National Aeronautics and Space Administration

MCLAURIN Jacobs Space Exploration Group NASA

SPACE LAUNCH SYSTEM

Design, Instrumentation, and Data Analysis for the SLS Core Stage Green Run Test Series

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John Wall (Mclaurin Aerospace / ESSCA), Huntsville, AL
Chris Russell, (The Boeing Company), Huntsville, AL
Richard Moore (Mclaurin Aerospace / ESSCA), Seattle, WA
Jeb Orr, (Mclaurin Aerospace / ESSCA), Knoxville, TN
Abran Alaniz, (Mclaurin Aerospace / ESSCA), Houston, TX
Stephen Ryan, (MTS CPSS), Huntsville, AL

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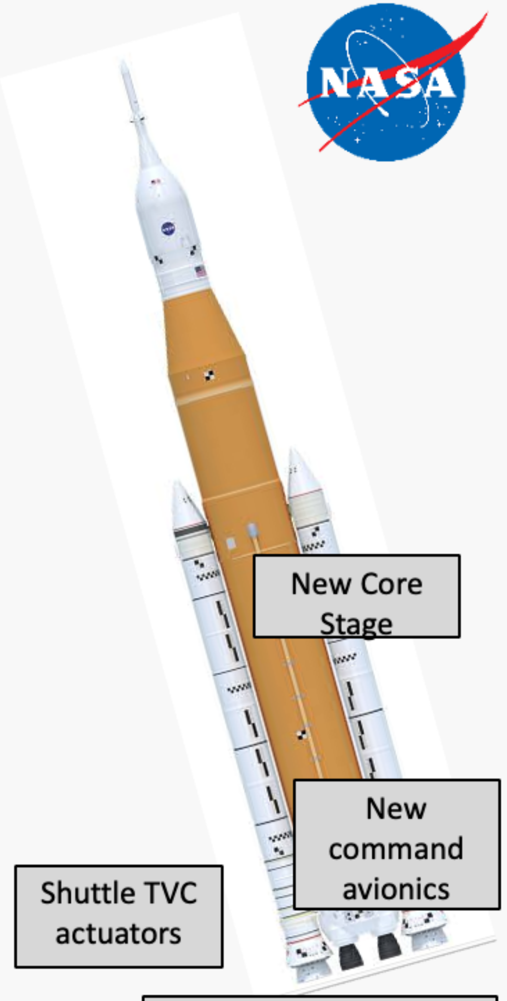
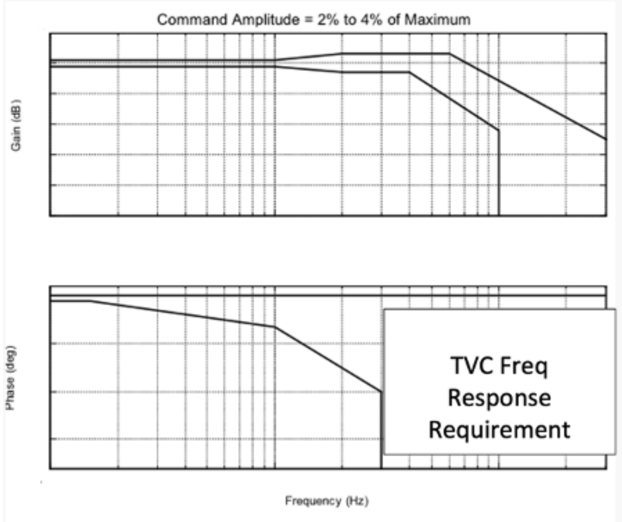
Agenda

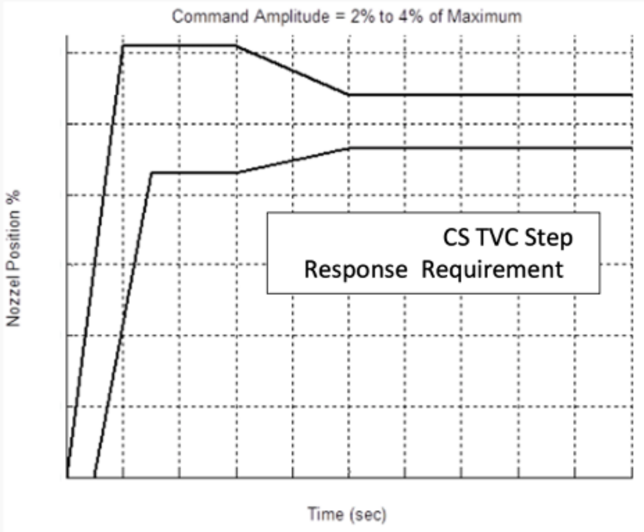
- **Overview**
- **Development Testing: Lab Environments**
- **Green Run Testing**
  - Ambient Modal
  - Ambient Vectoring
  - Hot Fire
- **Discussion of Results**

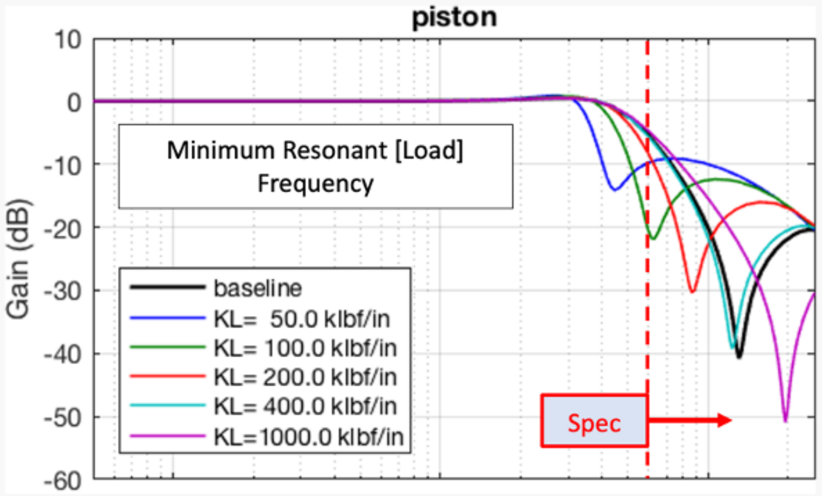
Overview

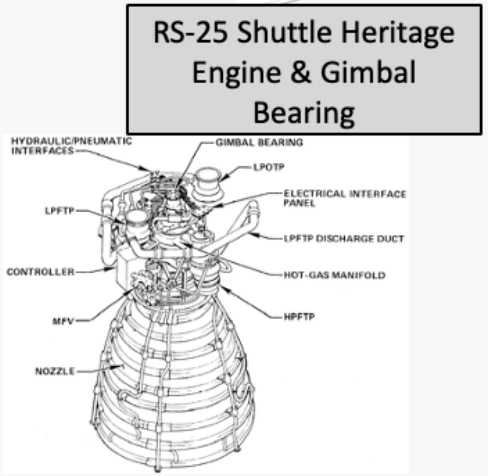
- **The SLS Core Stage (CS) TVC system is a mix of heritage and new hardware**
  - heritage Shuttle TVC actuators, RS-25 engine, gimbal bearing
  - Redesigned avionics and attached to a new vehicle structure
- **SLS Vehicle Flight Control imposed key CS TVC requirements**
  - frequency & step response requirements: flight control command to engine angle
  - Minimum [load] resonance frequency → observable in piston frequency response
- **Contractor TVC verification was largely through analysis with limited lab-based input**
- **NASA flight control & TVC collaborated with contractor to ensure proper instrumentation and testing was conducted prior to flight: nozzle instrumentation & integrated TVC tests**
- **Lab and Green Run testing was critical to reveal unmodeled behaviors and provide essential data for model updates and Artemis I flight confidence**
  - Green run testing showed violations both in ambient and hot fire conditions and departure from pre-test models





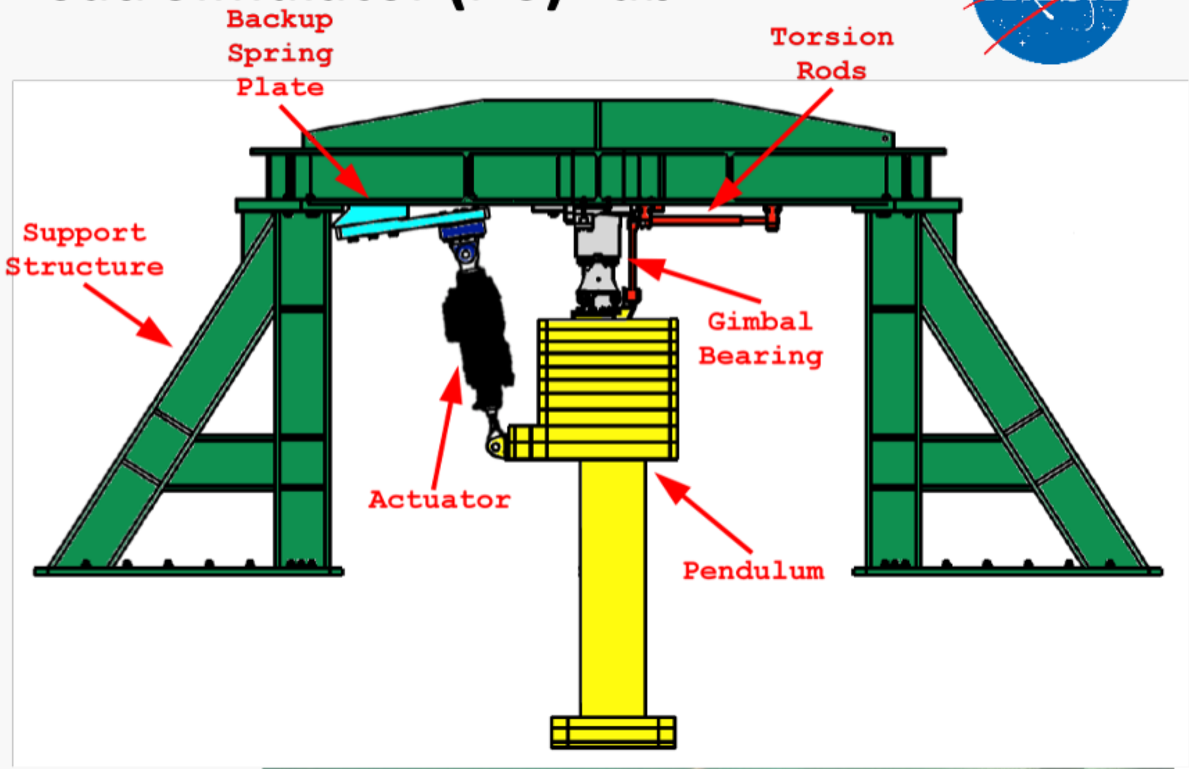


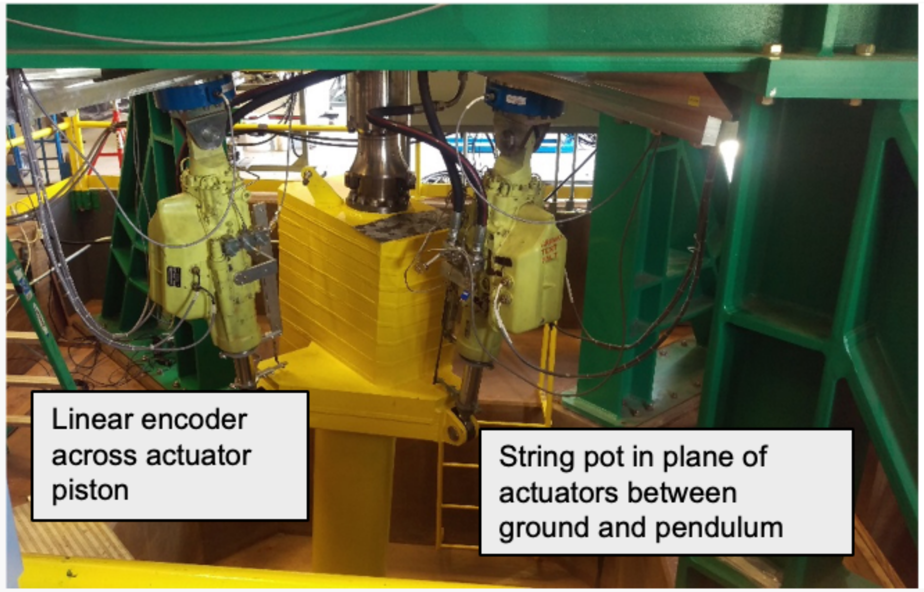




Early Development Testing: MSFC 2-axis Inertial Load Simulator (ILS) Lab

- **MSFC building 4205 facility built ILS to enable core stage TVC subsystem testing , nextdoor to hardware-in-the-loop lab**
  - Flight actuators, flight gimbal bearing
  - Backup structure and torsion rods simulate structural and engine duct "load" stiffnesses
  - Pendulum simulates engine pitch/yaw inertia
  - Facility provides hydraulics or flight hydrogen-driven power unit
  - Heritage analog or actual flight avionics
- **Means to test efficacy of instrumentation and vectoring command profiles prior to Green Run**
  - Lab @ 1000 Hz, Flight telemetry @ 50 Hz
  - [lab] String potentiometer (string pot) based nozzle instrumentation
  - [lab] Linear encoder & [flight] actuator piston position
  - Command path servo currents [flight]
  - [lab] load cell data

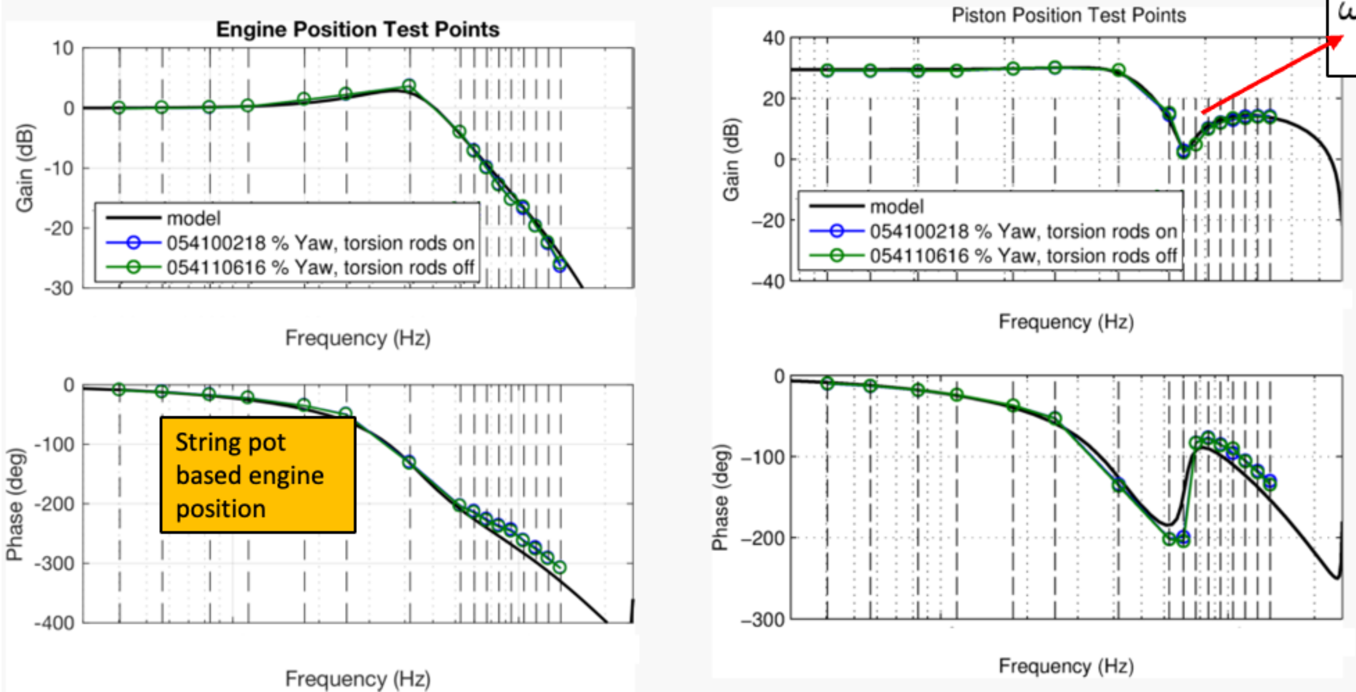




Early Development Testing: MSFC 2-axis ILS 2017 Results

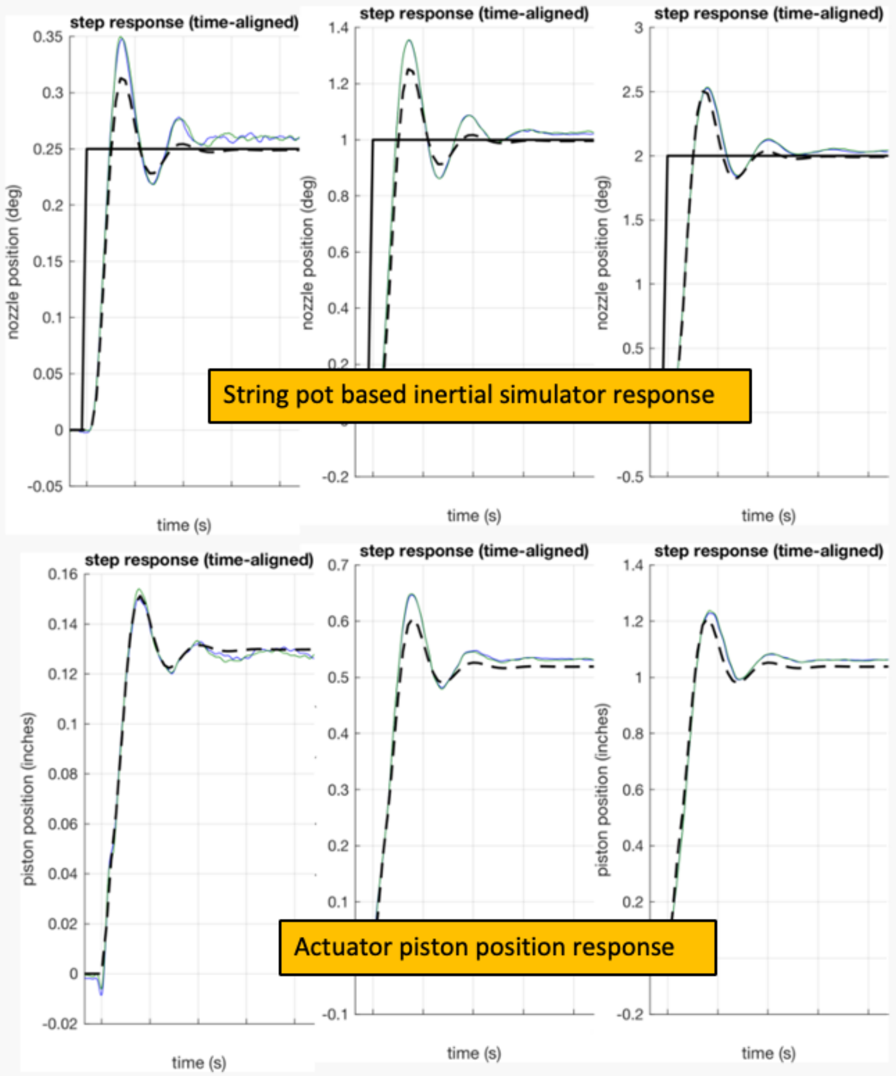
- **Shuttle MPTA Type III (same as flown on Artemis I) actuator testing in 2017 showed good comparison to linear planar simplex TVC models**
  - Discrete sine testing using Green Run vectoring approach
- **Piston-notch based identification of load resonance,**
  - Determination of load stiffness, KL from knowledge of load inertia, Jn moment arm, R, (negligible influence of torsion rod stiffness, Kn)
- **String pot length-based determination of engine/nozzle position**

Frequency Response to Actuator Commands



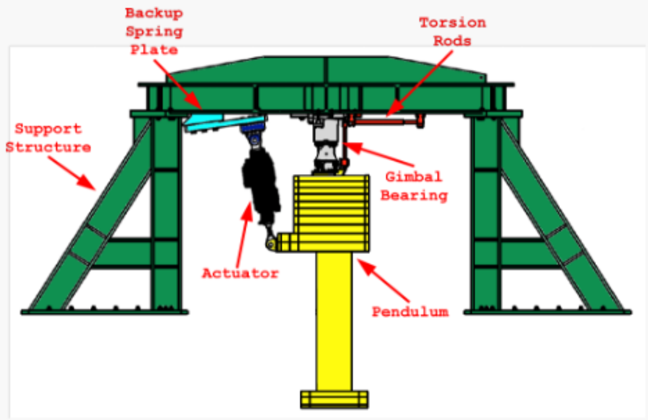
$$\omega_L = \sqrt{\frac{K_L R^2 + K_n}{J_n}}$$

Step Response

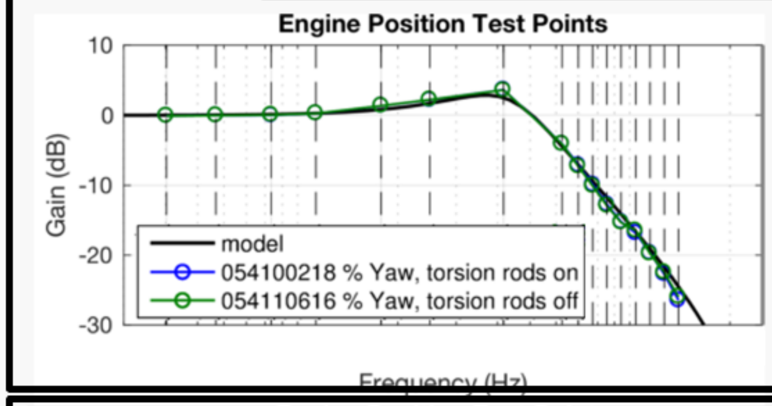


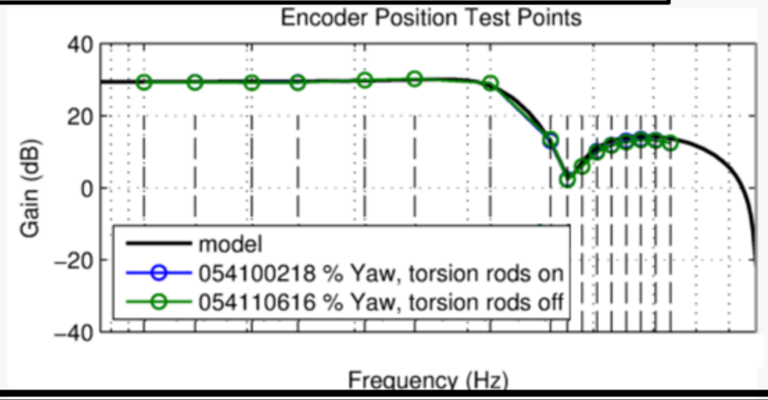
MSFC 2-axis ILS Results: SubSystem Test Article (SSTA)

- **SSTA testing was a stage contractor-performed test primarily to test the hydrogen-driven Core Auxiliary Power Unit (CAPU) hydraulic supply to the actuators**
- **SSTA setup (Fall 2020) changed from prior ILS 2017 testing**
  - Type III Shuttle MPTA actuators → Type II Shuttle actuators (different than SLS flight)
  - Command avionics TVC actuator controller (TAC) used
- **Verified the efficacy of the Green Run Profile with Flight Command Avionics**
  - Offset in response gain due to TVC actuator controller (TAC)



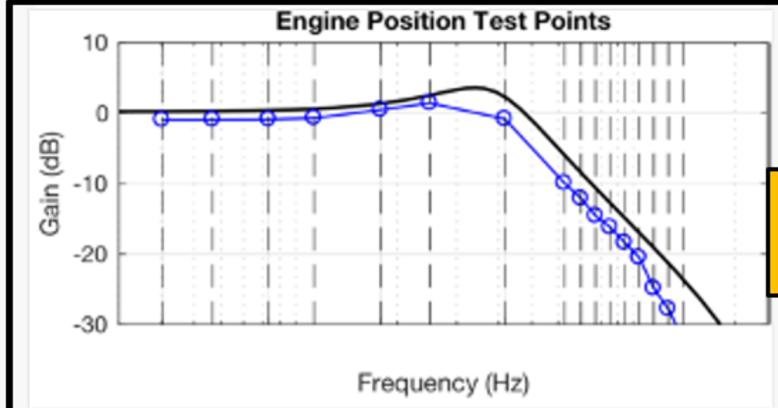
Frequency Response to Green Run Profile Actuator Commands

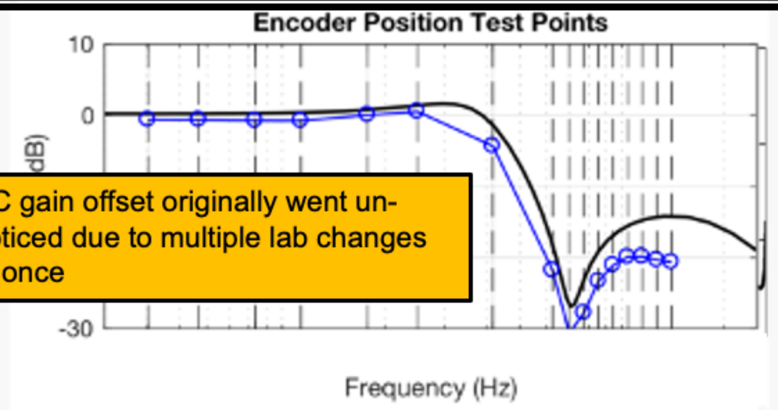




2017 NASA led testing

Analog Avionics, Type III actuators





DC gain offset originally went un-noticed due to multiple lab changes at once

2020 stage contractor led testing

Flight Avionics, Type II actuators

Stennis Space Center (SSC) "TC-5" Engine Section Modal Test

- **Engine Section modal test added after Crane-Hung empty stage modal test identification of engine-pendulum modes were inconclusive**
  - Accelerometers placed on engine and thrust structure
  - Mid-stroke locks placed on actuators (bypasses hydraulics) as in crane test
  - Lowest freq engine pendulum modes same as crane hung → lower than FEM

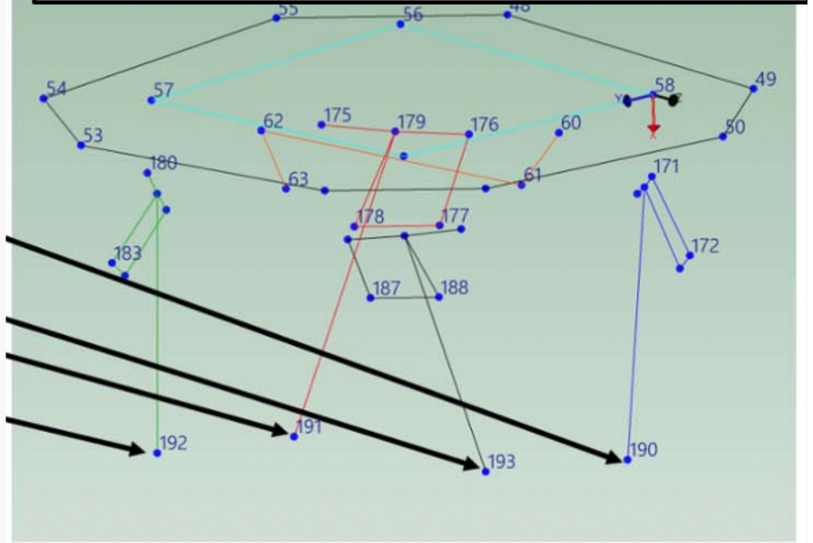
- **Unlocked, powered actuator testing showed observation of engine pendulum modes during 20 minutes of uncommanded quiescent hold period → lowest mode @ 6.1Hz → closure of min frequency requirement**
  - Unexpected result, expected TVC closed loop to damp modes
    - assumes that actuators are servo/powerspool deadband as piston response didn't fall out of quant and piston quant < assumed deadband

- **Observation of "total resonance" via engine pendulum mode assumes single load spring, KL, is sufficient to represent structure**
  - Later found not to be a suitable assumption for SLS Core Stage
  - Many modes in engine section influence equivalent static stiffness KL → single freq observation in modal test cannot determine KL

$$\omega_L > \omega_T = \sqrt{\frac{K_T R^2 + K_n}{J_n}}$$

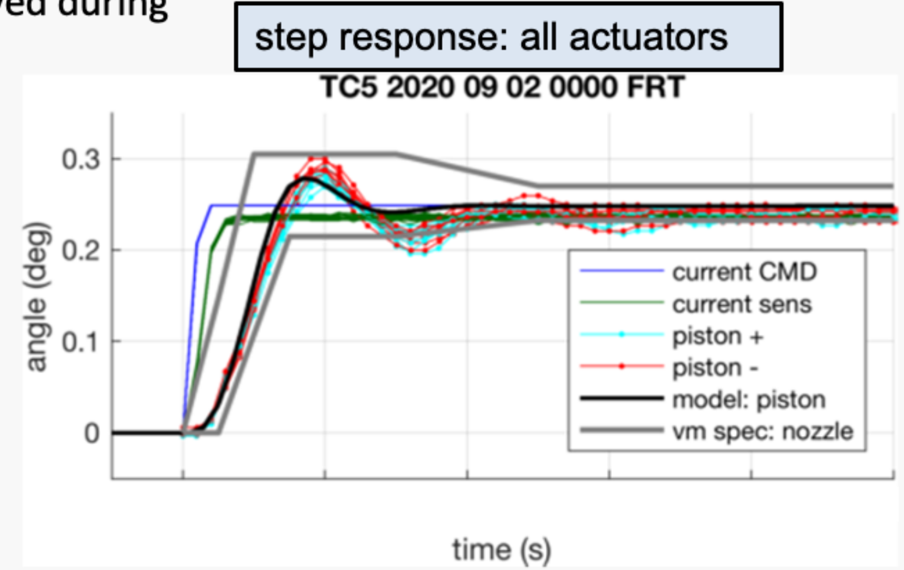
$$\frac{1}{K_T} = \frac{1}{K_L} + \frac{1}{K_{\text{oil}}}.$$

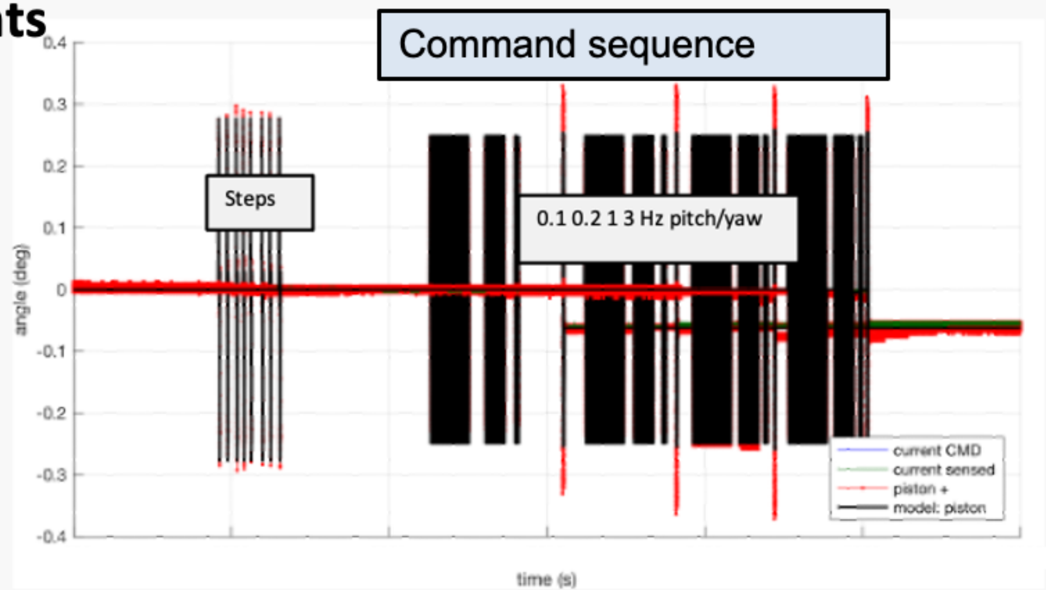
NASA MSFC added accelerometer instrumentation and performed modal ID

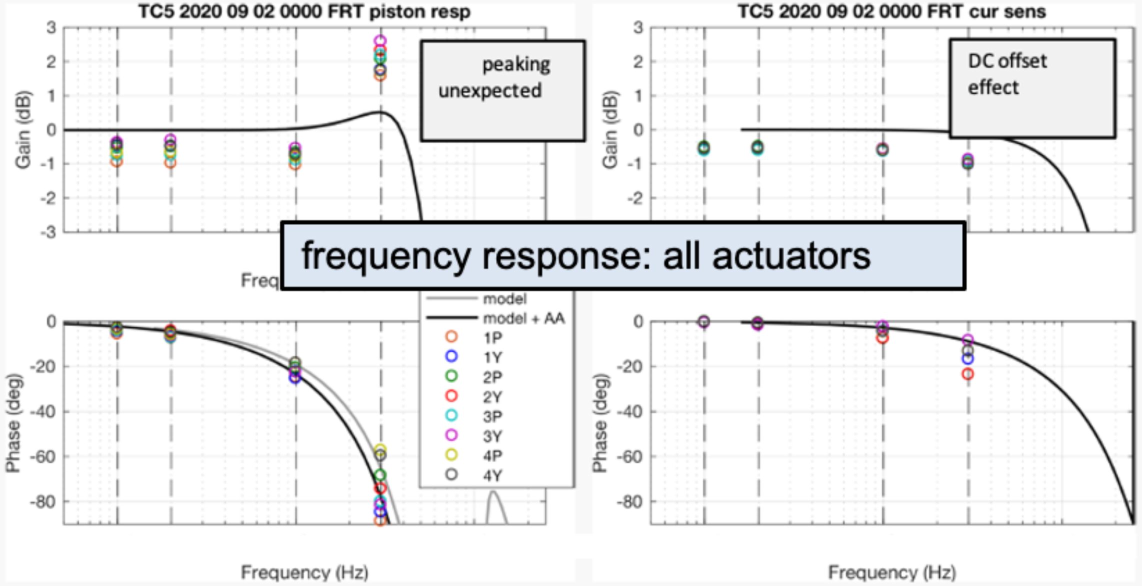


SSC TC-5: First Vectoring Test on Integrated Vehicle

- **TC-5 was only originally planned TVC vectoring test prior to Green Run Hot Fire**
  - Simple command sequence of freqs [0.1 0.2 1 3] Hz and steps [0.25] deg, same as employed during Shuttle pre-flight checkouts
- **String pot measurements were available but were not usable**
  - Data rate insufficient during steps (test coordination oops)
  - End point knowledge needed higher accuracy to determine angle from
  - string length measurement
- **DC offset observed in commanded currents and piston responses**
- **Piston frequency response showed unexpected peaking at 3Hz**
- **Piston step response showed more overshoot than the model**
  - Cause could not be determined without further testing
- **Overshoot and ringing corroborated by video feed and accelerometer measurements**

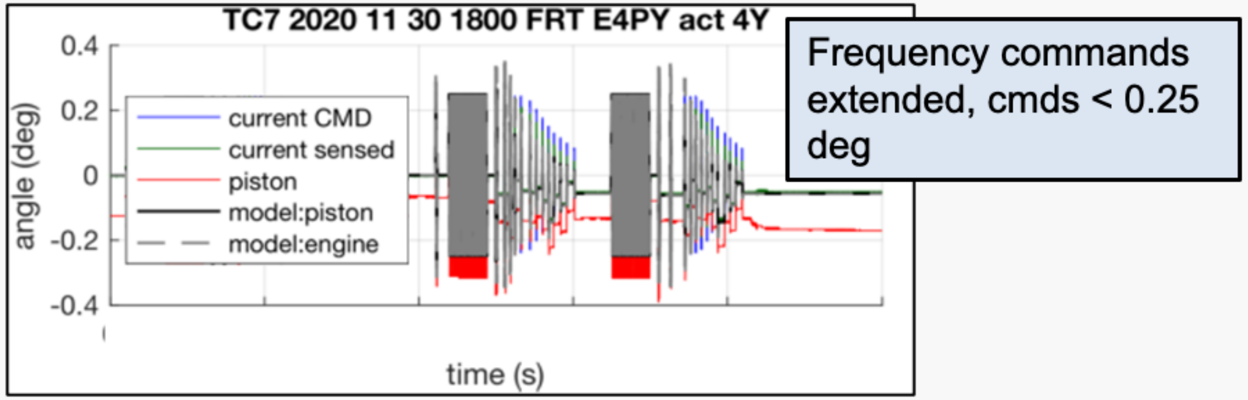


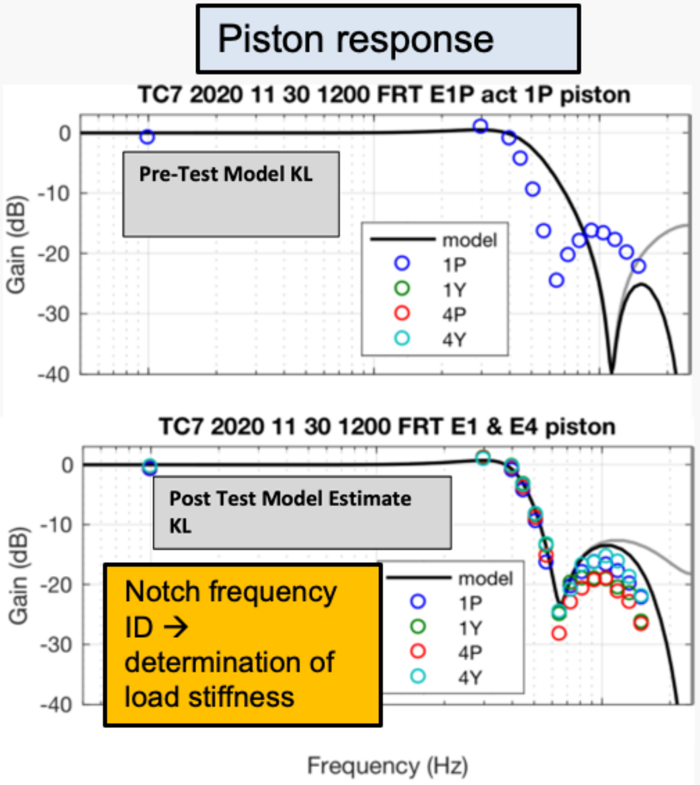


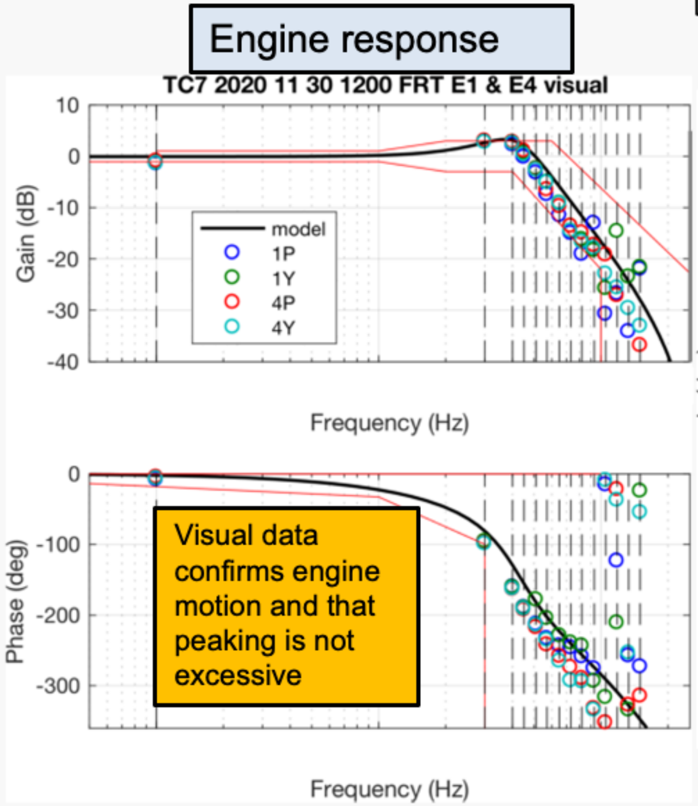


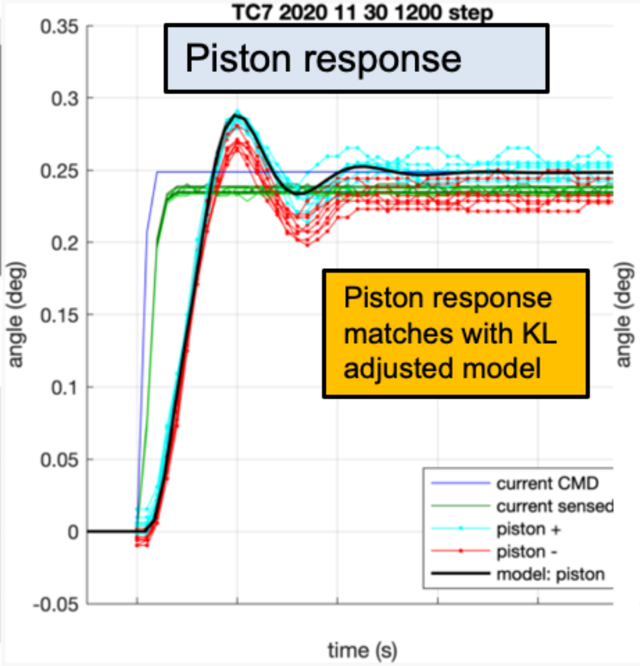
SSC TC-7: Extension of Ambient Vectoring Test

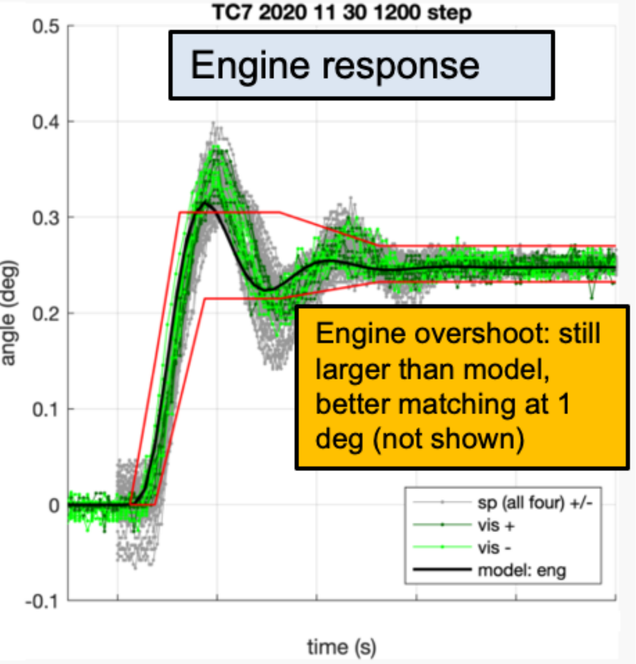
- **TC-7 vectoring test was added upon request of flight control and NASA TVC teams**
  - Survey of string pot end points and string pots recorded at full data rate
  - 12 camera visual data system corroborated string pot angle reconstruction
  - Extended frequency response showed primary reason for the differences: Load resonance was much lower than pre-test modeling → change in load stiffness









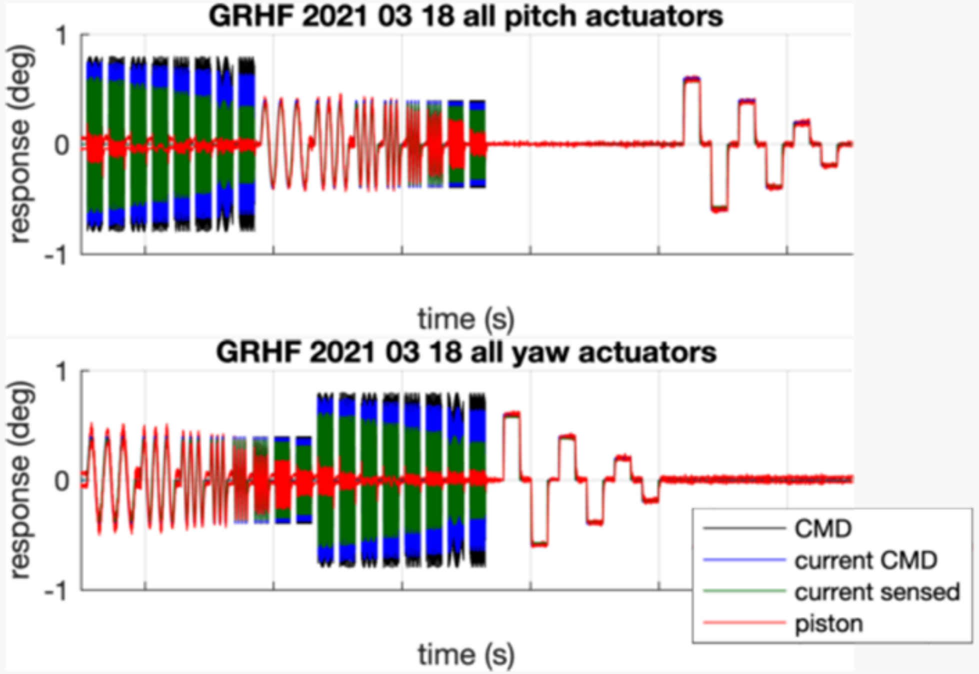


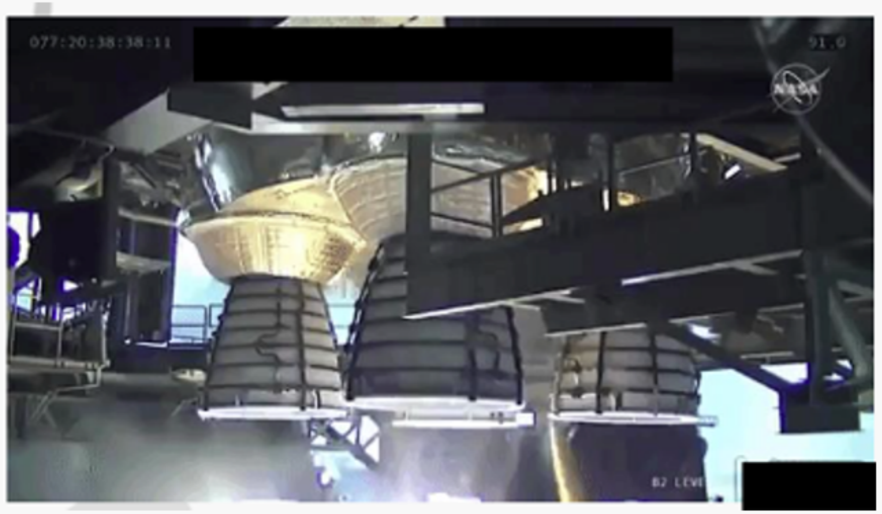
Green Run Hot Fire: Frequency & Step Response Test

- **Green Run Hot Fire: frequency & step commands over 130 seconds during full throttle periods**
  - Pitch and yaw performed simultaneously with disparate frequency bins to avoid cross talk
  - No net torques: coordinated motion to vector in the null space
  - Commanding beyond typ. software rate limit to maximize SNR given actual TVC response for higher freqs
    - 0.4 deg in low freq (~0.4-6.25), 0.8 deg in high (~7-14Hz)
  - Three step amplitudes: 0.6, 0.4, 0.2 deg: yaw, then pitch
- **All commands were properly sent and instrumentation was captured as intended**

Low Frequency Profile 0.4 deg Z-T-P	
Channel 1 (Hz)	Channel 2 (Hz)
0.4032	7.0-14.0 Hz increasing
0.5682	
0.8333	
1.1364	
1.7857	
2.5000	
4.1667	
6.2500	

High Frequency Profile 0.8 deg Z-T-P	
Channel 1 (Hz)	Channel 2 (Hz)
7.0000	0.40-6.25 Hz increasing
7.7286	
8.5331	
9.4213	
10.4020	
11.4847	
12.6801	
14.0000	

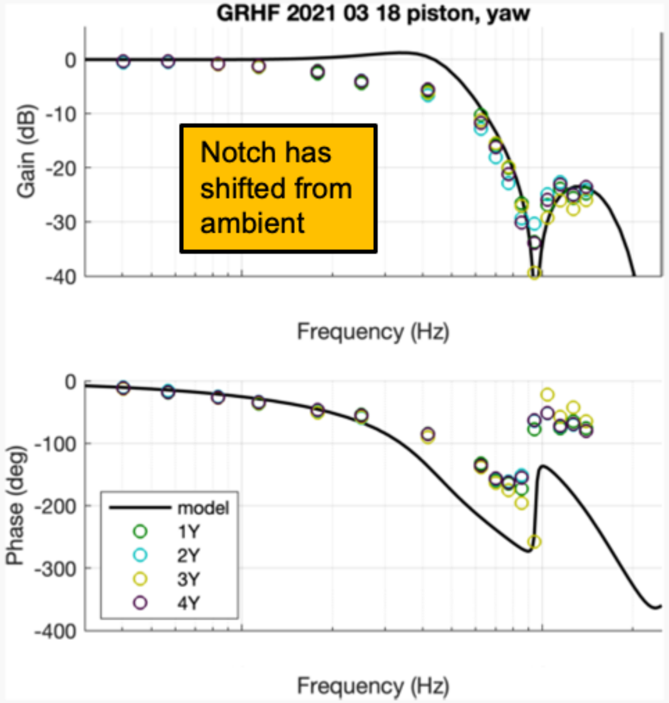




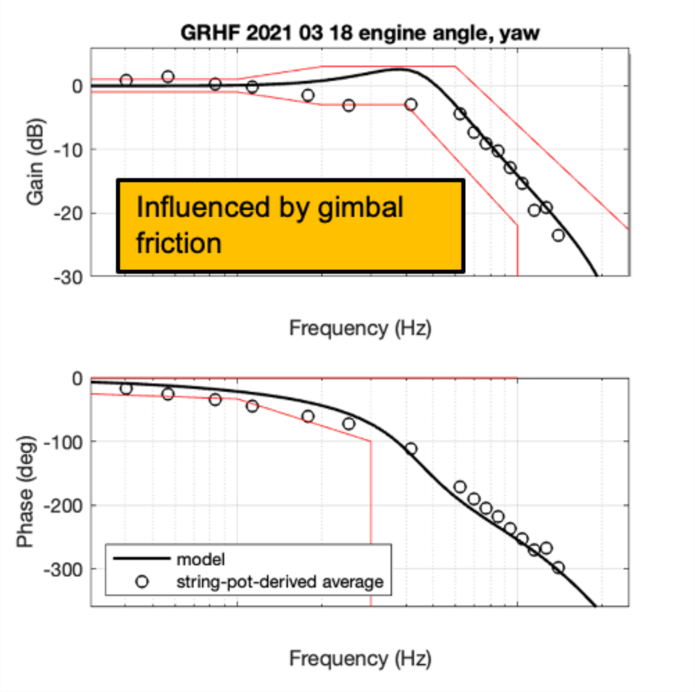
Green Run Hot Fire: Results

- **Response during hot fire is significantly different from TC-7 ambient Response**
  - Much more damped step responses → thrust loaded gimbal exhibits friction
  - Unexpected and not observed during Shuttle MPTA testing: Load resonance frequency shift (piston notch)
- **Responses do not follow linear model, even after load stiffness K adjustment to align with notch**
- **String pot derived engine response provides trends but not absolute position due to sensitivity and uncertainty in geometric config**
  - Friction would result in more pronounced DC gain effect in engine

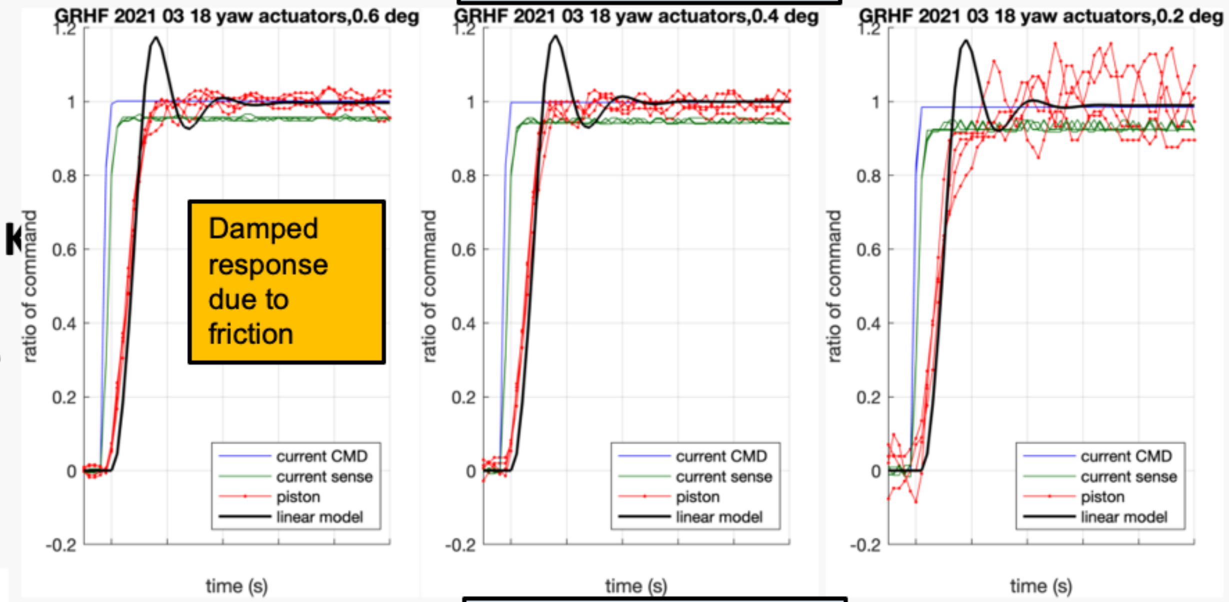
Piston response



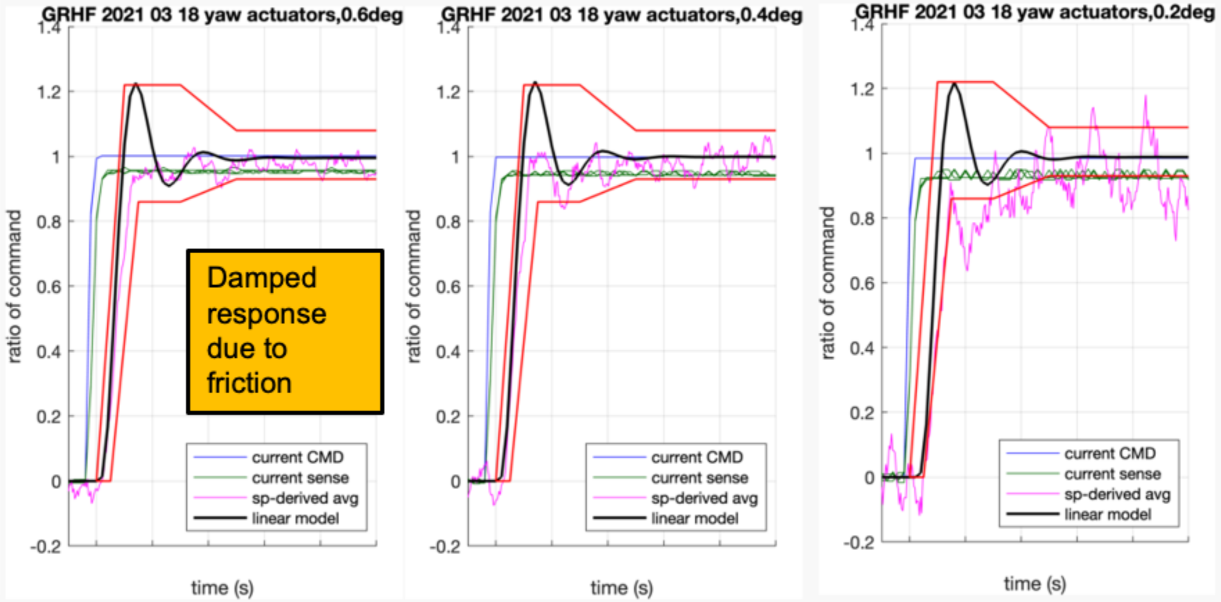
Engine response



Piston response

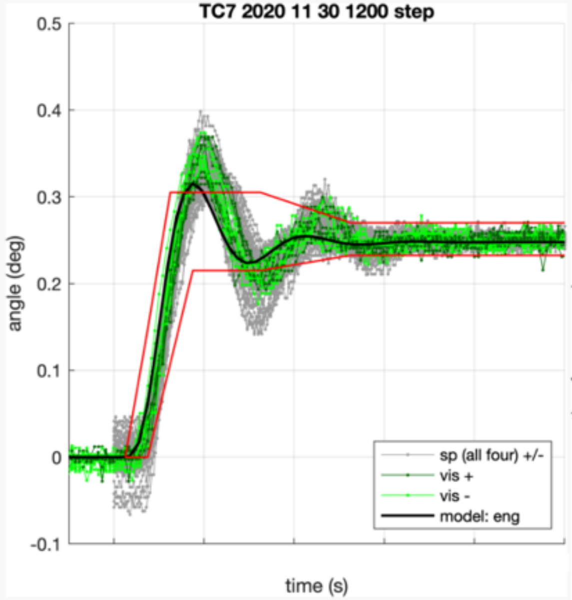


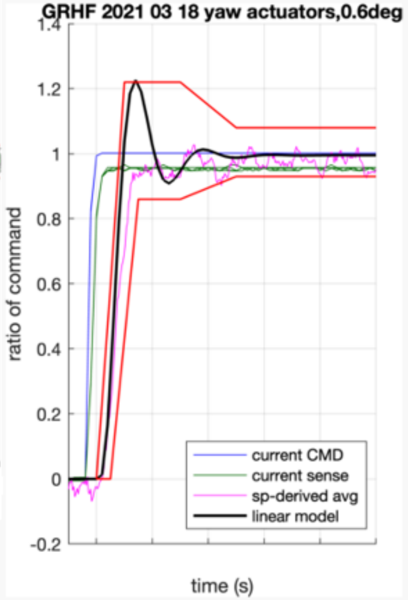
Engine response

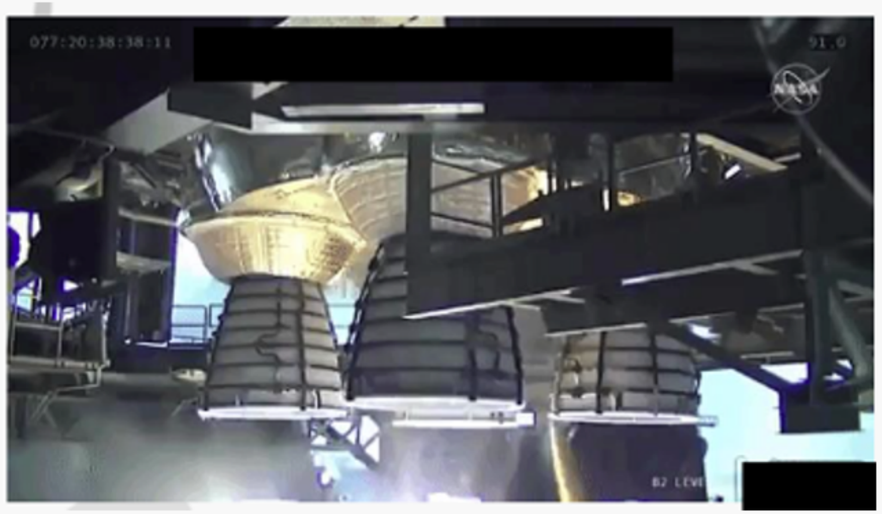


Discussion of Green Run Results

- **Post test correlation and model activities determined that three key factors were responsible for the results at Green Run**
  - TVC command avionics exhibited nonlinear amplitude dependent scale factor → DC offset
  - Gimbal friction is present when gimbal is loaded
    - More advanced friction models than simple coulomb were required to sufficiently model the Green Run responses
  - Shift in load resonance: apparent load stiffness change due to thrust loaded gimbal bearing & amplitude-dependent nonlinear effects
- **Long standing assumption of the MSFC flight control and TVC team was that gimbal friction could be neglected was reversed**
- **Shuttle MPTA testing showed similar evidence of gimbal friction in available responses**
    - Hot fire TVC ramp testing measured coulomb effects
    - No measurement of engine was available but piston data showed damped behaviors
  - Shuttle flight never exhibited Limit Cycle Oscillation characteristic of gimbal frictional effects → friction is negligible
- **Step & frequency response deviations were accepted for Artemis I flight by determining bounding estimate for possible friction induced LCO:**
  - Hot fire anchored friction coupled with softer observed ambient load stiffness
- **Green run provided critical data to SLS flight control engineers to update knowledge, models, and confidently proceed to Artemis I first flight**







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