A87-50475

COMPARISON OF DIFFERENT ATTITUDE CONTROL SCHEMES FOR LARGE COMMUNICATIONS SATELLITES

87-2391

S.K. SINGH*
INTELSAT
Washington, D.C.

R. GRAN
Grumman Aerospace Corporation
Bethpage, NY

B.N. AGRAWAL
INTELSAT
Washington, D.C.

ABSTRACT

A comparative study of the robustness of various spacecraft body attitude control systems with structural flexibility is presented in this paper. The control systems examined are: (a) 3-Reaction Wheels (b) Body-fixed momentum wheel with offset thrusters (c) Skewed body-fixed momentum wheels with offset thrusters and (d) Body-fixed momentum wheel with two reaction wheels. For the size of large spacecraft considered in this paper, all these systems are shown to result in satisfactory performance. In order to exhibit their relative merits, the presence of severe structural interaction had to be introduced. Comparison was then made in terms of stability, which is affected by non-colocation of actuators and sensors. Performance borne out of the nonlinear simulation with both the large flexible spacecraft and dummy unstable interacting low structural mode is illustrated. This latter study shows that a system with single body-fixed momentum wheel along pitch axis and two reaction wheels oriented along roll and yaw axes, is the most robust.

NOMENCLATURE

$I_{x,y,z}$ -Moment of Inertias of the spacecraft about spacecraft body axes.
ω_0, ω_η -orbital rate $\approx 7.28 \times 10^{-5}$ rad/s, nutation freq. (rad/s)
ϕ, θ, ψ -euler angles roll, pitch and yaw
$h_{x,y,z}$ -angular momentum of wheels along body axes
$HW_{1,2,3}$ -angular momentum of wheels along spin axes
$M_{x,y,z}$ -external moments such as : environmental disturbance torques (solar, impulse, secular), thruster torques, magnetic torques, etc.
α -offset angle of thrusters
β -cant angle of wheels
G(s) -forward loop transfer function
H(s) -backward loop transfer function
Hzt -total momentum along yaw axis
K_1, τ_1 -gain and time constant for wheel control law
K_2, τ_2-gain and time constant for thruster control law
K_3, K_4, T_1 - gains and time constant of the filter, for the non-minimum phase.
K_5, K_6, K_7, T_2-gains and time constant of the filter for the transition controller.

INTRODUCTION

The structures that are being proposed for the next generation of communications satellite include large solar arrays, large deployable antenna and masts, and lengthy booms. This makes it imperative to study the structural/control interaction, and to ensure that the design is sufficiently robust to assure that substantial tolerances can be accommodated in the structural model.

Work has been done in the past to understand and design control systems for isolating or accommodating such structural disturbances(Refs. 3 & 4). The concept of multiple controls for a flexible spacecraft has been defined in Ref. 5. The INTELSAT contract (Ref. 1.) to Grumman Aerospace Corporation was to investigate the potential for interaction between the 'rigid body' control system and the flexible appendages of a 3-reaction wheels controlled communications satellite. The work involved a linear time invariant analysis through modern control approach and a nonlinear simulation to verify the results.

The objective of this study was to come up with a spacecraft body attitude control system that can be used for future communications satellites. It involves the examination of stability of different types of spacecraft body attitude control systems with structural flexibility. Systems examined are branched into the following types:

(a) 3-reaction wheels oriented along the roll, pitch and yaw axes;

(b) Body-fixed momentum wheel with offset roll/yaw thrusters for attitude control;

(c) Skewed body-fixed momentum wheels with offset roll/yaw thrusters for momentum/attitude control;

(d) Body-fixed momentum wheel with two reaction wheels oriented along roll and yaw axes.

The stability of a large flexible spacecraft is dependent on the class of design concept chosen from the following (Refs. 1,2,5):

Class 1 - actuators and sensors colocated at the central core with no active control at the antenna;.

Class 2 - actuators at the core but sensors at the antenna so that the spacecraft rigid body motion can react to antenna motions;

Class 3 - actuators and sensors distributed on the spacecraft so the antenna may be controlled independent of the spacecraft rigid body, and not colocated with sensors so that the unstable interacting modes are a problem.

Effort is made to model the control system types (b) and (c) similar to those of INTELSAT V and INSAT. The linearized analysis carried out to design and compare the control systems parameters (feedback gains, time constants, offset angle of thruster, etc.) is based on the classical rootlocus. The nonlinear simulation program (SATSIM) interfaces with NASTRAN to simulate the structural / control interaction. It allows nonlinear actuator, sensor and spacecraft dynamics with stochastic disturbance to be simulated along with many flexible bending modes.

LARGE SPACECRAFT CONFIGURATION

The spacecraft is large enough so that flexible motion has a significant effect on the line of sight (LOS), and is developed to be a representative of a shuttle deployable communications satellite. The total mass of the

---

* Technical Specialist,Spacecraft R&D, Member AIAA

This paper is based upon the work sponsored by and performed at the International Telecommunications Satellite Organization (INTELSAT). Views expressed in this paper are not necessarily those of INTELSAT.

spacecraft is 1838 kg. It consists of a central core that contains the electronics, control mechanisms and mechanical assemblies. Attached to this core are astromasts deployable modules that carry the two solar arrays, the two booms that carry the antenna, and the antenna itself. Mechanical drawing of the envelope is shown in Fig. 1.

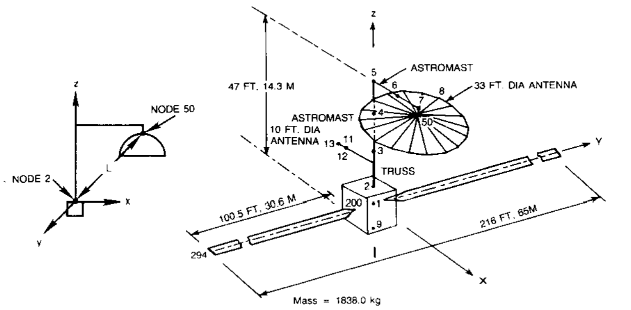


Figure 1: LARGE SPACECRAFT CONFIGURATION

The antenna is pivoted with a 2 D.O.F. actuator at nodes 7 & 8, and there are six sensors mounted below the gimbal to measure roll,pitch,yaw and their respective rates. In addition, a defocus actuator (nodes 4 & 6) was provided to squeeze the two astromast beams and thereby control the antenna-to-feed distance. On the central body, node 2 is the location of actuators and sensors.

For the rigid body feedback (Class 1), the rates are either measured with rate gyros or derived from the PWPF modulator based on the attitudes. These attitudes inturn are measured by a horizon sensor (Refs. 6-16) and yaw by a yaw estimator (Ref 17), or by a gyrocompass.

The rates and inertial attitudes for Class 2/3 are measured from either inertial sensors (rate gyros) on the antenna or with a RF sensor that gives attitudes. The distance from the feedhorn to the antenna is measured, along with the rate of change of this distance using either a RF sensor or an optical device.

Characteristics of the flexible spacecraft as obtained by NASTRAN is given in the Table 1. The 31 sructural modes including their frequencies, generalized mass and a description of their type are given.

Table 1: Configuration - Modes and Frequencies

Mode	Frequency, Hz	G.M. kg x 10^{-3}	Description
1-6	0		Rigid Body Modes
7	.0589	.0900	Solar array – first sym bending
8	.0619	.0256	Large antenna – first lateral trans
9	.1329	.0107	Large antenna & solar array – pitch } Antenna Joint Pivot Modes
10	.1346	.00885	Large antenna – roll
11	.1361	.1843	Solar array – 1st anti-torsion
12	.1368	.0614	Large antenna pitch – sol array & 1st sym torsion
13	.1791	.1096	Solar array – 1st anti-bending-ant roll
14	.2205	.0268	Large antenna pitch & lat trans
15	.3528	.0899	Solar array – 2nd sym bending
16	.4465	.0633	Solar array – 2nd anti bending
17	.5747	.0992	Solar array – 2nd anti-torsion
18	.5747	.0991	Solar array – 2nd sym torsion
19	.7362	.1046	Solar array – 1st in-plane bending
20	.7668	.0367	Astro mast bending – spacecraft roll
21	.9694	.0908	Solar array – 3rd sym bend
22	1.152	.0498	Solar array – 3rd anti-bend
23	1.188	.0609	Astro mast bending – spacecraft pitch
24	1.224	.0679	Solar array – 3rd anti-torsion
25	1.224	.0684	Solar array – 3rd sym torsion
26	1.375	.0320	Astro mast bending – spacecraft-roll
27	1.885	.0926	Solar array – 4th bend
28	2.055	.1030	Solar array – 4th anti bend
29	2.130	.0569	Solar array – 4th anti torsion
30	2.130	.0568	Solar array – 4th sym torsion
31	3.000	.1086	Solar array – anti-in-plane bending
1908-027P			

CONTROL SYSTEMS DESCRIPTION

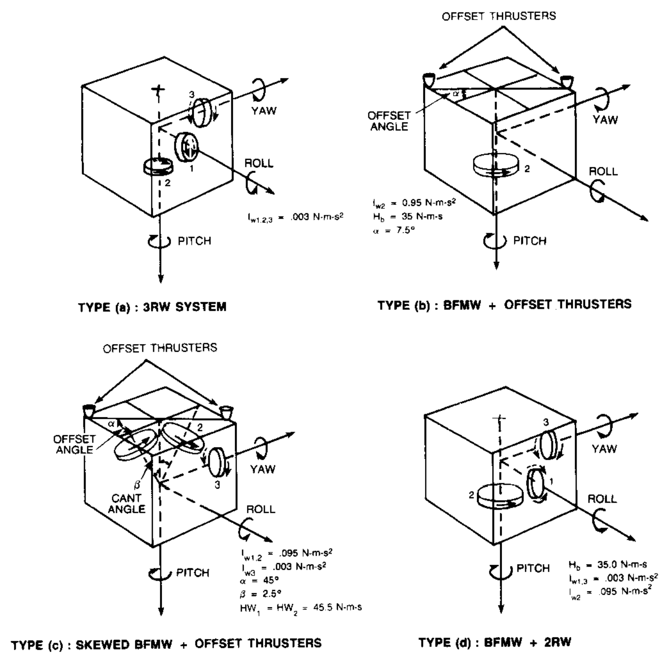
In the basic mode of operation the communications satellite requires no rapid maneuvers and associated settling time requirements, so the control problem is one of maintaining the attitude against very low frequency disturbances such as: solar, gravity gradient, magnetic and thermal. Therefore, the specification taken for this study is given by an rms antenna pointing error of .01 deg. or less, which is accomplished by allowing the attitude errors (proportional to bandwidth) in the presence of the disturbances to be as:

.05 in pitch (θ) and roll (ϕ)
.4 in yaw (ψ)

The linearized equations of motion used in the analysis are :

$$M_x = I_x\ddot{\phi} + \dot{h}_x + h_z(\dot{\theta} - \omega_o) - h_y(\dot{\psi} + \phi\omega_o)$$
$$M_y = I_y\ddot{\theta} + \dot{h}_y + h_x(\dot{\psi} + \phi\omega_o) - h_z(\dot{\phi} - \psi\omega_o) \quad \text{..(1)}$$
$$M_z = I_z\ddot{\psi} + \dot{h}_z + h_y(\dot{\phi} - \psi\omega_o) - h_x(\dot{\theta} - \omega_o)$$

The four types of body attitude control systems are shown in Fig. 2, with their inertias and design parameters. Each system provides conventional wheel control of the pitch error by modulating a single reaction wheel or a body-fixed momentum wheel or skewed body-fixed momentum wheels. The control law along the pitch axis is proportional-plus-derivative (negative with lead compensation) throughout, and is based on the bandwidth $_{WC}$ of the control system.



I_x = 2747.0 N-m-s², I_y = 1360.0 N-m-s², I_z = 2154.0 N-m-s²

Figure 2: BACS CONFIGURATIONS

Mathematically, it could be represented as :

$$\dot{h}_{cy} = K_1(\tau_1\dot{\theta} + \theta)$$

where, $$K_1 = I_y\omega_c^2 \qquad \tau_1 = \frac{2\xi}{\omega_c} \qquad \text{(2)}$$

We note that the main difference between the candidate systems lies in their approach to control roll and yaw attitudes. This is due to the biased momentum concept. Each system is discussed hereunder along with its strategy to correct roll and yaw:

(a) 3-RW : It provides active control of the roll by modulating the roll wheel, and yaw by yaw wheel. The control law is the same as eq(2).

(b) BFMW: This standard concept is used in INTELSAT V, SATCOM and TVSAT for 3-axis stabilization. When the roll attitude encounters the roll deadband, the corresponding thruster fires a series of pulses and the momentum is removed. The roll acccuracy is then established by the threshold and not by the wheel size (which is based on the desired yaw accuracy). The control law for the roll/yaw thrusters as found in Refs. 7,8,9 is:

$$TJP_x = -K_2(\tau_2\dot{\phi} + \phi)\cos\alpha$$
$$TJP_z = K_2(\tau_2\dot{\phi} + \phi)\sin\alpha \qquad \textbf{(3)}$$

which results in the transfer function

$$G(s)H(s) = \frac{K_2\ \tau_2\cos\alpha\ (s + 1/\tau_2)\left(s - \sqrt{\frac{\omega_o h_b}{I_z}}\right)^2}{I_x\ (s^2 + \omega_o^2)\ (s^2 + \omega_\eta^2)}$$

This equation is based on the condition that for complete damping of the orbital mode and rapid yaw response, the offset angle of the thruster

$$\tan\alpha = 2\sqrt{\frac{I_z\omega_o}{h_b}}$$

Rootlocus for the above transfer function is shown in Fig. 3.

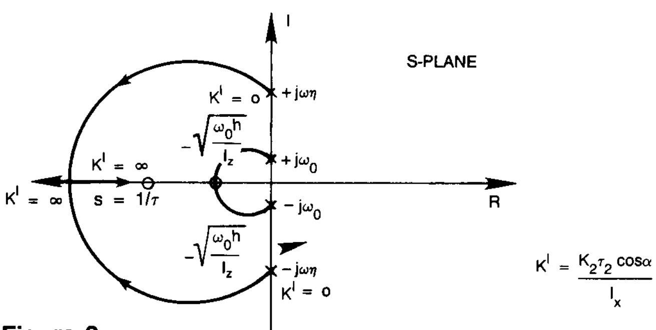


Figure 3:
ROOT LOCUS FOR TYPE (b) THRUSTER CONTROLLER

(c) SKEWED BFMW's: This design is used in INSAT and uses two skewed momentum wheels. Roll attitude is controlled and roll/yaw nutation is damped by varying the angular momentum along the yaw axis. Excessive accumulation of angular momentum on either wheel due to secular environment torques is prevented by firing a short pulse from a thruster. The total angular momentum along the yaw axis for a two axis momentum storage is:

$$H_{zt} = h_z + h_b\phi$$

An approximate measure of this angular momentum can be obtained from the horizon sensor and tachometer signals. This yaw momentum control loop provides active roll ,but passive yaw control. During normal orbit the yaw momentum control is based on the roll error only. The yaw momentum control law is the Terasaki non-minimum phase as found in Refs. 12 & 15:

$$h_{cz} = -\frac{(K_3/s - K_4)\ \phi}{T_1 s + 1} \qquad \textbf{(4)}$$

Transfer function for a short term motion is:

$$G(s)H(s) = -\frac{h_b\ (K_4 s - K_3)}{I_x I_z\ s(s^2 + \omega_\eta^2)(T_1 s + 1)}$$

Rootlocus for this function is shown in Fig. 4.

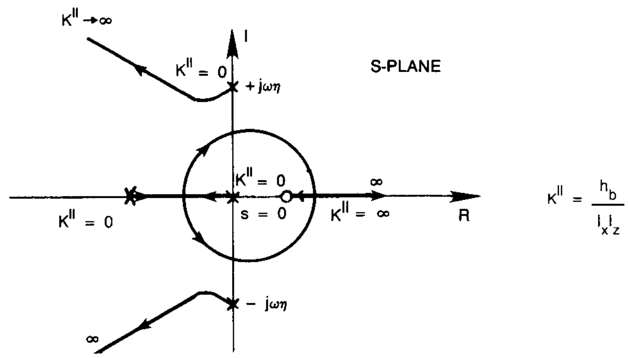


Figure 4: ROOT LOCUS FOR TYPE (c) NORMAL MODE CONTROLLER

In order to increase the nutation damping ratio, the transition controller (Refs. 15 & 16) used is:

$$h_{cz} = -\frac{(K_5/s + K_6 s + K_7)\ \phi}{T_2 s + 1} \qquad \textbf{(5)}$$

For a single axis yaw control, the transfer function becomes:

$$G(s)\ H(s) = \frac{h_b\ (K_5 + K_6 s^2 + K_7 s)}{I_x I_z s\ (s^2 + \omega_\eta^2)(T_2 s + 1)}$$

The rootlocus is shown in Fig. 5. The proportional gain is very small (Zero PID controller), so that the closed loop nutation frequency is very near the open loop nutation frequency.

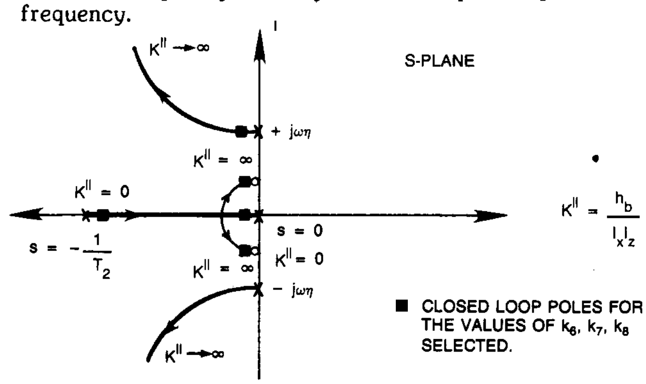


Figure 5: ROOT LOCUS FOR TYPE (c) TRANSITION CONTROLLER

(d) BFMW + 2 RW: It provides active and continious control of roll by modulating the roll wheel, and yaw by the yaw wheel.
The control law is same as eq. (2) which is given by:

$$\dot{h}_{cx} = K_1 \ (\tau_1 \dot{\phi} + \phi)$$
$$\dot{h}_{cz} = K_1 \ (\tau_1 \dot{\psi} + \psi) \qquad \textbf{(6)}$$

A few nonlinear simulation models are shown in Fig. 6 for types (c) and (d). The flexible motion due to a large deployable antenna is superimposed on the rigid body as shown by various connections marked alphabetically. Table 2 shows the controllability, observability, stable and unstable interacting modes for the structure found by looking at the mode shapes (Refs. 1 & 2). For example the mode no.23, which is an unstable interacting mode, is shown in the Fig. 7.

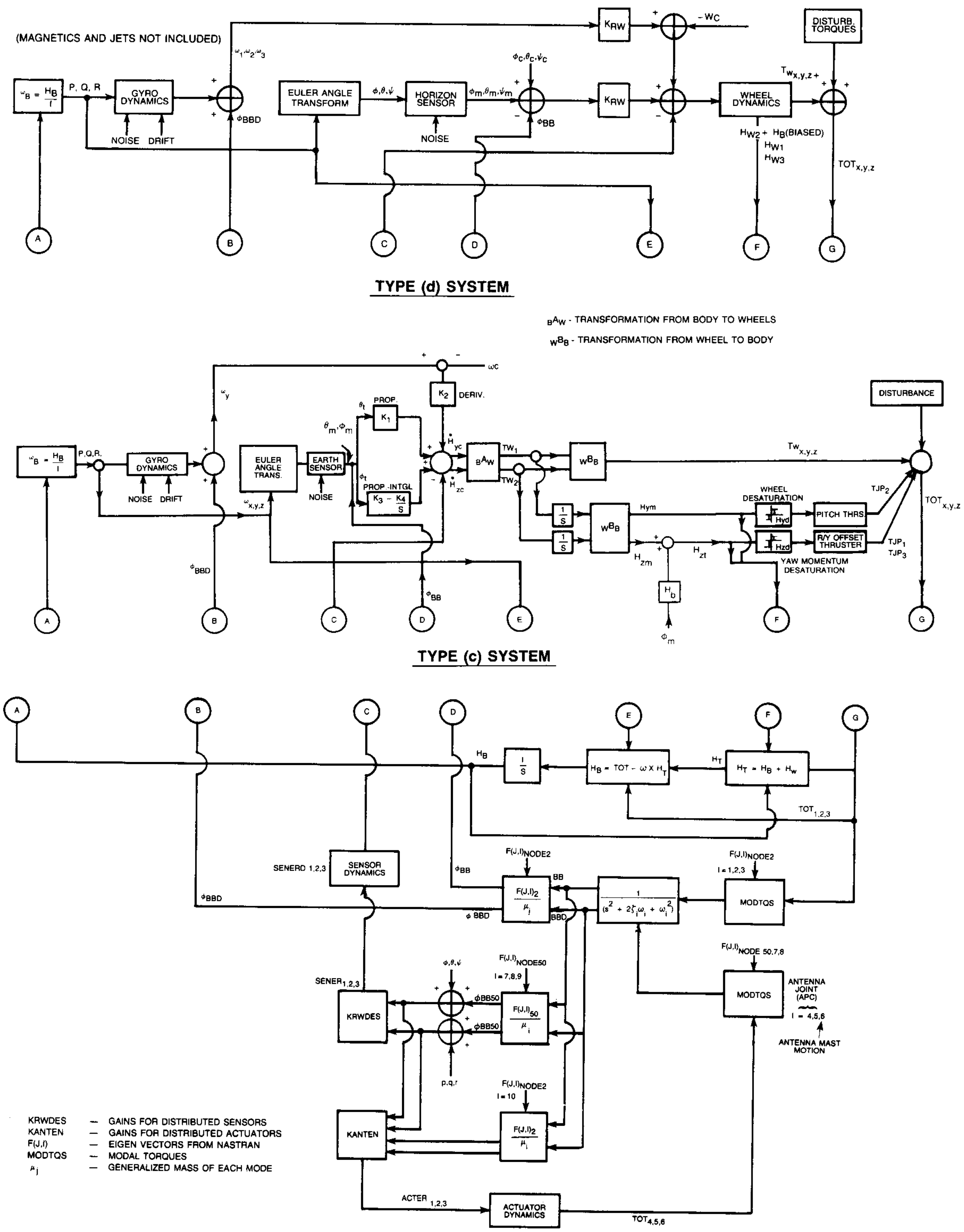


Figure 6: NONLINEAR SIMULATION MODELS (Types (a) & (b) are similar to Type (d)) (7/03/2618)

Table 2: Observability and Controllability of Structural Modes

Mode No.	Observability: No	Observability: Yes	Stable or Unstable Interactive at: Solar Array	Stable or Unstable Interactive at: Antenna	Retain R or Discard D: Class 1	Retain R or Discard D: Class 2	Retain R or Discard D: Class 3
7	√				D	D	D
8	At Core	At Antenna			D	R	R
9	At Core	At Antenna			D	R	R
10	At Core	At Antenna			D	R	R
11	√				D	D	D
12	√				D	D	D
13		√	U	U	R	R	R
14		√	2	S	R	R	R
15	√				D	D	D
16		√	S	U	R	R	R
17	√				D	D	D
18	√				D	D	D
19	√				D	D	D
20		√	S	U	R	R	R
21	√				D	D	D
22		√	U	U	R	R	R
23		√	3	U	R	R	R
24	√				D	D	D
25	√				D	D	D
26		√	U	S	R	R	R
27	√				D	D	D
28		√	S	S	R	R	R
29	√				D	D	D
30	√				D	D	D
31		√	S	U	R	R	R

NOTES:
1 For attitude sensor located in center body, nodes 400 through 410
2 Will not excite solar array
3 Neutral because control torque is uniformly distributed on solar array about Y axis

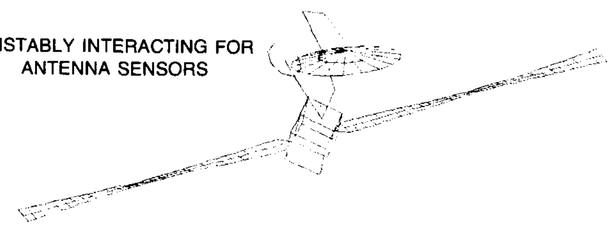


Figure 7: MODE 23 FREQ. 1.188

RESULTS

The following results are borne out of the digital computer simulations of the large spacecraft with a deployable antenna and ten flexible bending modes. These modes selected are controllable, observable and unstable interacting. The control law design parameters and results of the analysis are contained in Table 3. The bandwidth for all body attitude control systems is taken about 0.05 rad/s, which is based on disturbance and noise minimization.

It was found that for the size of spacecraft considered in this study (Fig 1), all the candidates body attitude control systems result in stable attitudes motion (actual data Table 3). Although some unstable interacting modes do exist, the motion is not affected. This is because the influence coefficients are small and the natural frequency of the first unstable interacting mode is 1.12 rad/s, which is quite high as compared to the bandwidth of the control system. This, however, could also be inferred from Table 3. The complete orbit simulation was performed with solar torques. The technique mentioned in Refs. 9 & 11 (deadbeat nutation attenuation scheme) is used to keep the attitudes for type(b) system within bounds.

Table 3: Results of Simulation for a Single Unstable Interacting Mode & Actual Data of Structure from NASTRAN

TYPE OF SPACECRAFT BODY ATTITUDE CONTROL SYSTEM DESIGN PARAMETERS	STRUCTURAL MODE FREQUENCY rad/s	STABILITY: CLASS 1	STABILITY: CLASS 2	STABILITY: CLASS 3
(a) 3 RW $K_{1\ x/y/z}$ = 6.86/3.4/5.385 N•m/rad τ_1 = 40.0 sec	.0223 .05 ACTUAL	S S S	U S S	U S S
(b) BFMW + OFFSET THRUSTERS K_2 = 13.4 N•m/rad, τ_2 = 30.0 sec	.10 .14 ACTUAL	S S S	U S S	U S S
(c) SKEWED BFMW + OFFSET THRUSTERS K_3 = .24, N.m/rad, K_4 = 45, N.m.s/rad T_1 = 47.6 sec K_5 = .005, N.m/rad K_6 = 50.0, N.m.s^2/rad K_7 = .0001, N.m.s/rad T_2 = 10.0 sec	.10 .14 ACTUAL	S* S S	U ** S S	U *** S S
(d) BFMW + 2RW SAME AS TYPE (a)	.003 .022 ACTUAL	S S S	S S S	S S S

NOTES:
ACTUAL — 10 STRUCTURAL MODES
U — UNSTABLE RESPONSE
S — STABLE RESPONSE

** Fig. 8
* Fig. 9
*** Fig. 10

In order to compare the performance of each control system in the presence of severe structural interaction, it was necessary to introduce a dummy unstable interacting mode. This mode has influence coefficients of opposite signs (ϕ_{a1}=+.01,ϕ_{s1}=-.01) and causes a phase shift of 180 degs. between the actuators and sensors. The natural frequency of this mode was varied to find the stability region of various spacecraft body attitude control systems. Results are shown in Table 3. for each system and for each class. It is seen that type (a) can withstand much lower structural frequencies than types (b) and (c). Results of types (b) and (c) were found to be same. The severity of the structural modes do not seem to have any effect on the stability of type (d) system even for very low structural modes.

It should be noted from Table 3 that at the frequency of 0.14 rad/s the Class 2 design results in an unstable attitude motion (Fig 8), whereas the Class 1 design results in a stable motion (Fig 9). This is because the actuators and sensors are colocated at the core (node 2). The Class 3 design is stable as long as the actuators and sensors are colocated. But, as seen from Fig 10, the motion is unstable. This is the consequence of intentionally non-colocating the actuators and sensors. The stability margin for types (a) and (d) was found to be different because of the added stiffness due to biased momentum wheel.

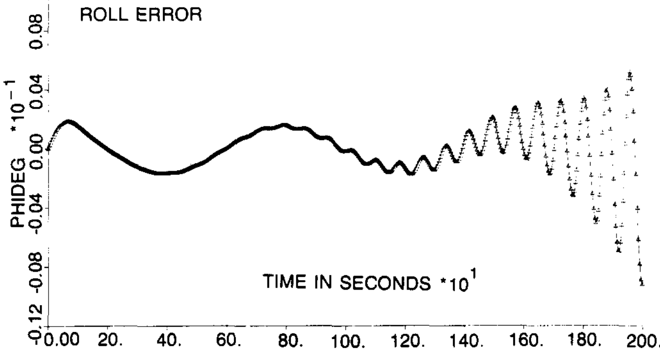


Figure 8: ω = .10 rad/s CLASS 2

Figure 8a

Figure 8b

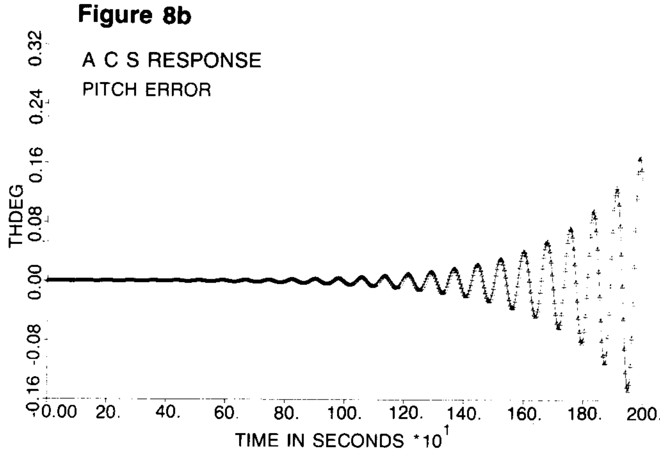


Figure 8c

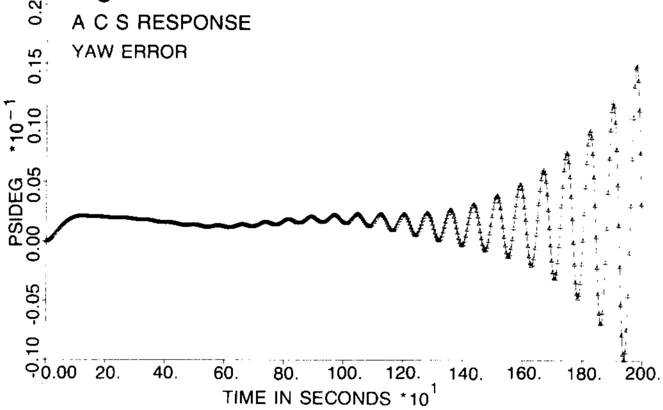


Figure 8d

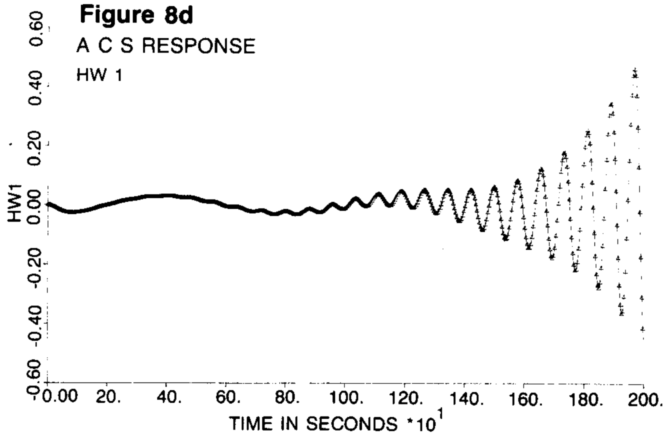


Figure 8e

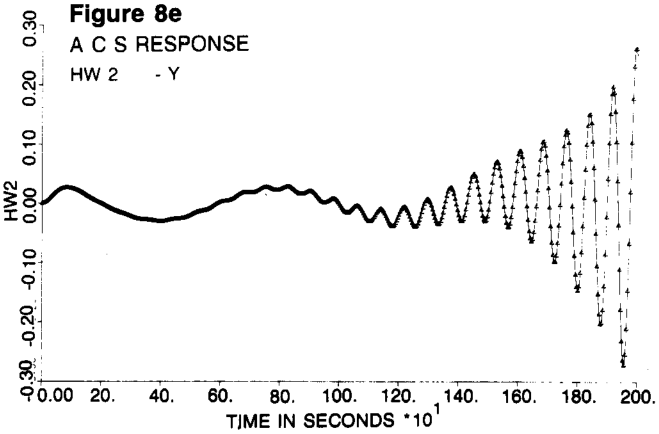


Figure 9: ω = .10 rad/s CLASS 1

Figure 9a

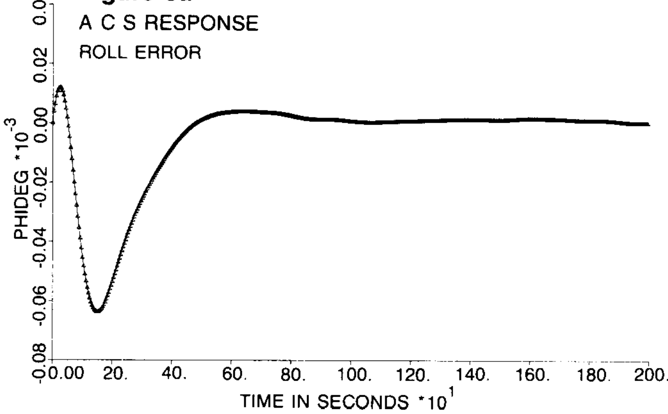


Figure 9b

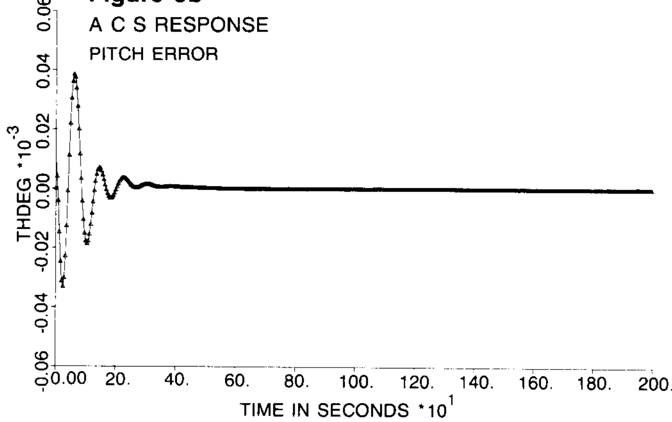


Figure 9c

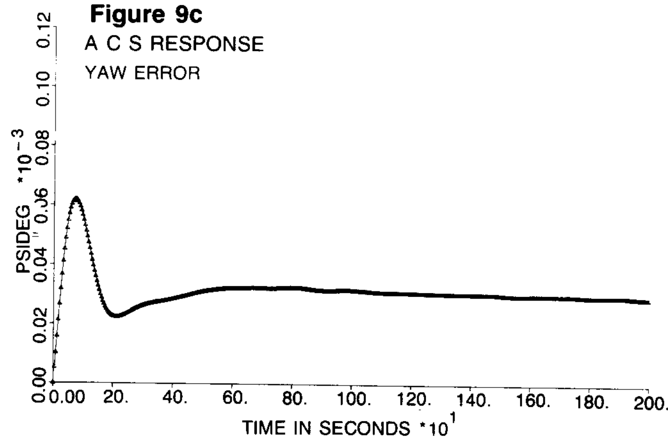
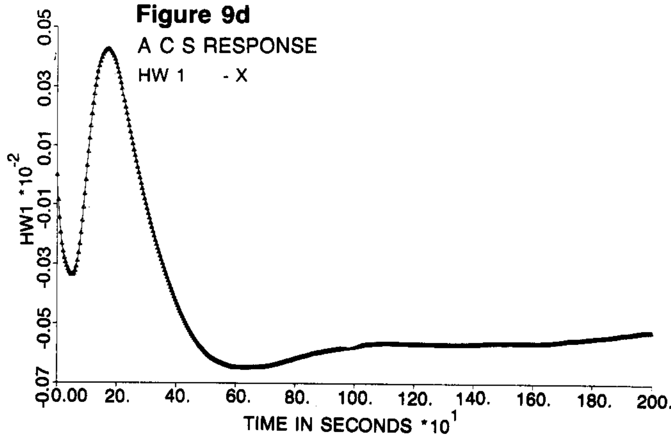
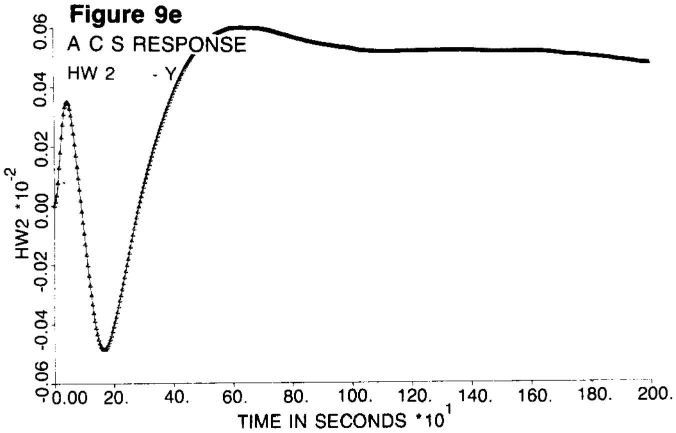


Figure 9d





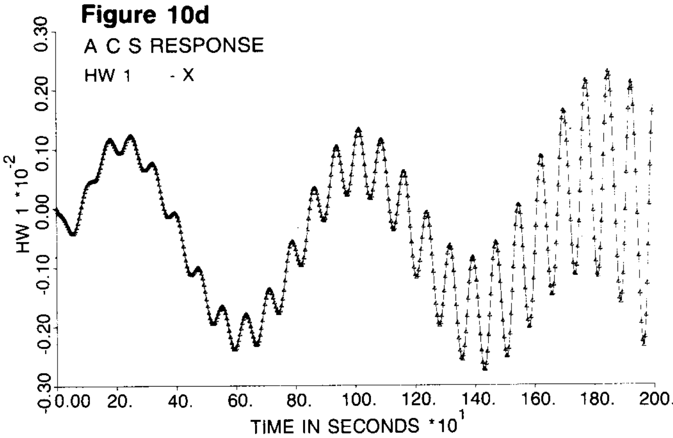
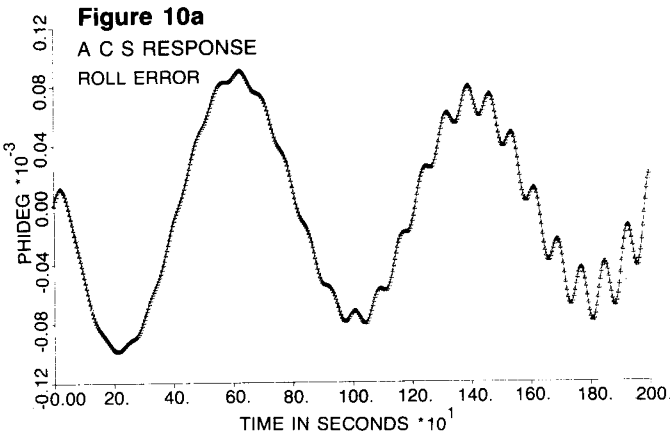
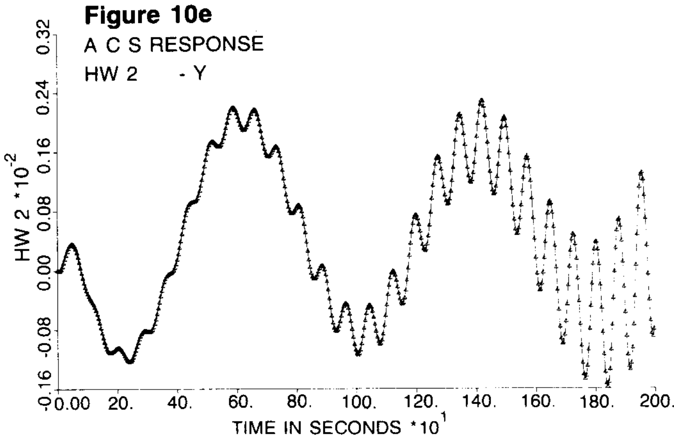
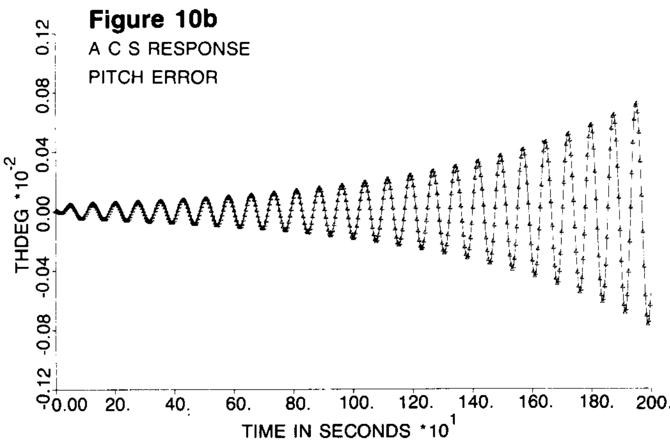
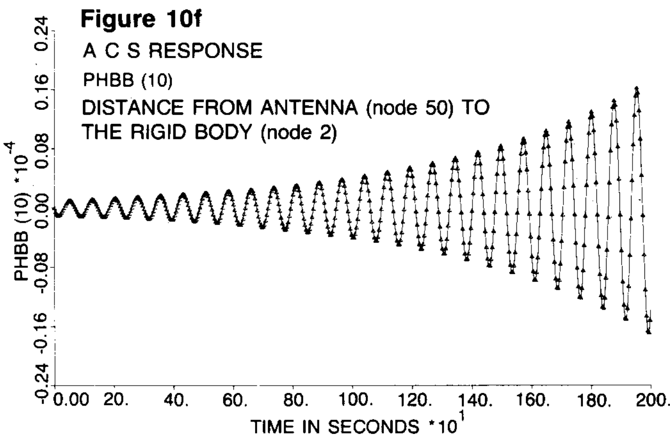


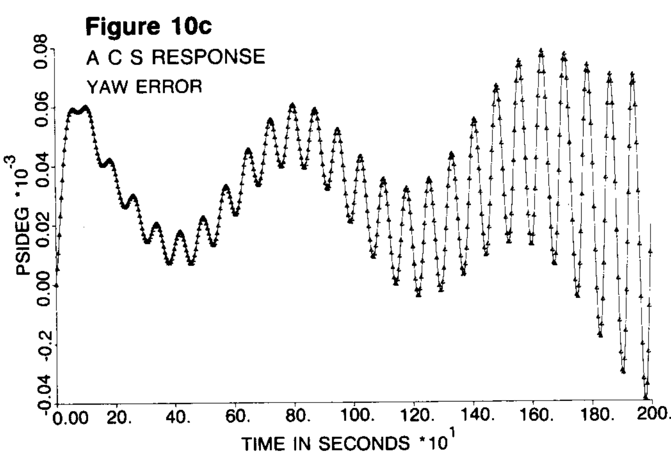
Figure 10: ω = .10 rad/s CLASS 3

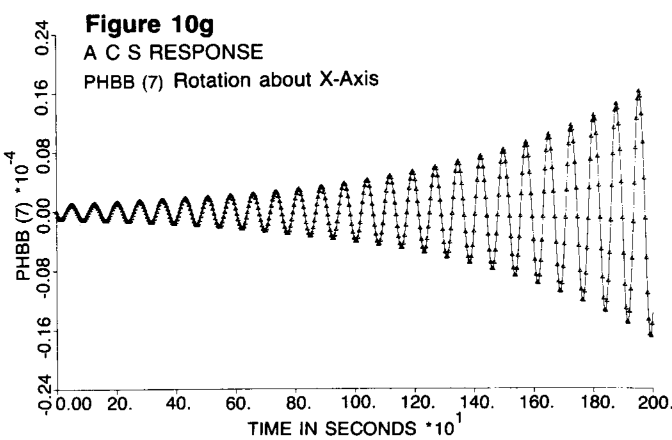


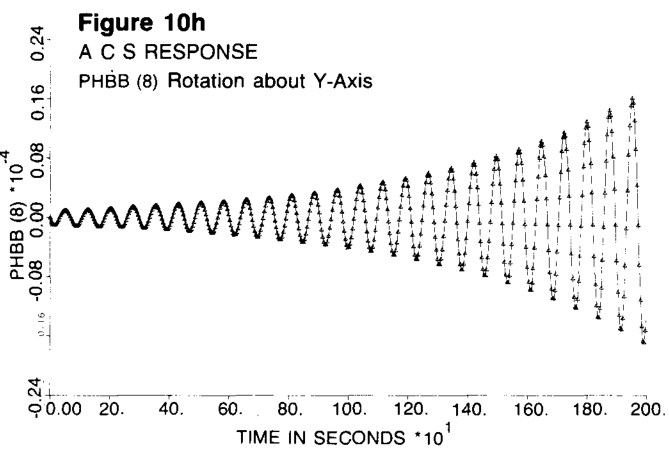












CONCLUSIONS

For the size of large spacecraft considered in this paper, all the attitude control systems result in a stable attitude motion. This is because the first unstable interacting mode occurs at a frequency of 1.12 rad/s, which is quite high as compared to the bandwidth of the control system. The thruster mode for momentum desaturation or attitude control could be accomplished with a pulse duration period that is long enough so that no structural/control interaction is possible.

To simulate the worst condition of structural interaction, a single dummy unstable interacting mode was introduced. The results demonstrate that the spacecraft body attitude control system with a single body-fixed momentum wheel along pitch axis and two reaction wheels along roll and yaw axes, is the most robust. The stability of single momentum wheel system and skewed momentum wheels system is found to be very sensitive to structural frequency variations. The qualitative performance of 3-reaction wheels system is found to lie between the above two extremes.

REFERENCES

1. R.Gran & M. Proise, ' Magnetic Control System for Satellites in Synchronous Orbit', AAS-81-006, Vol 45, Proceedings of the Annual Rocky Mountain Guidance & Control Conference held Jan 31-Feb 4., 1981, Keystone ,CO.

2. R.Gran, 'Qualitative Stability of Large Space Structure with non-colocated actuators and sensors', Proc of 20th IEEE Conference on Decision and Control, San Diego, CA, Dec 1981.

3. G.S. Nurre, R.S. Ryan, H. N. Scoffield & J.L.Sims, 'Dynamics & Controls of LSS', J of Guidance, Vol 7, No. 5.,Sept-Oct 1984.

4. Likins P.W. , 'Dynamics & Controls of flexible Spacecraft', TR 32-1329, Rev 1, Jan 15,1970, JPL, Pasadena, CA.

5. G. Porcelli, 'Attitude Control of flexible space vehicles' AIAA Journal, No. 6, June 1972.

6. H. Bittner, E. Bruderle, Chr Roche & W. Schmidts, ' The ADCS of INTESLAT V spacecraft', Proc of ADCS Conference held in Noordijk, 3-6 Oct, 1977.

7. H.J.Dougherty, E.D. Scott, J.J. Rodden,' Analysis and design of WHECON an attitude control concept', AIAA 2nd communications satellite systems conference, San Francisco, CA, April 8-10,1968.

8. H.J.Dougherty, K.L.Lebsock, J.J.Rodden,' Attitude stabilization of synchronous comm. satellite employing narrow beam antennas', J of Spacecraft, Vol 8, No. 8, Aug 1971.

9. R.P.Iwens, A.W Fleming and V.A. Spector,' Precision attitude control with a single BFMW', AIAA Mech & Control of Flight Conference, Papaer 74-894, Aug 5-9, 1974, Anaheim, CA.

10. E.D. Scott, ' Pseudorate Sawtooth Pulse-Reset control system and design', J of S/C, Vol 4, No 4, No. 6, June 1967.

11. J.S.C. Yuan, ' Deadbeat nutation controller for momentum bias stabilized S/C', Vol 3, No. 4, July-Aug 1980, Journal of Guidance and Controls.

12. R.M.Terasaki, 'Dual reaction wheel control of S/C pointing', Symposium of attitude stabilization and control of spin S/C, SAMSO and Aerospace Corp., El Segundo, CA , Aug 1967.

13. K.L.Lebsock,' High pointing accuracy with a momentum bias ACS, J of Guid. & Controls, Vol. 3, No. 3., May-June 1980.

14. B. Wie, J.Lehner, Carl T. Plescia, ' Roll/Yaw control of flexible S/C using skewed bias momentum wheels', J of Guidance, Vol 8, No. 4, July-Aug 1985.

15. B. Wie , Carl T. Plescia, ' Attitude stabilization of flexible S/C during station keeping maneuver', J of Guidance, Vol 7, July-Aug 1984, pp 430-436.

16. S. Manabe, K.Tushiya, M. Inoue, ' Zero PID control for bias momentum satellites'; paper 76-4, presented at IFAC 8th congress, Kyoto, Japan, Aug 1981.

17. V.A.Spector and R.P.Iwens, ' Attitude control of connunications satellite during stationkeeping using a yaw estimator, AIAA paper 80-1733.