Time Domain Stability Margin Assessment
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SLS Vehicle

- NASA’s Space Launch System (SLS) is an advanced launch vehicle that will use Shuttle heritage main engines, re-usable solid rocket motors, and thrust vector control.
- SLS will be capable of launching up to 290,000 lb to LEO, opening new possibilities for new scientific robotic missions.
Outline

- Introduction and Purpose
- Stability Margin Assessment Method
- Time Domain Stability Margin Assessment Results
- Summary
Introduction

- Gain and Phase margins of a system are essential metrics in determining stability and robustness of a control system.
- Frequency-domain analysis at MSFC is done in FRACTAL (Frequency Response Analysis and Comparison Tool Assuming Linearity).
- Full 6-dof time-domain simulation is done in MAVERIC (Marshall Aerospace VEHICLE Representation in C).
- No work has been done to verify the margins computed by FRACTAL in MAVERIC.
Purpose

- Verify margins derived in the frequency domain in the full nonlinear 6-dof time domain.
- Will modify time domain gain and delays until unstable behavior is observed and compare results with frequency domain margins.
Rigid Body Gain Margin Method

- The overall gain of the system was artificially increased to the neutral stability point derived in FRACTAL at each time step and then adjusted to some value +/- the neutral point.
The overall gain of the system was artificially decreased to the neutral stability point derived in FRACTAL at each time step and then adjusted just like the rigid gain margins.
Phase Margin Method

- When assessing the rigid-body phase margin, a constant time delay was applied to the system starting at the time point under consideration.
Variables Assessed

- **Body Rates**: Divergent oscillation in body rate is said to be unstable.
- **Max engine saturation ratio**: Max of the ratio of the commanded gimbal angles/actual gimbal angles. If larger than 1, gimbals are saturated.
- **Actuator Duty Cycle**: Integral of the actuator angles. Divergent behavior is indicative of instability.
Rigid Body Gain Instability Example

- Unstable behavior observed at 0.2 dB above FRACtAL-derived rigid body gain margin.
Rigid Body Gain Margin Assessments

- Margins evaluated at 80, 140, and 300 seconds.
- FRAC{TAL}-derived margins are consistently verified in the time domain (with the exception of 300 seconds in pitch/yaw).
Phase Margin Assessments

- Error bars to show ambiguity associated with phase margin identification.
- System is consistently stable beyond baseline margins derived in FRACTAL after 100 seconds.
Aero Gain Margin Assessments

- Only evaluated at 300 seconds.
- Requires significant time (at least 100-200 seconds) for instability to show in the time domain.
Summary

- The gain and phase in the time domain were artificially adjusted relative to the margins derived in the frequency domain until unstable behavior was observed via divergent body rates.
- Time domain gain margins matched frequency domain margins well (with a few exceptions). Phase margins were consistently higher in the time domain.
- This method can be applied to adaptive controllers and any time-varying nonlinear effects not captured in frequency domain analysis.
Backup
Rigid Body Gain Instability Example
Rigid Body Gain Instability Example

Core Engine 1 Duty Cycle

Time [s]

dB Above
Gain Margin

-0.8 dB
-0.6 dB
-0.4 dB
-0.2 dB
0 dB
0.2 dB
Effects of Slosh

- The slosh damping values used in the FRACTAL frequency domain were based on the requirement damping profile at a fixed wave height of 4”.
- In the full 6-dof time-domain MAVERIC simulations, the slosh damping follows a nonlinear slosh damping model that is a function of wave height.
- This leads to more stable simulations in the presence of rigid body gain instabilities when slosh is the driving factor behind the gain margin.
Effects of Slosh

- As the gain is increased, the wave height is increased. This leads to increased damping and therefore a more stable vehicle.
- When slosh drives the gain margin, the gain must be increased beyond the point of being slosh dominated in order to display an instability.
Significant Finding - Frozen Guidance

- Closed-loop guidance destabilized before the controller when testing aero gain margins.
- Results in 3-5 dB of low-frequency gain margin degradation in the full closed-loop GNC simulation.

Frozen Guidance

Regular Guidance