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# Spacecraft Flight Control System Design Selection Process for a Geostationary Communication Satellite

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TECHNICAL PAPER

# SPACECRAFT FLIGHT CONTROL SYSTEM DESIGN SELECTION PROCESS FOR A GEOSTATIONARY COMMUNICATION SATELLITE

## I. INTRODUCTION

The Earth's first artificial satellite, *Sputnik I*, slowly tumbled in orbit. The first U.S. satellite, *Explorer I*, also tumbled out of control.[1] In 1962 *Alouette I*, and in 1964 *Explorer XX*, both suffered rapid spin decay due to solar torque. In 1969, the Applications Technology Satellite 5 (ATS5) quickly began to tumble and went unstable due to energy dissipation in the heat pipe, and entered a flat spin.[2] Today, as we launch the Mars observer and the Cassini spacecraft, and with missions demanding increasing life expectancies, satellite stability and control has become a much higher priority.

In order to select an attitude control system for a spacecraft (S/C) and to investigate the stability requirements of that S/C, first the anticipated disturbance torques must be identified and quantified. Next, appropriate attitude control system options to counteract these torques must be reviewed according to the specifications of the S/C mission, and the dynamic stability of the S/C verified. To see the process, a geostationary communication satellite with a life expectancy of 10 to 14 years is used as an example.

## II. ASSESSMENT OF DISTURBANCE TORQUES

The anticipated disturbance torques consist of environmental torques and torques internal to the S/C.

**Aerodynamic.** The interaction of the upper atmosphere with a S/C's surface produces an aerodynamic torque about its center of mass. For S/C below 400 km,[3] the aerodynamic torque is the dominant environmental disturbance torque. It is customary to neglect aerodynamic effects above 500 km. In geostationary orbit (GEO) where the altitude is 35,786 km, this torque can be safely neglected.

**Magnetic.** Magnetic disturbance torques result from the interaction between the S/C's residual magnetic field and the geomagnetic field. The primary sources of magnetic disturbance torques are: S/C magnetic moments, eddy currents, and hysteresis. Of these, the S/C's magnetic moment is usually the dominant source of disturbance torque. This disturbance torque is a function of the geocentric magnetic flux density, and is of significant consideration below 1,500 km. Since the flux density decreases with altitude, the magnetic torque can be neglected for an S/C in GEO.

**Gravity Gradient.** Any nonsymmetrical S/C in orbit is subject to a gravitational torque because of the variation in the Earth's gravitational force over the S/C body. A spherical or non-spherical Earth model can be used. The noncircularity of the equatorial cross section of the Earth, as expressed by the tesseral terms of the Earth's gravitational potential, causes a longitude drift rate which is a function of longitude over which the satellite is stationed. For a satellite whose longitude is maintained within a narrow band by station-keeping maneuvers, this tesseral acceleration can be

assumed to be constant. Gravity gradient torque is normal to the local vertical and vanishes for a spherically symmetric S/C. The gravity-gradient disturbance torque for a low Earth orbit (LEO), weak at best, is over 200 times weaker at GEO, and can be neglected.

Collision. Longitudinal separations of neighboring S/C in GEO are regulated by the International Telecommunication Union to restrict both intersatellite and intersystem interference. Studies are being conducted to investigate the possibilities of sharing an allocated longitudinal slot by more than one satellite.[4] Current longitudinal band separation is ±0.1° (74 km). This sharing of assigned longitudinal slots will increase chances of collision and demand more accurate S/C control systems. A communication satellite in a shared slot would need increased accuracy. More stringent specifications in terms of jitter and drift rate and higher stability are covered in the literature.[5] Collision torque is neglected in this assessment.

Debris, Micrometeorite. Encounters with large particles can degrade S/C surface properties in time, can deteriorate thermal coatings and solar cells, and small high speed particles can cause cratering. However, these encounters usually do not produce significant disturbance torques. For this assessment, the disturbance torque from debris and micrometeorites is neglected.

Solar Radiation Torque. Because the solar radiation varies as the inverse square of the distance from the Sun, the solar radiation pressure is essentially altitude independent for S/C in Earth orbit. The major factors determining the radiation torque on a S/C are the intensity and spectral distribution of the incident radiation, the geometry of the surface and its optical properties, and the orientation of the Sun vector relative to the S/C. Torque due to solar radiation pressure, $T_{SP}$, is highly dependent on the type of surface being illuminated, and also on the S/C geometry. An ideal surface is either transparent, absorbent, or a reflector, but most S/C surfaces are a combination of all three. Reflectors are diffuse or specular. In general, solar arrays are absorbers and the S/C body is a reflector.

The torque due to solar radiation can be estimated by

$$T_{SP} = P_S A_S L_S (1+q) \cos i \ ,$$

where

$P_S = 4.617 \times 10^{-6} \ \text{N/m}^2 = $ solar constant

$A_S = $ area of S/C surface

$L_S = $ center-of-pressure to center-of-mass offset

$i = $ angle of incidence of Sun

$q = 0.6 = $ reflectance factor .[6]

Internal Torques. Internal torques are defined as torques exerted on the main body of a S/C by internal moving parts such as its reaction wheels, flexible booms, or partially filled propellant tanks. In the absence of external torques, the total angular momentum remains constant. However, internal torques can alter the system's kinetic energy and redistribute the S/C's angular momentum among its component parts in ways which can change its dynamic characteristics.[3] For example, in a spinning S/C, angular momentum can be transferred from the nominal spin axis to another principal

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axis, resulting in nutation, uncontrolled tumbling, or flat spin. These undesirable results are often best countered by attitude-stabilization systems based on other internally generated torques such as reaction control systems (RCS's), nutation dampers, reaction wheels, and other movable-mass stabilizing mechanisms.

The most important anticipated S/C disturbance torques have been assessed. At the design altitude, the quantified dominant disturbance torque has been determined to be the solar radiation torque. Figure 1 shows the relative magnitudes of the considered environmental disturbance torques.[1]
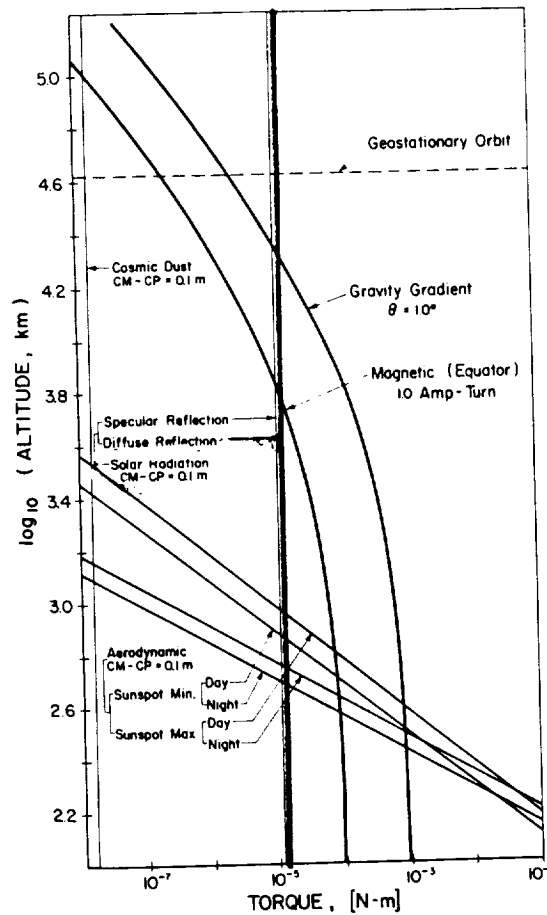


Figure 1. Environmental disturbance torque comparisons.

## III. CONTROL TORQUE OPTIONS

Spin Stabilization. This is the most common passive control technique in which the entire S/C is rotated so that the momentum vector remains approximately fixed in inertial space. However, this method requires the use of an active control system to periodically adjust the S/C attitude and spin rate and to counteract disturbance torques. RCS's are commonly used. A minimum of two reorientation thrusters and two spin rate control thrusters are required. This type of control system also requires nutation damping where the nutation is caused by an unbalanced S/C or the elasticity of the S/C structure. The S/C normally spins about its major principal axis for stability and is called single-spin control. Spin stabilization is a simple and effective control technique and requires no moving parts, however, it is limited to S/C for which the spin itself does not inhibit the S/C function.

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Dual Spin Control. The S/C has a rotating wheel and a platform, or consists of two rotating components spinning at different rates. This is a passive control system, but it requires the use of an active control system to adjust the S/C attitude and spin rate and to counteract disturbance torques. This type control system also requires nutation damping due to imbalances in the S/C and elasticity. Dual-spin control operates on the same principle as a single-spin, but provides platforms for both scanning and pointing instruments. With a two-component S/C, additional complexity arises because of the need for bearings and support structures separating the two components.

Gravity Gradient. The differential gravitational forces acting on an asymmetric S/C force the minor axis to be perpendicular to the gravitational equipotential. The pointing accuracy is typically 1° to 4°. This type of control is only applicable on S/C where one principal axis is less than the others, and best on a prolate body, causing the minor axis to align along the nadir vector. To obtain the differential in moments of inertia, booms are often deployed along the minor axis. The gravity-gradient control torque causes the S/C to oscillate or librate about the pitch axis, and a passive damper is generally required to minimize the amplitude of the oscillation. Gravity-gradient control systems require no moving parts other than in some cases extendable booms which can be 230-m long each. Because the gravity-gradient torque decreases as the inverse cube of the vector distance from the Earth, these control systems are best for LEO.

Nutation Damping. A nutation damper aligns the spin axis with the angular momentum vector by dissipating the excess kinetic energy and moves the S/C by removing the nutational motion. A momentum control system will tend to exhibit nutation when within the RCS deadbands. The amplitude of this nutation is dependent on the minimum impulse bit for the RCS.[7] A new method of nutation damping control which does not require momentum desaturation has been proposed by Davis and Levinson in reference 8.

Passive Versus Active Control. The most common active S/C control systems involve mass expulsion devices, such as gas jets or ion thrusters; momentum wheels; and electromagnetic coils. Reference 7 presents a variety of momentum control systems. Greater vehicle control flexibility is possible, and control torques are larger with active control.

Magnetic Coil. These control systems use magnetic torquing for control. Electromagnets and iron-core magnets are used for both stabilization and maneuvering. Electromagnetic control systems vary the control coils' polarity and direction to match the Earth's magnetic field to produce a torque to change attitude. In most systems, a set of three mutually perpendicular coils are used.[3] Some S/C use combinations of magnetic coil control and RCS to augment a momentum wheel system. Magnetic coil control systems require no moving parts, complex hardware, or expendables, however, they are slow in maneuvering and also, only appropriate for S/C at altitudes less than GEO.

Momentum Control. Momentum wheel control systems can be used for S/C maneuvering and stabilization. They maintain attitude by momentum exchange between the S/C and the wheel. As a disturbance torque acts on the S/C along one axis, the wheel reacts, absorbing the torque and maintaining the attitude. The wheel spin rate increases or decreases to maintain a constant attitude. Momentum wheel control systems are particularly suited for attitude control in the presence of cyclic torques or random torques. Secular torques cause the wheel speed to either increase or decrease monotonically until the wheel speed is outside the operational constraints. An active control system must then be used to restore the momentum wheel speed to its nominal operating value. Momentum wheel control systems can have wheels on one, two, or three axes. Figure 2 shows several possible configurations.[7] A two-wheel system for an Earth oriented S/C normally has one wheel along the pitch axis for pitch control and the other on either the roll or the yaw axis for roll/yaw control.
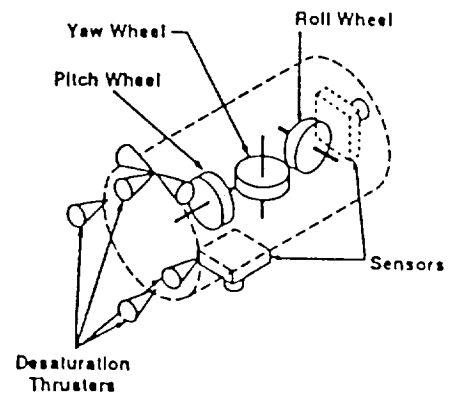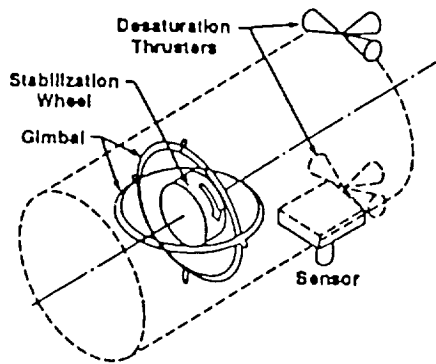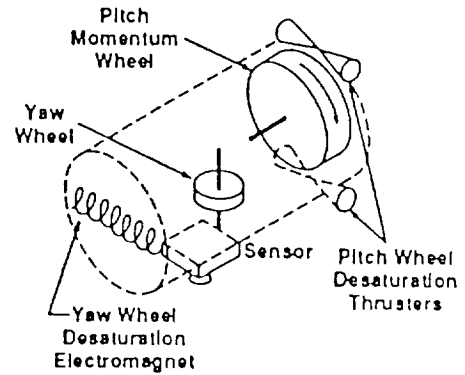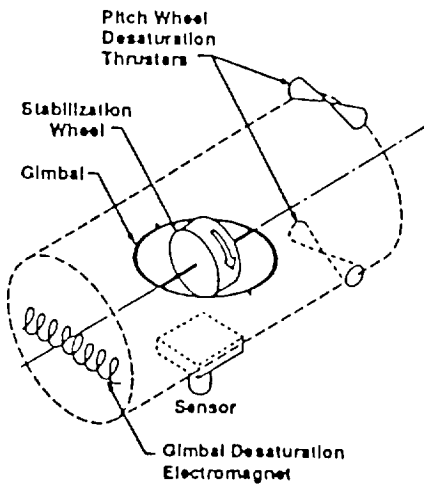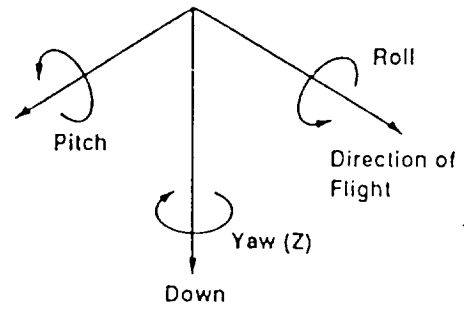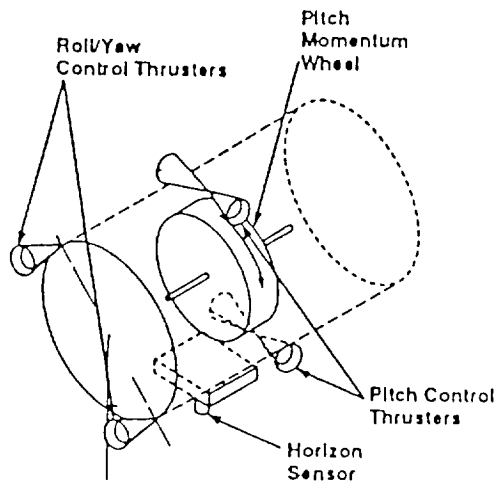
Figure 2. Various momentum control systems.

Gimbaled momentum wheels change both momentum magnitude and direction. The double-gimbaled momentum wheel permits a continuous rotation of a S/C if the nominal direction of the momentum vector and the S/C's rotation axis are aligned. The three-axis control provided by the gimbaled momentum wheel control system is well suited for S/C that must be aligned periodically to different ground stations. Momentum control systems have proven performance and relative simplicity, permit high accuracies, operate more smoothly than mass expulsion systems, and produce no exhaust contaminants. They can be mixed and matched to suit specific requirements, but do need auxiliary torque to desaturate the momentum wheels.

Bias Momentum. In this type of control system, one or more wheels provide a bias or nonzero angular momentum. Gyroscopic stiffness is provided against periodic disturbance torques, and variable momentum storage capability is provided about its spin axis. Small, high-speed wheels are usually preferred due to their low size and weight. Advantages of this control system are short-term stability against disturbance torques similar to spin stabilization, roll/yaw coupling that permits yaw angle stabilization without a yaw sensor, and a momentum wheel that may be used as an actuator for pitch angle control. Thus, a momentum bias control system can provide three-axis control with less instrumentation than a three-axis reaction wheel.

Control Moment Gyro (CMG). This control system can be a single or double gimbaled wheel spinning at a constant rate. Single-gimbal CMG's are used for high torque maneuvering. Double-gimbal CMG's are used to absorb cyclic disturbance torques. This method of S/C control is used on the *MIR* Space Station and Space Station *Freedom*, and is most suitable where large control torques are required.

Reaction Wheels. Reaction torques are generated about the spin axis by accelerating or decelerating a wheel from its nominal spin rate of zero. The reaction torque causes the S/C to rotate in the opposite direction. Three orthogonal reaction wheels can provide three-axis control and high pointing accuracy. Reaction wheel control systems are well suited for cyclic torque absorption and for low torque momentum transfer during reorientation maneuvers.[7] Because the disturbance torques in GEO are small, it is possible to use small reaction wheels to absorb them with an active control system to maintain three-axis stability. Advantages of three-axis reaction wheel control systems are capability of continuous high-accuracy pointing control, large angle slewing maneuvers without fuel consumption, and compensation for cyclic torques without fuel consumption. Configurations of more than three reaction wheels can be used providing backups. In this case, a steering law is required to distribute the momentum between the wheels when all are operating simultaneously. For example, the Hubble space telescope uses a four-wheel reaction control system.

Three-Axis Control. Attitude acquisition can take up to a few weeks and involves the maneuvering necessary to reorient and reconfigure the S/C from tip-off (separation from the launch vehicle) to its mission operation mode. The control problems unique to attitude acquisition include the deployment of extendable booms, antennas, solar panels, and flight control surfaces. A new method of attitude acquisition for a communication satellite has been developed using quaternion feedback to autonomously despin the S/C.[9] For a short mission, three-axis control can be achieved entirely by an RCS. Thrusters are usually fired in pairs to minimize translational motion. RCS thrusters are efficient in maneuvering the S/C, are simple to operate, and are not limited to a specific environment. However, they are more costly, require more hardware, and are limited by fuel onboard.

For a mission life of 10 to 14 years, a control system composed entirely of RCS is not recommended. Various combinations of momentum control systems can be used to provide three-axis control. A three-axis momentum control system has momentum wheels along all three axes and may have six or more wheels along nonorthogonal axes. Figure 3 lists various three-axis control system configurations. Reference 14 incorporated a hybrid of these.

| | |
|---|---|
| SINGLE MOMENTUM WHEEL | PITCH MOMENTUM WHEEL/YAW REACTION WHEEL |
| PITCH MOMENTUM WHEEL/THRUSTER | DOUBLE-GIMBAL MOMENTUM WHEEL |
| SINGLE-GIMBAL MOMENTUM WHEEL | THREE REACTION WHEELS |
| CANTED SCAN WHEEL MOMENTUM BIAS | |

Figure 3. Three-axis control configurations.

## IV. FLIGHT CONTROL SYSTEM DESIGN

After assessing the disturbance torque environment, and the S/C mission, and reviewing the control systems available, the selected flight control system design is:

An active, three-axix control, double-gimbaled, bias momentum control system with

        a. RCS

or

        b. Solar flight control surfaces

for desaturation.

The three-axis control provided by the gimbaled momentum wheel control system is well suited for satellites that must be aligned periodically to different ground stations and can be powered electrically from solar cells or onboard generators. Options A or B can be used for momentum desaturation of the wheel. In sizing the RCS, the duration of the desaturation impulses is a function of the amount of excess momentum. This is typically about 1 percent of the nominal wheel momentum. Efforts to reduce thruster usage on GEO satellites in order to reduce fuel consumption are well documented.[10]

Option B uses flight control surfaces which put the dominant disturbance torque, the solar disturbance torque, to advantage to provide vehicle control and wheel desaturation, instead of using an RCS. Figure 4 shows a recommended flight control system, and figure 5 shows a typical configuration of a S/C using flight control surfaces. This particular configuration has eight flight control surfaces for attitude stabilization and control.[11]
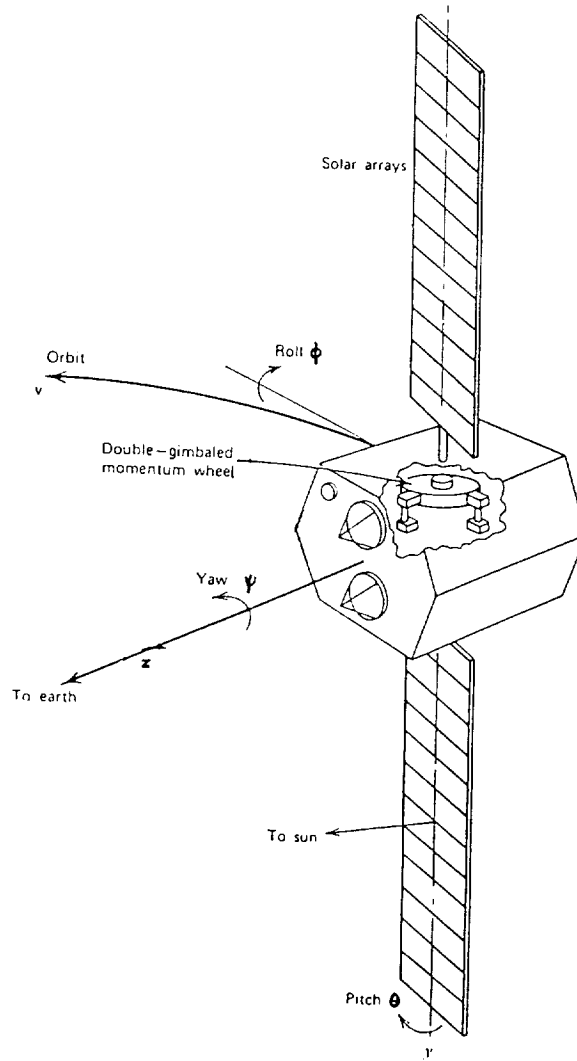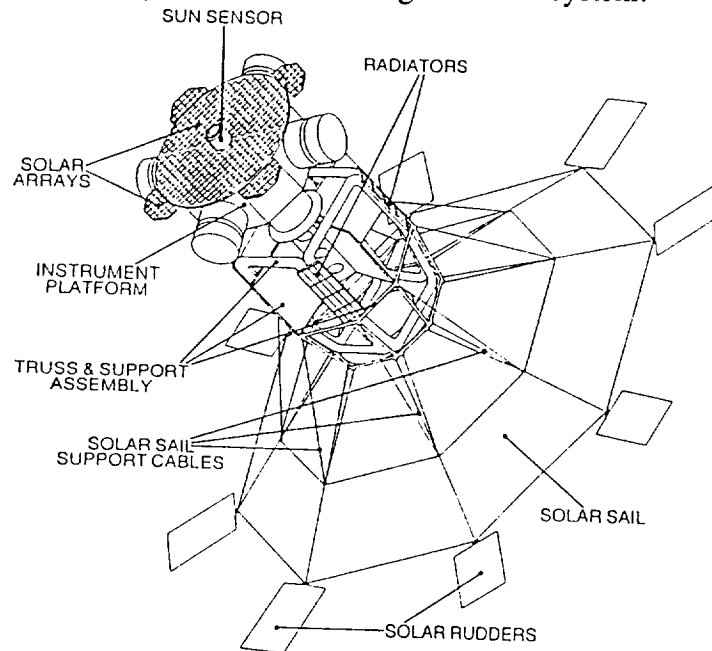
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Figure 4. Selected flight control system.



Figure 5. Option B using flight control surfaces for desaturation.

Euler's moment equations for this S/C control system design are,

$$\bar{T} = \dot{\bar{h}} = \dot{\bar{h}}_b + \bar{\omega} \times \bar{h} \quad ; \quad \bar{h} = \bar{h}_v + \bar{h}_w \quad ; \quad \bar{h}_v = I_x \omega_x \bar{i} + I_y \omega_y \bar{j} + I_z \omega_z \bar{k}$$

$$\bar{T} = [I_x \dot{\omega}_x - \dot{\delta}(\sin\delta\sin\gamma)h_w + \dot{\gamma}(\cos\delta\cos\gamma)h_w + (\cos\delta\sin\gamma)\dot{h}_w$$

$$+ \omega_y(\omega_z I_z - h_w \sin\delta) - \omega_z(\omega_y I_y - h_w \cos\delta\cos\gamma)]\bar{i}$$

$$+ [I_y \dot{\omega}_y + \dot{\delta}(\sin\delta\cos\gamma)h_w + \dot{\gamma}(\cos\delta\sin\gamma)h_w - (\cos\delta\cos\gamma)\dot{h}_w$$

$$+ \omega_z(\omega_x I_x + h_w \cos\delta\sin\gamma) - \omega_x(\omega_z I_z - h_w \sin\delta)]\bar{j}$$

$$+ [I_z \dot{\omega}_z - \dot{\delta}(\cos\delta)h_w - (\sin\delta)\dot{h}_w + \omega_x(\omega_y I_y - h_w \cos\delta\cos\gamma)$$

$$- \omega_y(\omega_x I_x + h_w \cos\delta\sin\gamma)]\bar{k} \quad , \quad \text{(ref. 2)}$$

where

$T$ = the total disturbance torque on the S/C

$\bar{h}$ = the total angular momentum

$\dot{\bar{h}}_b$ = the rate of change of angular momentum with respect to the body

$\bar{\omega}$ = angular velocity

$\bar{h}_v$ = angular momentum of vehicle

$\bar{h}_w$ = angular momentum of wheel

$\delta$ = roll gimbal angle

$\gamma$ = yaw gimbal angle.

Wheel momentum components are,

$$h_{wx} = (\cos\delta\sin\gamma)h_w \quad ; \quad h_{wy} = -(\cos\delta\cos\gamma)h_w \quad ; \quad h_{wz} = -(\sin\delta)h_w \ .$$

These equations are highly nonlinear, and Lyapunov's direct method is still one of the most powerful techniques available today for stability analysis of nonlinear systems.[12][13]

For small gimbal deflections, small deviations from nominal wheel momentum, and

$$h_n \gg \max [I_x \omega_o, I_y \omega_o, I_z \omega_o] \ ,$$

and $I_x = I_z$, the above becomes three equations in pitch $\theta$, roll $\phi$, and yaw $\psi$. Setting two of the three principal moments of inertia equal avoids the asymmetric case, where the solution of Euler's moment equations cannot be written in terms of trigonometric functions. In the asymmetric case the solution involves the Jacobian elliptic functions (see references 15, 16, and 17).

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Pitch: $T_y = I_y \ddot{\theta} + \dot{h}_y$ ,

Roll: $T_x = I_x \ddot{\phi} + \omega_o h_n \phi + h_n \dot{\psi} + \dot{h}_x - \omega_o h_z$ ,

Yaw: $T_z = I_z \ddot{\psi} + \omega_o h_n \psi - h_n \dot{\phi} + \dot{h}_z - \omega_o h_x$ ,

where $\dot{h}_y, \dot{h}_x, \dot{h}_z$ are control functions

$h_n$ = nominal wheel momentum

$\omega_o$ = GEO orbital rate = $7.28 \times 10^{-5}$ rad/s

$T_x = 2 \times 10^{-5}$ (1–2 sin $\omega_o t$) Nm $\Big\rangle$

$T_y = 10^{-4}$ (cos $\omega_o t$) Nm $\Big\}$     Solar pressure torques ($t = 0$ at 6 a.m./p.m.)

$T_z = -5 \times 10^{-5}$ (cos $\omega_o t$) Nm $\Big/$

$I_x = I_z = 3{,}000$ Nms$^2$

$I_y = 660$ Nms$^2$

S/C mass = 1,000 kg

Pitch and roll accuracy = 0.05°

Yaw accuracy = 0.40°.

Pitch Control. To provide the required pitch damping, a pitch control law is selected

$$\dot{h}_y = K_P(\tau_P \dot{\theta} + \theta) \ ,$$

where $K_P$ = pitch autopilot gain in Nm/rad and $\tau$ = time constant in seconds. Therefore,

$$T_y = I_y \ddot{\theta} + K_P \tau_P \dot{\theta} + K_P \theta \ \Rightarrow$$



PSEUDORATE MODULATOR
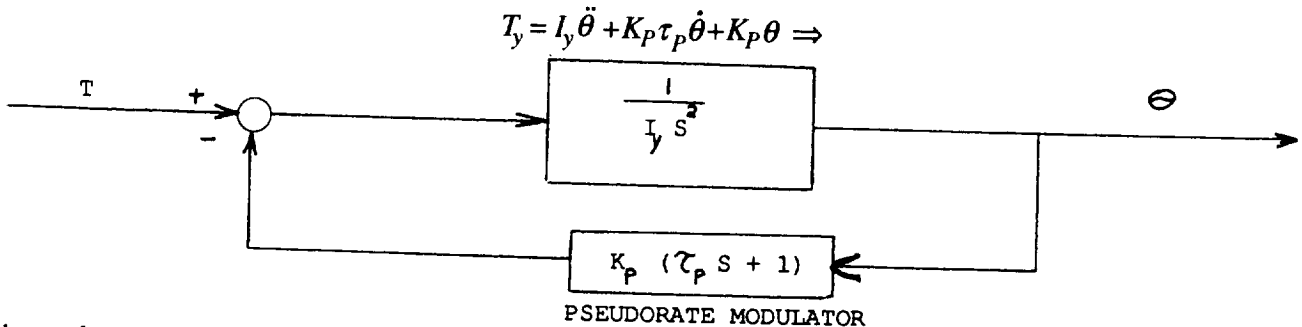
Since the sensors employed can provide only direct measurement of angles and damping requires knowledge of angular rates, a pseudorate modulator using a Schmitt trigger with hysteresis is used in this loop.

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$$\frac{\theta(S)}{T(S)} = \frac{1}{I_y S^2 + K_P \tau_p S + K_P} \Rightarrow$$

(Rate gyros are not appropriate here because they cannot detect very low rate while satisfying the long-life requirement.)

$$\omega_{\text{pitch}} = \sqrt{\frac{K_P}{I_y}} \quad ; \quad \zeta_{\text{pitch}} = \frac{\tau_P}{2}\sqrt{\frac{K_P}{I_y}} \quad ; \quad \tau_{\text{pitch}} = \frac{2}{\omega_P} ,$$

where $\omega_P$ = pitch motion natural frequency and $\zeta_P$ = pitch damping.

Selection of pitch autopilot gain $K_P$ is based on steady-state error and response time. Steady-state errors must be well below the pitch accuracy limit. The maximum magnitude of solar pressure torque is expected to be $10^{-4}$ Nm about the pitch axis. Assuming $\tau_P \ll$ orbital period, and the critical damping $\zeta_P = 1$, the maximum steady-state error is estimated through the final value theorem ($S = 0$) as

$$\theta_{SS} = \frac{T_y}{I_y \omega_P^2} \text{ rad} \quad \Rightarrow \quad \frac{10^{-4}\,\text{Nm}}{K_P} < 0.000873 \quad \Rightarrow$$

$$K_{\text{pitch}} > 0.1145 \text{ Nm/rad} .$$

Since,

$$\tau_P = 2\sqrt{\frac{I_y}{K_P}} \quad ; \quad K_{\text{pitch}} = 0.1145 \text{ Nm/rad} \quad \Rightarrow \quad \tau_{\text{pitch}} = 152 \text{ seconds} .$$

Fast response times are desirable, and larger values of $K_P$ will result in faster response time.

Choose

$$\boxed{K_{\text{pitch}} = 0.4125 \text{ Nm/rad}}$$

which will give a response time of 80 seconds.

Roll/Yaw Control. Control torques are produced through gimbal deflections. Damping can be provided through selection of an actuator control law. This will also yield a steady-state yaw error whose magnitude is a function of $h_n$.

Active roll/yaw control is investigated using the above roll and yaw equations. Roll response to disturbance torques should be fast and well damped. This will also minimize coupling of roll errors into yaw. The roll control law used is,

$$M_{xc} = \dot{h}_x - \omega_o h_z = K \tau \dot{\phi} + K \phi - \omega_o h_n \phi ,$$

where $M_{xc}$ is the commanded roll control torque.

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The ideal yaw response should be well damped and decoupled from roll. The yaw control law used is,

$$M_{zc} = \dot{h}_z + \omega_o h_x - h_n \dot{\phi} = -kK(\tau\dot{\phi} + \phi)$$

where $M_{zc}$ = commanded yaw control torque and $k$ = yaw-to-roll gain ratio.

When orbit rate decoupled momentum commands are used, the above control laws become:

$$M_{xc} = \dot{h}_{xd} - \omega_o h_{zd} = K(\tau\dot{\phi} + \phi) \ ,$$

$$M_{zc} = \dot{h}_{zd} + \omega_o h_{xd} = -kK(\tau\dot{\phi} + \phi) \ .$$

Using a Laplace transformation on this set of equations and solving the developed transfer function,

$$\omega_{roll} = \sqrt{\frac{K}{I_x}} \ , \quad \zeta_{roll} = \frac{\tau}{2}\sqrt{\frac{K}{I_x}} \ ,$$

$$\omega_{yaw} = \sqrt{\frac{h_n \omega_o}{I_z}} \ , \quad \zeta_{yaw} = \frac{k}{2}\sqrt{\frac{h_n}{I_z \omega_o}} \ .$$

The high frequency roots ($\omega_{roll}$, $\zeta_{roll}$) are characteristic of roll dynamics, while the low frequency roots ($\omega_{yaw}$, $\zeta_{yaw}$) dominate the yaw motion during yaw error correction. A large value of $h_n$ will result in fast yaw corrections with respect to orbit period.

The roll autopilot gain $K_R$ is selected to limit steady-state roll error caused by a constant roll torque and to provide a fast response. The steady-state roll error produced by a constant roll torque is

$$\phi_{SS} = \frac{T_x}{K_R} \ .$$

Based on the maximum roll torque resulting from solar pressure and the allowable roll error of 0.05°, this yields

$$K_{roll} > 0.07 \ nm/rad \ .$$

$$K_{roll} = 0.07 \ Nm/rad \quad \Rightarrow \quad \tau_{roll} = 414 \ seconds \ ,$$

where

$$\tau_{roll} = 2\sqrt{\frac{I_x}{K_{roll}}} \ .$$

Choose,

$$\boxed{K_{roll} = 1.875 \ Nm/rad}$$

which will give a response time in roll of 80 seconds.

$$\tau = 80 \ s \quad \Rightarrow \quad \omega = 0.025 \ rad/s \ .$$

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The solutions in yaw control from above are:

$$\omega_{yaw} = \sqrt{\frac{\omega_o h_n}{I_z}} \qquad k = 2\sqrt{\frac{I_z \omega_o}{h_n}} \quad .$$

For

$$h_n = 200 \text{ Nms} \;, \; k = 0.0033 = \frac{K_{yaw}}{K_{roll}} \;\Rightarrow$$

$$\boxed{K_{yaw} = 0.06188 \text{ Nm/rad} \;.}$$

The above satisfies

$$K_{roll}\tau_{roll}I_z > kh_n I_x$$

$$1.875 \,(80)\,(3,000) > (0.033)\,(200)\,(3,000)$$

$$150 \qquad > \qquad 6.6 \quad \Rightarrow$$

$$\boxed{h = 200 \text{ Nms} \;.}$$

Using $M = 3.2\, h^{.4}$ the mass of the wheel housing and electronics is 27 kg. Also,

$$\psi_{SS} = \frac{T_z + kT_x}{\omega_o h_n} = \frac{5\times10^{-5} + (0.033)\,6\times10^{-5}}{7.28\times10^{-5}\,(200)}$$

$$\psi_{SS} = 0.0036 \text{ rad} = 0.20° \;,$$

which is well below the yaw accuracy requirement of 0.40°.

In option A, the momentum saturation could be relieved with pitch thrusters. The time between impulses can vary from several minutes to about an hour. Typical pulse times range from 0.025 s to 0.1 s. For redundancy, six 0.1 N desaturation jets are recommended, two on each axis, although only three thrusters would be needed if thrust vectoring were employed. In option B, the momentum saturation could be relieved with the flight control surfaces.

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# V. S/C DYNAMIC STABILITY

In a S/C with a passive control system, such as a simple spin system, an unstable design will precess, then wobble, and finally tumble out of control due to the dissipation of energy. Even a wobble can generate irregular signals from a satellite. It has been well documented that dissipative torques on dynamically prolate S/C make them tumble out of control, while dynamically oblate S/C are stabilized spinning about their axis of symmetry. If the nominal S/C spin axis is other than the major principal axis, energy dissipation will result in an increase in nutation, which will finally become rotation about an axis perpendicular to the original axis and known as a flat spin. Recovering from a flat spin requires reorientation of 90° and has been approached in the literature using nonlinear S/C attitude dynamics.[13] Nutational stability has been studied using Lyapunov's second method by Pringle (1969). If the S/C has many rotating components with many dampers, the resulting equations have periodically varying coefficients, and stability can be studied using Floquet analysis. New possibilities for stabilization are made possible by constructing the S/C from two or more parts that spin with respect to each other.

A communication satellite attitude acquisition system can have reduced propellant consumption and smaller errors by scaling the feedback control system gains proportional to the S/C moments of inertia.[9] Additionally, Lyapunov stability analysis can be used to show this type of gain control is globally stable and robust to inertia uncertainty.[12][13] If the wheel nominal momentum has been correctly selected, momentum exchange permits cancellation of the cyclic torques, and only periodic momentum adjustment is necessary due to secular disturbance torques for on-station nominal operation. During the attitude acquisition sequence, the S/C can be spin-stabilized in apogee transfer, before the momentum wheel control system is activated. The despin can be executed with yo-yo or thrusters. A residual spin of 1° per second can be left to provide stability. Since the proposed flight control system uses feedback control, the preliminary stability criteria have been met by a selection of control system gains and wheel momentum which satisfy the Routh stability criteria.

# VI. CONCLUSIONS

(1) In order to see the design selection process, an assessment of anticipated disturbance torques has been conducted and the dominant disturbance torques identified and quantified.

(2) Appropriate S/C flight control systems for a communication satellite have been reviewed.

(3) A flight control system design has been selected. This is an active, three-axis control system which consists of a bias momentum system with the momentum wheel mounted along the pitch axis. Momentum desaturation can be obtained by either RCS or flight control surface options.

(4) Preliminary stability criteria have been investigated and met with a determination of the pitch, roll, and yaw autopilot gains, and sizing of the momentum wheel.

(5) Future work would include a root locus analysis for final gain selection and a Lyapunov stability analysis for the nonlinear S/C dynamics during the attitude acquisition sequence.

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The Earth's first artificial satellite, Sputnik I, slowly tumbled in orbit. The first U.S. satellite, Explorer I, also tumbled out of control. Now, as we launch the Mars observer and the Cassini spacecraft, stability and control has become a higher priority. This paper reviews the flight control system design selection process using as an example a geostationary communication satellite which is to have a life expectancy from 10 to 14 years.

Disturbance torques including aerodynamic, magnetic, gravity gradient, solar, micrometeorite, debris, collision, and internal torques are assessed to quantify the disturbance environment so that the required compensating torques can be determined. Then control torque options including passive versus active, momentum control, bias momentum, spin stabilization, dual spin, gravity gradient, magnetic, reaction wheels, control moment gyros, nutation dampers, inertia augmentation techniques, three-axis control, reaction control system (RCS), and RCS sizing are considered. A flight control system design is then selected and preliminary stability criteria met by the control gains selection.

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