Development of a Magnetically-Suspended Antenna Pointing Mechanism—System Recovery in Case of Electromagnet/Sensor Damage in a Redundant System

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ABSTRACT

The authors refer to a magnetically–suspended, tetrahedron–shaped antenna pointing system as a " T–MAPS." A digital controller with a digital signal processor (DSP controller) was developed to improve the T–MAPS mechanism reliability. A DSP controller is considered to be absolutely essential for system recovery in case of an electromagnet/ sensor damage in a redundant system. This paper presents the magnetic suspension control structure, damage identification algorithm, decoupling compensation, and functional test results for the DSP controller. According to these results, the T–MAPS has adaptability to mechanism parameter change, and always maintains good dynamic behavior conditions.

1. INTRODUCTION

Satellite broadcasting with aims for regional services, such as high definition television is planned for the future in Japan. An offset Cassegrain antenna, constructed with a main–reflector, a sub–reflector, and feed horns, will be loaded in the satellite antenna system. The transmitted and received electric waves will be correctly directed to Japan in appropriate conformity by driving the sub–reflector adequately to counteract any satellite perturbation movement. At present, the allowed pointing error for the antenna system is within 0.01 degrees.

Generally, a magnetically suspended antenna pointing system (MAPS) has such advantages as simple structure, high pointing accuracy, jitter isolation, and mechanism reliability [1]. MAPS is clearly superior to other mechanical APSs, since it is able to drive the armature contactlessly in 6 degrees of freedom. The authors have already announced a tetrahedron–shaped MAPS (T–MAPS) [2]. The pointing accuracy of the T–MAPS has been confirmed to be 0.002 degrees based on

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results of tracking tests with a laser beam instead of an RF beacon using an analog controller. Furthermore, the authors have developed a digital controller with a digital signal processor (DSP controller) to improve the function of the T–MAPS mechanism [3]. The DSP controller is considered to be absolutely essential for system recovery in case of an electromagnet/sensor damage. A previous paper [3] which reported on the T–MAPS mechanism emphasizes system reliability with redundancy. It is true that the pointing function can be maintained even if some of the electromagnets/sensors are damaged. This paper presents the magnetic suspension control structure, damage identification, decoupling compensation, and functional test results for the DSP controller.

2. DESIGN CONCEPT

Figure 1 is a photograph in which an experimental sub–reflector is mounted on the mechanism. The T–MAPS mechanism consists of a hollow tetrahedral armature, 9 electromagnets, 9 eddy current type displacement sensors, several support members, and a base. The sub–reflector is fixed to a support shaft on the armature. Nine electromagnet/sensor units are placed so that 3 units are against the bottom face of the armature, and 6 units are arranged around 3 side faces of the armature. The clearance gap between the individual unit and the armature corresponds to the pointing range. The pointing range was decided to be ± 1.5 degrees, taking into account satellite movements and misalignment between these antennas and the satellite body. The high precision pointing of the armature in 6 degrees of freedom results from 3 translational and 3 rotational motions controlled by the 9 electromagnets.

Though an electromagnet generates only a pull force in one direction, a sensor is available in both plus and minus directions. Therefore, essentially only 6 sensors are required. Even in case of damage to any three of the sensors, the T–MAPS maintains normal operation by changing the control parameters. However, the maximum number of dispensable sensors should be held to 2, since the identification process restricts the number of sensors. Similarly, the minimum number of electromagnets which assures 6 degrees of freedom positioning is considered to be 7. Therefore, the T–MAPS mechanism has redundancy for its electromagnets. It is very effective for system performance to use the redundant units not only in case of damage but also in normal operation.

The final position value for the step input does not depend on the redundant electromagnets. This is the reason why the pointing function is reliable. However, apart from pointing which is the most essential function in the system, the decoupling function, for example, which enhances the pointing dynamics, is lost. On the other hand, the redundant sensor signals are effectively used even in normal conditions. For this reason, it is necessary to redefine the above–mentioned control parameters in order to recover the pointing function after a redundant sensor damage.

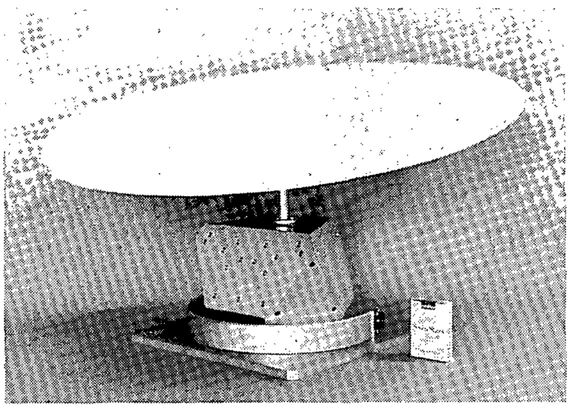

Figure 1 T–MAPS MECHANISM

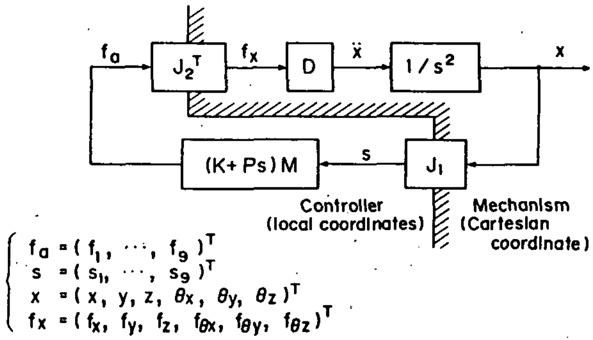

Figure 2 BLOCK DIAGRAM OF MAGNETIC SUSPENSION CONTROL SYSTEM

The most important feature in magnetic suspension, contactlessness, allows easily removing a damaged unit out of the busy area and making the remainder to start working to the best of the in ability. The DSP controller is expected to provide the system with adaptability to time dependent or unexpected changes in the system parameters, so as to always realize approximately the best pointing conditions as well as the best dynamic behavior.

3. CONTROL SYSTEM
3.1. MAGNETIC SUSPENSION CONTROL

The closed control loop for the T–MAPS mechanism consists of a suspension control loop and a pointing control loop. The former loop stabilizes the armature in the local coordinate system. The latter has a precision pointing capability in the Cartesian coordinate system, and is controlled by the RF beacon (pointing signal) from the earth station. The suspension control loop is shown in Fig.2.

Six independent armature position coordinates in a Cartesian coordinate are described by the vector X $(x, y, z, \theta x, \theta y, \theta z)$, and the displacement vectors at the sensor positions are described by S (s1,...,s9). The relationship between X and S is as follows:

$$S = J1 \cdot X \tag{1}$$

where J1 is the transformation matrix. Similarly, the force vectors perpendicular to the armature plane, which a magnetic force operates on, are described by A (a1,...,a9). The relational equation between X and A is shown as:

$$A = J2 \cdot X \tag{2}$$

where J2 is the transformation matrix. Linear approximations are applied to J1 and J2 around the center of the pointing ranges. These transformation matrices are geometrically obtained from the armature dimensions, number of electromagnets/sensors, and the magnetic force vector directions. The linear equation of motion in a suspension control system is described using Eqs. (1) and (2), as follows:

$$
\begin{aligned}
s^2 \cdot X &= -D \cdot J2^T \cdot C \cdot J1 \cdot X \\
&= -W \cdot X
\end{aligned} \tag{3}
$$

where W is the dynamic characteristic matrix of the stabilized control loop, s is a Laplacian operator, D is the inverse matrix of the inertia matrix (inertance matrix), $J2^T$ denotes the transposed matrix for J2, and C is the control matrix. Each electromagnet is independently controlled in this servo control system by an individual compensator in the local coordinate system. Therefore, the control matrix, C, is written as:

$$
\begin{aligned}
C &= (k+ps) \cdot E \\
&= K+Ps
\end{aligned} \tag{4}
$$

where k is the proportional gain, p is the derivational gain, and E is a 9*9 unit matrix. Eliminating X using Eqs. (1) and (2), the transformation matrix, M, which transforms the sensor position displacements, S, into displacements of the force operating point, A, will be obtained. Therefore, using the method of least squares, the matrix ,M, is finally obtained as follows:

$$
\begin{aligned}
A &= M \cdot S \\
&= J2 \cdot J1^{-1} \\
&= J2 \cdot (J1^T \cdot J1)^{-1} \cdot J1^T
\end{aligned} \tag{5}
$$

where $(J1^T \cdot J1)^{-1}$ represents the inverse matrix for $(J1^T \cdot J1)$. The matrix, M, is necessary when the sensors are not collocated with electromagnets. Applying Eqs. (4) and (5), the matrix, W, becomes

$$
W = (K+Ps) \cdot D \cdot J2^T \cdot M \cdot J1 \tag{6}
$$

Equation (6) gives the closed loop characteristics.

3.2. DAMAGE IDENTIFICATION

An electromagnet damage can be caused by coil breakdown due to over–current or a wire disconnection. It is possible to avoid electromagnet damage due to over–current by monitoring the current value from the power amplifier. Moreover, a sensor damage can be caused by a wire disconnection or by damage in the sensor converter due to over–heat. When the sensor is broken, the sensor output voltage is either set at −12 V or +12 V which correspond to the source voltages, or becomes fixed at somewhere between −2 V and +2 V which correspond to normal output voltages. If the output voltage is fixed between −2 V and +2 V, it is not possible to find out the broken sensor, even through monitoring the output voltages. Therefore, it is necessary to logically identify the damaged sensors. A method to identify a damaged sensor in a redundant system has been reported [4]. The identification process is explained as follows. First, we select 6 sensors among 9 sensors in the T–MAPS mechanism. Second, the sensor signal from the residual 3 sensors using 6 selected sensor signals are calculated.

TABLE I IDENTIFICATION PROCESS
(In case of sensor number ④ and ⑦ are damaged)

Selected Sensor Number	Calculated Sensor Number i	Judge $\lvert di-Si \rvert \leqq \varepsilon$	Residual Sensor Number m n
④5 6⑦8 9	1	×	2 3
1 5 6⑦8 9	2	×	3 ④
1 2 6⑦8 9	3	×	④ 5
1 2 3⑦8 9	④	×	5 6
〃	〃		〃
1④5⑦8 9	2	×	3 6
1 2 5 6 8 9	3	○	④ ⑦
1 2 3 6⑦9	④	×	5 8
〃	〃		〃
1 2 3 5 6⑦	8	×	9 ④
2 3④6⑦8	9	×	1 5

If the calculated sensor signal differs from an actual sensor signal, it is indicated that the damaged sensor is included among the 6 selected sensors and the actual sensor in the system. Similarly, 36 kinds of comparison calculations are executed in total. Here, there is only one combination that makes a complete agreement between the calculated sensor signal and the actual sensor signal in case of two sensor damages, for example, as shown in Table I. It turns out in the combination that the residual 2 sensors which are not involved in the calculation are damaged. A basic identification equation which allows a systematic design of a redundant system has been formulated below.

Equation (1) can be used to form the matrix equality.

$$S=J1\cdot X$$

$$=\begin{bmatrix} \cdots & j1 & \cdots \\ & \vdots & \\ \cdots & j9 & \cdots \end{bmatrix}\cdot X \qquad (1)'$$

Each sensor displacement, Si, described by each column vector, ji, of the matrix, J1, is written by:

$$Si=ji\cdot X \qquad i=1,2,\ldots,9 \qquad (7)$$

where i denotes the sensor number calculated by the identification. Using the 6*6 square matrix, P, which is newly built neglecting column vectors, ji, jm and jn from the matrix, J1, the relationship between X and q is described as follows:

$$q=P\cdot X \qquad (8)$$

where q is a 6*1 row vector, and m and n are the residual sensor numbers. This Eq. (8) is used to transform the armature position vectors into the 6 sensor position displacements. Eliminating X using

Eqs. (7) and (8), the relationship between q and Si will be obtained:

$$Si = ji \cdot P^{-1} \cdot q$$
$$= Di \cdot q \quad (9)$$

where Di is an identification vector. Furthermore, the 1*9 column vector, Di, is newly built placing zero on the i–th, m–th, and n–th elements. Therefore, the state transition matrix, WSi, can be written using Di:

$$WSi = D \cdot S \quad (10)$$

where D is an identification matrix of order 36*9, WSi is a row vector of order 36*1. The DSP controller can calculate the damage sensors from the 9 sensor signals using the identification matrix, D, in real time. This identification method judges damaged sensors from the following criteria:

$$|di - Si| <= \varepsilon \quad (11)$$

where di is an actual sensor signal and ε is an allowable limit level for judgment. If di and Si satisfy Eq. (11), the sensor is judged as carrying out normal operation. The new control parameters which were built neglecting the damaged sensors according to this Eq. (11) are applied to the system. In concrete, the control parameters indicate the proportional gain, K, the derivational gain, P, and bias current value for linearization.

3.3. DECOUPLING COMPENSATION

The decoupling concept is a way for protecting against disturbances from the satellite to assure high pointing accuracy. If it is established in a system, stability analysis of the whole system can be simplified. Decoupling compensation is the diagonalization of the dynamic characteristic matrix, W, described in Eq. (3). Therefore, the matrix, M, which is newly built adopting a matrix, C_D, for decoupling compensation is described as follows:

$$M = C_D \cdot J2 \cdot (J1^T \cdot J1)^{-1} \cdot J1^T \quad (12)$$

and C_D is given by:

$$C_D = J2 \cdot (J2^T \cdot J2)^{-1} \cdot D^{-1} \cdot Wpf\ (J2^T \cdot J2)^{-1} \cdot J2^T \quad (13)$$

where Wpf is a 6*6 diagonal matrix for a required suspension response in the Cartesian coordinate system.

4. DSP CONTROLLER

The DSP controller structure is shown in Fig.3. The structure mainly consists of 2 DSPs, a host computer, 12 bit A/D converters, 12 bit D/A converters, and sensor converters. DSP1 is driven by an

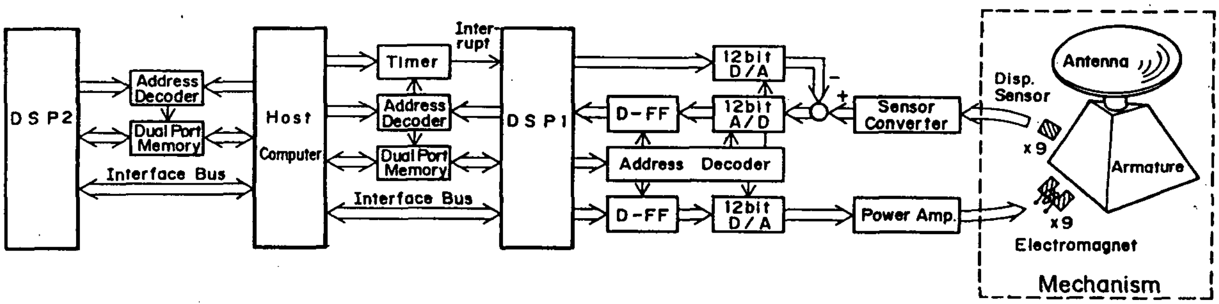

Figure 3 STRUCTURE OF DSP CONTROLLER

interrupt signal from an external timer. Nine sensor signals which are converted to digital signals by the 12 bit A/D converters are input to DSP1, which calculates the control signals from the sensor signals to stably suspend the armature. The control signals are converted to analog signals by the 12 bit D/A converters, which are input to the power amplifier. Then, the control current is supplied to the electromagnets in the mechanism. The control parameters are set by the host computer, such as the sampling period. The host computer obtains up–to–date sensor signals from DSP1 through the dual port memory. Using the sensor signals that are fed from the host computer, DSP2 judges the damaged sensors in accordance with the identification process described already, and its results are transmitted to the host computer. The host computer redefines the control parameters according to the judgment of DSP2. Therefore, the controller has sufficient adaptability to mechanism parameter change such as electromagnet breakdown. The block diagram of the suspension control system is shown in Fig.4 including the damage identification function. The run time for 1 cycle of the suspension control loop becomes about 210 micro–seconds. This cycle time is sufficient to control a 9 axis magnetic suspension.

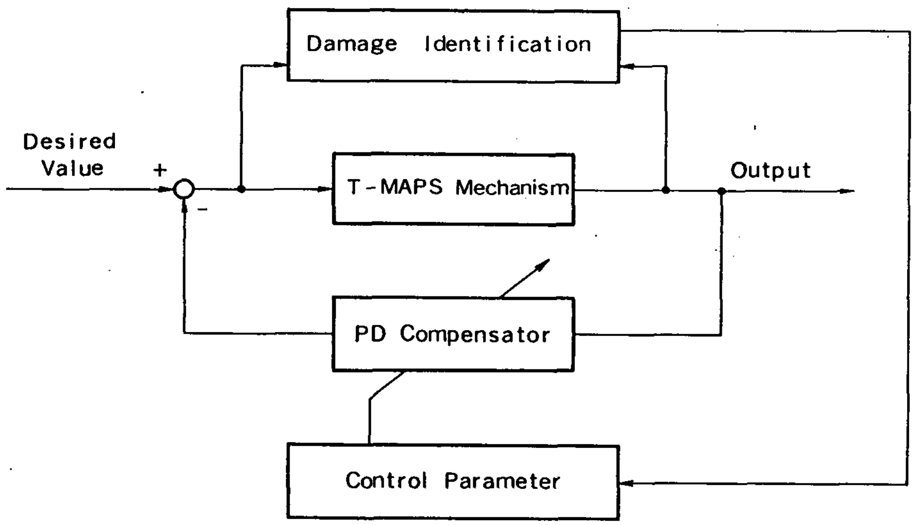

Figure 4 BLOCK DIAGRAM OF T–MAPS CONTROL SYSTEM

5. EXPERIMENTAL RESULTS

An optical system using a laser beam was constructed to confirm the T–MAPS pointing accuracy. Since the authors already reported about the optical system in a previous paper [2], a detailed explanation will not be made in this paper. In the laser tracking system, a circle is drawn on the tracking sensor by a laser beam in accordance with the satellite rotational movement when the tracking servo is not working. The rotation frequency is about 0.1 Hz, and the amplitude is 0.1 degrees for the attitude control error of satellite stabilization. The pointing accuracy was confirmed using an optical test system to become as precise as 0.0024 degrees at the moment of tracking start, as shown in Fig.5. Similarly, Fig.6 shows the tracking test result in case of two electromagnet damages. According to this figure, the result indicates that the pointing function can be maintained even if two electromagnets are damaged. At this time, the pointing accuracy was confirmed to be 0.0036 degrees. The reason why the pointing accuracy becomes lower is that the magnetic levitational characteristics of the T–MAPS suffer a decline because of asymmetricity. Figure 7 shows the step response in case of normal operation and electromagnet damage. In case of an electromagnet damage, for instance, the settling time takes about 4 times longer than in normal operation. Here, as the DSP controller can find out which is the damaged electromagnet using the identification function, it is possible to recover dynamic operation with a control parameter change, as shown in Fig.8. It is desirous to set the controller to realize a resonance frequency of 12.5 Hz and a damping ratio of 0.3 for the impulse response. At this time, the proportional gain, k, and the derivational gain, p, of the control parameters are shown in each figure, and also the measured values of the resonance frequency and the damping ratio in the same figure. The bias current value is determined from the equilibrium condition without damaged electromagnets. The results exhibit that good dynamic characteristics for the T–MAPS are maintained even in case the redundant electromagnets are damaged. The DSP controller up–dates the control parameters at each sampling period, and so it can closely

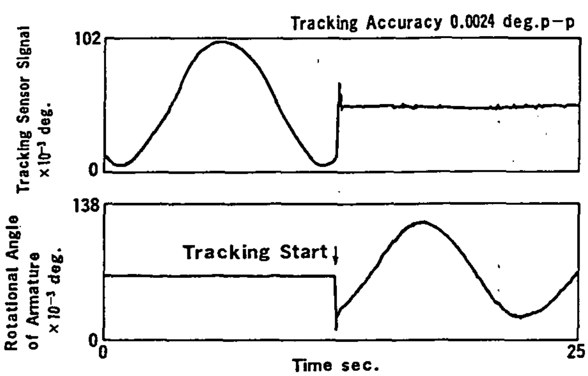

Figure 5 TRACKING RESPONSE

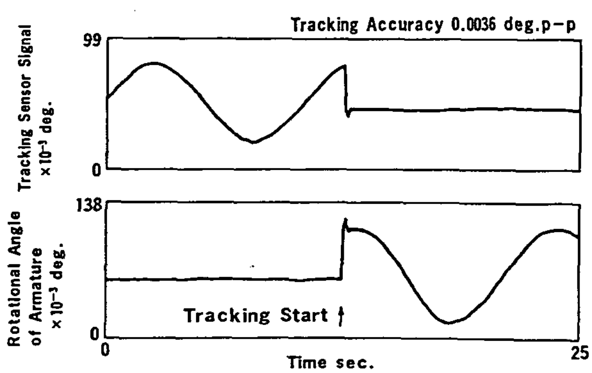

Figure 6 TRACKING RESPONSE IN CASE OF DAMAGED ELECTROMAGNET NUMBER (4)AND(7)

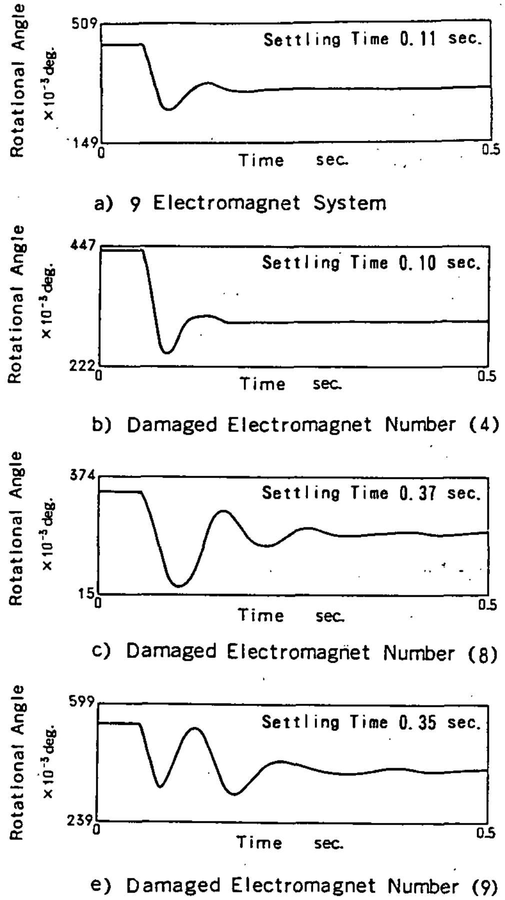

Figure 7 STEP RESPONSE IN θx–AXIS

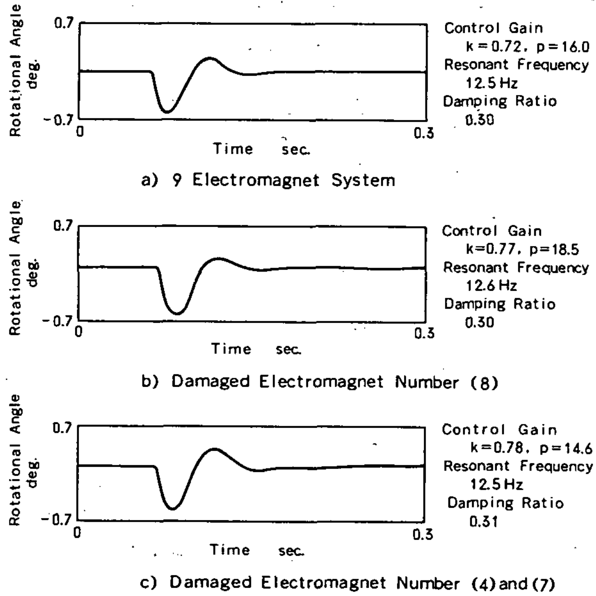

Figure 8 IMPULSE RESPONSE IN θx–AXIS

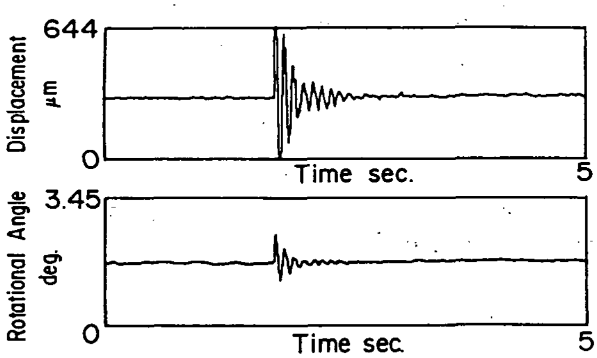

Figure 9
IMPULSE RESPONSE OF CONTROL SYSTEM WITHOUT DECOUPLING COMPENSATOR
(UPPER:x–AXIS INPUT
LOWER:θy–AXIS OUTPUT)

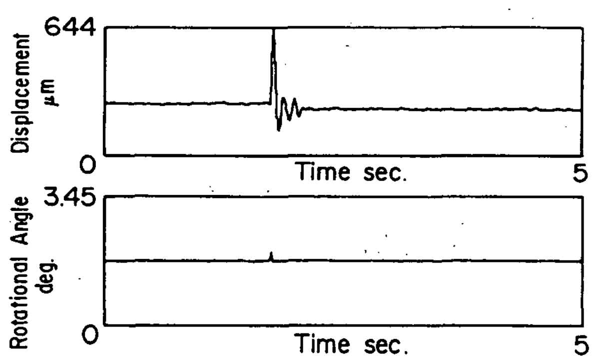

Figure 10
IMPULSE RESPONSE OF CONTROL SYSTEM WITH DECOUPLING COMPENSATOR
(UPPER:x–AXIS INPUT
LOWER:θy–AXIS OUTPUT)

follow up any change in the mechanism parameters. These functional tests were performed in the authors' laboratory.

Figure 9 shows the impulse response indicating the coupling characteristics of a control system without a decoupling compensator. The upper plot is the armature motion when an impulse signal is input in the x–axis, and the lower plot is the coupling response in the θy–axis. Similarly, Fig.10 shows the impulse response with a decoupling compensator. According to these results, the desired effect was obtained in the T–MAPS by adding the decoupling compensation process in the coupling system. Similar results were obtained for the other axes.

6. CONCLUSIONS

The authors have developed a redundant antenna pointing system using a DSP controller to enhance the function of the T–MAPS mechanism. The DSP controller provides the following features.

(1) The DSP controller has sufficient ability to achieve a 9 axis magnetic suspension control. Moreover, the DSP controller updates the control parameters at each sampling period, so it can closely follow up any change in the system parameters.

(2) Using the damage identification function, it is expected that the best dynamic characteristics for the T–MAPS are maintained even in case of damage among redundant electromagnets/sensors.

(3) Decoupling of the 6 degrees of freedom motion in the Cartesian coordinate system can be realized by an easy parameter design, in spite of the strong coupling in the local coordinates.

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