Design and Stability of an On-Orbit Attitude Control System Using Reaction Control Thrusters

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Overview

• NASA is providing preliminary design and requirements for the Space Launch System Exploration Upper Stage (EUS).

• The EUS will provide upper stage capability for vehicle ascent as well as on-orbit control capability.

• Requirements include performance of on-orbit burn to provide Orion vehicle with escape velocity.

• On-orbit attitude control is accommodated by a on-off Reaction Control System (RCS).

• Paper provides overview of approaches for design and stability of an attitude control system using a RCS.

  ▪ Draws heavily from research and development in support of Space Shuttle and Space Station programs. Includes pitfalls and lesson’s learned from flight experience.
Paper Summary

- Vehicle Attitude Dynamics and Phase Plane Control
- Phase Plane Stability and Filter Design
- Jet Selection
- Maneuver/Steering Algorithms
- Thruster Hardware Specifications
Vehicle Attitude Dynamics and Phase Plane Control

• Attitude Dynamics are summarized:

\[
\begin{align*}
J_1 \omega_1 &= (J_2 - J_3) \omega_2 \omega_3 + T_{1\text{axi}} + u_1 \\
J_2 \omega_2 &= (J_3 - J_1) \omega_1 \omega_3 + T_{2\text{axi}} + u_2 \\
J_3 \omega_3 &= (J_1 - J_2) \omega_1 \omega_2 + T_{3\text{axi}} + u_3 \\
\eta &= \cos\left(\frac{\varphi}{2}\right) \quad \dot{\eta} = -\frac{1}{2} \varepsilon^T \dot{\varphi} \\
\dot{\varepsilon} &= \hat{\alpha} \sin\left(\frac{\varphi}{2}\right) \quad \dot{\varepsilon} = \frac{1}{2} (\varepsilon^T + \eta I) \dot{\varphi} \\
\Lambda_{\text{sh}} &= \begin{bmatrix} \eta & \dot{\varepsilon} \end{bmatrix}
\end{align*}
\]

• Phase Plane Design Examples are Provided:

- Simple Switch Lines
- Hysteresis Added
- Ares I-X Design
- Shuttle Design
Phase Plane Stability and Filter Design

- Phase Plane control designs are nonlinear, hence traditional linear design approaches are generally not available.
- Paper presents RCS filter design and phase plane stability approaches based on research performed on the Space Shuttle and Space Station programs.
- Stability margin design goals are provided:
Phase Plane Stability (continued)

- Paper describes approaches to derive a linear representation of the nonlinear system, concentrating on describing functions.

- Phase plane is converted into an equivalent PD controller with a relay:

- Relay is modeled by a describing function.
Phase Plane Stability and Filter Design (continued)

- Describing function relay representation is still a nonlinear system as describing function gain is dependent on input amplitude (A):

  \[
  N(A) = \begin{cases} 
  0 & \text{if } A < \delta \\
  \frac{4}{\pi A} \sqrt{1 - \left(\frac{\delta}{A}\right)^2} & \text{if } A > \delta 
  \end{cases}
  \]

- Linearize system by deriving value of A which maximizes the describing function (A*):

  \[
  A^* = \sqrt{2\delta} \quad \rightarrow \quad N(A^*) = \frac{2}{\pi \delta}
  \]

- Maximizing the describing function gain represents peak RCS control response to state error, which maximizes flex response to RCS firings (conservative approach).
Given a System:

Substitute the relay with a peak gain representation derived from the describing function:

\[ A^* = \sqrt{2}\delta \rightarrow N(A^*) = \frac{2}{\pi\delta} \]

The resulting derivation is a linear representation of phase control system.
Phase Plane Stability (continued)

- Example. Model rigid body control and ideal latency:

\[ \Psi(s) \xrightarrow{\alpha_c} \frac{1}{s^2} \xrightarrow{\phi} \frac{1 - T_D s}{2(1 + T_D s)} \xrightarrow{\frac{2}{\pi\delta} + \frac{2}{\pi(RL)s}} \Psi_c(s) \]

- The phase plane controller is a PD representation with the gains proportional to the phase plane deadzone (attitude and rate) limits.

- The closed loop transfer function is derived:

\[
\Psi_c(s) = \frac{2\alpha_c \left[ -\frac{T_D}{2(RL)} s^2 + \left( \frac{1}{RL} - \frac{T_D}{2\delta} \right) s - \frac{1}{\delta} \right]}{\Psi_c(s) = \frac{T_D}{2} s^3 + \left( 1 - \frac{\alpha_c T_D}{\pi(RL)} \right) s^2 + \frac{2\alpha_c}{\pi} \left( \frac{1}{RL} - \frac{T_D}{2\delta} \right) s + \frac{2\alpha_c}{\pi\delta}}
\]

- And the necessary Condition for stability derived:

\[
\frac{1}{RL} - \frac{T_D}{\delta} - \frac{\alpha_c T_D}{\pi(RL)^2} + \frac{\alpha_c T_D^2}{2\pi(RL)\delta} > 0
\]
Phase Plane Stability (continued)

- Given the stability condition:

\[
\frac{1}{RL} - \frac{T_D}{\delta} - \frac{a_T D}{\pi(RL)^2} + \frac{a_T D^2}{2\pi(RL)\delta} > 0
\]

- Stability thresholds can be derived:

\[
\delta > \frac{T_D - \frac{a_T D^2}{2\pi(RL)}}{1 - \frac{a_T D}{\pi(RL)^2}}
\]

\[
T_D < \frac{a_T \delta - (a_T^2 \delta^2 + \pi^2(RL)^4)^{\frac{3}{2}} + \pi(RL)^2}{a_T(RL)}
\]

Smallest Deadband

Allowable Latency
Phase Plane Stability (continued)

- Paper provides an example of how the stability condition maps to the RCS time domain simulation.

\[ T_D < \frac{a_c \delta - (a_c^2 \delta^2 + \pi^2 (RL)^4)^{1/2} + \pi (RL)^2}{a_c (RL)} \]

- Stable RCS Control:

- Unstable RCS Control:
Key RCS Filter Design Principles

- Paper provides key filter Design Principles for RCS:
  - Key Filter Design 1: Rigid body Stability
  - Key Filter Design 2: Flex Gain Margins
  - Key Filter Design Principal 3: Minimizing Filter Induced Lag
  - Key Filter Design Principal 4: Feed Forward during Thruster Firings
Key Filter Design 2: Flex Gain Margins

- Flex body dynamics can drive an RCS unstable.
Filter induced lag can result in a RCS limit cycle instability.
RCS Jet Selection

- Paper Addresses multiple RCS jet selection approaches:
  - Table look-up.
  - Algorithms that accommodate mass property changes.
  - Fuel Optimal Jet Select.
  - Command preshaping to avoid structural excitation.

Two Space Shuttle Jet Select Algorithms

- Dot Product: Would select jets 1 and 2
- Minimum Angle: Would select jets 2 and 4
RCS Maneuvering/Steering Algorithms

- Paper Addresses multiple RCS maneuvering/steering approaches:
  - Eigen Axis Maneuvers.
  - Torque-Free Maneuvers (Russian MIR).
  - Steering Formulation.
  - Fuel Optimal (Space Station “Zero Prop Maneuver”).
Thruster Hardware Specifications

- Discusses Shuttle RCS hardware design/control criteria:
  - Control authority must exceed all known disturbances by a factor of two.

\[ \hat{T}_c > 2 \times \left[ \max(-\hat{\omega} \times \hat{J} \hat{\omega}) + \max(\hat{T}_{ext}) \right] \]