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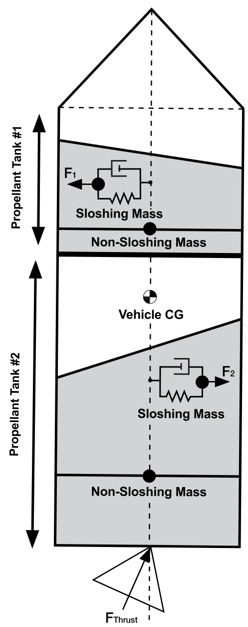
Treatment of Slosh Stability Margin Reductions for Human-Rated Launch Vehicles

Slosh dynamics pose a stability concern for human-rated launch vehicles during ascent. Historical perspectives on the treatment of slosh dynamics, newly developed rules of thumb, the utility of flight data, and methods for analyzing and dispositioning slosh instability risks should be considered when linear stability margins are lower than typically accepted for human-rated systems.

Historical Perspective on Slosh Treatment for Human Space Flight (Ascent)

No conclusive example has been found in Space Shuttle or Saturn Program crewed flight history in which transient negative linear slosh stability margins were permitted. The uncrewed Saturn 1 S-IV had low-to-negative slosh margins, but tank baffles and a slosh deflector were added to gain-stabilize slosh prior to human-rating the S-IVB vehicle. Precedent exists in Saturn and Shuttle to rely on time domain performance metrics to accept reduced slosh margins. Time domain simulations included external forcing functions to quantify impacts (e.g., gimbal oscillations, attitude error, crew acceleration) associated with worst-case slosh excitation due to disturbances (e.g., staging and guidance command transients).



Typical Slosh Model

Slosh Fundamentals

Each slosh mode can be accurately modeled as a linear mass-spring-damper or spherical pendulum with two degrees of freedom. The mechanical model parameters are scheduled as a function of flight condition (e.g., propellant liquid level, acceleration) based on test-correlated analytical and empirical relationships. This mechanical analog provides insight into the basic nature of slosh response. Analysis of fundamental physics involved in sloshing propellants can demonstrate the nature of the slosh response and serve as a foundation for understanding and verifying responses from more complex vehicle simulations. A rule of thumb known as the slosh "danger zone" was established in the Saturn era for a single tank. This zone predicts poor phasing of slosh dynamics will occur when the slosh mode location falls below the center of percussion and above a location near the vehicle center of gravity (CG). An advanced analytical technique was recently developed to determine the propensity for unfavorable phasing with dual-tank sloshing modes that would be undetected by the single-tank danger zone criteria. Slosh interactions with flexible structural dynamics can also impact vehicle stability. Analysts should verify consistency between rules of thumb, linear analyses, nonlinear analyses, and flight data.

Utility of Flight Data for Slosh Stability Model Validation

Flight data is typically inconclusive regarding slosh stability margins as it may not provide sufficient information to anchor slosh model predictions or validate stability margins. Even when slosh is predicted to be unstable in the frequency domain, slosh instability detection from flight data is elusive due to inadequate excitation and small growth rates. Thus, the lack of observable ascent slosh response is not a demonstration of vehicle stability robustness. Without targeted excitation, sufficient sensing, and dwell time, specific vehicle model response validation (e.g., aero, rigid body, slosh, or flex) is not possible. In-flight response of lightly damped flexible/slosh modes can provide frequency confirmation if sufficient excitation exists, but long dwell times may be needed to identify slosh gain and phase margins. In contrast to slosh, bending-mode models can typically be verified to higher accuracies because the signatures in flight data tend to be cleaner. In summary, flight experience raises confidence but cannot validate slosh models or determine stability margins without targeted provisions (e.g., programmed test inputs).

Methods for Treatment of Low or Negative Slosh Stability Margins

Vehicle stability margins should be reported with the inclusion of all relevant dynamics (i.e., rigid body, slosh, flexible body, and aerodynamics). If slosh stability margins are below industry standards, routine analysis should be augmented by an evaluation of sensitivities and consequences. Targeted sensitivity studies conducted in the frequency and time domains should be designed to analyze the effects of parameter and system variations. In the frequency domain, this can include dispersing the relative slosh frequency in multiple tank scenarios, investigating the effects of flexible body/slosh coupling, evaluating mitigations afforded by nonlinear damping, and computing the time to double. In the time domain, this can include application of a doublet and direct slosh state initialization during stressing flight conditions or periods of instabilities for nominal and worst-case dispersed vehicle parameters. When slosh margin instabilities are present, slosh amplitude doubling times can be compared against the duration of the instability. The purpose is to evaluate opportunities for instability to occur in flight and analyze the relevant indicators (e.g., growth rate/decay, actuator usage, slosh wave amplitude, crew acceleration, abort margins). Stressing cases of concern can then be evaluated for credibility, probability, and consequences from the perspective of overall vehicle risk. Early in a development program, and for pre-flight certification, it is good practice to automate stressing simulations and incorporate them into the standard analyses to increase design confidence and coverage for effects not otherwise captured even when the linear margins indicate stability.

References

1. NESC Technical Bulletin No. 22-05, "Launch Vehicle Flight Control Stability Margin Reduction Considerations," August 2022. 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. Ottander, J. et al., AIAA SciTech 2018, "Practical Methodology for the Inclusion of Nonlinear Slosh Damping in the Stability Analysis of Liquid Propelled Launch Vehicles."
4. Bauer, H. F., 1964, "Fluid Oscillations in the Containers of a Space Vehicle and Their Influence on Stability," NASA TR R-187.
5. Pei, J., "Analytical Investigation of Propellant Slosh Stability Boundary on a Space Vehicle," Aerospace Research Central. Published April 23, 2021. https://doi.org/10.2514/1.A35024.

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