A Trial Product of Ultra Precision Spindle

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ABSTRACT

Generally, it is said that an air bearing spindle is one type of the spindle with the highest rotation accuracy, but it still involves rotary motion error of 50 - 100nm. It is practical enough for oridinary high accuracy rotation, but a spindle with rotary motion error endlessly close to zero is required in optical parts making machines and the like and the air bearing spindle under the current phase is not good enough as yet. For this application, permissible error is less than a few nm and it is extremely hard to materialize it by the existing method.

This study attempts to obtain ultra precision rotation by means of : (1) adding active magnetic bearings to both ends of the air bearing spindle, and (2) compensating rotary motion error stemmed from the air bearing by force of the magnetic bearings. In other words, it is to realize highly accurate rotation by organizing a so-called servo system.

The target specification is aimed at rotary motion error of 10 nm or less at 500rpm. In designing this system, there were two major problems. One of them was geometrical accuracy of a sensor target and another one was response speed of a magnetic controller. The magnetic bearing has the sensor and the sensor target to detect a position of rotation spindle. This sensor target is a reference to apply compensation and it must be a perfectly cylindrical form. However, it is almost impossible to machine a perfectly cylindrical form at an accuracy of 10 nm or less. Therefore, a device to compensate the form of the sensor target was added. A three point method is a very good method to measure the form of the sensor target under rotation and the form of the target can be found even during machining.

The magnetic controller is basically the same as the one used for ordinary magnetic bearings, provided that it must be of extremely high resolution and S/N ratio. 3nm resolution and 60db S/N ratio are required. These almost depend on performance of the sensor console. A control circuit is simply made for four-axis PID control. The thrust direction uses the air bearing only and magnetic compensation is not applied. It is very difficult to increase speed of response. A feedback loop necessarily contains various mechanical resonance modes. What can be avoided

by the notch filter is limited, and as response speed increases, what cannot be avoided also increases. Response frequency of 600Hz became control limit. Stiffness at this point is 4.8Kgf/μm, and this value is the minimal stiffness value all over the frequency. This restoring force acts against force of air and compensates undesirable rotary motion error of the air bearing. As a result, we could suppress rotary motion error to somewhere about 10nm when speed is 500rpm.

1.PREFACE

Recently, a very high precision main spindle is required by such fields as the optical industry and the like, but the existing air bearing spindle cannot cope with this requirement due to a limit in accuracy[1]. In this study, we tried to attain high precision rotation by means of detecting and compensating the error. The first target was to make rotary motion error less than 10nmp-p at 500rpm.

First selection is to determine an actuator. For this, we adopted an electro magnet, taking a number of such parameters as maximum load power, speed of response, heat generation due to power comsumption and so forth into consideration.

The next problem is to measure, as correctly as possible, the form of the sensor target on the actual machine under the same condition as the operating condition. If the target can be reinstalled, there are other methods[2]. But it is feared that wrong result is obtained due to different measuring conditions. The three-point method was adopted to solve this problem[3]. We prepared a signal generator that generates an electrical form signal according to this measured form. We made it generate a voltage that is equivalent to the form, synchronized with the rotational angle of the rotor. We connected this with the reference input terminals of the controller to compensate the form component.

For the controller, we used one utilized with ordinary active magnetic bearings, provided that it has a resolution of 3 nm. Since 3μm is required practically as the span, 60db is necessary for S/N ratio. The controller has sensor input and reference input, and makes up a feedback by which the difference between the two signals becomes zero.

The load-displacement characteristic of the whole spindle made up in this manner shows a characteristic like Fig. 1. The air bearing handles the maximum load, and the magnetic bearing provides the dynamic stiffness.The maximal load of the air bearing is more than 20kgf. In order to increases safety in an emergency, We set the maximum force of the magnetic bearing at 2kgf. Stiffness of the air bearing only is 2.5kgf/μm. Besides,the static stiffness of the magnetic bearing only is 250kgf/μm or more, but it is limited below 2kgf in force.

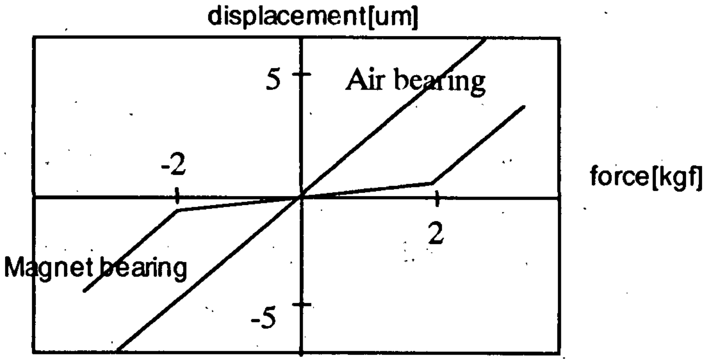


Figure 1. Static load and displacement

2. SENSOR TARGET FORM

In general, with the magnetic bearings currently used, the form of the sensor target does not become a problem. Rotary motion error of the spindles of these bearings is on the order of 2-3 μm and there is no problem, even if the geometrical form error is 1 μm. However, this study aimed at an accuracy of 10nm and discussed everything, starting from the fundamentals, so that the measurement may be conducted on the actual machine under operating conditions.

The main items, obtained necessary for the results, are as follows:

- Non -contact capacitance type displacement gage
- Adoption of three-point method that does not require the target to be reinstalled
- Input/output circuits are isolated from CPU and provided with shielding
- CPU clock is disconnected after completion of computing

Next, the form of the sensor target obtained is shown in Fig. 2. The sensor signal, which contains the runout and the sensor target form, is shown in Fig. 3 as a polar display. So, the subtraction (Fig3 - Fig2) is the runout, namely, the shaft movement. It is shown in Fig. 4. There are no other means to verify this directly at present. However, both Fig.2 and Fig.3 are measured at an accuracy of 3nm, the accuracy of Fig.4 is considered to be of about the same order.

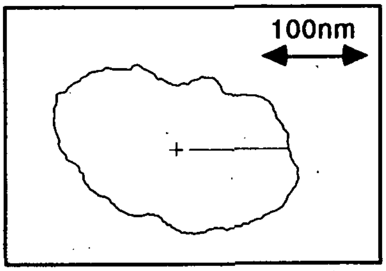


Figure 2. sensor target
(by 3-point method)

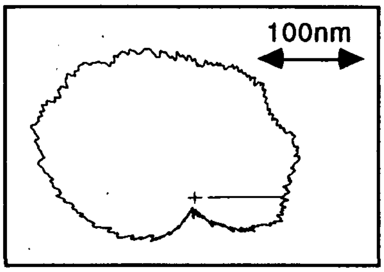


Figure 3. sensor signal
(measured)

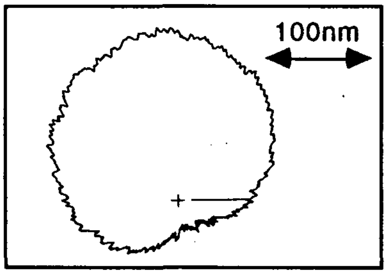


Figure 4. Shaft movement
(Fig 3. - Fig 2.)

3. Removal of rotary motion error by feedback

A principle of removing rotary motion error is the same as the improvement of various characteristics of an OP amp by feedback. A block diagram and a bode diagram are shown in Fig. 5. If there is no feedback when external noise is contained in the OP amp output, this noise comes direct to the output. However, if feedback is applied, the emerging noise decreases in proportion to its amount. Suppose now that an open loop transfer function is A(s) and a feedback loop is formed by R1 and R2. The transfer function from Vin to Vout is :

$$(R1 + R2) / R1 \qquad (1)$$

The transfer function from Vnoise to Vout is :

$$(R1 + R2) / R1 * 1/A(s) \qquad (2)$$

Therefore, if a removal rate is observed by logarithm, it becomes:

$$\log((R1 + R2) / R1) - \log(A(s)) \qquad (3)$$

resulting in the difference between the two lines of the open loop and the closed loop on the bode diagram. A similar principle can be applied to a case of compensating error motion of the spindle by feedback. Suppose the stiffness characteristic of the air bearing only is Ga(s), and the stiffness of the magnetic bearing is Gm(s). On the other hand, the air bearing brings about irregular rotary error more or less at the time of rotation by it's inherent nature. This error can be deemed external noise in the above mentioned OP amp circuit. It's block diagram is shown in Fig. 6. A difference between these two lines becomes a removal rate of error motion.

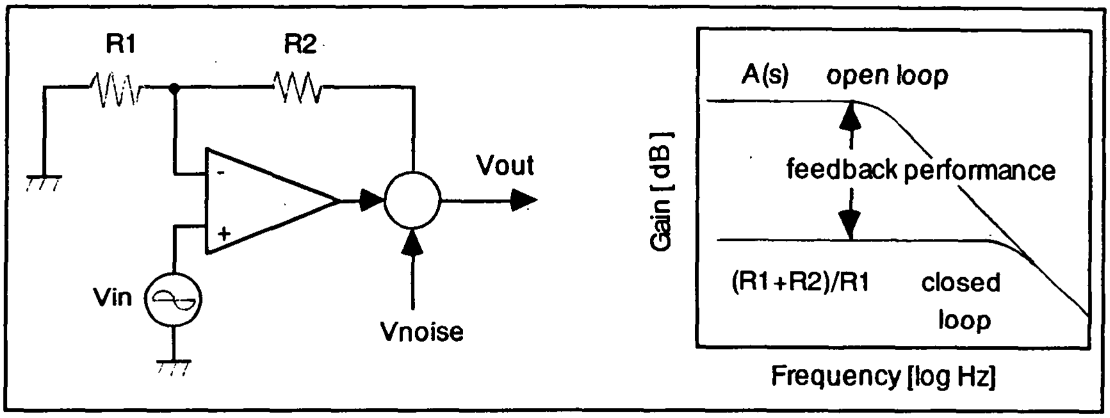


Figure 5. OP amp circuit and bode diagram

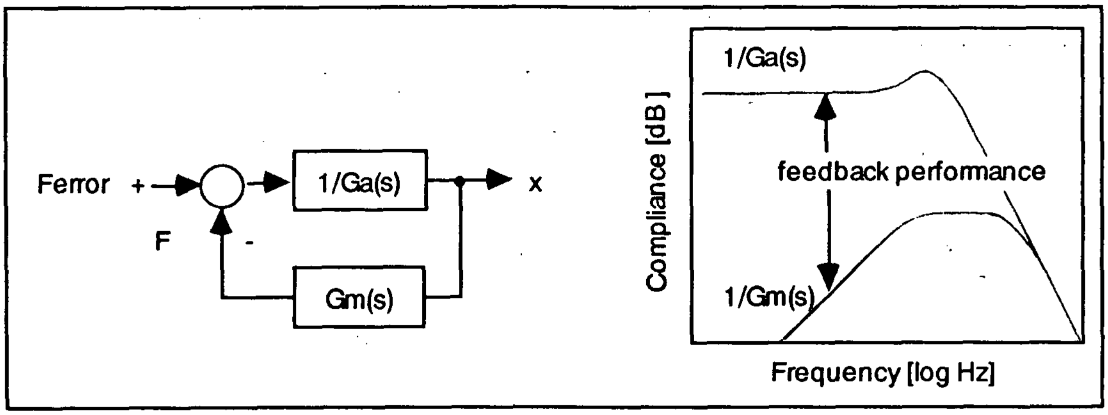


Figure 6. Feedback System and bode diagram

4. PROTOTYPE

4-1 SPINDLE

The spindle has a form in which the center part is the air bearing and the magnetic bearings are attached to both ends. A touch down bearing is substituted by the air bearing. A sectional drawing is shown in Fig. 7 and various constants are listed in Table 1.

4-2 CONTROLLER

The controller consists of the most simple PID system.The basic design of the total construction is similar to that of MATSUMURA[4]. In order to avoid unstable phenomenon at the bending resonance frequencies of the spindle, notch filters are inserted in three stages, and are set for the resonance frequencies. In spite of the simple control system like this, we could achieve a much higher stiffness than that of the air bearing. We believe that this is due solely to success in the distribution of the resonance frequencies in the machine design. Electrical noise is very severe in the whole circuit. A switching power supply is not acceptable because of noise. For the power supply, we adopted linear circuit without exception. As a result, power consumption for the electro-magnetic driver part became quite large. For this part, a drop type stabilized power supply that normally uses 500VA, but can provide up to a maximum of 1.5kVA, is employed.

A block diagram of the whole system is shown in Fig.8. Ga(s) is the stiffness characteristic of the air bearing. The measured dynamic compliance is shown as a continuous line in Fig. 9. With the exception of a part of the bending resonance frequency above 2 kHz, this characteristic is the secondary low pass characteristic, having a relatively small attenuation term, and it's transfer characteristic, attenuation value and cut-off frequency can be represented by formulas (4),(5),(6). These are so simple that is no problem at all to put them in the control loop.

TABLE I. PARAMETERS OF THE SPINDLE

rotor	diameter =75mm, length = 400mm, mass = 14kg
air bearing	self chalk nozzle, pressure supply 5kgf/cm^2
magnet bearing	gap = 50 um, 16 slot 8 pole
sensor	static field type, 10nm resolution at 40kHz bandwidth

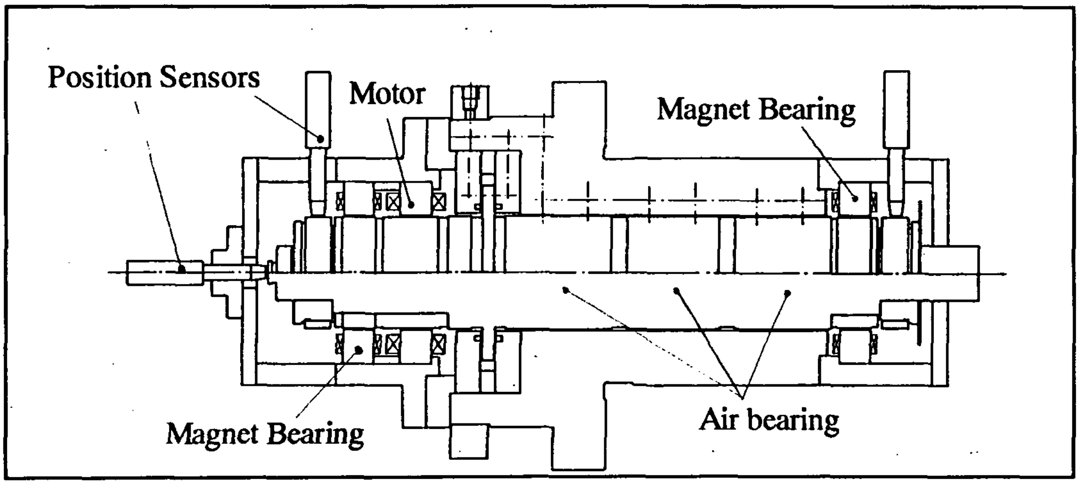


Figure 7. Schematic structure of the spindle

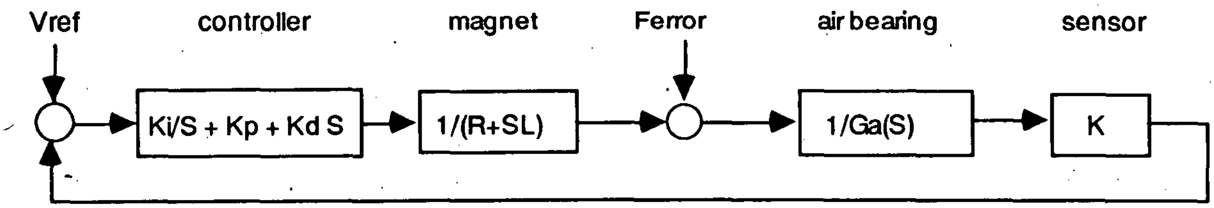


Figure 8. block diagram of control system

$$Ga(s) = \frac{1}{M} \cdot \frac{1}{S^2 + 2\eta\omega_0 S + \omega_0^2} \qquad (4)$$

$$\omega_0 = 2\pi \cdot 400 \text{ rad/sec} \qquad (5)$$

$$\eta = 0.2 \qquad (6)$$

5. CONTROL CHARACTERISICS

The broken line in Fig. 9 shows the combined compliance characteristic of the magnetic bearing and the air bearing. Control of the magnetic bearing is effective up to 600Hz. Since the static stiffness of the air bearing is 2.5kgf/μ m, the stiffness at 600Hz is calculated to be 4.8kgf/μ m. A difference between the two lines is a rotary motion error removal rate. For instance, we can expect improvement of 20db at 100Hz. Fig. 10 indicates, by X-Y, the error signal of the controller when the magnetic bearings are operated and not operated. The speed is 500rpm. A runout value of about 0.3μ m, in the case of the air bearing only, is reduced to within a range of about 10nm as a result of operating the magnetic bearing.

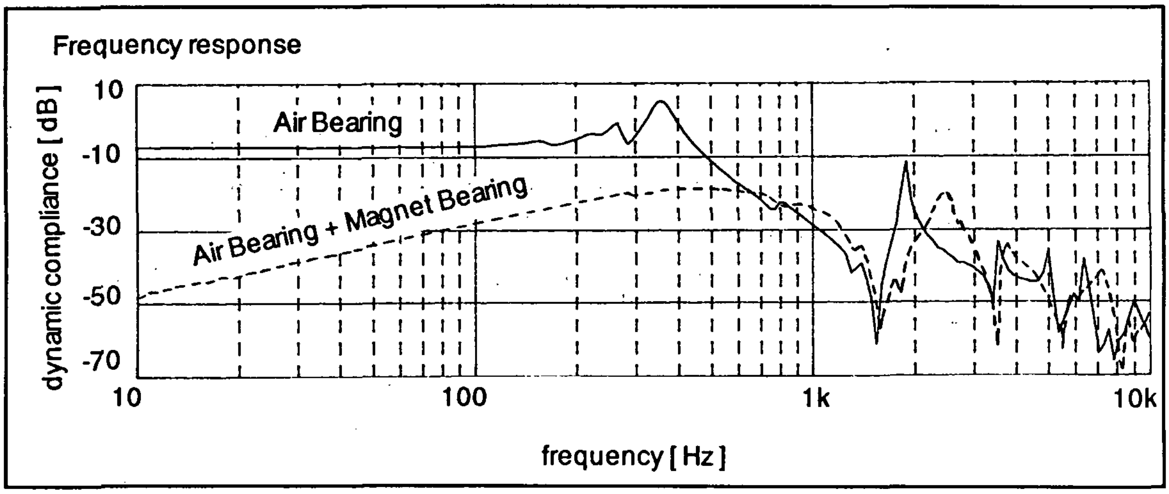
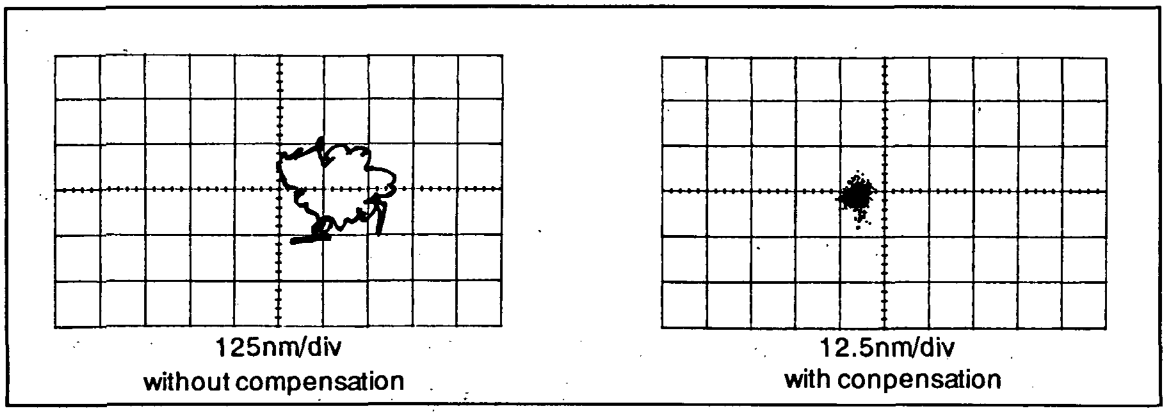


Figure 9. Dynamic compliance



125nm/div
without compensation

12.5nm/div
with conpensation

Figure 10. Runout without compensation and with compensation

6. CONCLUSION

We made a very high precision spindle by means of : (1) adding the magnetic bearings to the air bearing, (2) clarifying the rotary motion of the air bearing,and (3) compensating the error motion. We could attain a rotation accuracy of 10nm at 500rpm.

However, there are many more problems. To apply this to a high speed spindle, we have to raise the dynamic stiffness. However, generally, if we increase feedback, the system on the whole becomes unstable, because, even though there is no problem theoretically, many unstable factors that cannot be modeled are hidden in the physical loop. These factors become noticeable if the feedback gain goes up, causing the whole system to fall into an uncontrollable condition. Control theory is important as a matter of course, but we believe that the mechanical structure design of the spindle will become more important to conquer these instability problems.

7.APPENDIX

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8. REFERENCES

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