National Aeronautics and Space Administration

SPACE LAUNCH SYSTEM

George C. Marshall Space Flight Center

Modeling and Test of Space Launch System Core Stage Thrust Vector Control

Jeb S. Orr, Ph.D. / Draper (Jacobs ESSSA)
MSFC Control Systems Design and Analysis Branch (EV41)

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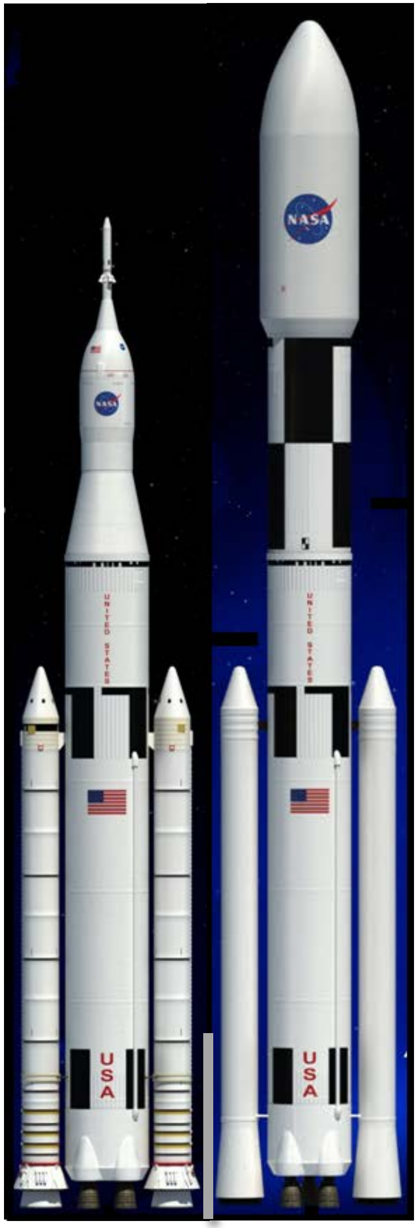
Introduction

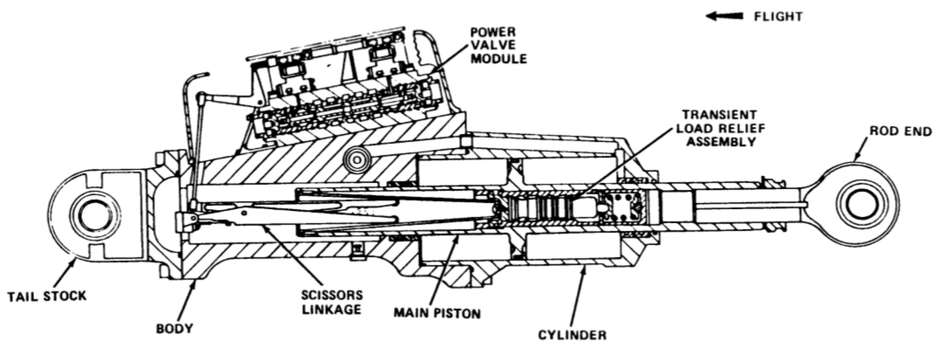
- **Space Launch System (SLS)**
  - NASA-developed launch vehicle for large-scale (exploration-class) crew and cargo access
  - Shuttle-derived hardware and processes leveraging Constellation program development experience (tanks, engines, boosters)
  - Primary development configurations are 70t crew (Block I) and 130t cargo (Block II)

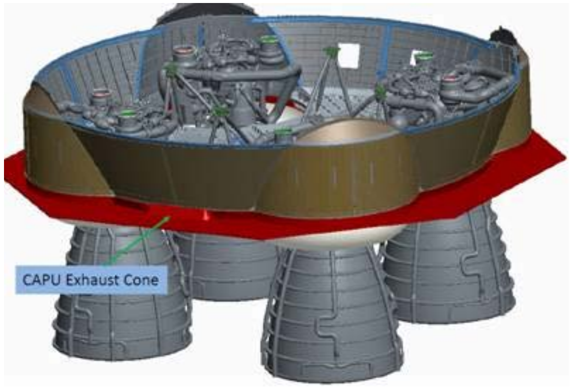
- **SLS Thrust Vector Control (TVC) Actuators**
  - SLS uses a total of 12 TVC DoF (boost phase) and 8 TVC DoF (core phase)
  - TVC performance is critical for stability, loads, and integrated vehicle control
  - A novel approach to analysis and test has been undertaken to verify and validate TVC models used for flight dynamics and control design



Heritage TVC System Considerations

- **SLS TVC actuators are Shuttle heritage**
  - Quad-redundant, mechanical feedback hydraulic actuator
  - Closed-circuit hydraulic power provided by redundant APUs
    - GHe (core stage), hydrazine (booster)
  - Robust dynamic pressure feedback (DPF) provides active load damping over a wide range of load resonances
  - **Core stage structure, interfaces, hydraulic support system, and TVC Actuator Controller (TAC)** are a new design
  - There exists a need to update and certify existing high-fidelity models prior to flight

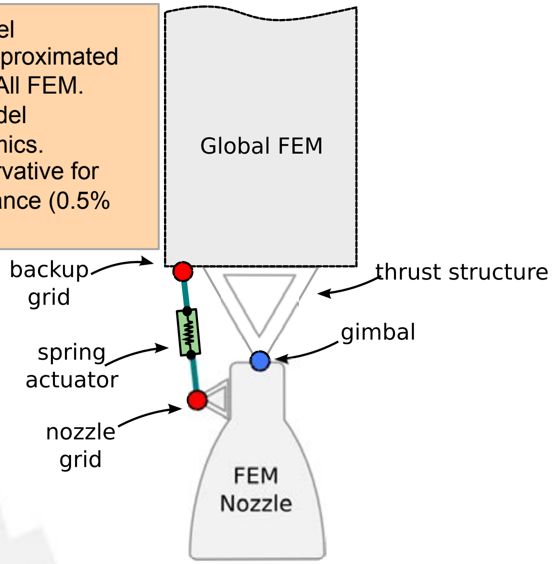


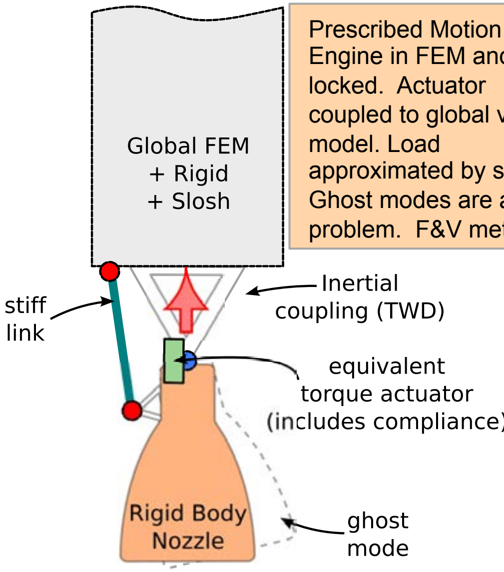


SLS combines a novel modeling approach with preflight testing to anchor model predictions

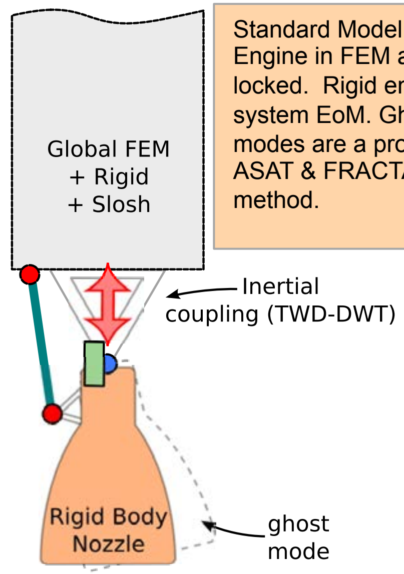
Modeling Methods

Loads Model
Actuator approximated by spring. All FEM. Cannot model servodynamics. Overconservative for load resonance (0.5% damping).





Prescribed Motion
Engine in FEM and locked. Actuator coupled to global vehicle model. Load approximated by spring. Ghost modes are a problem. F&V method.

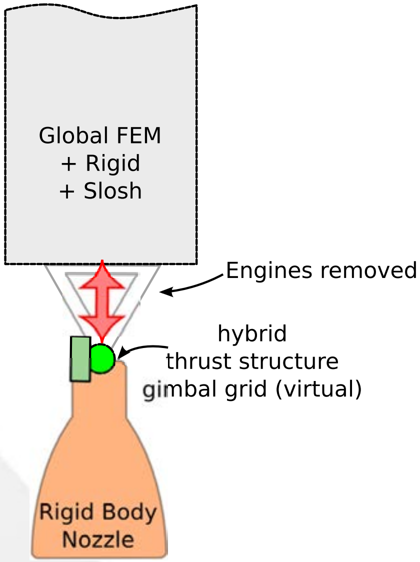


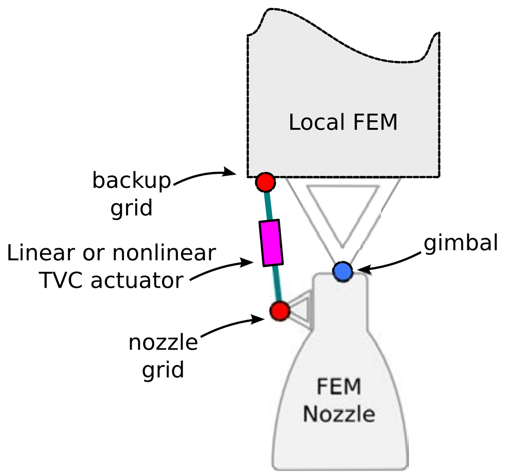
Standard Model
Engine in FEM and locked. Rigid engine in system EoM. Ghost modes are a problem. ASAT & FRACTAL 1 method.

Traditional Methods

New Methods

Reduced Body Model
Engines removed from FEM. Load approximated by spring. Good approximation for global vehicle dynamics. Ghost modes eliminated. FRACTAL 2 method.





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

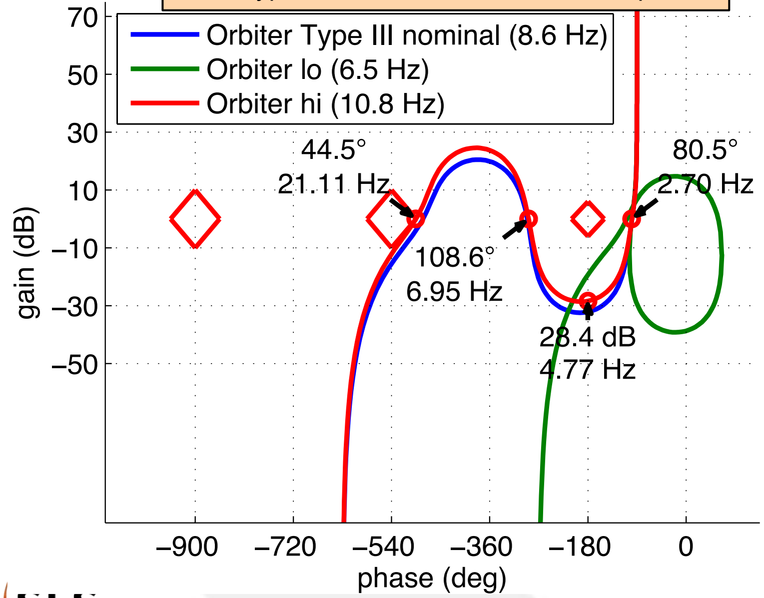
Motivation for Detailed Modeling

- **The STS SSME TVC actuator is robust to load resonance variations within the Orbiter design range**
  - The single-spring load resonance frequency is given by $\omega = \sqrt{\frac{(K_n + K_T R^2)}{J_n}}$

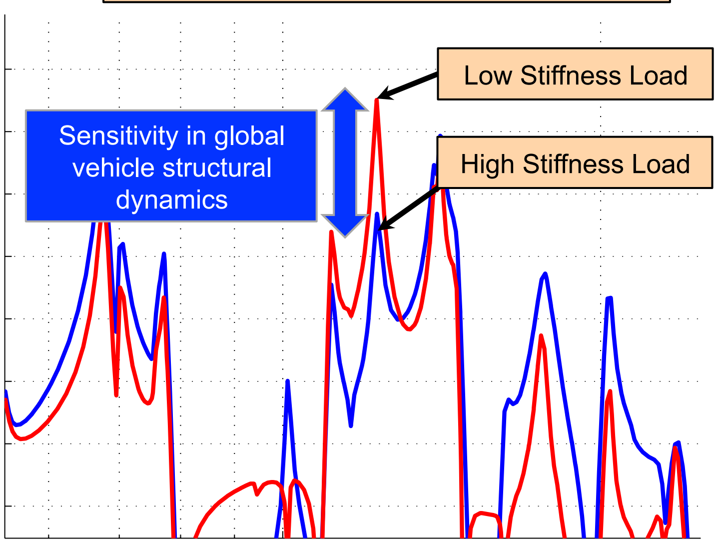
    where $K_n,\ K_T$ are the nozzle angular and total linear system stiffness, R is the actuator moment arm, and J_n is the engine inertia

- **The servoactuator DPF network phase stabilizes the load resonance (active damping)**
- **Analysis shows sensitivity to values outside of the Orbiter load frequency range**
  - Stability of the actuator (inner loop) is affected – linearization of DPF may not be accurate
  - SLS FCS uses advanced servoelastic feedback model to aid in global bending stabilization

Typical **Shuttle Orbiter** Inner Loop

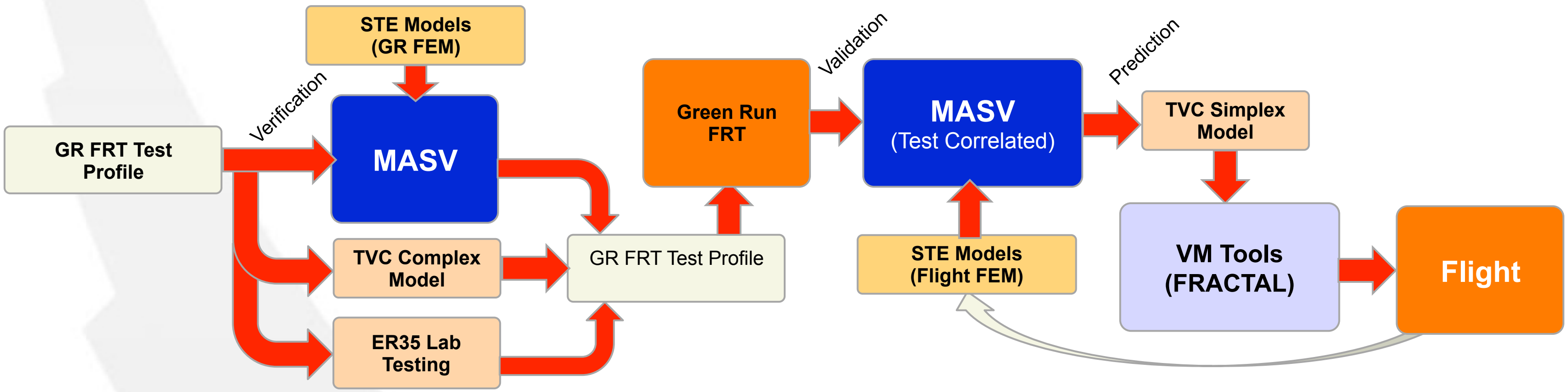


SLS Autopilot Open Loop Response (typ.)



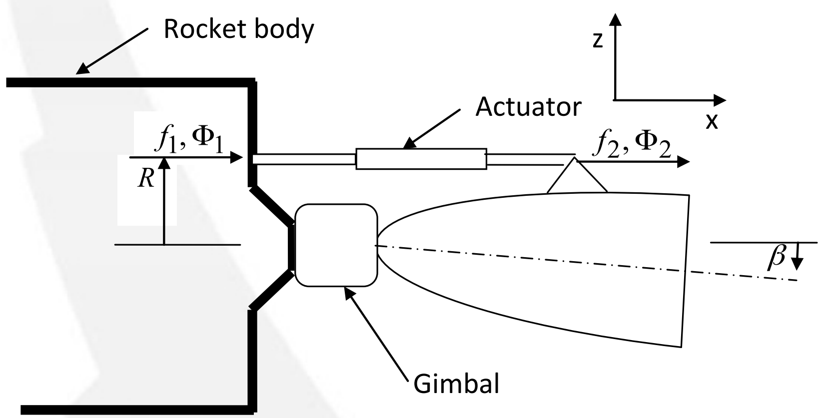
TVC Model V&V Using MASV

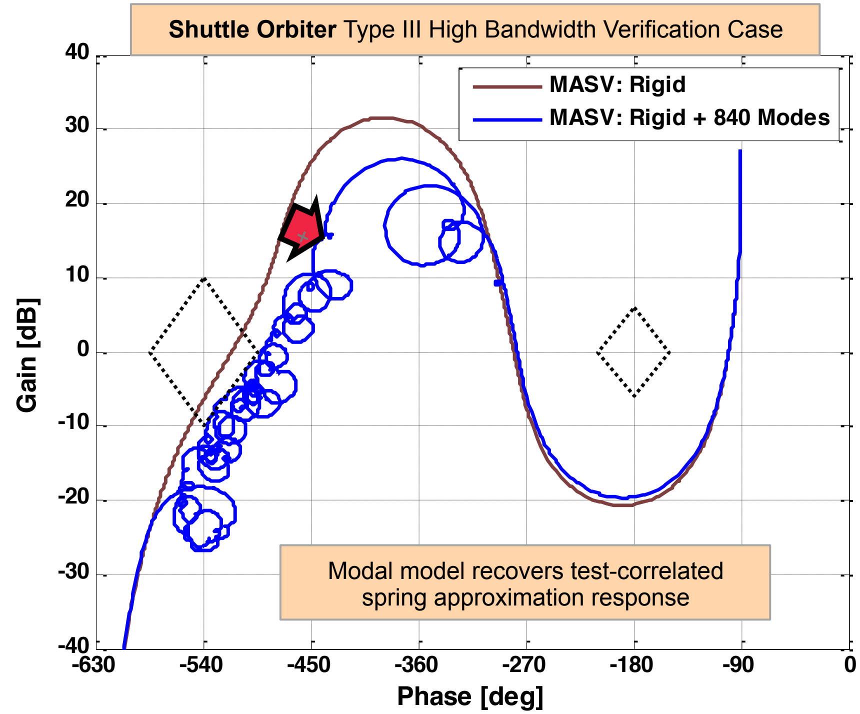
- **Multiple Actuator Stage Vectoring (MASV) Model**
  - Developed by Draper to improve modeling of interactions between TVC servodynamics and local structure
  - Reduce risk and increase understanding of core stage TVC dynamics
  - Verify TVC performance and stability using high-fidelity structural response
    - Eliminate single-spring approximation of load compliance
  - Used along with "Complex" single-axis model and 2-axis ILS (lab testing) to *verify* TVC FRT test procedure (excitation and data recovery)
  - MASV *validated* using GR FRT data and used to parameterize VM Simplex model (*prediction*)



Multiple Actuator Stage Vectoring (MASV) Model

- **Approach**
  - Engine dynamics are replaced with a high-fidelity modal representation of the core stage thrust structure
  - Allows coupling of multiple actuators with a single set of dynamic modes
  - A partitioning procedure is used to identify and group generalized coordinates that do not contribute to dynamic response to reduce the number of DoF

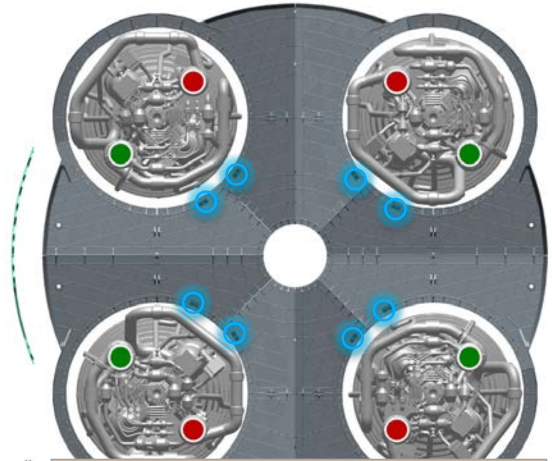




Frequency Response Testing

- **FRT is necessary to characterize TVC behavior in flight-like boundary conditions**
  - Space Shuttle Orbiter used a dedicated test article (MPTA) and an extensive test program to reduce TVC modeling uncertainty
    - 12 static firings from 1978-1981
- **SLS will execute a limited test on flight hardware at the Core Stage Green Run (GR)**
  - Determine frequency response and transient response of the coupled actuator-structure system in hot-fire conditions
  - 120 second test window at 109% PL
  - Instrumented using existing flight piston position TM sensors and drag-on string potentiometers
  - Testing reproduces boundary conditions and effects that are difficult to model & predict accurately, especially coupling, gimbal friction, oil air entrainment, thermal drift, etc.

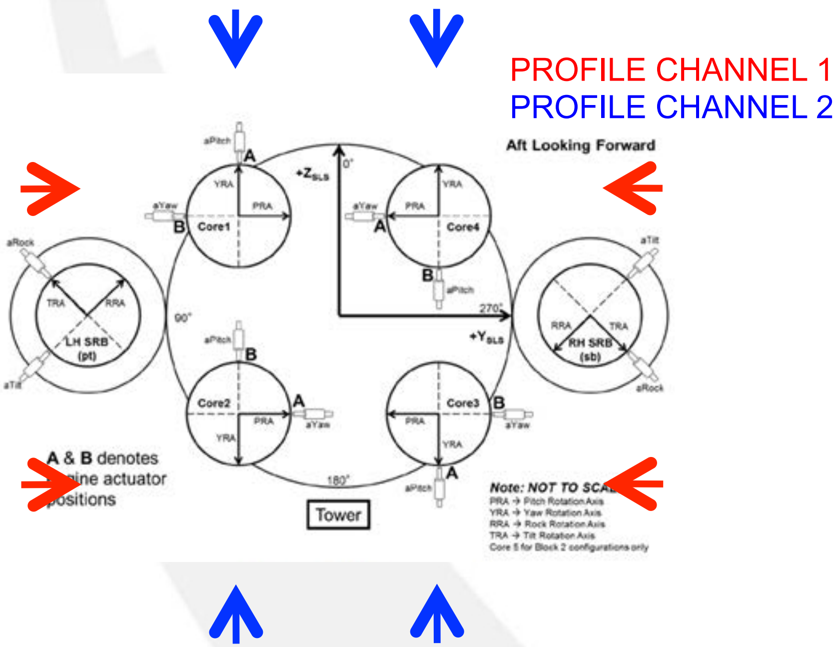
TRSD MATRIX	Page 1	4/20/81
TRSD Paragraph and Test Requirement		Test Number Duration(sec) Thrust(%) Gimbal POGO Engine Out
TDS 5.1.1 TVC Performance Evaluation		
1. Sinusoidal Engine Gimballing		
- 0.2° Amplitude		
- 0.4 degrees amplitude		
- 0.6 degrees amplitude		
2. Step Response		
3. Ramp Response		
4. Stroking Response		
5. Flight Profile		
6. Simultaneous Engine Gimballing/Throttling		
7. Routine Engine Positioning/SSME Side Load Evaluation		
8. Engine Clearance Checks (Non-Firing)		
9. Hydraulic Power Failure Simulation (Non-Firing)		
10. TVC Channel Failure Simulation		
11. Halting Ramp Response		
12. Simultaneous Gimballing annd POGO		

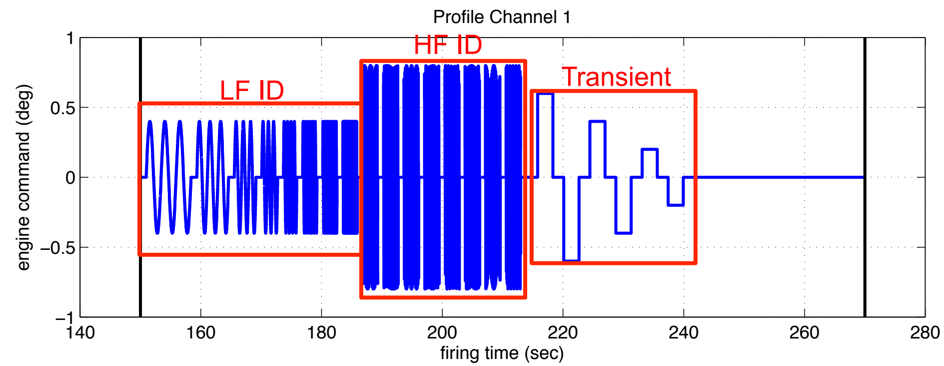


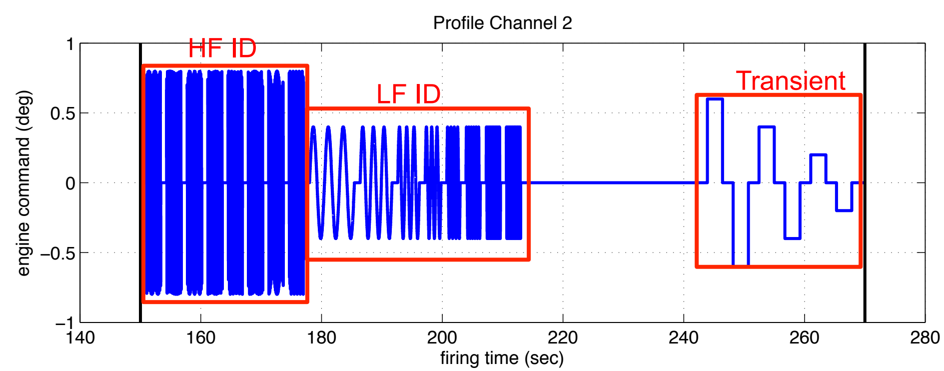
Instrumentation locations on base heat shield

FRT Profile Design

- **FRT profile is executed in the thrust vector null space of the CSEs**
  - Profile results in no net *commanded* off-axial loads on the stage structure
  - Some small loads will result due to non-ideal tracking of the commands, stage structural dynamics/asymmetry, actuator/engine variability
  - Commanded in two channels (null pitch, null yaw) @ 50 Hz, 120 sec, 109% PL
  - Low-frequency and high-frequency ID on each engine on orthogonal DoF
  - Transient ID (varying amplitude step response) on each channel

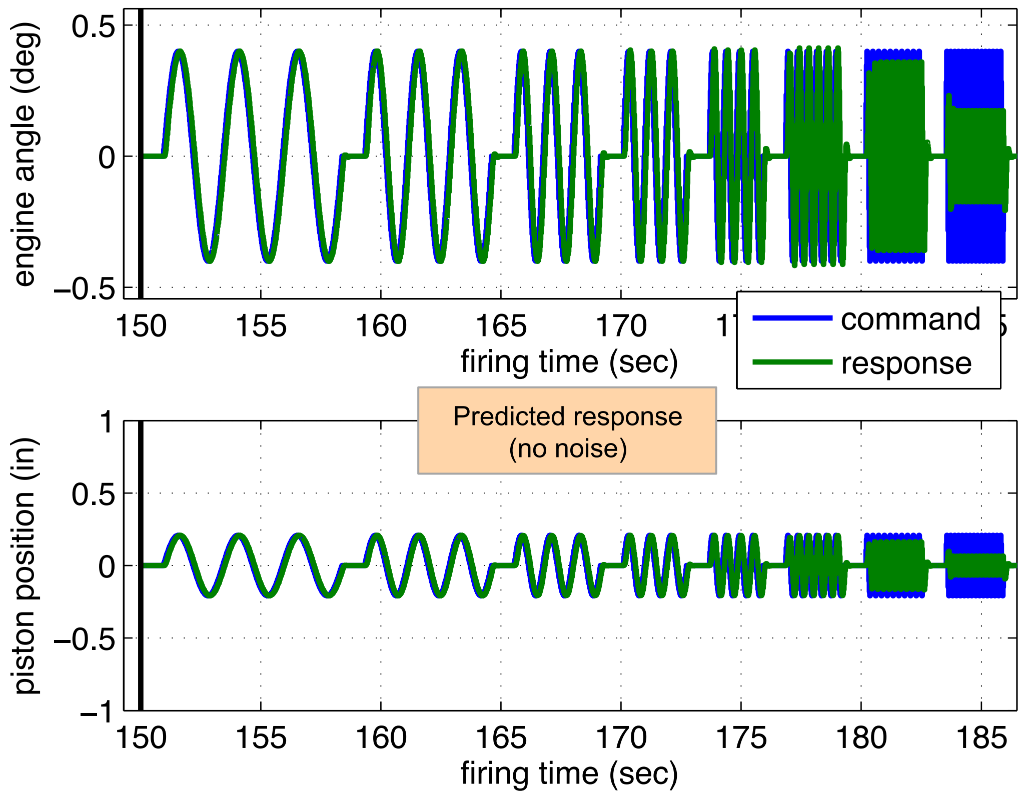






Low Frequency ID

- **All maneuvers are individual sinusoids with start-stop buffers of 3 settling periods**
  - Minimum of 3 periods or 8 setting times, whichever is longer
  - Enables frequency domain recovery using least squares, much more accurate than FFT with sine sweep in noise environment if command profile is known
  - Multisine cannot be easily mechanized with null constraint and system is **not** linear
- **Low frequency ID maneuver consists of 8 sample-aligned frequencies (log spacing)**
  - Reach full command amplitude (quarter-period alignment) @ 0.4 deg Z-T-P (STS MPTA)
  - There are no sample-aligned frequencies between 6.25 and 12.5 Hz @ 50 Hz rate



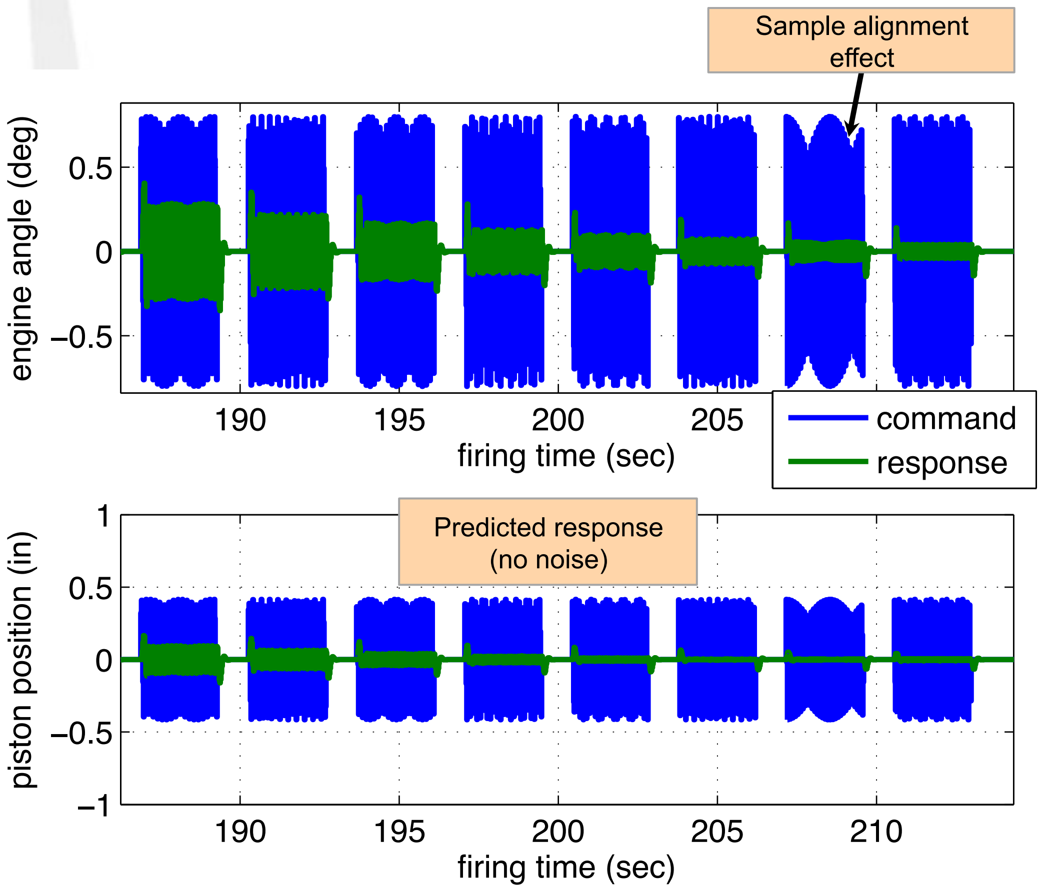
Channel 1 (Hz)	Channel 2 (Hz)
0.40-6.25 Hz increasing	7.0-14.0 Hz increasing

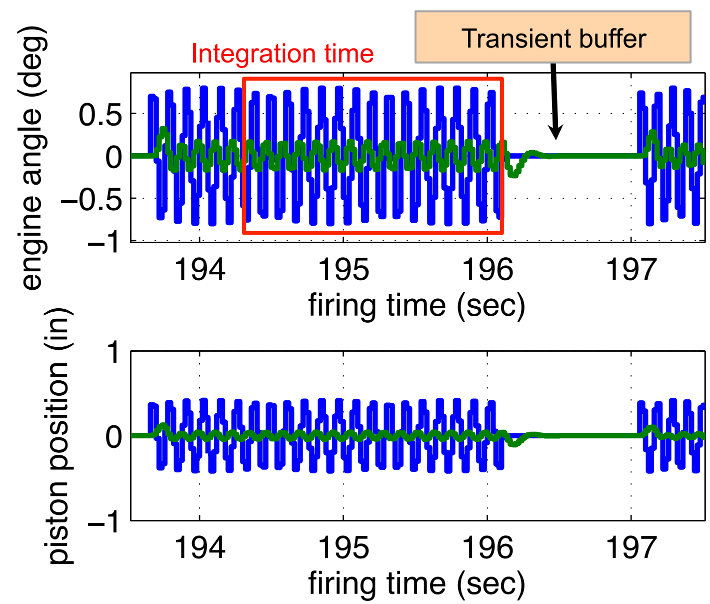
Concurrent testing on coupled axes is possible through frequency separation since single-component frequency-domain LSQ is used for signal recovery

High Frequency ID

- **High frequency ID maneuver consists of 8 non-sample-aligned frequencies**
  - Log spacing from 7 Hz-14 Hz (bounds predicted nominal closed-loop load frequencies with ~25%-30% margin)
  - Command amplitude increased to 0.8 deg Z-T-P to increase SNR on piston measurement

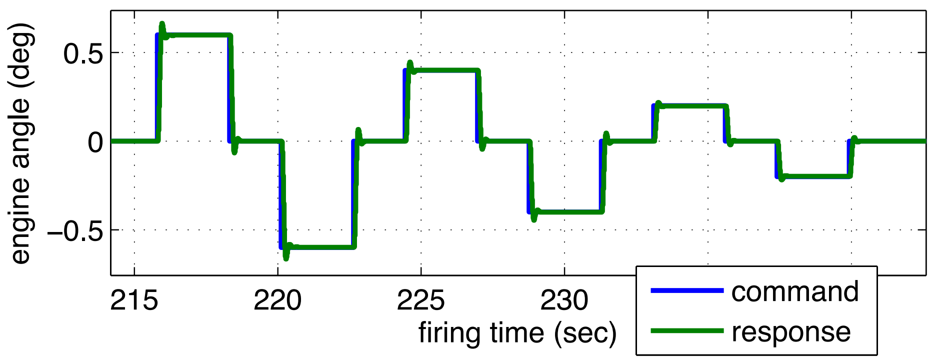
Channel 1 (Hz)	Channel 2 (Hz)
7.0-14.0 Hz increasing	0.40-6.25 Hz increasing

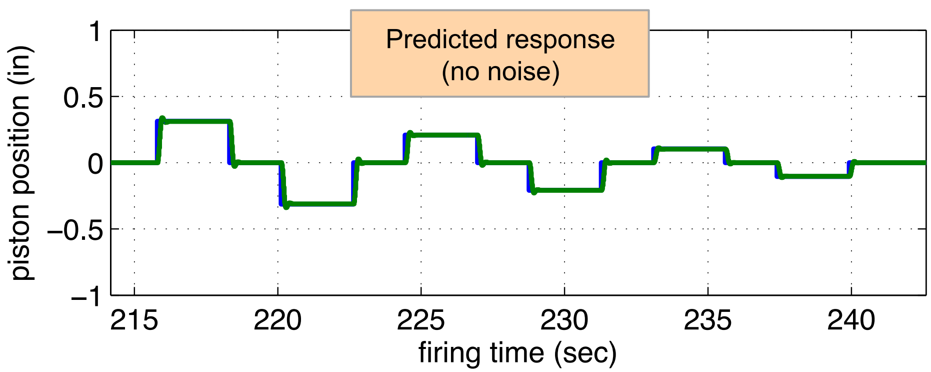


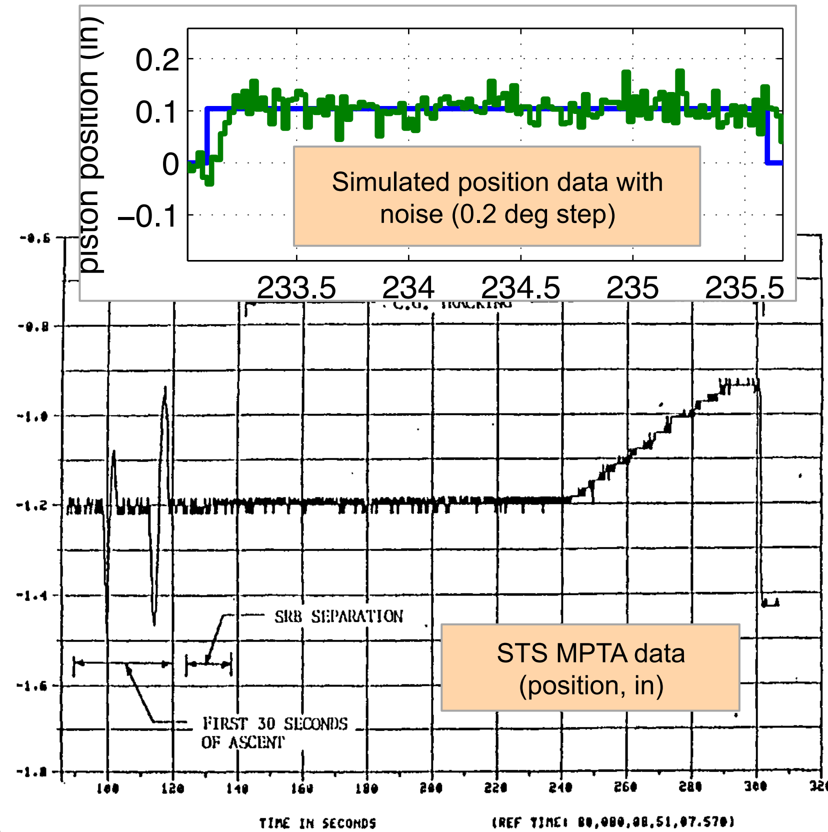


Transient ID

- **Transient ID maneuver consists of 3 positive and negative steps at 0.2, 0.4, and 0.6 degree amplitude**
  - Similar procedure to STS; Opposite channel is quiescent during step
  - 6 settling times between steps (~2 seconds) and 2.5 second persistence time
  - Evaluate cross-axis coupling, load effects, push-pull symmetry, amplitude nonlinearity, bias, scale factor error, drift
  - Limited resolution/quantization/noise can limit utility of steps at very small amplitudes







Data Processing

◆ **Frequency-domain reconstruction using a describing function-like approach**

- Given an unknown SIS(M)O nonlinear system described by

$$\dot{z} = f(z, u)$$
$$q = h(z, u) + n$$

with a known input $u = A \sin \omega t$ and stochastic noise *n*, an estimate of the linear frequency response (first harmonic, dependent on amplitude *A*) is computed from

$$|N| = \frac{\sqrt{a_1'^2 + b_1'^2}}{A} \qquad \angle N = \tan^{-1}\left(\frac{a_1'}{b_1'}\right)$$

using the Fourier coefficients (*k*=number of integration periods)

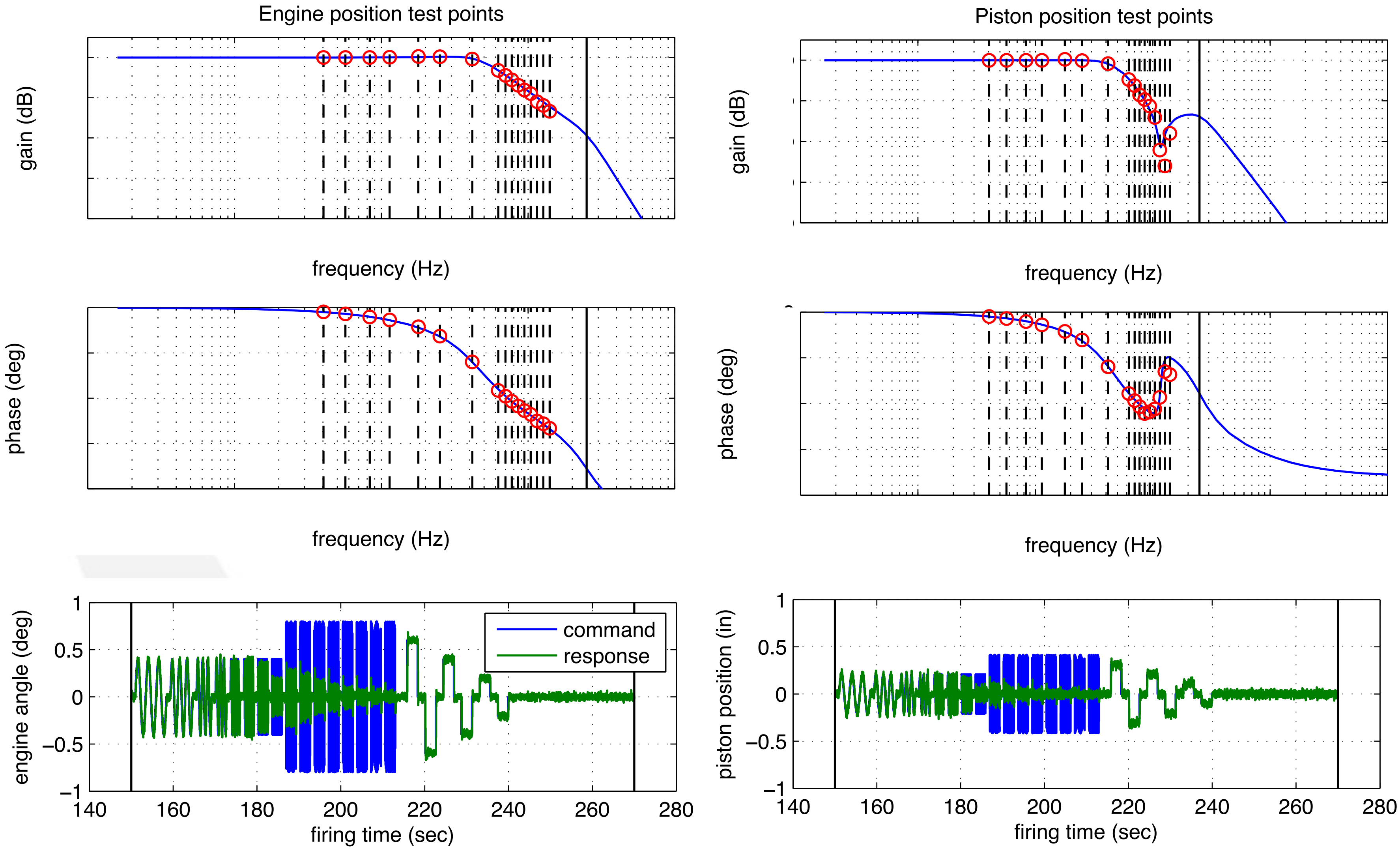
$$a_1' = \frac{2}{kT}\int_{-kT/2}^{kT/2} q(t)\cos(\omega t)\ dt$$

$$b_1' = \frac{2}{kT}\int_{-kT/2}^{kT/2} q(t)\sin(\omega t)\ dt.$$

- Implemented in discrete time using 50 Hz trapezoidal integration.
- Correction for ZOH delay is applied to post-processed complex arrays.

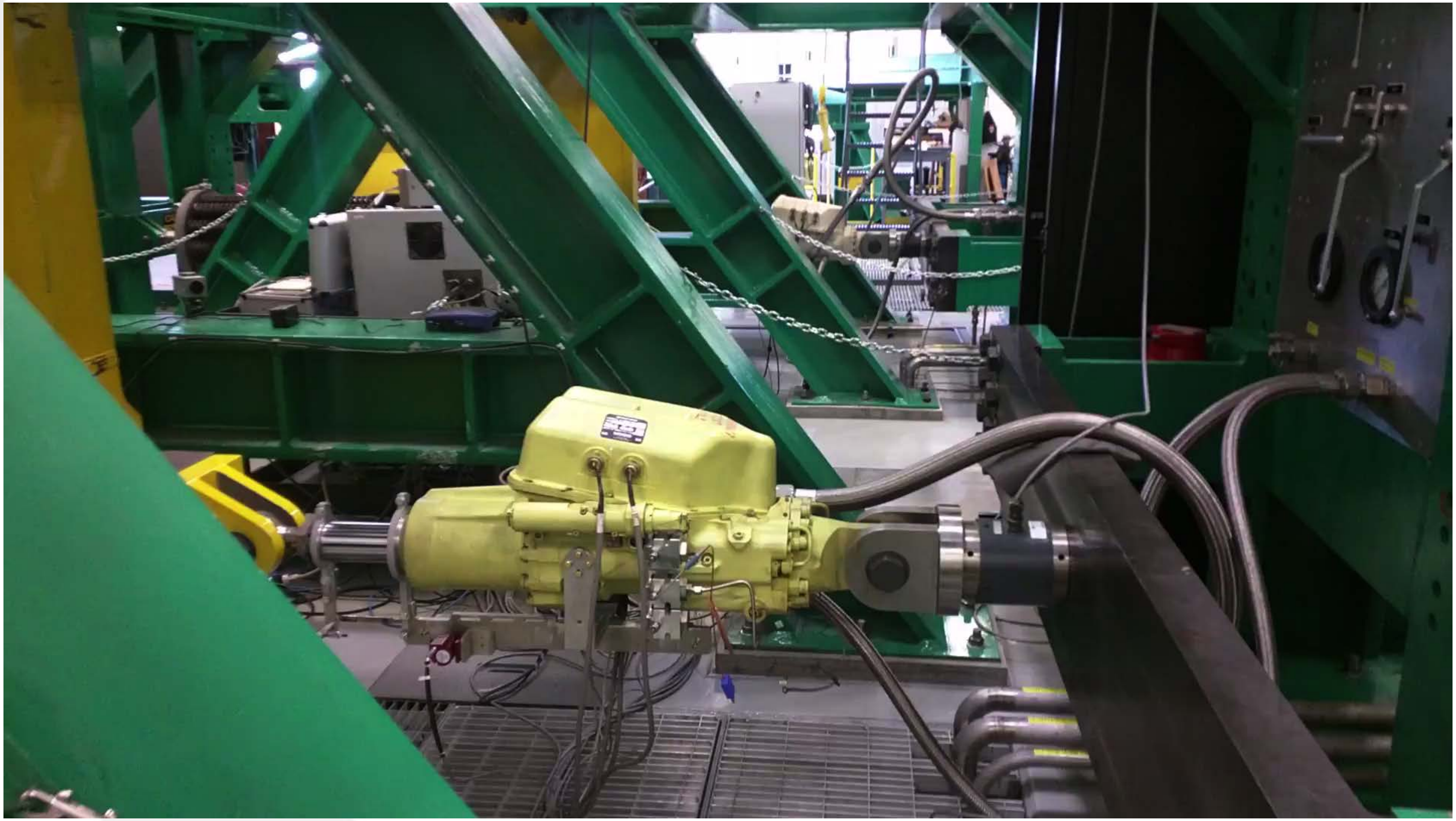
Frequency ID Results

- Good frequency ID of engine position and load resonance is possible with noise and quantization error



Lab Testing

- Test profile verification on the MSFC SSME TVC Inertial Load Stand



Summary

- The SLS Program has leveraged a unique combination of advanced analysis techniques and testing to validate TVC models for flight
- Flight control stability and performance is assured with high confidence based on extensive flight experience with high performance NASA heritage hydraulic actuators
- Test and performance data collected throughout this effort will directly support flight certification as well as post-flight reconstruction and anomaly resolution