National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

Advanced Modeling of Control-Structure Interaction in Thrust Vector Control Systems

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Overview

- SLS Core Stage (CS) is a 27.6 ft x 212 ft stage with over 2.4 Mlbm of structure and propellant
- Thrust vector control is provided by vectoring 4 RS-25E Core Stage Engines
- 4 (booster) + 8 (core) TVC DoF

- New thrust structure, STS heritage engines & actuators
- Extensive TVC modeling & test to ensure performance & control risk

- Fully successful first flight Nov 16, 2022

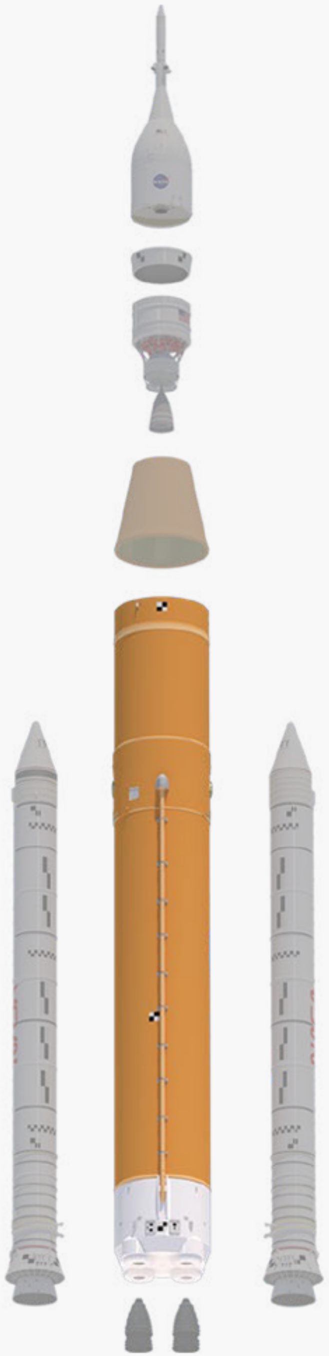
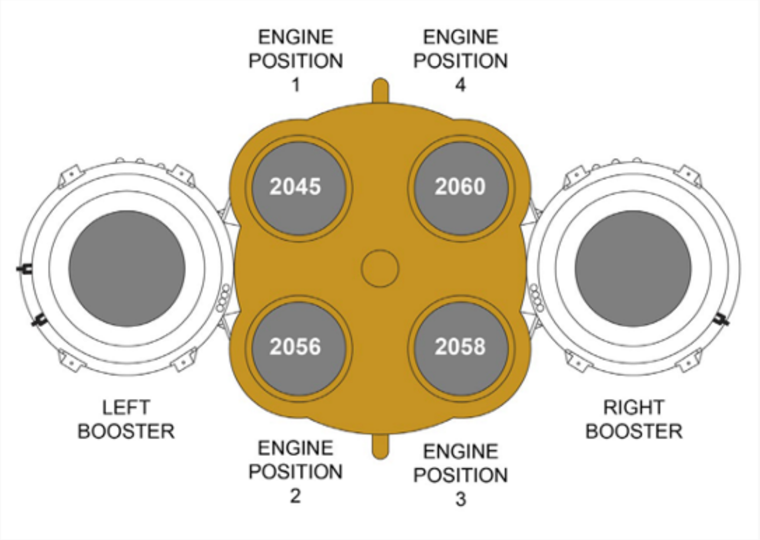


Image: NASA / SLS Ref. Guide



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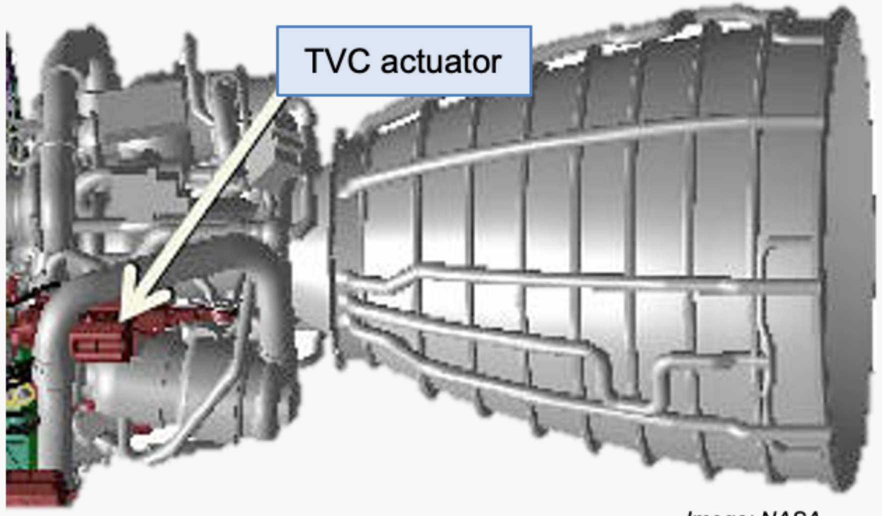
Traditional TVC Models

- Traditional models assume single DoF
- All load path compliance is lumped into a single load spring K_L
- Engine is a planar rigid body

- Linear model ("simplex") used for flight control design and stability analysis
  - 4-6 states, flow/rate limits, etc.
  - Coupled with 2-DoF engine for global servoelastic analysis (TWD/DWT)

- Nonlinear model ("complex") used for requirements verification
  - Full representation of hydraulics, faults
  - Typ. 10 kHz integration rate



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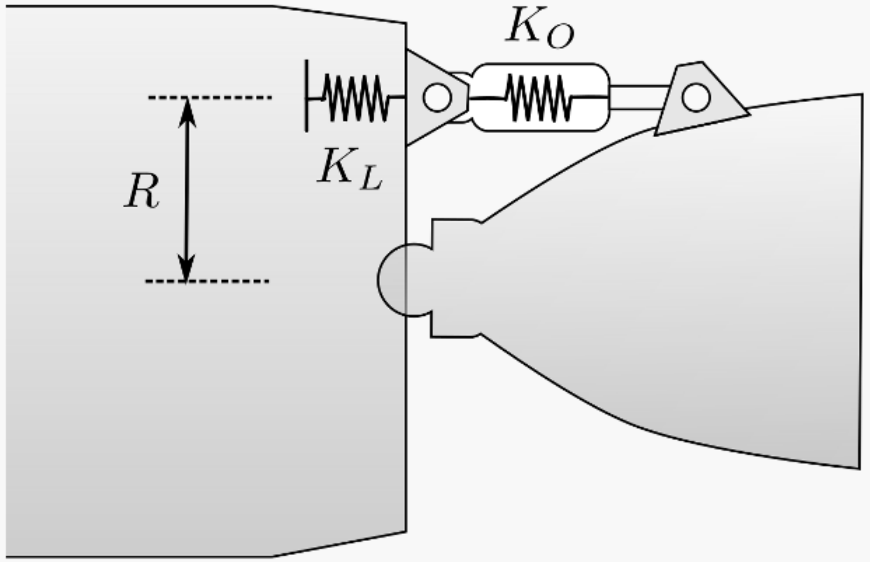


Motivation for Improved TVC Models

- Actuator-engine interface to new thrust structure
- Verify stability of servo-load feedback (with local modes)
- Verify coupling dynamics of engines with global structure for flight control models (DWT damping effects)

- Resolve discrepancies between modeling and test observed in Green Run Hot Fire
  - Coupling of TVC with structure was different than expected

Green Run Hot Fire, March 18, 2021

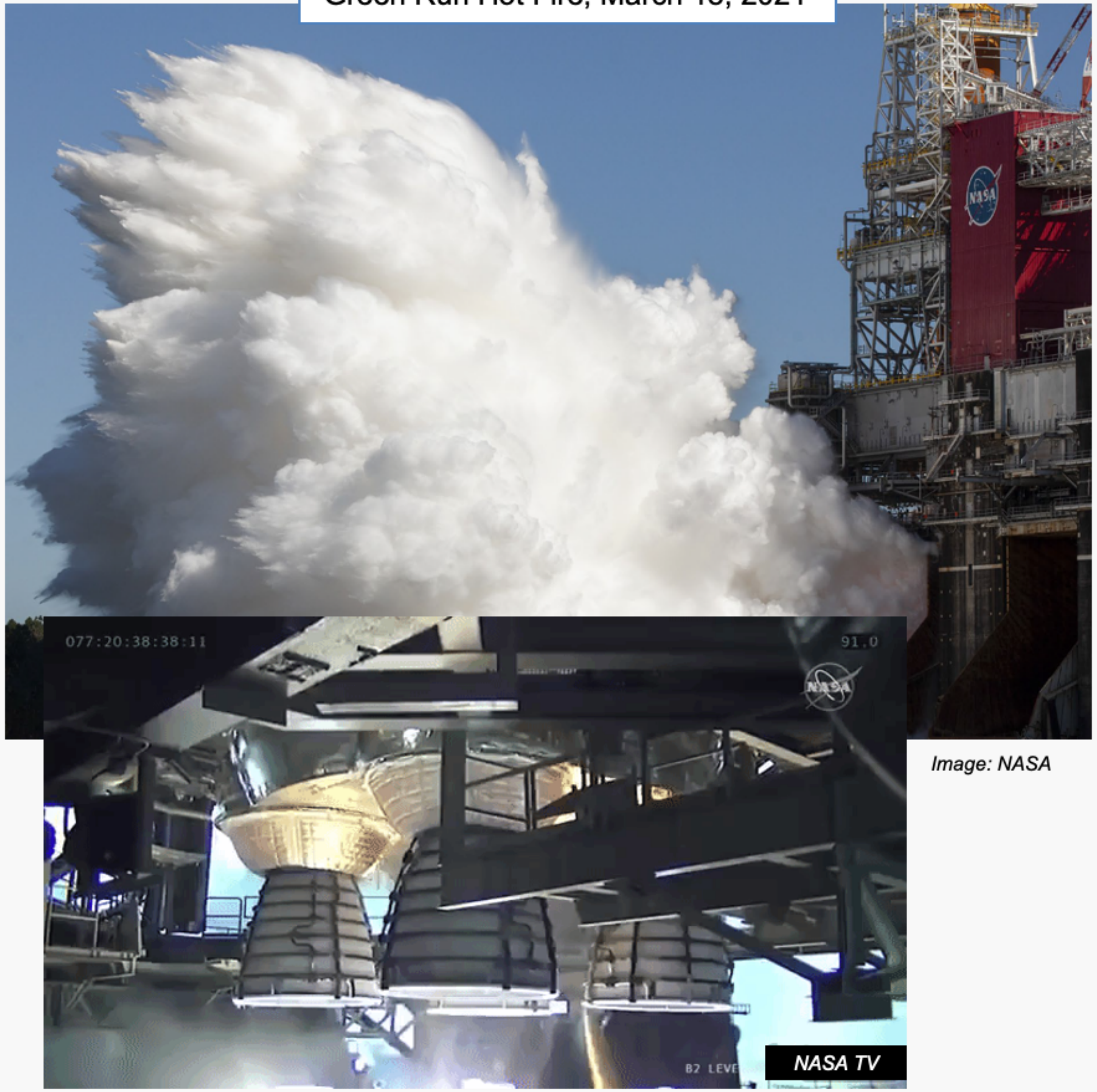
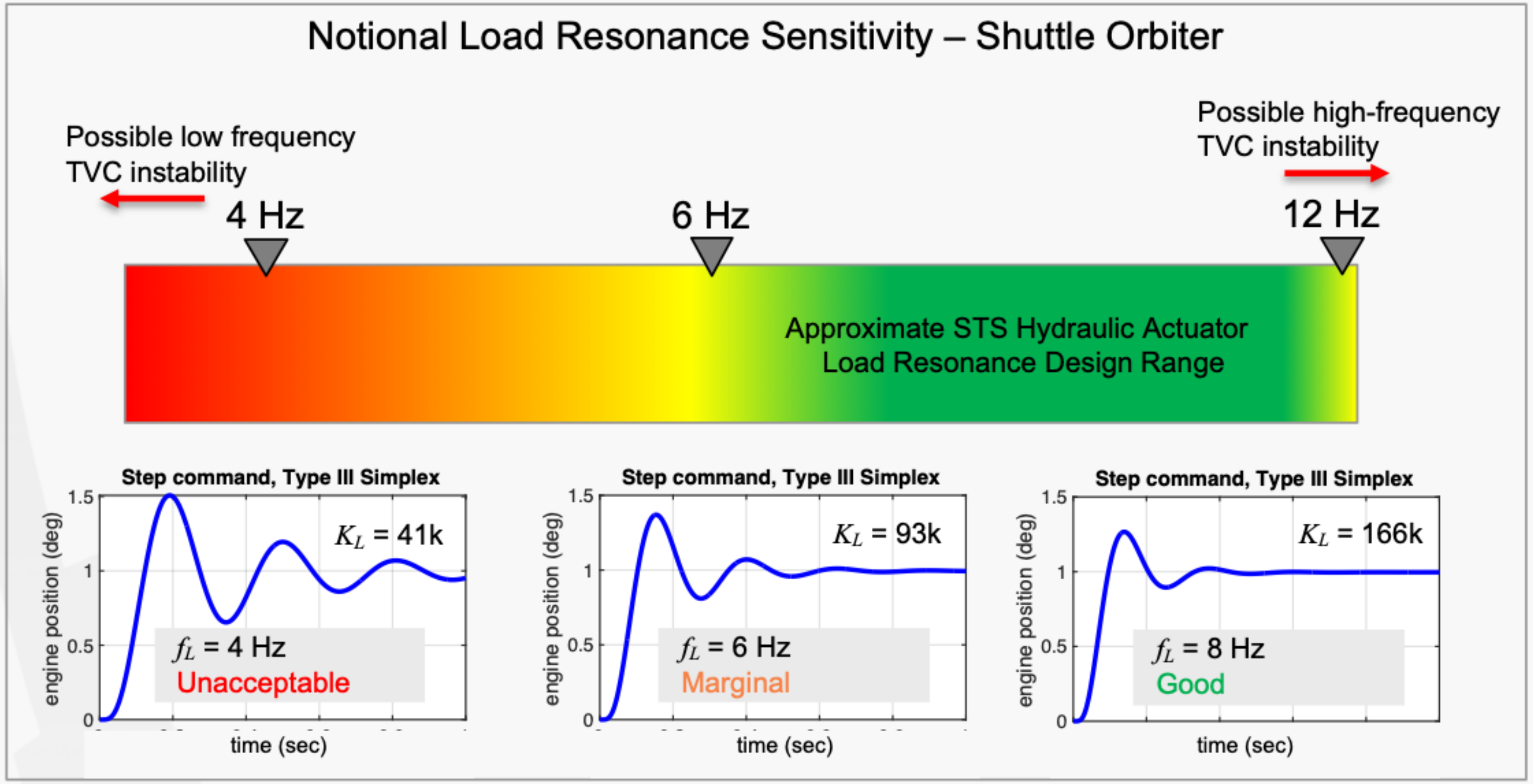


Image: NASA

Importance of the Load Resonance

- <u>Open-loop</u> load dynamics with engine feedlines, gravity loading and damping

$$J_n\ddot{\beta} = \underbrace{K_T R x_i}_{\text{Actuator torque}} - \underbrace{C_n\dot{\beta}}_{\text{Damping}} - \underbrace{\left(K_n + K_T R^2\right)}_{\text{Pendulum mode stiffness}}\beta$$



Total Stiffness

$$K_T = \left(\underbrace{\frac{1}{K_L}}_{\text{Load}} + \underbrace{\frac{1}{K_o}}_{\text{Oil}}\right)^{-1}$$

Pendulum Mode (Open Loop)

$$\omega_p \approx \sqrt{\frac{K_T R^2 + K_n}{J_n}}$$

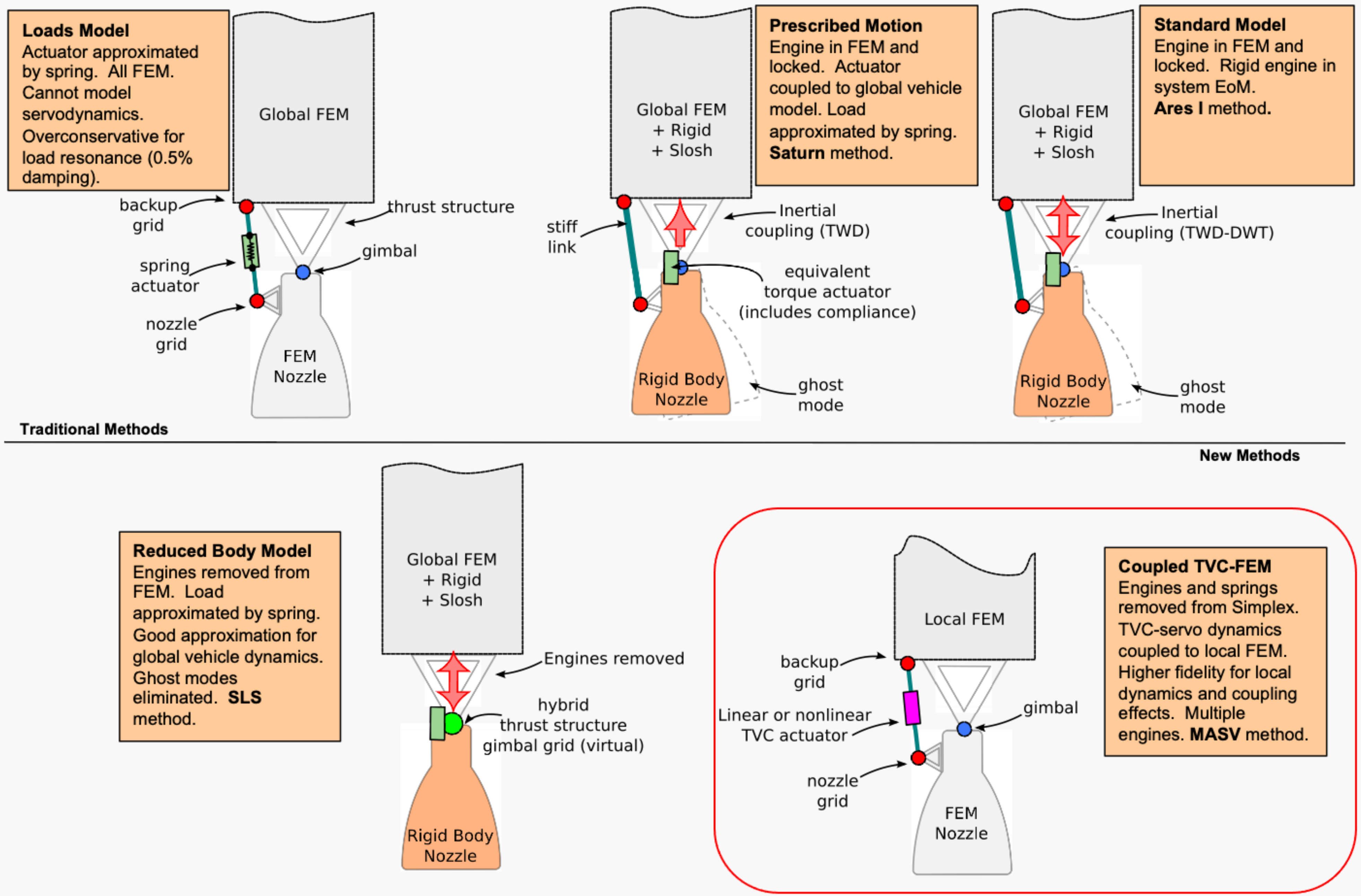
Includes Oil Compliance (not observable)

Load Resonance (Closed Loop)

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

<u>Observable In Test</u> (Notch Frequency)

Vehicle-TVC Modeling Approaches



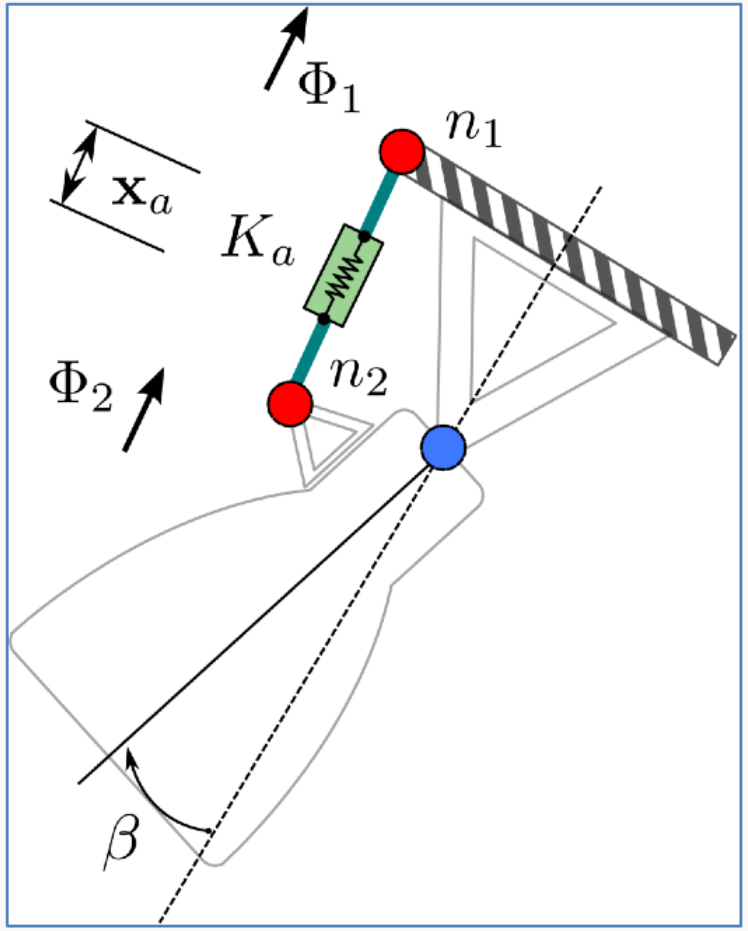
Multiple Actuator Stage Vectoring (MASV)

- **Replace engine(s) with a detailed Finite Element Model**

- Account for distributed load path of engine-TVC coupling
- Support multiple engine DoF simultaneously
- Incorporate thrust loading and follower effects

- 8 rigid-body or low-frequency DoF (engine motion)
- Thousands of elastic DoF + residual vectors
- Separate slow bending dynamics from static (fast) dynamics via convergence analysis

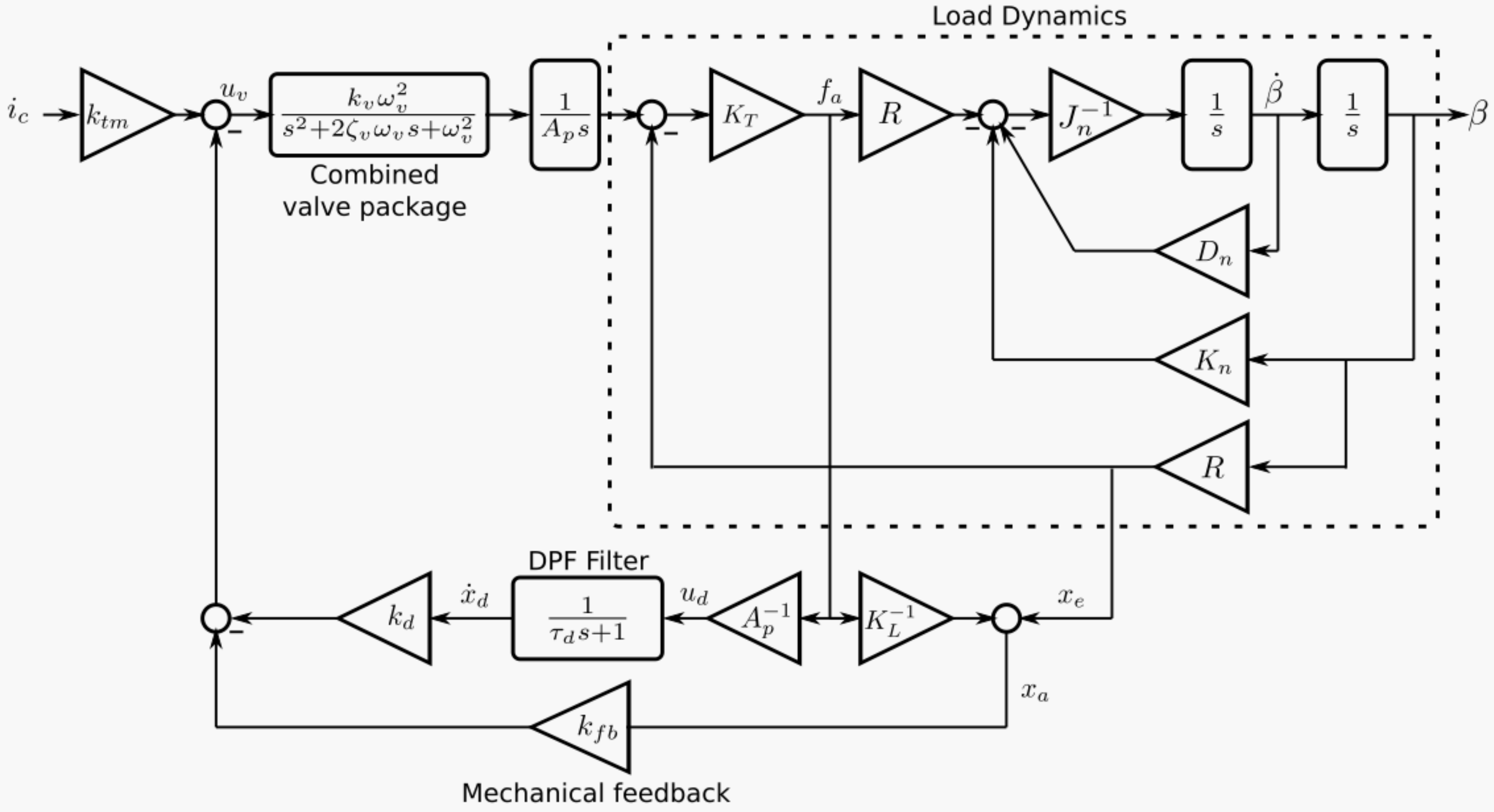
- Complements Two Actuator Operational Simulation (TAOS), used for friction characterization



Linear Simplex Model

- Open-loop load dynamics with rigid engine:

$$J_n\ddot{\beta} = \underbrace{K_T R x_i}_{\text{Actuator torque}} - \underbrace{C_n\dot{\beta}}_{\text{Damping}} - \underbrace{\left(K_n + K_T R^2\right)\beta}_{\text{Pendulum mode stiffness}}$$



MASV Model

- Actuator deflection:

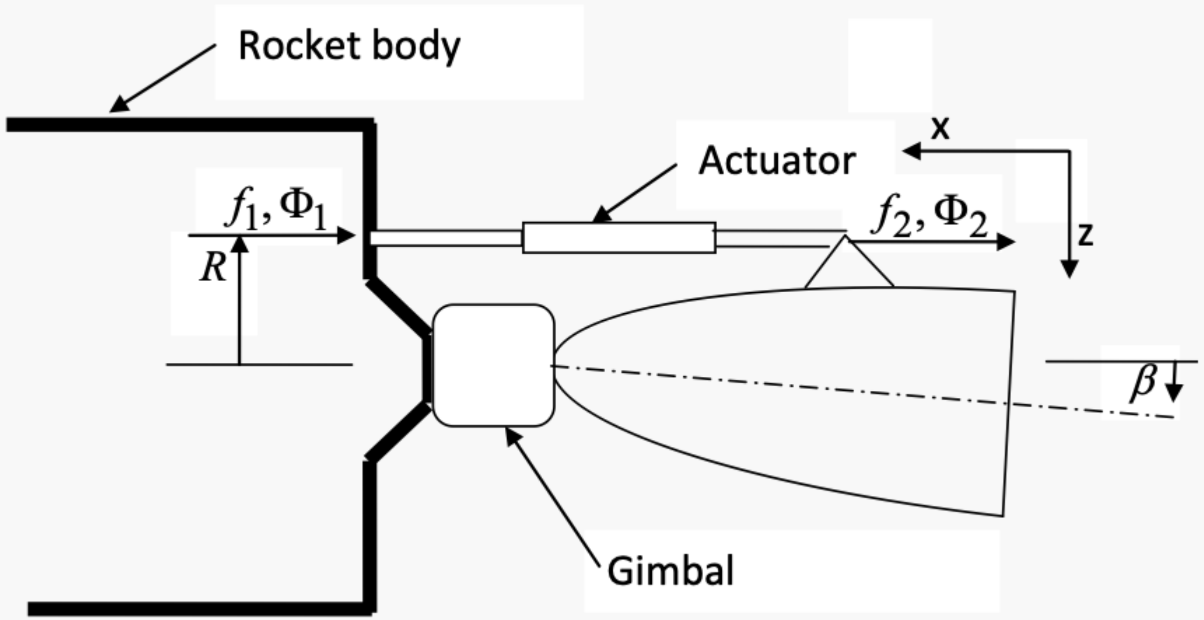
$$x_a = \mathbf{p}^T (\mathbf{\Phi}_2 - \mathbf{\Phi}_1) \boldsymbol{\eta} = \boldsymbol{\gamma}^T \boldsymbol{\eta}$$

Unit vector   Mode shapes

- Actuator force:

$$f_a = K_{ac} x_{ac} = K_{ac} \left(x_i - \boldsymbol{\gamma}^T \boldsymbol{\eta} \right)$$

Actuator compliance



- Open-loop load dynamics with FEM:

$$\ddot{\boldsymbol{\eta}} = \boldsymbol{\gamma} K_{ac} x_i - \left(\mathbf{D} + \tilde{\mathbf{\Psi}}_\beta^T \mathbf{D}_n \tilde{\mathbf{\Psi}}_\beta \right) \dot{\boldsymbol{\eta}} - \left(\mathbf{\Omega^2} + K_{ac} \boldsymbol{\gamma} \boldsymbol{\gamma}^T + \tilde{\mathbf{K}} \right) \boldsymbol{\eta} + \mathbf{\Phi}_0^T \left(F_T \mathbf{u}_0 - m_n \mathbf{g}_0 \right)$$

Actuator force   Damping   Coupled stiffness matrix   Thrust and gravity loads

Model is extended to *n* actuators.

Engine Loads

- External loads account for thrust, feedline, and follower effects.

$$\boldsymbol{\beta}_g = \boldsymbol{\Psi}_\beta \boldsymbol{\eta}$$ Global engine angle

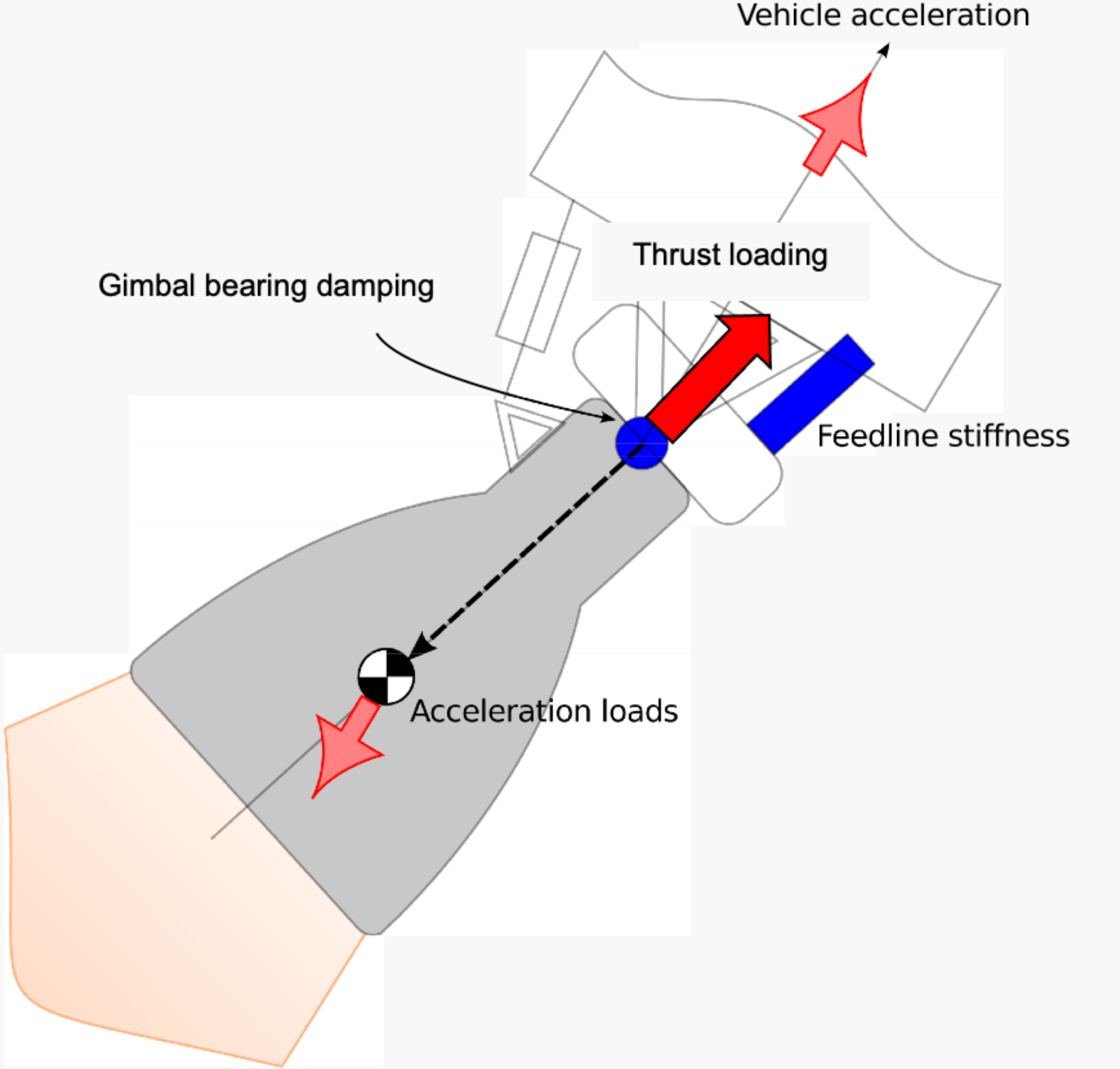
$$\boldsymbol{\beta} = \left(\boldsymbol{\Psi}_\beta - \boldsymbol{\Psi}_0\right)\boldsymbol{\eta} = \tilde{\boldsymbol{\Psi}}_\beta \boldsymbol{\eta}$$ Local engine angle

- Auxiliary stiffness matrix:

$$\tilde{\mathbf{K}} = \tilde{\boldsymbol{\Psi}}_\beta^T \left(\underbrace{\mathbf{K}_n \tilde{\boldsymbol{\Psi}}_\beta}_{\text{Feedline}} - \underbrace{m_n \mathbf{g}_0^\times \mathbf{r}_n^\times \boldsymbol{\Psi}_\beta}_{\text{Gravity load}}\right) + \underbrace{F_T \boldsymbol{\Psi}_0^T \mathbf{u}_0^\times \boldsymbol{\Psi}_\beta}_{\text{Follower forces}}$$

- Static loads:

$$\mathbf{Q}_0 = \boldsymbol{\Phi}_0^T \left(F_T \mathbf{u}_0 - m_n \mathbf{g}_0\right)$$



Static and Dynamic Modes

- "Fast" dynamics (high-frequency modes) can be collapsed into an equivalent static stiffness acting along the actuator force unit vector.

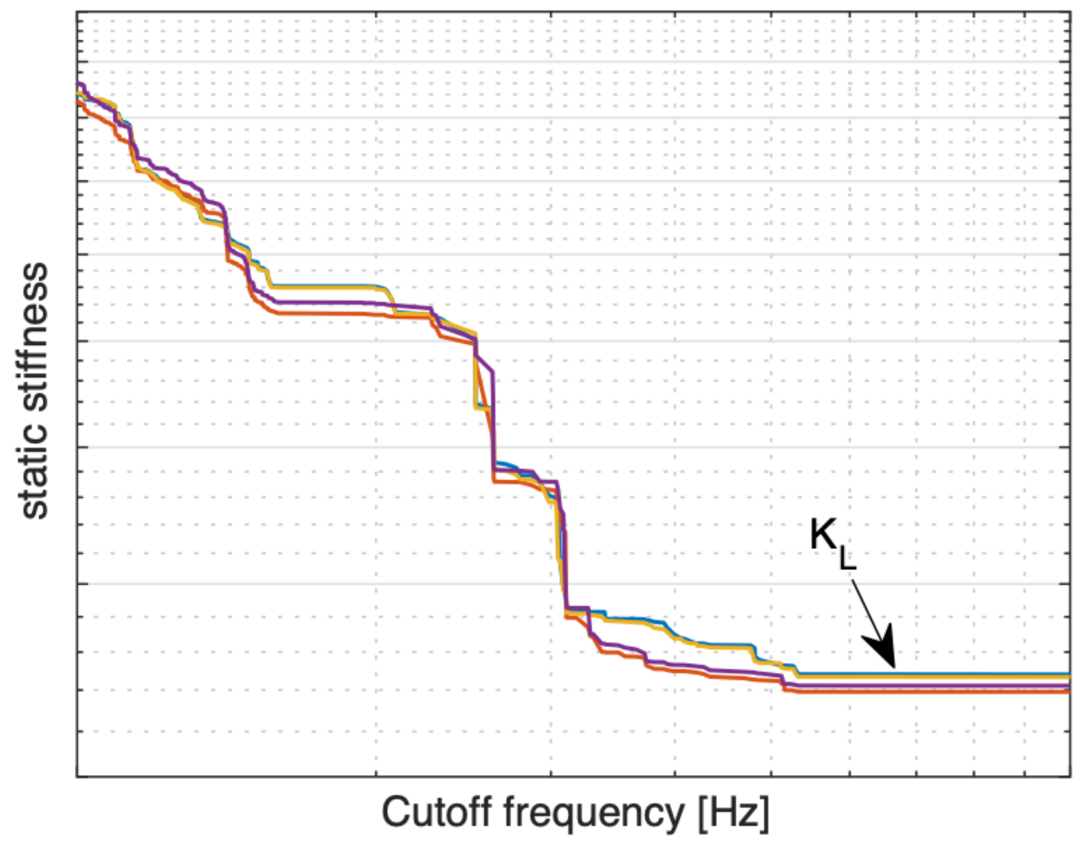
$$x_s = \sum_{k=J+1}^{K} \gamma_k \eta_k \approx \sum_{k=J+1}^{K} \frac{\gamma_k^2 f_a}{\Omega_k^2}$$

Static displacement

$$C_s = \frac{x_s}{f_a} = \sum_{i=J+1}^{K} \frac{\gamma_k^2}{\Omega_k^2}$$

Partial load compliance
Approaches K_L for large K!

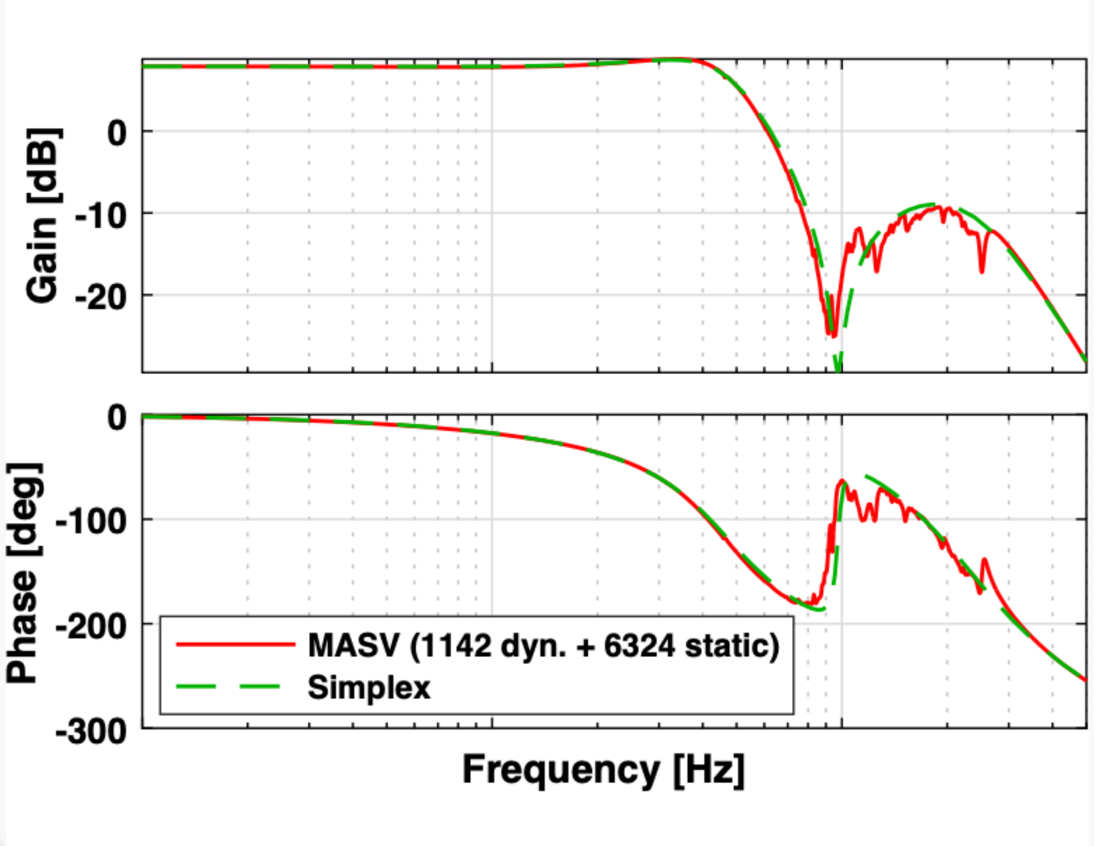
- A convergence study is used to determine the cutoff frequency.
- Typical cutoff ~60 Hz, ~1000 dynamic modes, ~6000 static modes.
- Reduces computational burden.

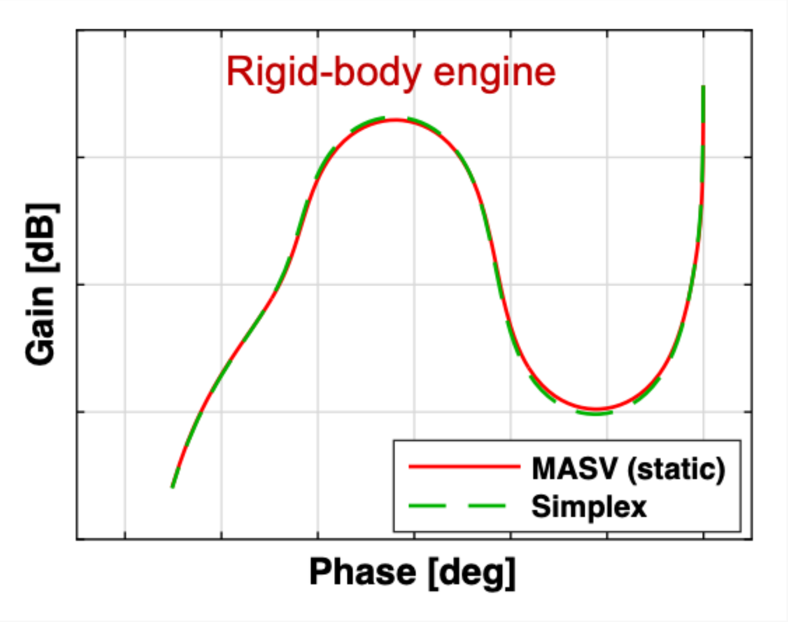


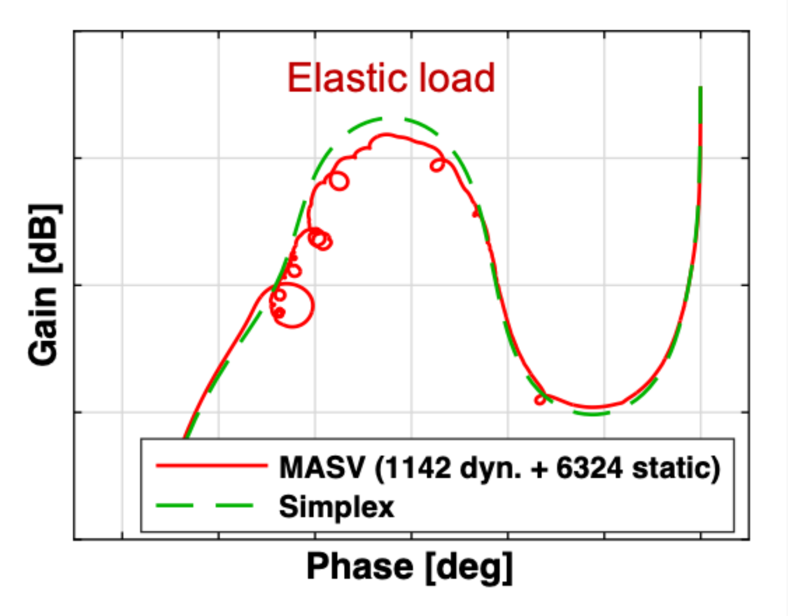
MASV static convergence provides a reliable method to compute the equivalent load stiffness for the simplex model.

Typical Results

- Open-loop frequency response used to verify stability of actuator loop with all engine DoF
  - Ample stability margin; load spring is sufficient for servo stability analysis.
- MASV used to reproduce observed load resonance as seen in Green Run and predict static TV angles.







Concluding Remarks

- Detailed modeling of thrust structure elasticity is important for verification of TVC stability
- A load spring approximation was shown to be adequate for flight control analysis; <u>however</u>
- Determining the load spring depends on detailed test and analysis (and load path/engine condition!)

- The MASV formulation is a test-validated approach for predicting the dynamic response of a complex, flexible, and highly coupled thrust structure.
  - Time domain, frequency domain, and static effects;
  - Reliable estimation of parameters for simpler models.

Image: NASA / Bill Ingalls