Fine Pointing System for Large Orbiting Telescopes

WERNER O. SCHIEHLEN*
Technical University of Munich, Munich, F.R. Germany

Theme

LARGE orbiting telescopes as the NASA Large Space Telescope (LST) require ultrahigh pointing stability within 0.005 arcsec rms. A fine guidance system is designed to body-point the entire spacecraft within this limit. The system's controller utilizes the disturbance accommodation for the deterministic external torques and the optimization for the sensor noise and the stochastic external torques. Present results are based on Ref. 1, whereas related work is given in Ref. 2.

Contents

The LST spacecraft is assumed to be a rigid body; this is a legitimate assumption for the control system analysis since the structural frequencies are considerably higher than that of the control system. The pitch motion of the LST, affecting the telescope axis, is based on the equation of motion or

$$\dot{x} = Ax + Bu + Fw + Gs \tag{1}$$

where $x_1 = \theta$ and $x_2 = \dot{\theta}$ are given by the pitch angle and pitch angular velocity, u is the control variable due to the pitch reaction wheel, w is the deterministic disturbance variable given by the gravity-gradient and magnetic torques, and s is the stochastic disturbance variable due to aerodynamic and solar pressure torques. The matrices A, B, F, G are obtained from the equation of motion. The sensor signal corresponding to the pitch angle can be represented by

$$y = Cx + v \tag{2}$$

where y is the measurement variable, v is the sensor noise, and the matrix C follows from the measurement equation. Disturbances and noise are specified as

$$w = \beta + \gamma \cos(\omega t + \chi) \tag{3}$$

$$s \sim (0, q), \qquad v \sim (0, r) \tag{4}$$

where ω is the twice orbital rate, β, γ, and χ are constants, and s, v are stationary white noise processes with zero mean and constant spectral densities q, r.

For the LST modeled by Eqs. (1) and (2), the following phenomena was found,[3] using a lead network and a Proportional Controller (PC): with an increasing characteristic frequency of the closed-loop system, the response to the deterministic torques is decreasing while the response to the sensor noise is increasing. Thus, an optimal pointing stability of 0.01 arcsec rms was found. However, a further improvement of the pointing stability can be obtained by the cancellation of the deterministic torques using the disturbance accommodation principle.[4] Then, the control law reads as

$$u = \Gamma\hat{w} - L\hat{x} \tag{5}$$

where the estimations $\hat{x}$, $\hat{w}$ are obtained from an observer-accommodator and the identity $F = B\Gamma$ has to be satisfied. The deterministic disturbance Eq. (3) has to be modeled by the differential equation

$$\dot{z} = Dz, \qquad w = Hz \tag{6}$$

where $\dot{z}_1 = 0$, $\dot{z}_2 = \omega z_3$, $\dot{z}_3 = -\omega z_2$ and D, H are corresponding matrices. Now the observer-accommodator can be specified

$$\dot{\hat{x}} = (A - BL + K_1 C)\hat{x} - K_1 y \tag{7}$$

$$\dot{\hat{z}} = K_2 C\hat{x} + D\hat{z} - K_2 y \tag{8}$$

where the matrices L, K_1, K_2 summarize seven control gains. The open-loop system, Eqs. (1) and (2), results with the controller, Eqs. (5–8), in a closed-loop system of order seven

$$\dot{X} = \bar{A}X + \bar{F}W + \bar{G}V \tag{9}$$

where $X = [x^T \hat{x}^T \hat{z}^T]^T$ is a generalized state vector, $W = w$ the deterministic disturbance variable, and $V = [s\ v]^T$ a generalized noise vector. Furthermore, $\bar{A}$, $\bar{F}$, and $\bar{G}$ are the corresponding matrices. A block diagram is shown in Fig. 1.

The designed control system proves to be completely controllable and completely observable. Therefore, the eigenvalues can be arbitrarily chosen as a sevenfold eigenvalue $\lambda = -\alpha$ where α is the system's characteristic frequency. The asymptotic stability of the closed-loop system is now guaranteed for all $\alpha > 0$ and the control gains are unique functions of α. The pointing stability of the spacecraft depends only on the steady-state response of the pitch motion. The steady-state response of the deterministic disturbance is designed to be zero on account of the disturbance accommodation. However, the steady-state noise response remains, and is characterized by the standard deviation σ_θ. After some lengthy algebraic calculations given in Ref. 2, one obtains the following result:

$$\sigma_\theta{}^2 = \frac{1}{2048}(2275\alpha^{-3} - 6454\omega^2\alpha^{-5} + 9888\omega^4\alpha^{-7} - 882\omega^6\alpha^{-9} + 21\omega^8\alpha^{-11})q + \frac{1}{2048}(7875\alpha - 7350\omega^2\alpha^{-1} + 2800\omega^4\alpha^{-3} - 210\omega^6\alpha^{-5} + 5\omega^8\alpha^{-7})r \tag{10}$$

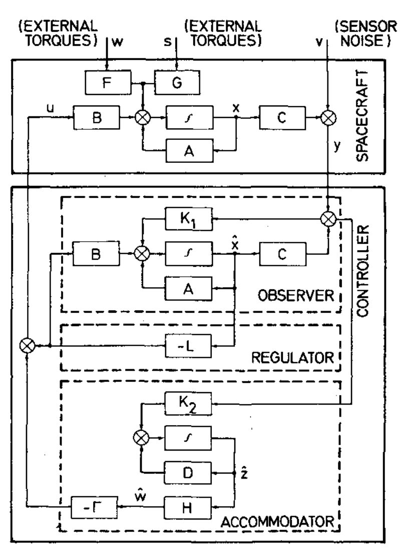

Fig. 1 Block diagram of the system.

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Index categories: Navigation, Control, and Guidance Theory; Spacecraft Attitude Dynamics and Control.

* Associate Professor, Institute B for Mechanics. Member AIAA.

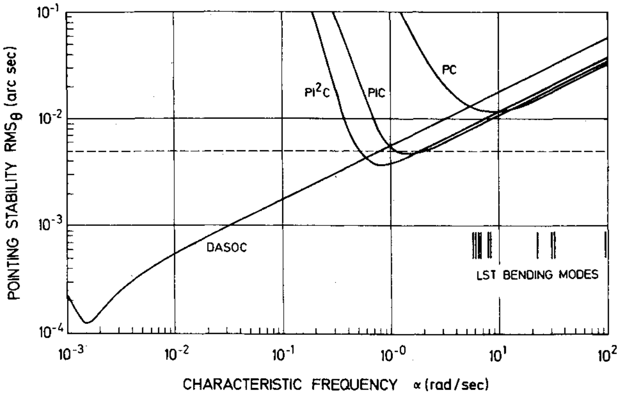

Fig. 2 Pointing stability for different controllers.

It turns out that the variance $\sigma_\theta{}^2$ is a linear combination of the disturbance noise term characterized by q and the sensor noise term given by r. The limit cases, $\alpha \to 0$ and $\alpha \to \infty$, result both in $\sigma_\theta \to \infty$, even if the disturbance noise is vanishing, i.e., $q = 0$. Thus, there will be at least one minimum which can be found from the condition $d\sigma_\theta/d\alpha = 0$. The optimization was conducted for the twice orbital rate $\omega = 2 \cdot 10^{-3}$ rad/sec representing an altitude of 800 km and for the sensor noise $r = 8.394 \cdot 10^{-6}$ arcsec²sec corresponding to a magnitude 12 guide star with 20 arcmin offset. The disturbance noise was either $q = 0$ or $q = 1 \cdot 10^{-12}$ arcsec²/sec³. The absolute minimum $\sigma_\theta = 1.247 \cdot 10^{-4}$ arcsec found for $q = 0$ occurs at $\alpha = 1.5 \cdot 10^{-3}$ rad/sec while $\sigma_\theta = 8.867 \cdot 10^{-4}$ arcsec found for $q = 10^{-12}$ arcsec²/sec³ occurs at $\alpha = 1.8 \cdot 10^{-2}$ rad/sec. In both cases, the pointing stability is significantly below the required $\sigma_\theta = 5 \cdot 10^{-3}$ arcsec. Furthermore, the characteristic frequency of the pointing system is far below the structural bending frequencies. With these optimizations, the Disturbance Accommodation Standard deviation Optimal Controller (DASOC) is completely defined.

A sensitivity analysis of the DASOC system with respect to errors of the orbital rate ω shows that the sensitivity is strongly increasing with decreasing characteristic frequency α. Thus, the orbital rate ω has to be accurately adjusted within DASOC to obtain full advantage. This can be done by updating during the mission.

So far DASOC has shown good behavior but there is no question that this sophisticated controller results in more complex hardware and increasing cost. By comparison with simple conventional controllers, it can be determined if DASOC is worth the additional expense. The conventional controllers PC, PIC, and PI²C, and vanishing stochastic disturbances, $q = 0$, will be used in the comparison.[3] Figure 2 indicates that PC does not meet the requirement of 0.005 arcsec rms. The PIC meets the 0.005 arcsec with little margin, and PI²C is scarcely better. On the other hand, DASOC easily meets the requirement and a large safety factor remains for the compensation of possible deteriorations. Some additional errors may be caused by aerodynamic and solar pressure torques and by incorrect orbital rate adjustment. But the extreme accuracy of DASOC allows also greater tolerance on other sources of errors such as gyro and reaction wheel vibrations, bending modes, nonlinearities, etc.

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