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KOREASAT On-Orbit Normal Mode Attitude Control System

Dong Hwan Kim*, Jong Nam Won**, Sung Joong Kim**
Sung Soo Kang*, Han Dol Kim*, Myung Soo Rhee** *Regular Members*

무궁화위성의 정상운용모드에서의 자세제어 시스템

正會員 金東桓* 正會員 元鍾男** 正會員 金聖中**
正會員 姜聲秀* 正會員 金한돌* 正會員 李明洙**

ABSTRACT

Koreasat spacecraft requires accurate and reliable attitude control to provide beam pointing for tenyear long communication and direct broadcasting services. This paper describes the detailed design and performance of an on-orbit normal mode attitude control subsystem for the spacecraft.

Koreasat uses a momentum wheel which has a nominal momentum 475in-1b-sec(547.6 cm-kg-sec) aligned with the pitch axis to control pitch attitude and provide gyroscopic stiffness in roll/yaw plane and uses a 300 atm^2 magnetic torquer to control the roll and yaw attitudes. An Earth Sensor Assembly(ESA) is used to provide pitch and roll information for the on-board micropocessor. The roll/yaw control uses bang-off-bang control and while pitch axis control uses proportional and integral control law. Control system errors during the operational normal mode are 0.03 deg, 0.1 deg and 0.01 deg in roll, yaw and pitch axes, respectively. Current attitude control system provides adequate control performances to capture initial attitude errors and spacecraft nutation.

要 約

무궁화 위성체는 10년 수명기간 동안 통신 및 직접방송 위성서비스에 필요한 빔의 지향성을 유지하기 위하여 정확하고 신뢰성있는 자세제어 시스템을 요구하고 있다.

본고에서는 무궁화 위성체가 정지궤도에서 정상운용모드로 동작하는데 요구되는 자세제어부속시스템에 대한 상세설계기법 및 성능에 대해서 기술하고자 한다.

Ⅰ. Introduction

Two Koreasat satellites are scheduled to be launched on June and December 1995. The spacecraft is based on the flight-proven Martin Mariet-

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* 美國 마틴마리에타社
** 韓國通信
Korea Telecom

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ta Series 3000 momentum-biased bus with high performance direct broadcast and communication payloads. The spacecraft is passively spin-stabilized during transfer orbit and uses three-axis stabilization in geosynchronous orbit. Figure 1 shows a in orbit deployed configuration of a Koreasat spacecraft. During the normal operational mode, the Attitude Control Subsystem (ACS) senses pitch and roll attitudes and maintains 3 axis attitude via closed-loop control to meet beam point requirements. In addition, ACS provides control for propulsive torquing utilizing thrusters to perform stationkeeping, momentum adjustment and attitude control.

This paper presents the Koreasat normal mode ACS design, analysis and performance verification. The manueuver mode design and performance will be discussed in a separate paper.

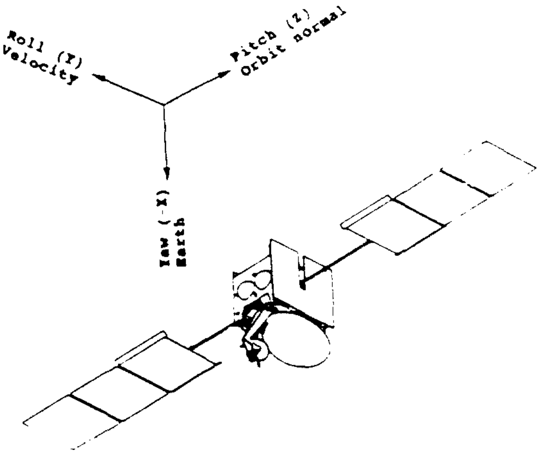

Figure 1. Koreasat orbital configuration and spacecraft body coordinate frame

Note that yaw and pitch attitudes in the following are referenced to the operational attitude control axes which are rotated from the body axes by +2 deg about the roll axes.

Ⅱ. Dynamic & Control

2-1. Normal Mode ACS Functional Description

Koreasat uses a magnetic Roll/Yaw Torquer (RYT) and a Momentum Wheel Assembly (MWA) to maintain roll/yaw and pitch pointing, respectively, in the presence of an environmental disturbance torque. An earth sensor assembly (ESA) is used to provide pitch and roll information for the Attitude Processing Electronics (APE). The APE is a micro-processor-based controller which implements the attitude control logic and commands the MWA and the magnetic torquer.

The roll/yaw control is primarily a bang-off-bang type control system. Depending on the polarity of the roll error, the switching logic commands an opposite dipole moment in the electromagnet.

The pitch loop controls the spacecraft pitch angle by momentum exchange between the MWA and the spacecraft.

2-2. Dynamic

The equation of motion for a momentum-biased satellite is expressed by the Euler's equation[1]

$$H = \dot{H} + \omega \times H$$

where T = torque on spacecraft
H = vehicle momentum
ω = pitch rate

These terms are further approximated as

$$T = Td + Tc$$
$$H = Hw + Hb$$
$$Hw = [\,0 \;\; 0 \;\; hz\,], \quad Hb = I \cdot \omega$$

where Td = disturbance torque on the satellite
Tc = control torque
Hw = angular momentum of the MWA
Hb = angular momentum of the spacecraft

I = spacecraft inertia dyadic
ω = angular velocity in three axis.

The Euler's equation is solved by a numerical integration with the angular rates and rotation angles as state variables.

Roll/yaw dynamics in the x-y plane is represented by very slowly varying dynamics, and the spacecraft is modeled as a rigid body. However, a flexible mode is incorporated in pitch axis dynamics to account for the array stepping or slewing motion during normal operation. In a singles axis representation, spacecraft pitch dynamics with the dominant array torsional mode is expressed as

$$Ic\theta + Ia(\theta + \delta) = Tz$$
$$Ia(\theta + \delta) + c\delta + k\delta = 0$$

where
Tz = momentum wheel torque along pitch axis
θ = pitch angle of the spacecrft core
δ = array torsional flex angle relative to core
k = array stiffness coefficient
c = array damping coefficient
Ic = core moment of inertia along pitch axis
Ia = array moment of intertia along pitch axis

Thus, the array flex mode is considered by modifying the z-components of Euler's equation and computing also flex-angular velocity and acceleration. The detailed description of spacecraft dynamics, kinematics and simulation technique are provided in [2].

2-3. Roll/Yaw Magnetic Control

The RYT consists of a dipole, which is offset from the roll axis in the roll/yaw plane by a skew angle of 59 deg[3]. Figure 2 illustrates the dipole skew orientation and earch magnetic field vector. The dipole has a constant magnitude, but can be activated in either direction. Dipole moment vector(Mc) interacts with the Earth's magnetic field vector (B) in order to provide corrective torques (Tc) on the spacecraft[1]. Therefore,

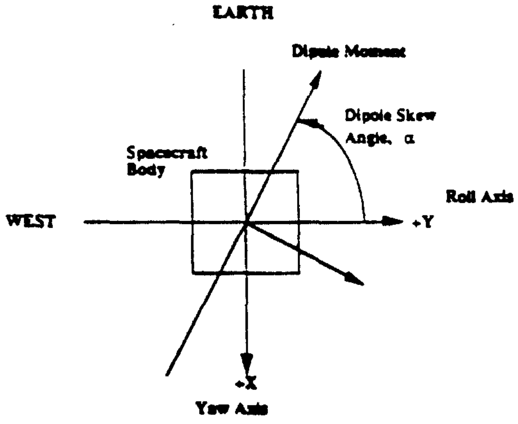

Figure 2. RYT skew angle and geometry

$$Tc = Mc \times B$$

Figure 3 shows the roll/yaw control system block diagram. The phasing of the torquer switching is controlled by setting the predetermined MAND(Magnetic Active Nutation Damping) time delay(tD).

Dipole is activated tD seconds after the magnitude of the 32-sample averaged roll signal exceeds the roll threshold. In order to provide some damping, the dipole remains on until tD seconds after the averaged roll signal changes sign. The roll threshold is selectable by ground command. The MAND time delay used for the roll/yaw control is given by[4]

$$tD = \tau(\alpha + 163)/360$$

where α is the skew angle and τ is the nutation period of the satellite.

2-4. Pitch Loop Control

RPM command are sent to the torque motor driving the momentum wheel aligned to the orbit normal.

The pitch loop functional block diagram is presented in Fig. 4. Nominal, worst-case parameters and control gains are found in[5]. The APE pitch compensation is a proportional plus Integral type. Thus the digital compensator filters the error signal via

$$G(z) = K_2[K_1 + z/(z-1)]$$

where K_1, K_2 are control gains and z is the forward difference operator. The MWA contains a brushless DC motor with a speed demand tachometer loop. The MWA in the block diagram is simplified to

$$G_{MWA}(s) = M_M s/t_M s + 1$$

where K_M is MWA gain in in-lb-sec/volts and t_M us MWA time constant in seconds. For nominal case, $K_M = 100.5$ in-lb sec(115.8 cm kg-sec)/volts, $t_M = 1.66$ sec, and the control gains are $K_1 = 80$ and $K_2 = 0.018$ MWA rpm demand/deg.

2-5. Sensor/Actuators

ESA consists of a scanning type sensor and as-

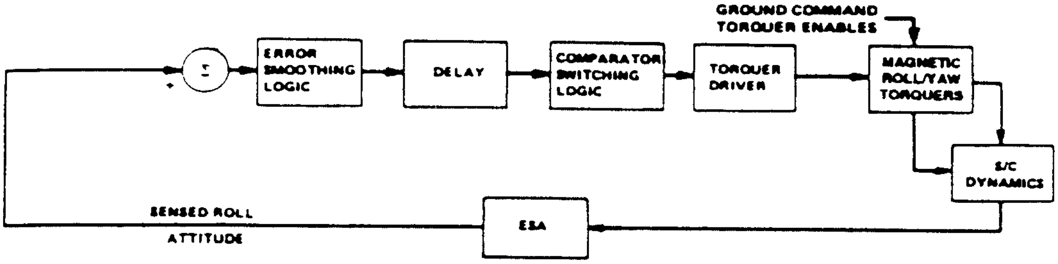

Figure 3. Roll/yaw control block diagram

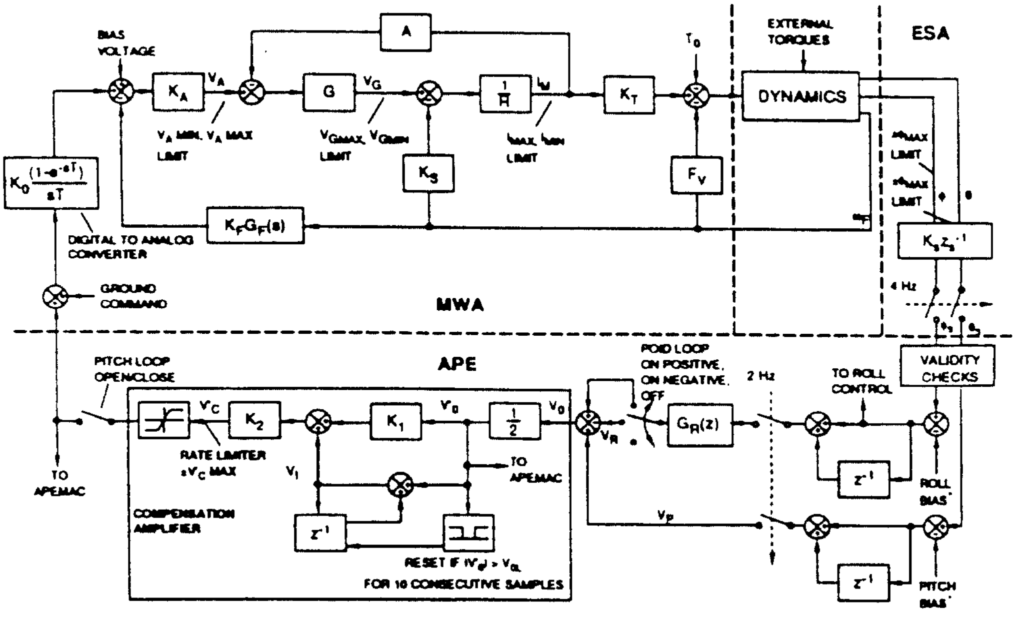

Figure 4. Pitch control block diagram

sociated sensor processing electronics. It generates roll and pitch attitude signals every 0.25 second. The measurement range is ±2.25 deg and ±6.4 deg for the roll and pitch axis, respectively and the 3σ accuracies are ±0.049 deg and ±0.075 deg, respectively.

A RYT with a size of 300 atm^2 is selected to provide sufficient control at the worst-case condition. This torquer provides a factor-of-two design margin to cover unmodelled disturbance torque. Roll/yaw performance verification for a number of different skew angles, different environmental conditions, indicate that the skew angles of 59 deg is a nearoptimal accommodation. MWA has a momentum of 475 ± 40.6 in-1b-sec(547.6 ± 46.8 cm-kg-sec) at a 6000 rpm operating speed. The output resolution of the APE wheel speed demand is 0.5 rpm.

2-6. Pitch Loop Frequency Response

The stability of the loop is evaluated by a frequency response analysis. The open loop frequency of pitch loop with the worst-case parameter at EOL and the relative stability margins are presented in Figure 5. The stability analysis results indicate that the sufficient gain and phase margins of 24 dB and 69 degrees exist for the worst case.

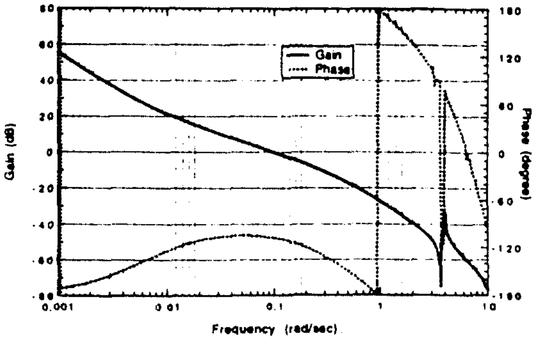

Figure 5. Pitch open-loop frequency respons

Ⅲ. Simulation

3-1. Modelling and Parameters

The external environmental disturbance torques on the spacecraft are modelled through a three-term Fourier series expansion. Fourier coefficients are calculated for each disturbance source, then summed to obtain the total environmental disturbance torque about each axis in the form

$$Tdu = a_{0i} + \sum_{k=1}^{3} a_{ki} \cos(\omega t + \beta) + b_{ki} \sin(\omega t + \beta)$$

where i = axis (yaw, roll, or pitch)
Tdi = disturbance torque about axis i
ω = orbit frequency
β = initial orbit clock angle (measured from spacecraft midnight)
a_{ki}, b_{kt}, $k = 1, 2, 3$: Fourier coefficients

The primary environmental disturbance is solar pressure. The worst case in the environmental disturbance occurs near the end-of-life(EOL) solstices. Solar pressure disturbance torque is calculated for the spacecraft configurations with sloar array panel deployed. The EOL coefficient are calculated for the case where the arrays are parallel and have a tip deflection of 3 inches.

Table 1 shows the Fourier coefficients for environmental disturbance torque. The values in the table also includes contributions from worst-case

Table 1. Fourier coefficients for Koreasat environmental disturbance torque

	yaw	roll	pitch
a0	4.6	27.3	−1.8
a1	−1.8	23.1	−22.9
a2	0.3	−1.2	−3.6
a3	−1.2	−1.5	5.5
b1	38.9	6.3	58.0
b2	−3.1	−3.8	−1.1
b3	−1.3	1.4	6.8

residual dipole of 5 atm² on each axis, gravity gradient torque and RF radiation torque. The more detailed information on environmental disturbance calculation is provided in [7].

Table 2 lists the coefficient for the Earth magnetic field model. The magnetic field of Earth is approximated by

$$Bz = (P/100)\,(A - B\cos\theta)\cos l_m$$

where

Bz = North component of Earth's magnetic field.

θ clock angle, measured from spacecraft mid night.

l_m = earth magnetic dipole inclination.

To approximate the degradation of the magnetic field due to the effect of solar storms, 70% performance of the Earth's magnetic field strength is used in the roll/yaw control analysis.

Table 2. Earth's Magnetic Field Model

	A [nT]	B [nT]
Winter Solstice	80	25
Equinox	85	30
Summer Solstice	85	25

[1 nT = 10^{-9} Tesla = 8.820×10^{-9} (in lb/atm²)

= 10.2×10^{-9} (cm kg/atm²)]

The mass properties include the first torsional frequency of solar array, 5.66 rad/sec. Inertia dyadic in the spacecraft body frame is

$$I = \begin{bmatrix} 16525 & -6 & 5 \\ -6 & 16452 & -65 \\ 5 & -65 & 2630 \end{bmatrix} \text{ in lb sec}^2$$

$$= \begin{bmatrix} 19038.8 & -6.9 & 5.8 \\ -6.9 & 18954.7 & -74.9 \\ 5.8 & 74.9 & 3030.1 \end{bmatrix} \text{ cm kg sec}^2$$

These inertia values are transformed to the operational attitude control axes via

$$I = F I F^T$$

where F is the transformation matrix between the body frame and operational attitude frame.

Ⅳ. Results

The nonlinear performances of the roll/yaw and pitch loop are evaluated using a 3-axis rigid body (including torsional mode in pitch axis) time simulation program. The purpose of the non linear simulations is to verify pitch capture capability and pitch pointing accuracy during normal operations in the presence of non linearities such as ESA signal saturation, on-off switching of the torquer, MWA motor torque speed saturation, and the integral reset limit in the control logic.

4-1. Normal Roll/Yaw Operations

Nominal worst case simulations are run at EOL over four days with a ground selectable roll control threshold of 0.02 deg. Current magnetic control configuration yields 60% three-hour duty cycle and 27% one day duty cycle. Figure 6 shows the niminal roll/yaw performance at winter-solstice.

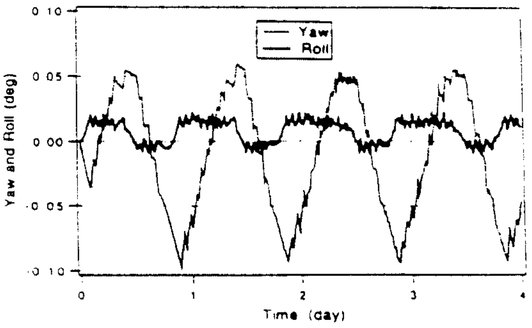

Figure 6. Nominal roll/yaw performance

4-2. Roll and Yaw Capture

Simulations are run to demonstrate that the proposed control system can capture large yaw and roll errors. Figure 7 demonstrates the ability of the control to recover a 0.5 degree initial roll error at winter solstice. An initial error of 0.5 degree either roll is corrected within about 12 hours (0.5 days). A three-hour duty cycle is 100% at the initial part of the captures, meaning that the torquer is saturated for those portions of the orbit. Figure 8 shows the spacecraft performance for 0.5 deg initial yaw error acquisition.

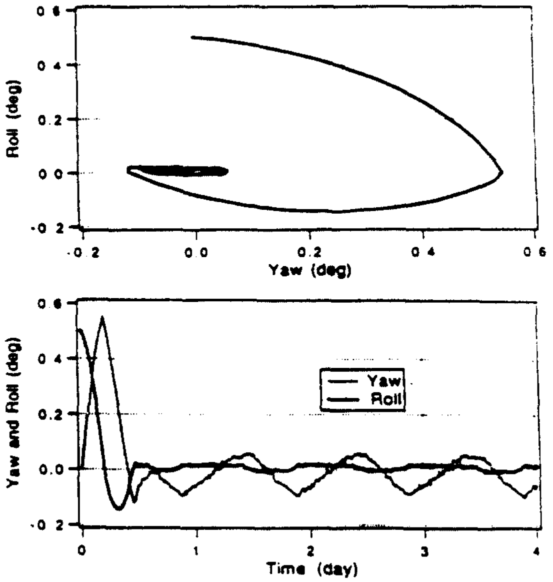

Figure 7. Roll angle acquisition performance

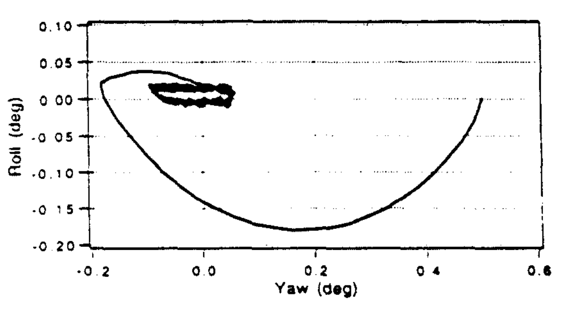

Figure 8. Yaw angle acquisition performance

There is no active yaw control in the current design. However, yaw control is performed by using the roll/yaw momentum interchange occuring every quarter orbit.

4-3. Nutation Damping

Fig. 9 shows the response to an initial nutation angle of 0.2 deg at summer and winter solstices. Nutation angle is the angle between the spin axis and the angular momentum vector. The nutation angle is damped within approximately 12 hours (0.5 days).

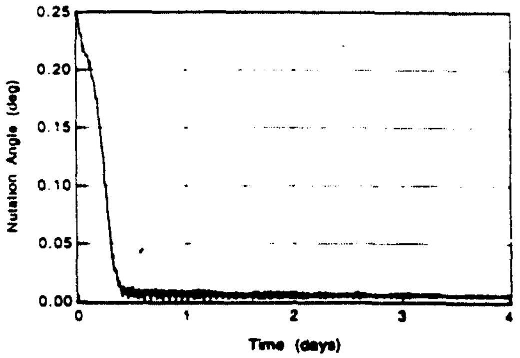

Figure 9. Nutation damping performance

4-4. Pitch Capture

The pitch capture is simulated for various combinations of initial pitch angle, the system momentum and wheel momentum. Fig. 10 shows the pitch capture with the nominal parameters. The

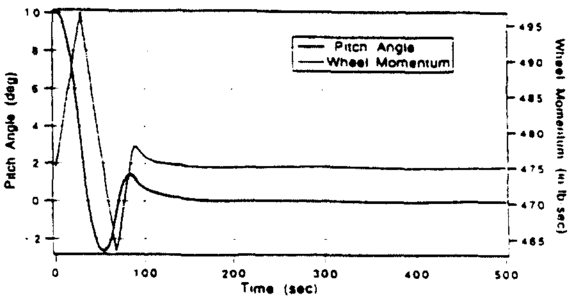

Figure 10. Pitch capture nominal performance (1 in-1b-sec = 1.152 cm-kg-sec)

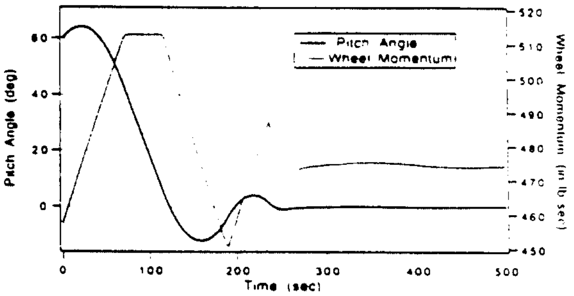

Figure 11. Pitch capture at momentum offset (1 in lb sec = 1.152 cm kg sec)

system damps out in less than 200 seconds. Fig. 11 shows the pitch capture from 60 degrees of pitch offset with the 19 in-lb-sec(21.9 cm-kg-sec) of initial pitch momentum offset and 10 deg. of roll error.

4-5. Steady State Operation

The steady state pitch pointing is investigated for the normal operation. In the presence of the worst-case environmental disturbance torques, ESA noise, system non-linearities and array stepping at 0.25 Hz the maximum pitch pointing error is 0.012 degrees. Figure 12 shows the pitch pointing during normal operations.

Also of concern is the pointing performance during the slew maneuver of the solar arrays. Note that, slewing frequency, 8 Hz, is not close to the solar array dominant torsional mode leaving little possibility for the interaction with the spacecraft dynamics. Figure 13 shows the spacecraft pitch response during the solar array slew. Appropriate initial values of pitch integrals are imposed to properly simulate the steady state condition without having to run the simulation over long periods of time.

Ⅴ. Conclusion

Design and performance verification are presented for the Koreasat normal mode attitude control system. Current design is based on the flightpr

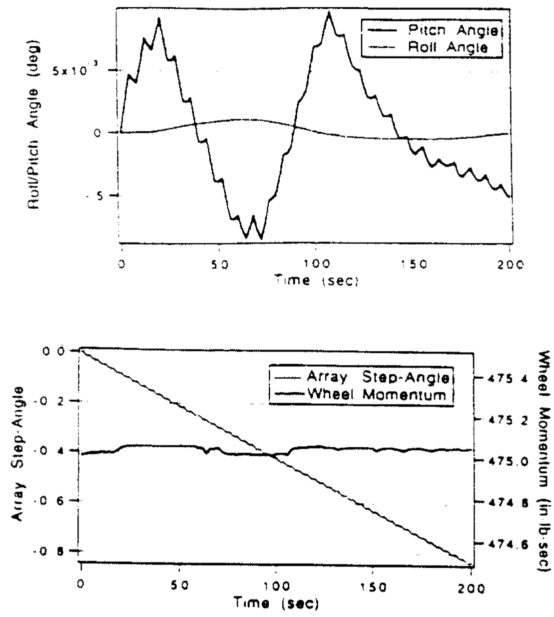

Figure 12. Nominal pitch loop performance (1 in lb-sec = 1.152 cm kg sec)

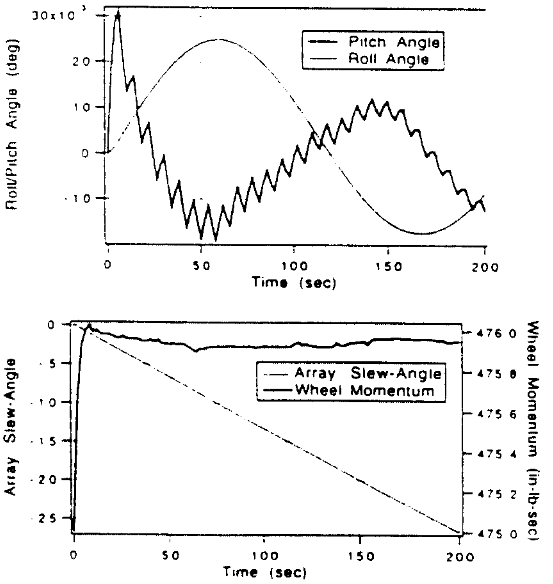

Figure 13. Pitch response during array slew (1 in-lb-sec = 1.152 cm kg sec)

oven heritage 3-axis control system using a magnetic torquer with a coil size of 300 atm^2 at skew angle of 59 deg and momentum wheel with nominal momentum of 475 in-1b-sec(547.6 cm-kg-sec).

Performance verification assumes a 3 inch(7.62cm) tip deflection, the worst-case environmental disturbance and worst case magnetic field.

The roll/yaw control system maintains maximum roll/yaw attitude errors under 0.03 deg and 0.1 deg, respectively. The highest duty cycle encountered over any one-day period is 27 ; during the worst-case three-hour period it does not exceed 60%. The reponses to an initial roll, yaw or nutation indicate that the roll/yaw control system eliminates those errors effectively.

Frequency analysis of the pitch loop shows good stability margins even under worst-case loop conditions. Gain and phase margins are at least 23 dB and 69 degrees, repectively. The Maximum pitch error is no more than 0.01 degrees. The pitch loop is capable of achieving a pitch capture from any initial pitch angle.

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金 東 桓(Dong Hwan Kim) 정회원
1976년 ~ 1980년 : 서울대 항공과(학사)
1980년 ~ 1982년 : KAIST 항공과(석사)
1983년 ~ 1985년 : 국방과학연구소 연구원
1985년 ~ 1990년 : Univ. of Texas Austin 항공과(박사)
1990년 ~ 현재 : 미국 마틴 마리에타 항공우주사업단 선임연구원

金 聖 中(Sung Joong Kim) 정회원
1972년 ~ 1976년 : 서울대학교 전기공학과(학사)
1976년 ~ 1978년 : 서울대학교 대학원 전기공학과(석사)
1978년 ~ 1983년 : 국방과학연구소 연구원
1984년 ~ 1991년 : 미국 버지니아 Tech 전기공학과(박사)
1991년 ~ 1992 : 한국통신 위성사업단 발사감리부장
1992년 ~ 현재 : 무궁화위성 제작감리단 선임연구원(미국 마틴마리에타사 위성체제작현장 사무소 파견)

元 鍾 男(Jong Nam Won) 정회원
1979년 ~ 1983년 : 아주대학교 전자공학과(학사)
1983년 ~ 1985년 : 아주대학교 대학원(석사)
1986년 ~ 1992년 : 한국통신 전임연구원
1992년 ~ 현재 : 무궁화위성 제작감리리단 선임연구원(미국 마틴마리에타사 위성체제작현장 사무소 파견)

姜 聲 秀(Sung Soo Kang) 정회원
1985년 ~ 1992년 : 서울대학교 제어계측공학과(학사)
1992년 ~ 현재 : 삼성항공연구원 미국마틴마리에타사 위성체기술전수단 파견

金 한 돌(Han Dol Kim) 정회원

1978년~1982년 : 한양대학교 기계공학과(학사)

1982년~1984년 : Drexel Univ. 기계공학과(석사)

1984년~1990년 : Drexel Univ. 기계공학과(박사)

1991년~현재 : 한국항공우주연구소 선임연구원 미국마틴
마리에타사 위성체기술전수단 파견

李 明 洙(Myung Soo Rhee) 정회원

1976년~1983년 : 연세대학교 전자공학과(학사)

1983년~1985년 : 연세대학교 대학원 전자공학과(석사)

1985년~1989년 : 연세대학교 대학원 전자공학과(박사)

1990년~1994년 : 한국통신 위성사업단 위성기술부장

1994년~현재 : 한국통신 사업개발센터 이동통신개발부장