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)
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
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
♦ 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
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)

\[ l_{\text{slosh}} > -\frac{J_{\text{vehicle}}}{(M_{\text{vehicle}} l_{\text{tvc}})} \]

Previous danger zone was fwd of CM

\[ l_{\text{slosh}} < 0 \]

Inclusion of an extra term shifts the danger zone aft of the CG

\[ l_{\text{slosh}} < \frac{F_{\text{thrust}} (M_{\text{vehicle}} - m_{\text{slosh}})}{(M_{\text{vehicle}}^2 \omega_{\text{slosh}}^2)} \]

SLS 28001 Mass Location, 500,000–1,800,000 sec

VEHICLE IMAGE IS APPROXIMATE
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