National Aeronautics and Space Administration

MCLAURIN Jacobs Space Exploration Group

SPACE LAUNCH SYSTEM

Gimbal Bearing Friction in the SLS Core Stage Thrust Vector Control System

45th American Astronautical Society GN&C Conference
3 February – 8 February 2023, Breckenridge, CO

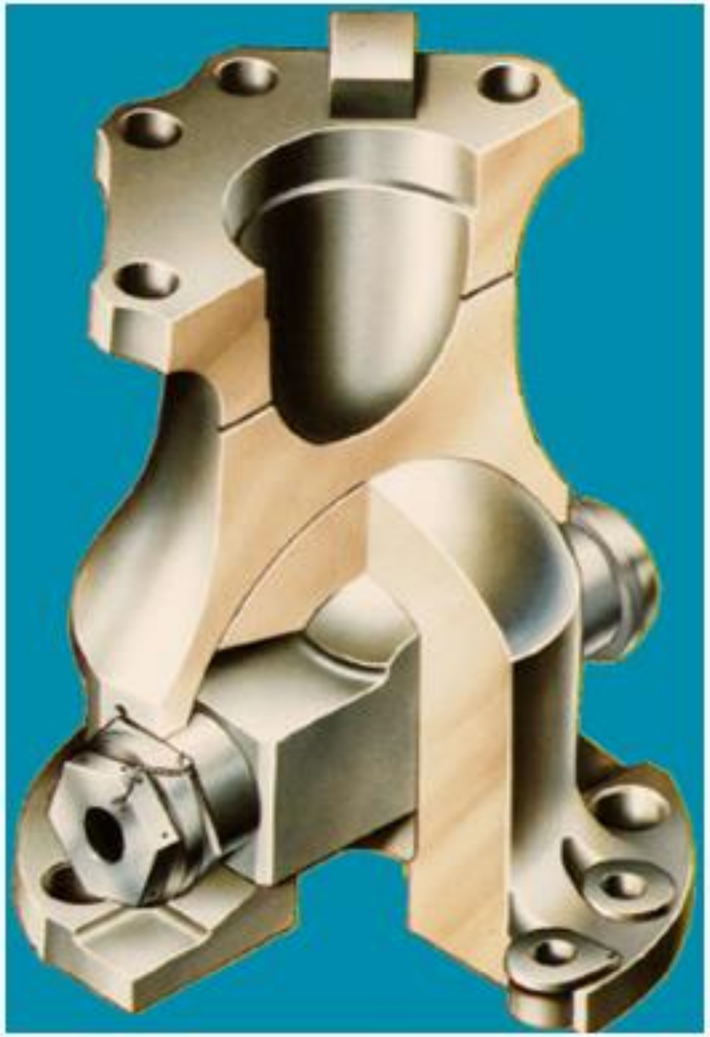
Colter Russell, Flight Systems Technical Staff (Mclaurin Aerospace / ESSCA), Knoxville, TN
Jeb Orr, Space Launch System Flight Dynamics and Control Technical Specialist
(Mclaurin Aerospace / ESSCA), Knoxville, TN
Jeff Brouwer, Navigation, Guidance, and Control Subject Matter Expert,
(Troy 7, Inc. / Jacobs ESSCA), Huntsville, AL
Stephen Ryan, SLS Chief Engineer's Office (MTS CPSS), Huntsville, AL
Nathaniel Stepp, TVC Controls Engineer, NASA MSFC, Huntsville, AL

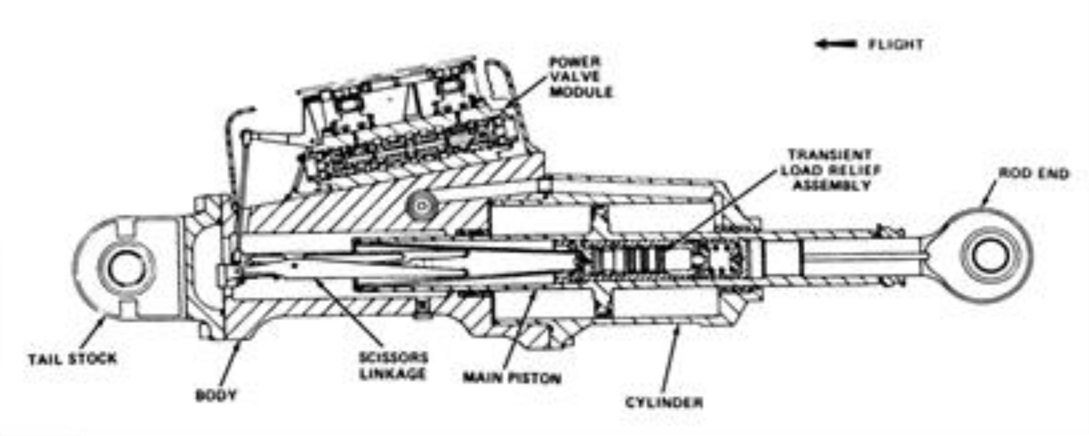
Overview

- Introduction
- GRHF Test and Findings
  - Test Design
  - Frequency and Time Results
- Historical Friction Modeling
  - Coulomb, Dahl, and LuGre
- Additional TVC Modeling Fidelity
  - Multi-axis effects
  - Structure of the Gimbal
  - Vibration effect on friction
- Simulation vs Test Data
  - Frequency and Step Responses
- Final Thoughts

Introduction

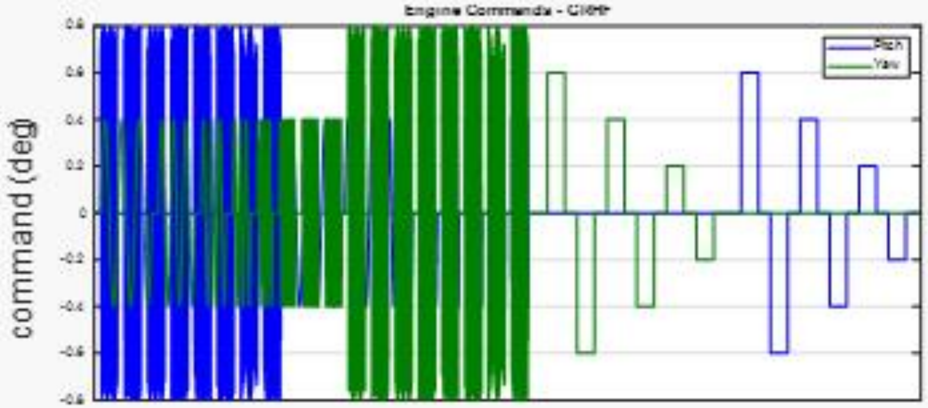
- Friction will always be a control consideration for gimbaled rocket engines
- The RS25 engine has a long heritage with the Space Shuttle program where friction was assumed negligible [1]
  - Friction was shown to be in the gimbal, but flight continuously proved it to be at a level acceptable to vehicle stability
- However, the SLS Green Run test series allowed the controls team to reinvestigate the RS25 performance
  - Results showed that RS25 response was altered by the friction environment present in the gimbal bearing
- A new approach to modeling the friction environment was required to be confident of performance in flight

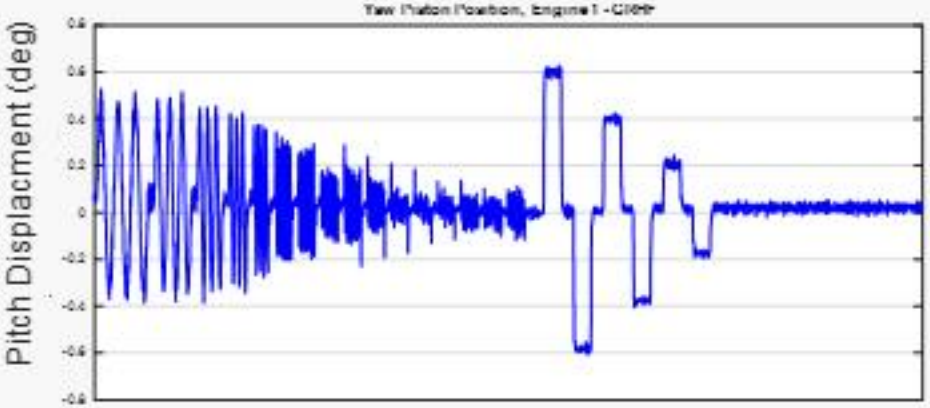




Green Run Hot Fire - Test Design

- Measuring response
  - String potentiometers for engine position
  - Commanded current, sensed actuator position, sensed current at servovalve
- GRHF Test profile [2]
  - Set of sine profiles in each axis
  - 3 step response amplitudes in each direction for each axis





[redacted]

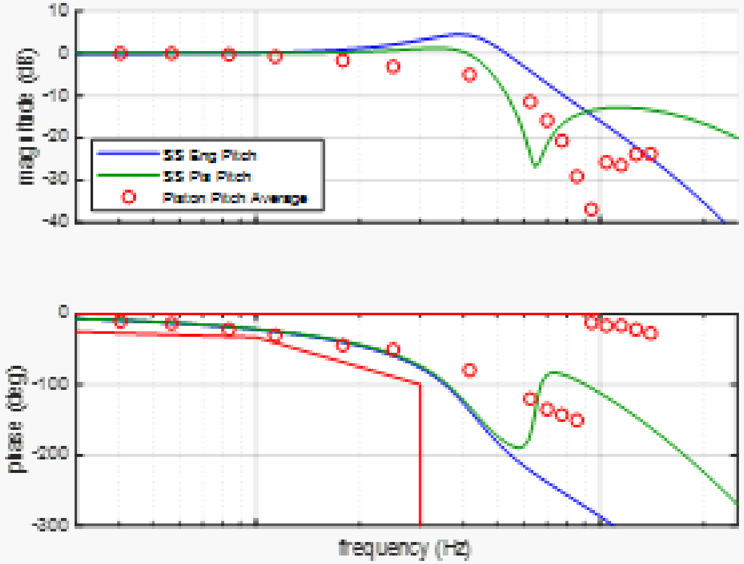
Green Run Hot Fire

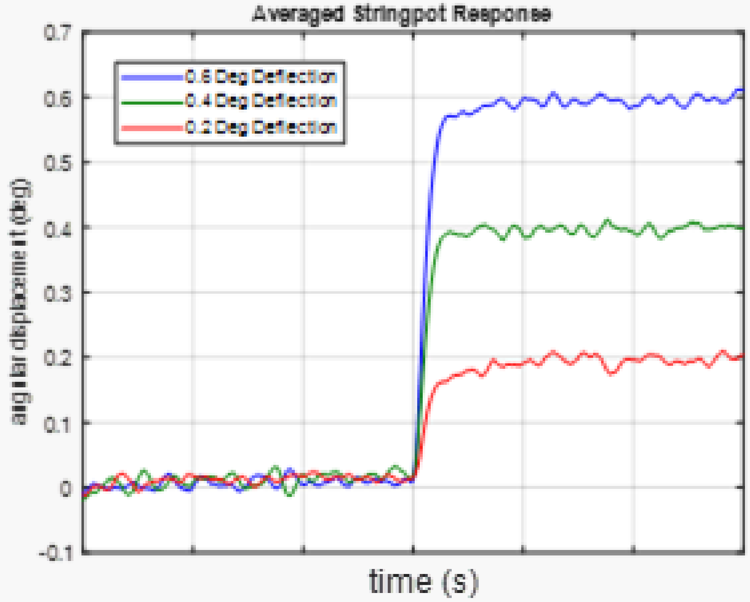
Pitch	Yaw
7-14 Hz @ 0.8°	0.40-6.25 Hz @ 0.4°
0.40-6.25 Hz @ 0.4°	7-14 Hz @ 0.8°
-	0.6°, 0.4°, 0.2° steps
0.6°, 0.4°, 0.2° steps	-

Green Run Hot Fire - Results

- Frequency Response
  - Hot fire shows clear resonance at 9.5 Hz
    - Represents an apparent shift from the ambient vectoring test result of 6.5 Hz
  - Gain degradation in low-mid frequencies
    - Indicative of friction effects
- Step Response
  - Step response shows hesitation not seen in prior modeling
  - Step shows a more damped response than in ambient test
- Importance of Proper TVC Modeling
  - Need to ensure stability of TVC and vehicle loop as they are coupled
  - Frictional effects may induce limit cycling in flight
  - Long standing question regarding the presence of gimbal friction in the RS25 gimbal (back to SSME)
- Overall
  - Nonlinear effects that were thought to be negligible needed to be modeled to match test data
  - Simplest possible model that could recreate these effects from test data was pursued (TAOS)

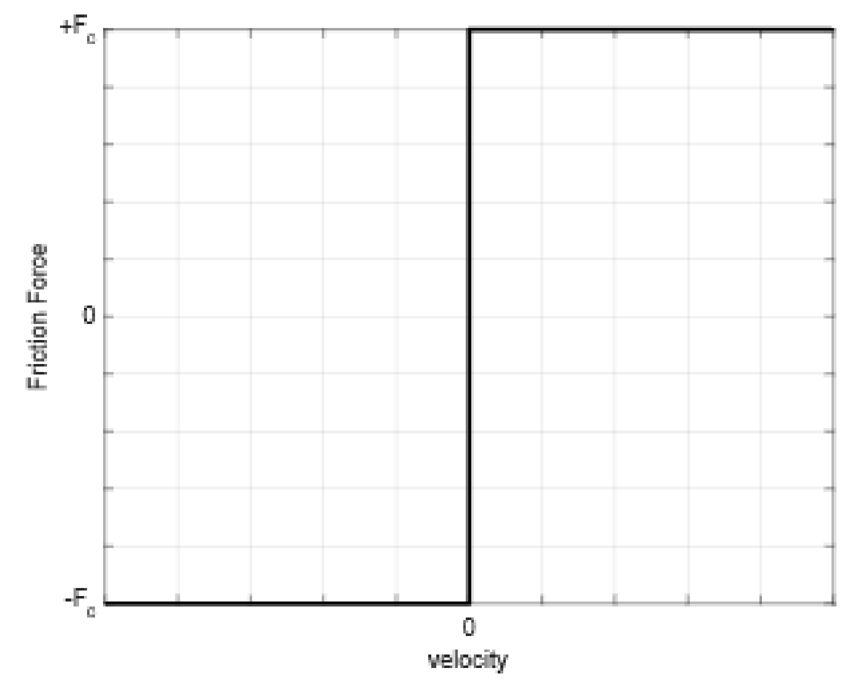
Command to Engine and Actuator Position Frequency Response





Coulomb Friction

- Coulomb friction is a simple approach to friction modeling that operates via the following logic:
  - A Coulomb friction force direction will always be opposite to the velocity vector if in motion and opposite to the external force if not in motion
  - The magnitude will be the same as the external force up to a maximum defined by the friction coefficient times the normal force.
  - Additional considerations for simulation implementation:
    - Coulomb force should never add energy to a system
    - Coulomb force should never cause a velocity reversal

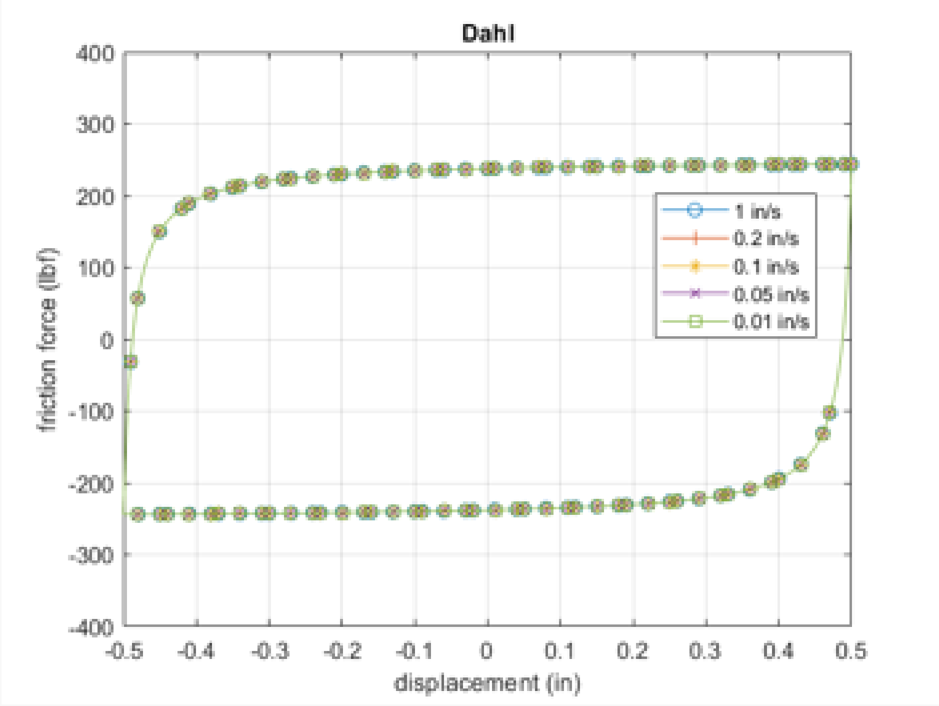


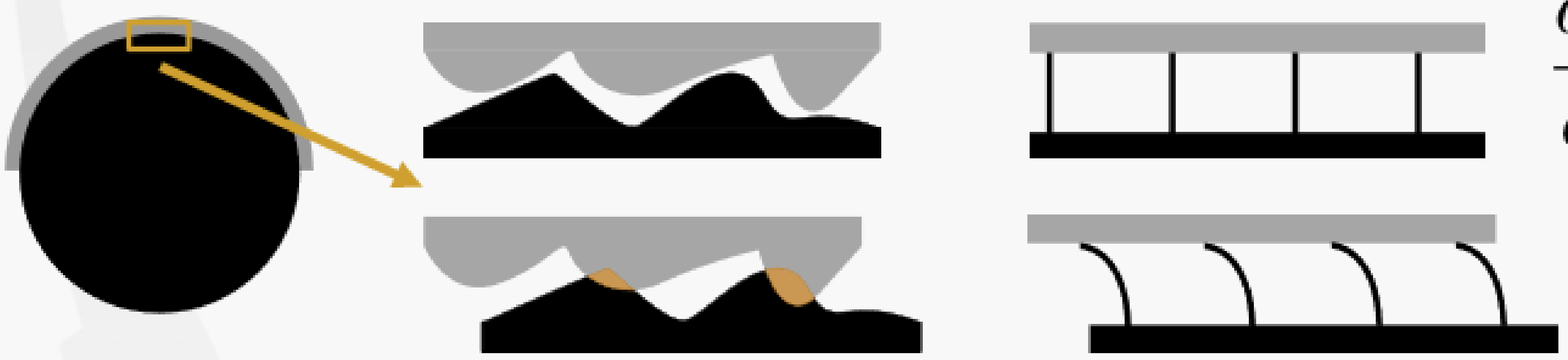
$$
\begin{cases} F_c = F_{ext}, & \mu N \geq F_{ext} \\ F_c = \mu N, & \mu N < F_{ext} \end{cases}
$$

Note: Direction always opposes velocity!

Dahl Friction

- Model developed by Philip Dahl of Aerospace Corporation for ball bearings in 1970s [3]
  - Modeled to match behavior of stress-strain curve
- Assumes disparities in material can be modeled as “bristles”
  - The “bristles” act as springs and deflect as engine moves
  - Stiffness value is used to relate deflection to force
  - Position dependent friction model





Direction of gimbal motion →

$$\frac{d\vec{z}}{dt} = \|\vec{v}\|(\hat{v} - \frac{\vec{F}_f}{F_c})^{\alpha}$$

$$\vec{F}_f = \sigma_0 \vec{z}$$

LuGre Friction

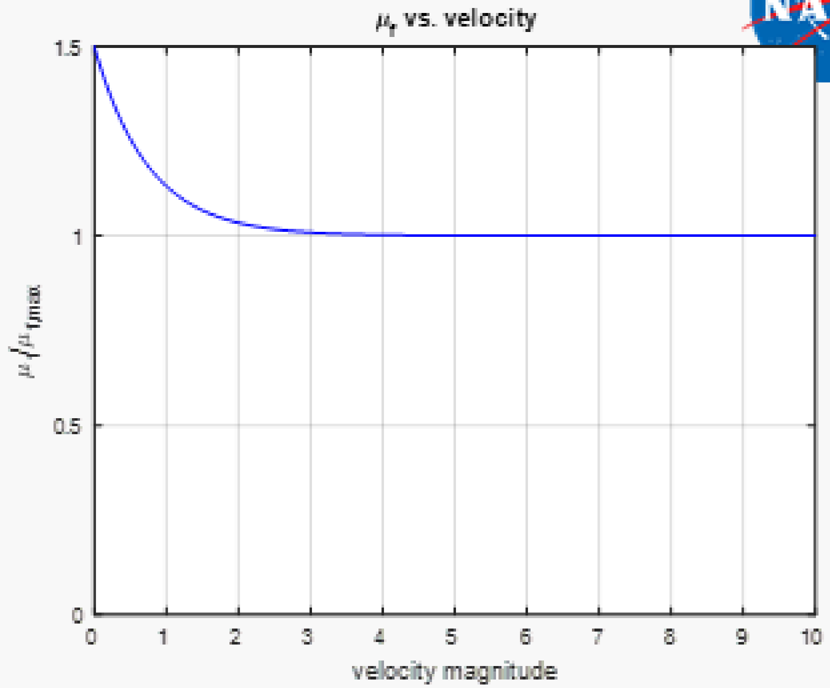
- LuGre friction [4] is very similar to Dahl except it has three extra features:
  - Damping terms for the bristle velocity
  - Viscous term for the gimbal surface velocity
  - Velocity dependent Stribeck effect
    - Friction coefficient is higher at lower velocity
    - Meant to incorporate the stiction phenomenon
      - Deflection of disparities causes local increases in stiffness due to plastic deformation of material

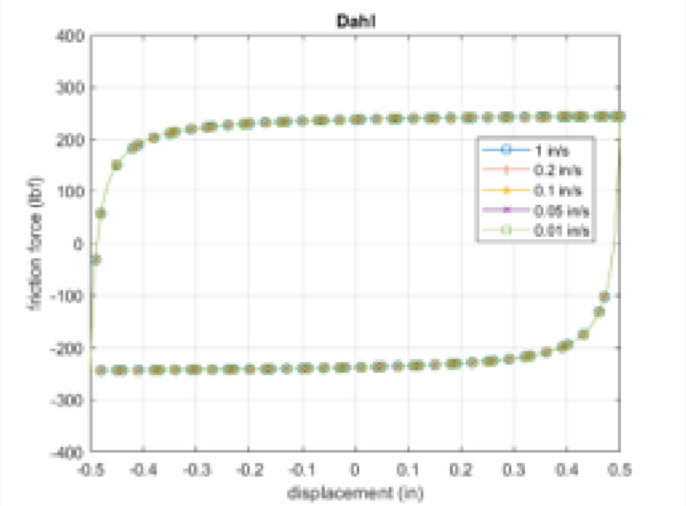
$$\vec{F}_f = \overset{\text{Bristle Stiffness}}{\overset{\downarrow}{\sigma_0}}\vec{z} + \underset{\underset{\text{Bristle Damping}}{\uparrow}}{\sigma_1}\frac{d\vec{z}}{dt} + \overset{\text{Viscous Damping}}{\overset{\downarrow}{\sigma_2}}\vec{v}$$

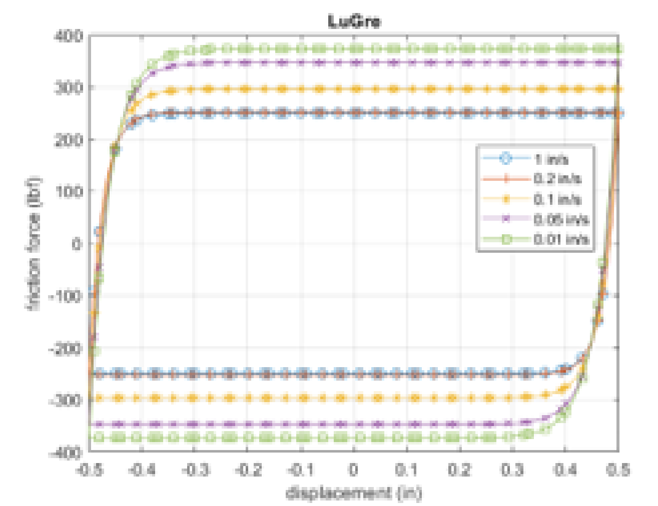
Stribeck Effect:

$$F_s = F_c\left(1 + (\gamma - 1)\, e^{-\left(\frac{\|\vec{v}\|}{v_s}\right)^2}\right)$$

$$\frac{d\vec{z}}{dt} = \|\vec{v}\|(\hat{v} - \frac{\sigma_0\vec{z}}{F_s})$$

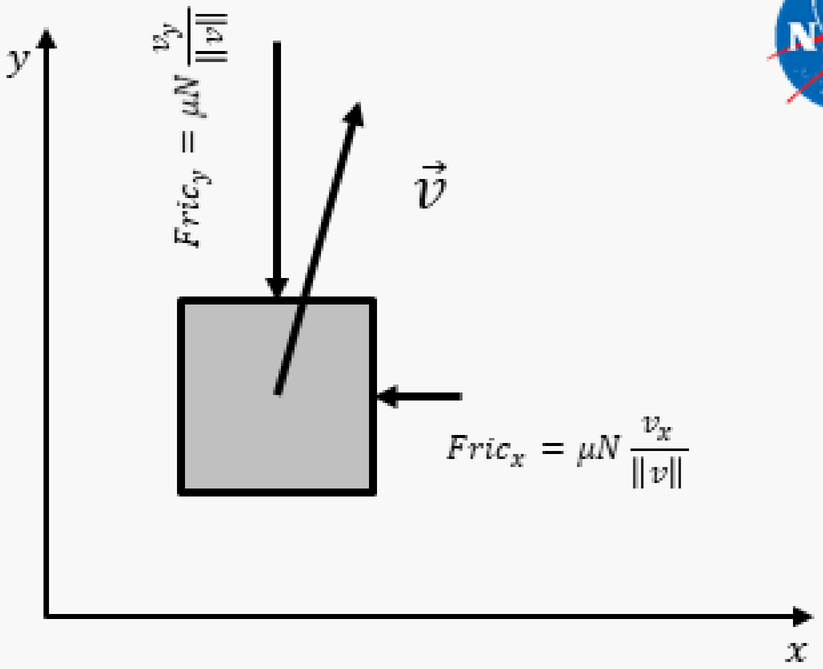




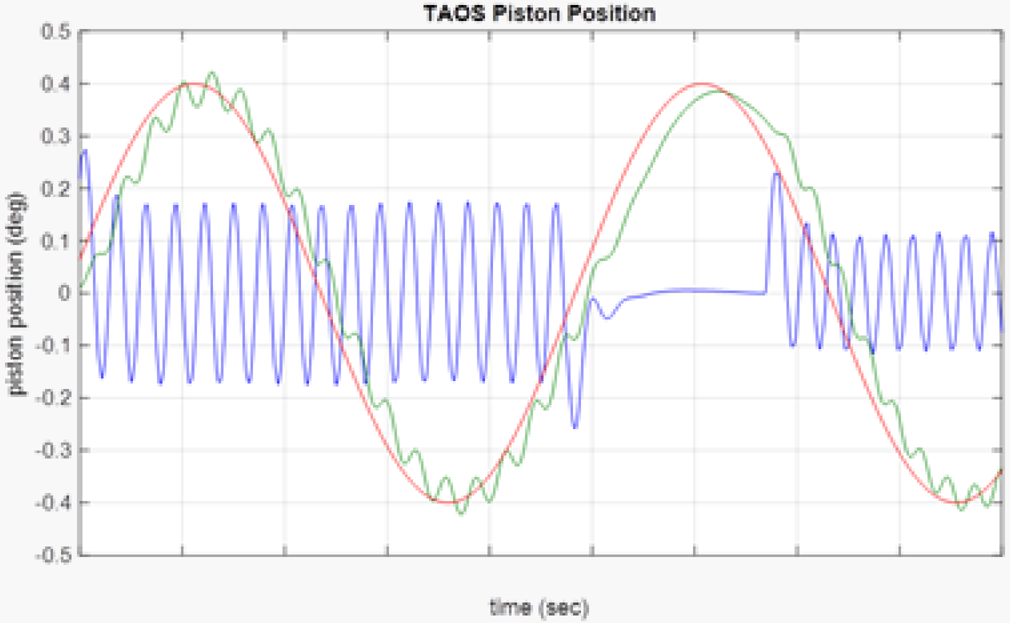


Additional Modeling – Multi-Axis Modeling

- **Multi axis behavior captured with TAOS model**
  - Each axis modeled at the same time and had effects on each other
  - Agreed well with GRHF cross axis behavior
- **Friction models now acted in multiple DoF**
  - Allowed for proper friction maximum and projection (friction vector effect)
  - Measurable friction reduction present in model and data due to this effect

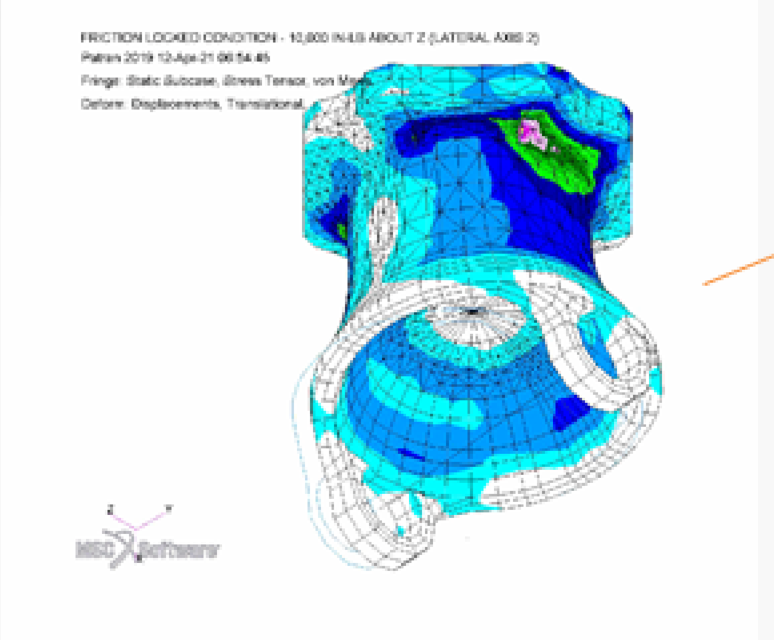


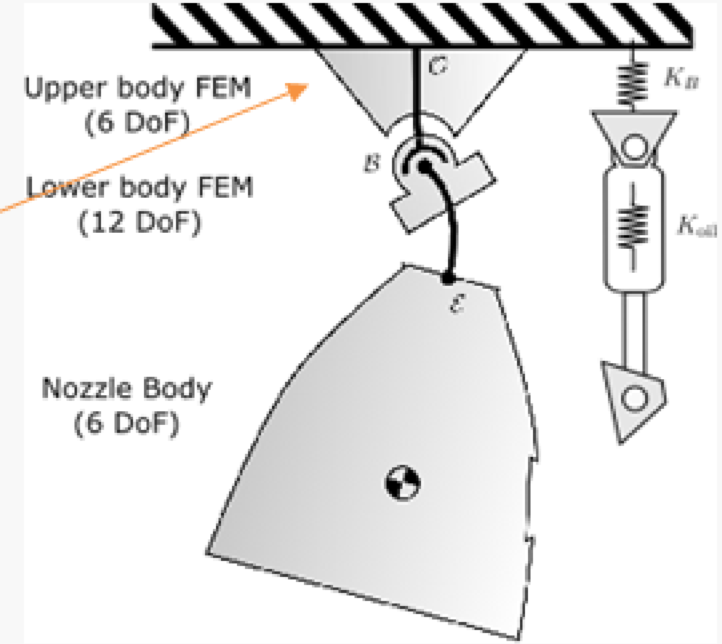

GRHF Piston Position

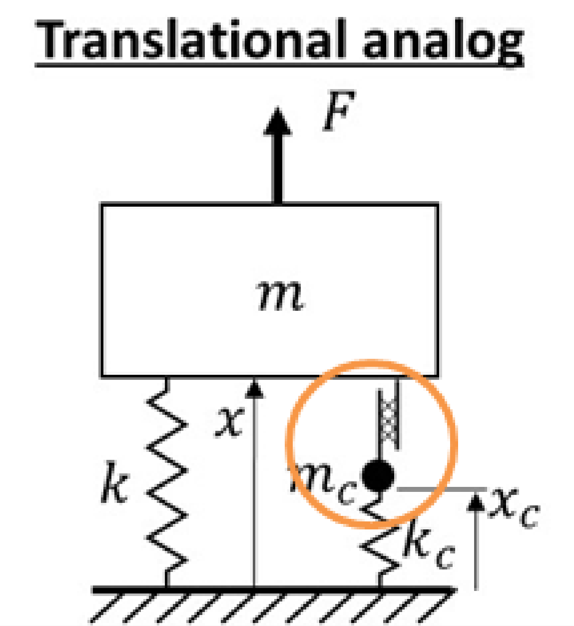

TAOS Piston Position

Additional Modeling – Gimbal Structure

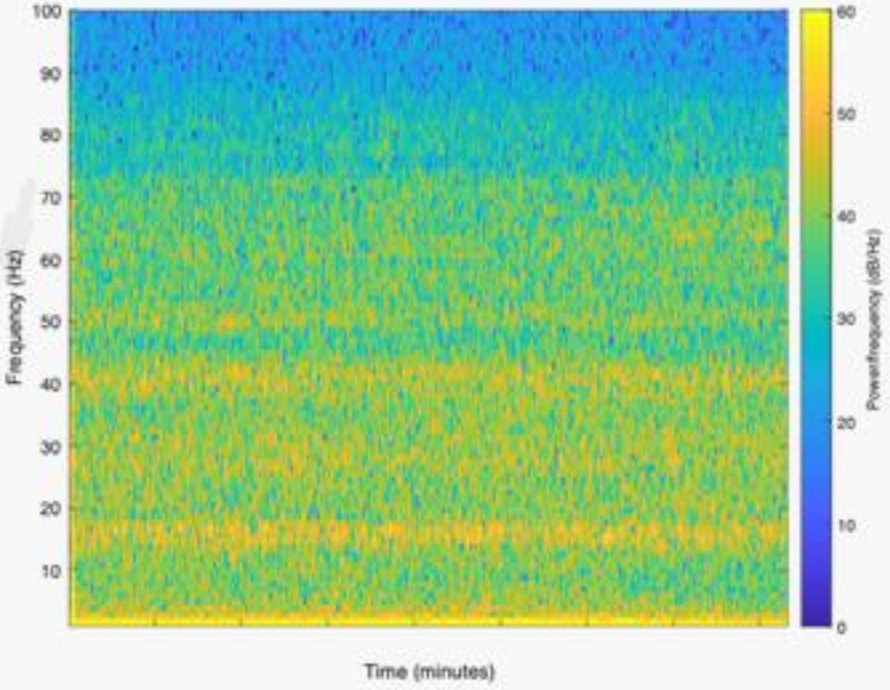
- Gimbal structural compliance now modeled via finite element model (FEM) derived stiffness matrices
  - Additional DoF for gimbal elements modeled as beams
- Gimbal compliance due to thrust and actuator forces
- Friction torque deformations present on both halves of the gimbal
- Actuator stiffness is now variable with position and friction condition
- Actuator force direction and moment arm are not constant

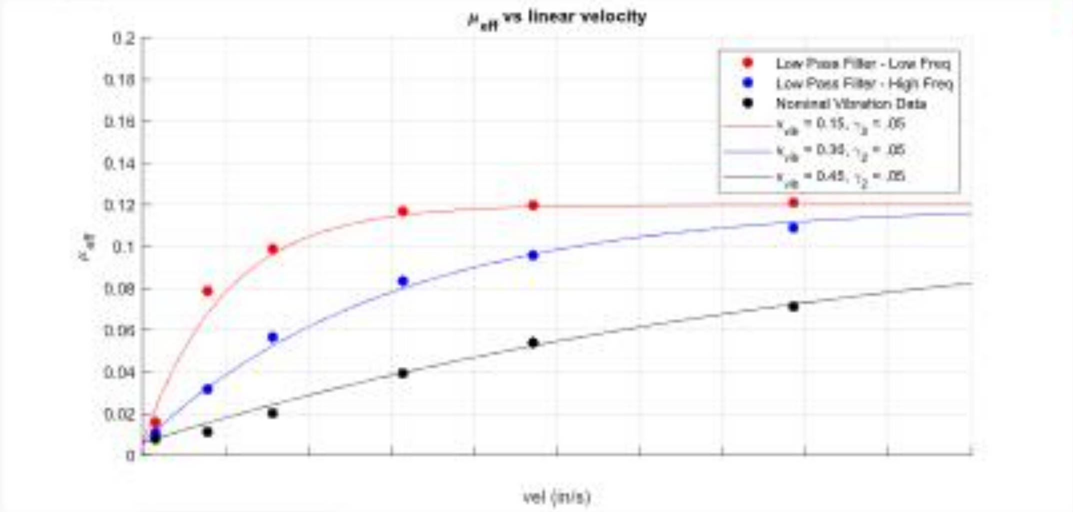






Additional Modeling - Vibration





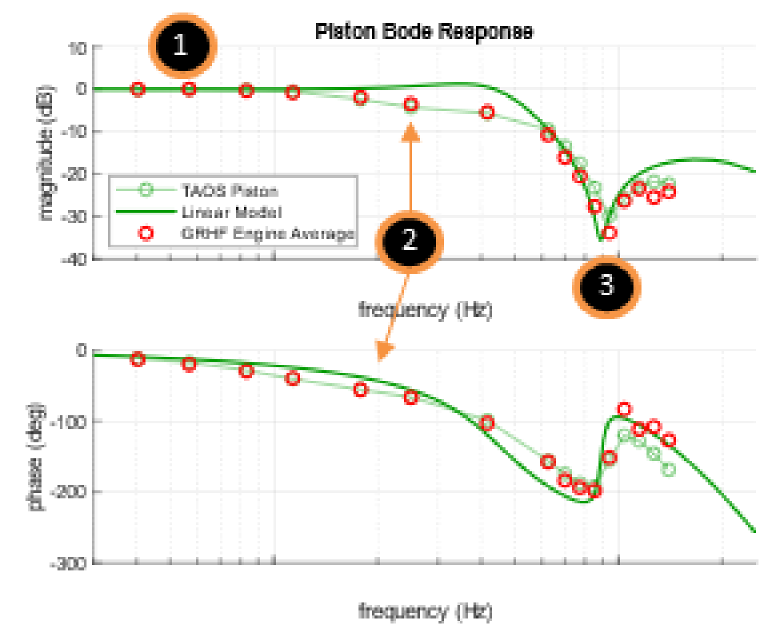
- Friction modeling efforts led to vibration and friction coupled modeling
  - Literature on models is sparse, but experimentation on effects is present [5,6]
  - Experiments show decrease in friction effects at low velocity ranges
- LuGre model simulated with A1 test stand measured force and torque inputs
  - Model shows reduced friction at low velocity
  - Higher frequency content shown to be more important to friction degradation
- Modification to LuGre model implemented to lower friction response at low velocity

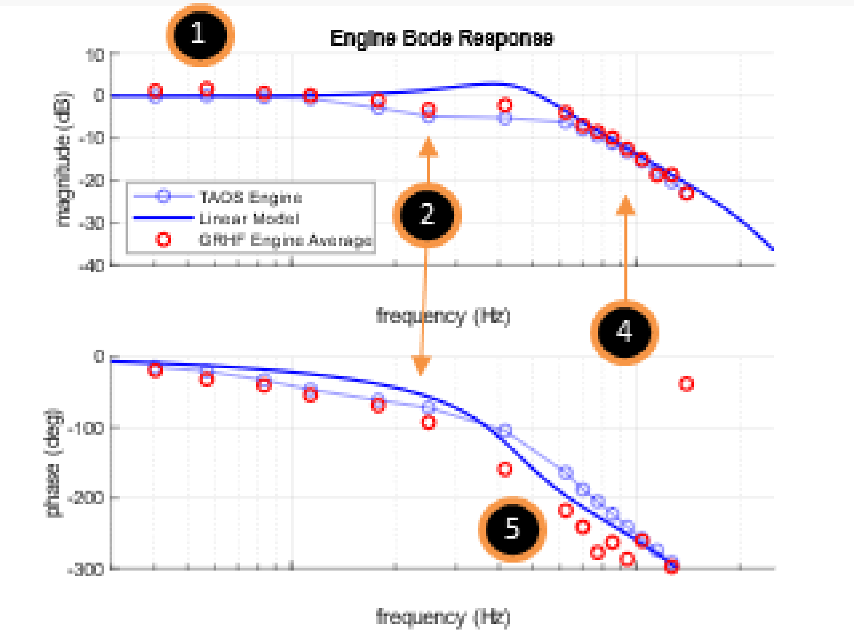
$$F_c = \mu N(1 + (\gamma_2 - 1)e^{-\frac{||\vec{v}||}{v_s}})$$

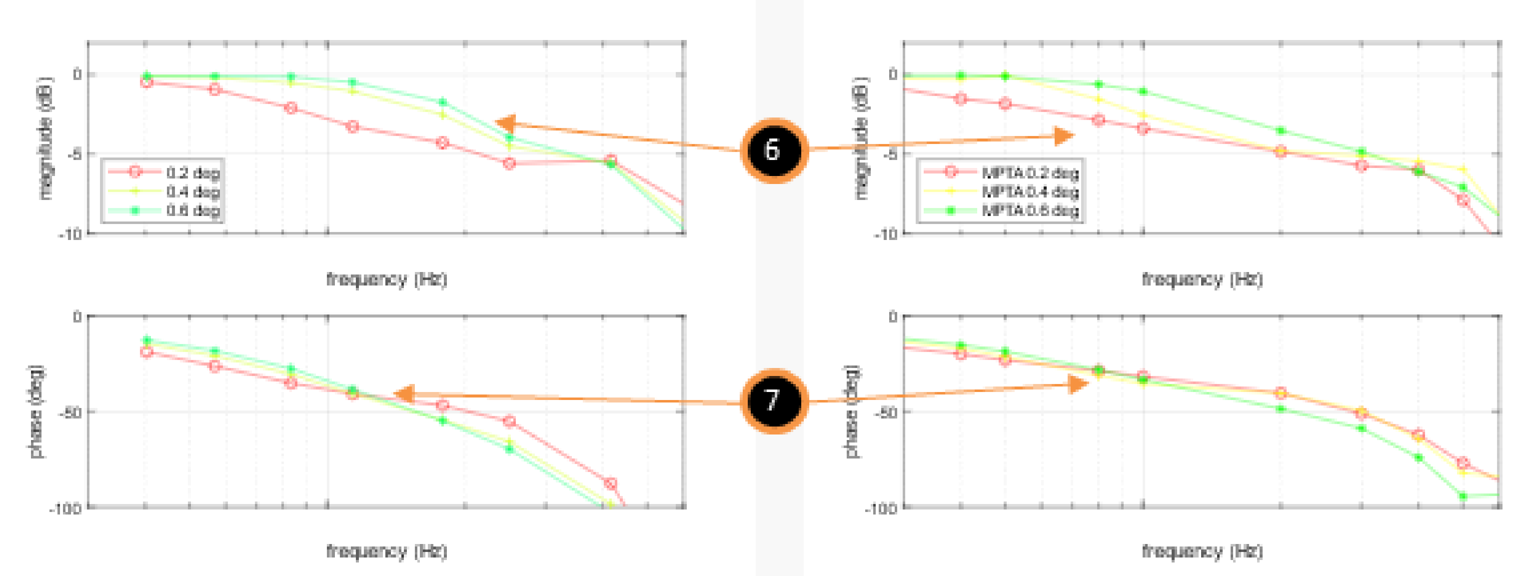
Matching GRHF - Frequency Response

Post model updates agree well with GRHF response:

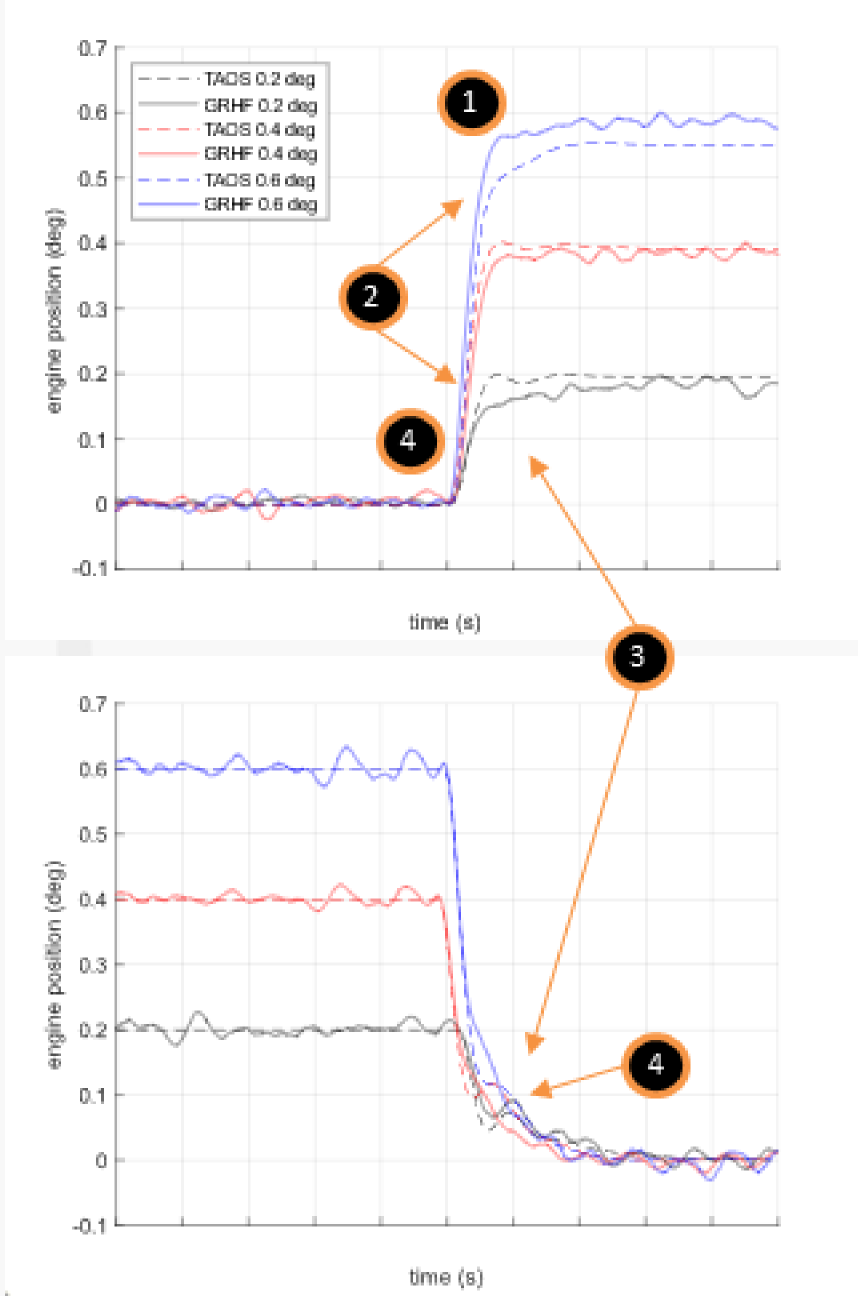
1. Low frequency behavior follows linear model
2. Friction adds gain degradation and phase lag from 1-6 Hz in piston and engine response
3. Piston notch location and approximate gain drop
4. Engine gain response matches well at high frequency
5. High frequency engine phase is affected by structural modes
6. Gain amplitude dependence matches previously observed Shuttle MPTA test
7. Phase amplitude dependence shows similar distribution including amplitude dependent lag-lead swap





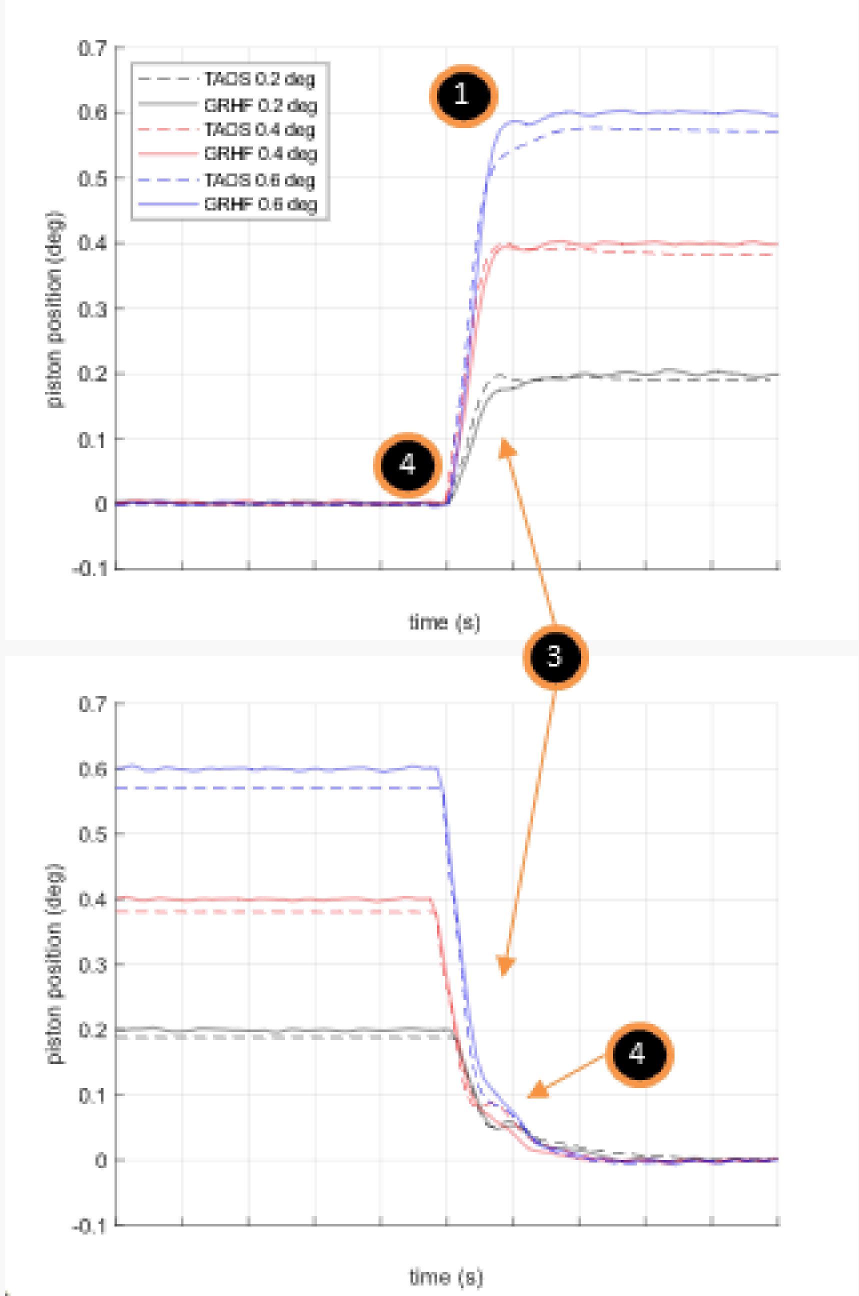


Matching GRHF - Step Response



- Post model updates agree well with GRHF response:

1. Highly damped step characteristic
2. Amplitude dependency in step response
3. Difference in return vs deflect
4. Rise and fall time constant



Final Thoughts

- Demonstrated high fidelity modeling of coupled DoF with a custom tool
  - Additional fidelity over the heritage planar approach
  - Improved test correlation via advanced friction modeling
  - Coupled axis effects and kinematic effects demonstrated with updates

- Frictional Effects on TVC System
  - Decrease in gain response and additional phase lag
  - Amplitude dependent behavior in frequency and step responses
  - Step response appears heavily damped in thrusting case

- Future work
  - Friction model approximations for linear system analysis
  - Further analysis in structural impacts during flight
  - Possible control architecture design to reduce or remove burden of friction in flight

Backup: References

1. Gerstner, B. A., “MPT Engineering Analysis Second Interim Report Static Firings S/F-5A Through S/F-12” Rockwell Report STS 81-0254, May 1981.
2. Wall, J., et al., “Design, Instrumentation, and Data Analysis for the SLS Core Stage Green Run Test Series,” AAS 23-156, American Astronautical Society Guidance, Navigation, and Control Conference, February 2023.
3. Dahl, P. R., “Solid Friction Damping of Mechanical Vibrations,” AIAA Journal, vol. 14, no. 12, pp. 1675-1682, 1976.
4. C. C. de Wit, H. Olsson, K. J. Astrom and P. Lischinsky, "Dynamic Friction Models and Control Design," in 1993 American Control Conference, pp. 1920-1926, 1993.
5. Popov, M. and Qiang, L., “Multi-mode Active Control of Friction, Dynamic Ratchets and Actuators,” Phys Mesomech, vol. 20, no.5, pp. 26-32, 2017.
6. Wang, P., Ni, H., Wang, R., Liu, W., and Lu, S., “Research on the Mechanism of In-Plane Vibration on Friction Reduction,” Materials, vol. 10, no. 9, 2017.