National Aeronautics and Space Administration

MCLAURIN Jacobs Space Exploration Group


# SPACE LAUNCH SYSTEM

# Flight Performance and Stability of Space Launch System Core Stage Thrust Vector Control

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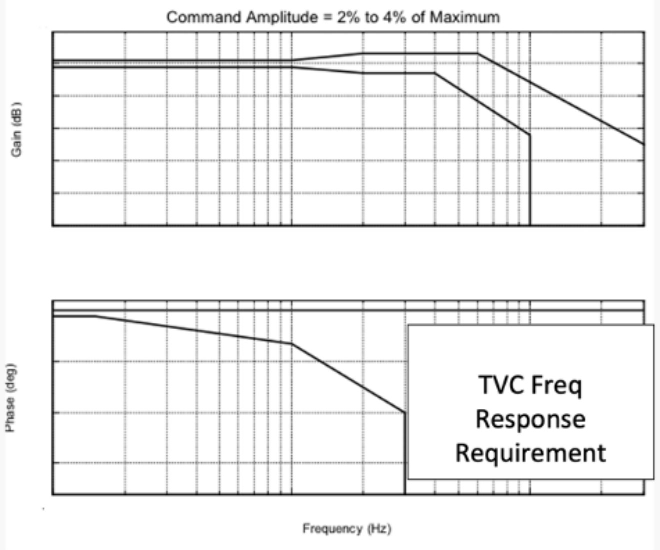
# Agenda

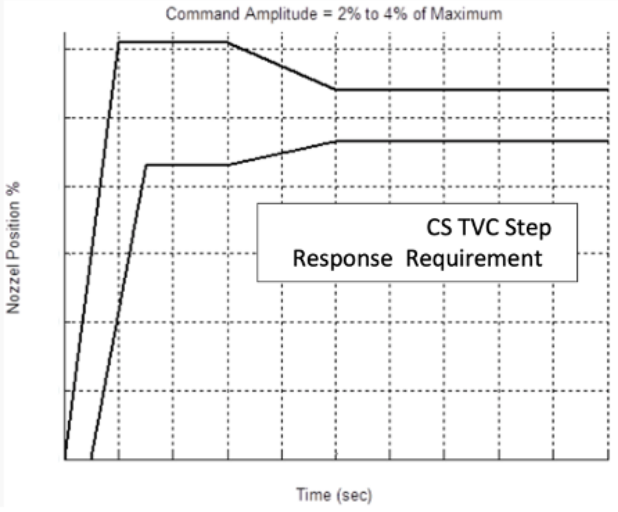
- **Overview**
- **TVC Test Activities and Findings**
- **Artemis I Flight Rationale: Approach**
- **Post Flight Rationale  Activities:**
  - Modeling, Evaluation and Path Forward
- **Flight and Preliminary Post Flight**

# Overview

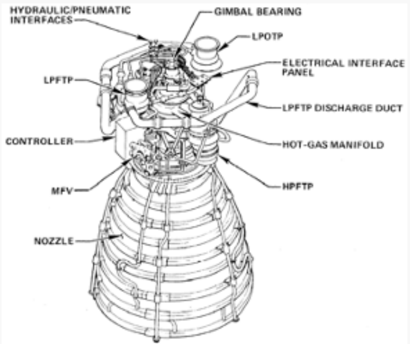
- **The SLS Core Stage (CS) TVC system is a mix of heritage and new hardware**
  - heritage Shuttle TVC actuators, RS-25 engine, gimbal bearing
  - Redesigned avionics and attached to a new vehicle structure
- **SLS Vehicle Flight Control imposed CS TVC frequency & step response requirements: command to engine angle**
  - Green run testing showed violations both in ambient and hot fire conditions and departure from pre-test models
- **SLS flight control determined that friction, load stiffness, and amplitude dependent nonlinearities dominated physical cause of differences**
- **Flight Rationale for Artemis I based on prediction of in-flight Limit Cycle Oscillation (LCO)**
- **Integrated team refined understanding of friction & stiffness**
- **Flight Data showed some evidence of small LCO**



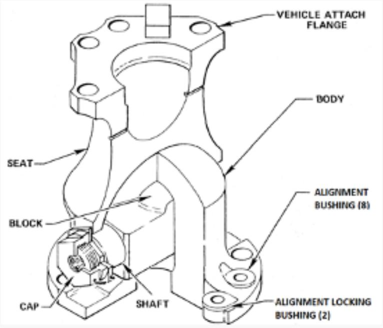

TVC Freq Response Requirement



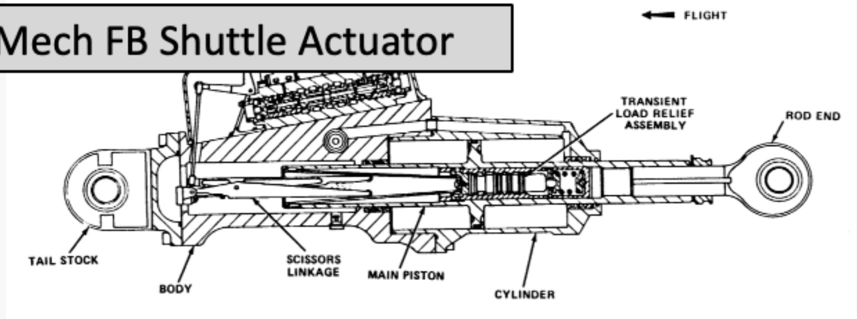

CS TVC Step Response Requirement




RS-25 Shuttle Heritage Engine & Gimbal Bearing




Mech FB Shuttle Actuator

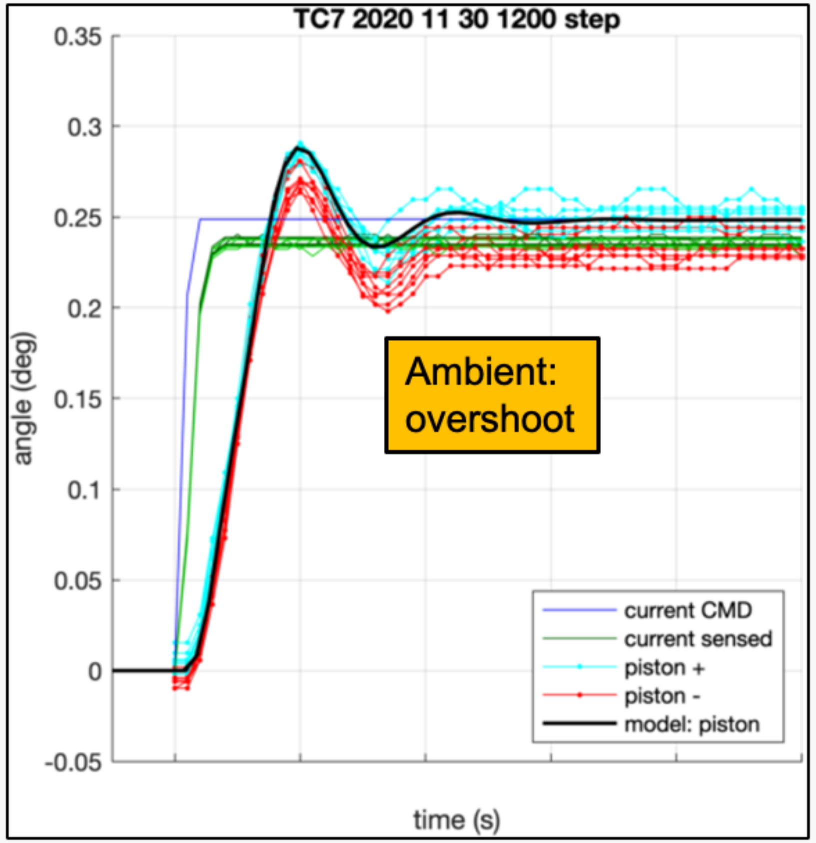


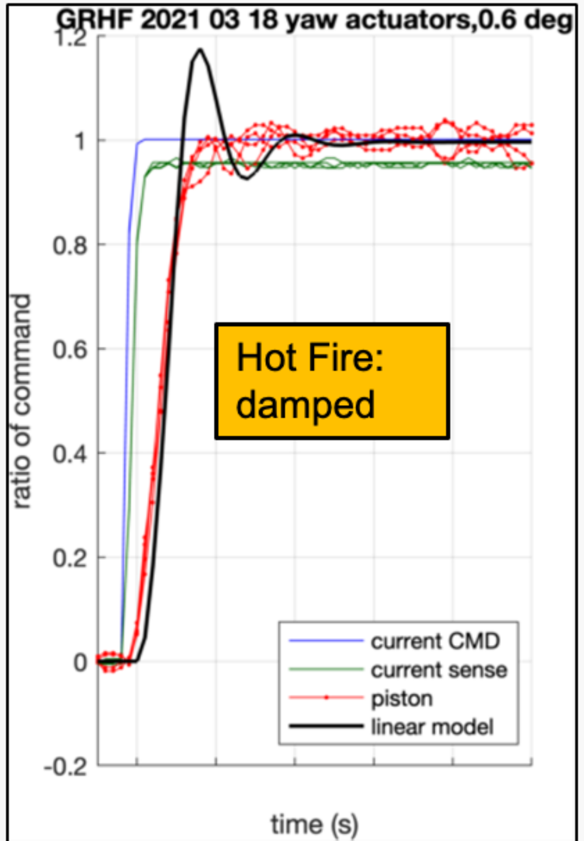

New Core Stage

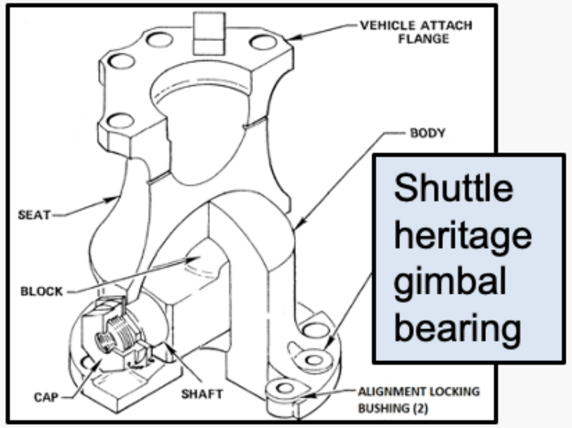
# TVC Model Updates after Green Run Testing: Friction

- **Effects of gimbal Friction clearly observed during SLS hot fire [1]**
- **Shuttle observed friction in Main Propulsion Test Article (MPTA) hot fire vectoring, but an LCO never appeared in flight [8]**
  - Simple models of gimbal friction appear in historical models
- **Prior to Green Run SLS models never included gimbal friction**
  - Longstanding assumption that it could be neglected
- **After Green Run, friction models included using multiple approaches [2]**
  - Simple: Keene & Jeff Brouwer implementations
  - Dahl & LuGre
  - Modified LuGre





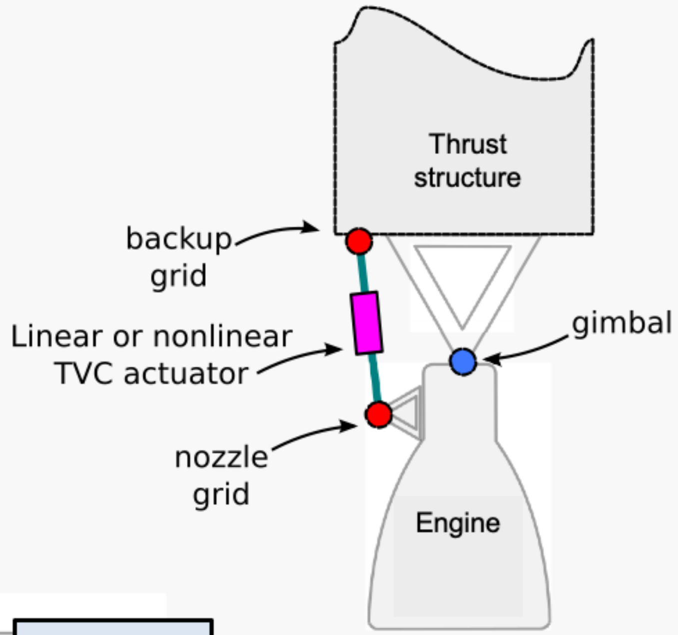



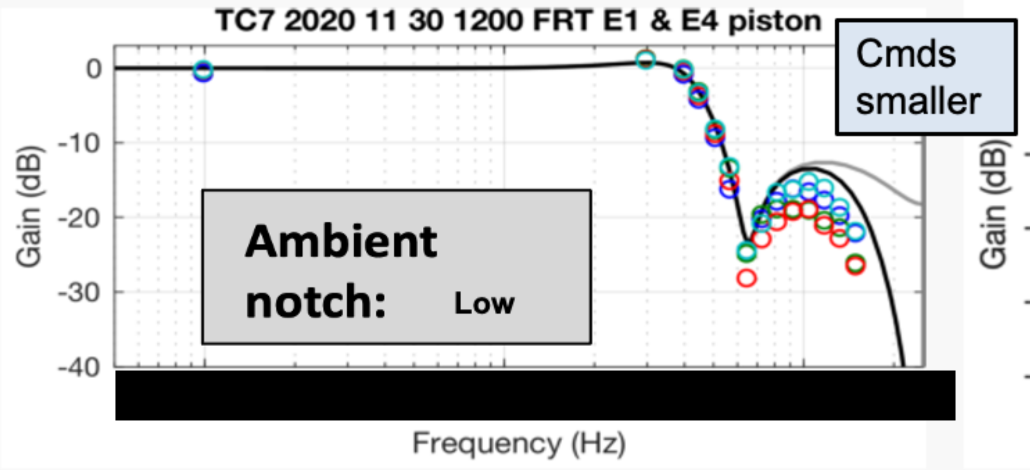
# TVC Model Updates after Green Run: Stiffness

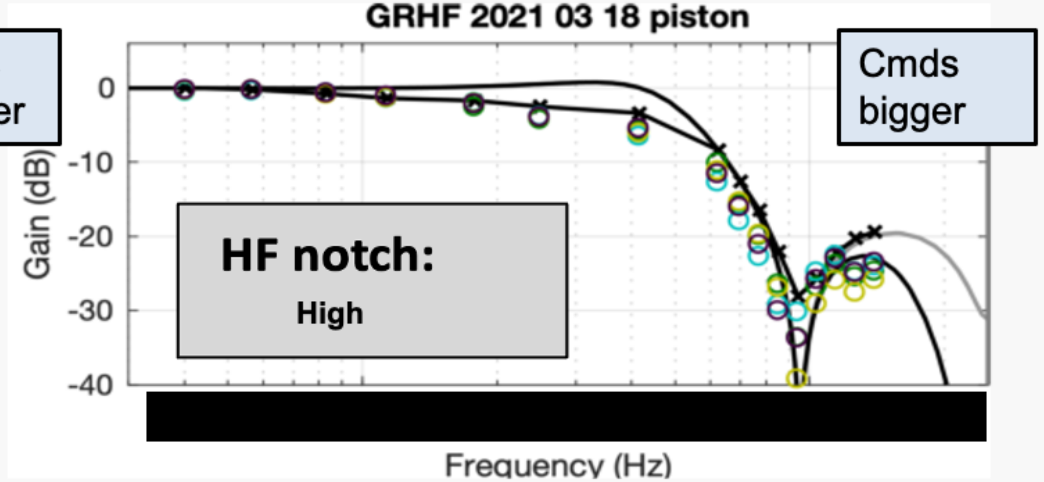
$$\omega_L = \sqrt{\frac{K_L R^2 + K_n}{J_n}}$$

- **Green Run ambient & Hot Fire showed different load resonance frequency**
  - Observed via notch in command to piston frequency response
- **Simplex Model lumps all stiffness outside the actuator control loop into a load stiffness, KL**
  - KL → all compliances in path: engine, gimbal, clevises, thrust structure
- **KL can be determined from load resonance**
  - Moment arm, R, Engine Inertia, Jn are known and duct stiffnesses, Kn negligible
- **Bounding analysis for flight rationale assumes the softer structure**
  - Conservative prediction of LCO
- **Cause for change in stiffness eventually determined**
  - Nonlinearities associated with loaded gimbal and small amplitude actuator behavior




Load resonance derived from actuator command to piston notch frequency

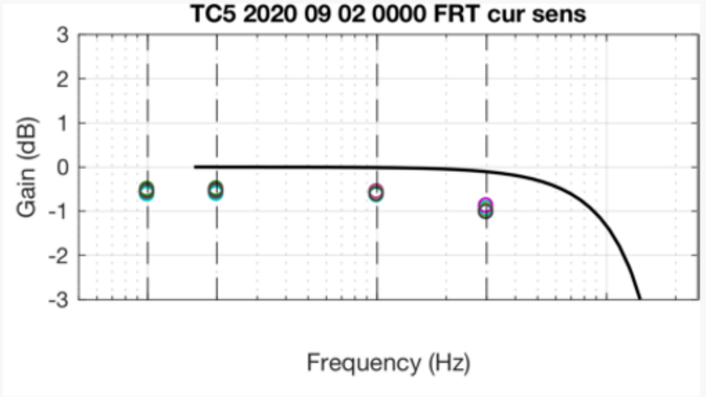


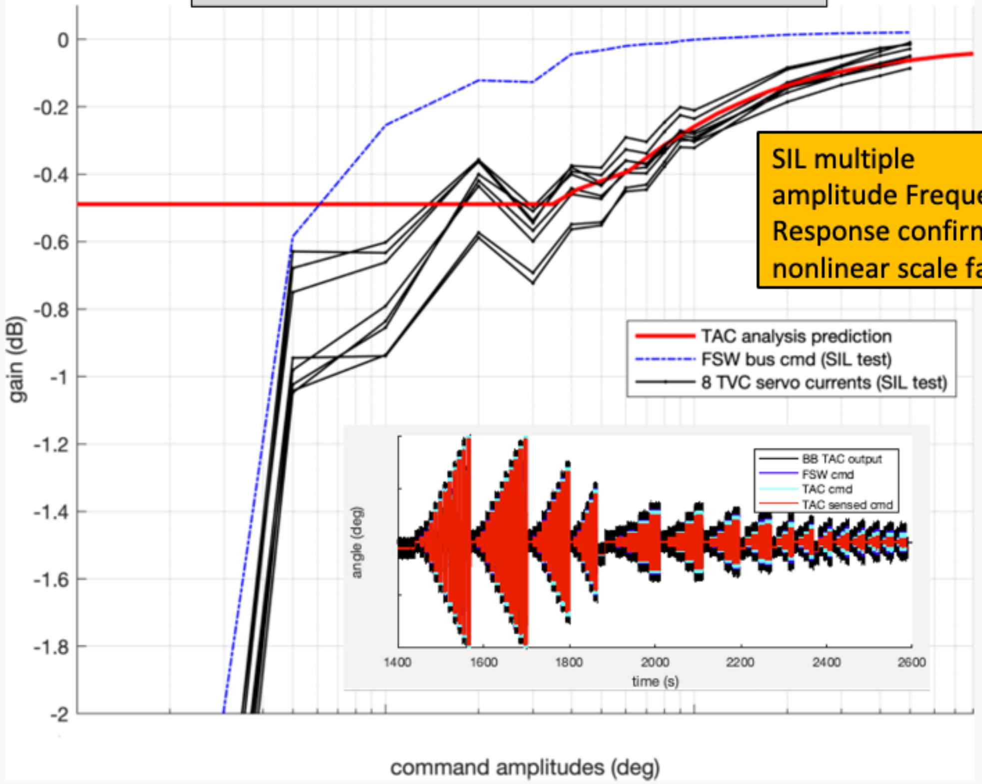
# TVC Model Updates after Green Run: Avionics Command Path Gain

- **SLS TVC Actuator Controller (TAC) commands Core Stage TVC**
  - New digital component designed to mimic Shuttle's analog box, Shuttle Ascent Thrust Vector Controller (ATVC)
- **MSFC 2-axis Inertial Load Simulator (ILS) & Green Run testing showed DC offset**
- **Actuator vendor confirmed presence of scale factor nonlinearity in commanded current**
  - due to crossover distortion in servo-amplifier design
- **Hardware in the Loop Systems Integration Lab (SIL) Frequency Response Testing confirmed behavior**
  - Also discovered FSW truncation operation in command quantization that can yield similar gain decrease
- **Later SLS missions will include updates to FSW & TAC**
- **Command gain offset ~ -1dB for typical operating signals**
  - Included in analysis for LCO predictions

Command to servo current shows DC offset during Ambient GR Testing



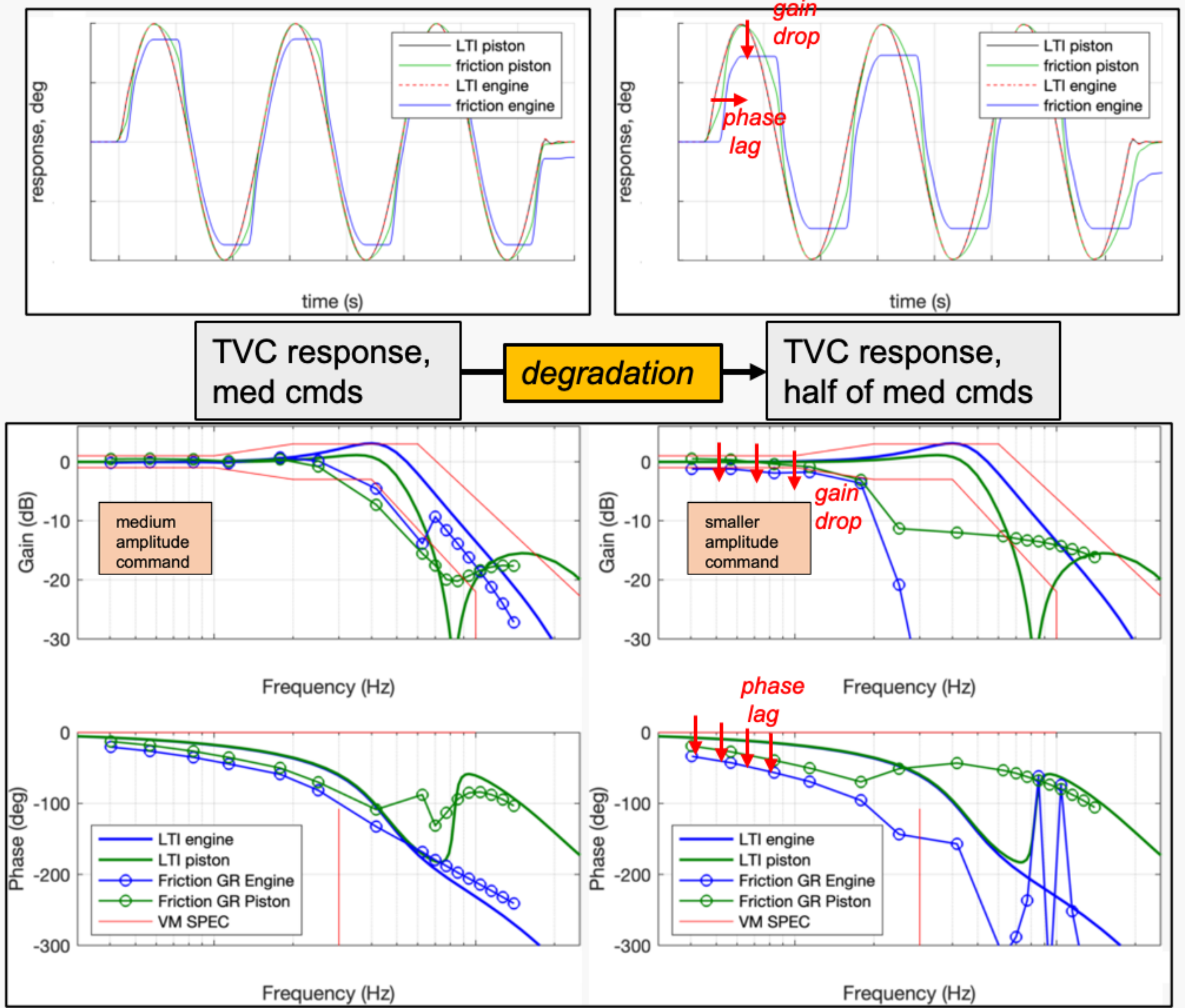

SIL 2022 03 01 Multiple-Amplitude Frequency Response Test



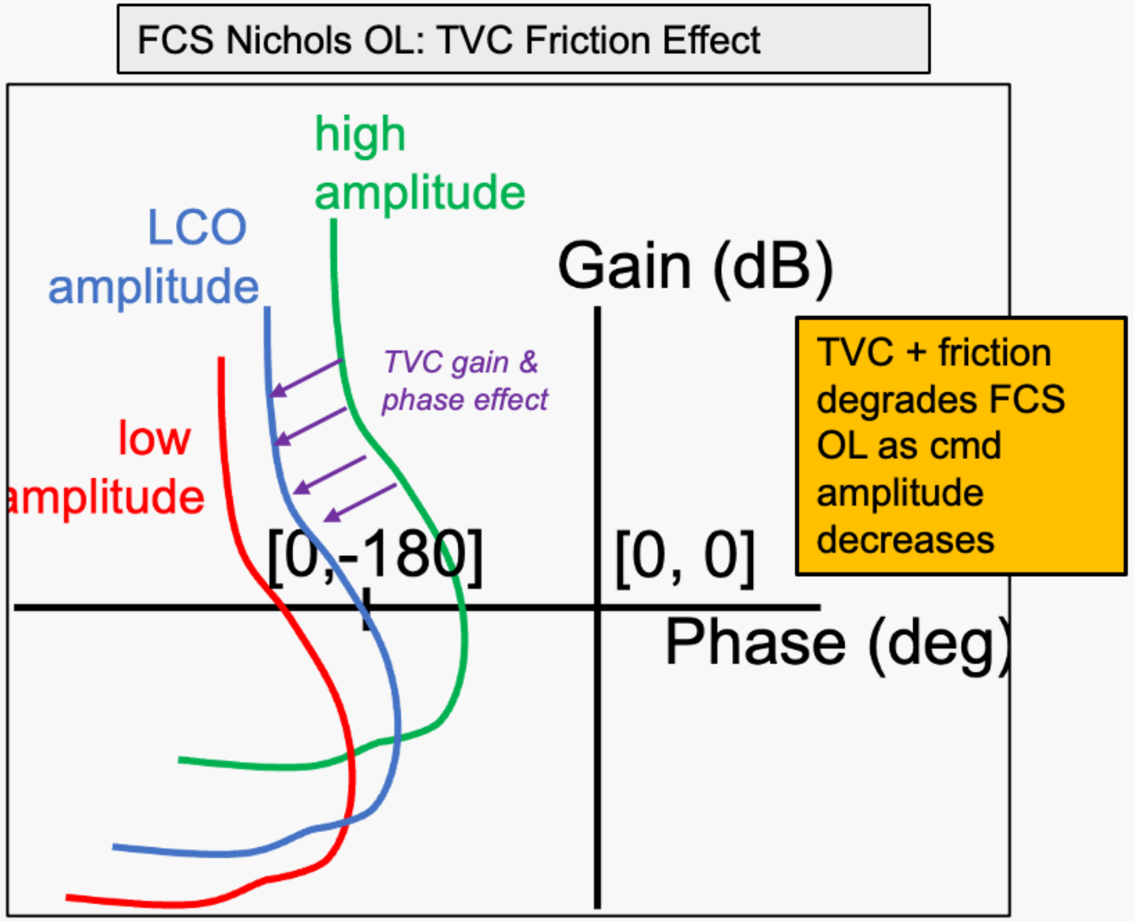

SIL multiple amplitude Frequency Response confirms nonlinear scale factor

# Gimbal Friction Degrades TVC Response, Produces Flight Control LCO

- Gimbal friction results in degradation of the TVC piston and engine responses
- This nonlinearity can produce a Limit Cycle Oscillation (LCO) in Vehicle Flight Control System Loop

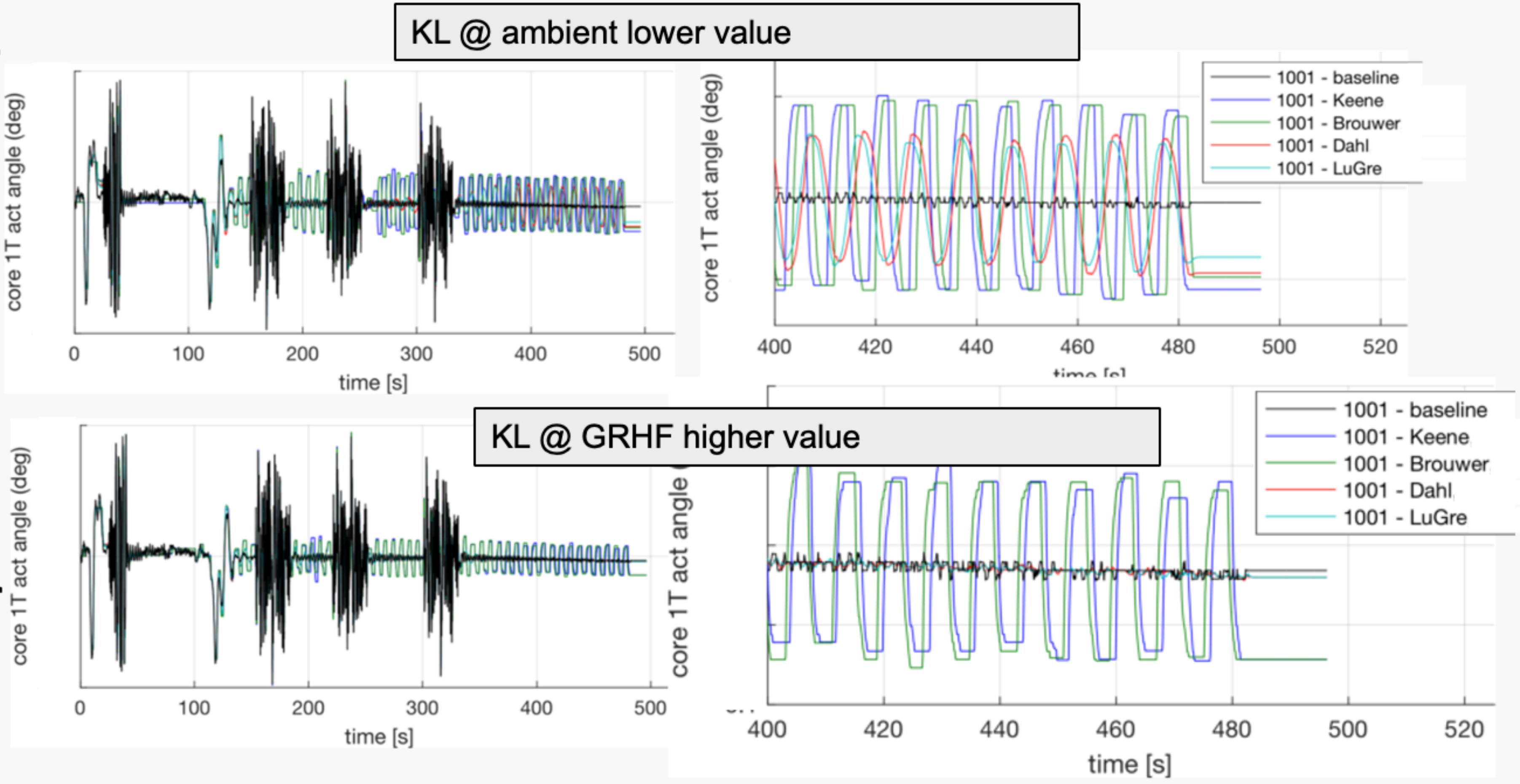



- Amplitude at which TVC gain & phase causes FCS open loop (OL) to reach [0dB,-180deg] will indicate LCO amplitude



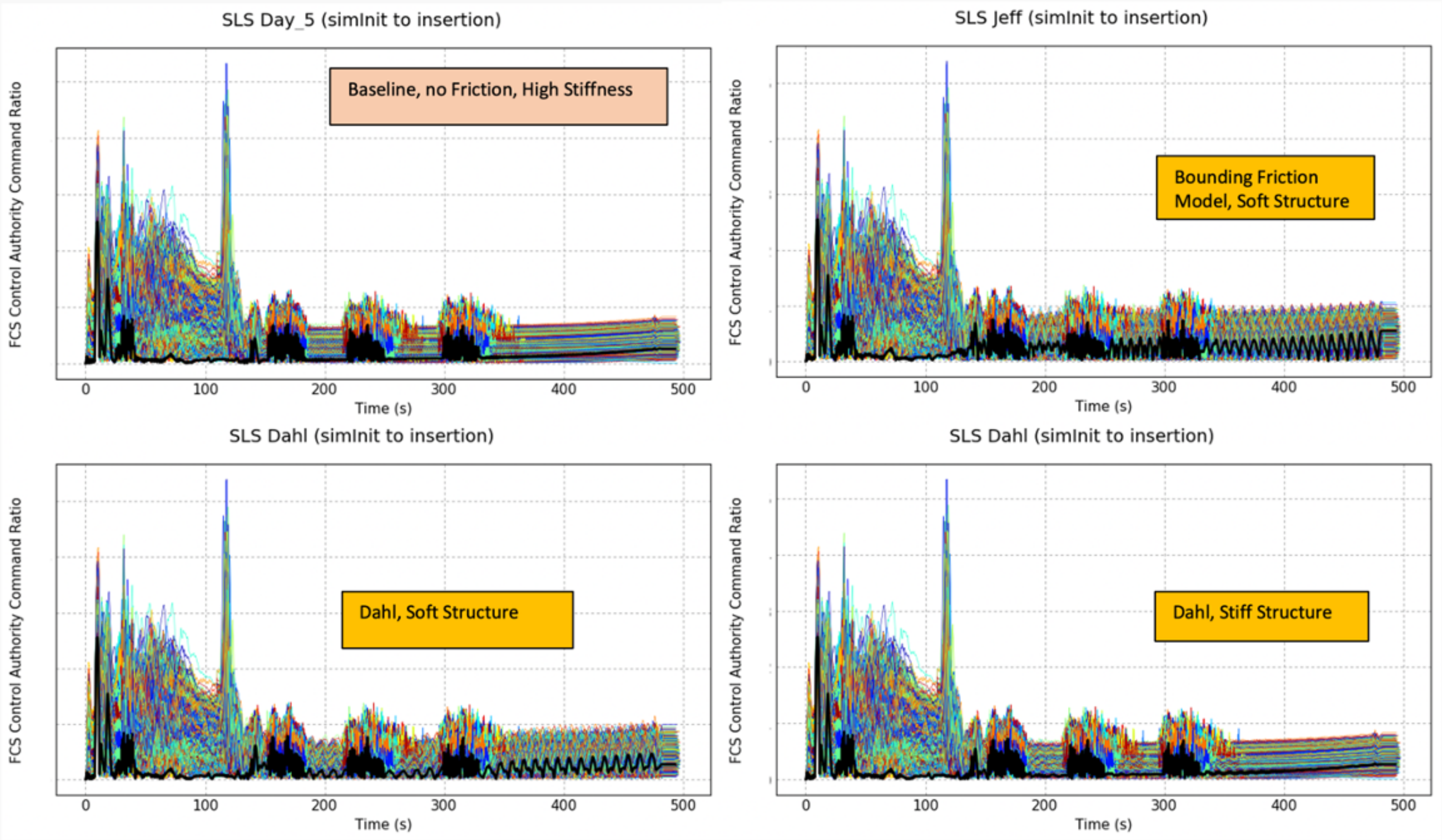
# Bounding LCO Predictions for Artemis I Flight Rationale

- **TVC Step and Frequency Response departures accepted for for Artemis I**
- **Artemis I flight rationale based on acceptability of LCO prediction**
- **Simplex model adjustments bound the solution**
  - Variety of friction models: Simple (Keene/Brouwer), Dahl, LuGre, tuned based on Green Run & Shuttle MPTA
  - Utilized Range of stiffnesses observed during Green Run testing
  - Included the -1dB TAC command gain effect
- **Time domain analysis shows LCO at small amplitude, near FCS crossover frequency**
  - Core flight only, boost flight shares authority with Solid Rocket Booster (SRB) TVC
- **Not additive with Programmed Test Input periods (PTIs)**
  - Amplitude of PTI larger than LCO amplitude
- **Simple models show more distorted behavior, larger LCO**
- **Dahl/LuGre show smoother, smaller LCO**
- **Higher load stiffness reduces propensity for LCO**
  - eliminates LCO with Dahl & LuGre



# Time Domain Monte Carlo LCO Predictions Consistent with Nominal

- **Monte Carlo runs performed**
  - Baseline, pre-test model, no friction
  - "Jeff" Brouwer implementation of simple coulomb friction, KL @ low stiffness
  - Dahl friction, KL @ low stiffness
  - Dahl friction, KL @ high stiffness
- **LCOs from Monte Carlo predictions show consistency with the nominal, as expected**
  - Dispersions in vehicle parameters and environment do not change fundamental LCO result, being driven by friction and stiffness in the TVC model
- **Simple Coulomb model + soft structure produces largest LCO**
- **Dahl model + stiff structure → no LCO**



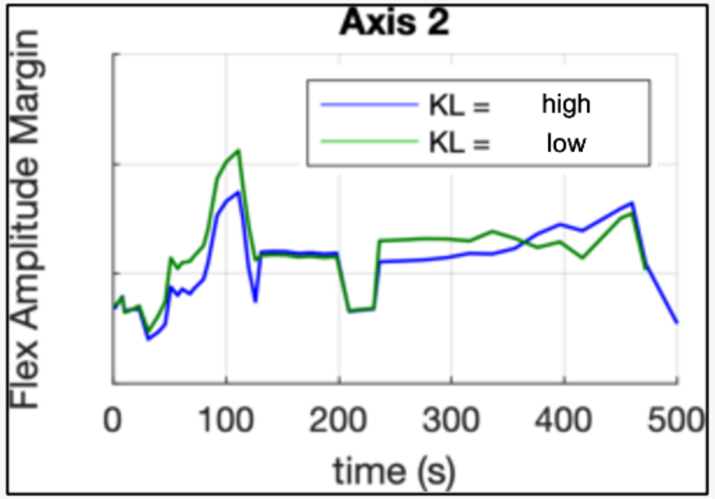

- **The SLS Vehicle Loads & Dynamics group incorporated the additional LCO content in core stage flight and found it to be acceptable**
  - Negligible impact due to small amplitude, low frequency, and only present during quiescent periods
- **All other disciplines and elements accepted the potential for LCO in Artemis I first flight**

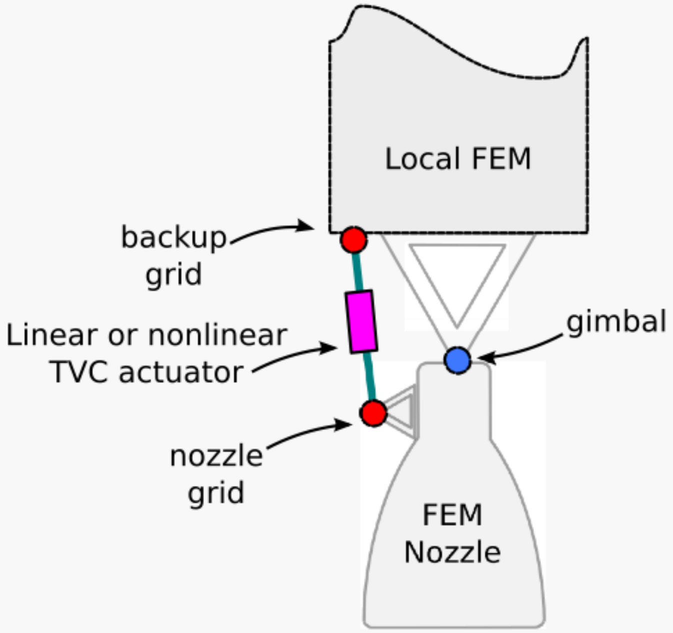
# Frequency Domain Analysis of Softer Structure

- **An independent evaluation of the load stiffness was conducted using linear frequency domain toolset**
  - Setting KL to lowest observed value from GR ambient testing and comparing against baseline high stiffness assumption prior to Green Run

- **Objective 1: ensure vehicle flight control stability margins and frequency response is not significantly altered by the presence of softer structure**
  - Rigid Body margins were not significantly affected with assumption of softer load stiffness
- **Objective 2: ensure no significant difference in higher frequency flex mode response**
  - This analysis was of particular interested as global bending modes > ~6Hz are advantageously coupled with the core stage TVC system via inertial-structural interaction (Tail-Wag-Dog (TWD) and Dog-Wag-Tail (DWT) flex forces) [12]

- **Servo-elastic torque break (open loop cut at DWT-flex torque interface) used to evaluate KL drop**
  - beneficial phase stabilized effect of structural modes the TVC is retained
- **Overall vehicle flex margins maintained throughout flight across full load stiffness range**



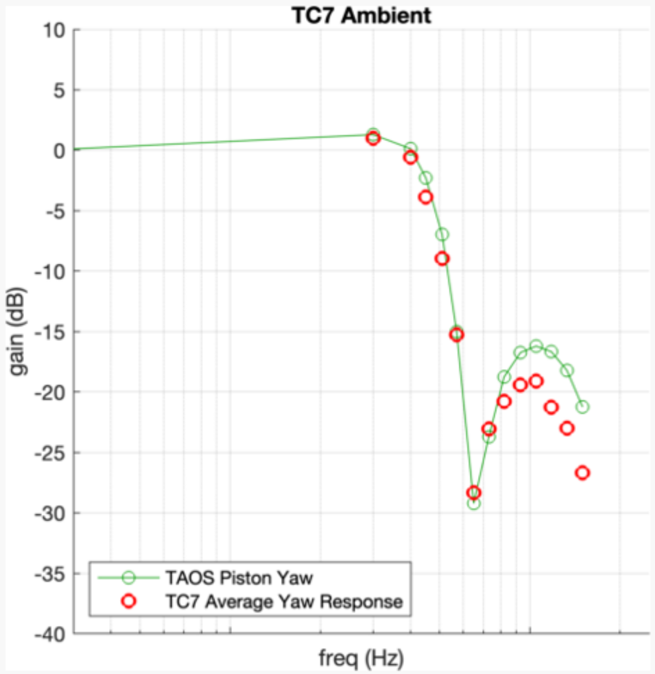



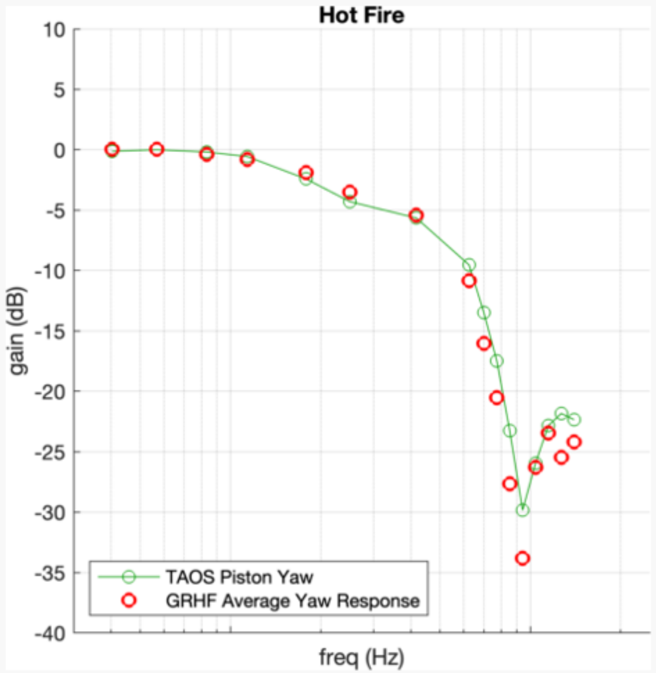
# Developments after Acceptance of Flight Rationale

- **Acceptability of flight control stability analysis and predictions of Bounding LCO → Artemis I Flight Rationale**
- **Following development of flight rationale, a cross-disciplinary team was formed with loads & dynamics, TVC, and flight control engineers along with core stage & engine contractors**
  - To improve friction modeling
  - To explain difference in stiffness between hot fire and ambient
  - To determine acceptability of and/or mitigations for Core Stage TVC on future SLS vehicles

**<u>Advances in Understanding:</u>**

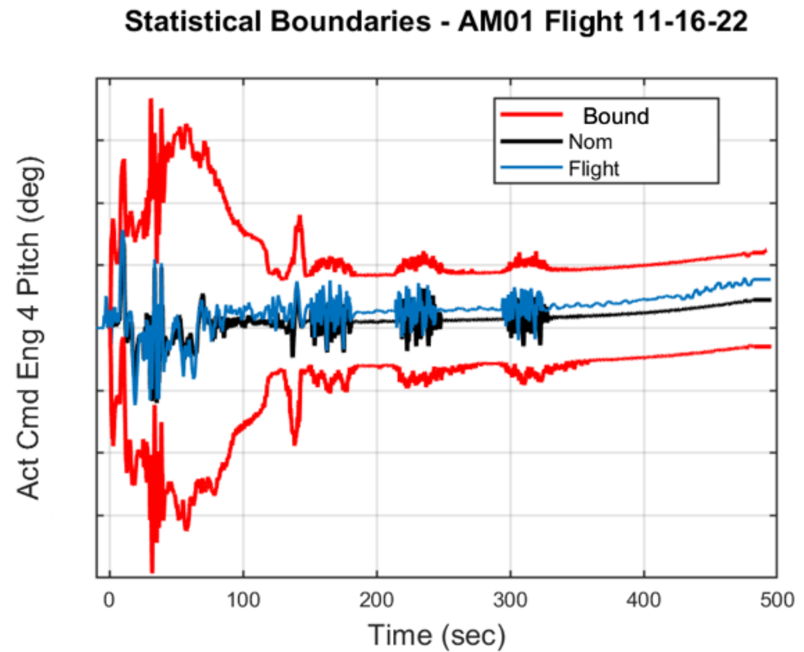
- **Flight expected to have higher stiffness as was observed in Green Run**
  - Gimbal stiffness under loaded conditions
  - Small loads and command amplitudes during ambient shows
- **TAOS (Two Actuator Operational Simulation)**
  - Flex body effects of the gimbal required modeling each half as a separate stiffness in addition to the typical single-spring load stiffness
  - Vector model of gimbal joint and friction torques
  - Advanced model of friction developed "modified LuGre" that best fit Green Run
- **TAOS fidelity with Green Run Hot Fire anchored suggested no LCO would be present in flight**

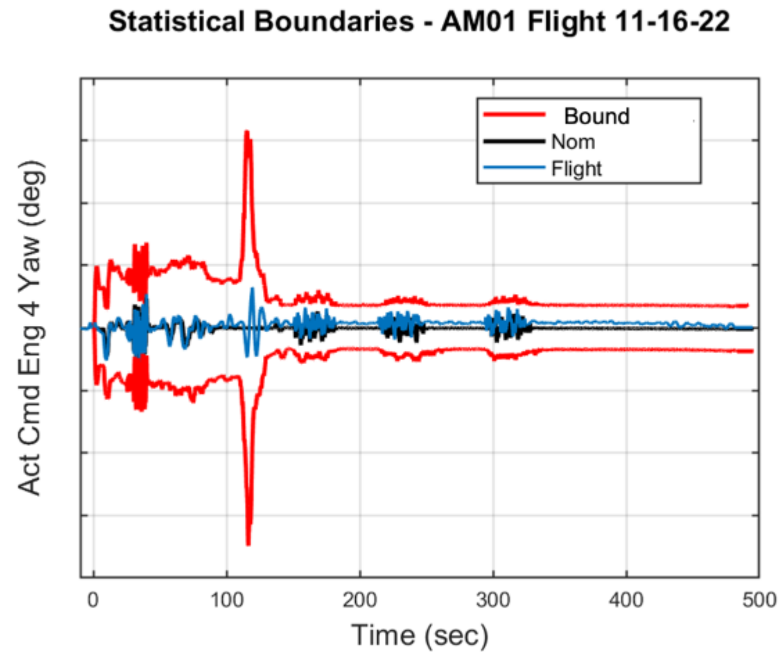


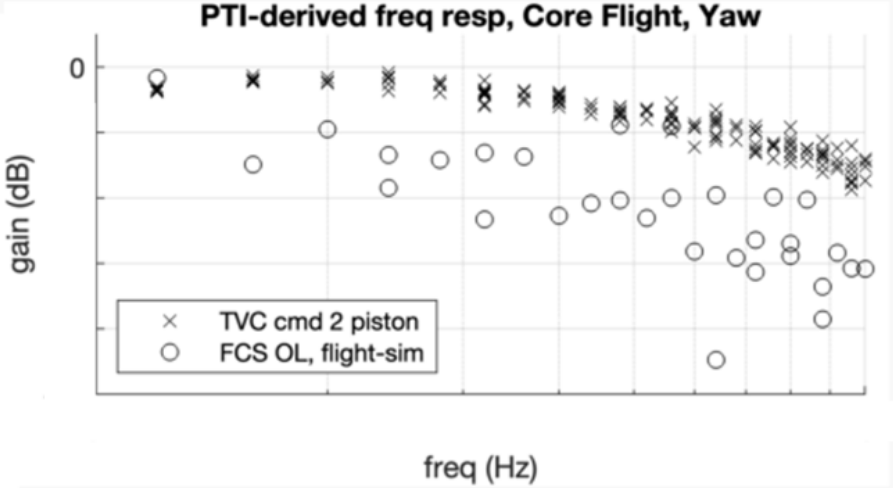



# Artemis 1 Flight Response

- **Artemis I flight on Nov 16, 2022: FCS was close to nominal predictions**
- **Some small TVC amplitude oscillation present**
  - Not as clearly persistent as pre-flight LCO predictions but within bounding pre-flight predictions
- **Program Test Inputs (PTI) response of FCS open loop show evidence of decreased gain effect that could be considered consistent with modeled gimbal friction effects**
  - Friction has worse effect on engine than piston → engine necessarily shows up in PTI FCS OL
  - Green Run Hot fire could not determine absolute gain of engine response
- **Post Flight Prelim Evaluation: gimbal friction appears larger than at Green Run, but still a small amplitude effect**
  - Green run simultaneous high and low frequency commanding produces dither
  - Higher acoustically-induced vibratory environments at Green Run lowers friction
  - Exoatmospheric Flight thrust larger than sea level Green Run Hot fire test



## Concluding Remarks

- Green Run testing was essential to uncover critical knowledge about the response of Core Stage TVC System in various conditions
- Test anchored models confidently certified FCS for first flight Artemis I
- First flight of SLS provided confirmation of Green Run findings showing responses consistent with small amplitude LCO caused by gimbal friction
- In-flight PTI excitations reveal key information about the SLS response

- This foundation of data and experience will help reduce cost, minimize risk, and maximize mission capability as NASA shapes the SLS generation of heavy-lift launch vehicles.

c/o NASA fb

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