Momentum Management and Attitude Control Design for a Space Station

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Control moment gyro momentum management via the periodic and continuous methods is presented for a "dual-keel" space station. For the periodic method, the gains in the momentum loop are based on momentum derivatives. For the continuous method, a linear quadratic regulator approach provides a means to achieve an integrated momentum management and attitude control system that seeks a torque equilibrium attitude and bounds the system momentum profile. By selecting the momentum and the controller gains, the system can emphasize attitude control and/or minimize control moment gyro momentum to satisfy experimental and dynamic conditions. Cross-feedback gains between the roll and yaw axes are selected to handle momentum coupling. The linear-quadratic performance index includes system momentum, control torque, attitude, and attitude rate errors. The system's stability and robustness to disturbance and uncertainties are established by classical frequency response and singular-value response methods.

Introduction

NONCYCLICAL external torques acting on the space station (Fig. 1) will lead to the momentum saturation of the control moment gyros (CMGs) unless a momentum management system is provided. To manage momentum, control torques are generated through the use of desaturation effectors, gravity-gradient torque, and/or aerodynamics to counter these disturbances. The gravity-gradient method, using attitude change, is preferred to the use of the reaction control system (RCS), which imposes disturbance to experiments, propellant penalty, and contamination. The low control authority and high cost of magnetic torquers are not desirable for the large momentum dumping demand of the station.

The gravity-gradient method tilts the station from the local vertical/local horizontal (LVLH) orientation to balance the aerodynamic torque with the gravity-gradient torque. This torque equilibrium attitude (TEA) can be commanded to an average value and updated periodically or continuously.

The early use of CMG momentum dumping for manned vehicles was applied for Skylab by Kennel.[1] The Skylab CMG momentum dumping method required maneuvers about two principal axes of large inertia. The day portion of the orbit was mainly for inertial hold, and desaturation maneuvers during orbital night removed secular momentum by gravity-gradient torques or RCS. Contrary to the Skylab, the space station attitude is constrained near LVLH to accommodate experiments without a pointing system. The disturbances on the station are greater due to more crew members, larger moment arms, and a varying configuration.

Hopkins and Hahn[2] have surveyed methods for planar space platform momentum management with attitude adjustment and aerodynamic desaturation using panels. A proportional, integral momentum loop was used by Shain and Spector[3] to cause the spacecraft to seek a pitch equilibrium attitude about which it would oscillate such that the momentum in the system is bounded.

Woo and Almanza[4] have developed a periodic momentum management concept that uses the derivative of gravity-gradient momentum as desaturation gains. The method featured a feed-forward momentum profile to handle expected momentum changes and emphasized the use of threshold logic for momentum dumping during an orbit. Hattis[5] suggested a predictive approach that required an environment model and CMG momentum to shape a desaturation function at once-per-orbit for removing expected momentum. Both the predictive and periodic concepts have advocated the use of a reference CMG momentum profile to determine the need for RCS assistance.

The emphasis of this paper is on summarizing a periodic method and elaborating on a continuous momentum management method applicable to the "dual-keel" configuration. Requirements and design goals are first identified. System dynamics and environmental disturbances are summarized for the LVLH flight mode. For the periodic method, the gravity-gradient momentum derivatives are presented. The approach of using linear quadratic regulator (LQR) design is emphasized together with the classical frequency response method to assure stability. The system dynamics modes present the expected dynamics for the open- and closed-loop cases. Singular-value frequency responses are used to demonstrate system performance sensitivity and robustness. Classical frequency and simulation response results are presented to demonstrate the stability and performance of the integrated design.

Requirements and Design Goals

The momentum management and attitude control system must provide space station attitude within 5 deg of LVLH, with an attitude rate boundary of 0.02 deg/s. These performance requirements may be exceeded during activities such as reboost, Orbiter berthing/docking, Orbiter plume impingement, and mobile service center activities and while the Orbiter is attached.

The design goal for nominal operation is to maintain the station attitude excursion to less than 0.2 deg from the average TEA and the total attitude within 5 deg of LVLH. The attitude excursion is relaxed to 1 deg during TEA seeking. The CMG momentum storage is sized to cover initial TEA seeking, worst-case natural environment, induced disturbances, system errors, and one CMG failure. The CMG momentum requirement for worst-case natural environment should be bounded to less than one CMG each for the in-plane and out-of-orbital plane direction.

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Linearized Dynamic Model

Assuming small roll, pitch, and yaw angles (ϕ, θ, and ψ) from LVLH and an average angular rate equal to the orbital rate ω_o, the linearized form of station dynamics can be shown as

$$I_X\ddot{\phi} - H\dot{\psi} + J_X\phi + T_{CX} = T_{DX} \quad (1a)$$

$$I_Y\ddot{\theta} + J_Y\theta + T_{CY} = T_{DY} \quad (1b)$$

$$I_Z\ddot{\psi} + H\dot{\phi} + J_Z\psi + T_{CZ} = T_{DZ} \quad (1c)$$

for the roll, pitch, and yaw axis, respectively, where

$$H = \omega_o(I_X + I_Z - I_Y) \quad (2)$$

is the station momentum coupling and

$$J_X = 4\omega_o^2(I_Y - I_Z) \quad (3a)$$

$$J_Y = 3\omega_o^2(I_X - I_Z) \quad (3b)$$

$$J_Z = \omega_o^2(I_Y - I_X) \quad (3c)$$

are the combined gravity-gradient and gyroscopic torque in roll, pitch, and yaw, respectively. The last two terms in Eq. (1) are the CMG control (T_{CX}, T_{CY}, T_{CZ}) and other external disturbance torques (T_{DX}, T_{DY}, T_{DZ}), respectively. The roll and yaw attitude motions are coupled through the gravity-gradient and gyroscopic terms while the pitch axis is uncoupled. The CMG momentum dynamics expressed in terms of control torque are

$$\dot{H}_X = T_{CX} + \omega_o H_Z \quad (4a)$$

$$\dot{H}_Y = T_{CY} \quad (4b)$$

$$\dot{H}_Z = T_{CZ} - \omega_o H_X \quad (4c)$$

The roll and yaw momentum couple through the orbital rate while the pitch axis is uncoupled. The given linearized model is used as the basis for the development of the flight control and momentum management system for the space station.

One of the disturbances, the aerodynamic torque, can be expressed by the average and cyclic components

$$T_{\text{AERO}} = T_{\text{AVE}} + T_{\text{CYC1}} \sin\omega_o t + T_{\text{CYC2}} \sin 2\omega_o t \quad (5)$$

The location of the static bodies contributes to the average torque. The diurnal bulge effect causes the cyclic torque component at orbital frequency, while the rotating power panels cause cyclic aerodynamic torque at twice the orbital frequency.

The average-pitch aerodynamic torque, $T_{\text{AVE}Y}$, causes secular momentum in the pitch axis. Similarly, secular momentum exists in the in-orbital-plane (roll/yaw) axes. The pitch secular aerodynamic torque can be balanced with the gravity-gradient torque [Eq. (3b)] by establishing an average pitch attitude from the LVLH as

$$\theta_{\text{AVE}} = T_{\text{AVE}Y}/3\omega_o^2(I_X - I_Z) \quad (6)$$

Once this average attitude is achieved by a momentum management system, the sum of the average torques is theoretically zero, and no secular momentum exists on successive orbits. Instantaneous TEA is achieved by the feedback from momentum and continuous attitude adjustment.

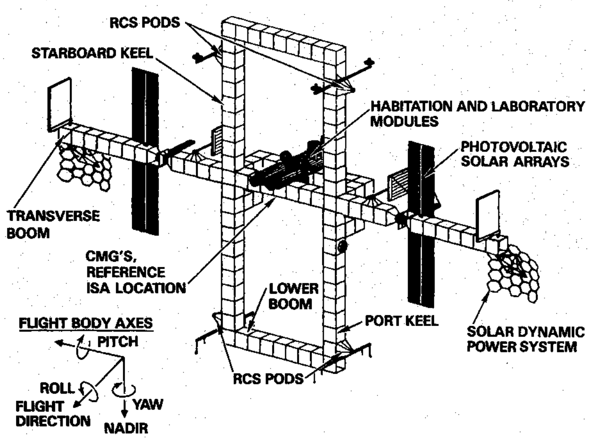

Fig. 1 "Dual-keel" space station.

Momentum Management Methods

The periodic momentum management method will be summarized and the continuous method will be discussed to greater depth.

Periodic Momentum Management

This method is suited for steady-state operation where the average TEA is adjusted once-per-orbit or as required. Figure 2 shows a functional diagram for this method. The attitude control design is separated from the momentum management design without optimizing the use of CMG momentum. The attitude control bandwidth of 0.01 Hz is established classically, and it is at least a factor of 10 separation between control and dominant structural frequencies. A sixth-order filter is used in each axis to attenuate and gain-stabilize the flexible body modes.

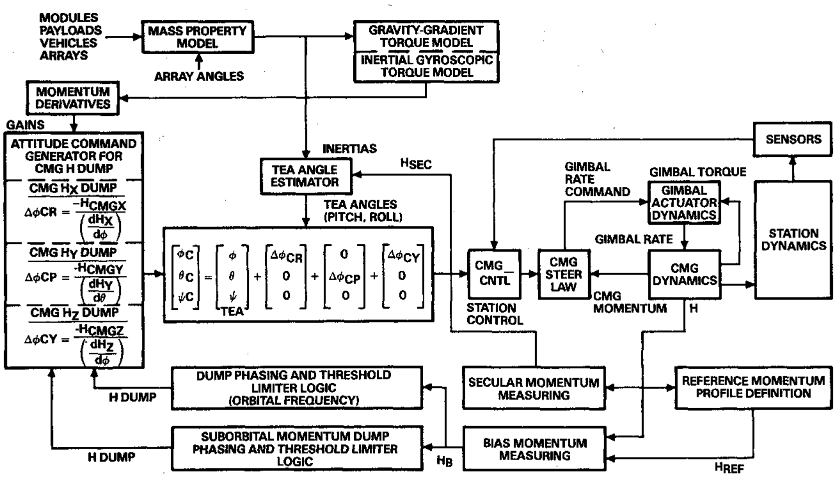

Fig. 2 Periodic momentum management system.

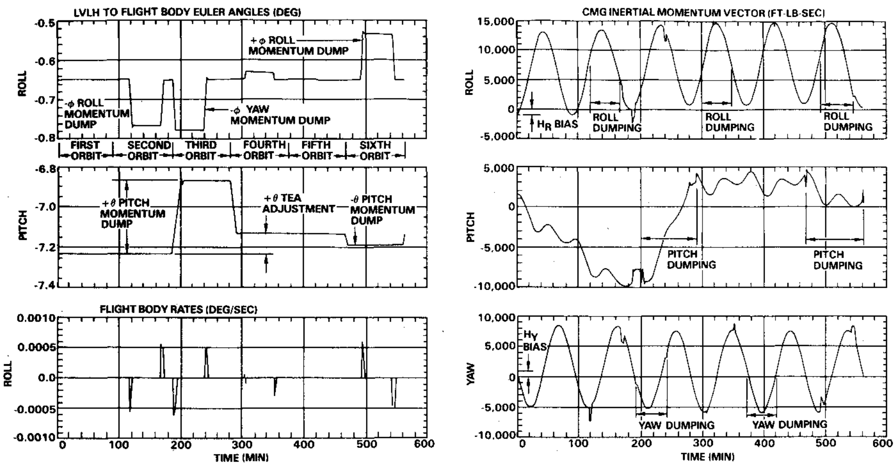

Fig. 3 Attitude, attitude rate, and momentum for periodic method.

Periodic momentum management depends on the reference and sampled momentum profile to establish attitude commands to dump undesired momentum. CMG system momentum is computed from wheel speed and gimbal angles and is used in conjunction with reference and past-orbit momentum profiles to compute the secular and bias momentum. The roll and pitch axes are used for secular momentum dumping, although a TEA is permitted in all three axes to reduce cyclic momentum in roll/yaw and secular momentum in pitch. The yaw momentum can be dumped more effectively with roll attitude adjustments due to larger roll gravity-gradient torques. Dump phasing, threshold, and limiter logic are provided to determine when and how much of the secular momentum is dumped at suborbital or orbital intervals. Dump phasing is referenced to universal time and orbit states. The momentum threshold is set relative to a reference momentum and is adjustable according to station operations. A steering function interfaces with the attitude control system so that the attitude and attitude rate commands are smoothed and bounded.

The initial-pitch TEA estimate is based on Eq. (6). The attitude change to remove accumulated momentum and center the cyclic momentum is then

$$d\theta = -\left(\frac{d\theta}{dH_y}\right)[H_y(n) - H_y(n-1) + H_{y\text{AVE}}] \qquad (7)$$

where the present momentum $H_y(n)$ and past momentum $H_y(n-1)$ determine the bias momentum. The average momentum, $H_{y\text{AVE}}$, centers the momentum profile.

The gain for attitude adjustment is the inverse of the gravity-gradient momentum derivative. This momentum derivative is computed as

$$\frac{dH_y}{d\theta} = T_o[3\omega_o^2/(180/\pi)](I_X - I_Z) \qquad (8)$$

where T_o is the orbital period. Based on mass property updates from a mass property model with only major elements, gain adjustments can be made over the orbit.

The initial roll/yaw TEA are based on an average angular misalignment of the respective principal axes from the body-fixed axes. Alignment of the roll/yaw axes reduces the cyclic gravity-gradient torque. The bias CMG momentum profile from previous orbits is fedback to generate attitude command profiles to bound the cyclic momentum of the current orbit. The inverse of the momentum derivatives are used as gains. The momentum derivatives $dH_x/d\phi$ and $dH_z/d\phi$ are proportional to the difference in the Y and Z principal axes of inertia. The roll attitude change for yaw momentum dumping is selected because the yaw momentum derivative with respect to the roll angle is greater than that for yaw attitude change. Due to roll and yaw coupling, the dumping of momentum is initiated at alternate quarter points in the orbit to prevent improper momentum transfer. Roll momentum dumping can be initiated at either the one-quarter or three-quarter orbit point. Yaw momentum dumping can be initiated at either the start of the orbital reference point or the halfway point. A toggled roll attitude command profile can remove accumulated momentum in roll/yaw from previous and current orbits.

Periodic TEA Adjustment Results

Figure 3 shows the simulation results with gravity-gradient and aerodynamic torques for the periodic momentum management method.[6] An initial error in pitch TEA and adverse momentum conditions are assumed for a station with an Orbiter attached when the 5 deg of LVLH requirement is not stipulated. Since a relatively stiff controller is applied, a significant portion of the CMG momentum capability is used for maintaining attitude while the undesired momentum must be removed.

Continuous Method

The continuous method integrates momentum management and attitude control functions and design. This system includes out-of-plane and in-plane control laws with attitude and momentum feedback as shown in Fig. 4. The attitude control loop consisting of attitude and attitude rate feedback provides for rigid body positioning and damping. The momentum feedback loop, consisting of CMG system momentum and the momentum integral, bounds and centers the momentum profile. The functions of the two loops tend to oppose one another, and good attitude control is obtained at the expense of momentum and vice versa. The design goal is to establish a satisfactory tradeoff between attitude error and momentum while maintaining overall system robustness.

Two modes of operation are considered. The TEA seeking and nominal modes are applicable to the dynamic and experimental conditions respectively. The TEA seeking mode emphasizes momentum feedback to allow for large attitude initialization errors without exceeding the available CMG momentum. Prior to the start of microgravity experiments on the station, TEA-seeking attitude oscillations in the order of 1 deg about the average TEA is permitted.

At the switchover to nominal operating mode, reinitialization to the estimated average TEA is made to reduce the residual bias in momentum. A low-pass filter, not shown as part of the control system, is used to estimate the average value of the TEA from the sensed attitude data. The filter has a bandwidth lower than the orbital rate and converges to the average TEA during the seeking period. The estimated average TEA is subsequently issued to attitude control and enhances attitude tuning during the nominal mode.

For the nominal mode, momentum loop gains are reduced and the attitude loop gains are increased to achieve a band-

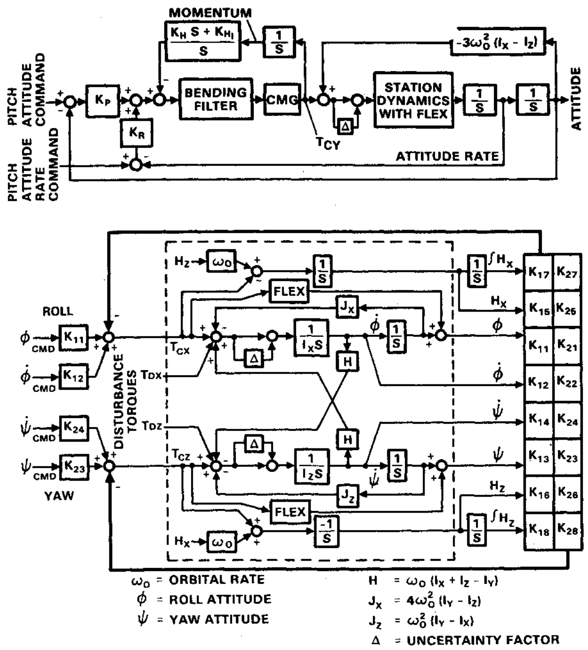

Fig. 4 Pitch and roll/yaw axes flight control system.

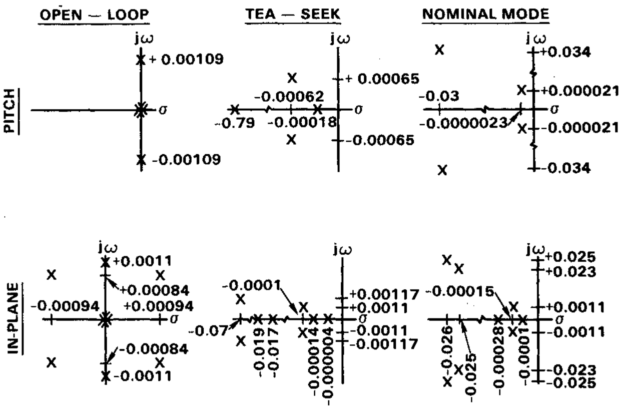

Fig. 5 Pitch and roll/yaw axes dynamic modes.

width close to 0.01 Hz. A fader function smooths the transition from a relaxed to a tighter controller bandwidth. The fader uses a prespecified allowable time for computing the slope from the initial to the final gain value. A typical time interval is about one-third of an orbit.

Design Approach for Continuous Method

The linearized system dynamic Eq. (1) is implemented in a linear stability analysis computer program on a personal computer to derive controller gains. The system dynamic modes are then observed for the open- and closed-loop cases. At this point the model is augmented to include the flexible modes and the analysis continues in mainframe programs. The system stability is analyzed with Bode and Nichols plots. The performance robustness to disturbances and stability robustness to station uncertainties is analyzed using singular-value frequency response plots. Finally, a multi-degree-of-freedom simulation program is used to check the performance of the integrated system.

Out-of-Orbital-Plane (Pitch Axis) Design

The goal for the pitch axis controller is to remove secular momentum by centering and minimizing the cyclic momentum about zero while maintaining satisfactory attitude control. The

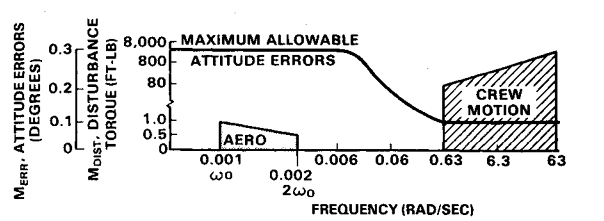

Fig. 6 Characterization of disturbances and attitude error tolerance vs frequency.

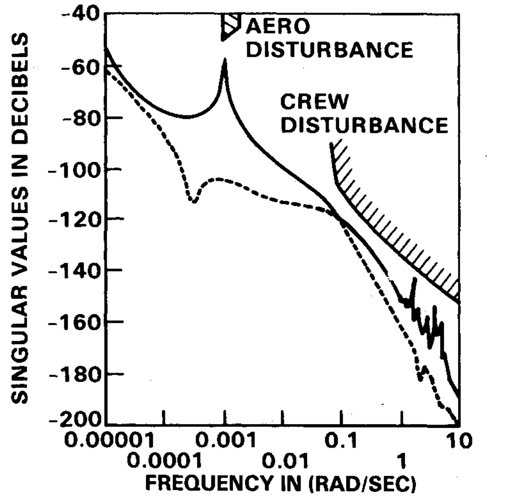

Fig. 7 System sensitivity satisfies performance boundaries.

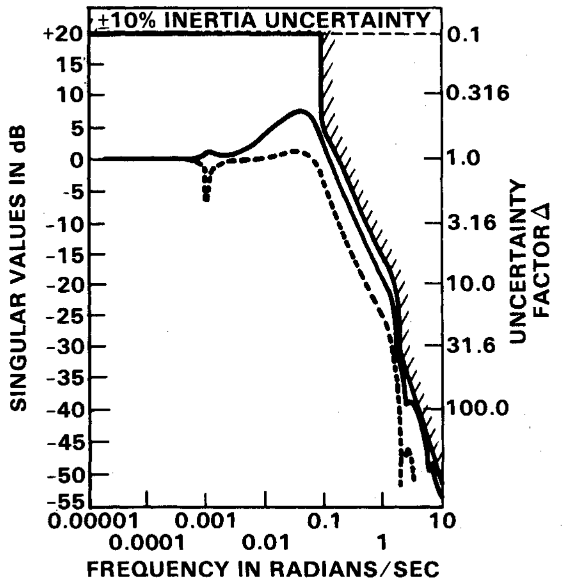

Fig. 8 System robustness is within model uncertainty boundary.

pitch control torque command is expressed as follows:

$$T_{CY} = K_P\theta_e + K_R\dot{\theta}_e - K_H H_Y - K_{HI}\int H_Y \qquad (9)$$

where K_P and K_R are the gains for attitude error θ_e and attitude rate error $\dot{\theta}_e$, respectively. The momentum and momentum integral gains are K_H and K_{HI}, respectively. The pitch axis gains are derived by minimizing the following performance index using gradient optimization methods[7]:

$$PI_Y = \int_0^\infty \left(W_\theta \theta_e^2 + W_R \dot{\theta}_e^2 + W_H H_Y^2 + W_{HI} \left(\int H_y \right)^2 + W_C T_{CMGY}^2 \right) \mathrm{d}t \tag{10}$$

where W_θ and W_R are attitude control performance weighting factors, W_H and W_{HI} the momentum management performance weighting factors, and W_C the control weighting factor. These penalty weighting factors are chosen to provide a satisfactory tradeoff between attitude performance and momentum levels. Table 1 shows a typical set of gains for the TEA-seeking and nominal modes.

In-Orbital-Plane (Roll/Yaw) Design

The design approach for the roll/yaw controller is to derive crossfeed gains that achieve stable attitude control and decoupling. Full-state feedback was applied as follows:

$$T_c = [K]x \tag{11}$$

where the control vector has two components $-T_{CX}$ and $-T_{CZ}$. The state feedback gain matrix $[K]$ is

$$[K] = \begin{bmatrix} K11 & K12 & K13 & K14 & K15 & K16 & K17 & K18 \\ K21 & K22 & K23 & K24 & K25 & K26 & K27 & K28 \end{bmatrix} \tag{12}$$

The state vector $x = [\phi_e \dot{\phi}_e \psi_e \dot{\psi}_e H_X H_Z \int H_X \int H_Z]^T$. The controller matrix $[K]$ is designed to minimize the performance index

$$PI_{XZ} = \int_0^\infty (x^T Q x + T_c^T R T_c)\, \mathrm{d}t \tag{13}$$

where Q and R are diagonal weight matrices that penalize the states and control vectors, respectively. The weight matrices provide a tradeoff between attitude errors and momentum so that attitude errors and CMG momentum levels satisfy operational requirements.

System Dynamics Modes

The rigid-body dynamics modes are shown in Fig. 5. The open-loop pitch axis has a complex pair of poles on the imaginary axis corresponding to the pitch gravity-gradient undamped libration mode and a double pole at the origin corresponding to the CMG momentum and momentum integral. The gravity-gradient oscillatory mode is damped mainly with attitude and rate feedback while the momentum modes are stabilized with momentum integral feedback. The pole locations for the closed-loop pitch axis indicate that the nominal mode will exhibit greater bandwidth than the TEA-seeking mode.

The in-plane axes exhibit unstable open-loop dynamics as shown by the right-half s plane poles in Fig. 5. The complex pair at $\pm j\,0.0011$ rad/s is due to orbital rate coupling between the roll and yaw axes. The two poles at the origin correspond to the momentum integral. As shown by the location of poles in Fig. 5, the in-plane closed-loop design is expected to allow bounded attitude oscillation during TEA seeking and a more stable attitude during the nominal mode.

Sensitivity Robustness to Disturbances

Figure 6 shows the magnitudes of the predicted disturbances M_{DIST} and the maximum allowable attitude deviations M_{ERR} from the average TEA during normal operation as a function of frequency. The aerodynamic torque occurs at orbital and twice the orbital frequency with an expected maximum disturbance torque of 1 and 0.5 ft-lb, respectively. The crew disturbance torques are based on the maximum crew forces and moment arms from the c.g. The maximum allowable attitude error is 0.3 deg for frequencies below 0.001 Hz. At the desired control bandwidth of 0.01 Hz, the maximum allowable error is 0.2 deg. For frequencies above 0.1 Hz, less than 0.1 deg error is allowed.

The station attitude response is desired to be within the allowable error in the presence of the prescribed disturbances for all axes. The control system design goal results in the following criteria for robust performance:

$$\text{SIGMA}_{\max}[S(j\omega)] \le M_{\text{ERR}}(\omega)/M_{\text{DIST}}(\omega) \tag{14}$$

where $S(j\omega)$ is the sensitivity function and represents the system closed-loop attitude response to disturbance torque (rad/ft-lb). The performance requirements of Fig. 6 are mapped as

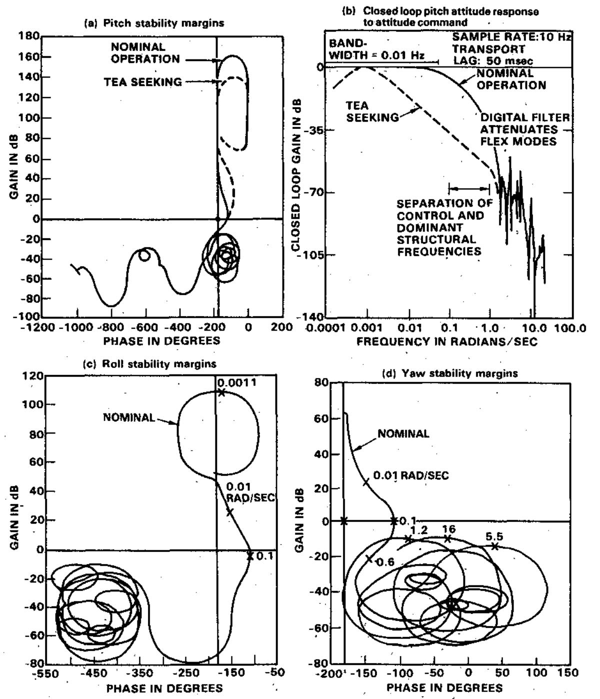

Fig. 9 Stability margins and closed-loop pitch attitude response to attitude commands.

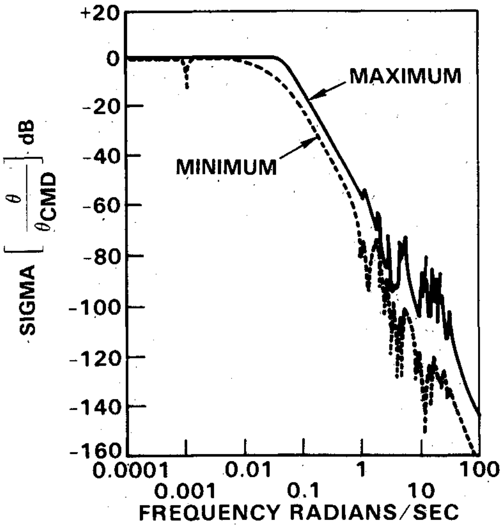

Fig. 10 Closed-loop transfer function singular-value frequency response to attitude commands.

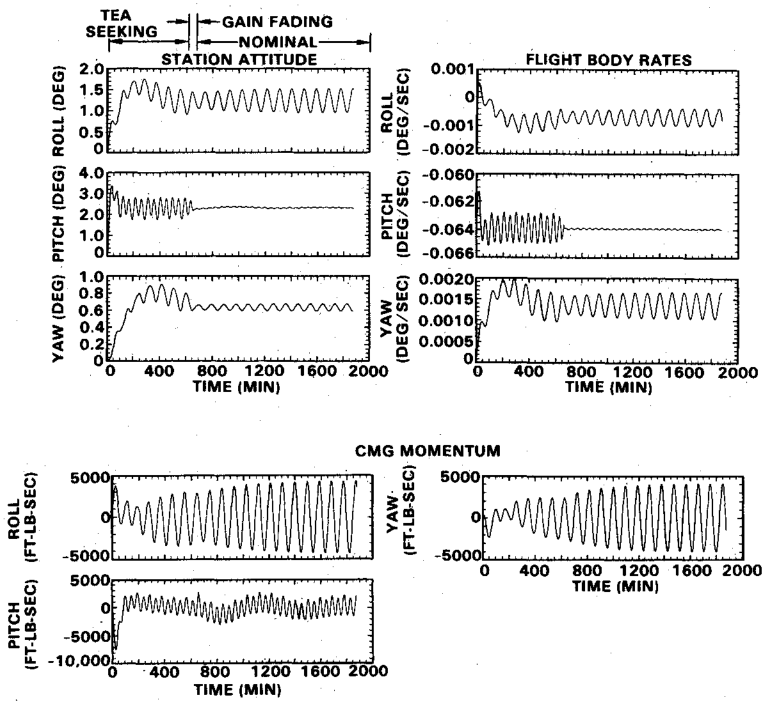

Fig. 11 Stable response achieved and CMG system momentum bounded and centered after TEA seeking.

upper bounds in Fig. 7 by the right side of Eq. (14). Figure 7 shows that the maximum singular value $SIGMA_{max}$ does not exceed the bounds set by the requirements specified in Fig. 6. A flexibility model using 20 structural modes was included in the sensitivity and robustness analysis. A transfer function block representing structural flexibility is shown in Fig. 4 and described in detail in Ref. 8.

System Robustness

The closed-loop system should be robust to parameter uncertainties. The following equation characterizes the station uncertainty:

$$G_R(\omega) = G(\omega) + \Delta(\omega)G(\omega) \tag{15}$$

where $G_R(\omega)$ is the real station dynamics. The transfer function $G(\omega)$ is the station model. The function $\Delta(\omega)$ is the parameter uncertainty factor, which includes 10% inertia uncertainties ($\Delta = 0.1$) from 0.0–0.06 rad/s and larger structural mode uncertainties ($\Delta = 30$) occurring at frequencies greater than 1 rad/s (see Fig. 8).

The design goal for robustness is to satisfy the following equation:

$$SIGMA_{max}[M_{11}(\omega)] < 1/\Delta(\omega) \tag{16}$$

where $M_{11}(\omega)$ is the 3 × 3 closed-loop system function for all axes across the perturbation $\Delta(\omega)$.[9] Figure 8 shows the characteristics of the uncertainty factor in the frequency domain and indicates that Eq. (16) is satisfied at all frequencies. This criteria assures stability in the presence of parameter uncertainty. Further analysis in the classical sense is performed to determine stability margins.

Frequency Response Analysis Results

The integrated system stability, including structural flexibility, was analyzed in the frequency domain to derive the phase and gain stability margins. The results of the open-loop frequency response analysis for the nominal operation are shown in Fig. 9. The control system provides at least 60 deg of phase margin and 10 dB of flex-mode attenuation. Figure 9b shows the closed-loop system attitude response to attitude commands. The solid line corresponds to the nominal mode with a 0.06 rad/s bandwidth. The dotted line corresponds to the TEA-seeking mode. The poor response at low frequencies is due to a dominating momentum feedback, since the main goal of the TEA-seeking mode is to orient the station to an attitude that minimizes overall momentum with little emphasis on attitude commands. The system stability in the flexible structural frequency region is compensated by a sixth-order filter per axis. The closed-loop system response to attitude commands for nominal operation is shown in Fig. 10 by the singular-value frequency response plot. The solid line is the maximum singular value and is dominated by the pitch axis. The dotted line corresponds to the minimum singular value and is dominated by the roll/yaw axes, which perform at a lower bandwidth.

Table 1 Inertia and control law gains without Orbiter attached

Inertia:
$I_X = 0.1152 \times 10^9$; $I_Y = 0.3221 \times 10^8$; $I_Z = 0.104 \times 10^9$ slug-feet^2

Gains	TEA seeking	Nominal	Unit
K_P	$0.7 \times 10^{+5}$	$0.8 \times 10^{+5}$	ft-lb/rad
K_R	$0.2 \times 10^{+7}$	$0.3 \times 10^{+7}$	ft-lb/rad
K_H	-0.4	-0.2×10^{-1}	s^{-1}
K_{HI}	-0.1×10^{-3}	-0.1×10^{-4}	s^{-2}
K_{11}	$0.102 \times 10^{+6}$	$0.165 \times 10^{+6}$	ft-lb/rad
K_{12}	$0.824 \times 10^{+8}$	$0.632 \times 10^{+8}$	ft-lb/rad
K_{13}	$-0.624 \times 10^{+5}$	$-0.303 \times 10^{+5}$	ft-lb/rad/s
K_{14}	$-0.325 \times 10^{+7}$	$0.637 \times 10^{+7}$	ft-lb/rad/s
K_{15}	0.4164	0.2161	s^{-1}
K_{16}	-0.299×10^{-1}	0.58×10^{-1}	s^{-1}
K_{17}	-0.418×10^{-4}	-0.3×10^{-7}	s^{-2}
K_{18}	-0.178×10^{-3}	-0.5×10^{-6}	s^{-2}
K_{21}	$0.403 \times 10^{+5}$	$0.117 \times 10^{+5}$	ft-lb/rad
K_{22}	$0.715 \times 10^{+7}$	$0.162 \times 10^{+7}$	ft-lb/rad
K_{23}	$0.951 \times 10^{+5}$	$0.158 \times 10^{+6}$	ft-lb/rad/s
K_{24}	$0.277 \times 10^{+8}$	$0.189 \times 10^{+8}$	ft-lb/rad/s
K_{25}	0.428×10^{-1}	0.953×10^{-2}	s^{-1}
K_{26}	0.1697	0.543×10^{-2}	s^{-1}
K_{27}	0.178×10^{-3}	0.5×10^{-6}	s^{-2}
K_{28}	-0.418×10^{-3}	-0.3×10^{-7}	s^{-2}

Continuous Method Simulation Results

Figure 11 shows the simulation results of how the integrated system allows for large attitude initialization errors without exceeding the available CMG momentum. The TEA-seeking mode achieves an average roll, pitch, and yaw TEA of 1.25, 2.4, and 0.65 deg, respectively, as can be seen in Fig. 11. The attitude excursion about the average TEA is less than 1 deg. When a higher bandwidth controller is faded in after one-third of an orbit, the attitude excursion is well below 0.2 deg in pitch and below 0.5 deg in roll. The attitude rate is below 0.002 deg/s and well within the attitude rate boundary specified. The momentum history indicates initial transient for TEA seeking, but the profile is bounded.

Conclusions and Recommendations

Both the periodic and continuous momentum management methods have been presented. A combined modern and classical design approach to an integrated momentum management and attitude control system is emphasized. A set of linear dynamic equations has been shown and implemented in analysis programs to expertise gain determination, show sensitivity robustness, and confirm system stability. Designing the integrated system as a whole assures good performance and stability robustness according to the design goals of the two modes of operation. The integrated system is demonstrated with frequency and simulation response results to have sufficient stability margins and stable attitude characteristics without penalizing CMG momentum. The integrated design approach is viewed as necessary, considering the evolving configuration and the variety of disturbances acting on the space station. Further investigation of specific disturbance characteristics will be performed in future disturbance accommodation studies.

Acknowledgments

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