2nd International Symposium on Magnetic Beaing
July 12-14, 1990, Tokyo, Japan

Development of Magnetically-Suspended, Tetrahedron-Shaped Antenna Pointing System

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Abstract

A magnetically-suspended,tetrahedron-shaped antenna pointing system with digital control is proposed for use in a multibeam broadcasting satellite system in the near future. Already, the authors reported a paper emphasizing the advantages of a magnetically-suspended antenna pointing mechanism with the tetrahedral armature using analog controller. According to that paper, it was confirmed to have a 0.002 degree pointing accuracy by tracking tests with a laser beam in the laboratory. However, it remains to be made the most of the features inherent to magnetic suspension, particularly in space, far from human maintenance. Accordingly, we designed the digital controller for magnetic suspension to enhance its function. This paper presents the conception of this system and explains its mechanism, magnetic suspension control system and digital controller with digital signal processor.

1.Introduction

Satellite broadcasting, with aims at regional services such as high definition television, is planned for the future in Japan.[1] An offset Cassegrain antenna constructed with a main reflector, a sub reflector and feed horns will be loaded in the satellite antenna system shown in Fig.1. Since the main reflector is fixed to the satellite body, directly driving its large reflector is almost impossible. Therefore, the small sized sub reflector should be effectively driven by such an antenna pointing mechanism (APM). According to the plan, aperture diameters for the main and sub reflectors are about 3 meters and 0.7 meters. By driving the sub reflector adequately against the satellite perturbation movement, the transmitted and received electric waves should be correctly directed to Japan in conformity. At this time, the allowed pointing error for the antenna system is within 0.01 degree.

In the conventional APMs, the lubricated ball bearings or the flexible pivot is used. On the other hand, the APM using magnetic suspensions has such advantages as simple structure, high pointing accuracy, jitter isolation and mechanism reliability[2,3]. Further, it's possible to change the rotational center by adjusting misalignments between the satellite body and the antenna. Here, the magnetically-suspended, tetrahedron-shaped antenna pointing system (T-MAPS) with digital control is proposed. The important feature of the T-MAPS is to use a tetrahedral armature. The T-MAPS, since it's able to drive the armature contactlessly in 6 degrees of freedom, is clearly superior to other mechanical APMs. Pointing accuracy of the T-MAPS is already confirmed to be 0.002 degree by tracking tests with a laser beam instead of the RF beacon using analog controller[4].

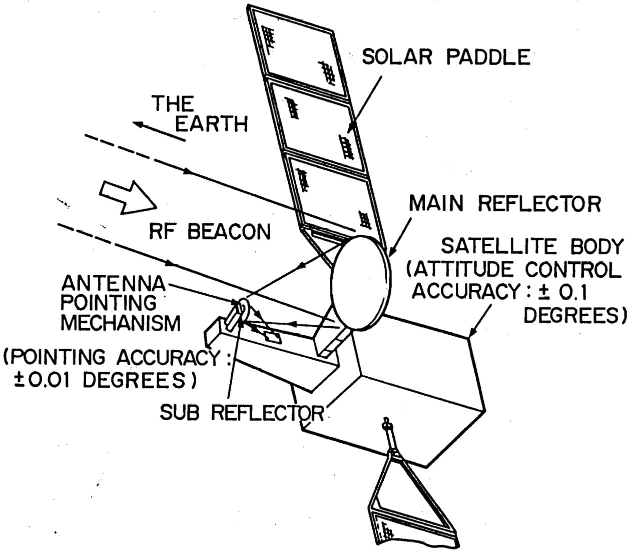


Figure 1 Broadcasting Satellite Antenna System

2.Mechanism Description

Fig.2 shows its photograph, in which the assumptive sub reflector is fixed to the mechanism, and Fig.3 shows its photograph which took out a tetrahedral armature from the mechanism. The T-MAPS consists of a tetrahedral armature made of ferromagnetic material, 9 electromagnets, 9 eddy current type displacement sensors, several support members and a base. The sub reflector is fixed to a support shaft of the armature. 9 electromagnet and displacement sensor units (actuator units) are placed 3 units against bottom face of armature and 6 units against 3 side faces of armature. The clearance gap between individual actuator unit and the armature corresponds to the pointing range for the T-MAPS. The pointing ranges decided on ±1.5 degrees taking account of satellite movements and misalignment between these antennas and the satellite body. The high precision pointing of 6 degrees of freedom of the armature, that is 3 translations and 3 rotations are controlled by the 9 actuator units. The actuator unit is il-

Table 1 **DESIGN PARAMETERS**

DEGREE OF FREEDOM : 6
PAYLOAD MOMENT OF INERTIA : 0.7 kg m^2
POINTING RANGE TRANSLATION : ±2 mm
ROTATION : ±1.5 deg.
NUMBER OF ELECTROMAGNETS : 9
NUMBER OF DISP. SENSORS : 9
TOTAL WEIGHT : 8 kg

<ARMATURE>
SHAPE : HOLLOW TETRAHEDRON (EDGE LENGTH:180 mm)
MATERIAL : SILICON STEEL
WEIGHT : 2.1 kg
MOMENT OF INERTIA : 4×10^{-3} kg m^2

<ELECTROMAGNET>
SHAPE : HORSESHOE SHAPE
YOKE MATERIAL : SILICON STEEL
COIL MATERIAL : COPPER WIRE
WIRE DIAMETER : 1.2 mm
TURNING NUMBER : 190 TURNS
MAGNETIC POLE AREA : 773 mm^2
MAGNETIC CORE AREA : 437 mm^2

<DISP. SENSOR>
TYPE : EDDY CURRENT SENSOR
MEASURING RANGE : 0～4 mm
FREQUENCY RESPONSE : 0～20 kHz(-3dB)
RESOLUTION : 0.01%(FS)
OUTPUT VOLTAGE : 0～5 V

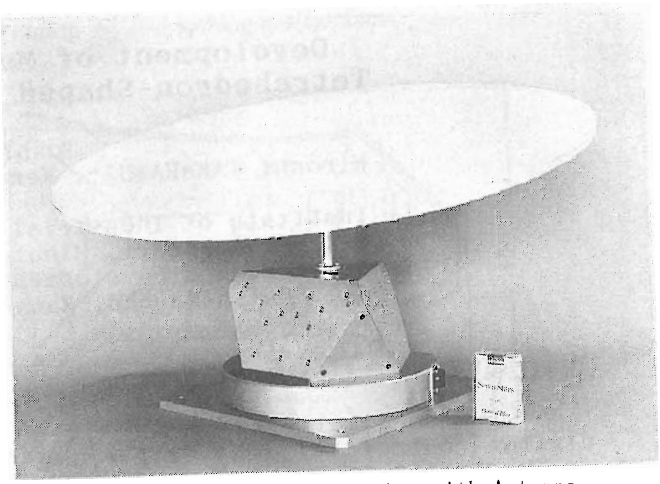


Figure 2 T-MAPS Mechanism with Antenna

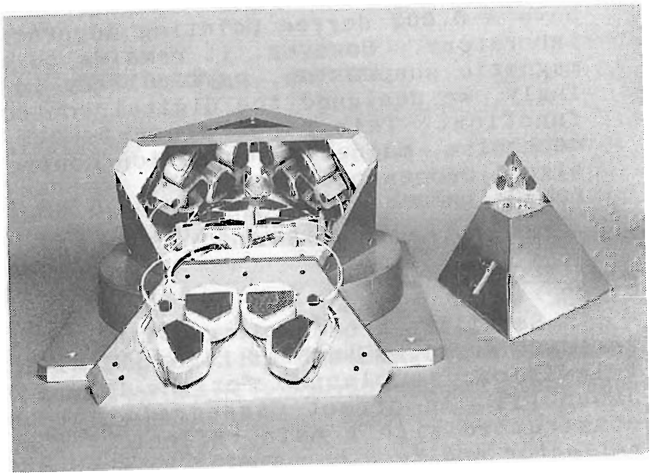


Figure 3 Inside of the Mechanism and Armature.

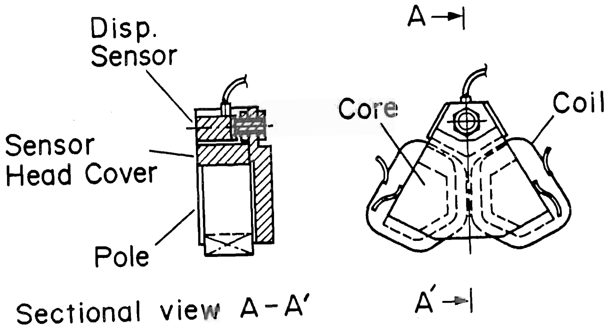


Figure 4 Actuator Unit
(electromagnet/displacement sensor unit)

lustrated in Fig.4. This unit is easy to design and to manufacture for the reason of the same shape and dimension of all units. The design parameters for the T-MAPS are shown in Table 1. These units of this time are designed all the same as the previous[4].

3.Magnetic Suspension Control System

The control closed loop for a magnetically-suspended antenna pointing mechanism consists of the suspension loop and the pointing loop. The former loop stabilizes the armature in the local coordinate system. The latter has a precision pointing capability in a Cartesian coordinate system, and is controlled by the RF beacon (pointing signal) from the earth station. The magnetic suspension control loop is shown in Fig.5. In this servo control system, each actuator unit is independently controlled by an individual compensator in the local coordinate system. The displacement between the armature and the displacement sensor is detected by each displacement sensor. Then these signals are fedback to compensators. In this control block diagram, there are two transformation matrices. One is a command transformation matrix, Max. This matrix transforms commands in a Cartesian coordinates into local ones in the local electromagnet coordinates. The other is a position transformation matrix, Mas. This matrix transforms displacement signals of displacement sensors in the local sensor coordinates into displacement signals in the local electromagnet coordinates. These transformation matrices, are shown below as an example.

$$
\mathrm{Max}=\begin{bmatrix}
0.000 & 0.000 & 1.000 & 0.629 & -0.002 & 0.000 \\
0.000 & 0.000 & 1.000 & -0.311 & 0.541 & 0.000 \\
0.000 & 0.000 & 1.000 & -0.311 & -0.545 & 0.000 \\
0.000 & 0.943 & -0.333 & 2.177 & -0.180 & -0.511 \\
0.000 & 0.943 & -0.333 & 2.177 & 0.182 & 0.513 \\
-0.816 & -0.471 & -0.333 & -0.932 & 1.976 & -0.511 \\
-0.816 & -0.471 & -0.333 & -1.246 & 1.795 & 0.513 \\
0.816 & -0.471 & -0.333 & -1.246 & -1.795 & -0.511 \\
0.816 & -0.471 & -0.333 & -0.932 & -1.976 & 0.513
\end{bmatrix}
$$

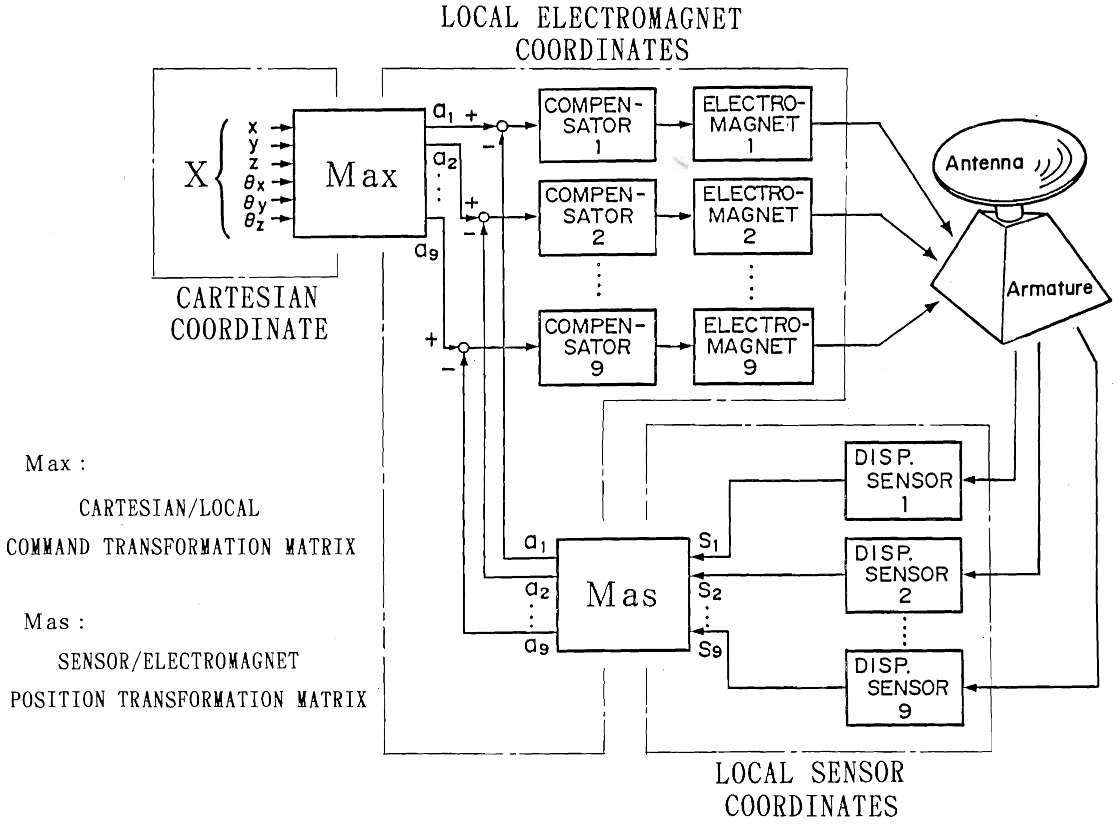


Figure 5 Control Block Diagram for Magnetic Suspension System

$$\mathrm{Mas}=\begin{bmatrix} 0.567 & 0.126 & 0.126 & -0.091 & -0.091 & -0.018 & -0.164 & -0.164 & -0.017 \\ 0.126 & 0.566 & 0.126 & -0.164 & -0.018 & -0.091 & -0.091 & -0.018 & -0.164 \\ 0.126 & 0.126 & 0.566 & -0.018 & -0.164 & -0.164 & -0.018 & -0.091 & -0.091 \\ -0.230 & -0.095 & 0.052 & 0.474 & 0.253 & -0.098 & -0.175 & -0.028 & -0.244 \\ -0.230 & 0.052 & -0.095 & 0.254 & 0.474 & -0.245 & -0.028 & -0.175 & -0.098 \\ 0.052 & -0.230 & -0.095 & -0.028 & -0.244 & 0.474 & 0.254 & -0.098 & -0.175 \\ -0.095 & -0.230 & 0.052 & -0.157 & -0.098 & 0.254 & 0.474 & -0.245 & -0.028 \\ -0.095 & 0.052 & -0.230 & -0.098 & -0.175 & -0.028 & -0.245 & 0.474 & 0.254 \\ 0.052 & -0.095 & -0.230 & -0.244 & -0.280 & -0.175 & -0.097 & 0.254 & 0.474 \end{bmatrix}$$

Though an electromagnet generates only a pull force in one direction, a displacement sensor is available in both plus and minus directions. Therefore, essentially only 6 displacement sensors are required. Even in case of damage of any three of the displacement sensors, the T-MAPS maintains normal operation by changing the position transformation matrix, Mas. Similarly, the minimum number of electromagnets, which assures 6 degrees of freedom positioning, is considered to be 7. Therefore, the T-MAPS has redundancy of the electromagnets. It is so effective for the system performance to use the redundant units not only in case of damage but in case of normality. Damage of electromagnet is caused by breakdown of coil due to over current, or wire cut. It is possible to avoid the damage of electromagnet due to over current, by monitoring the current value of the power amplifier. Moreover, displacement sensor damages are caused by wire cut, or by damages of sensor converter due to over heat. When the displacement sensor is broken, sensor output voltage is set -12V or +12V that correspond to the source voltages, or is fixed -2V to +2V that correspond to the normal output voltages. If output voltage is fixed -2V to +2V, it is difficult to find out the broken displacement sensor, even though by monitoring output voltages. Therefore, it's necessary to logically identify the damaged displacement sensors. A method to identify a damaged sensor in a redundant system is reported[5].

4.Digital controller with DSP

4-1.Why digital controller ?

The paper[4] that reported about the T-MAPS laid emphasis to the reliability of the system because of the redundancy. It is true that the function of pointing is maintained even if some of the electromagnets broke down. In other words, the final value of the position for the step input does not depend on the redundant electromagnets. This is the reason why the pointing function is reliable. But, apart from the pointing that is the most essential function in the system, the decoupling function for example that enhance the pointing performance, is lost. On the other hand, on the redundant displacement sensors whose signals are effectively used even in normal condition, depends the pointing accuracy. For that reason, in order to recover the pointing accuracy after the redundant displacement sensor failure, it is necessary to redefine the above mentioned transformation matrix, Mas.

The most important of the features of magnetic suspension, the contactlessness allows to easily remove the injured out of busy area and to start working to the best of its ability. The digital controller is expected to provide the system the adaptability to the time dependent or unexpected change of the system parameters, always realizing nearly the best conditions of pointing as well as dynamic behavior. We developed a digital controller with DSP to improve the function of T-MAPS. The digital controller is considered to be absolutely essential for recovery of system in case of displacement sensor damages.

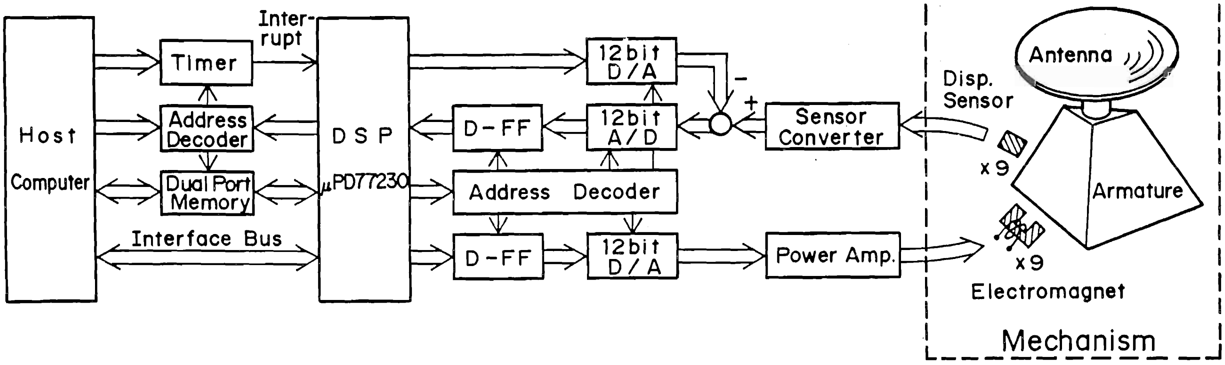


Figure 6 Structure of Digital Controller

4-2. Structure of the digital controller

The structure of the digital controller is shown in Fig.6, and Fig.7 shows its photograph. The structure mainly consists of 12 bit A/D converters, 12 bit D/A converters, sensor converters, DSP and a host computer. The DSP can execute floating point multiplication and adding for a instruction in 150 nsec. The DSP control flowchart is shown in Fig.8. The DSP is driven by the interrupt signal of the external timer. Nine displacement sensor signals which are converted to digital signals by the 12 bit A/D converter are inputted to the DSP, which out of the inputted signals, calculates the control signals to stably suspend the armature. The control signals are converted to the analog signals by the 12 bit D/A converter, which are inputted to the power amplifier and then the control current is supplied to the electromagnets. The displacement sensor signals are adjusted to zero value by means of adding the calculated values to the converted signals. The DSP performs to set the control parameters, such as a sampling period, a stiffness matrix Kc and a damping matrix Pc, and host computer gets the present sensor value from the DSP through the dual port memory. As the dual port memory access from both the DSP and the host computer is impossible at the same time, the data input/output must be performed according to the prescribed hand-shaking rules. The following two flags are provided. One is the host computer access flags. The other is the DSP access flags. These flags are fed through the interface bus in the Fig.6.

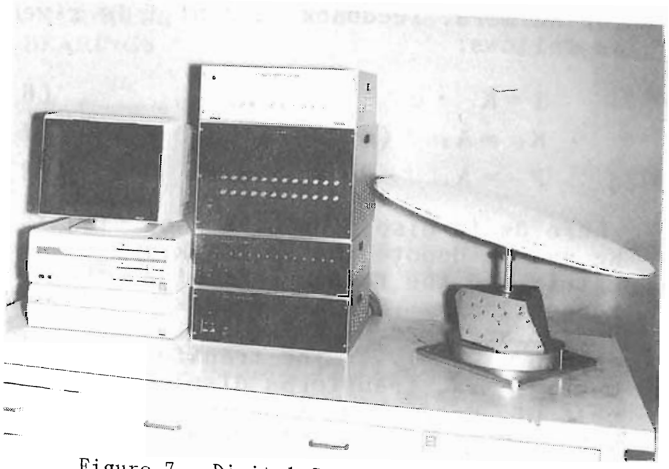
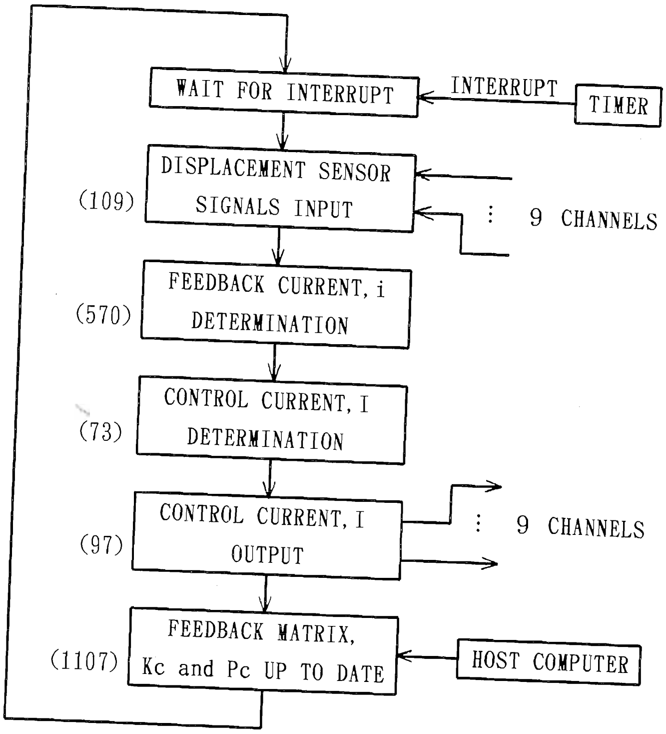


Figure 7 Digital Controller and T-MAPS



() number of instructions

Figure 8 Flowchart of the DSP Operation

4-3. Suspension control algorithm

The linear equation of motion in a suspension control system is described as follows:

$$m\ddot{x}=F_0+A_i\cdot i-A_d\cdot d \qquad (1)$$

where m is the armature mass, x is the armature displacement in a Cartesian coordinate, i is feedback current, d is the armature displacement in the local electromagnet coordinates, and the others are as follows:

$$F_0=Q\,(i_0{}^{\rho}/d_0{}^{\sigma}) \qquad (2)$$

$$A_i=\rho Q\,(i_0{}^{\rho-1}/d_0{}^{\sigma}) \qquad (3)$$

$$A_d=\sigma Q\,(i_0{}^{\rho}/d_0{}^{\sigma+1}) \qquad (4)$$

where Q, ρ and σ are coefficients obtained from the electromagnet characteristics, and the suffix "0" shows the bias value. Applying the linear approximation around the center of the pointing ranges, the eq.(1) becomes :

$$K\cdot M_{ax}{}^{-1}\cdot d+P\cdot M_{ax}{}^{-1}\cdot\dot{d}=A_i\cdot i-A_d\cdot d \qquad (5).$$

Furthermore, feedback current i is given as follows:

$$i = K_C \cdot d_s + P_C \cdot \dot{d}_s \qquad (6)$$

$$K_C = A_i^{-1} (K \cdot M_{sx}^{-1} + A_d) M_{as} \qquad (7)$$

$$P_C = A_i^{-1} \cdot P \cdot M_{sx}^{-1} \cdot M_{as} \qquad (8)$$

where ds is displacement sensor signals , Kc and Pc denote the feedback stiffness matrix and the feedback damping matrix, respectively. These feedback matrices,Kc and Pc are determined so as to support the armature stably. The transformation matrix, Msx, transforms displacement signals of displacement sensors in the local sensor coordinates into displacement signals in a Cartesian coordinate. This matrix has only constant elements as follows:.

$$Msx = \begin{bmatrix} 0.000 & 0.000 & 1.000 & 1.223 & -0.002 & 0.000 \\ 0.000 & 0.000 & 1.000 & -0.608 & 1.055 & 0.000 \\ 0.000 & 0.000 & 1.000 & -0.608 & -1.059 & 0.000 \\ 0.000 & 0.943 & -0.333 & 2.474 & -0.352 & -0.996 \\ 0.000 & 0.943 & -0.333 & 2.474 & 0.353 & 0.997 \\ -0.816 & -0.471 & -0.333 & -0.933 & 2.318 & -0.996 \\ -0.816 & -0.471 & -0.333 & -1.542 & 1.967 & 0.997 \\ 0.816 & -0.471 & -0.333 & -1.542 & -1.966 & -0.996 \\ 0.816 & -0.471 & -0.333 & -0.933 & -2.319 & 0.997 \end{bmatrix}$$

The run time of one cycle at this algorithm, becomes 293 micro-sec in 1956 instructions. In the eq.(2) to (4), these coefficients Q,ρ,σ are given by testing the electromagnetic force as follows:

$Q=6.55$
$\rho=2.15$
$\sigma=1.76$

where the calculation units are Newton, millimeter and Ampere.

5.Conclusions

We developed a digital controller with digital signal processor to enhance the function of the T-MAPS. The digital controller is absolutely essential for the recovery of the system in case of displacement sensor damages in a redundant system. And,it is expected that the best dynamic characteristics of the APM is maintained in spite of the damages among redundant elements. The digital signal processor, coupled with the performance of the host computer, provides the feature of the digital controller as follows.

(1) The digital controller has sufficient ability for the magnetic suspension control of 9 axes.

(2) The DSP up date the stiffness matrix Kc and the damping matrix Pc of the control parameters at each sampling period, so it can follow well to the change of the plant parameters.

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