National Aeronautics and Space Administration

SPACE LAUNCH SYSTEM

Marshall Space Flight Center Recent Flight Controls Activities

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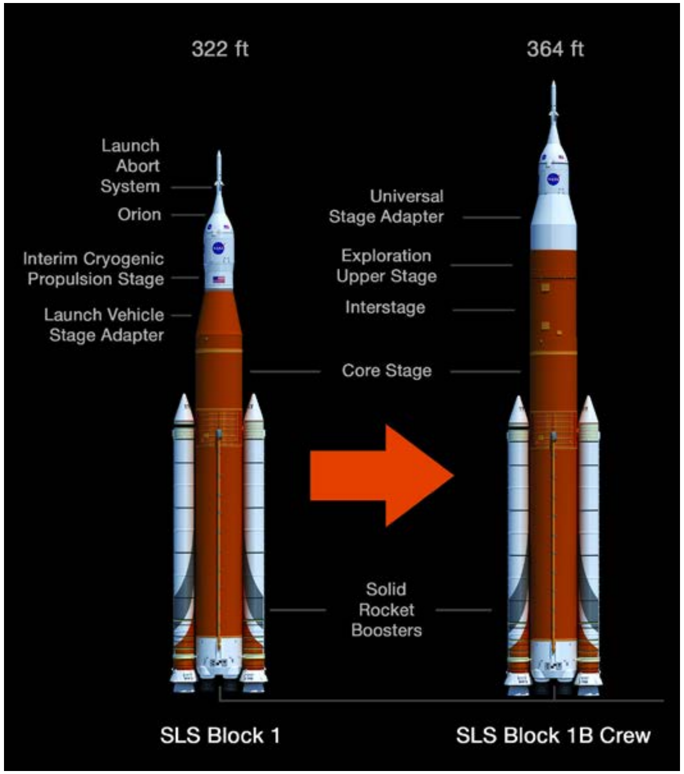
Introduction/Agenda

- **The Space Launch System (SLS) Ascent Flight Control System (FCS) is a primary focus of the Control System Design & Analysis Branch at the Marshall Space Flight Center (MSFC)**

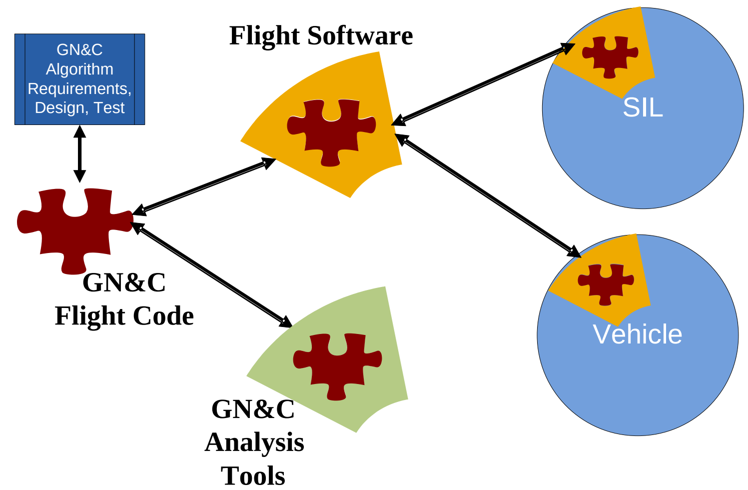
- **Status**
  – Block1 flight control design and software complete with unmanned test flight scheduled for late 2018
  – Current focus on Block1 verification and Block1B design

- **Topics**
  – Flight control software
  – Non-linear slosh damping in time domain and frequency domain analysis
  – Program test input (PTI) for launch vehicle flight test



SLS Flight Control FSW

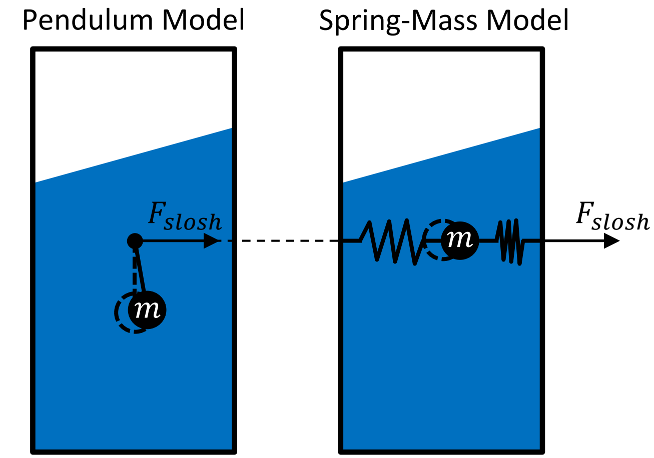
- **Flight control algorithms implemented in C++ and used in both GN&C time domain analysis tools and as part of flight software running on flight computers**
  - Eliminates need to re-implement flight control algorithms in flight software
  - Code is thoroughly reviewed and must meet flight software standards
  - Significant testing both in GN&C analysis tools and in Software-In-The-Loop (SIL) Facility



- **Notable Flight Control Software Features**
  - Structural Dynamics Filter Initialization Logic
    - Filters scheduled as a function of flight conditions during atmospheric flight. To eliminate filter initialization transients, an upcoming filter is fully initialized and run in parallel to the current filter. Upon transition, the upcoming filter states become the current states. Avoids issues caused by interpolating filter coefficient between dissimilar filters
  - Adaptive Augmenting Control (AAC)
    - Adaptive element augmenting linear control system adding protection for adverse control-structure interactions and low frequency aerodynamic instability and disturbances
  - Saturation Protection
    - Protects control allocation, integral, and disturbance rejection in the event that the control system requests a greater engine gimbal angle than is achievable

Non-Linear Slosh Damping Analysis

- **MSFC Test and CFD analysis revealed limitations in the use of the Miles equation[1][2] used to predict fluid damping in the presence of baffles for SLS tanks**
  - Modified method presented at JANNAF conference[3]
- **Reductions in predicted damping at low wave heights motivated investigations into non-linear slosh damping**
  - In the presence of slosh baffles, the critical damping ratio is a strong function of slosh wave amplitude
  - As a result, system stability and control margins are a function of assumed amplitude
- **Describing function like approach developed which allows the prediction of the resulting neutral stability slosh limit cycle amplitude (slosh and TVC) either nominally or with degraded stability margins using frequency domain methods**
  - Thresholds can be chosen on the TVC and slosh amplitudes with degraded stability margins to accept as designed baffle-provided damping



$$\frac{d^2x}{dt^2} + 2\zeta\omega_0\frac{dx}{dt} + {\omega_0}^2 x = \frac{F}{m}$$

Fig: Liquid Slosh Mechanical Analogues

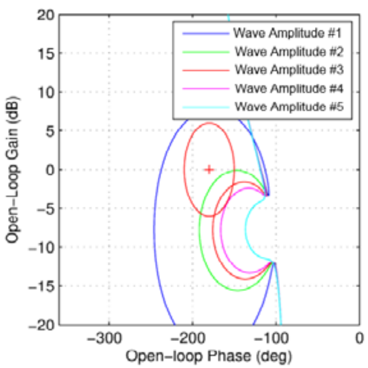


Fig: Slosh + Rigid Body + PID Control (For Hypothetical Large Upper Stage)

1. H. N. Abramson, “The Dynamic Behavior of Liquids in Moving Containers,” NASA SP-106, 1967.
2. J. W. Miles,” Ring Damping of Free Surface Oscillations in a Circular Tank,” J. Appl. Mech., vol. 25, no. 2, June 1958, pp. 274-276.
3. J. West, H.Q. Yang, J. Brodnick, “Extension of Miles Equation for Ring Baffle Damping Predictions to Small Sloshing Amplitudes and Large Baffle Widths”, JANNAF Propulsion Meeting, December 2016.

Non-Linear Slosh Damping Time Domain Analysis

- **Assuming a non-linear damping acceleration follows an odd square law of slosh velocity**

$$Acc_{\mathrm{d,nonlinear}} = -b_1 \dot{z}_{sj} \left|\dot{z}_{sj}\right|^{n}, \qquad n = 1$$

- **Using a describing function for sinusoidal input or the equivalent energy dissipation over a cycle, it can be shown that the equivalent linear damping ratio is a linear function of the slosh displacement amplitude ($A_{z_{sj}}$)**

$$\zeta_{\mathrm{sj}} = f_{\zeta_{\mathrm{sj}}}\left(A_{z_{sj}}\right) = A_{z_{sj}}\left(\frac{b_1}{2}\frac{8}{3\pi}\right)$$

- **The above process can be reversed to go from a provided damping vs. amplitude curve (e.g. from test or CFD) to a non-linear acceleration contributions which can be used in a non-linear time domain simulation**
  - Although this method is derived from an odd square law, it has shown to a be a good approximation for damping relationships following the same form but with different n

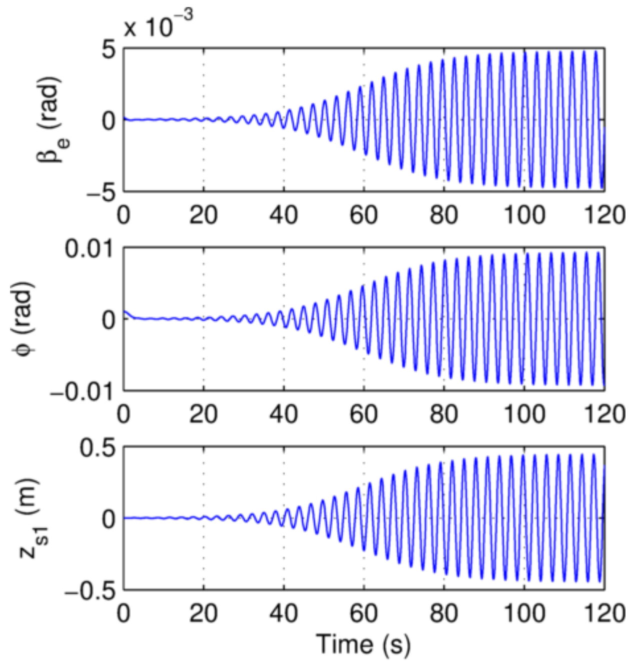
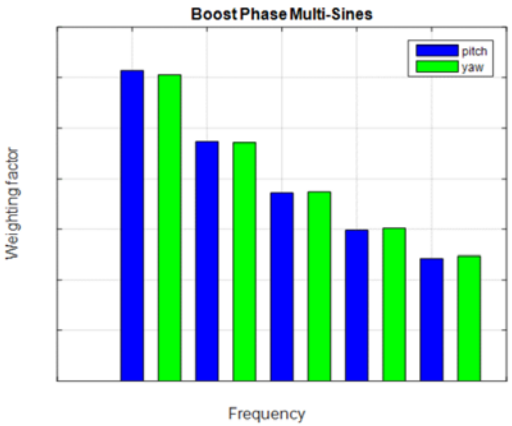


Fig: Perturbed initial condition non-linear time domain simulation with severely degraded stability margins. (For Hypothetical Large Upper Stage Using Odd Square Law Slosh Damping)

Program Test Inputs

- **Program Test Input (PTI) inputs planned for SLS test flight with objectives:**
  - Estimate the open-loop system frequency response to help validate the control system stability margins and pre-flight plant models
  - Estimate the frequency, mode shape, and damping of the first several structural modes to help validate the structural dynamics models
- **PTI is a combination of an optimized pitch/yaw multi-sine and a pitch/yaw sine sweep added to the angular acceleration command**
  - Power is reduced at higher frequencies to reduce actuator rates
- **PTI designed not to adversely affect integrated vehicle**
  - PTI avoids critical time periods of flight and is disabled if failure conditions occur
  - Integrated loads analysis includes PTI and ensures it does not drive vehicle load envelopes
  - Main propulsion system analysis to ensure induced slosh motion of cryogenic propellants does not cause excessive tank pressurization or ullage collapse



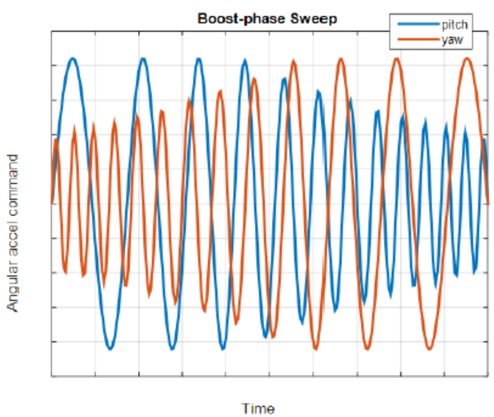


Fig: Boost phase multi-sine weighting and sine sweep time history.