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

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San Diego, California, January 4-8, 2016
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:**

\[
\begin{align*}
J_1 \dot{\omega}_1 &= (J_2 - J_3) \omega_2 \omega_3 + T_{1\text{ext}} + u_1 \\
J_2 \dot{\omega}_2 &= (J_3 - J_1) \omega_3 \omega_1 + T_{2\text{ext}} + u_2 \\
J_3 \dot{\omega}_3 &= (J_1 - J_2) \omega_1 \omega_2 + T_{3\text{ext}} + u_3 \\
\eta &= \cos \left( \frac{\varphi}{2} \right) \\
\dot{\eta} &= -\frac{1}{2} \varepsilon^T \dot{\omega} \\
\dot{\varepsilon} &= \hat{\alpha} \sin \left( \frac{\varphi}{2} \right) \\
\dot{\hat{\varepsilon}} &= \frac{1}{2} (\varepsilon^T + \eta \hat{\omega}) \\
\Lambda_{12} &= [\eta \quad \dot{\varepsilon}] 
\end{align*}
\]

- **Phase Plane Design Examples are Provided:**

- Simple Switch
- 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:

![Diagram showing stability margin and phase plane](image)
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):

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

  \[ A^* = \sqrt{2\delta} \]

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

- Maximizing the describing function gain represents peak RCS control response to state error, which maximizes flex response to RCS firings (conservative approach).
Phase Plane Stability (continued)

• Given a System:

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

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

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

- Example. Model rigid body control and ideal latency:

- 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:

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

- And the necessary Condition for stability derived:

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

- Given the stability condition:

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

- Stability thresholds can be derived:

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

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

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.
Key Filter Design Principal 3: Minimizing Filter Induced Lag

- 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.*

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