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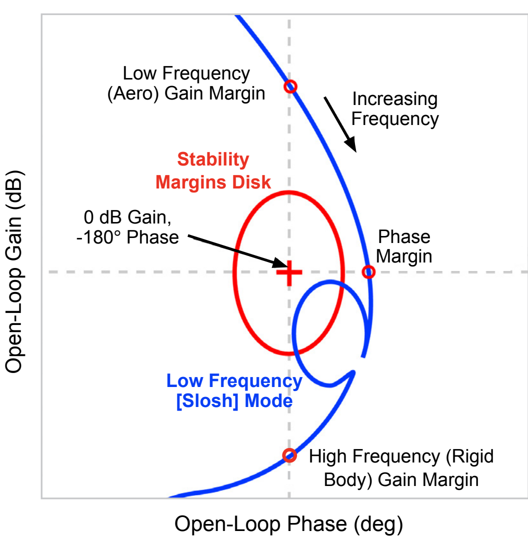
Launch Vehicle Flight Control Stability Margin Reduction Considerations

Launch vehicle ascent stability analyses typically rely on a combination of frequency and time domain analyses. Frequency domain analysis uses a sequence of high-fidelity linear models with constant parameters spanning the ascent trajectory. Complementary time domain analysis is performed using high-fidelity, nonlinear 6-DOF simulations. Analyses are typically dispersed to verify robustness to parameter variations by showing the vehicle meets frequency domain stability margin requirements and time domain performance metrics. This Technical Bulletin outlines standard stability margin best practices and provides recommendations for treatment of deviations from industry-standard launch vehicle stability margins due to vehicle flexibility, slosh dynamics, aerodynamics, other offending dynamics, or coupling thereof.

Stability Margin Best Practices

Current best practices for launch vehicle flight control design target 6 dB/30 degrees undispersed rigid body gain/phase margins and 12 dB amplitude margin for gain-stabilized flexible body modes. Well-characterized fundamental (low-frequency) flexible body modes can potentially be phase-stabilized to maintain 45 degrees of undispersed phase margins. Best practices for dispersed analysis ensure 3 dB/20 degrees on the rigid body gain/phase margin, 6 dB amplitude margin for gain-stabilized flexible body modes, and 30 degrees for phase-stabilized flexible body modes. All relevant dynamics, including engine inertial coupling, bending, and slosh dynamics, are included in the linear plant model and should respect the same stability margin requirements. Due to the nonlinear and uncertain characteristics of propellant slosh modes in the absence of passive damping devices (e.g., ring baffles), analysis beyond that of the standard frequency and time domain analyses may be needed to address the effects of sloshing propellant for bare-walled tanks. Any other vehicle dynamics exhibiting significant nonlinearities or complex coupling, or where the available model representation is of low fidelity and/or not anchored to test data, may similarly necessitate an extended treatment.



Notional Nichols Plot with Adversely Phased Propellant Slosh Mode

Recommended Treatment for Deviations from Standard Launch Vehicle Stability Margin Requirements

Stability margins should be reported with the inclusion of all relevant dynamics (i.e., rigid body, slosh, flexible body, and aerodynamics). If the resulting stability margins deviate from industry standards, the routine analysis approach should be augmented by an adequately extensive treatment, including:

- Analysis of the **fundamental physics** involved, with applicable simulation tool verification. Verify consistency among rules of thumb, linear analyses, nonlinear analyses, and flight data.
- **Sensitivity studies** in frequency and time domains to analyze effects of possible parameter and system variations.
- Assessment of the **consequences of potential instability** associated with offending modes by evaluating stressing cases in the time domain.
- **Assessment of alternative flight control designs** to demonstrate, in the context of risk/consequence, that the baseline design appropriately balances overall launch vehicle risk. Appropriate risk management trades may vary depending on the program's development/operational stage. Lower margins (i.e., larger deviations from industry standards) may be considered following successful flight demonstration and test-validated model analysis.

Regardless of the margin posture, sensitivity studies and stress cases can be automated and evaluated as a standard practice to establish high confidence in the design and its robustness.

References

1. NESC Technical Bulletin No. 14-01, "Designing for Flight Through Periods of Instability," September 2014. https://www.nasa.gov/nesc/technicalbulletins.
2. NESC Report "Treatment of Launch Vehicle Flight Control Stability Margin Reductions for Crewed Missions with Emphasis on Slosh Dynamics," June 2022. https://ntrs.nasa.gov/citations/20220009857.
3. NESC Technical Bulletin No. 22-06, "Treatment of Slosh Stability Margin Reductions for Human-Rated Launch Vehicles," August 2022. https://www.nasa.gov/nesc/technicalbulletins.

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