

A photograph of a Space Launch System (SLS) rocket being launched from the launch pad. The rocket is orange and white, with a large plume of fire and smoke at the base. The launch pad structure is visible on the left and right sides. The sky is blue with some clouds.

# SPACE LAUNCH SYSTEM

George C. Marshall Space Flight Center

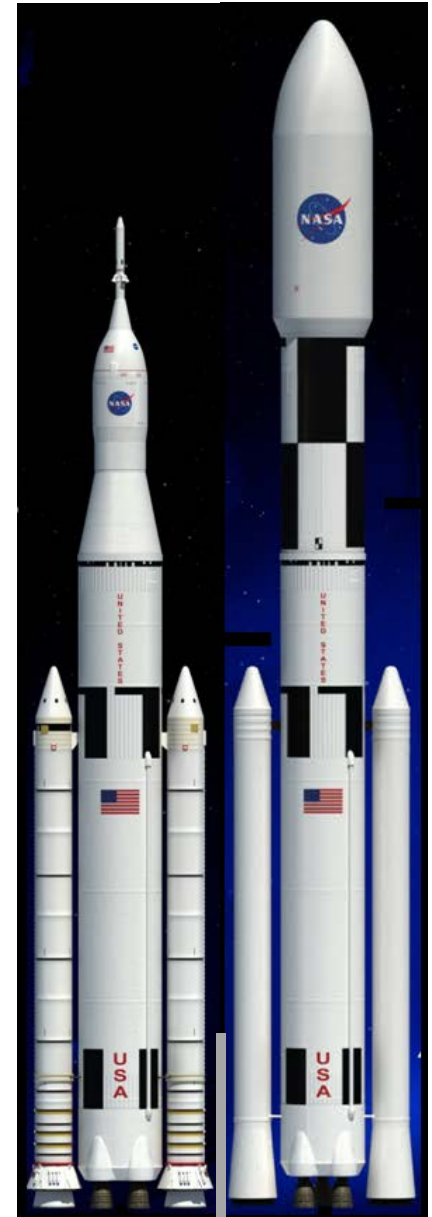
## Modeling and Test of Space Launch System Core Stage Thrust Vector Control

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MSFC Control Systems Design and Analysis Branch (EV41)**

Aerospace Control and Guidance Systems Committee Meeting 116  
March 15-18, 2016

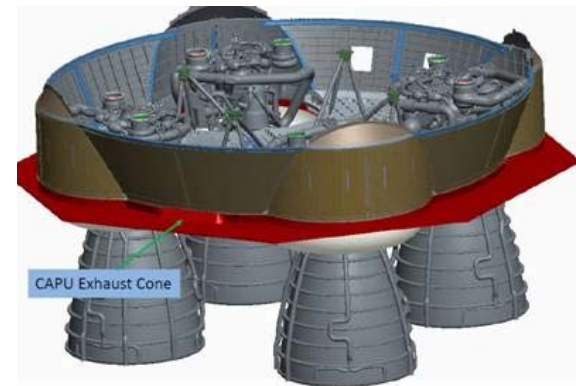
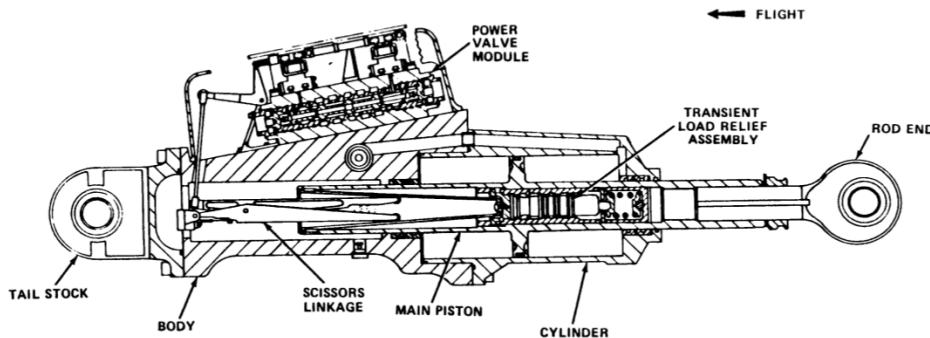
# Introduction

- **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

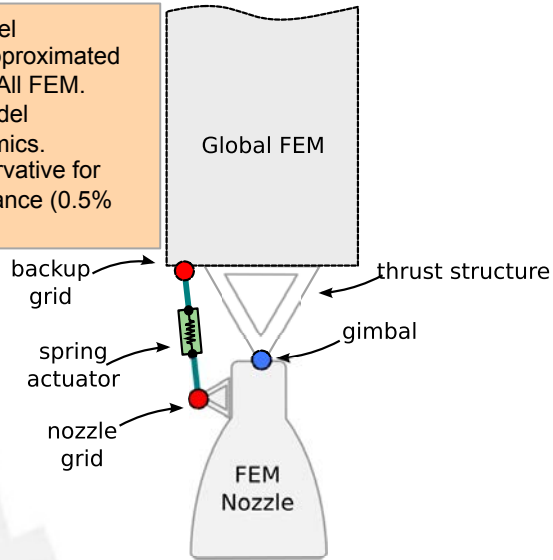
- **SLS TVC actuators are Shuttle heritage**
  - Quad-redundant, mechanical feedback hydraulic actuator
  - Closed-circuit hydraulic power provided by redundant APUs
    - GHe (core stage), hydrazine (booster)
  - Robust dynamic pressure feedback (DPF) provides active load damping over a wide range of 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



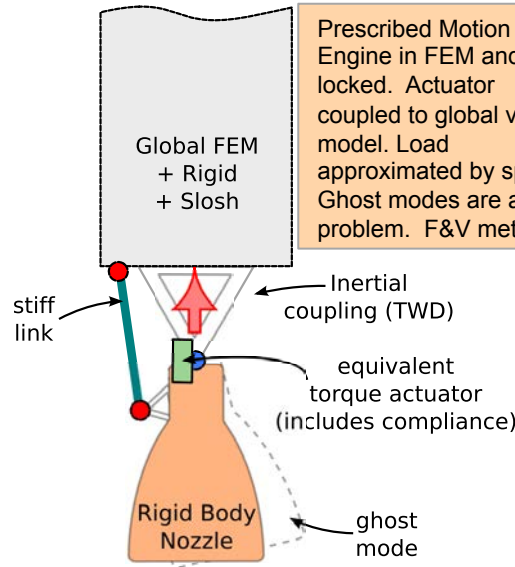
**SLS combines a novel modeling approach with preflight testing to anchor model predictions**

# Modeling Methods

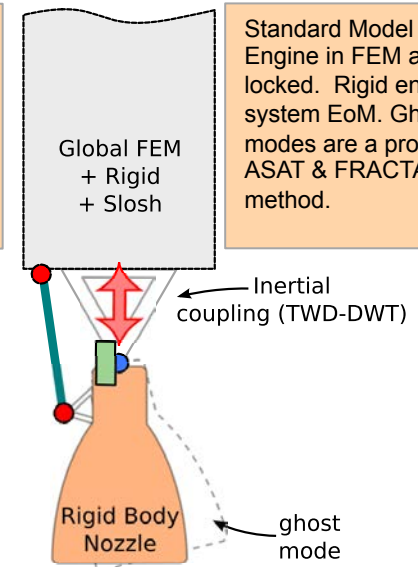
Loads Model  
Actuator approximated by spring. All FEM. Cannot model servodynamics. Overconservative for load resonance (0.5% damping).



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.



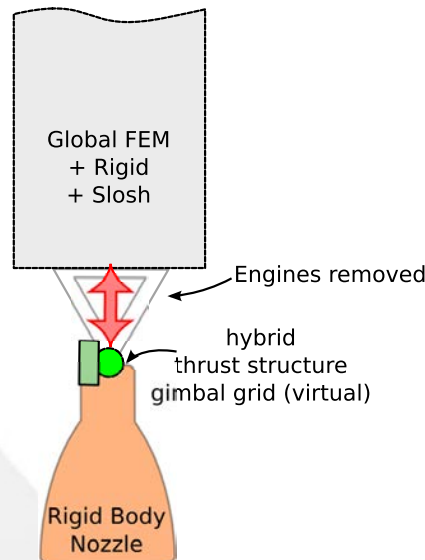
Standard Model Engine in FEM and locked. Rigid engine in system EoM. Ghost modes are a problem. ASAT & FRACTAL 1 method.



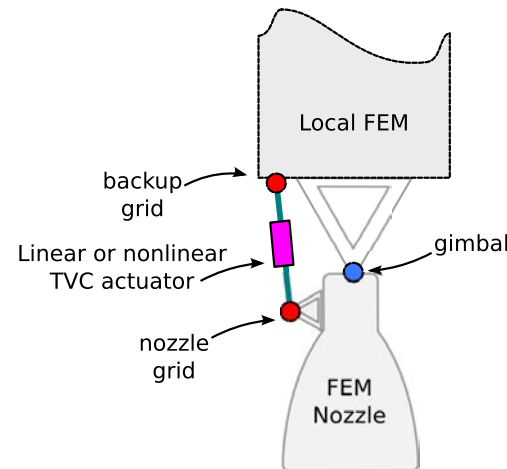
Traditional Methods

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.



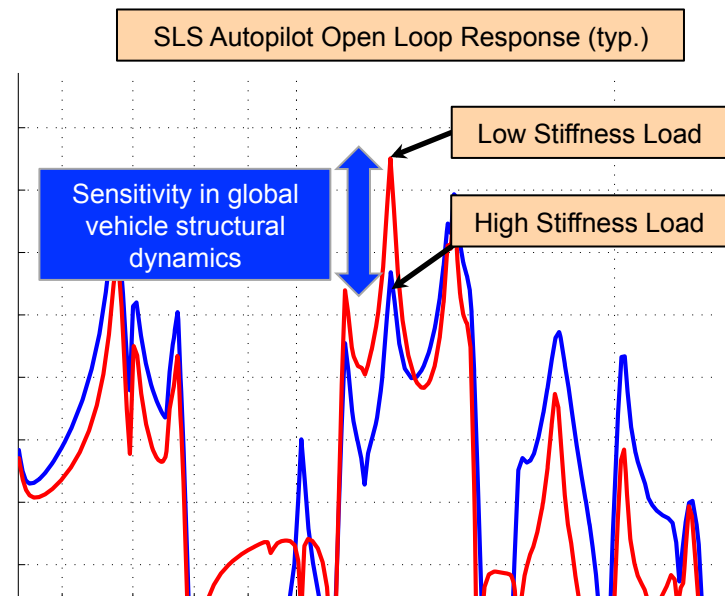
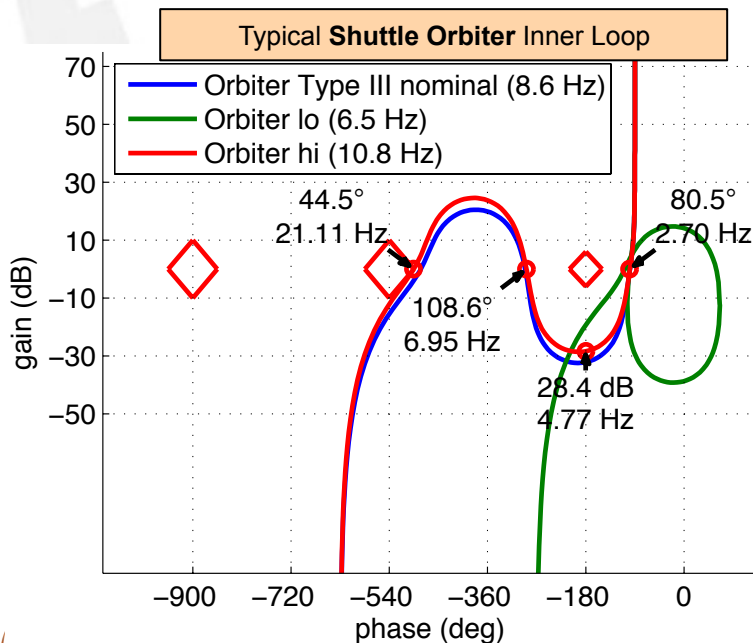
# Motivation for Detailed Modeling

- ◆ 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

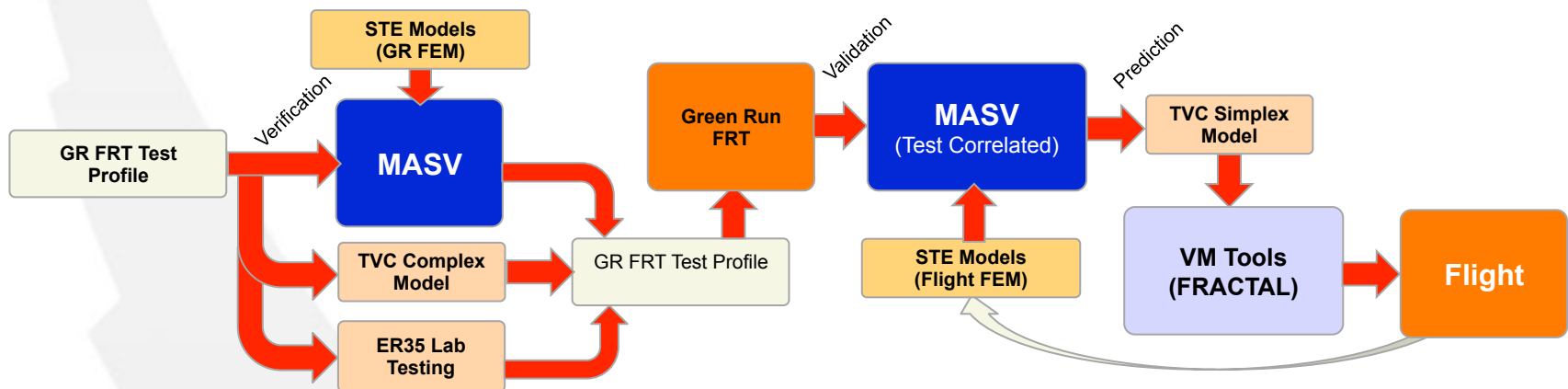
- ◆ The servoactuator DPF network phase stabilizes the load resonance (active damping)
- ◆ Analysis shows sensitivity to values outside of the Orbiter load frequency range
  - Stability of the actuator (inner loop) is affected – linearization of DPF may not be accurate
  - SLS FCS uses advanced servoelastic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



# 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*)

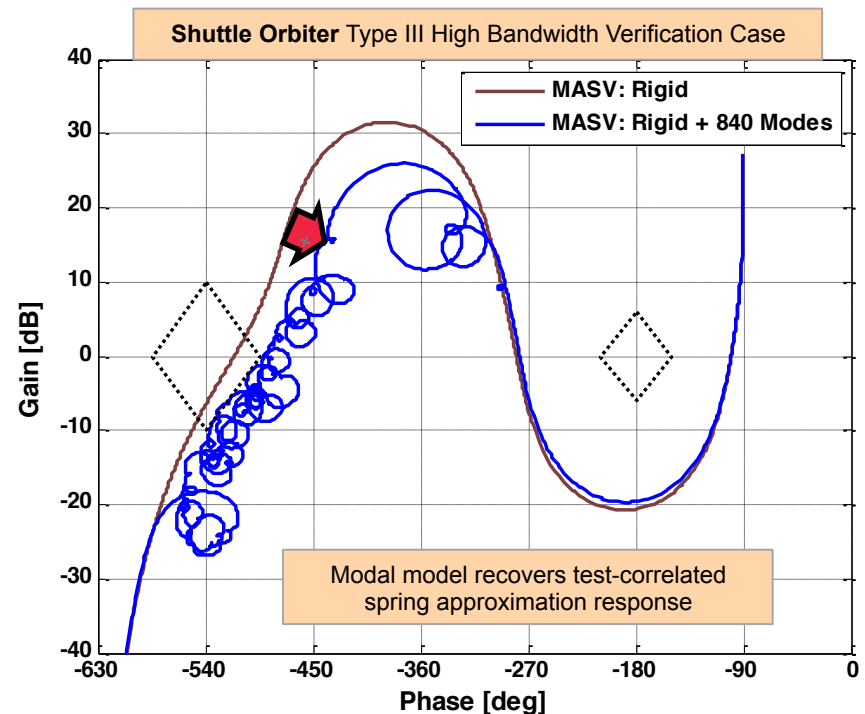
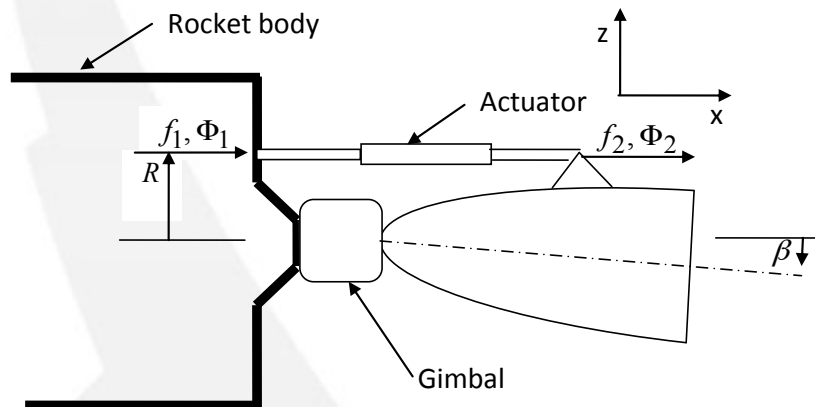




# Multiple Actuator Stage Vectoring (MASV) Model

- **Approach**

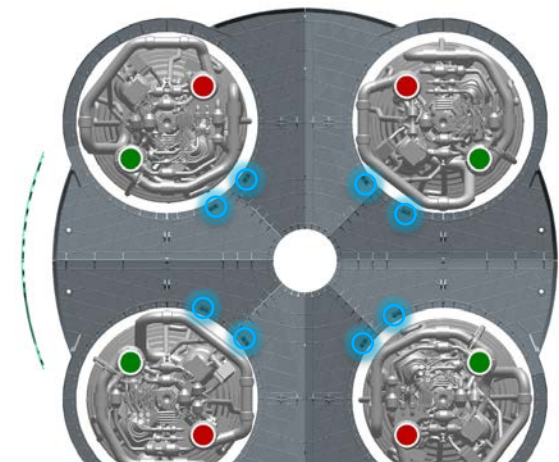
- Engine dynamics are replaced with a high-fidelity modal representation of the core stage thrust structure
- Allows coupling of multiple actuators with a single set of dynamic modes
- A partitioning procedure is used to identify and group generalized coordinates that do not contribute to dynamic response 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
		Test Number
		Duration(sec)
		Thrust(\$)
		Gimbal
		POGO
		Engine Out
<b>TDS 5.1.1 TVC Performance Evaluation</b>		
<b>1. Sinusoidal Engine Gimbaling</b>		
– 0.2° Amplitude		
– 0.4 degrees amplitude		
– 0.6 degrees amplitude		
<b>2. Step Response</b>		
<b>3. Ramp Response</b>		
<b>4. Stroking Response</b>		
<b>5. Flight Profile</b>		
<b>6. Simultaneous Engine Gimbaling/Throttling</b>		
<b>7. Routine Engine Positioning/SSME Side Load Evaluation</b>		
<b>8. Engine Clearance Checks (Non-Firing)</b>		
<b>9. Hydraulic Power Failure Simulation (Non-Firing)</b>		
<b>10. TVC Channel Failure Simulation</b>		
<b>11. Halting Ramp Response</b>		
<b>12. Simultaneous Gimbaling and POGO</b>		

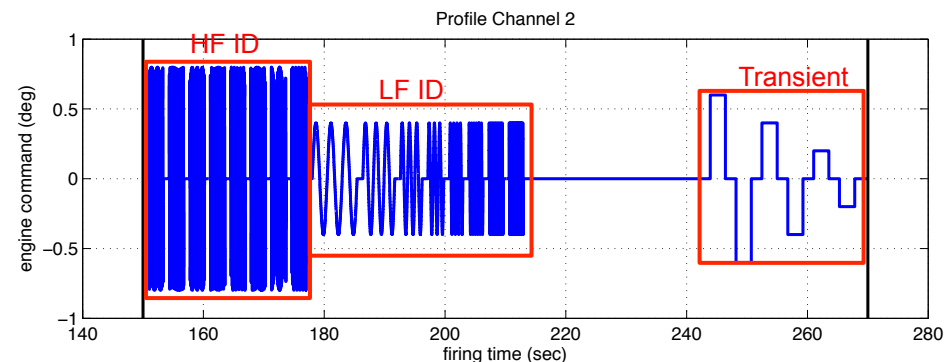
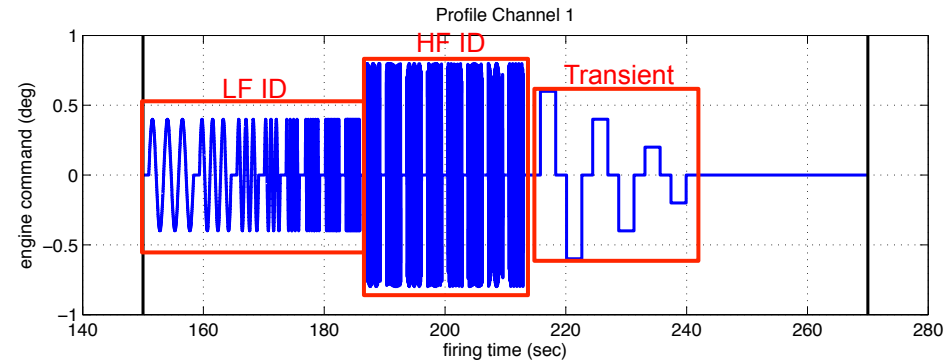
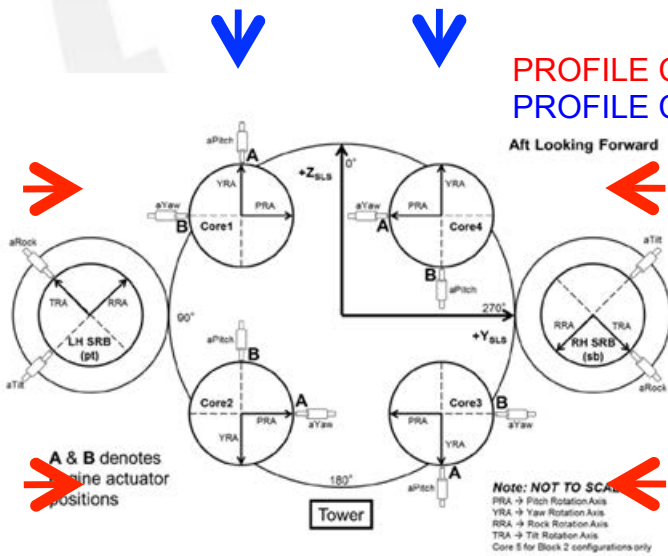


Instrumentation locations on base heat shield



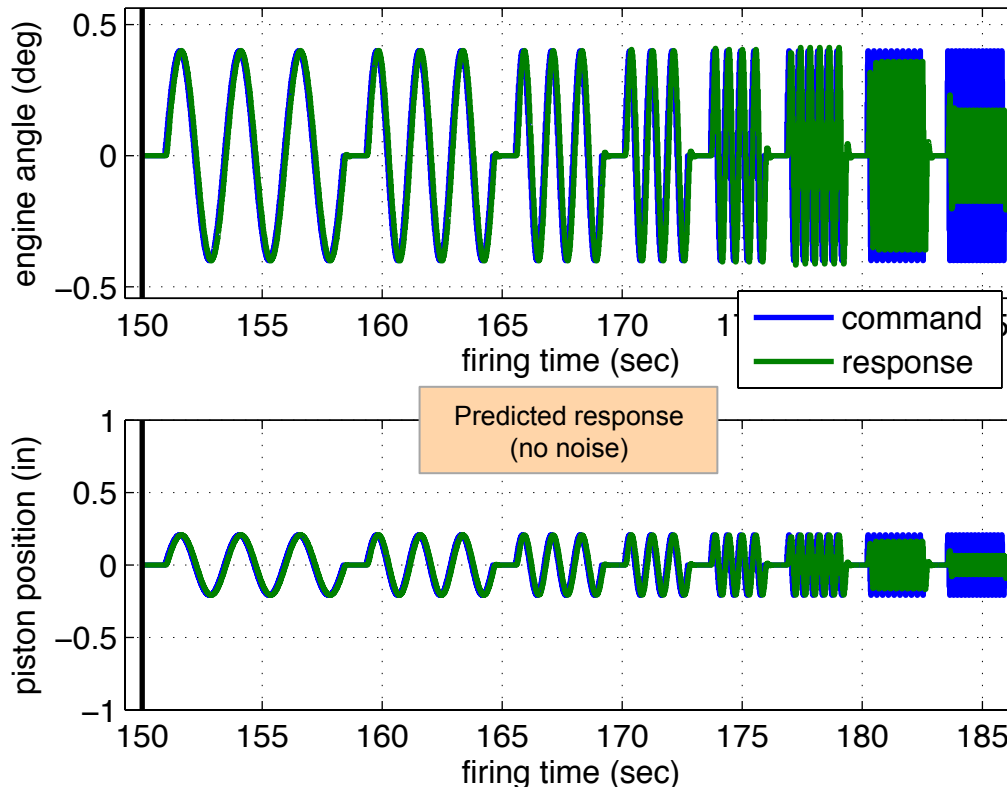
# FRT Profile Design

- ◆ **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



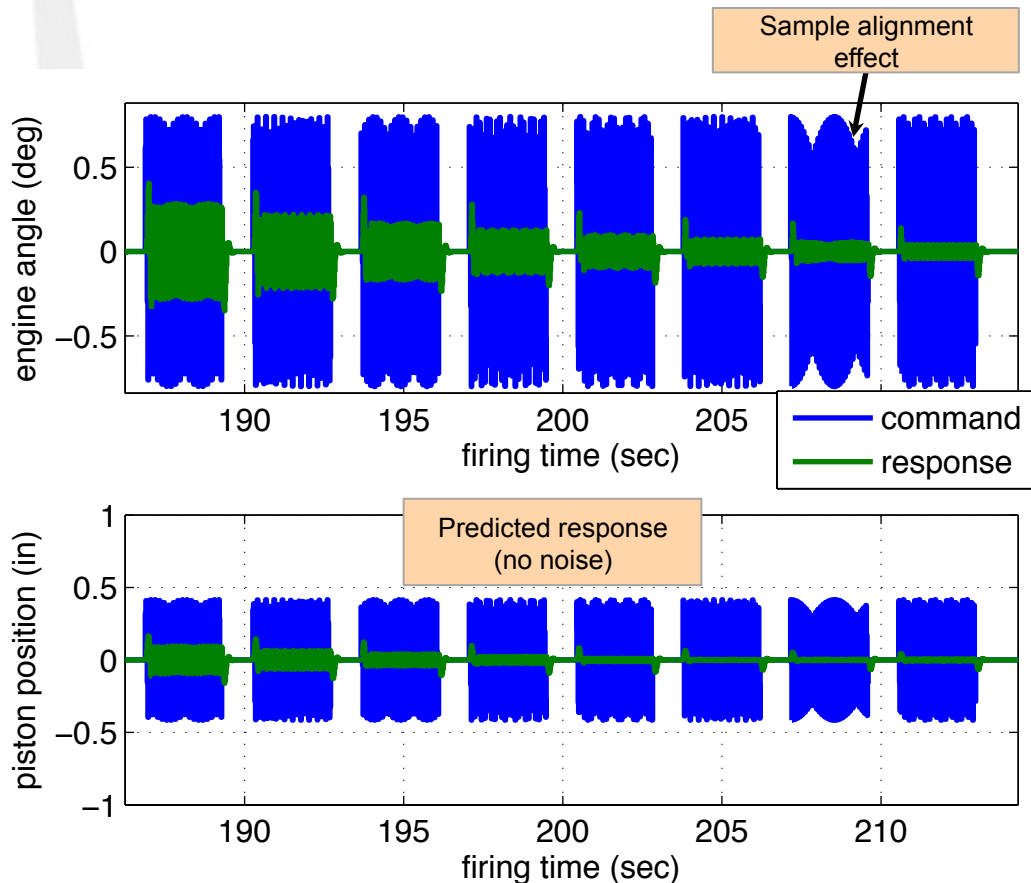
Channel 1 (Hz)	Channel 2 (Hz)
0.40-6.25 Hz increasing	7.0-14.0 Hz increasing

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

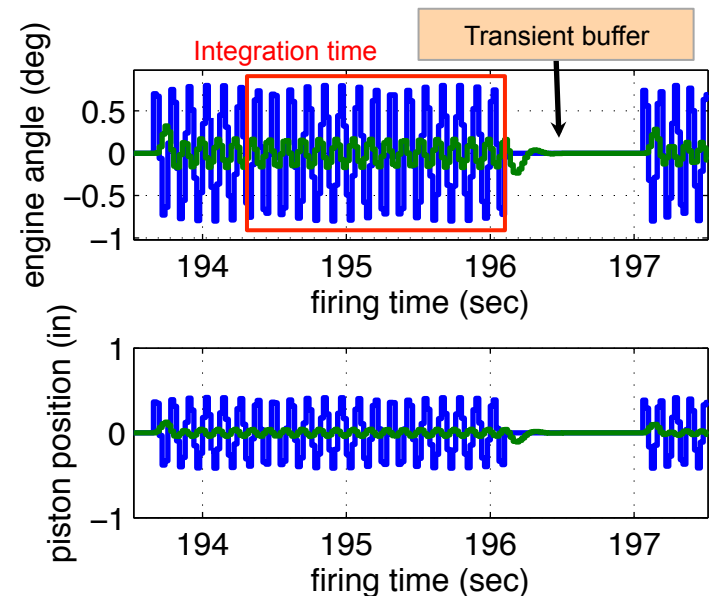
# High Frequency ID

## ◆ 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



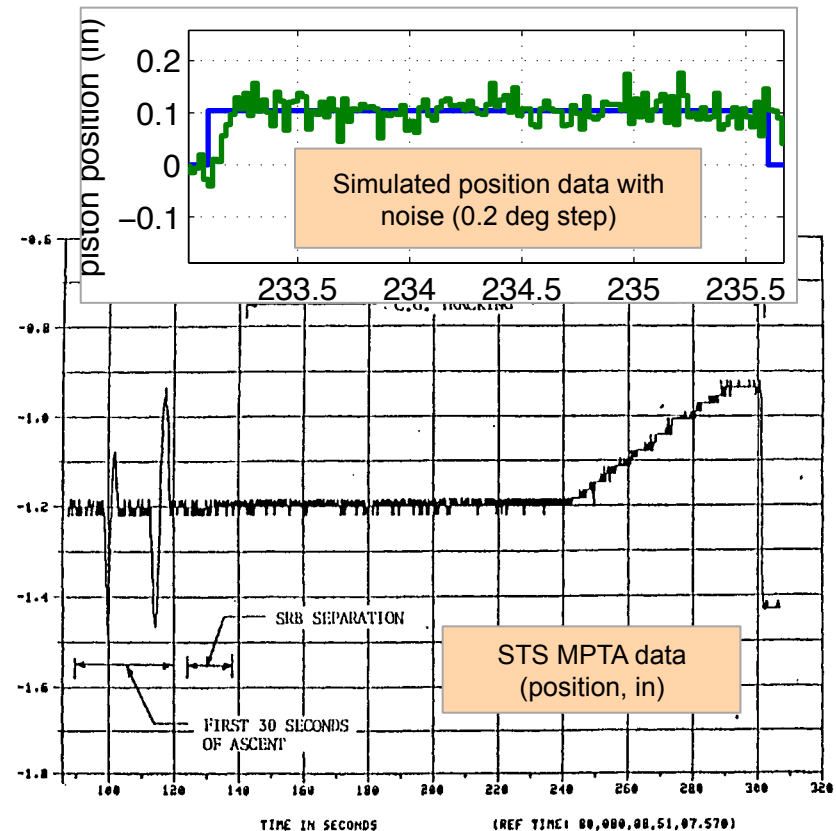
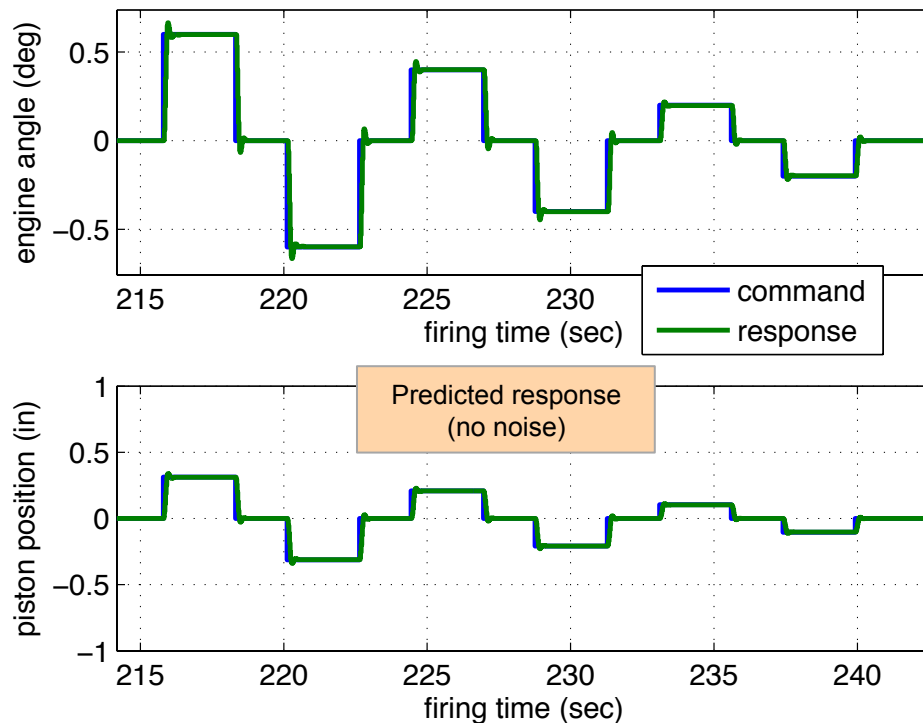
Channel 1 (Hz)	Channel 2 (Hz)
7.0-14.0 Hz increasing	0.40-6.25 Hz increasing



# 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

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

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

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

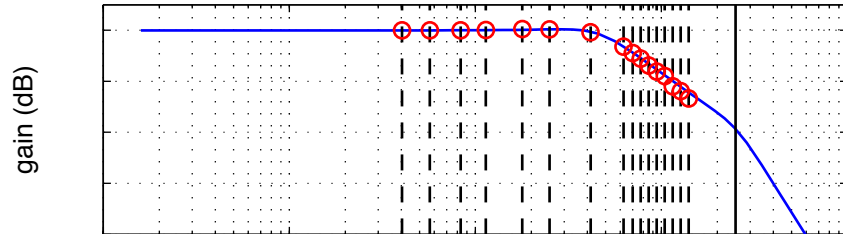
$$b_1' = \frac{2}{kT} \int_{-kT/2}^{kT/2} q(t) \sin(\omega t) dt.$$

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

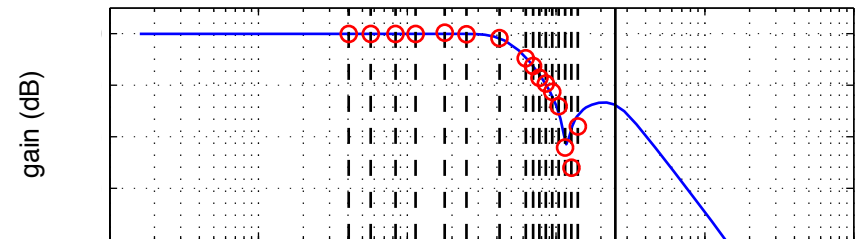
# Frequency ID Results

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

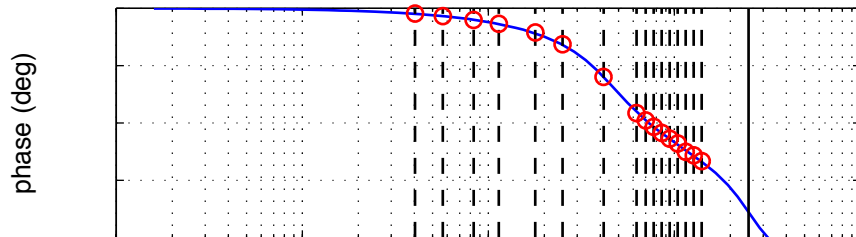
Engine position test points



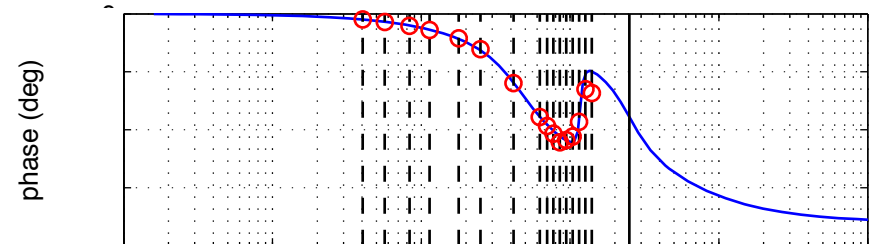
Piston position test points



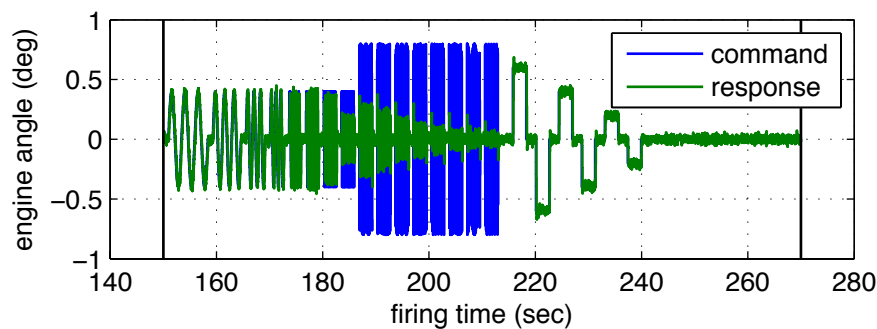
frequency (Hz)



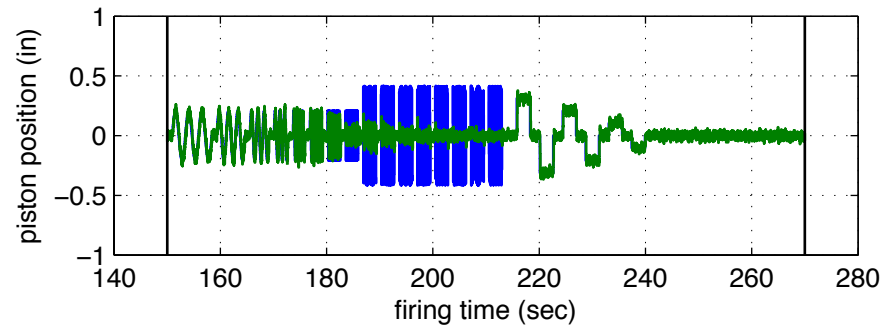
frequency (Hz)



frequency (Hz)



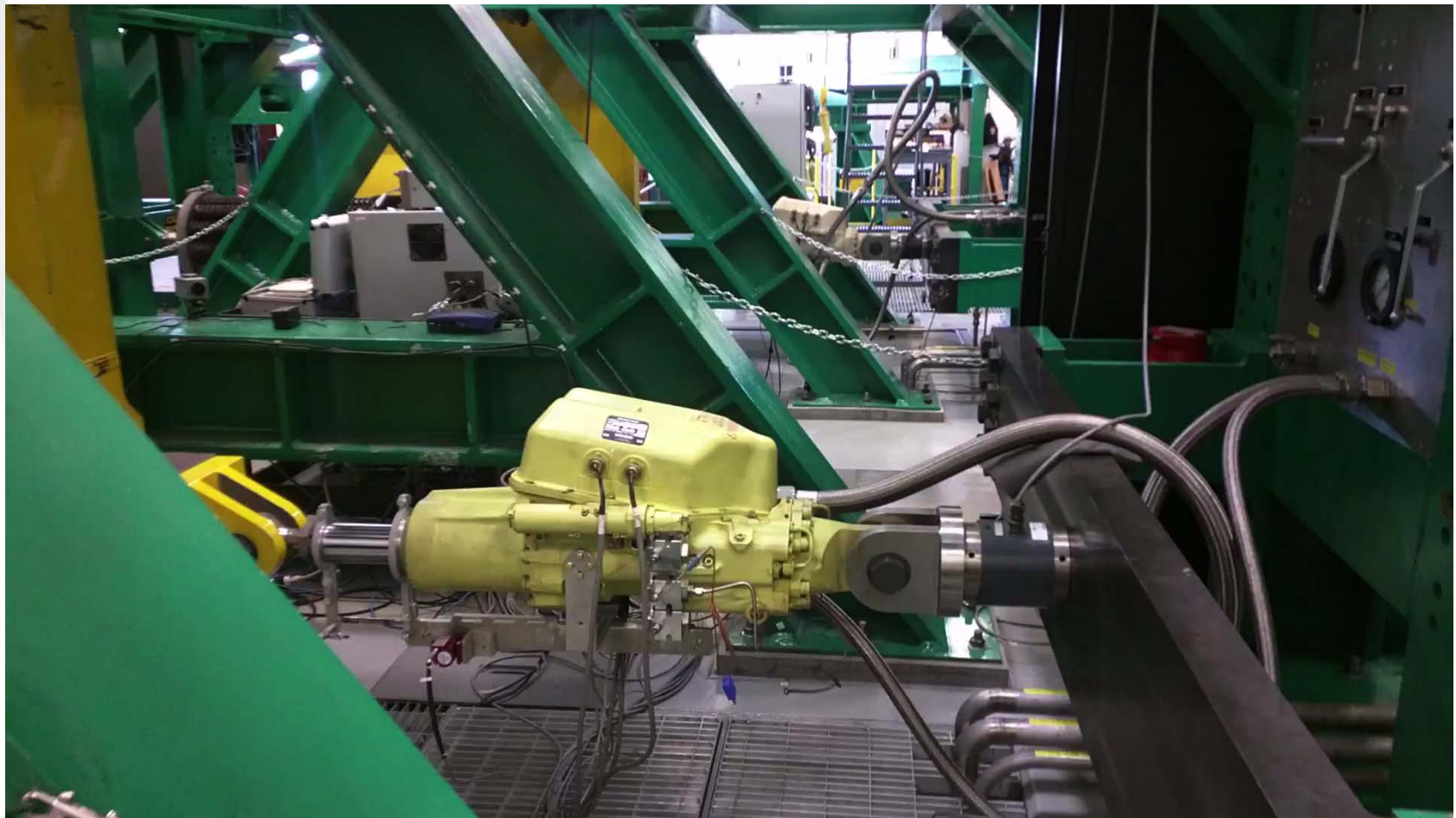
frequency (Hz)





# 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**

