MAGNETICALLY LEVITATED CONVEYER USING SUPERCONDUCTING MAGNETIC LEVITATION

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INTRODUCTION

Applying high T_c superconductors to magnetic bearings as levitation mechanisms is very promising [1,2]. Superconducting magnetic bearings are tried to apply to some devices such as magnetic bearings, magnetic levitation systems, energy storage flywheel systems, and motors, superconducting Maglev transportation systems, etc. Anyway, magnetic levitation is very promising for contact-free rotation systems and transportation systems.

On the other hand, semiconductor manufacturing industry needs a lot of clean rooms and vacuum chambers for their fabrication processes. Even a small dust gives damage to silicon wafers deposited with a lot of electric circuits. During fabrication processes, dusts in the air should be eliminated as much as possible. In order to carry out semiconductor manufacturing processes, silicon wafers have to be carried between manufacturing devices. Then, silicon wafers might be damaged by a lot of floating dusts in the air. This is an unavoidable fact during fabrication processes. Thus, non-contact conveyer systems are very beneficial to semiconductor manufacturing industry because the systems don't produce dusts in vacuum chambers or clean rooms [3,4].

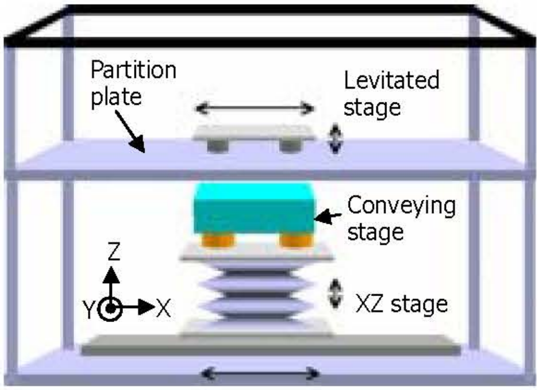

FIGURE 1: A total conveyer system which is composed of a magnetically levitated stage and a conveying stage

Among many applications of superconducting levitation, a magnetically levitated conveyer is very promising to move silicon wafers in vacuum chambers or clean rooms. This is because semiconductor manufacturing devices with mechanical contacts inevitably produce and release a lot of dusts in the air. If silicon wafers are carried by magnetically levitated conveyers in vacuum chambers or clean rooms, some processes are completely finished without any dusts.

Thus, our group has developed a prototype of magnetically levitated conveyer using superconducting levitation technique for these clean environments. To realize a magnetically levitated conveyer, a displacement sensor using Hall sensor is applied to the system. In this paper, dynamic characteristics of a prototype of the magnetically levitated conveyer are discussed.

SYSTEM

Fig. 1 shows a total conveyer system which is composed of a magnetically levitated stage and a conveying stage. In the figure, the upper side of the partition plate is supposed to be a clean room or a vacuum chamber, and the lower side of the partition plate is supposed to be outside of a clean room or a vacuum chamber. The conveying stage of the conveyer moves in the XYZ directions. Thus, the levitated stage moves according to the conveying stage. That is, the levitated stage moves keeping a constant gap between the conveying stage and itself. The XYZ positions of the conveying stage are controlled by a personal computer.

As shown in Fig. 2, the conveyer is composed of a levitated stage with four permanent magnets (PMs) and a conveying stage with four superconductors, four

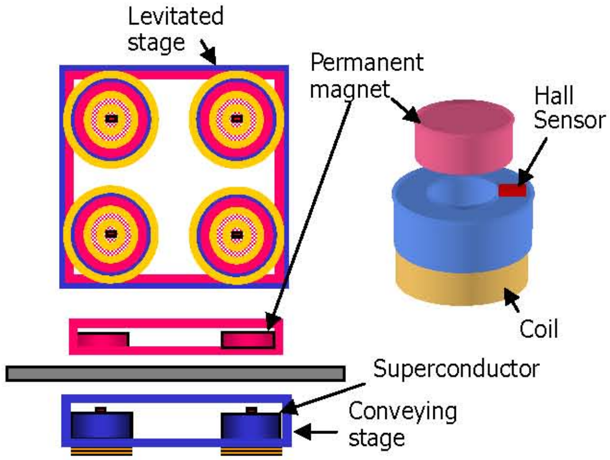

FIGURE 2: A magnetically levitated superconducting conveyer composed of four hybrid magnetic bearings

coils, and four Hall sensors. Thus, the conveyer is composed of four hybrid magnetic bearings. Each hybrid magnetic bearing consists of a permanent magnet, a superconductor, a coil, and a Hall sensor. The dimensions of these superconductors are OD45mm × ID25mm × T20mm. The permanent magnets measure 24 mm in diameter and 4 mm in thickness. Under each superconductor, each coil (150 turns, ϕ 0.3 mm) is put to produce magnetic field. Each coil doesn't have a core in the center of it. The vibrations of permanent magnets are suppressed by the attractive/repulsive force of the coil. Each Hall sensor is put on each superconductor to detect magnetic field. The permanent magnets (PMs) of the levitated stage are used to produce magnetic field. In the system, field cooling process for the superconductors is carried out to make a stable magnetic levitation of the levitated stage. Thus, the levitated stage is basically supported by conveying stage and the vibrations of the levitated stage are suppressed by the four coils.

In this paper, a hybrid magnetic bearing composed of a permanent magnet, a superconductor, a coil, and a Hall sensor is discussed. The static and dynamic characteristics of the hybrid magnetic bearing are described.

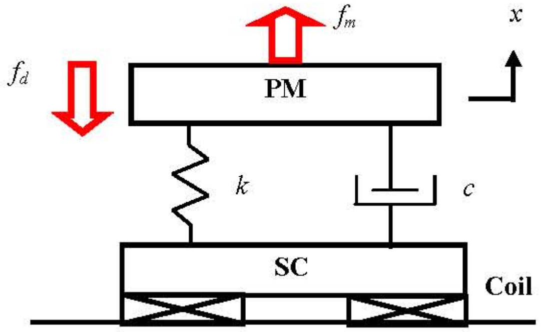

FIGURE 3: Dynamic model for the hybrid magnetic bearing

MODELING

In order to do some simulations of the dynamics for the hybrid magnetic bearing shown in Fig. 2, a simple dynamic model is assumed as shown in Fig. 3 [1]. The dynamic model for the hybrid magnetic bearing is composed of a superconductor, a permanent magnet, and a coil. Since the permanent magnet is supported by the superconductor due to its pinning force, a spring with stiffness k (72.8 N/m) and a damper with damping coefficient c (0.043 Ns/m) are introduced [1]. The dynamic model for the levitation system is written as

$$m\ddot{x}+c\dot{x}+kx+f_m-f_d=0\,, \tag{1}$$

where x is a displacement of the permanent magnet from the original position, m (14 × 10^{-3} kg) is a mass of the permanent magnet, f_m is a control force, and f_d is a disturbance. Since the permanent magnet is first located at the original position, the force f_m is represented by

$$f_m=k_i i\,, \tag{2}$$

where k_i is a constant for the control current i. Thus, the displacement of the permanent magnet is controlled by the coil force. PD control using adoptive control method is applied to the model. Control forces are produced by the coil under the superconductor. Though the gap between the coil and the permanent

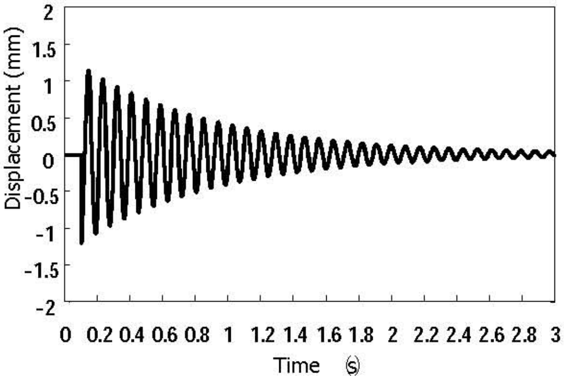

FIGURE 4: Impulse response without control showing natural damped vibration for the hybrid magnetic bearing

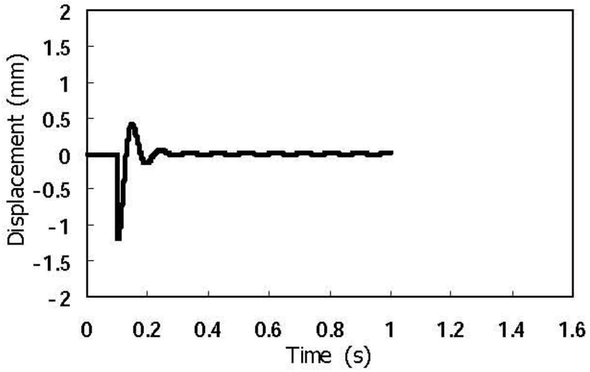

FIGURE 5: Impulse response of the hybrid magnetic bearing (simulation)

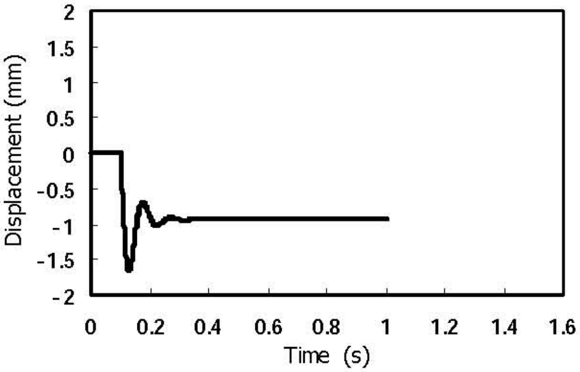

FIGURE 6: Step response of the hybrid magnetic bearing (simulation)

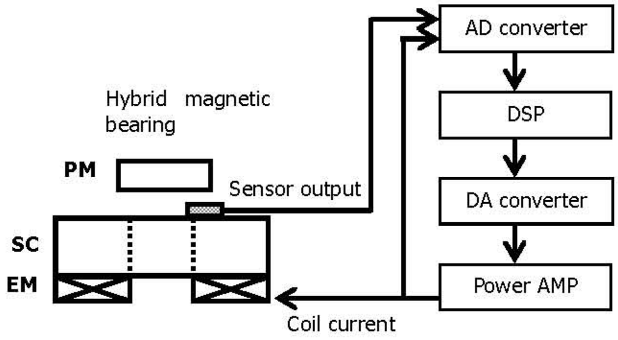

FIGURE 7: Experimental setup for the hybrid magnetic bearing

magnet is a little big, vibrations of the permanent magnet are suppressed due to the magnetic field through the superconductor hole.

Fig. 4 shows the impulse response of the hybrid magnetic bearing without control. A natural damped vibration for the magnetic bearing is observed. This shows that vibrations decrease as the time increases. It takes more than 3.0 s for the vibrations to disappear. The stiffness *k* and damping coefficient *c* are obtained by the impulse response.

Fig. 5 shows the impulse response of the hybrid magnetic bearing. In the simulation, let the first displacement amplitude be about -1.0 mm. From Fig. 5, it is found that the vibrations disappear within 0.2 s. This indicates that vibration control is working well. The vibration time in Fig. 5 is very shorter than the time in Fig. 4.

Fig. 6 shows the step response of the hybrid magnetic bearing. In the simulation, an impulse force 10^{-1} N was applied to the hybrid magnetic bearing. This is supposed that some wafers are put on the levitated stage of the hybrid magnetic bearing. As shown in Fig. 6, the vibrations disappear within 0.2 s.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 7. The setup consists of the hybrid magnetic bearing, a DSP controller, an AD converter, a D/A converter, and a power amplifier. A Hall sensor is installed in the superconductor hole. The Hall sensor detects the magnetic field produced by the permanent magnet and the coil. When the coil is not excited, the Hall sensor detects magnetic field of the permanent magnet as a function of gap. When the electromagnet is excited, the Hall sensor detects magnetic field as a function of gap with considering magnetic fields by the permanent magnet and the coil. Thus, the gap between the levitated permanent magnet and the superconductor is represented by the function of magnetic fields of the permanent magnet and the coil.

Since the gap of 10 mm is an original position, the Hall voltage corresponding to the displacement was measured near the gap of 10 mm. Fig. 8 shows the relationship between gap and Hall voltage. The displacement 0 mm indicates a gap of 10 mm. Thus, the displacement means the small gap around 10 mm. The Hall voltage 0 V is adjusted to the displacement 0 mm. The relationship between them is almost linear, especially in the Hall range near 0 V.

The Hall voltage as a function of coil current was also measured. The relationship between Hall voltage and coil current is shown in Fig. 9. In this case, the Hall voltage 0 V is also adjusted to the coil current 0 A. As shown in Fig. 9, the relationship is almost linear in the coil current range near 0 A. Figs. 8 and 9 show that the Hall voltage has linear relationships with the displacement and the coil current. Thus, the displacement is estimated by using these experimental results.

In this study, PD control is adopted for

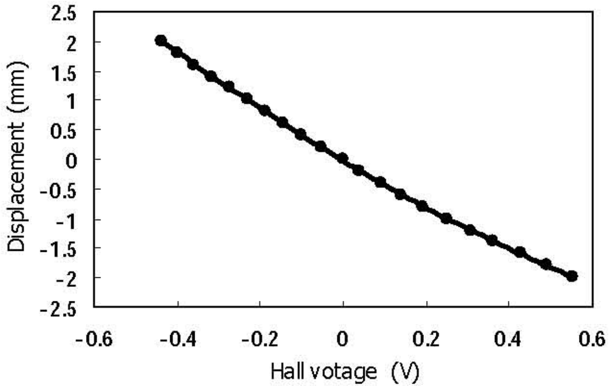

FIGURE 8: Relationship between gap and Hall voltage

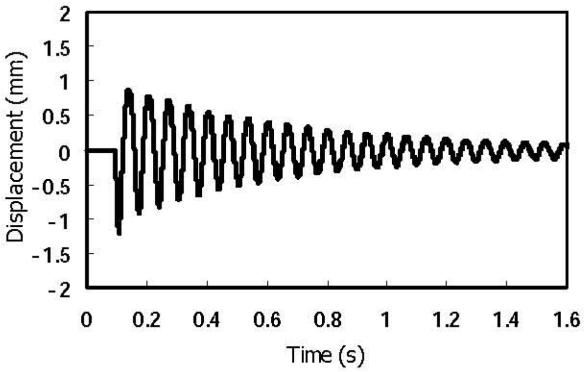

FIGURE 10: Impulse response of the hybrid magnetic bearing without control showing natural damped vibration

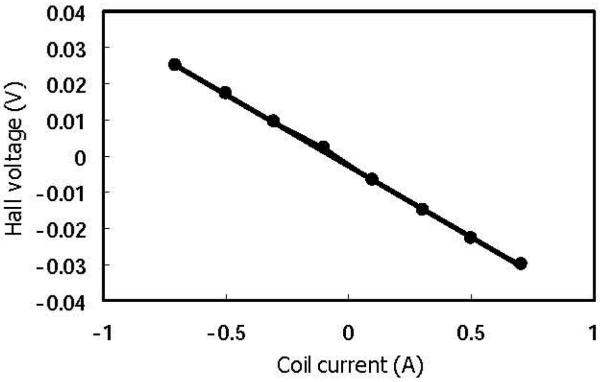

FIGURE 9: Relationship between Hall voltage and coil current

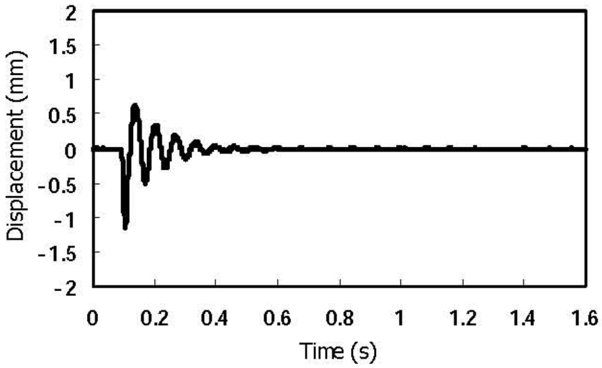

FIGURE 11: Impulse response of the hybrid magnetic bearing with PD control

suppressing the vibrations of the hybrid magnetic bearing. Moreover, only D control is also applied to the hybrid magnetic bearing because the levitation force of the hybrid magnetic bearing caused by the pinning effect works as P control.

RESULTS AND DISCUSSIONS

Impulse responses for the hybrid magnetic bearing without control were measured experimentally. In the experiment, impulses were applied to the permanent magnet in the vertical direction. The vibrations in the vertical direction were measured. Let the first displacement amplitude be -1.0 mm. One of the results is shown in Fig. 10. The result shows that natural damped vibrations are observed and decrease exponentially. The vibrations continue for more than 1.5 s. The damping of the permanent magnet is very small due to the strong pinning effect of the superconductor.

Fig. 11 shows the impulse response of the hybrid magnetic bearing. In the experiment, let the first displacement amplitude be about -1.0 mm. From Fig. 11, it is found that the vibrations disappear within 0.3 s. This indicates that vibrations of the permanent magnet are suppressed well. Compared with the result in Fig. 10, the vibration time in Fig. 11 is very shorter than the time in Fig. 10. The experimental result is similar to the simulation result in Fig. 5.

Fig. 12 shows the step response of the hybrid magnetic bearing without control. In the experiment, a mass of 10×10^{-3} kg was put on the permanent magnet as a step force. This is supposed that some wafers are put on the levitated conveyer stage. As shown in Fig. 12, natural damped vibrations are observed and they decrease exponentially. The vibrations continue for more than 1.5 s. Since the mass is added on the permanent magnet, the final displacement becomes about -0.7 mm. The final displacement is smaller than the gap 10 mm.

Fig. 13 shows the step response of the hybrid

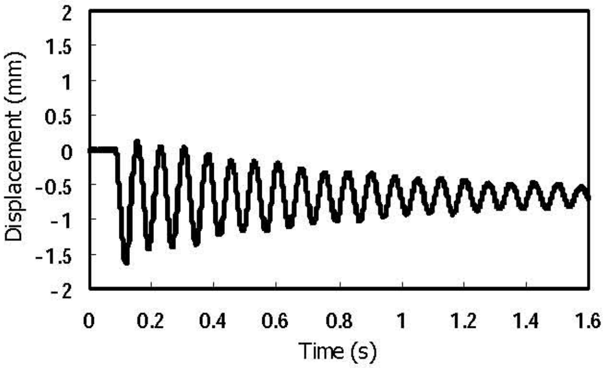

FIGURE 12: Step response of the hybrid magnetic bearing without control

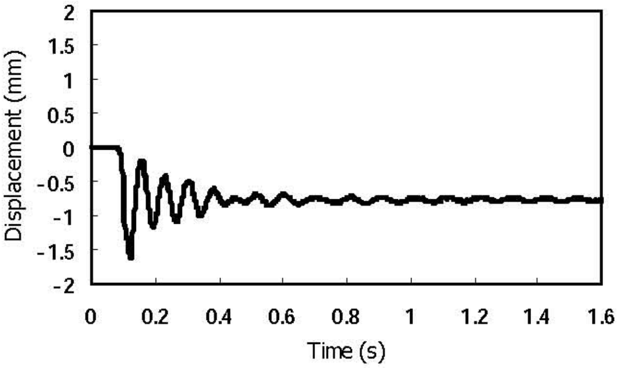

FIGURE 13: Impulse response of the hybrid magnetic bearing with PD control

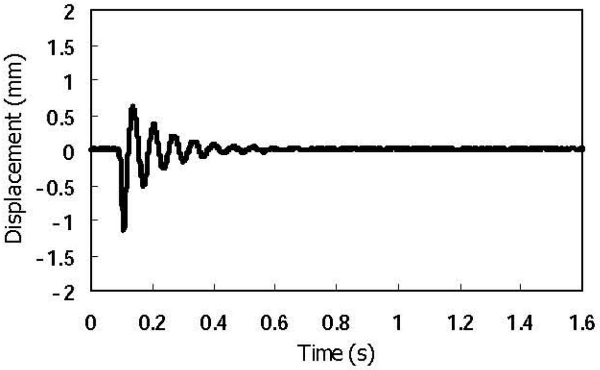

FIGURE 14: Impulse response of the hybrid magnetic bearing with only D control

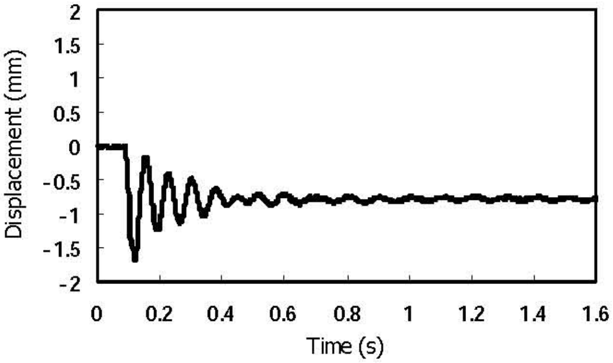

FIGURE 15: Step response of the hybrid magnetic bearing with only D control

magnetic bearing. In the experiment, a mass 10^{-1} N was applied to the permanent magnet in the same manner as the experiment in Fig. 12. This is supposed that some wafers are put on the conveyer levitated stage. As shown in Fig. 13, the vibrations disappear within 0.3 s. This indicates that vibrations of the hybrid magnetic bearing are suppressed well. Compared with the result in Fig. 12, the vibration time in Fig. 13 is very shorter than the time in Fig. 12. Small vibrations remain after 0.4 s. This is caused by the rolling motion of the permanent magnet. These experimental results are similar to the simulation results in Fig. 6.

The permanent magnet of the hybrid magnetic bearing is supported by the repulsive force due to pinning effect. That is, the hybrid magnetic bearing has its stiffness caused by the pinning effect. The levitation force of the hybrid magnetic bearing due to the pinning effect works as P control. Thus, we have applied only D control to the levitation system. Fig. 14 shows the impulse response of the hybrid magnetic bearing. The impulse responses were performed in the same manner as the experiments in Fig.11. The vibration disappears within 0.4 s. From the result, the vibrations are well suppressed without P control. Compared with the impulse response with PD control shown in Fig. 11, the impulse response in Fig. 14 is similar to the result in Fig. 11. This is because P gain in Fig. 14 is not so large compared with stiffness k. This shows that only D control is useful for suppressing the vibration of the hybrid magnetic bearing.

Step responses with only D control were investigated. Fig. 15 shows the step response of the hybrid magnetic bearing. The vibration disappears within 0.4 s. From the result, the vibrations are well suppressed without P control. Compared with the impulse response with PD control shown in Fig. 13, the impulse response in Fig. 15 is similar to the result in Fig. 13. This shows that only D control is useful for the hybrid magnetic bearing.

From the results in Figs. 14 and 15, it is found only D control is useful for suppressing the vibration of the hybrid magnetic bearing. This is very good benefit for the hybrid magnetic bearing because the bearing needs just a small amplifiers for supplying control current corresponding to D control.

SAMMARY

A magnetically levitated conveyer using superconducting magnetic levitation is proposed. The dynamics of the hybrid magnetic bearing are investigated. The gap sensor with a Hall sensor is installed in the hybrid magnetic bearing. The gap sensor detects the position of the permanent magnet. From the experimental results, vibrations of impulse responses are well suppressed by the PD controller. Moreover, only D control is applied to the hybrid magnetic bearing. With respect to the impulse and step responses, the results with only D control are similar to the results with PD control. This is very good benefit for the hybrid magnetic bearing because the system might become very small and simple.

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