SLS
Space Launch System

Recent Flight Control System Analyses in Support of Space Launch System

John Wall
Dynamic Concepts, Inc.
(Jacobs ESSSA Group)

Jeb Orr, PhD
Draper
(Jacobs ESSSA Group)

Bob Jurenko
Leidos, Inc.
(Jacobs ESSSA Group)

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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)**
  - Vehicle Critical Design Review (CDR) completed in 2015
  - First unmanned flight with Interim Cryogenic Propulsion Stage (ICPS) in 2018

- **Multiple Actuator Stage Vectoring (MASV) tool in development**
  - High fidelity stability analysis of thrust vector control (TVC) system

- **Specification of required slosh damping for upcoming design of Exploration Upper Stage (EUS)**
  - Process to develop early baffle requirements with limited model data
  - Sensitivities unique to exploration-class stage configuration

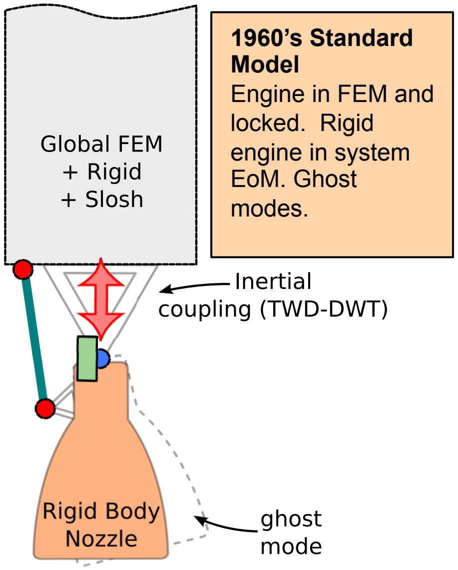
- **Time domain extraction of stability margins**
  - Method to assess gain & phase margins from full time-varying 6-DOF
  - Quantitative assessment of adaptive control improvement using nonlinear simulation

Multiple Actuator Stage Vectoring (MASV) Model and Green Run Frequency Response Test (FRT)

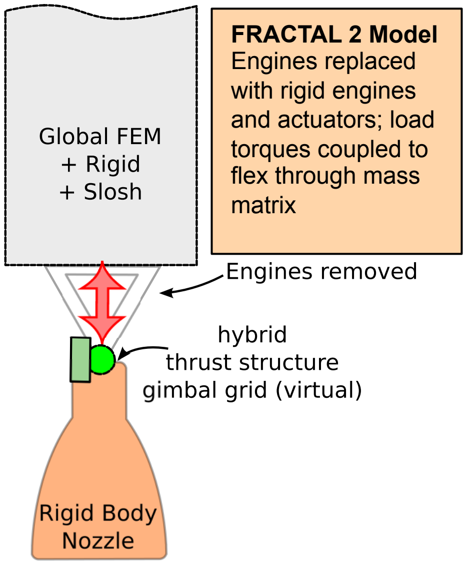
- **New dynamic coupling method was developed to support high-fidelity analysis of the servoelastic stability and performance of Space Launch System (SLS) core stage thrust vector control (TVC)**
  - Complements advanced global vehicle dynamic model coupling method (FRACTAL 2)

- **Multiple TVC DoF represented with high-fidelity finite element representation**
  - Capture all load compliance effects and eliminate spring approximations of backup structure and engine attach stiffness
  - MIMO system can be analyzed for performance, coupling, linear and nonlinear stability margin
  - Static compliance analysis technique (similar to residual modes) used to reduce number of simulated modes

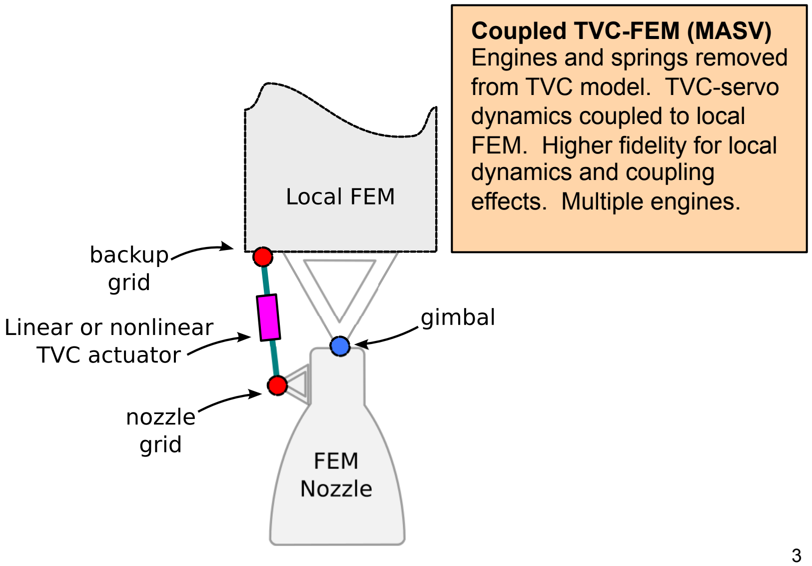
- **MASV used for design of the 4-engine profile to be executed on flight stage at NASA/SSC**
  - Data from this test will be used to anchor model predictions for flight



1960's Standard Model
Engine in FEM and locked. Rigid engine in system EoM. Ghost modes.



FRACTAL 2 Model
Engines replaced with rigid engines and actuators; load torques coupled to flex through mass matrix

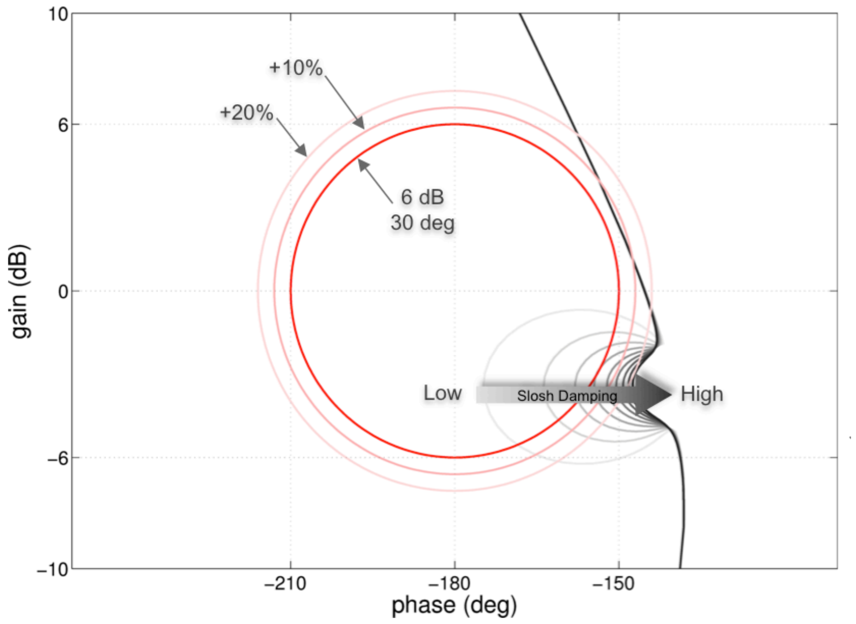


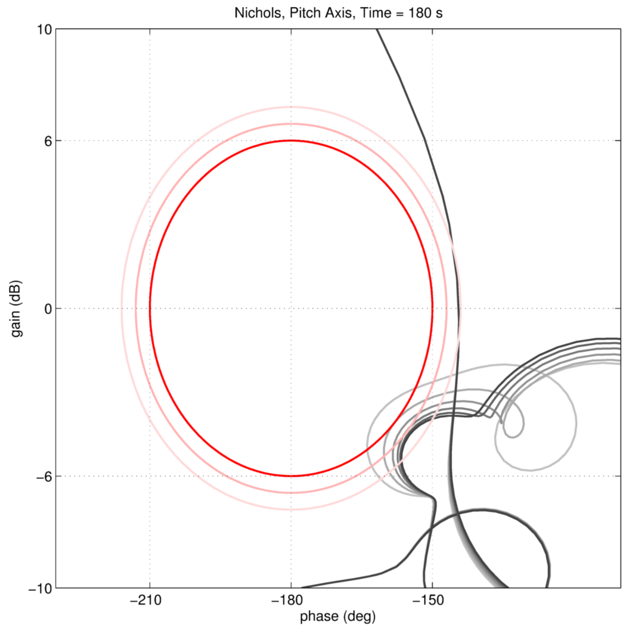
Coupled TVC-FEM (MASV)
Engines and springs removed from TVC model. TVC-servo dynamics coupled to local FEM. Higher fidelity for local dynamics and coupling effects. Multiple engines.

Exploration Upper Stage (EUS) Slosh Damping Specification

- **Rapid & rigorous development of EUS slosh damping specification facilitated by numerical optimization**
  - Given: preliminary control design, actuator, rigid body, and slosh parameters on 3-DOF trajectory
  - Optimize: slosh damping of single tank to achieve 20% margin on 6db/30deg Nichols keepout disc
    - Provides a buffer for future model updates (flex, actuator dynamics, bandwidth reqmts)

- **Exploration class vehicle configuration poses unique slosh challenges**
  - Same diameter (frequency) of upper & core stages exhibits coupling phenomena
  - Sloshing tanks exhibit large mass fraction of total vehicle
  - Upper stage slosh mass poorly phased for significant portion of flight





Slosh “Danger Zone” Extends Aft of CG

- ◆ **References [Bauer 1964] and [Greensite 1970] identify conditions on the equivalent spring-mass-damper model of slosh on vehicle stability**
  - Bauer defines “danger zone” for equivalent slosh mass location using roots of char eqn
    - Somewhat indirect measure of “inherent stability challenge”
  - Greensite quantifies undesirable slosh behavior via relative magnitude of slosh pole/zero
    - Direct “phase behavior” in open loop frequency response but does not include all relevant terms
- ◆ **Danger zone is always aft of Center of Percussion (CP)**

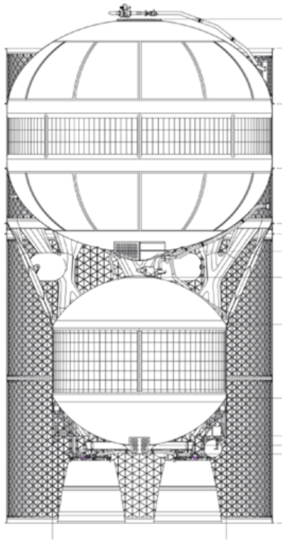
$$l_{slosh} > \frac{-J_{vehicle}}{(M_{vehicle} l_{tvc})}$$

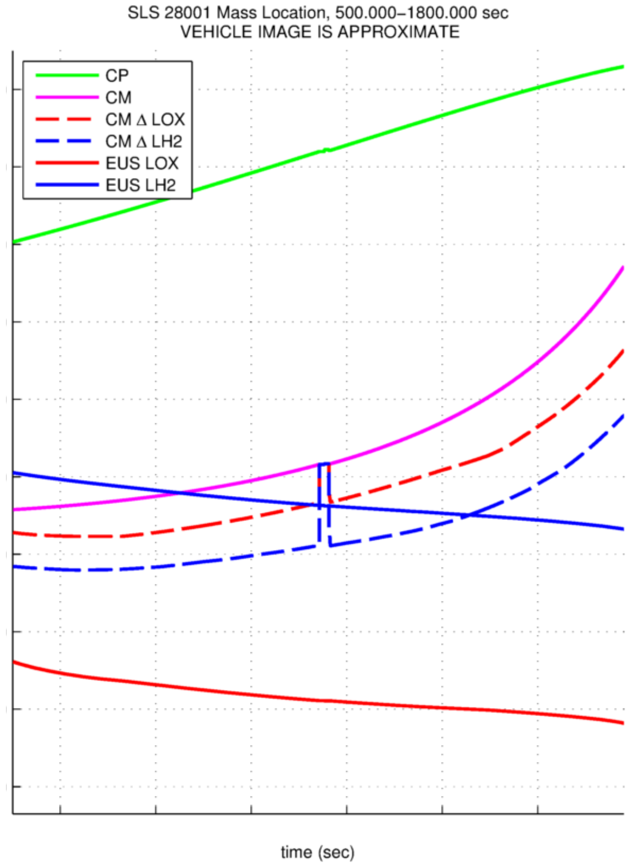
- ◆ **Previous danger zone was fwd of CM**

$$l_{slosh} < 0$$

- ◆ **Inclusion of an extra term shifts the danger zone aft of the CG**

$$l_{slosh} < \frac{F_{thrust}\left(M_{vehicle} - m_{slosh}\right)}{\left(M_{vehicle}^2 \omega_{slosh}^2\right)}$$





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Extract Stability Margins from Time Domain

- **Parametrically inject time delays & gain perturbations to 6-DOF high-fidelity simulation(s) and observe point of instability**
  - Incrementally apply offsets to phase & gain margin time history from stability analysis about the expected neutral stability values
  - Perform adjustments at different time points and observe when system diverges

- **Analysis technique provides**
  - Comparison of nonlinear time-varying system behavior to LTI frequency domain predictions
  - Frequency & time domain tool model validation under larger system excitation than nominal