Treatment of Launch Vehicle Flight Control Stability Margin Reductions for Crewed Missions with Emphasis on Slosh Dynamics

NASA Engineering and Safety Center

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Agenda

- **Bottom Line Up Front**
- **Stability Margins**
  - Historical perspective
  - Industry-standard stability margin guidelines
  - Reporting of slosh margins
- **Analysis**
  - Utility of flight data and time-domain analysis
  - Slosh fundamentals, sensitivities, and performance
  - Slosh sensitivities and consequences
  - Flight control stabilization trades
- **Findings, Observations, and NESC Recommendations (FORs)**
  - Distributed throughout presentation
  - Key big-picture recommendations at end of presentation
  - Summary of FORs in the backup

Bottom Line Up Front

- NESC's perspective for crewed spaceflight: **Acceptance of flight control gain/phase stability margin reductions from industry standards should be accompanied by an adequately extensive technical treatment, including:**
  - Analyzing the **fundamental physics** involved, with applicable simulation tool verification (particularly if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data)
  - Conducting **sensitivity studies** in time and frequency domains to analyze effects of possible parameter and system variations
  - Studying the effects of the **consequence of instability** associated with offending modes by running stressing cases in time domain
  - **Assessing alternative flight control designs** to demonstrate that present design appropriately balances overall vehicle risk (i.e., quantitatively delineate chosen tradeoffs between various stability margins and vehicle performance in the context of risk/consequence)
- **Work presented here represents an example summary of expected engineering work to flight-certify crewed missions with unstable slosh modes and reduced stability margins**

STABILITY MARGINS

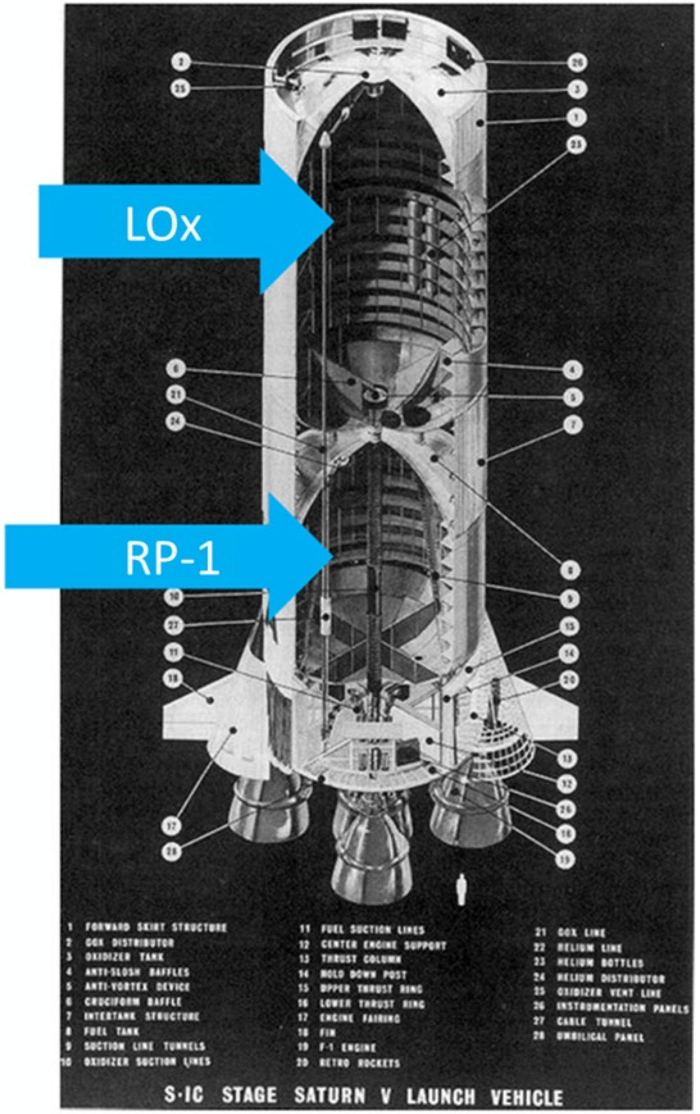
Historical Perspective

Slosh Treatment for Human Spaceflight (Ascent Stability)

- **No conclusive example found in Shuttle and Saturn crewed flight history where slosh instabilities were allowed**
  - The unmanned Saturn 1 S-IV had low, even negative, LH_2 slosh margins; however, 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 use time-domain performance metrics to allow reduced slosh margins**
  - Time-domain simulations included external forcing functions to bound worst-case slosh excitation due to transient disturbances, e.g., staging, guidance transitions
  - Limits on “slosh-induced” limit cycle oscillations from external forcing functions:
    - Shuttle: limited attitude error, crew linear (g) acceleration
    - Saturn examined bounds on engine gimbal oscillations

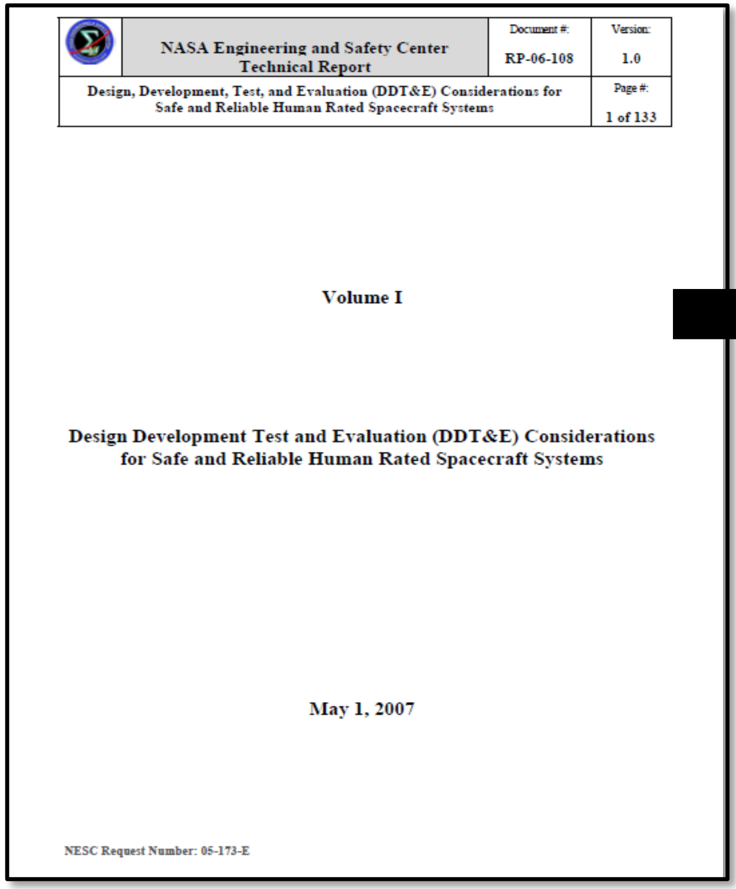
F-1. Human spaceflight launch vehicle propellant slosh has historically been stabilized (i.e., ascent vehicles for crewed spaceflight never flown with negative slosh margins).

F-2. Rigid-body phase margins for human spaceflight have been maintained at 30 degrees or more (non-dispersed).



List of relevant historical references provided in backup

Flight Control Stability Margin Industry Standards (1 of 2)



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Volume I

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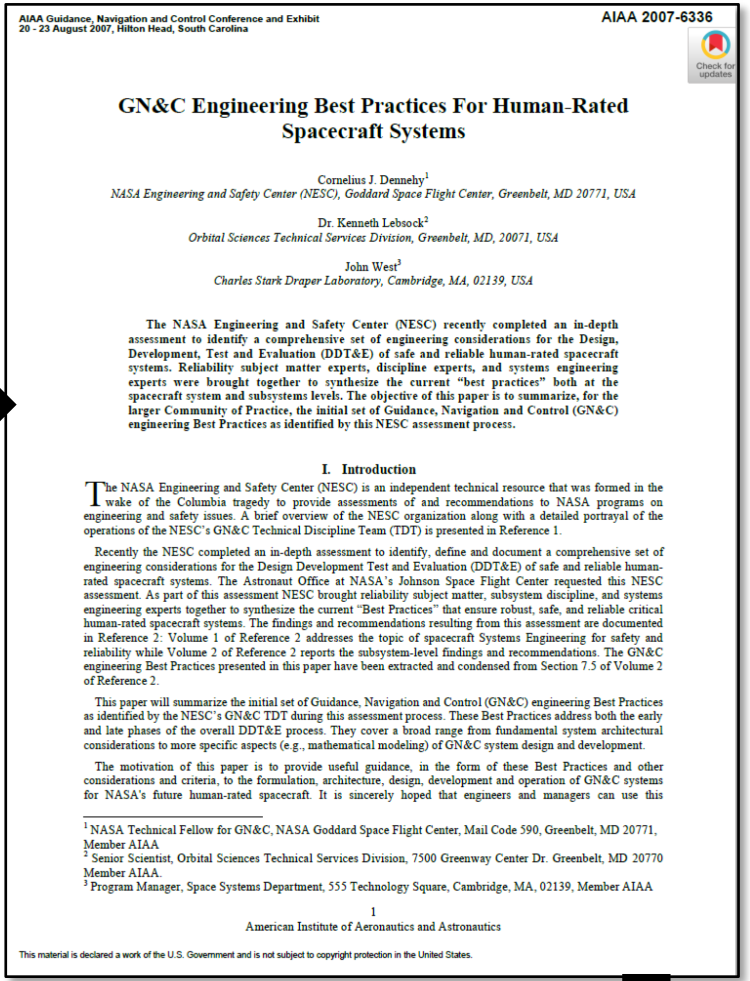

AIAA Guidance, Navigation and Control Conference and Exhibit
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AIAA 2007-6336

Check for updates

GN&C Engineering Best Practices For Human-Rated Spacecraft Systems

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The NASA Engineering and Safety Center (NESC) recently completed an in-depth assessment to identify a comprehensive set of engineering considerations for the Design, Development, Test and Evaluation (DDT&E) of safe and reliable human-rated spacecraft systems. Reliability subject matter experts, discipline experts, and systems engineering experts were brought together to synthesize the current "best practices" both at the spacecraft system and subsystems levels. The objective of this paper is to summarize, for the larger Community of Practice, the initial set of Guidance, Navigation and Control (GN&C) engineering Best Practices as identified by this NESC assessment process.

I. Introduction

The NASA Engineering and Safety Center (NESC) is an independent technical resource that was formed in the wake of the Columbia tragedy to provide assessments of and recommendations to NASA programs on engineering and safety issues. A brief overview of the NESC organization along with a detailed portrayal of the operations of the NESC's GN&C Technical Discipline Team (TDT) is presented in Reference 1.

Recently the NESC completed an in-depth assessment to identify, define and document a comprehensive set of engineering considerations for the Design Development Test and Evaluation (DDT&E) of safe and reliable human-rated spacecraft systems. The Astronaut Office at NASA's Johnson Space Flight Center requested this NESC assessment. As part of this assessment NESC brought reliability subject matter, subsystem discipline, and systems engineering experts together to synthesize the current "Best Practices" that ensure robust, safe, and reliable critical human-rated spacecraft systems. The findings and recommendations resulting from this assessment are documented in Reference 2: Volume 1 of Reference 2 addresses the topic of spacecraft Systems Engineering for safety and reliability while Volume 2 of Reference 2 reports the subsystem-level findings and recommendations. The GN&C engineering Best Practices presented in this paper have been extracted and condensed from Section 7.5 of Volume 2 of Reference 2.

This paper will summarize the initial set of Guidance, Navigation and Control (GN&C) engineering Best Practices as identified by the NESC's GN&C TDT during this assessment process. These Best Practices address both the early and late phases of the overall DDT&E process. They cover a broad range from fundamental system architectural considerations to more specific aspects (e.g., mathematical modeling) of GN&C system design and development.

The motivation of this paper is to provide useful guidance, in the form of these Best Practices and other considerations and criteria, to the formulation, architecture, design, development and operation of GN&C systems for NASA's future human-rated spacecraft. It is sincerely hoped that engineers and managers can use this

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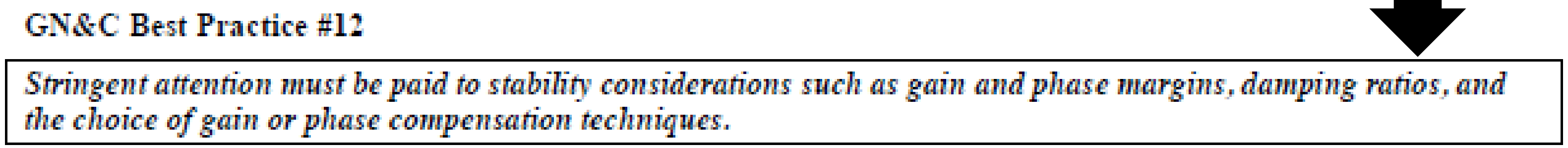


GN&C Best Practice #12

Stringent attention must be paid to stability considerations such as gain and phase margins, damping ratios, and the choice of gain or phase compensation techniques.

- **No NASA standard exists that addresses launch vehicle flight control requirements; however:**
  - The NESC published (in 2007) an assessment report, "**Design, Development, Test and Evaluation (DDT&E) Considerations for Safe and Reliable Human Rated Spacecraft Systems**," covering engineering best practices/guidelines for human-rated spacecraft
  - An AIAA paper, "**GN&C Engineering Best Practices for Human Rated Spacecraft Systems**," written by NESC GN&C TDT members, was subsequently published in 2007, summarizing the NESC assessment report
  - These industry standard guidelines for stability margins were adopted for the CCP 1140 guidelines
    - **CCT-STD-1140, Crew Transportation Technical Standards and Design Evaluation Criteria, Rev. B-1, April 8, 2015**
  - Goddard Space Flight Center Rules for the Design, Development, Verification, and Operation of Flight Systems (i.e., "**Goddard Gold Rules**") contain stability margins, but were not developed for use with human-rated launch vehicles

Flight Control Stability Margin Industry Standards (2 of 2)

- **Undispersed flight control system stability margins** in the open-loop transfer function
  - Rigid body gain/phase stability robustness margins should meet or exceed **6 dB/30 degrees**
  - All gain-stabilized flexible body modes should meet or exceed 12 dB amplitude (gain) margin
  - Well-characterized fundamental (low-frequency) flexible body modes may be phase-stabilized to maintain 45-degree phase margins
- **Dispersed flight control system stability margins** in the open-loop transfer function
  - Rigid body gain/phase stability robustness margins should meet or exceed 3 dB/20 degrees
  - All gain-stabilized flexible body modes should meet or exceed 6 dB amplitude (gain) margin
  - Well-characterized fundamental (low-frequency) flexible body modes may be phase stabilized to maintain 30-degree phase margin

Remarks

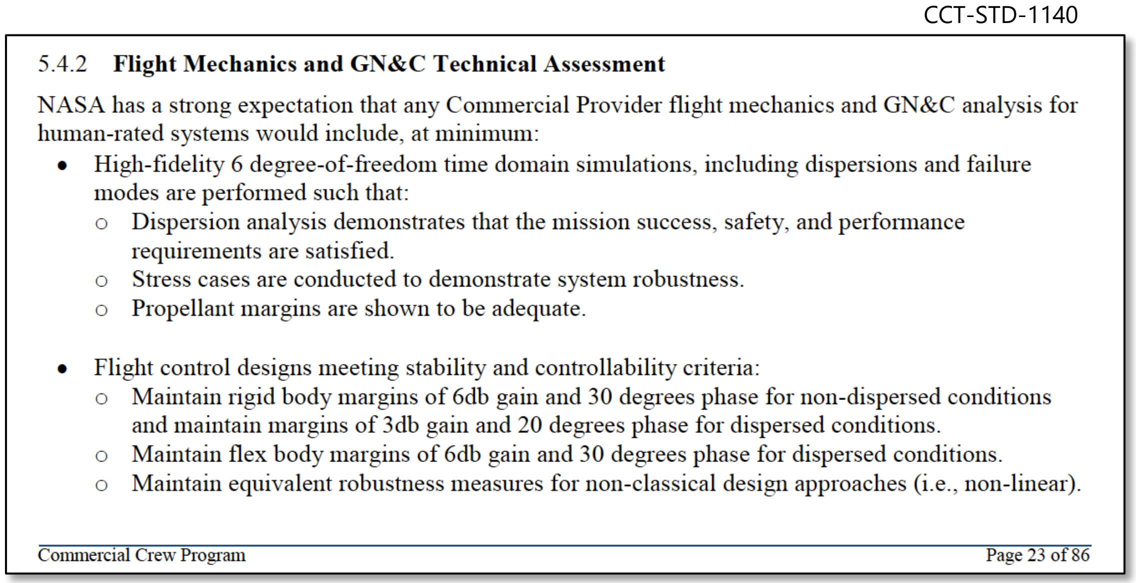
- **Launch vehicle flight control system stability analyses should include:**
  - All flexible body, slosh mode, and nozzle inertial coupling effects
  - All sampled-data and sensor/actuator latency effects
- **The stability analyses should evaluate system uncertainties, including frequency and damping of all modes, and consider flexible body mode shapes. Analysts should determine which dynamic coupling effects drive margins.**
- **Additional analysis beyond that of basic time and frequency domain analyses may be required to address the effects of nonlinear dynamics and/or complex interactions between modes. For example, sloshing propellant for bare-walled tanks merits supplementary analysis due to the nonlinear and uncertain characteristics of propellant slosh modes in the absence of passive damping devices (e.g., tank baffles).**

NASA's Commercial Crew Program (CCP) Defined Flight Control Stability Margins Consistent with Crewed Spaceflight Heritage and Industry Standards

F-6. CCP stability margin expectations are consistent with crewed spaceflight heritage and industry standards for launch vehicle control, yet are not firmly imposed as requirements.

F-7. While flight control stability margins provide metrics for demonstration of robustness, CCT-STD-1140 margin guidelines do not take into consideration system models and consequences of instabilities.

Excerpt from CCT-STD-1140, Revision: B-1, " Crew Transportation Technical Standards and Design Evaluation Criteria"



CCT-STD-1140

5.4.2 **Flight Mechanics and GN&C Technical Assessment**

NASA has a strong expectation that any Commercial Provider flight mechanics and GN&C analysis for human-rated systems would include, at minimum:

- High-fidelity 6 degree-of-freedom time domain simulations, including dispersions and failure modes are performed such that:
  - Dispersion analysis demonstrates that the mission success, safety, and performance requirements are satisfied.
  - Stress cases are conducted to demonstrate system robustness.
  - Propellant margins are shown to be adequate.

- Flight control designs meeting stability and controllability criteria:
  - Maintain rigid body margins of 6db gain and 30 degrees phase for non-dispersed conditions and maintain margins of 3db gain and 20 degrees phase for dispersed conditions.
  - Maintain flex body margins of 6db gain and 30 degrees phase for dispersed conditions.
  - Maintain equivalent robustness measures for non-classical design approaches (i.e., non-linear).

Commercial Crew Program Page 23 of 86

F-8. Departures from flight control stability margin design criteria in CCT-STD-1140 can represent an acceptable balance in overall flight risk posture.

F-9. Guidance is not provided in CCT-STD-1140 regarding the management of deviations from stability margin expectations.

Slosh Dynamics Should Be Included in Stability Margin Reporting

R-1. Require explicit reporting of stability margins with the inclusion of slosh. ("Slosh-off" margins could also be provided, but these should not replace the reporting of margins with all relevant dynamics.)

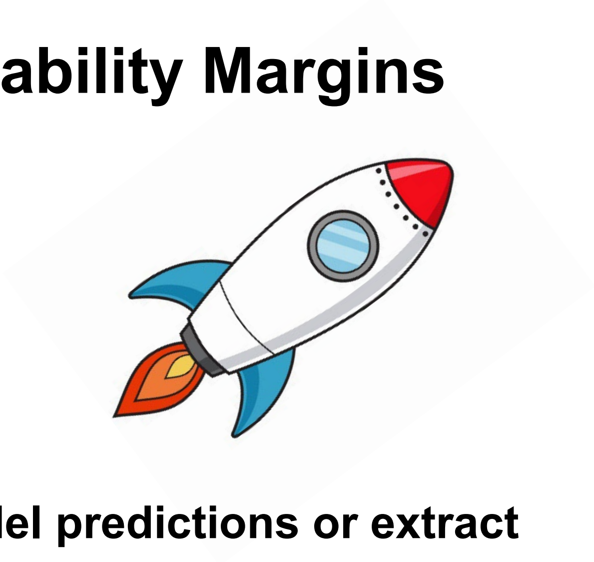
- **Setting the precedent**
  - While a full treatment of first-stage slosh dynamics for any given crewed mission may reveal that the negative to low margins pose no undue vehicle risk, slosh dynamics in general carry the potential for vehicle concern.
  - In the interest of full transparency and disclosure of all potentially challenging flight control dynamics, slosh margins should be a standard report alongside the results with slosh dynamics disabled.
- **Perceived risk illusion**
  - Absence of slosh margins in standard reporting may produce an environment in which slosh risk is not visible to management.

ANALYSIS

- **Utility of flight data and time-domain analysis**
- Slosh fundamentals, sensitivities, and performance
- Slosh sensitivities and consequences
- Flight control stabilization trades

Example summary of expected engineering work to flight-certify crewed missions with unstable slosh modes and reduced stability margins

Utility of Flight Data in Validating Slosh Model/Stability Margins



In-flight observation of slosh instability is known to be difficult

- Adequate excitation source may not exist
- Growth rates are small
- Chaotic, aerodynamic disturbances modify or break limit cycle oscillations (LCO)

Flight tests may not provide sufficient post-flight data to anchor slosh model predictions or extract and validate stability margins against guidelines

- The lack of slosh response in flight is not a positive test for vehicle robustness
- In the absence of targeted excitation with adequate persistency and sufficient sensing, specific vehicle model response validation (e.g., aero, rigid body, slosh or flex) is not possible
  - Recovery of slosh dynamics from flight data may not be possible with necessarily limited in-flight excitation
  - In-flight response of lightly damped modes (e.g., flex, slosh) can provide frequency confirmation if sufficient excitation exists. Very long excitation dwell times would be needed to identify slosh gain and phase margins.

Bottom Line: Flight experience raises confidence, but does not necessarily validate models or stability margins

F-13. Flight data is typically inconclusive regarding slosh stability margins.

Utility of Time Domain Analysis in Validating Stability Margins

- **Time domain analysis using a high-fidelity 6-DOF simulation, with or without targeted excitation, can confirm the expected response of slosh to demonstrate whether an observable response is likely**
  - Flight data may not reveal significant thrust vector control (TVC) response in the frequency spectrum of expected slosh dynamics
  - Slosh response may be clearly visible in spectrogram when slosh is excited, but absent without
- **Time-domain Monte Carlo analysis should be supplemented with a comprehensive treatment of offending dynamics:**
  - Analyzing the **fundamental physics** involved with applicable simulation tool verification (particularly if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data)
  - Conducting **sensitivity studies** in time and frequency domain to analyze effects of possible parameter and system variations
  - Studying the effects of the **consequence of instability** associated with offending modes by running stressing cases in time domain
    - Sensitivity studies aid in identifying parameter sets that most challenge the system stability so the associated consequences may be evaluated

F-10. Time domain responses alone, utilized in day-of-launch processes or otherwise, are not a sufficient means of addressing propensity for unstable conditions without a more comprehensive treatment of the offending dynamics.

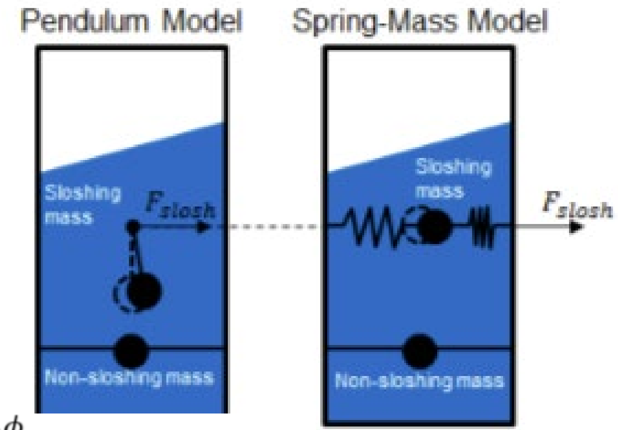
ANALYSIS

- Utility of flight data and time-domain analysis
- **Slosh fundamentals, sensitivities, and performance**
- Slosh sensitivities and consequences
- Flight control stabilization trades

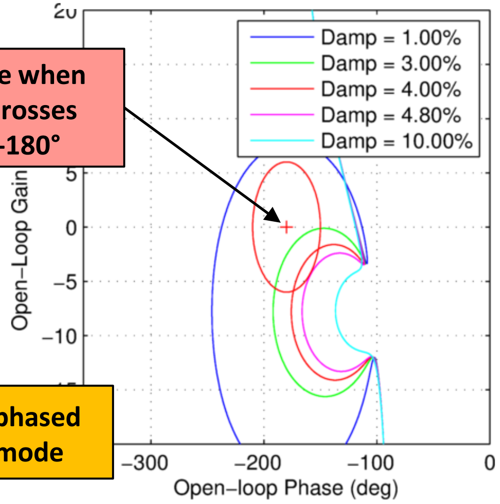
Example summary of expected engineering work to flight-certify crewed missions with unstable slosh modes and reduced stability margins

Slosh Fundamentals

- **Slosh is commonly modeled as linear 2-D mass spring damper or 2-D pendulum**
  - Mechanical model parameters are scheduled vs. flight time (liquid level) and conditions (acceleration) and based on established empirical relationships
- **Long-established slosh "danger zone" criteria exists for *single* tank** *[Bauer 1963]*, **which can indicate propensity for vehicle control instability**
  - Poorly phased slosh modes fall aft of center of percussion and forward of the CG; also visible as margin encroachment on Nichols chart
  - Recent results show that the danger zone extends aft of the CG *[Ottander 2018]*
- **More complex slosh phenomena include interactions with multiple propellant tanks and structural dynamics (flex), which impact vehicle stability**



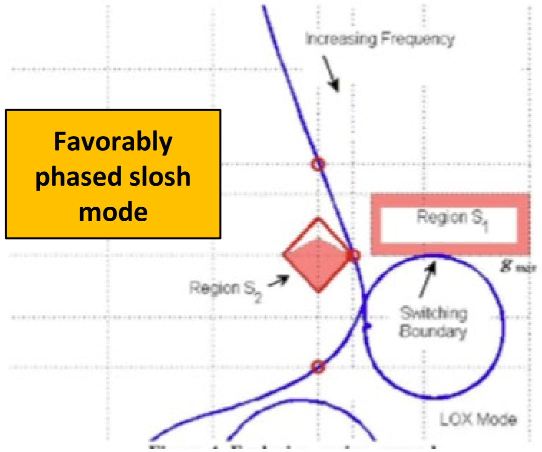
Nichols Example
Poorly Phased



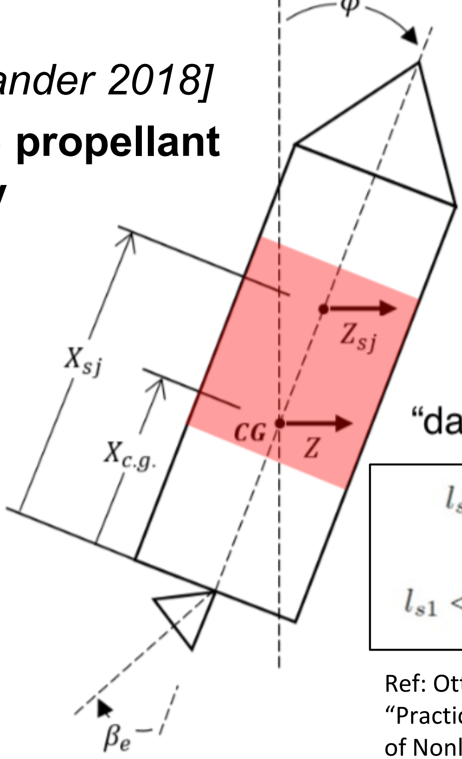
Unstable when mode crosses 0 dB, -180°

Poorly phased slosh mode

Nichols Example
Favorably Phased



Favorably phased slosh mode



"danger zone"

$$l_{s1} > \frac{-I}{M x_{c.g.}} \quad \text{(Center of Percussion)}$$

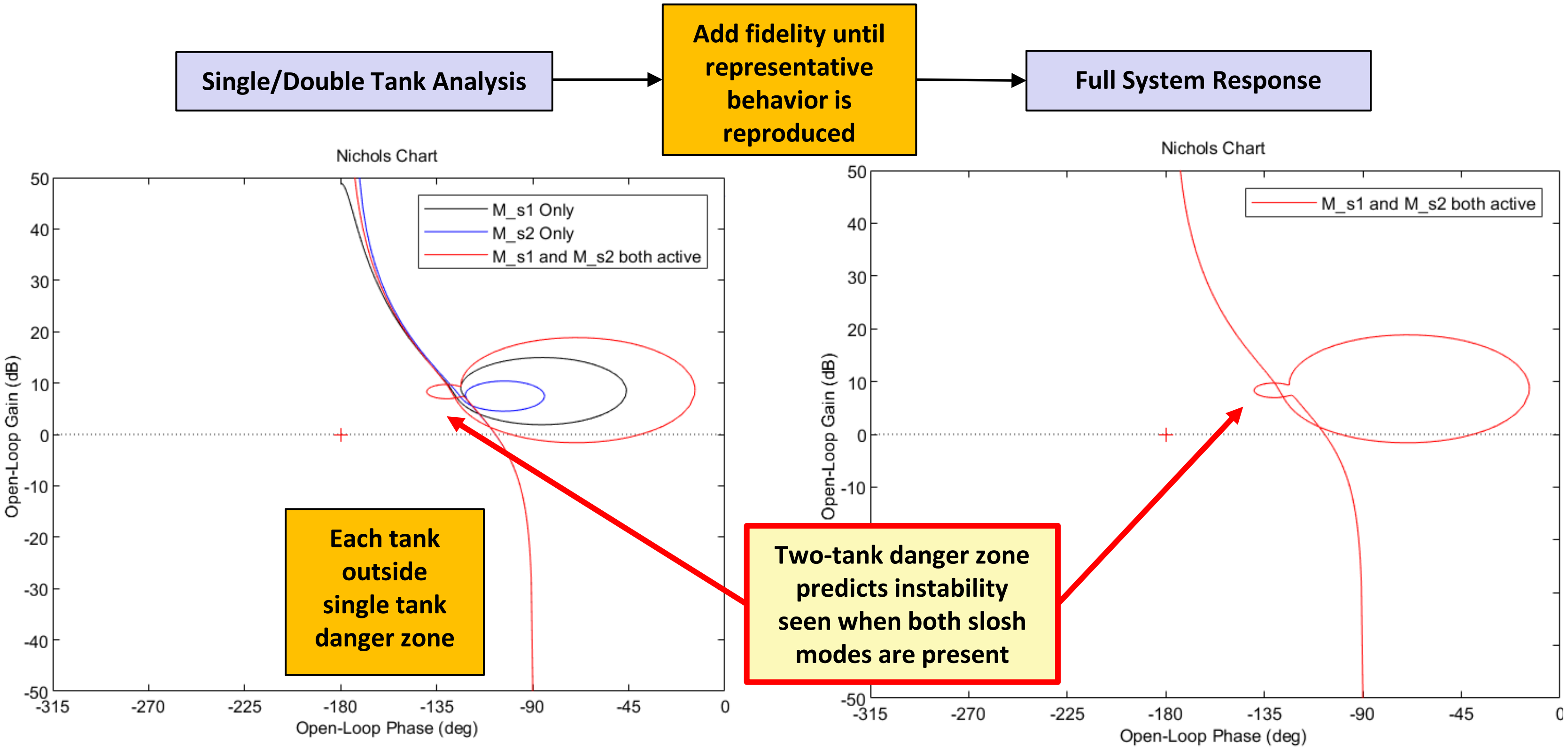
$$l_{s1} < \frac{F(M - m_{s1})}{M^2 \omega_{s1}^2}$$

Ref: 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"

Fundamental Slosh Behavior Should be Verified with Simplest Model

F-14. Time-domain simulations and flight data can show stable slosh response while linear time-invariant (LTI) tools exhibit negative slosh stability margins.

- Analysis of **fundamental physics** involved with applicable simulation tool verification is important if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data
- To ascertain fundamental physics:
  - Determine simplest physics model that matches the response of the full system model to develop an understanding of the driving dynamics
  - Add fidelity until sufficient matching to full system response
- Fundamental slosh frequency response example *[Pei 2021]*: simplified models confirmed using basic proportional-derivative (PD) feedback, rigid body (RB) dynamics, and first slosh modes of each tank



Single/Double Tank Analysis → **Add fidelity until representative behavior is reproduced** → **Full System Response**

Each tank outside single tank danger zone

Two-tank danger zone predicts instability seen when both slosh modes are present

Figures c/o Jing Pei, "Analytical Investigation of Propellant Slosh Stability Boundary on A Space Vehicle," Journal of Spacecraft and rockets Sept-Oct 2021 Vol 58, No. 5, and some contributions thereafter

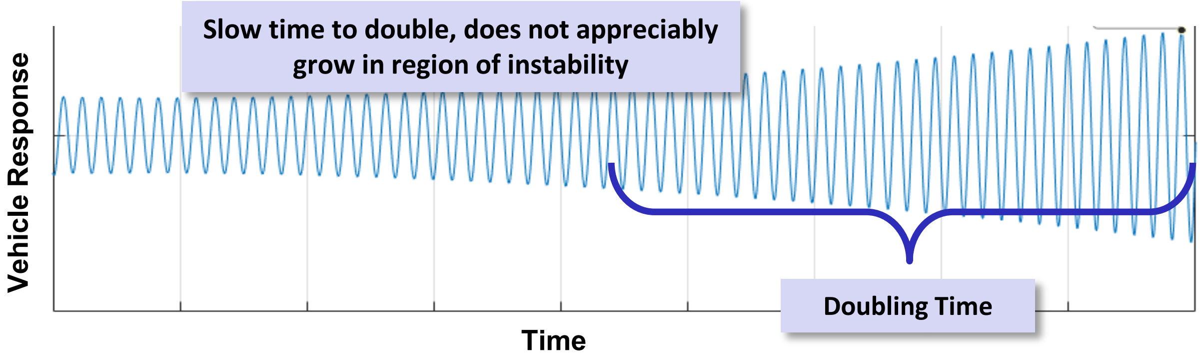
F-15. Simplified representation of launch vehicle two-tank physics model formulated on first principles may be required to reproduce the fundamental behavior seen in full system model.

Fundamental Physics Can Enable Understanding and Mitigation of Apparent Time/Frequency Discrepancy

F-18. Low damping slosh modes can exhibit very slow time to double, and therefore may not exhibit appreciable growth during the unstable region of flight.

- ➢ **Unbaffled booster tanks exhibit low damping with little dependence on wave amplitude**
  - For baffled tanks, damping increases with wave amplitude resulting in a bounded, small-amplitude LCO

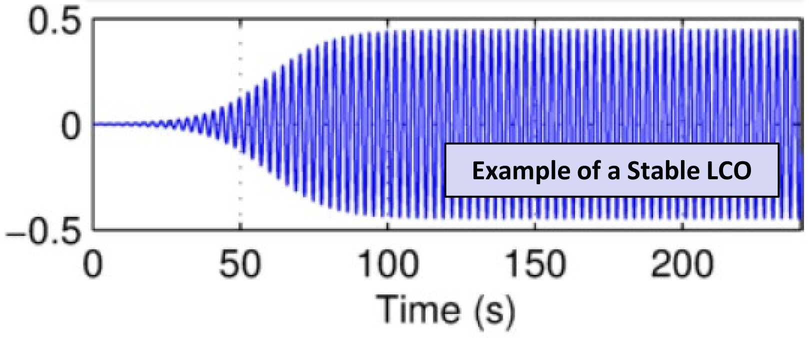
F-19. Low damping slosh modes, once excited, can *quickly* reach a near-constant amplitude response resembling an LCO in the period of flight of interest.



Slow time to double, does not appreciably grow in region of instability

- ➢ **Unbaffled slosh immediately responds with a near-constant amplitude oscillation that is proportional to its excitation source**
  - Stabilization of near-zero damping slosh mode via flight control modifications reduces the amplitude, but does not appreciably alter negligible growth rate or decay
  - Key questions for analyst:
    - *What is the maximum acceptable slosh amplitude?*
    - *What is the largest source of slosh excitation?*

Forced response rise time can be significantly faster for low damping modes (e.g., unbaffled slosh)

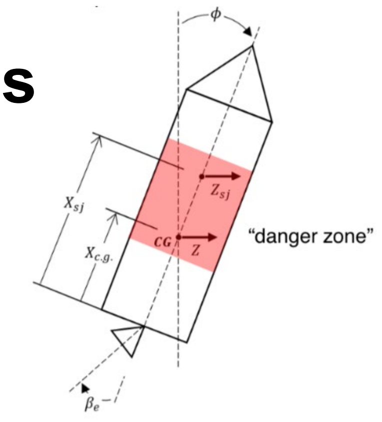


Example of a Stable LCO

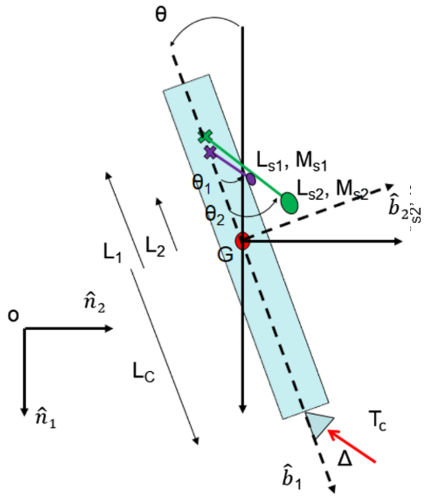
A *limit cycle oscillation (LCO)* is a stable, periodic oscillation characterized by a bounded amplitude and constant first harmonic frequency, determined by the nonlinear properties of the system

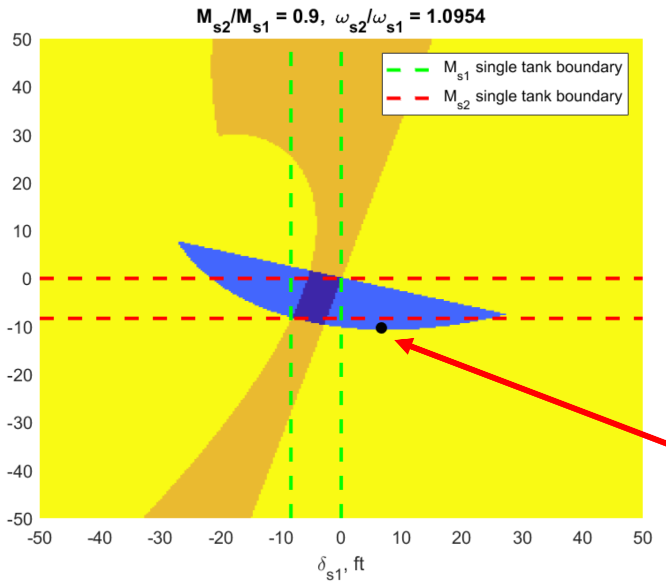
Slosh Instability: Single- vs. Dual-Tank Dynamics

- Single-tank predictions can be under-conservative in that each slosh mode can fall outside the “danger zone” (i.e., appearing to be favorably phased; stable)
- Dual-tank coupled dynamic response of the same vehicle can reveal unfavorable slosh phasing (i.e., propensity to be unstable)



Two-Tank Analysis





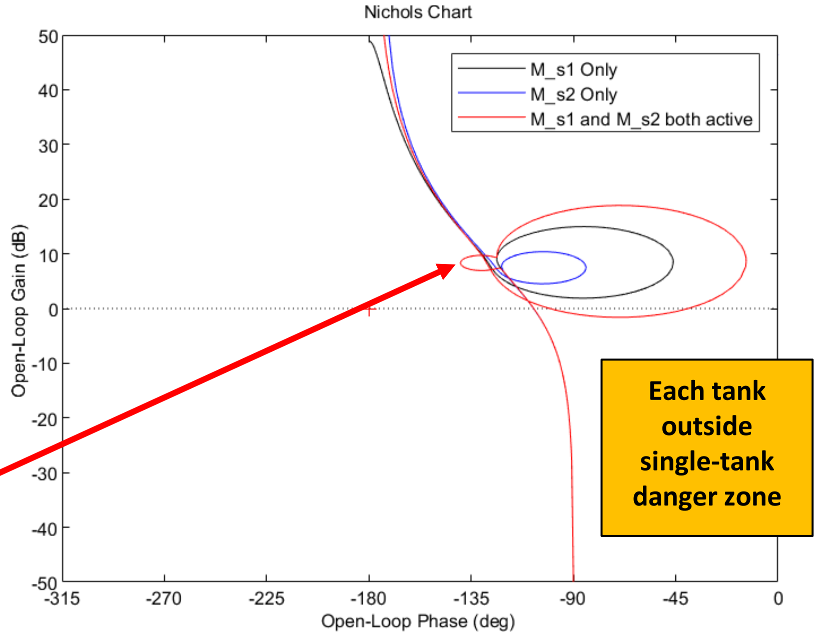
Red and **green** lines indicate classic danger zone for a single tank configuration

Blue region indicates modified danger zone for the LOX tank

Orange region indicates modified danger zone for the RP-1 tank

Yellow region: both tanks are phase stable

Two-tank danger zone can reveal an instability



Each tank outside single-tank danger zone

Figures c/o Jing Pei, “Analytical Investigation of Propellant Slosh Stability Boundary on A Space Vehicle,” Journal of Spacecraft and Rockets, Sept-Oct 2021 Vol 58, No 5, and some contributions thereafter

O-2. Slosh tanks exhibiting coupled behavior depart from expectations guided by classical single-tank criteria and can show instabilities when uncoupled tanks show stability.

F-16. Slosh instability can exhibit coupled dynamic behavior not predicted by single-tank metrics.

ANALYSIS

- Utility of flight data and time-domain analysis
- Slosh fundamentals, sensitivities, and performance
- **Slosh sensitivities and consequences**
- Flight control stabilization trades

Example summary of expected engineering work to flight-certify crewed missions with unstable slosh modes and reduced stability margins

Best Practice: Evaluation of Margin Deviations (Including Instabilities) and Consequences

National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 14-01

Designing for Flight Through Periods of Instability

For completeness, it is imperative that Flight Control System (FCS) designers use both complementary time and frequency domain techniques to address periods of instability. Use of standard frequency domain synthesis techniques alone may not always yield an FCS design with sufficient gain and phase stability robustness margins while simultaneously satisfying performance requirements.

Instability Cause and Consequence

Analysis and evaluation must be performed of any potential source of instability (e.g., propellant slosh, flexible structure, or aerodynamics), while flying through periods of rapidly changing dynamics. A large body of experience has been accumulated regarding successfully flying through not only degraded margins, but also relatively brief periods of linearized model instability. These instabilities occur as the flight environment and vehicle dynamics undergo rapid changes. When linearized stability robustness margin requirements cannot be satisfied, alternative methods are then needed to ensure that deficient stability margins do not present a high risk of losing control during the mission.

The Orion launch abort system successfully flew through brief periods of instability. Known instabilities and risks were evaluated prior to flight using best practices.

Best Practices for Flight Control System Design

FCS designers should consider employing non-linear system requirements that capture both stability and performance aspects. Occasionally, it may be necessary to set aside the traditional frequency domain gain and phase stability robustness margins in favor of another technique. The tried-and-true guideline that stability always comes before performance in the design process remains the same. However, since real flight systems behave in a non-linear manner, "stability" should be understood as control of the vehicle never being lost while simultaneously achieving attitude control performance requirements.

Consider four complementary recommendations for certifying FCS designs with deficient stability margins:

1) Accept some Relaxed or even Negative Stability Margins: additional analysis may not be required if a stability margin fails the requirement for only a brief time. Seek out prior experience with similar configurations and conditions.

2) Evaluation of Uncertainties: reassess whether the uncertainties input into the analysis are realistic. In certain cases, the effects of correlated variables can be taken into account to reduce the level of uncertainties used in the analysis.

3) Checking the Time to Double Amplitude: determine if the vehicle will fly through the region of concern before the oscillations reach unacceptable amplitudes, in which case a relaxed or even negative margin may be acceptable.

4) Use of Non-Linear Time-Domain Simulations: exploit the complete non-linear time-domain models to prove that the vehicle exhibits acceptable behavior, even with programmed test inputs to excite oscillations. Additionally, the loop gains and/or time lags can be adjusted in the simulation to evaluate the gain and phase stability margins remaining from a non-linear perspective.

Historically, some launch vehicles have been successfully flown with the known threat of slosh instabilities. The Atlas-II was successfully flown with linearly unstable (as viewed from a purely linear frequency-domain perspective) slosh modes.

An FCS designer should question the application of linear stability requirements and not rely exclusively on the frequency domain approaches to verify stable flight. The use and application of the frequency-domain synthesis and analysis tools must be balanced with the non-linear time-domain performance simulation tools and the Time to Double Amplitude criteria.

References

1. NASA/TM-2011-217183, NESC-RP-09-00602 v2.0, Independent Review of the Ares-I Control Sensitivity to Orion Service Module Tank Slosh Dynamics, Oct. 2011

2. NASA Document Number: EAM-CEV-09-001, Shuttle Ascent and Entry GN&C Stability Verification, Edgar Medina (PA-1 Flight Dynamics Team), Jan. 23, 2009

3. NASA/SP–2010–3408, Space Shuttle Entry Digital Autopilot, Section 9.0 Lessons Learned, Larry McWhorter and Milt Reed, Feb. 2010

For information contact the NESC at nesc.nasa.gov

www.nasa.gov

NESC Tech Bulletin 14-01, "Designing for Flight Through Periods of Instability"

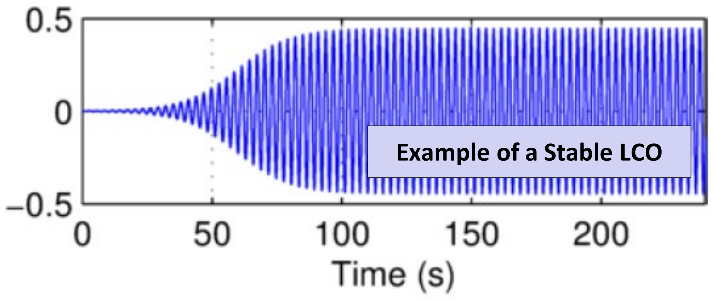
- Known instabilities and risks should be evaluated prior to flight using best practices.

Consequences of instability should be evaluated. For slosh:

F-18. Low damping slosh modes can exhibit very slow time to double, and therefore may not exhibit appreciable growth during the unstable region of flight.

F-19. Low damping slosh modes, once excited, can *quickly* reach a near-constant amplitude response resembling an LCO in the period of flight of interest.

<u>Question for analyst</u>: For range of possible disturbances, what is the corresponding slosh amplitude and associated consequence?



Forced response rise time can be significantly faster for low damping modes (e.g., unbaffled slosh)

A limit cycle oscillation (LCO) is a stable, periodic oscillation characterized by a bounded amplitude and constant first harmonic frequency, determined by the nonlinear properties of the system.

Evaluation of Sensitivities in Frequency-Domain

Dispersed stability analysis and targeted sensitivity studies can determine the propensity for impact on margins.

Sensitivities to investigate for propellant slosh include:

- **Vehicle flexibility**
  - Flex body dynamics can significantly impact phase margins
  - Flex body dynamics can reduce slosh margins or potentially destabilize a slosh mode
    - Impact of flex on time-domain slosh response characteristics may be modest
- **Relative slosh frequency**
  - Coupling effects between two tank slosh dynamics can be significantly influenced by relative slosh frequency
- **Actuator and sensor nonlinearities (details in backup)**
- **Rotary slosh (see backup)**
- **Autopilot filter, latency, and other source of phase lag**
  - May have destabilizing impact on poorly phased propellant slosh

O-1. Inclusion of flexible body dynamics can significantly reduce slosh phase margin due to dynamic coupling.

F-17. Two-tank coupled slosh behavior can be sensitive to relative frequency of the slosh modes.

O-4. Stiction in TVC actuators or equivalent effects can decouple the controller from propellant slosh effects (i.e., mask small-amplitude time-domain instabilities) during quiescent regions of flight until slosh amplitudes are large enough to induce motion.

Supplementary Analysis (Stressing Cases) in Time-Domain

Simulations

Simulate many possible opportunities for instability to occur in flight; once sensitivities are understood, evaluate whether they are credible/probable

Doublet (shuttle approach): Application of doublet(s) during periods of instability for (1) nominal system and (2) worst-case dispersed

- Multiple amplitudes: 0.5°, 1°, 1.5°, 2°, 3°
- Consider reasonableness of doublet amplitude

Direct Slosh Initialization: Initialize slosh states during periods of reduced margin for (1) nominal system and (2) worst-case dispersed

- Pure lateral (pitch, yaw, pitch/yaw)
- Pure rotary
- Attempt to cover the space in between
- Compare slosh amplitudes with what is seen from Monte Carlo simulation and intentional excitation via doublet analysis

Indicators

Indicators to consider with time-domain results:

- Observation of stability/instability
- Time to double/half
- Actuator usage
  - Amplitude
  - Rate (<10% capability?)
  - Impact to loads
- Slosh wave amplitude
  - Mechanical model breaks down
  - Loads
  - Thermal/fluid management (ullage collapse)
- Acceleration at crew location
- Abort margins

F-5. Supplementary analyses (i.e., stressing cases in the time domain) can determine if unanticipated stability concerns or sensitivities exist.

R-3. Simulate stressing cases, as recommended by CCT-STD-1140, to evaluate sensitivity to slosh dynamics for every crewed mission where FCS margins (inclusive of slosh) do not meet CCT-STD-1140 guidelines.

Time-Domain Response Indicators

- **Largest excitation/response should be evaluated under worst-case stressing conditions and slosh parameters to ensure that:**
  - Direct slosh initialization with large magnitudes does not affect vehicle system (no crew accel limits, TVC concerns, or significant vehicle motion)
  - Doublet required to produce such large magnitudes would cause abort due to rigid body response prior to exceeding load limits
  - Monte Carlo with worst-case conditions and direct slosh initialization would be in family with nominal slosh initialization predictions
  - Large slosh angles are not expected to be an issue for propellant thermal management or loads on the tank structure/baffles

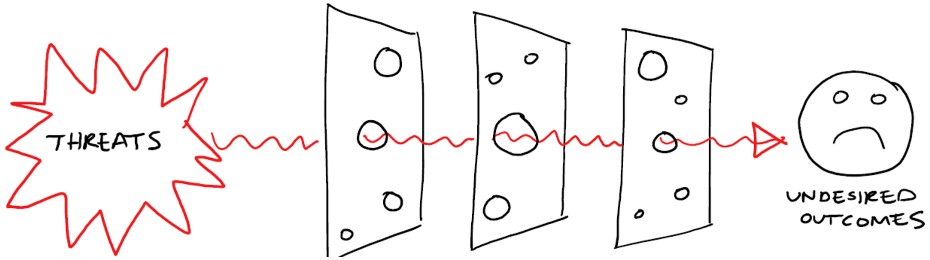
Thrust Vector Control (TVC) Considerations

- **TVC nonlinearities, especially those that affect low frequency, can potentially interact with slosh dynamics**
- **Flight control analysis can predict whether LCOs are driven by TVC response nonlinearities (e.g., gimbal friction) or slosh nonlinearities (damping dependence on wave height)**
  - If LCO is defined by TVC and not slosh, then there will be a TVC limit cycle before magnitudes increase to produce slosh responses at the LTI-assumed slosh wave height

F-20. Assessment of launch vehicle response in the presence of forced excitation of slosh instability can reveal which subsystem is limiting. For example, the doublet required to produce large-magnitude sloshing motion may trigger an abort due to the rigid-body response before appreciable slosh-induced control response is observed in the TVC command.

Failure to Meet Stability Margin Design Criteria: Implications

- **All launch vehicle flight control instabilities are not equal in their consequence**
  - For low damping modes (e.g., unbaffled slosh), a gradual increase in “limit cycle” amplitude occurs when the open loop reaches instability
  - For high damping modes (rigid body, high gain flex modes), the gain perturbation required to reach instability is greater, but the vehicle will exhibit a rapidly divergent response
- **Margin reductions can be acceptable when accompanied by a full body of technical justification**
  - However, maintain awareness that stress cases cannot exercise “unknown unknowns” that are key links in the accident chains leading to many flight anomalies/failures
  - Stability margins guard against unforeseen/unexpected conditions



F-11. Autopilot stress cases that are consistent with best practices for evaluation of robustness are unable to exercise “unknown unknowns” (i.e., stability margins guard against unforeseen/unexpected conditions).

ANALYSIS

- Utility of flight data and time-domain analysis
- Slosh fundamentals, sensitivities, and performance
- Slosh sensitivities and consequences
- **Flight control stabilization trades**

Example summary of expected engineering work to flight-certify crewed missions with unstable slosh modes and reduced stability margins

Evaluation of Flight Control Stabilization Trades

- **Clarify what constitutes an "optimal" design, given the complex trades between flight control filter/gain design, flex attenuation, slosh stability, rigid body phase margin, and aero margin**
- **Explore adjustments to the flight control system (FCS) parameters for a given architecture to determine the extent to which margins tradeoffs affect the driving dynamics**
  - Decreasing bandwidth can increase available phase margin for more aggressive filter attenuation of parasitic dynamics (slosh, flex)
  - FCS designs that favor increased phase margins (for rigid body or slosh) can reduce aerodynamic and flex margins
  - Reduction in nominal aerodynamic stability margins can result in increased error tracking performance and control overshoot even if dispersed aero margins meet dispersed stability margins guidelines
  - Gain stabilization of low damping slosh can attenuate amplitude of forced "limit cycle" response
  - Lowering phase stable flex mode gains → lower active damping → increased loads response
  - Consequences of margin trades can vary as a function of flight condition/time
- **Parameter adjustments may reveal opportunities to improve reduced margin by trading with areas having excess margin, lower sensitivity, or lower consequence**

F-21. Flight control design alternatives may be able to restore margins that do not meet the design criteria by trading margins in other areas.

Evaluation of Flight Control Stabilization Trades

Reduced Rigid Body Phase Margin Can Give Performance

- **What is the impact of reducing rigid body phase margins to below 30 degrees?**
  - Concern: Margin reductions with respect to NASA human spaceflight heritage (e.g., Saturn, Shuttle)
  - Launch vehicle general observations that could mitigate concern:
    - Tight dispersion band near gain crossover (well-characterized actuator lags, SIL-tested avionics delays)
    - Maneuvering capability adequate (short-duration steering maneuvers can be shaped according to anticipated control response)

- **Allowing reduced RB phase margin can provide FCS design flexibility to improve other margins**
  - Increased aero margins → reduction in loads → improved launch availability
  - Improved flex margins via filter attenuation (gain-stable modes) or filter phasing (phase-stable modes)

- **Maintaining 30 degrees of rigid body phase margin is consistent with accepted best practice**
  - Industry standard for launch vehicles, already lower than other applications (e.g., manned aircraft)
  - Ensures a reasonable control response overshoot during maneuvering
  - Provides robustness to unknown sources of additional lag to protect against rigid body instability (catastrophic)

- **Alternate flight control system designs with reduced phase margins should be assessed to evaluate consequences and determine overall vehicle risk. Include evaluation of:**
  - Control response overshoot on gust/transient loads
  - Loads benefits from increases in active damping of phase stabilized modes
  - Launch availability impacts of load response to wind gusts

Evaluation of Flight Control Stabilization Trades

Additional Remarks

- For cases in which stability margin expectations are not being met, best practices seek to **demonstrate specifically what is being traded** in terms of margin allocation and performance loss/gain.
- **Specific vehicle configurations may require additional margins in specific areas of sensitivity** (e.g., aerodynamic uncertainty and consequence of high aero loading) and can be traded against lower risk margin degradation (slosh and rigid body phase margins).
- Restoring an unstable system to stability will incur less margin trade penalty than achieving full margins.
  - Margin trades should be informed by the consequences associated with the modes in question.
- Appropriate **management of trades pertaining to margin reductions may vary depending on when in a program's history they occur.**
  - Lower margins (larger reductions) may be permissible following successful flight experience if post-flight mission analysis has allowed for validation of the models impacting the margin reductions in question.
  - Note that the utility of flight data with respect to validating slosh models may be minimal (see F-13).
- Early in the launch vehicle certification process, provider should **present full justification when advocating for reduced stability margins in the context of the overall vehicle risk**. Following sufficient justification of margin reductions, tailored requirements can alleviate an unnecessary resource burden in subsequent analysis cycles for a specific vehicle configuration.

Conclusions

Conclusions

- NESC perspective for crewed spaceflight: **Acceptance of flight control gain/phase stability margin reductions from industry-standards should be accompanied by an adequately extensive technical treatment, including:**
    - Analyzing **fundamental physics** involved, with applicable simulation tool verification (particularly if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data)
    - **Conducting sensitivity studies** in time and frequency domain to analyze effects of possible parameter and system variations
    - Studying the effects of the **consequence of instability** associated with offending modes by running stressing cases in time domain
    - **Assessing alternative flight control designs** to demonstrate present design appropriately balances overall vehicle risk (i.e., quantitatively delineate chosen tradeoffs between various stability margins and vehicle performance in the context of risk/consequence)
- **Work discussed here represents an example summary of expected engineering work to flight-certify crewed missions with unstable slosh modes and reduced stability margins**

Summary of Findings, Observations, and NESC Recommendations

Definition of Terms

Finding

A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.

Observation

A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a center/program/project/organization’s operational structure, tools, and/or support provided.

Recommendation

A proposed measurable stakeholder action directly supported by specific finding(s) and/or observation(s) that will correct or mitigate an identified issue or risk.

NESC Assessment Findings (1 of 4)

Note: Highlighted Findings, Observations, and Recommendations (FORs) also appear in the main body of the presentation

F-1. Human spaceflight launch vehicle propellant slosh has historically been stabilized (i.e., ascent vehicles for crewed spaceflight never flown with negative slosh margins).

F-2. Rigid-body phase margins for human spaceflight have been maintained at 30 degrees or more (non-dispersed).

F-3. Slosh damping dispersions in time-domain Monte Carlo simulations are the primary mechanism for gaining confidence in stability in the absence of positive slosh margins.

F-4. Shuttle and SLS conducted targeted stressing cases for slosh in scenarios where analytically determined flight control stability margins were low.

F-5. Supplementary analyses (i.e., stressing cases in the time domain) can determine if unanticipated stability concerns or sensitivities exist.

F-6. CCP stability margin guidelines provided in CCT-STD-1140, “Crew Transportation Technical Standards and Design Evaluation Criteria,” are consistent with crewed spaceflight heritage and industry standards for launch vehicle control, yet are not firmly imposed as requirements.

NESC Assessment Findings (2 of 4)

F-7. While flight control stability margins provide metrics for demonstration of robustness, CCT-STD-1140 margin guidelines do not take into consideration system models and consequences of instabilities.

F-8. Departures from flight control stability margin design criteria in CCT-STD-1140 can represent an acceptable balance in overall flight risk posture.

F-9. Guidance is not provided in CCT-STD-1140 regarding the management of deviations from stability margin expectations.

F-10. Time domain responses alone, utilized in day-of-launch processes or otherwise, are not a sufficient means of addressing propensity for unstable conditions without a more comprehensive treatment of the offending dynamics.

F-11. Autopilot stress cases that are consistent with best practices for evaluation of robustness are unable to exercise “unknown unknowns” (i.e., stability margins guard against unforeseen/unexpected conditions).

NESC Assessment Findings (3 of 4)

F-12. Launch vehicles may be able to “fly through” periods of instability. Evidence of acceptability may include:

- a) Model fidelity involving offending dynamics is sufficient for evaluation of sensitivities in both time and frequency domain.
- b) Limit cycles are manageable for disturbances within the abort limits.
- c) Time-to-double is greater than the period of instability.
- d) Sensitivities and stressing cases are investigated in high-fidelity time-domain simulations.

F-13. Flight data is typically inconclusive regarding slosh stability margins.

F-14. Time-domain simulations and flight data can show stable slosh response while LTI tools exhibit negative slosh stability margins.

F-15. Simplified representation of launch vehicle two-tank physics model formulated on first principles may be required to reproduce the fundamental behavior seen in full system model.

F-16. Slosh instability can exhibit coupled dynamic behavior not predicted by single-tank metrics.

NESC Assessment Findings (4 of 4)

F-17. Two-tank coupled slosh behavior can be sensitive to relative frequency of the slosh modes.

F-18. Low damping slosh modes can exhibit very slow time to double and therefore may not exhibit appreciable growth during the unstable region of flight.

F-19. Low damping slosh modes, once excited, can quickly reach a near-constant amplitude response resembling an LCO in the period of flight of interest.

F-20. Assessment of launch vehicle response in the presence of forced excitation of slosh instability can reveal which subsystem is limiting. For example, the doublet required to produce large-magnitude sloshing motion may trigger an abort due to the rigid-body response before appreciable slosh-induced control response is observed in the TVC command.

F-21. Flight control design alternatives may be able to restore margins that do not meet the design criteria by trading margins in other areas.

NESC Assessment Observations (1 of 2)

O-1. FCS design philosophy can result in gain and filter coefficients that prioritize certain stability margins over others (i.e., aerodynamic stability margins, flexible-body stability goals, and/or slosh margins).

O-2. Slosh tanks exhibiting coupled behavior depart from expectations guided by classical single-tank criteria and can show instabilities when uncoupled tanks show stability.

O-3. Inclusion of flexible body dynamics can significantly reduce slosh phase margin due to dynamic coupling.

O-4. Stiction in TVC actuators or equivalent effects can decouple the controller from propellant slosh effects (i.e., mask small-amplitude time-domain instabilities) during quiescent regions of flight until slosh amplitudes are large enough to induce motion.

O-5. An unbaffled, unstable slosh mode carries inherent risk due to its lack of mechanism for energy dissipation, and there is greater opportunity for lateral energy to transition to rotary slosh.

Note: Highlighted FORs also appear in the main body of the presentation

NESC Assessment Observations (2 of 2)

O-6. Alternative models to the spherical pendulum model are available, with limited modeling and test data, that better predict rotary motion used in nonlinear time-domain analysis to complete an evaluation of the expected behavior.

O-7. Launch vehicle FCS designs that do not meet the stability margins corresponding to the disc defined by 6dB (gain) and 30 degrees (phase) represent a departure from the accepted industry practice and introduce a stability risk.

O-8. NESC recommendations R-9 and R-10 are appropriate for launch vehicles under development intended to support human spaceflight where stability margin departures exist.

O-9. There does not exist an Agency standard defining requirements for launch vehicle flight control systems.

NESC Recommendations (1 of 4)

The following recommendations are directed to human spaceflight programs:

R-1. Require explicit reporting of stability margins with the inclusion of slosh. (“Slosh-off” margins could also be provided, but these should not replace the reporting of margins with all relevant dynamics.)

R-2. Include slosh damping dispersions in time-domain Monte Carlo analyses (all crewed flights).

R-3. Simulate stressing cases, as recommended by CCT-STD-1140, to evaluate sensitivity to slosh dynamics for every crewed mission where FCS margins (inclusive of slosh) do not meet CCT-STD-1140 guidelines.

R-4. Consider, as an offline risk reduction exercise, optimizing flight control gains to determine the extent to which positive stability margins can be recovered.

R-5. Ensure stability margin guidelines incorporate acceptance criteria for stability margin departures to enable selection of flight control designs that minimize and control overall vehicle risk.

- a) Departure acceptance criteria should include evaluation and documentation of overall vehicle flight risk, including stability and performance trades.
- b) Consider tailoring stability margin treatment for specific launch vehicle configurations once supporting evidence is provided that justifies a desired stability margin posture for the specific vehicle.

Note: Highlighted FORs also appear in the main body of the presentation

NESC Recommendations (2 of 4)

The following recommendations are directed to human spaceflight programs:

R-6. Ensure large slosh angles caused by stressing cases during boost phase do not cause a thermal (i.e., ullage collapse) or loads concern.

R-7. Require documentation of an adequately extensive technical treatment to accept proposed departure from stability margin expectations.

   a) Demonstrate that the selected design constitutes best effort at appropriately balancing and controlling overall vehicle risk via specific vehicle stability and performance trades.

   b) Conduct rigorous analysis to evaluate sensitivities in the time and frequency domain to gain confidence that the existing design is adequate.

NESC Recommendations (3 of 4)

The following recommendation is directed to human spaceflight programs:

R-8. Require the launch vehicle provider to (1) assess alternate flight control parameter sets that meet stability margin guidelines, (2) evaluate trades between stability and performance with respect to existing design, and (3) identify the parameter set that best balances overall vehicle risk.

a) Performance impacts with compliant parameter set(s) should be quantified against baseline parameter sets to identify the impact of margin trades.

b) Performance evaluation should consider trajectory, loads, launch availability, slosh response, and other analyses impacted by the flight control design.

c) Ensure full evaluation and certification of chosen parameter set (e.g., FSW, SIL).

NESC Recommendations (4 of 4)

The following recommendation is directed to the NASA OCE:

R-9. Develop a NASA Launch Vehicle Flight Control System Design, Development, Test, and Evaluation (DDT&E) Standard for Agency use that would define a set of requirements in lieu of the less rigorous guidelines/expectations.

The following recommendation is directed to future human spaceflight programs:

R-10. Programs should consider the use of requirements in lieu of guidelines/expectations to include provisions discussed in R-9 for flight control designs that do not meet the standard stability margin requirements.

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NESC Team Composition

NESC Technical Team Members

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Jeb Orr	Mclaurin Aerospace (GN&C TDT Member)
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Steve Gentz	NESC Chief Engineer’s Office
Dan Yuchnovicz	NESC Integration Office
Chris Miller	Armstrong Flight Research Center
John Davidson	Langley Research Center

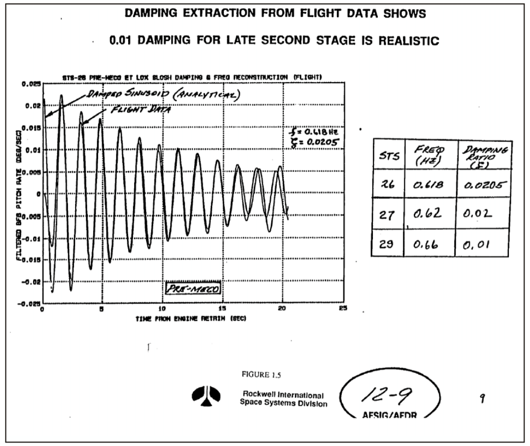
Impact of Actuator and Sensor Nonlinearities During Quiescent Flight

O-4. Stiction in TVC actuators or equivalent effects can decouple the controller from propellant slosh effects (i.e., mask small-amplitude time-domain instabilities) during quiescent regions of flight until slosh amplitudes are large enough to induce motion.

- **Open-loop slosh response due to TVC stiction used by STS during exoatmospheric flight to validate slosh models**

Reference: Altenbach, R. et al., Space Shuttle Ascent FCS Historical Data Recovery Document, SSD94D0286, Rockwell International Space Systems Division, September 30, 1994

- **If slosh instability occurs during boost phase near max-Q, atmospheric disturbance can mitigate the need to investigate the impact of these nonlinear effects**
- **Such a condition could occur with unstable slosh in a quiescent flight regime**
  - **Nonlinearities could mask a time-domain instability in repeated nominal flights**
  - **Anomaly could force larger amplitude motion, which excites the FCS and thus the slosh instability**



DAMPING EXTRACTION FROM FLIGHT DATA SHOWS

0.01 DAMPING FOR LATE SECOND STAGE IS REALISTIC

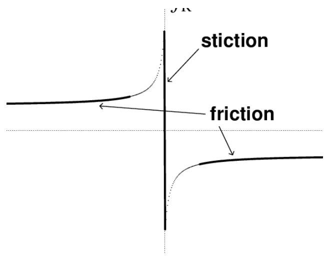
STS	FREQ (HZ)	DAMPING RATIO (ζ)
26	0.618	0.0205
27	0.62	0.02
29	0.66	0.01

FIGURE 1.5

Rockwell International
Space Systems Division

12-9
AFSIG/AFDR

9

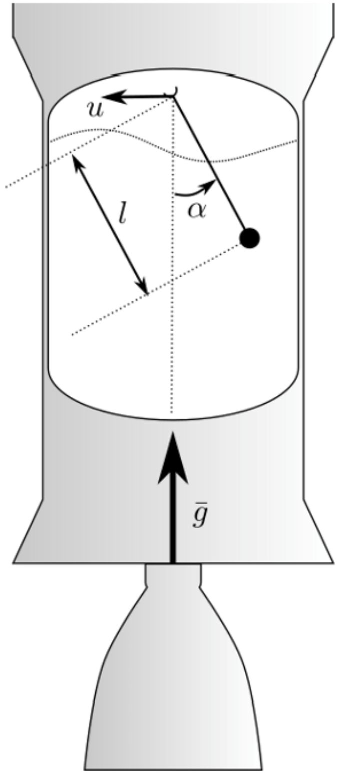


STS slosh damping flight test validation possible due to high quality rate gyros and presence of RS-25 gimbal bearing stiction

Aerodynamic disturbances
+
Boosters
=

(For Rockets)

Limited Treatment of Rotary Slosh



"Nonlinear Models for Rotary Sloshing Dynamics," J. Orr, April 2020

- Lateral sloshing energy can transition to rotational motion and/or rotary slosh, but no specific reason has been identified suggesting that rotary slosh is a concern for this vehicle
- Rotary slosh stressing cases can be evaluated in the time domain using a spherical pendulum slosh model with direct slosh initialization
- Bauer model investigated as a possible nonlinear rotary slosh model (more conservative than current model); limited nonlinear rotary slosh modeling and testing data exists (ref. 1)
- Forward work on rotary slosh modeling supported as a discipline-advancing activity under the NESC GN&C TDT

O-5. An unbaffled, unstable slosh mode carries inherent risk due to its lack of mechanism for energy dissipation, and there is greater opportunity for lateral energy to transition to rotary slosh.

O-6. Alternative models to the spherical pendulum model are available, with limited modeling and test data, that better predict rotary motion used in nonlinear time-domain analysis to complete an evaluation of the expected behavior.