CONTROL OF LEVITATION AND VIBRATION OF MAGNET BEARING TYPE ISOLATOR FOR ABSOLUTE GRAVIMETER

Yoichi Kanemitsu,[1] Shinya Kijimoto,[1] Koichi Matsuda,[1] Shinichiro Jyo,[1] Kazuaki Higashinakasu,[1] Katsuhide Watanabe,[2] Takahide Haga[2]

ABSTRACT

An electromagnetically levitated isolator of magnetic bearing type was applied to reduce bad influences from the ground vibration to the absolute gravimeter and improve a measurement accuracy of the gravimeter. Four types of the isolator controller were designed by paying attention to the low frequency vibration in the vertical direction in case that the isolator carries the gravimeter. The performance of each isolator controller was estimated by numerical simulations. The isolator with P controller for the levitation of the table and H_∞ controller for the isolation has a good isolation performance and also the isolator with P controller for the levitation of the table and H_∞ controller for both the levitation and the isolation has also a good isolation performance.

INTRODUCTION

Research on the gravity distribution on the earth surface is a way to investigate the inside of the earth in the scientific field on the earth and the planets. The gravity distribution on the earth surface is always measured by a precise gravimeter set on the ground. A power spectrum of ground vibration contains large component in low frequency and the natural frequency of the gravimeter is very low. Therefore the ground vibration has bad influences upon the measured results of the earth surface absolute gravity in measuring the absolute gravity on the earth surface [Nitta1995].

The electromagnetically levitated isolator constituted by an active magnetic bearing has a possibility to achieve lower natural frequency and higher isolation performance to the ground vibration with low frequency and small amplitude than a vibration isolator using the conventional spring element such as a rubber spring , an air spring and a coil spring because of a optimal tuning of the controller of the electromagnetically levitated isolator. Usually, a magnetic bearing regulates a relative displacement between a fixed casing on the ground and a floating shaft but an absolute vibration acceleration(displacement) should be regulated in the application.

At present, we will attempt to apply the electromagnetically levitated isolator of magnetic bearing type to reducing bad influences from the ground vibration to the absolute gravimeter and improve its measurement accuracy. The controller of the isolator is designed by paying attention to the low frequency vibration in the vertical direction in case that the isolator carries the gravimeter. Four kind of isolator controller are designed to levitate the floating table and isolate the table from the ground vibration.

---

[1] Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan.
[2] Ebara Research Co., Ltd., 4-2-1 Hon-fujisawa, Fujisawa-shi 251, Japan.

The performance of the isolator controller is estimated by numerical simulations.

ABSOLUTE GRAVIMETER

The absolute gravimeter is a system to measure the gravity acceleration on the earth surface by free falling method of a body in the gravity field. Figure 1 shows a schematic diagram of the absolute gravimeter FG5 made by Micro-g Solutions, Inc.(USA). The free falling body, which is formed into a corner cube and acts as reflector, is set in a vacuum chamber in order to eliminate the friction between the body and the air. Velocity of the body falling freely in the vacuum chamber is measured by the interference phenomena of laser beams which is reflected at the falling mirror and another fixed mirror which is called a internal reference corner cube.

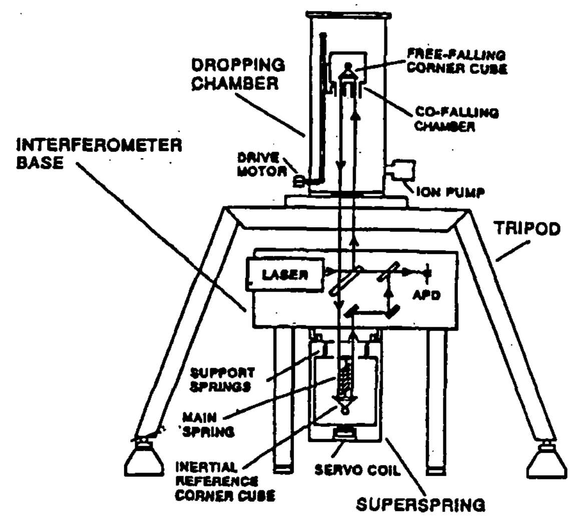


Figure 1 Schematic diagram of the absolute gravimeter

Vibration of the fixed mirror makes errors on the measured gravity by the gravimeter. The fixed mirror is hanged by a soft spring from the interferometer casing which is called " super spring " and has very low natural frequency to avoid the vibration of the fixed mirror transmitted through the structure of the device from the ground. Therefore, as a countermeasure against the low frequency vibration from the ground, it is planned to fix the absolute gravimeter on a vibration isolator which is applied with the electromagnetic levitation technology and in which a radial magnetic bearing and a thrust magnetic bearing are built in. The electromagnetically levitated isolator has a possibility to achieve lower natural frequency than a vibration isolator using the conventional spring element such as a rubber spring, an air spring and a coil spring by a optimal tuning of the controller of the electromagnetically levitated isolator

Usually, a magnetic bearing regulates a relative displacement between a fixed casing on the ground and a floating shaft. The elecrtomagnetically levitated isolator has not only a relative displacement controller, but also a controller for the absolute acceleration on the floated isolator table.

In this paper on the assumption that the isolator carries the absolute gravimeter shown in Figure 1, we study both the controllers to levitate the isolator table and to eliminate the vibration on the table from the ground in very low frequency.

Velocity of the corner cube, which falls freely in the vacuum chamber, is measured by a laser interferometer. The laser beams radiated from the laser source is reflected at the free falling corner cube and the inertial reference corner cube which is hanged from the interferometer base by support springs and super spring (main spring). The reflected beam interferes with the direct beam from the laser source at APD. The vibration of the internal reference corner cube is a major and direct reason of measuring error. The internal reference corner cube is supported by two kind of springs and its nattural frequency is about 1Hz. It is moved by the low frequency vibration of the ground where the gravimeter is set. The two kind of springs do not succeed in sufficiently suppressing the ground vibration which contains low frequency component. The problem of the bad influence from the ground vibration is expected to be solved by using a isolator, of which natural frequency is below 1 Hz, to support the interferometer base.

It is difficult to reduce the lowest natural frequency of a conventional isolator, which uses rubber spring, air spring or coil spring, below 1 Hz. Then we will apply the proposed electro-magnetically levitated isolator[Kanemitsu93, Kanemitsu94, Watanabe96, Cui96,], which has a same structure as the active magnetic bearing, to the gravimeter.

It is assumed that the vertical vibration from the ground to the interferometer base mainly excites the internal reference corner cube.

In this paper, the controller of the isolator is designed by paying attention to the low frequency vibration in the vertical direction in case that the isolator carries the interferometer base and the performance of the isolator controller is estimated by numerical simulations.

ELECTROMAGNETICALLY LEVITATED VIBRATION ISOLATOR

The three pedestals of the interferometer base are set on the isolator table. As the center of gravity of the interferometer base has been decided before setting it on the table, the isolator with 3 electro-magnetic actuators is adopted instead of 4 actuators as shown in Figure.2 and Figure.3 Mass of the interferometer base of the absolute gravimeter FG5 is 56kg. A trial product of the vibration isolator is designed to carry one third of the interferometer base mass and to study feasibility of the simultaneous control of levitation and isolation of the isolator. Therefore each electromagnetic actuator supports 6.3kg.

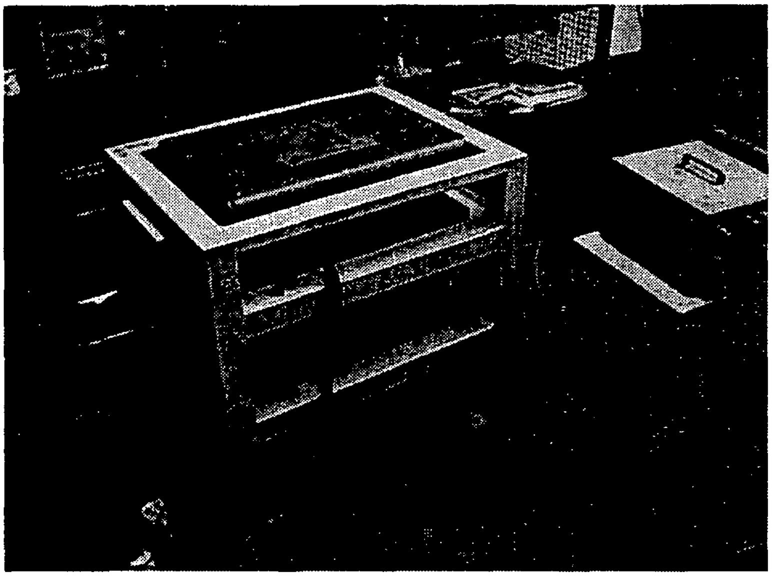


Figure 2 Photograph of the magnetically levitated isolator

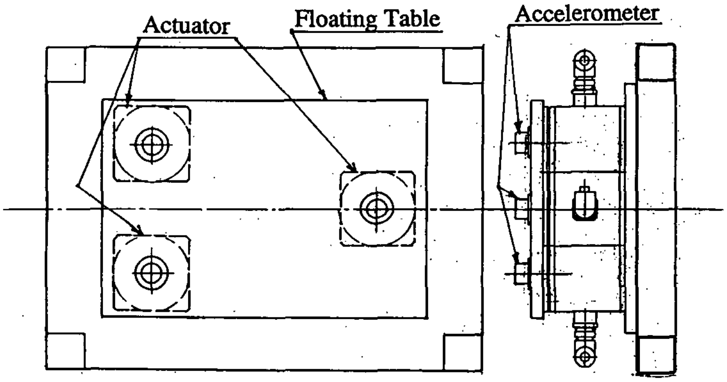


Figure 3 Drawing of the electromagnetically levitated isolator

MAGNETIC BEARING TYPE ACTUATOR

Each actuator has 3 relative displacement sensors for measurement of clearances between the floated shaft and the fixed actuator casing in vertical direction and 2 horizontal directions and a pair of electro-magnets for each measurement direction, that is to say, it has one thrust bearing and one radial bearing.

The cross-sectional view of the actuator is shown in Figure 4. The upper clearance and lower clearance between the magnet core and disk of the thrust bearing are 0.35(mm). Allowable control current is ±1.5(A). Bearing displacement rigidity k_u is estimated 0.577 (MN/m) and bearing control rigidity k_c is estimated 364 (N/A).

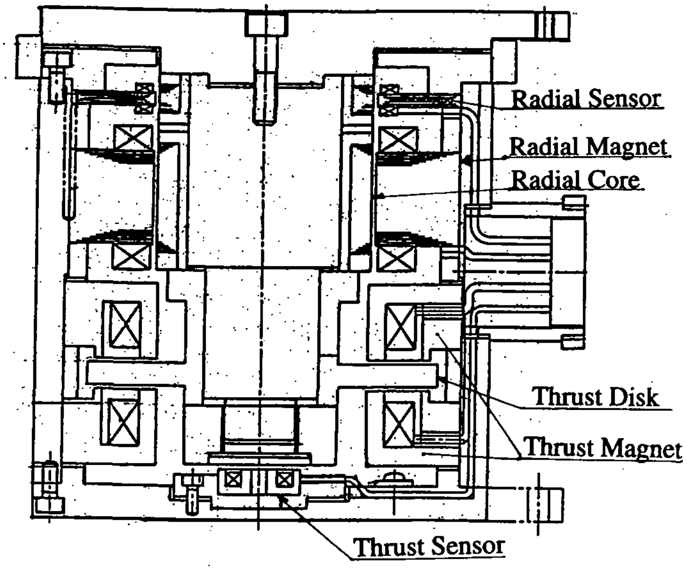


Figure 4 Sectional drawing of the magnetic bearing type actuator

CONTROLLER FOR LEVITATION AND ISOLATION

A schematic diagram of the gravimeter and the isolator is shown in Figure 5 and the isolation control system in vertical direction is modeled as Figure 6.

Total mass of the floating parts of the isolator and the gravimeter for each actuator m is 12.6kg.

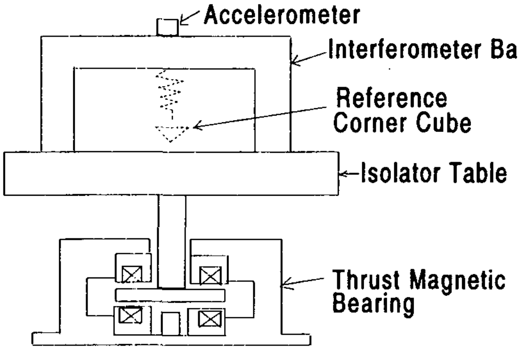


Figure. 5 Schematic diagram of the gravimeter and the isolator

The levitation of the isolator table is controlled using the relative displacement vibration $x-x_g$ measured by the relative displacement sensor in vertical direction, where x is absolute displacement of the floated table and x_g is the ground displacement. But the magnetic pull due to the bearing displacement rigidity k_u is proportional to the relative displacement and destabilizes the levitation.

"Eddy" represents a transfer function between the magnetizing flux and the exciting current due to the eddy current in the disk of the thrust magnetic bearing and is expressed in eq(1).

$$Eddy = \frac{650}{s+650} \qquad (1)$$

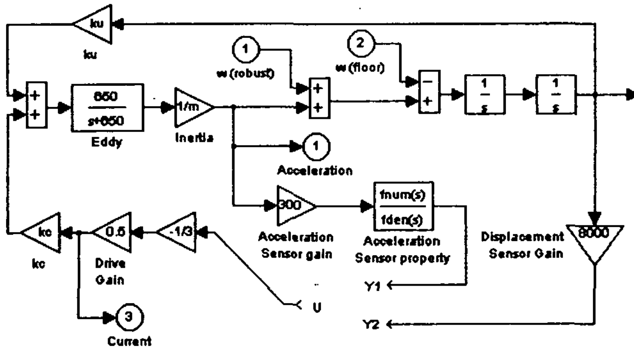


Figure 6 Block Diagram of the isolator

The isolation control is mainly based on the absolute acceleration $\ddot{x}$ of the floated table. "Acceleration sensor property" in Figure 6 represents the frequency characteristics of the servo type accelerometer and its bode diagram is shown in Figure7. Four kinds of controller are designed and put between two sensor outputs y_1, y_2 and a controlled input u in Figure 6.

Mass of the internal reference corner cube is less than 0.1kg and the total levitated mass is nearly 12kg.. Accordingly, the internal reference corner cube is much lighter than the levitated mass so it is estimated that the seismic system of the internal reference corner cube does not affect on the main levitation and isolation control of the isolator is neglected in the isolator plant in Figure 6.

The vibration transmissibility ratio of the ground to the levitated table around 1 Hz should be decreased by the isolator.

The levitation control system aims to levitate the isolator table with a constant clearance between the ground and the levitated table according to the ground motion.

On the other side, the isolation control system aims to decrease the absolute vibration on the levitated table. The design specifications of the both control systems seem to conflict with each other. But the major purpose of the isolation system eliminates the transmission of the ground vibration to the isolator table, so that the clearance between the thrust disk and the magnetic stator core may change while the ground vibration is eliminated on the table.

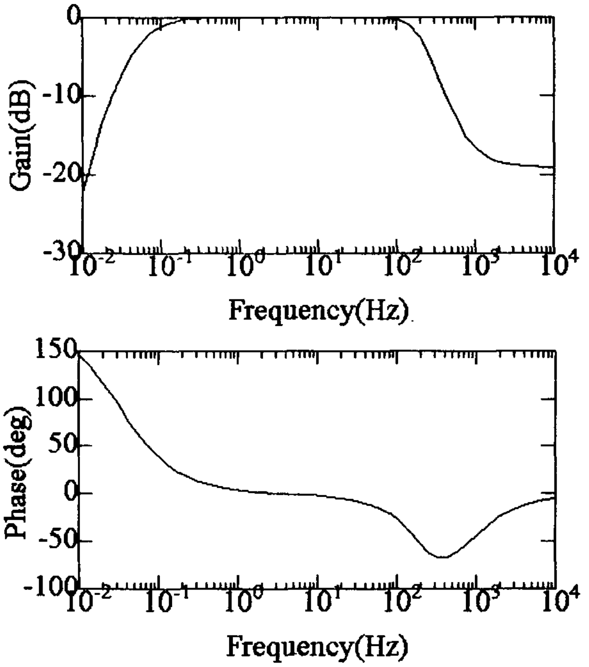


Figure 7 Frequency characteristics of the servo type accelerometer

CONTROLLER DESIGN

Four design methods for the magnetic levitation and isolation control of the isolator are adopted , in three of which the controller for the levitation of the isolator table and controller for the isolation from the ground vibration are designed separately, and in the other the controller for the levitation and controller for the isolation are designed at the same time, as shown in Table 1.

In the first through third controller design methods, the control system for the magnetic levitation is designed firstly and then the isolation controller is designed for the system which has been levitated by the designed levitation controller as a plant. It is not necessarily assured that the levitation control is stable in these control systems.

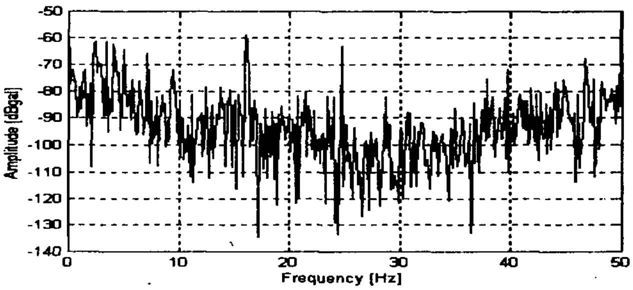
In the fourth design method, the controller is designed for both levitation of the table using the relative displacement and isolation of the table from the ground motion using the absolute acceleration as 2 input and 1 output system.

Table1 Comparison of control design methods and results

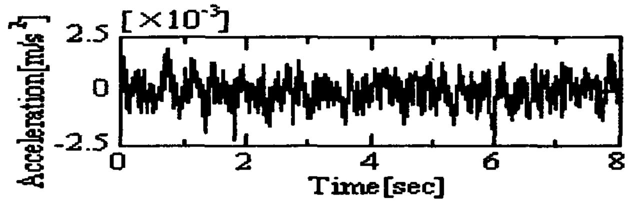
method no.	Levitation	Isolation	result
1	P	H∞	Figure 13
2	PI	H∞	Figure 14
3	PD	H∞	Figure 15
4	P+H∞		Figure 16

Figure 8 shows an example of the ground vibration spectrum. It has large component in low frequency. Therefore, a frequency weighted model is employed in order to consider the ground vibration in low frequency and also the dynamics of the table whose flexibility is ignored in making the basic plant model. Figure 9 shows the frequency weighted model of the isolator and Figure.10,11 show the bode diagram of the weight functions W_s, W_t. The weight function W_s for the ground motion isolation has a weight between 0.1 and 10Hzz. The weight function W_t for the robust control to the model uncertainty has a weight between 100 and 10,000Hz as the first natural frequency of the levitated table is about 350Hz

In the first control method, a negative feedback of only proportional signal of the relative displacement is applied for the levitation control, whereas the levitation control system is not sufficiently stable because of the negative bearing displacement rigidity k_u and little damping in the system. The design of the isolation control employs H_∞ theory weighted at low frequency to isolate the table from the ground vibration assuming the levitated table to be a SISO plant. When a stable isolation controller can be achieved, the levitation control may be stabilized by the isolation controller. Stabilization of the levitation



(a) spectrum



(b) time series data(m/s²)

Figure 8 Example of the ground vibration

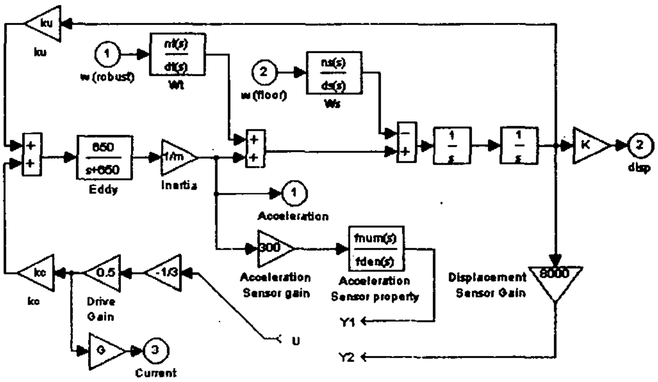


Figure 9 Frequency weighted model of the isolator

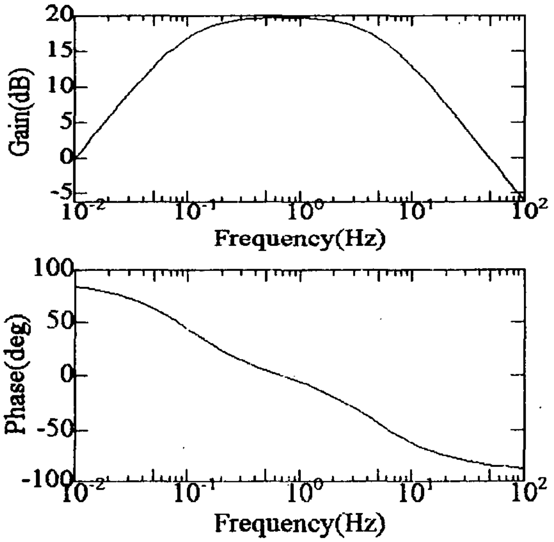


Figure 10 Weight function W_s

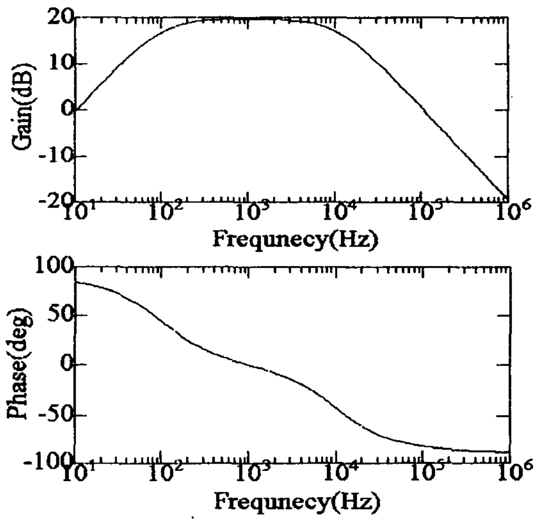


Figure 11 Weight function W_t

control may be simultaneously achieved by the isolation H_∞ controller.

The block diagram with the H_∞ controller is shown in Figure12 in case that the levitation control is a proportional control and the isolation control is H_∞ control.

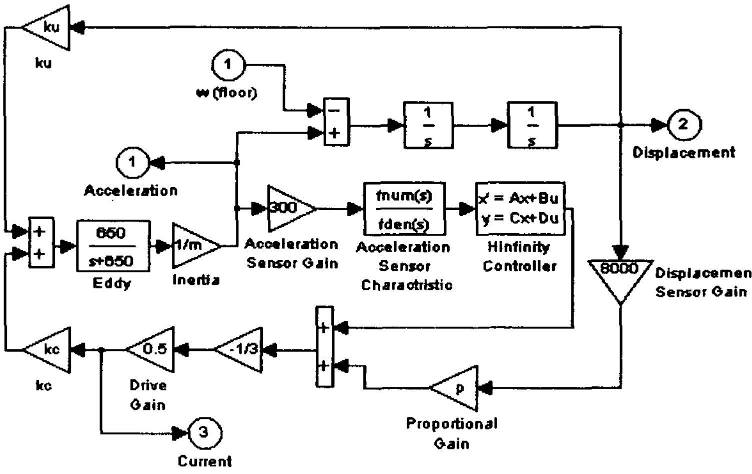


Figure 12 Block diagram of the system with $P+H_\infty$ controller

In the second control method, a negative feedback PI control of the relative displacement is applied for the levitation control, where the levitated table is aimed to be at rest. The design of the isolation control employs H_∞ theory weighted at low frequency assuming the levitated table to be a SISO plant. Stabilization of the levitation control may be achieved by the isolation H_∞ controller.

In the third control method, a negative feedback PD control of the relative displacement is applied for the levitation control, where the levitated table is aimed to be stable sufficiently. The design of the isolation control employs H_∞ theory weighted at low frequency assuming the levitated table to be a SISO plant.

The fourth control method is like the first control method. In the fourth method, a negative feedback of only the relative displacement is applied for the levitation control in the same way as the first method, where the levitation control system is unstable. The design of the isolation control employs H_∞ theory weighted at low frequency assuming the levitated table to be 2 outputs (the relative displacement and the absolute acceleration) and 1 input (the electric voltage) plant. Stabilization of the levitation control may be achieved by the controller.

SIMULATION RESULTS

The designed transfer functions between the levitated table acceleration and the ground vibration, between the relative displacement and the ground vibration and between the control current and the ground vibration are presented in Figure13 through 16 (a), (b),(c). The simulation results on the table acceleration, the relative displacement and the control current are shown in Figure13 through 16 (d), (e), (f) under the ground vibration in Figure 8(b).

The maximum relative displacement in every controller is within the thrust bearing clearance ± 0.35(mm) and the control current from the power amplifier of the bearing is also within an allowable maximum current of the amplifier ±1.5(A).

From the transfer functions between the table acceleration and the ground vibration, we can see that the isolation performance of the system designed and controlled by the first and fourth control design method are much better than the second and third ones because the gain of transfer function of the former is under -40dB around 1Hz. But the gain of transfer function of the latter is nearly 0dB around 1Hz. That is to say, the isolation control systems designed by the second and third design method have not sufficient vibration isolation capability around 1Hz.

CONCLUSIONS

The controller design method for vibration isolator of magnetic bearing type for the absolute gravimeter has been discussed herein. Comparison of the isolation performance among the four design methods has brought the following conclusions;

(1) The isolator with P controller for the levitation of the table and H_∞ controller for the isolation has a good isolation performance.

(2) The isolator with P controller for the levitation of the table and H_∞ controller for both the levitation and the isolation has also a good isolation performance.

(3) The isolator with PD controller for the levitation of the table and H_∞ controller for the isolation and the isolator with PI controller for the levitation of the table and H_∞ controller for the isolation have not isolation capability.

We are going to apply the control methods discussed herein to a trial production of test apparatus and verify the conclusions according to the control design method of the vibration isolator levitated by the electro-magnets for the absolute gravimeter.

REFERENCES

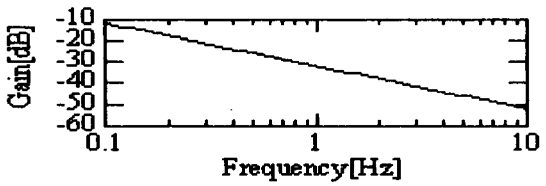
Nitta,H.,et.al., Precise Vibration System for absolute gravity measurements Proceedings of joint meeting of earth and planet science(in Japanese) p.387(1995-3)

Watanabe,K., et.al., Combimation of H_∞ and PI control for an electromgnetically levitated vibration isolation system, Proceedings of IEEE 35th Conference on Decision and Control ,pp1223-1228(1996)

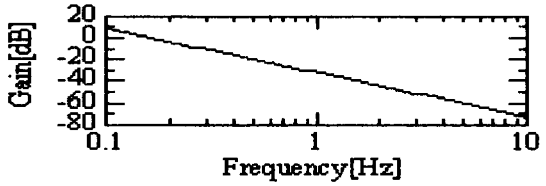
Kanemitsu,Y., et.al., Active Micro-vibration Control System Using Both air spring and Magnetic Bearings (Control performance with Absolute velocity feedback), Proceedings of 2nd Conference on Motion and Vibration Control . pp7-12, 1994-9.

Cui,W., et.al., Isolation Performance of Hybrid Isolation System by H_∞ Control and disturbance cancellation control, Proceedings of 3rd Conference on Motion and Vibration Control . pp7-12, 1996-9.

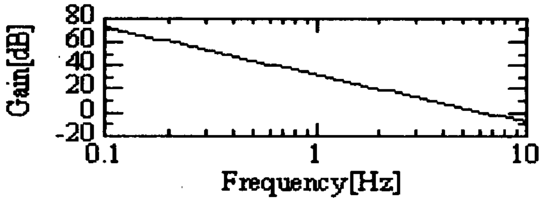
Kanemitsu,Y., et.al., Electromagnetically levitated vibration isolation system for the manufacturing process of silicon monocrystals, NASA CP-3247, pp479-497(1993)



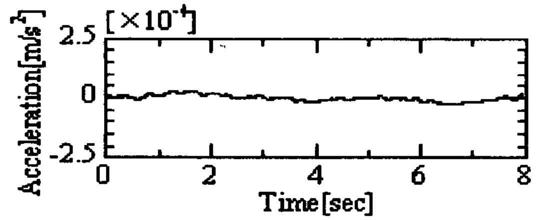
(a) transfer function between the table acceleration (m/s^2) and the ground vibration (m/s^2)



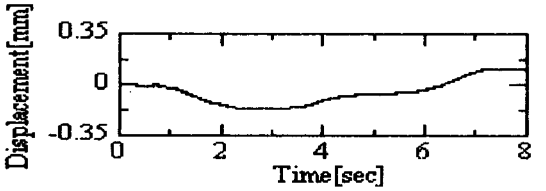
(b) transfer function between the relative displacement (m) and the ground vibration (m/s^2)



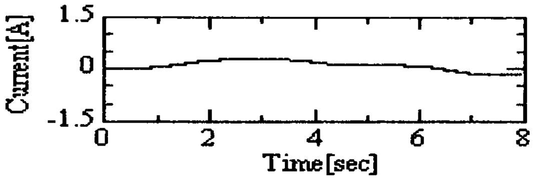
(c) transfer function between the control current (A) and the ground vibration (m/s^2)



(d) table acceleration

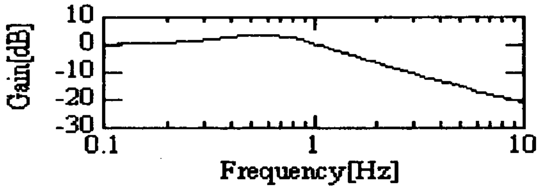


(e) relative displacement of the table

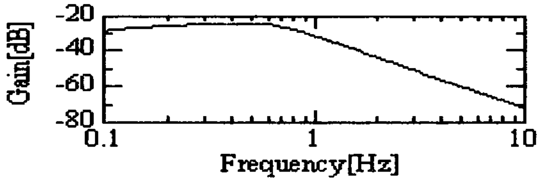


(f) control current

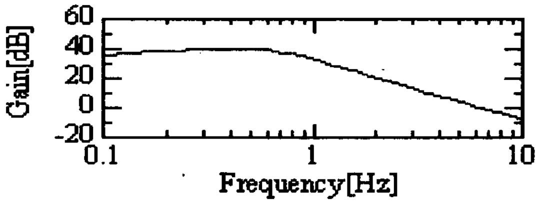
Fig.13 Transfer functions and simulation results of the system designed by the first method



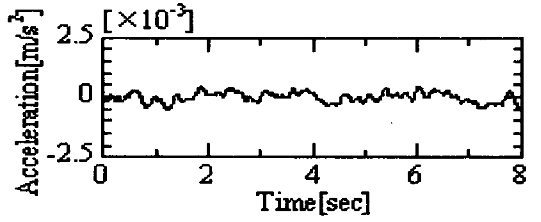
(a) transfer function between the table acceleration (m/s^2) and the ground vibration (m/s^2)



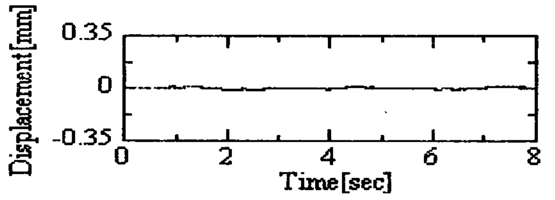
(b) transfer function between the relative displacement (m) and the ground vibration (m/s^2)



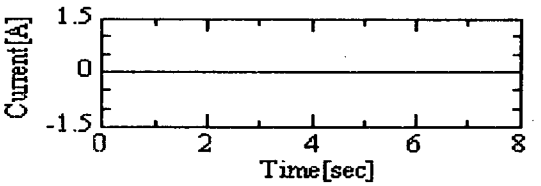
(c) transfer function between the control current (A) and the ground vibration (m/s^2)



(d) table acceleration

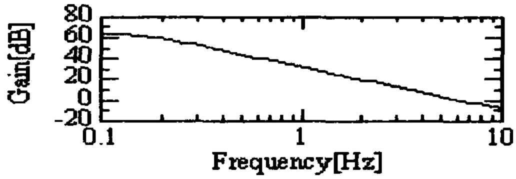


(e) relative displacement of the table

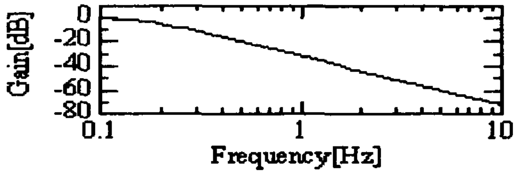


(f) control current

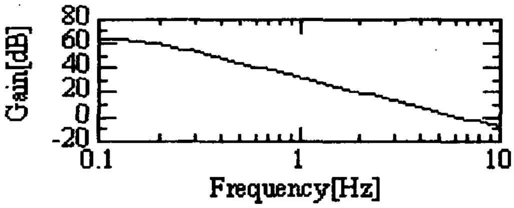
Fig.14 Transfer functions and simulation results of the system designed by the second method



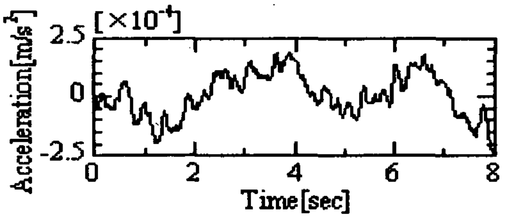
(a) transfer function between the table acceleration (m/s^2) and the ground vibration (m/s^2)



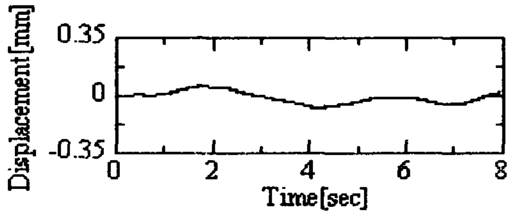
(b) transfer function between the relative displacement (m) and the ground vibration (m/s^2)



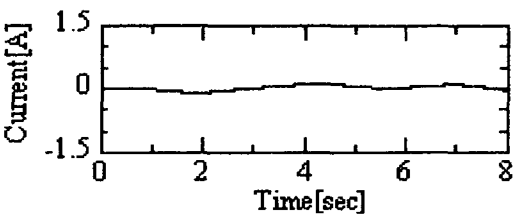
(c) transfer function between the control current (A) and the ground vibration (m/s^2)



(d) table acceleration

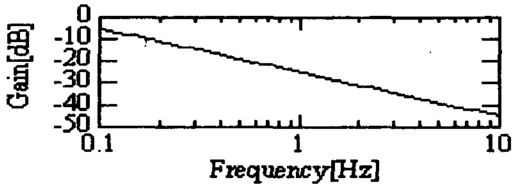


(e) relative displacement of the table

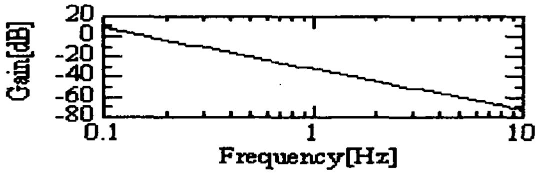


(f) control current

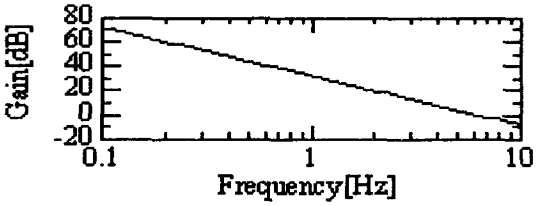
Fig.15 Transfer functions and simulation results of the system designed by the third method



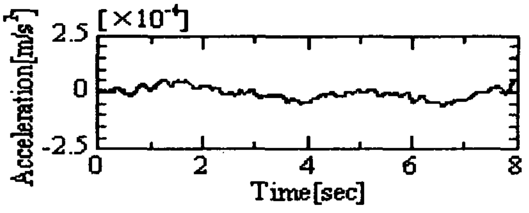
(a) transfer function between the table acceleration (m/s^2) and the ground vibration (m/s^2)



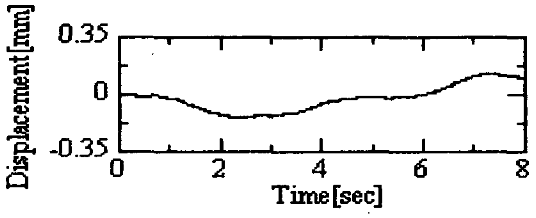
(b)transfer function between the relative displacement (m) and the ground vibration (m/s^2)



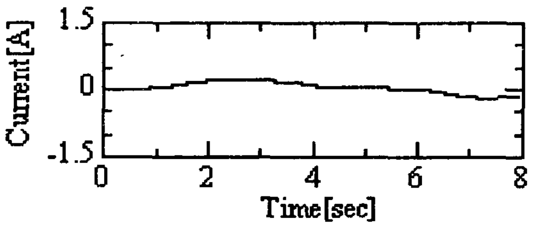
(c) transfer function between the control current (A) and the ground vibration (m/s^2)



(d) table acceleration



(e) relative displacement of the table



(f) control current

Fig.16 Transfer functions and simulation results of the system designed by the fourth method