SLS

Space Launch System

Use of Higher Fidelity Slosh Models to Reduce Conservatism in Launch Vehicle Flight Control Designs

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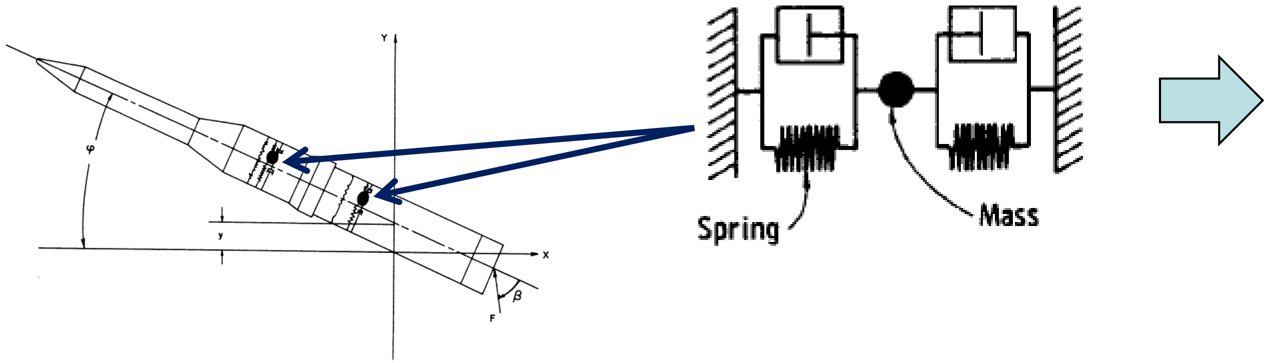
Overview

- **Slosh dynamics are generally modeled as a spring/mass (or pendulum) model.**
  - Linear model, easily implemented.



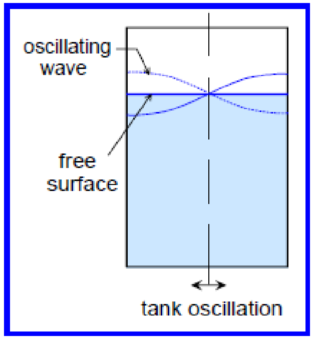


Figure 1.1. Schematic illustration of a slosh wave

See Ref [1]

- **To ensure stability, generally weight-intensive baffling is added to the tanks to keep slosh motion small.**
  - Baffling is essentially found in every vehicle where slosh is a concern, physically to ensure small slosh motion, and analytically to allow the use of simplified linear models.
  - “High amplitude” slosh motion becomes nonlinear, invalidating linear model assumption.

Two notable Slosh Instabilities in Launch Vehicles

- **Two notable slosh-induced instabilities in Launch Vehicles:**
  - SpaceX Falcon 1 Demo Flight 2[1]
    - Vehicle oscillations in pitch/yaw due LOX slosh ~90 seconds into flight during Second Stage, and induced roll torque.
    - Roll torque overcame the RCS thrusters and centrifuged the propellants, causing engine flame-out.
    - Falcon 1 did not use slosh baffles in the second stage tanks.
    - Apparently, preflight analysis relied on time-domain simulation, and failed to adequately capture all slosh transient dynamics during ascent flight.
    - Extensive 2nd stage slosh baffles added, as is currently the case with the 1st stage.
  - Saturn Test Flight SA-1[2]
    - Slosh instability occurred in lower region of tanks, below the last baffle.
    - Slosh instability started as linear motion and transitioned to rotary motion.
    - Last minute flight control design change was implemented to protect for late-test data input, which added ill-advised lag at slosh frequencies.
      - New design did not go through same rigor as initial design.
    - Slosh instability resulted in premature engine cut-off.
    - Solution was to add more baffles, including anti-vortex.

1. "Falcon Demo Flight 2 Flight Review Update", Released by Space Exploration Technologies Corp, June 15, 2007.
2. Bauer, H. F., "Propellant Sloshing Problems of Saturn Test Flight SA-1", NASA TM-X-50497, November 1960.

Ascent Flight Control System (Continued)

Success Story

- Conservative approach used in slosh baffle implementation
  - STS-1 8 LO2 baffles
  - STS-17 4 LO2 baffles
  - SLWT 3 LO2 baffles
- Slosh baffles are easily removed, but difficult to add as the program matures

Lesson

- Retain a conservative approach for slosh baffle implementation
  - Avoids redesign to increase slosh damping
  - Allows easy weight reduction as FCS stability is confirmed by flight data

Higher fidelity Slosh Models to Remove Conservatism

- **If flight control analysis can model/design-to higher-fidelity (including nonlinear) slosh dynamics, it is possible to remove conservatism in GNC design, hence increasing vehicle performance while decreasing vehicle weight (less baffles)?**

- **Particularly challenging to GNC designers, when using conservative linear slosh models, is the temptation to significantly baffle secondary tanks.**

- **There is precedence for "cashing in" on higher fidelity slosh models and analyses approaches to remove conservatism in launch vehicle GNC design:**

  1. Slosh damping increases with slosh amplitude (nonlinear effect), so can we design to a nonlinear slosh model?
     – Process requires derivation of a model of nonlinear relationship between slosh amplitude and slosh damping.

  2. Can metrics (or rule of thumbs) be defined where slosh dynamics are considered second order effects and hence not considered in the design?
     – Can tanks with a small slosh mass, or a small tank radius, be ignored?

  3. Is it acceptable to fly-through a potential slosh instability?

- **Presentation will briefly address these questions.**

First Question: nonlinear slosh model use?

1. Slosh damping increases with slosh amplitude (nonlinear effect), so can GN&C design to a nonlinear slosh model/dynamics?
   - Process requires derivation of a model of nonlinear relationship between slosh amplitude and slosh damping.

Shuttle Heritage: Nonlinear Slosh Model used in Shuttle FCS Certification

- **Shuttle used nonlinear slosh model to support flight control certification where low-damping slosh modes proved very challenging with traditional linear control design approaches[3].**
  - Shuttle "Marble in a Bowl" model increases damping when slosh pendulum mode displacement exceeds 20 deg.

The "Marble in a Bowl" concept is used for the non-linear slosh model, where the angular displacement from the horizontal slosh surface is used to determine the applied slosh damping and associated frequency. That is, as the computed angular displacement of the slosh mass increases, the damping is increased. And, the slosh frequency is updated for the present acceleration. The displacement, velocity, and acceleration of the slosh mass are held to the maximum slosh angle values.

The angles used for the non-linear slosh dynamics are as shown:

Magnitude of Angular Displacement (deg)	LOx, LH2 Applied Damping
$\theta_{sl} < 1.0$	Fixed *
$1.0 < \theta_{sl} < 10.$	Fixed *
$10. < \theta_{sl} < 20.$	Fixed *
$20. < \theta_{sl} < 25.$	0.1
$25. < \theta_{sl} < 35.$	0.4
$\theta_{sl} > 35.$	0.5

*Nominal or user-specified value.

This model was apparently used for all Shuttle tanks, regardless of smooth wall vs baffle design.

3. "Space Shuttle Ascent FCS STIVANS (Time Domain) program Documentation", SSD93D0594 Rev A, Rockwell International, September 10, 1996.

Time Domain Performance Criterion with Nonlinear Slosh

- Shuttle stability certification process allowed waiver for reduction in frequency domain stability margin requirements provided time domain criterion is met[4].

3.4 Analysis Procedures

In summary, the procedures for the FCS stability analysis are as follows.

- Perform a linear frequency-domain analysis of the FCS with the DIGIKON computer program to determine gain margins, phase margins, and bending mode attenuations for the nominal and intact-abort trajectories with and without tolerances.
- Verify that the frequency-domain stability meets the criteria in Section 2.3.
- If the frequency-domain stability fails to meet criteria, perform a nonlinear time-domain analysis to re-verify that the FCS stability meets the limit-cycle criteria in Section 2.3.

The FCS stability is considered adequate if the frequency - or time - domain criteria are satisfied.

- Time domain criterion is related to allowable vehicle rate transients for given input attitude command (doublet):

PARAMETER	CONDITION NOMINAL	CONDITION DISPERSED
RIGID BODY GM (DB)	6	3
RIGID BODY PM (DEG)	30	20
SLOSH PM (DEG)	25	15
SLOSH GM (DB)	6	3
MODE ATTENUATION (DB)	10	6
ATTITUDE RESPONSE LIMIT-CYCLE (DEG, PLEAK-TO-PEAK)	0.5	1.0
ACCEL @ PILOT STATION LIMIT-CYCLE (G,PEAK-TO-PEAK)	0.1	0.25

GM = GAIN MARGIN PM = PHASE MARGIN

4. "Space Shuttle Ascent FCS Cumulative Summary of Analysis Data (CSAD) From Ascent Flight Control System Stability Assessments", SSD94D0289, Rockwell International, September 30, 1994.

Question 2: Can metrics (or rule of thumbs) be defined where slosh dynamics are considered second order and hence not considered in the design?

- **If slosh-mass-to-vehicle-mass ratio is small, is there a threshold on this ratio where slosh dynamics can be ignored in GN&C design?**
  1. Is there a shuttle precedent? A comment from shuttle LOX damping documentation[5]:
     - "The [Shuttle LOX tank baffle] requirement defines the minimum slosh damping between the fluid levels where the slosh mass is greater than 10% of the total vehicle mass. Within this critical slosh region, the slosh suppression system must provide the required minimum slosh damping in order to meet guidance stability margins defined by the Rockwell International (RI) guidance and control group".
  2. SLS also uses slosh inertia (slosh_mass*moment_arm^2/I_vehicle) to get initial indication of sensitivity to slosh mass.

- **If the slosh amplitude which could cause instability exceeds the actual tank radius, can this be a mitigation factor for slosh instability concerns? A comment from Shuttle Thrust Vector Control (TVC) stability analysis:**
  - "In addition, an analytical derivation of possible OMS propellant slosh effect has shown that its effect would be so small that the worst case (i.e., all slosh masses in the OMS tanks acting in unison starting with the maximum possible initial slosh displacement) would result in body rates which would not exceed the rate gyro quantization levels. For this reason the slosh model was not incorporated in this simulation or in any verification work."

- **SLS has not been able to obtain confidence in a "rule of thumb" derivation based on slosh mass, slosh inertia, or tank radius thresholds where slosh dynamics can be ignored.**

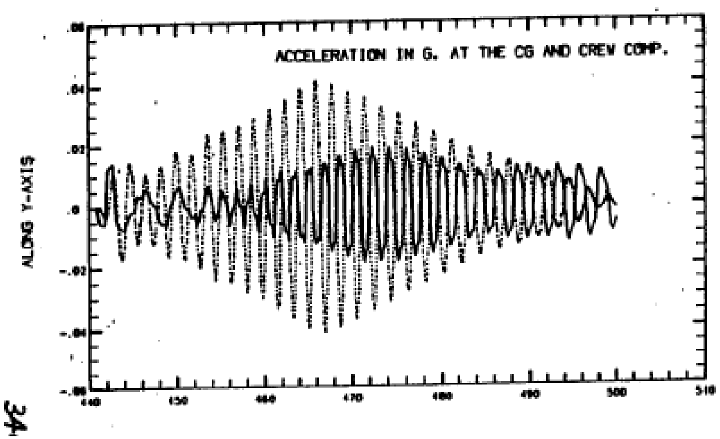
5. **"Slosh Damping Predictions for the SLWT Three Baffle Slosh Suppression System", 4410-96-044, Lockheed martin memorandum, September 23, 1996.**
6. **Penchuk, A., Croopnick, S., "The Digital Autopilot for Thrust Vector Control of the shuttle Orbital Maneuvering System", AIAA 82-1579, 1982.**

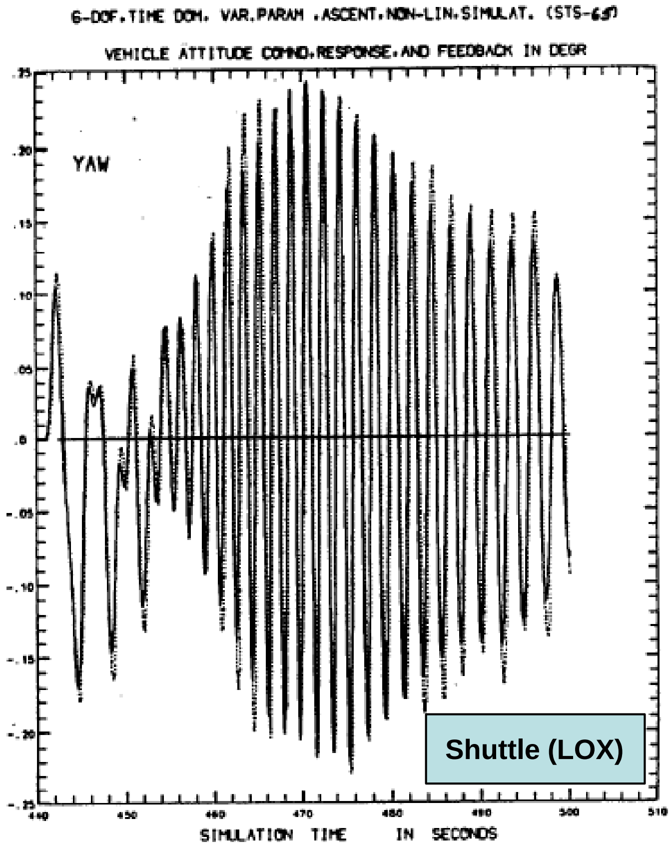
Third Question: Is it acceptable to fly-through a potential slosh instability?

- If slosh dynamics can be proven to not couple with flex modes, is it feasible to “fly-through” slosh instabilities?
- “Time to Double” is a metric than can be used to quantity acceptable divergence (say in attitude or gimbal command).
- Shuttle time-domain “limit cycle” amplitude performance does allow short duration low amplitude divergence in time-domain simulation

SUMMARY OF STIVANS RESULTS:
STS-65 @ 440.08sec
NO TOLERANCE

FLIGHT CONDITION	ATTITUDE RESPONSE (peak-to-peak, deg)	ACCEL. @ PILOT STATION (peak-to-peak, g)
YAW DOUBLET (+/- 0.5 deg) CMD, NONLINEAR MODELS TIME-VARYING, NO FLEX	CONVERGENT WITH PEAK AMPLITUDE OF 0.46	CONVERGENT WITH PEAK AMPLITUDE OF 0.074
LIMIT-CYCLE CRITERIA	0.5	0.1





“Figures 4.2.1-1 through 21 show the roll, pitch, and yaw attitude responses and normal and lateral accelerations. As can be observed, nearly all the linear, time domain results are well below the limit-cycle criteria of 0.5 deg and 0.1 g (peak-to-peak); however, at T440 a very slow divergence in all 3 axes can be seen. Figures 4.2.1-22 and 23 at T430 and T460 show that the vehicle is subject to this (T440) marginal stability for less than 30 seconds.”

- SLS general rule is flight control design will not allow vehicle to “fly-through” instabilities.

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Concluding Thoughts

- **Lesson's Learned shows GN&C designers should use a conservative approach when designing baffle hardware to supply slosh damping.**

- **Standard approach calls for use of linear spring-mass-damper model (or pendulum equivalent) slosh model when designing control system.**
  - Provides a conservative design approach, however arguably *overly* conservative when dealing with secondary tanks and/or with smaller slosh masses.
    - Note SpaceX slosh instability example was second stage.
  - Pressure will exist to remove conservatism in GNC design, in particular with regard to slosh in secondary tanks, to save vehicle mass (do not over-baffle).

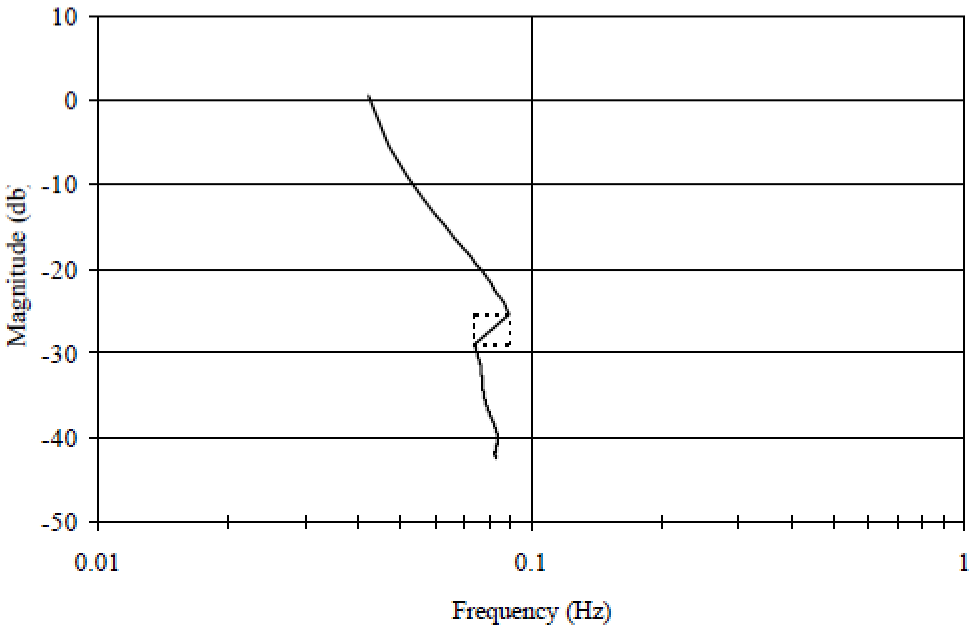
- **Precedence exists for using higher fidelity slosh models and flight control analysis to remove conservatism and same mass (fewer baffles).**
  - Model nonlinear effects, key one is slosh damping increase with slosh amplitude.
  - Is it feasible to derive rules of thumb where linear slosh model approach is too conservative?
    - Possible metric: slosh-mass-to-vehicle-mass ratio
    - Possible metric: slosh amplitude compared to tank radius
    - ?
  - Is it feasible to allow violations of slosh linear stability margin criterion if time-domain performance is deemed acceptable?
    - Shuttle defined peak limit cycles in vehicle attitude and linear acceleration to gather confidence that linear stability margin violations were acceptable.

Backup

- **Another example of Shuttle flight control engineers using a nonlinear dynamics model in flight control design/certification.**

Example of Nonlinear Structural Dynamics Used in Shuttle GNC Design/Certification (freeplay at Shuttle/ISS docking interface)

Modal Frequency Varies as a function of Modal Amplitude

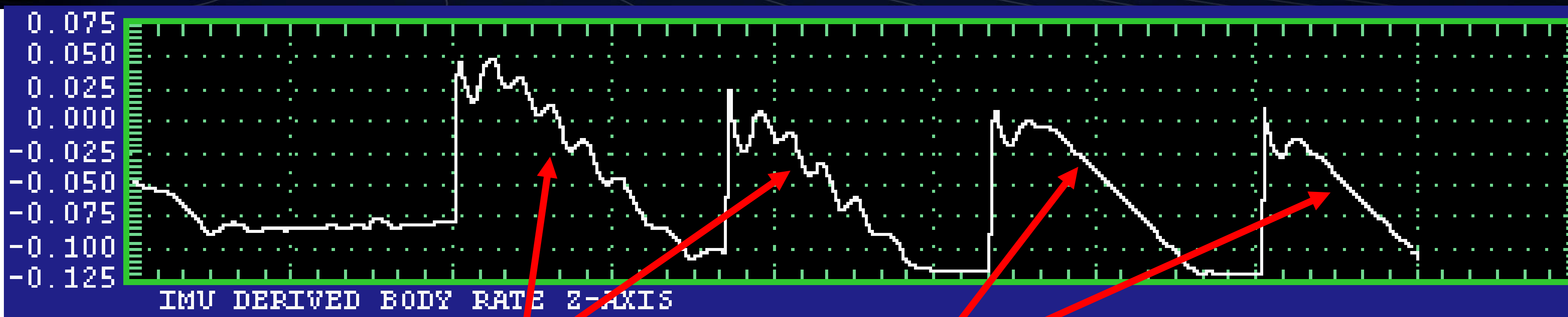


Notes:
1) The predicted response is subject to simultaneous uncertainties of 3db amplitude and 15% frequency when the response is dominated by the freeplay.
2) The predicted response is subject to simultaneous uncertainties of 6db amplitude and 30% frequency when the response is dominated by the linear frequency.
3) The transition between these two regions is designated by the boxed area on the figure.
4) The plotted magnitude is based on a 0.15 deg/sec rate limit.

FIGURE S.4.0.2.3.1.1-1 5A.1 ODS FREEPLAY FREQUENCY VS. ANGULAR RATE AMPLITUDE

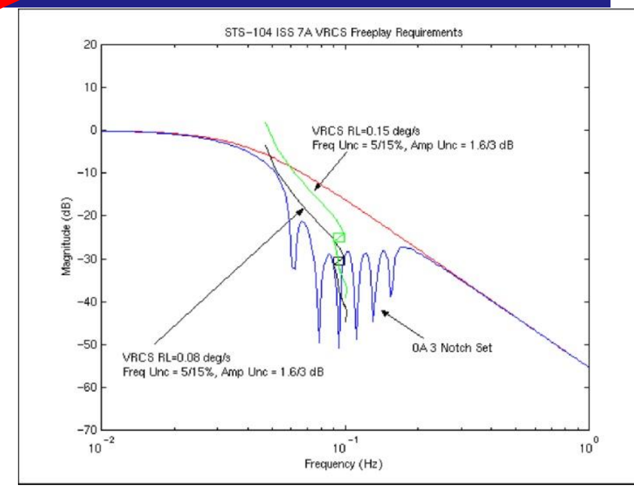
Mission ISS-5A.1 Orbiter/ISS On-Orbit Interface Requirements

STS-92 Nonlinear Dynamics: Shuttle/3A Pitch Rate (deg/sec) During Reboost



Nonlinear Interface Dynamics

Linear Interface Dynamics



Shuttle Notch Filter Design for Non-Linear Dynamics

Interface dynamics transitioned from nonlinear dynamics to linear dynamics upon pressurization of shuttle airlock.

From Draper Laboratory