Fifth International Symposium on Magnetic Bearings
Kanazawa, Japan, August 1996

Development of Magnetically Suspended Sliders for Deployable Antenna Test Facility

Yasushi Horiuchi *, Masao Inoue *, Kazuo Miyoshi **, Toshio Sugimoto **,
Teruki Okamoto *** and Ken-ichi Hariu ***

* Mitsubishi Electric Corp. Advanced Technology R&D Center
8-1-1, Tsukaguchi-hommachi, Amagasaki, Hyogo, 661 Japan
Tel:+81-6-497-7162; Fax:+81-6-497-7291; e-mail:horiuchi@mec.crl.melco.co.jp
** Mitsubishi Electric Corp. Kamakura Works
325, Kami-machiya, Kamakura, Kanagawa, 247 Japan
*** Advanced Space Communications Research Laboratory
2-12-5, Iwamoto-cho, Chiyoda-ku, Tokyo, 101 Japan

Abstract: Magnetically suspended sliders which can move freely in horizontal plane were developed and applied to original deployable antenna test facility for large antenna deployability tests on the ground. This paper describes slider construction for stable magnetic suspension, control methods and safeguards for reliability improvement. Moreover, as a result of several tests including single slider tests and 1-module antenna deployment tests, we obtained that the original test facility using magnetically suspended sliders was practical.

1. INTRODUCTION

1.1 Deployable Antenna and Its Deployability Test

In order to accomplish satellite-based mobile communications, a large deployable antenna should be launched in space; accordingly we must verify its deployability on the ground before launch. The precise simulation of its deployment motion on the ground is, however, quite difficult because the driving force for the deployment is not large enough against the weight of the antenna or the friction of supporting mechanisms. Thus deployable antenna requires the test facility to support its weight without disturbing its deployment motion.

Several methods have ever been tried, such as supporting an antenna with sliders levitated by air pressure[1] or hanging by many cables suspended from high ceiling[2]. The sliders levitated by air pressure move freely in horizontal plane; nevertheless they can not follow 3-dimensional deployment motion. The latter cable suspension system can follow 3-dimensional motion; however, the resisting force becomes larger as the deployment progresses because the cable slants more. Consequently we could not evaluate 3-dimensional antenna deployability precisely by using these traditional methods.

1.2 Advantage of Magnetically Suspended Sliders

To solve the above mentioned problems, we developed original deployable antenna test facility using magnetically suspended sliders as the antenna supporting mechanism. Because of non-contact magnetic suspension, these sliders move horizontally without constraint and suspend the antenna with quite few disturbance. Furthermore all the sliders control their cable tension in order to cancel the weight of the suspended antenna. For these reasons, the test facility supports the antenna without disturbing the deployment motion and enables us to evaluate the precise deployability.

There were, however, still several problems for accomplishment of the magnetically suspended sliders:

- Construction of autonomous slider control systems,
- Monitoring and controlling of many sliders,
- Improvement of stability and reliability of magnetic suspension control.

Accordingly, the sliders were designed to be equipped with the followings;

- All control systems including the magnetic suspension, the cable tension and the communications,
- Safeguards for magnetic suspension control by software.

This paper describes construction and control methods of the magnetically suspended sliders, and then refers the safeguards for reliability improvement and resonance suppression. As the results of single slider tests and 1-module antenna deployment tests, we conclude that the original deployable antenna test facility using the magnetic suspended sliders is practical.

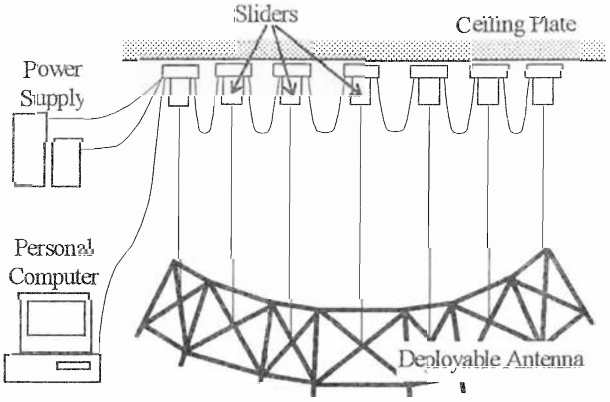

Fig.1. Deployable Antenna Test Facility

2. MAGNETICALLY SUSPENDED SLIDERS

Antenna deployment test using magnetically suspended sliders is achieved as shown in Fig.1. The test facility requires several functions as follows:

- 3-degree-of-freedom active magnetic suspension control,

- Cable tension control,
- Cable length control,
- Safeguards.

Moreover, the sliders are required to satisfy the specifications shown in Table 1.

Table 1. Specifications Required for Slider

Items	Specifications
Suspension Method	3-Degree-Of-Freedom Active Magnetic Suspension
Weight	< 4kg
Maximum Drag with Horizontal Motion	1N
Maximum Attractive Force	90N (Control ON) 170N(Control OFF)
Load Capacity	> 40N
Cable Tension Control Precision	0.5N
Power Consumption	< 50W

The construction and the control methods of the magnetically suspended sliders developed in order to accomplish these functions are described in this section.

2.1 Construction of Magnetically Suspended Slider

The schema of the magnetically suspended slider is illustrated in Fig.2. Table 2 shows the components of each slider.

Table 2. Component Parts of Slider

Components	Notations
Actuators	3 Electromagnets with Permanent Magnets for Magnetic Suspension Control D.C. Motor for Cable Tension / Length Control
Sensors	3 Eddy Current Induction Sensors for Magnetic Suspension Control Load Cell for Cable Tension Control
Cable	with Spring and Damper as Shock Absorber
Spherical Joint	for Resonance Suppression
Control Circuit	DSP : TMS320C25 Control Period : 0.3ms PWM Power Amp. Serial Communications Circuit

Each electromagnetic actuator consists of permanent magnet and electromagnet, so that the slider automatically clings to ceiling plate made of steel in case of controller trouble or power failure. This is detailed in section 3.1.

The ceiling plate has several seams because it is made of 4 steel plates. Small eddy current displacement sensors are sensitive to the seams. Therefore, we adopted ϕ 10mm sensors and they enable the slider to pass the seams stably.

2.2 Control Systems of the Slider

Each slider has magnetic suspension controller, cable tension controller and serial communication controller in its DSP algorithm program.

2.2.1 Magnetic Suspension Control System

Fig.3 shows the block diagram of the magnetic suspension control of the slider. PID compensator constituted in the DSP achieves the magnetic suspension control using 3 sensors and 3 actuators, where the control variables are one vertical translating displacement (Z) and two rotation angles (ϕ, θ) of the slider. For the control precision improvement the DSP linearizes the input-output character of each sensor, and adjusts the coil currents commands by their air gaps. Two coordinate transformations shown in Fig.3 are given by Eq.(1) and Eq.(2).

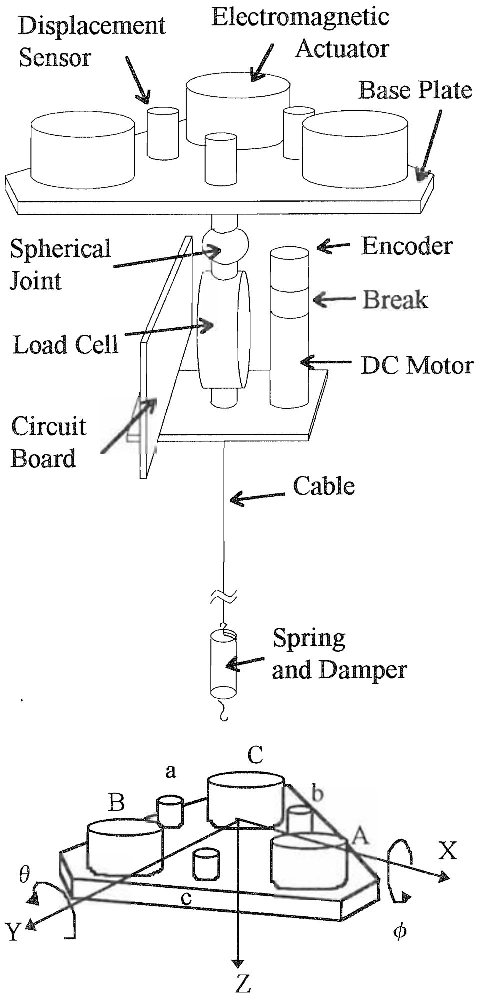

Fig.2. Schema of the Magnetically Suspended Slider

[Coordinate Transformation 1]

$$\begin{bmatrix} \phi \\ \theta \\ Z \end{bmatrix} = \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_3 \end{bmatrix} \begin{bmatrix} -1 & -1 & 2 \\ 1 & -1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} z_a \\ z_b \\ z_c \end{bmatrix} \qquad (1)$$

α_1 and α_2: [rad/m], α_3: [m/m]

[Coordinate Transformation 2]

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} \beta_1 & 0 & 0 \\ 0 & \beta_2 & 0 \\ 0 & 0 & \beta_3 \end{bmatrix} \begin{bmatrix} 1 & -1 & 1 \\ 1 & 1 & 1 \\ -2 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_\phi \\ F_\theta \\ F_Z \end{bmatrix} \qquad (2)$$

β_1, $\beta_2$and β_3: [A/N]

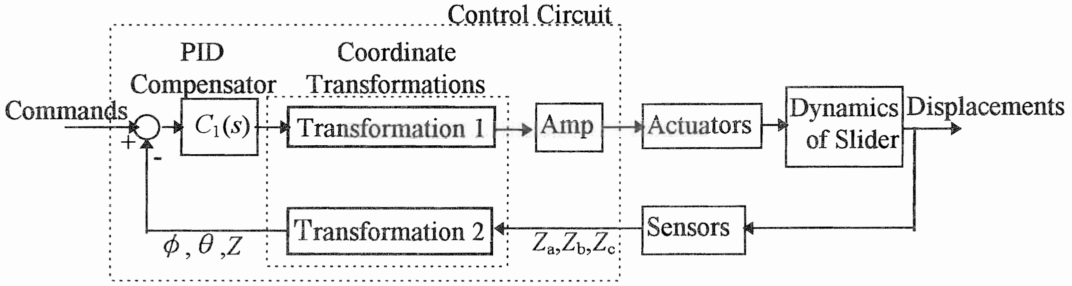

Fig.3. Block Diagram of the Magnetic Suspension Control

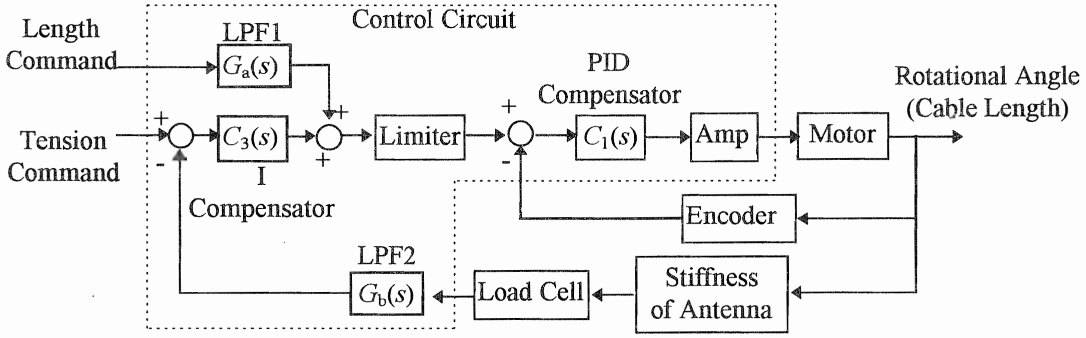

Fig.4. Block Diagram of the Cable Tension Control

where z, F and I are the displacement of each sensor, required force for each degree-of-freedom and required coil current, respectively, and α, β are the coefficients for unit transformation. The PID compensator $C_1(s)$ is given by

$$C_1(s) = K_1\left(1+\frac{1}{T_{i1}s}+\frac{T_{d1}s}{1+\tau_1 s}\right),$$

$$\begin{aligned} &K_1 : \text{gain},\\ &T_{i1} = 154ms,\\ &T_{d1} = 9.6ms,\\ &\tau_1 = 1.2ms \end{aligned} \tag{3}$$

The command for air gap, Z, is automatically adjusted using the cable tension. The enable/disable command for magnetic suspension control is given through the serial communication line.

2.2.2 Cable Tension Control System

Fig.4 shows the block diagram of the cable tension control. The cable tension controller contains servo system of the motor as its inner loop, so that the hybrid control of the cable tension and the cable length is implemented. The PID compensator $C_2(s)$ of servo system is given by

$$C_2(s) = K_2\left(1+\frac{1}{T_{i2}s}+\frac{T_{d2}s}{1+\tau_2 s}\right),$$

$$\begin{aligned} &K_2 : \text{gain},\\ &T_{i2} = 307ms,\\ &T_{d2} = 48ms,\\ &\tau_2 = 4.8ms \end{aligned} \tag{4}$$

The I-compensator $C_{i3}(s)$, the low-pass filters(LPF) $G_a(s)$ and $G_b(s)$ are given by Eq.(5).

The commands for the cable length and the cable tension are given through the serial communication line.

$$C_i(s) = \frac{1}{T_{i3}s},\quad G_a(s) = \frac{1}{1+\tau_a s},\quad G_b(s) = \frac{1}{1+\tau_b s}, \tag{5}$$
$$T_{i3} = 1.2ms,\quad \tau_a = 154ms,\quad \tau_b = 4.8ms$$

2.3 Serial Communications System

Each slider builds above mentioned control systems by itself. However, it has the serial communication line which transmits commands and data. Fig.5 shows the schema of the serial communications for a PC, a host DSP and 6 sliders. The host DSP sends the magnetic suspension control enable/disable commands, the cable tension and length commands while each slider returns its condition data. The commands and data are transmitted in original 16bit format shown in Fig.6. The serial communication line consists of the data line, frame synchronizing pulse line, clock line and ground line. The signal flow is one-way between one DSP ant the others while that is two-way between the host DSP and the PC. The PC controls the commands to be send, and displays the data of the slider conditions.

3. Safeguards for the Magnetic Suspension

Any slider must not fall down in any case, such as power failure or unexpected rapid variation of suspended load. The slider, however, should not have mechanical safeguards because they may disturb the free motion of the sliders. Therefore we carried out the fail-safe design and installed the safeguards implemented by software to improve safety and reliability of the sliders.

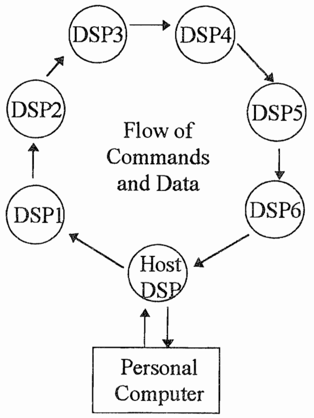

Fig.5. Serial Communications

5bits	3bits	8bits
Slider ID	Index	Data

Fig.6. Format for the Serial Communications

3.1 Fail-safe Design for Electromagnetic Actuators

The construction of the electromagnetic actuator is shown in Fig.7. The electromagnet controls the attractive force by reducing the magnetic flux of the permanent magnet. Consequently the slider clings to the ceiling plate automatically in case of power failure.

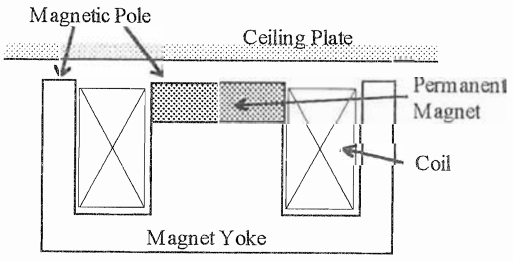

Fig.7. Schematic Cross Section of the Electromagnetic Actuator

3.2 Automatic Air Gap Adjustment of the Magnetic Suspension

When the permanent magnet is Sm-Co type, the magnetic flux density B and the attractive force F are given approximately by

$$B=\frac{\mu_0\left(H_0 w-E\right)}{2z+w}, \qquad (6)$$

$$F=\frac{1}{2\mu_0}B^2S, \qquad (7)$$

where μ_0 : Magnetic permiability
H_0 : Coercive force of permanent magnet
w : Thickness of permanent magnet
E : Magnetomotive Force by coil current
z : Air gap
S : Total area of magnetic pole

Fig.8 shows the *E-B* diagram of the actuator. The magnetic suspension is stable only in the case of Eq.(8).

$$\text{(Weight of Slider)} + \text{(Suspended Load)} = F \qquad (8)$$

From Eq.(7) and (6), one can obtain that the attractive force F is controlled with the magnetomotive force E and the air gap Z. Considering this fact, we applied the magnetomotive force modification to control higher frequency component of the load variation, and the air gap modification to control lower frequency component. Thus the coil currents of the actuators become almost constant regardless of the load variation. Consequently wider load variation shall be permissible.

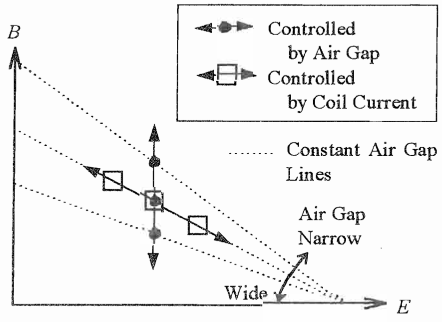

Fig.8. *E-B* Diagram

3.3 Control Conditions Monitoring System

Each DSP always monitors the air gap, coil currents, cable tension and serial communication interval of the slider. When any of them goes out of its permissible range, the DSP automatically interrupts the magnetic suspension control to make the slider cling to the ceiling plate. Furthermore the DSP sends emergency command to the other sliders connected with the serial communication line in order to interrupt their magnetic suspension controls. The PC supervises all the sliders individually through the host DSP.

4. Resonance Suppression

As shown in Fig.2, each slider has the spherical joint between the base plate and the load cell. This section describes that the joint is necessary for suppressing unstable mechanical resonances.

Fig.9 shows open-loop transfer function of the magnetic suspension control without the joint. From this figure one can recognize there is an unstable resonance at 200Hz. Even if this resonance could be suppressed by notch filter, the control precision will not be improved because of the phase margin deficiency.

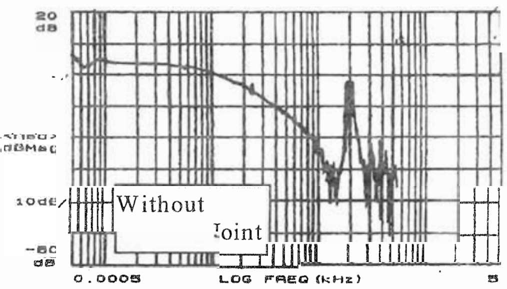

Fig.9. Open-loop Transfer Function of Magnetic Suspension Control(θ) without Joint

On the other hand, Fig.10 shows the open-loop transfer function with the joint. Here is no unstable resonance.

In order to solve the cause of the unstable resonance at

200Hz, we calculated the transfer function with simplified slider model illustrated in Fig.11 using the parameters shown in Table 3. In Case 1 we assumed that the bending stiffness of the load cell is equivalent to one of the joint.

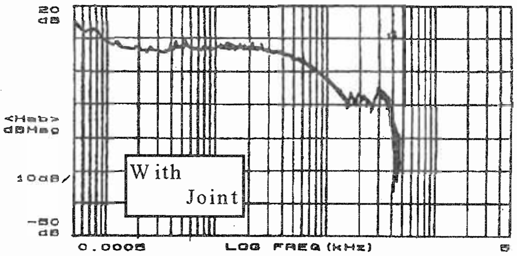

Fig.10. Open-loop Transfer Function of Magnetic Suspension Control(θ) with Joint

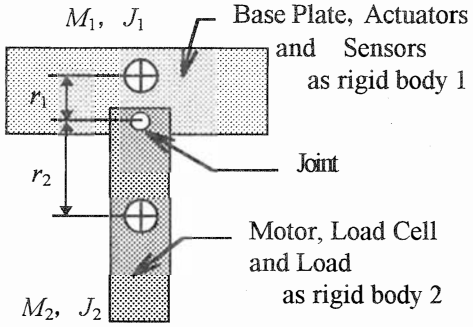

Fig.11. Simplified Slider Model

Table 3. Parameters for the Calculation

Parameters	Case 1 Without Joint	Case 2 With Joint
Inertia J_1 [kgm^2]	4x10^{-3}	
Inertia J_2 [kgm^2]	1x10^{-2}	
Mass M_1 [kg]	1.5	
Mass M_2 [kg]	5.0	
Length r_1 [mm]	50	55
Length r_2 [mm]	40	130

The calculated transfer functions of Case 1 and Case 2 are shown in Fig.12 and 13, respectively. Fig.12 is similar to Fig.9 in respect of the unstable resonance while there is no unstable resonance in Fig.13. From these results we obtained that the joint is necessary for suppressing unstable resonance at 200Hz. It would seem that the joint insertion shifted the eigen frequency of the slider into the actively controllable frequency region.

5. Experimental Results

We conducted individual slider tests and 1-module antenna deployment tests using 6 magnetically suspended sliders and deployable antenna test facility for 1-module antenna.

5.1 Individual Slider Tests

We conducted individual slider tests and verified that each slider was suspended stably with sufficiently small drag and that all safeguards performed satisfactorily.Fig.14 and 15 illustrate experimental open-loop transfer functions of the magnetic suspension control and the cable tension control, respectively. Fig.16 illustrates an example of the safeguards. Table 4 shows the control performance of the slider.

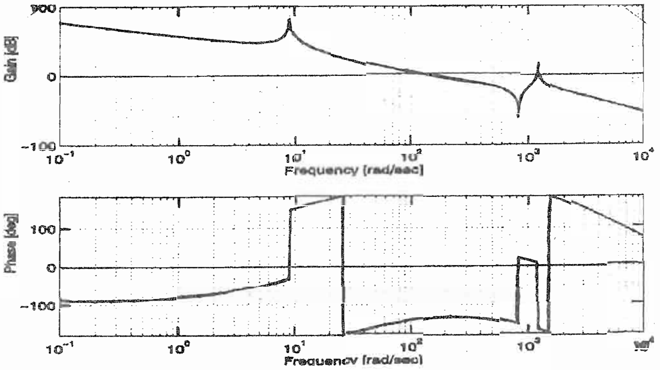

Fig.12. Calculated Transfer Function (Case 1)

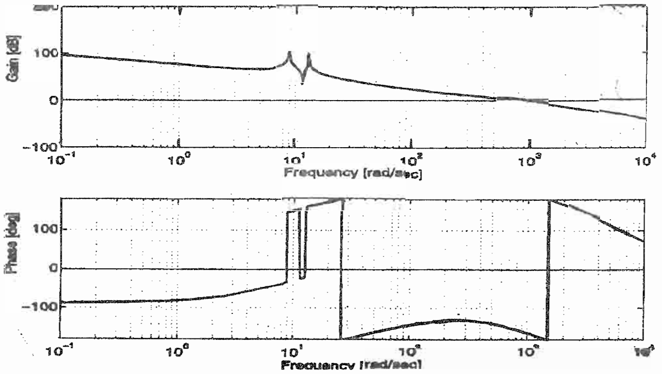

Fig.13. Calculated Transfer Function(Case 2)

Table 4. Control Performance

Items	Performance
Control Bandwidth	70 Hz : Magnetic Suspension 1 Hz : Cable Tension
Horizontal Drag	0.5 N
Cable Tension Control Precision	0.5 N
Weight	3.5 kg
Power Consumption	45 W

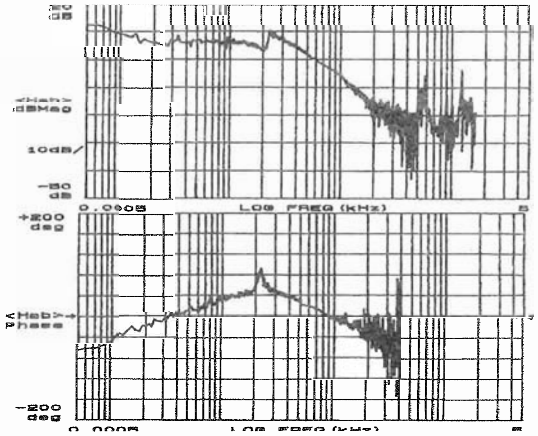

Fig.14. Open-loop Transfer Function of the Magnetic Suspension Control (ϕ)

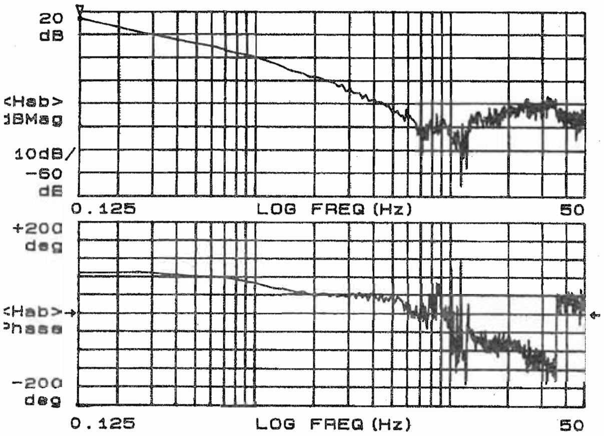

Fig.15. Open-loop Transfer Function of Cable Tension Control

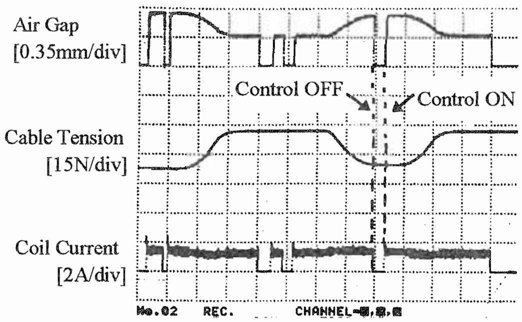

Fig.16. Air Gap Adjustment According to Load

5.2 1-Module Antenna Deployment Tests

The magnetic suspension controls, the cable tension controls of 6 sliders and the serial communications performed regularly. We implemented the deployment test of 1-module antenna which is 2m in diameter and verified that the antenna was deployed without being disturbed its deployment motion. Fig.17 and 18 illustrate the magnetically suspended slider and the deployable antenna test facility, respectively.

6. Conclusion

The deployable antenna requires the test facility to support the weight without disturbing its deployment motion. In order to accomplish this requirement, we developed the magnetically suspended sliders and applied them to the original deployable antenna test facility. The magnetic suspension and the cable tension of the slider were controlled stably and their performance was satisfactory. Moreover the safeguards by software improved reliability of the magnetic suspension control. As a results of these experiments, we obtained that the original deployable antenna test facility using the magnetically suspended sliders was practical to evaluate the in-orbit motion of the deployable antenna precisely.

[References]

[1] Toda, Y, et al., “Disturbance on 2-Dimensional Zero-Gravity Simulator,” Proceedings of the 37th Space Sciences and Technology Conference (Japan), Oct. 27-29, 1993, pp. 89-90.

[2] Akashi, A., et al. “Development of 6m ϕ Deployable Mesh Reflector,” Proceedings of the 37th Space Sciences and Technology Conference(Japan), Oct. 27-29, 1993, pp.461-462.

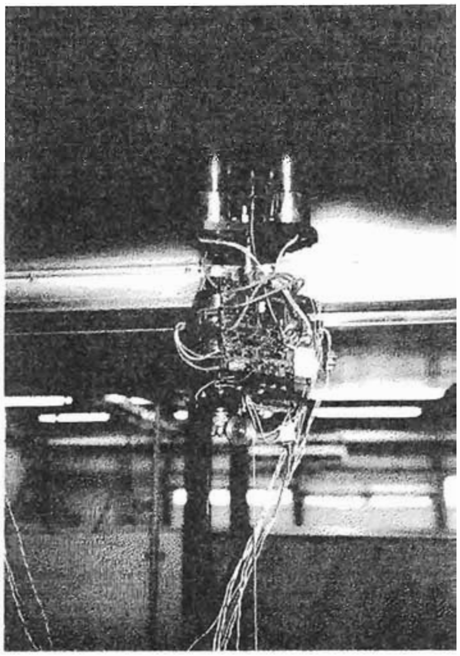

Fig.17. Magnetically Suspended Slider

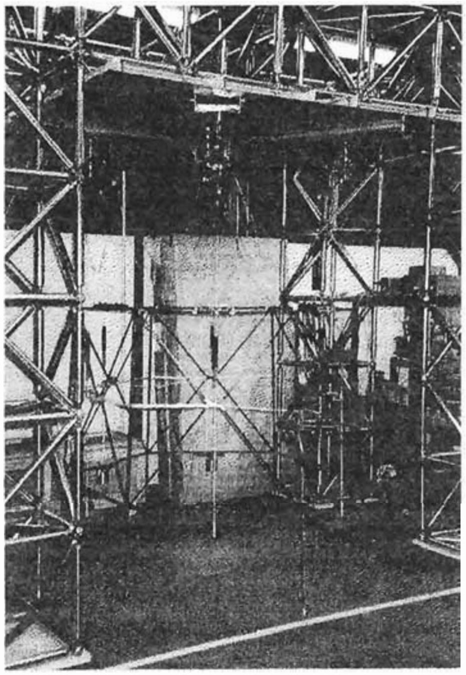

Fig.18. Deployable Antenna Test Facility