evaluation of rotational accuracy in consideration of the roundness of the sensor target, measurement of the heat generation under the control and improvement of the rotational accuracies at a speed of over 1,000 rpm using the repetitive controller.

Acknowledgments

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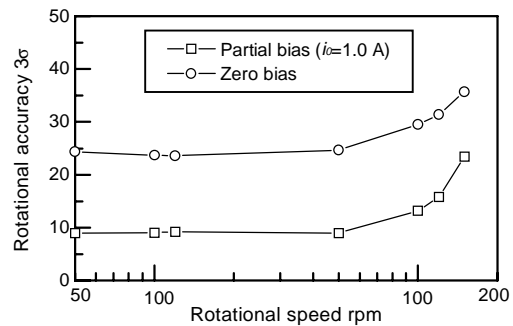


Figure 9 : Rotational accuracies

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