SPACE LAUNCH SYSTEM

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Space Launch System Thrust Vector Servoelastic (TVSE) Resonance

Jeb S. Orr, PhD
NASA MSFC Control Systems Design and Analysis Branch
Mclaurin Aerospace [Jacobs ESSCA]

MCLAURIN AEROSPACE

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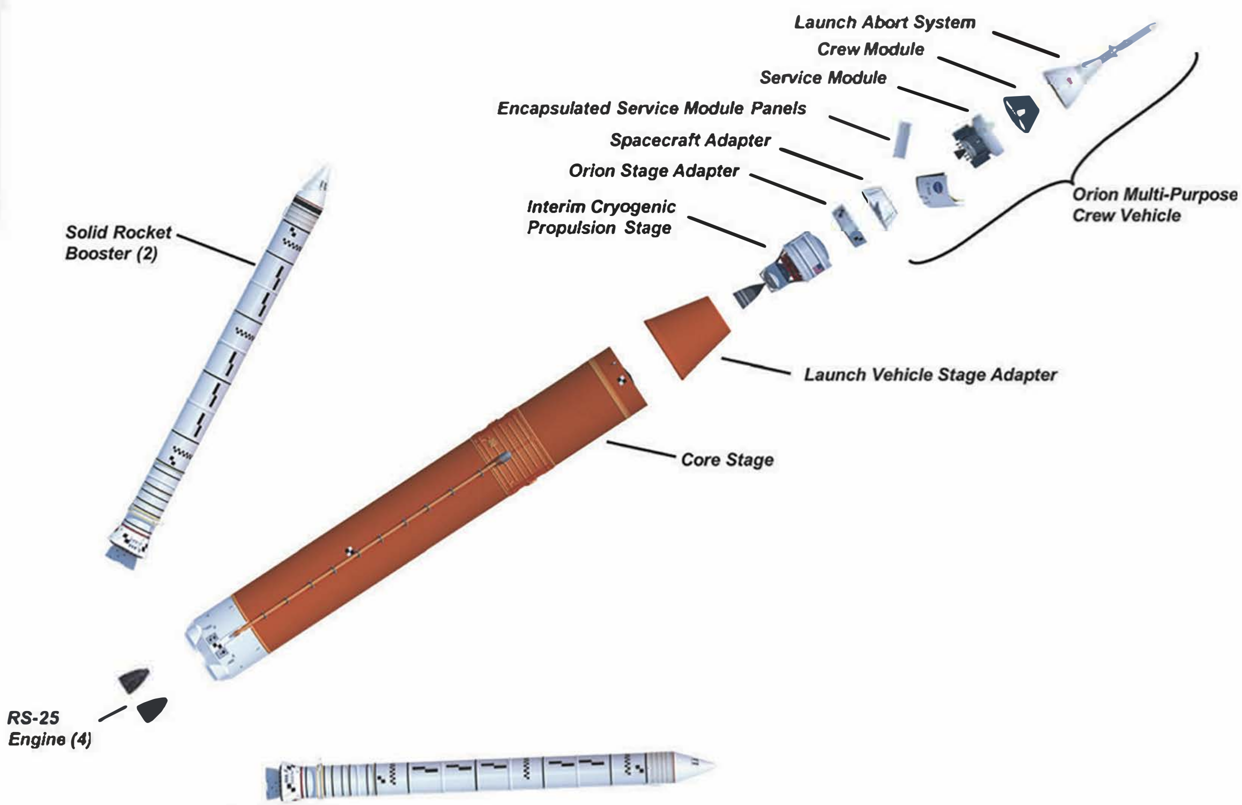
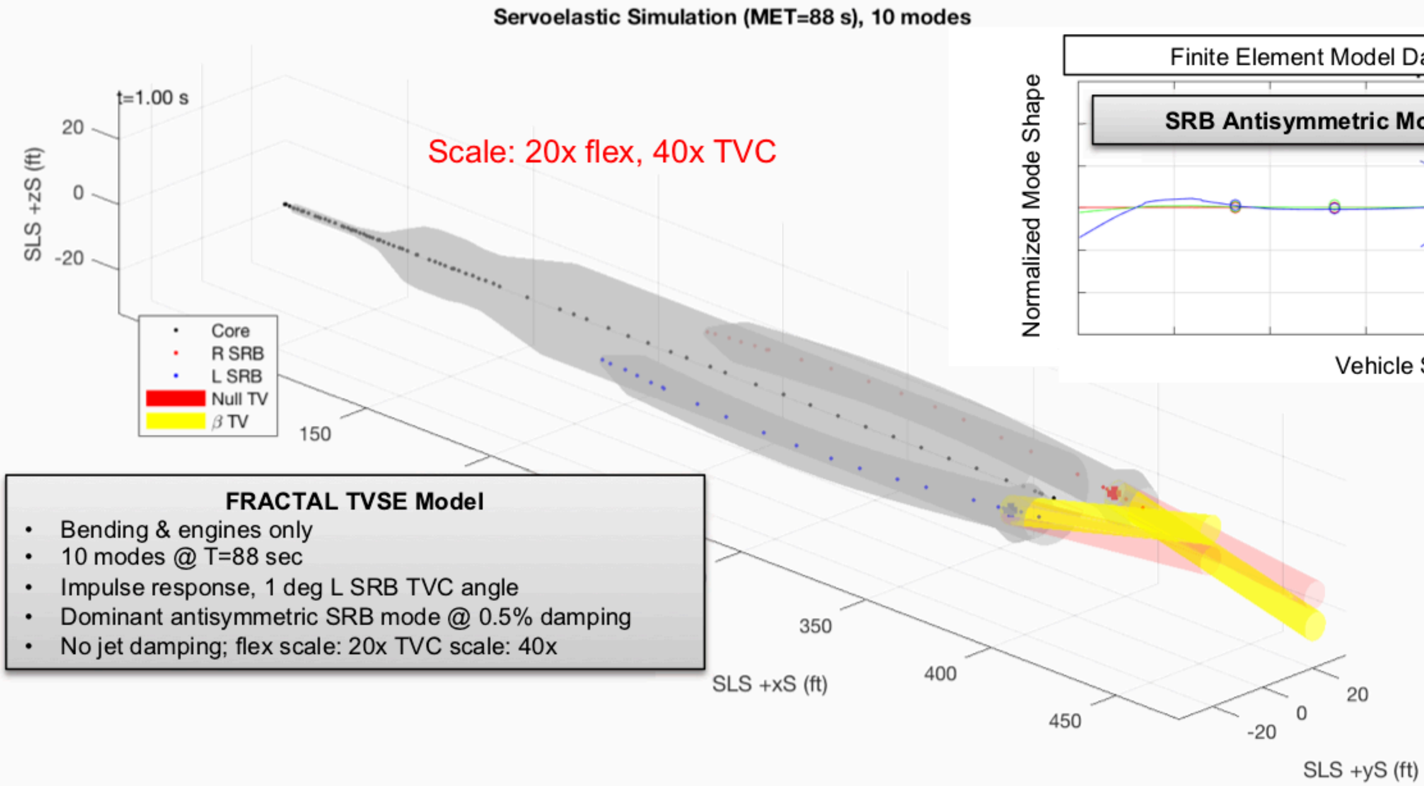
Introduction

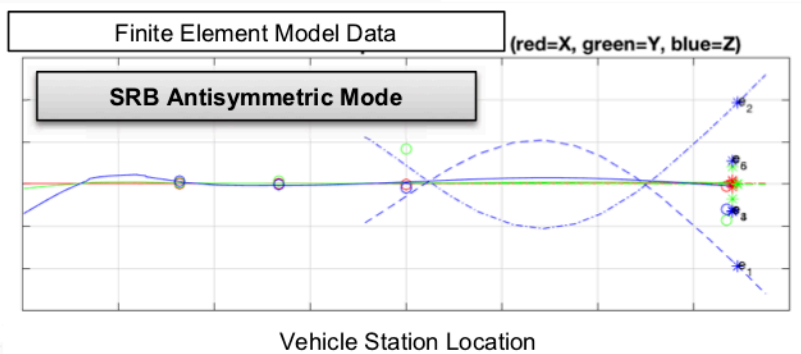
- **Space Launch System (SLS)**
  - NASA-developed, human-rated launch vehicle for large-scale (exploration-class) crew and cargo access
  - LEO: 95 t [~209 klbm] (Block I) / 130 t [~290 lbm] (Block II)
  - TLI: 26 t [~57 klbm] (Block I) / 37 t [~80 klbm] (Block II)
  - First uncrewed test flight (Artemis I) ~November 2020 (lunar)
  - First crewed test flight (Artemis II) ~October 2022 (lunar)



Thrust Vector Servoelastic (TVSE) Resonance

- **A thrust-driven servoelastic resonance manifests in the SLS Block 1 and 1B configurations in late boost flight (T70 -110 s)**
  - Coupling of engine dynamics, TVC hydraulics, booster thrust, and bending
  - Driven by hydraulic actuator feedback (no software or avionics)
- **With actuator hydraulic power vehicle bending can limit cycle near 90 s**
  - Result of high thrust, lag effect of actuator, and booster flexibility
  - Stability is restored with active flight control



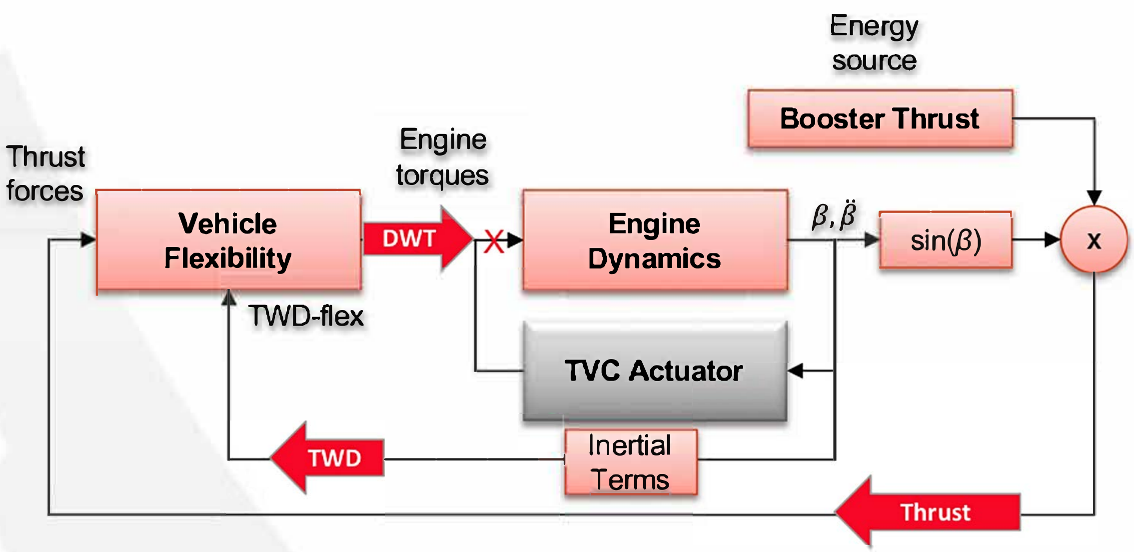


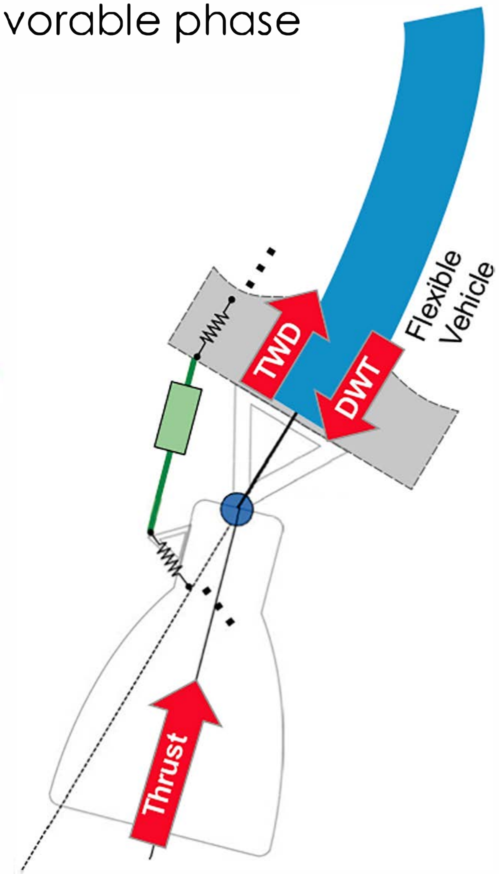
FRACTAL TVSE Model
- Bending & engines only
- 10 modes @ T=88 sec
- Impulse response, 1 deg L SRB TVC angle
- Dominant antisymmetric SRB mode @ 0.5% damping
- No jet damping; flex scale: 20x TVC scale: 40x

Mechanism Physics

- **Thrust vector servoelasticity (TVSE) is similar to aircraft aeroservoelasticity (ASE)**
  1. Inertial coupling of vehicle bending to engine (via gimbal) excites nozzle
  2. Thrust vector lags bending acceleration due to actuator dynamics
  3. Thrust force is partially in phase with velocity, providing an *un*damping effect

- **A combination of conditions must occur**
  1. Bending mode near TVC critical frequency (related to nozzle inertia)
  2. High thrust and large bending gain at gimbal with unfavorable phase
  3. Low structural mode damping





Mechanism involves only mechanical-hydraulic feedback

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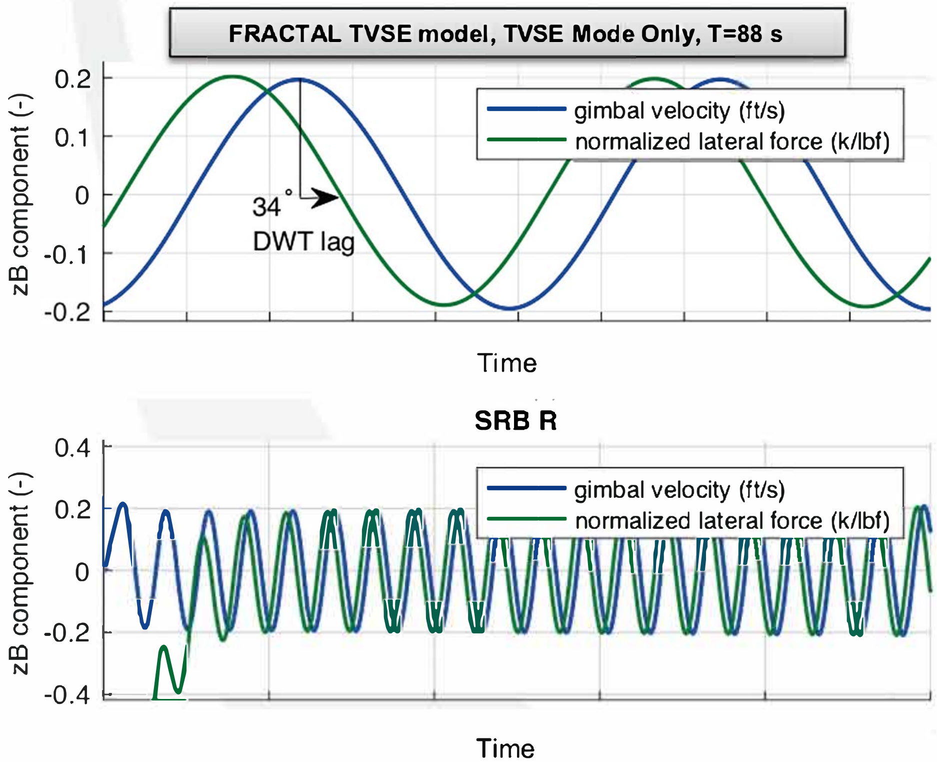
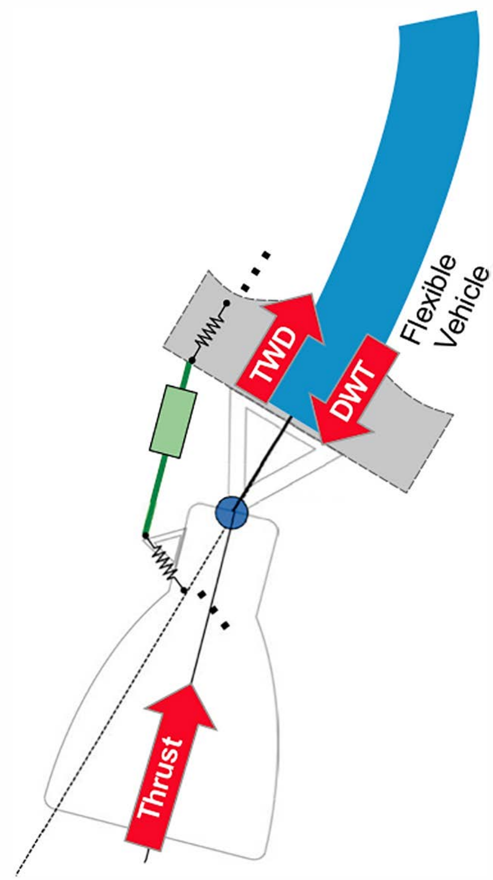
Relative Phasing of Bending

- **At low frequency, thrust angle is in phase with bending *displacement***
  - Thrust force is 90 degrees from bending *velocity*
  - *Force is orthogonal to velocity – no net energy transfer to bending*
- **At high frequency, thrust angle is 180° out of phase with bending *displacement***
  - Thrust force still 90 degrees from bending velocity – no net energy transfer
- **TVC lag can add energy to mode if coupled with sufficient bending gain**





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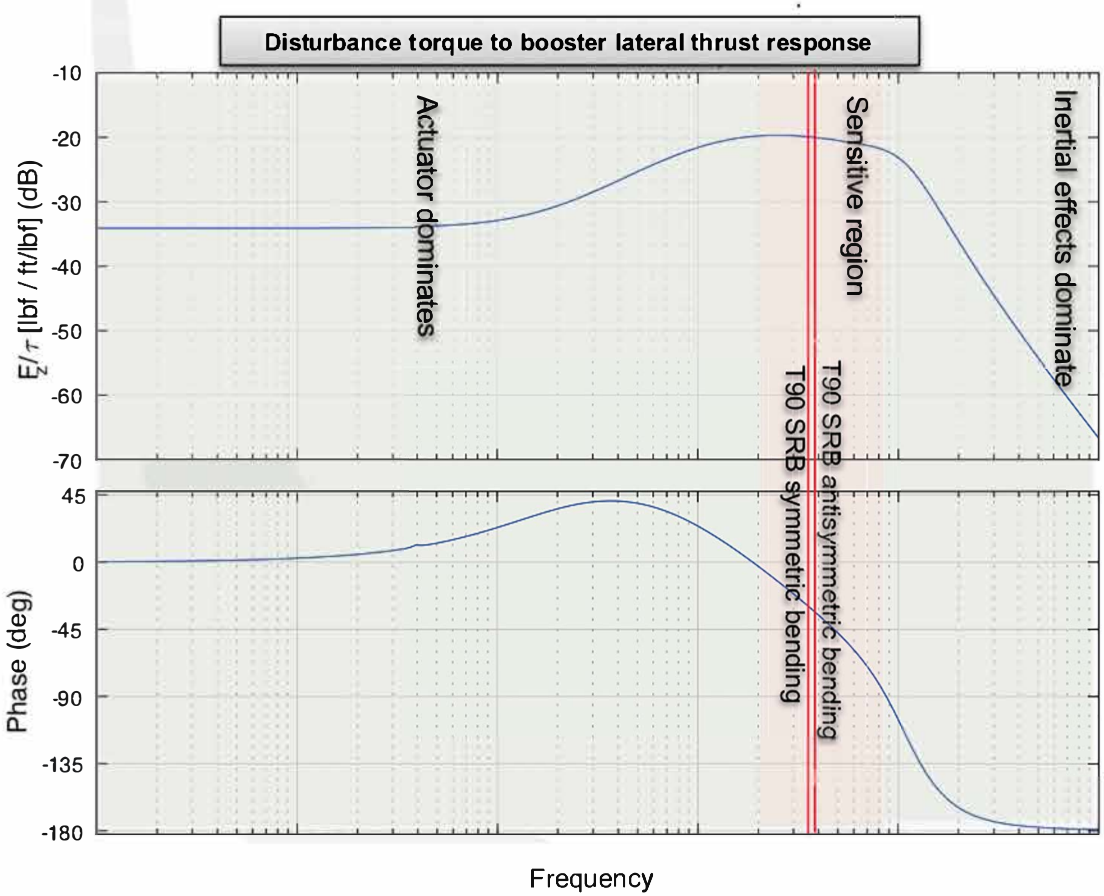
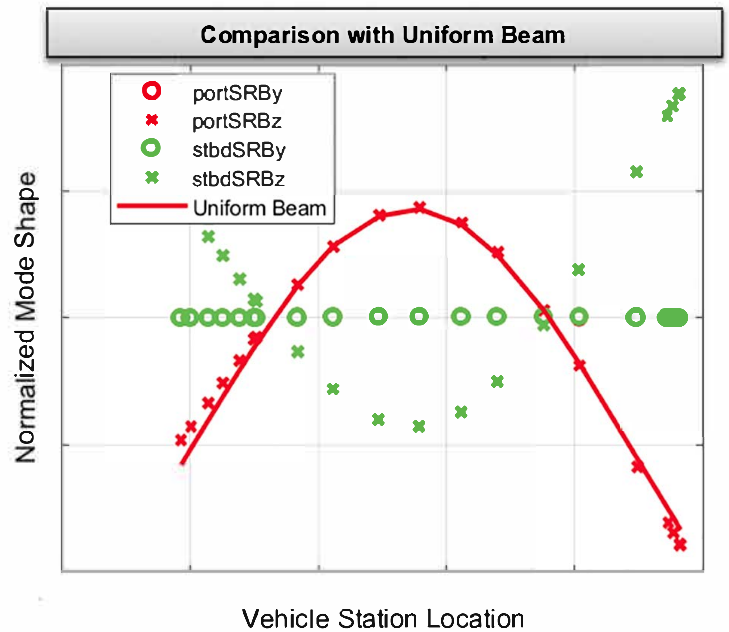
TVC Critical Frequencies vs. SRB Bending

- **TVC critical frequency range coincides with antisymmetric mode frequency**
  - Fundamental bending of SRB case
  - SRB mode is similar to a uniform beam
  - Mode can exhibit high gain in FCS roll channel

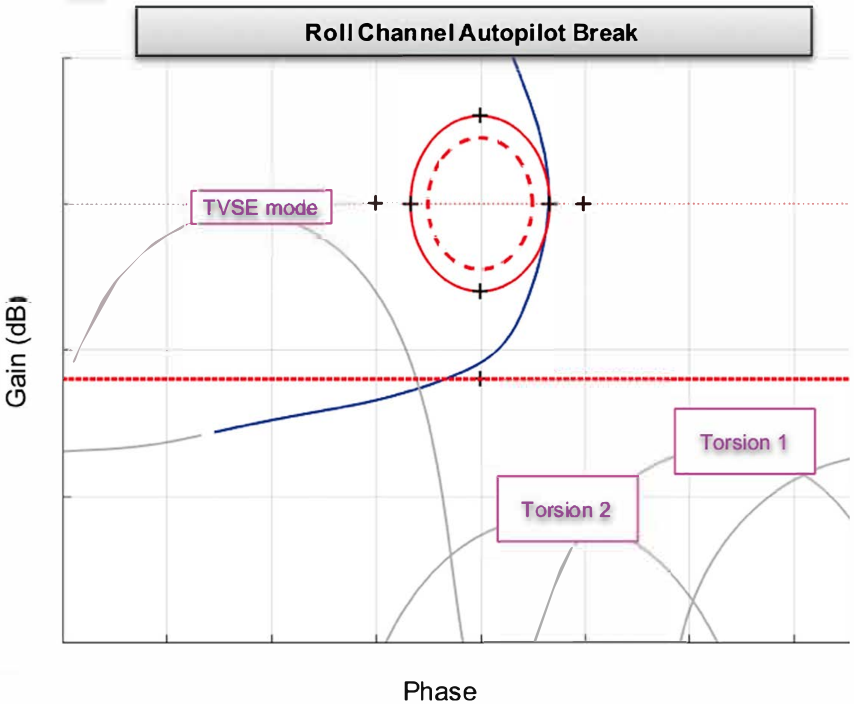


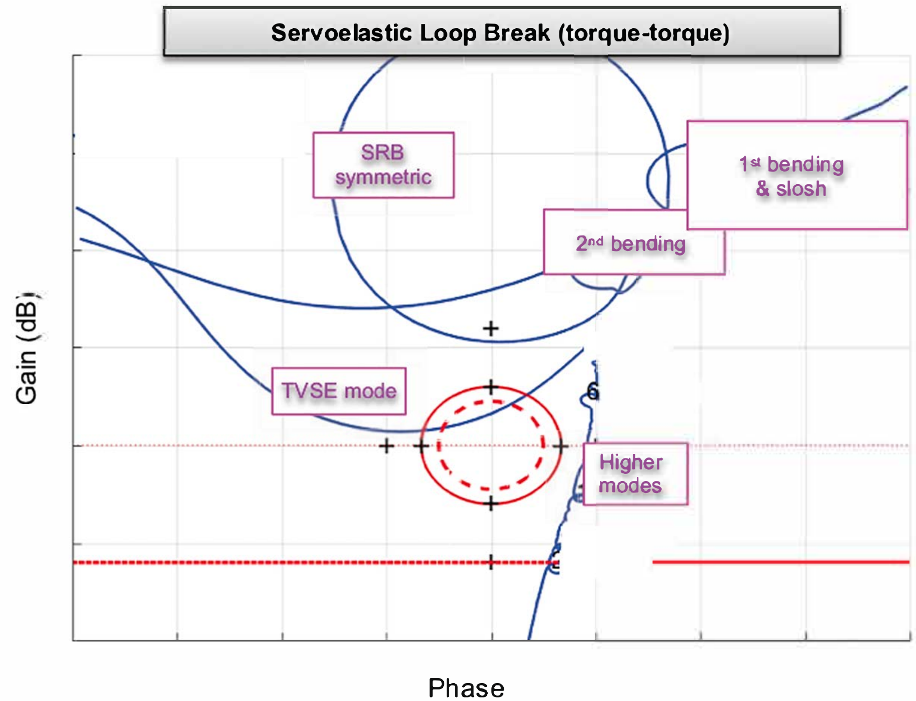


High gain modes in the sensitive region can lag such that force is in phase with velocity, reducing damping

TVSE Stability Analysis (Full model)

- **Reduced-order model predictions confirmed by high-fidelity fully-coupled model**
  - FRACTAL (Frequency Response Analysis and Comparison Tool Assuming Linearity)
  - Roll mode unstable from approximately 75-105 sec with no jet damping
  - Marginally stable with jet damping
  - Unstable with mass property and actuator performance dispersions





Plant with unstable high frequency bending cannot be robustly stabilized by FCS without dedicated sensors

[1] Orr, J. "Frequency Response Analysis and Comparison Tool Assuming Linearity (FRACTAL) Dynamics Engine," NASA MSFC, January 4, 2018.

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Q&A

- **Has this occurred on a previous launch vehicle, e.g. Shuttle?**
  - To our knowledge, no. It is unique to SLS.
  - STS had a lighter nozzle (23% lower I_{yy}) and ~1.5% antisymmetric modal damping in MVGVT (asymmetric structure)

- **Are there hardware mitigation options?**
  - Hardware options are cost/schedule/mass prohibitive or impractical
    - Forward skirt tuned mass dampers
    - Actuator hardware redesign (higher bandwidth) or hydraulics redesign
    - Lighter SRM nozzles

- **Are there software mitigation options?**
  - No, direct mitigation is not possible without dedicated sensors
    - TVSE is a hardware instability external to flight control
    - Coupled mode gain is too high to "notch filter" or *gain stabilize;* however
    - FCS influence is modest but favorable (enhances stability)
    - VM also deleted 2nd PTI to avoid exciting resonance

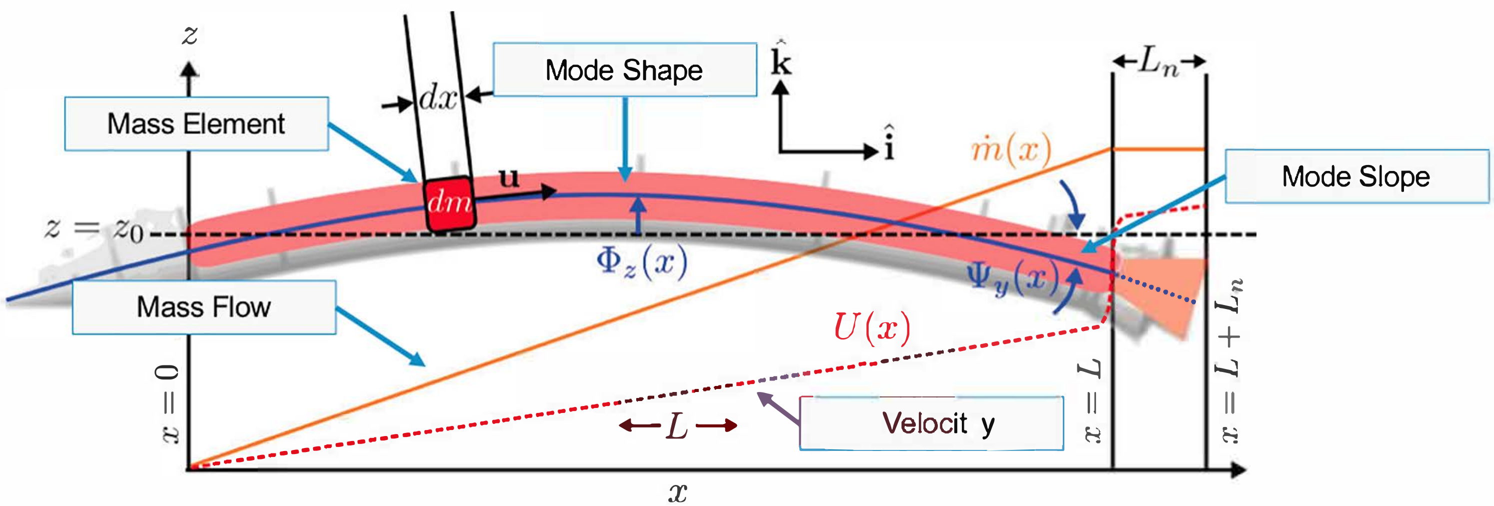
- **What about nonlinear simulation?**
  - Targeted simulations in to excite TVSE in high-fidelity fully-coupled model show no significant adverse effects.

Fidelity Improvements

1. **Elastic jet damping model with supporting data from MSFC/ER51**
   - Coriolis damping (turning of propellant flow) due to elastic/nozzle motion
   - Physics-based approach anchored to booster mass flow model data
   - Adds about 0.2%-0.3% damping to SRB bending

2. **Nozzle ablation model with supporting data from MSFC/ER43**
   - Captures loss of nozzle mass (~9%) over burn due to liner ablation
   - Vendor ablation model fitted to QM-2 nozzle erosion data
   - Improves stability by increasing actuator bandwidth

3. **Additional structural damping (above 0.5% viscous) based on STE analysis**



[2] Barrows, T. and Orr, J., "Jet Damping in FRACTAL," MSFC-EV41, November 2017

Elastic Jet Damping

- **Booster jet damping was applied to capture elastic coupling of gas flow dynamics**
  - Similar to approach used for rigid body damping in tactical missiles
  - Same method used for core stage, EUS, and booster nozzles
  - First principles analysis with conservative assumptions
  - Flow turning effects to first order are captured
  - Higher order terms in the velocity and mode shape derivatives verified to be negligible

- **Most significant jet damping effect occurs for same mode that drives TVSE**
  - Combined effect is about +0.2% to +0.3% damping to SRB bending
  - Sufficient to stabilize TVSE in the nominal case

Simplified Planar Analysis

$$\frac{Du_z}{Dt} = U\frac{d\Phi_z}{dx}\dot{\eta} + \Phi_z\ddot{\eta} + U\left(\frac{dU}{dx}\frac{d\Phi_z}{dx}\eta + U\frac{d^2\Phi_z}{dx^2}\eta + \frac{d\Phi_z}{dx}\dot{\eta}\right) \Rightarrow \frac{Du_z}{Dt} = 2U\frac{d\Phi_z}{dx}\dot{\eta}$$

			SRB Sym	SRB Antisym			
T80 Case Jet Damping	$\Delta\zeta_i \approx$	0.0541%	0.0290%	+0.1361%	+0.0170%	-0.0069%	+0.0219%
T80 Nozzle Jet Damping	$\Delta\zeta_i \approx$	0.0659%	0.0109%	0.0958%	0.0090%	0.0195%	0.0069%

[3] Orr, J., "Jet Damping and Servoelasticity," MSFC CWG, June 28, 2017
[4] Barrows, T., "Secondary Gas Flow Effects on SRB Flex Motion," MSFC-EV41, February 2018

Jet Damping - Case

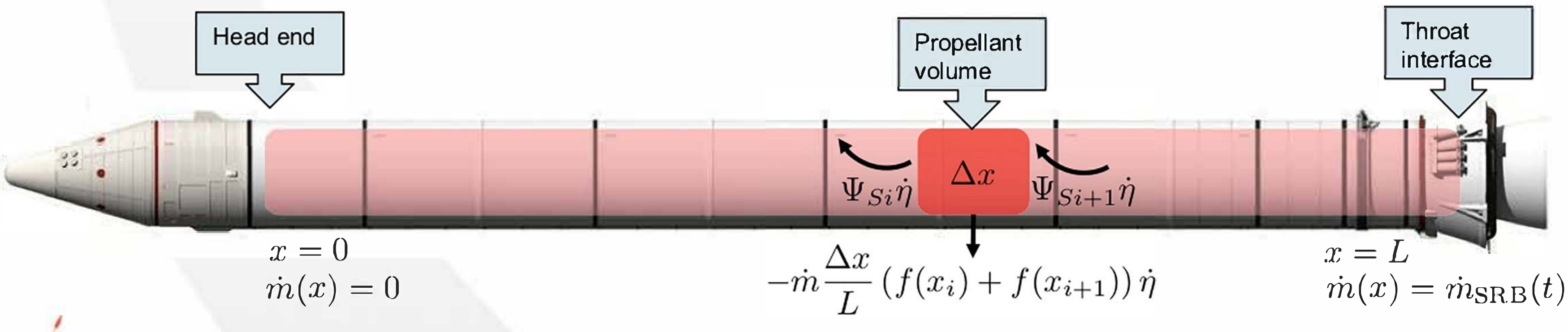
- **Approximately uniform burning in region along the propellant volume**
  - Zero mass flow at the head end (FWD segment factory joint)
  - Mass flow equal to propulsion model $\dot{m}(t)$ at nozzle throat (~gimbal point)
  - The jet damping generalized force is equal to

$$Q_{\text{case}} = -\dot{m}_{\text{SRB}}(t)\frac{2}{L}\int_0^L x\bar{\Phi}_S(x)\hat{\mathbf{i}}^\times \Psi_S(x)\,dx\,\dot{\eta}$$

- **The integral can be approximated using the piecewise eigenvectors and the non-uniform Δx along the booster using trapezoidal integration;**

$$Q_{\text{case}} \approx -\dot{m}_{\text{SRB}}(t)\frac{1}{L}\sum_{i=1}^{N}(x_{i+1}-x_i)\left(x_{i+1}\bar{\Phi}_{Si+1}\hat{\mathbf{i}}^\times\Psi_{Si+1} + x_i\bar{\Phi}_{Si}\hat{\mathbf{i}}^\times\Psi_{Si}\right)\dot{\eta} \;= -\Delta\mathbf{D}_{\text{case}}\dot{\eta} \in \mathbb{R}^{k\times k}$$

  - The delta-damping matrix can be added to the diagonal damping matrix.



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Jet Damping - Nozzle

- **Constant flow is assumed in nozzle section**
  - Mass flow equal to propulsion model $\dot{m}(t)$ from gimbal point to exit plane.
  - The angular rate of the nozzle has an elastic component and an actuator component.

$$Q_{\text{noz}} = -2\dot{m}_{\text{SRB}}(t)\int_0^{L_n} \bar{\Phi}_{\mathcal{G}i}\hat{\mathbf{i}}^{\times}\left(\Psi_{\mathcal{G}i}\dot{\eta} + [\mathbf{T}^{\mathcal{B}\mathcal{G}}]\omega_{\mathcal{G}i}\right)\,dx$$

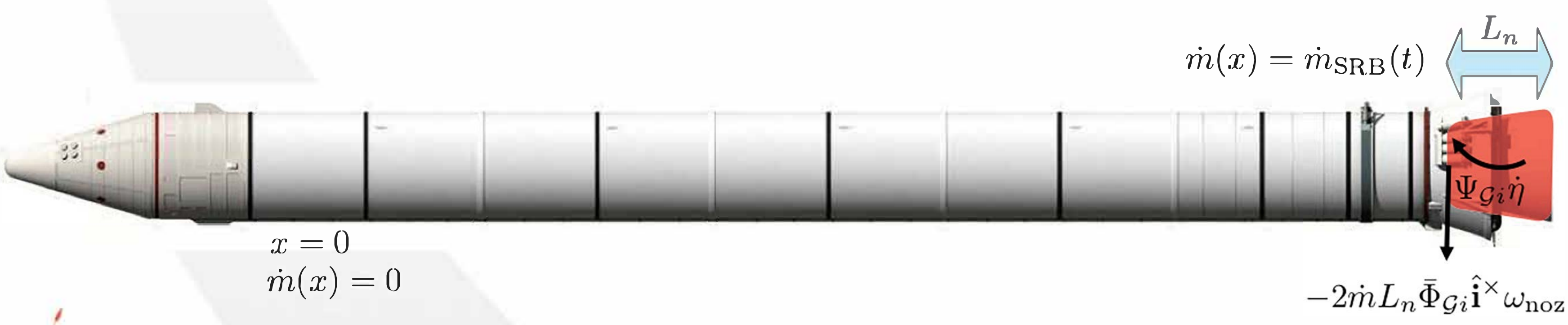
  - The elastic component also is a delta-damping matrix:

$$\Delta\mathbf{D}_{\text{noz}} = 2\dot{m}_{\text{SRB}}(t)L_n\bar{\Phi}_{\mathcal{G}i}\hat{\mathbf{i}}^{\times}\Psi_{\mathcal{G}i}$$

  - The actuator component depends on the nozzle angular rates:

$$\mathbf{A}_{\text{noz}} = -2\dot{m}_{\text{SRB}}(t)L_n\bar{\Phi}_{\mathcal{G}i}\hat{\mathbf{i}}^{\times}[\mathbf{T}^{\mathcal{B}\mathcal{G}}]$$

  - The effects combine due to (anti)symmetry.



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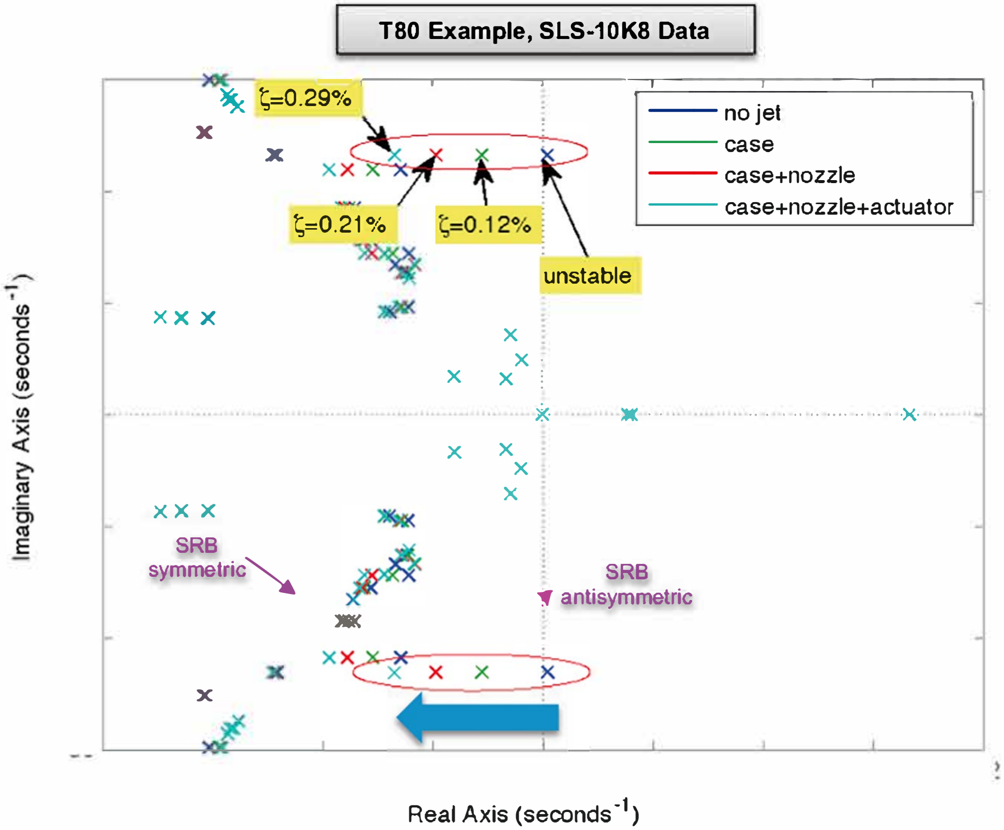
Cumulative Jet Damping Effect

- **The damping is computed for the system coupled mode (closed servoloop)**



– The cumulative effect is to shift the servoelastic resonance from ~0% to about +0.3% equivalent damping

Reviewing Modal Damping Assumptions

- **Orbiter stack SRB antisymmetric mode exhibited 1.5% modal damping in MVGVT**
  - Only about 1% damping (in addition to jet damping) is required to completely eliminate issue from consideration
  - Similar frequencies to those predicted in SLS FEM at ~T90 condition
  - These data and STE* parametric analysis using test-validated models of booster structure used to *very* slightly increase damping assumption

TABLE 17. MVGVT MODAL CORRELATION
[CONFIGURATION - BURNOUT (ANTISYMMETRIC)]

Test Mode				Analysis Mode			
Mode No.	Freq (Hz)	Damp	Description	Mode No.	Freq. (Hz)	Description	Percent Error
2	2.49	0.019	SRB Z Trans (0.45), and Roll (0.08), ORB Yaw (0.14) and Roll (0.11)	4	2.53	SRB Pitch (0.54), Roll (0.04), ORB Yaw (0.23) and Roll (0.03)	1.6
18	3.98	0.015	SRB Pitch (0.60), OMS Y (0.05), V.T. and Wing Bend (0.08)			None	
20	4.19	0.015	SRB Yaw (0.36) ORB Yaw (0.17), Wing Bending (0.13)	7	4.48	SRB Yaw (0.45), ORB Yaw (0.34)	6.9
8	6.82	0.023	FWD P/L Y (0.21), FUS Y Bend (0.21), OMS POD Y (0.10)	10	6.10	FWD P/L Y (0.54), FUS Y Bend (0.14)	10.6
10	7.529	0.016	SRB X Trans (0.54) and Y Bend (0.30), ET Y Bend (0.14)	17	8.41	SRB X (0.42), Y Bend (0.23), ET Y Bend (0.21)	11.7
21	7.92	0.037	SRB Z Bend (0.24), Roll (0.23), ORB Y Bend (0.11), Torsion (0.08)	12	6.721	SRB Z Bend (0.23), Roll (0.08), Y Bend (0.08), ORB Y Bend (0.28), and Torsion (0.11)	15.1
1C	8.49	0.016	Tuned on AFT Payload Y (0.04), SRB X (0.30), ORB Y (0.19)			None	
6	9.71	0.016	SRB Y Bend (0.37), ET Y Bend (0.15), AFT P/L Y (0.07), OMS POD Y (0.07)	22	10.01	SRB 1st Y Bend (0.38), Z Bend (0.20), ET Y Bend (0.24)	3.1
22	11.86	0.013	SRB Z (0.24) and Y Bend (0.22), and LH_2 Y Bend (0.32)			None	
12	12.52	0.009	ET Y Bending (0.90)	24	11.6	Elev Z (0.35), ET Y Bend (0.16)	7.4
17	13.35		LH_2 Shell (0.34), SRB Y Bend (0.18), CC Y (0.02)	36	14.83	LH_2 Shell (0.24), CC Y (0.08)	11.1

*Space Launch System (SLS) Structures and Thermal Environments (STE) Group

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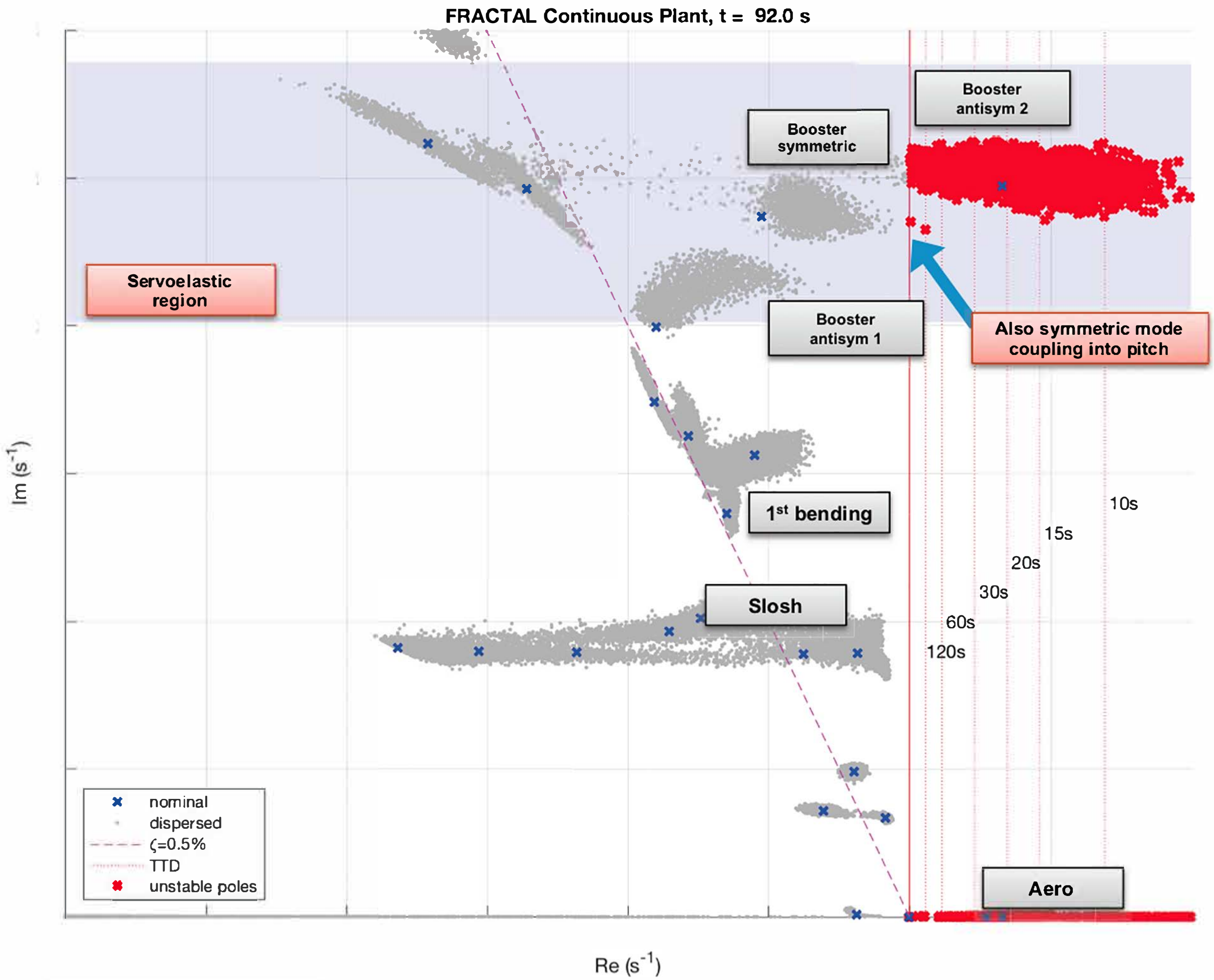
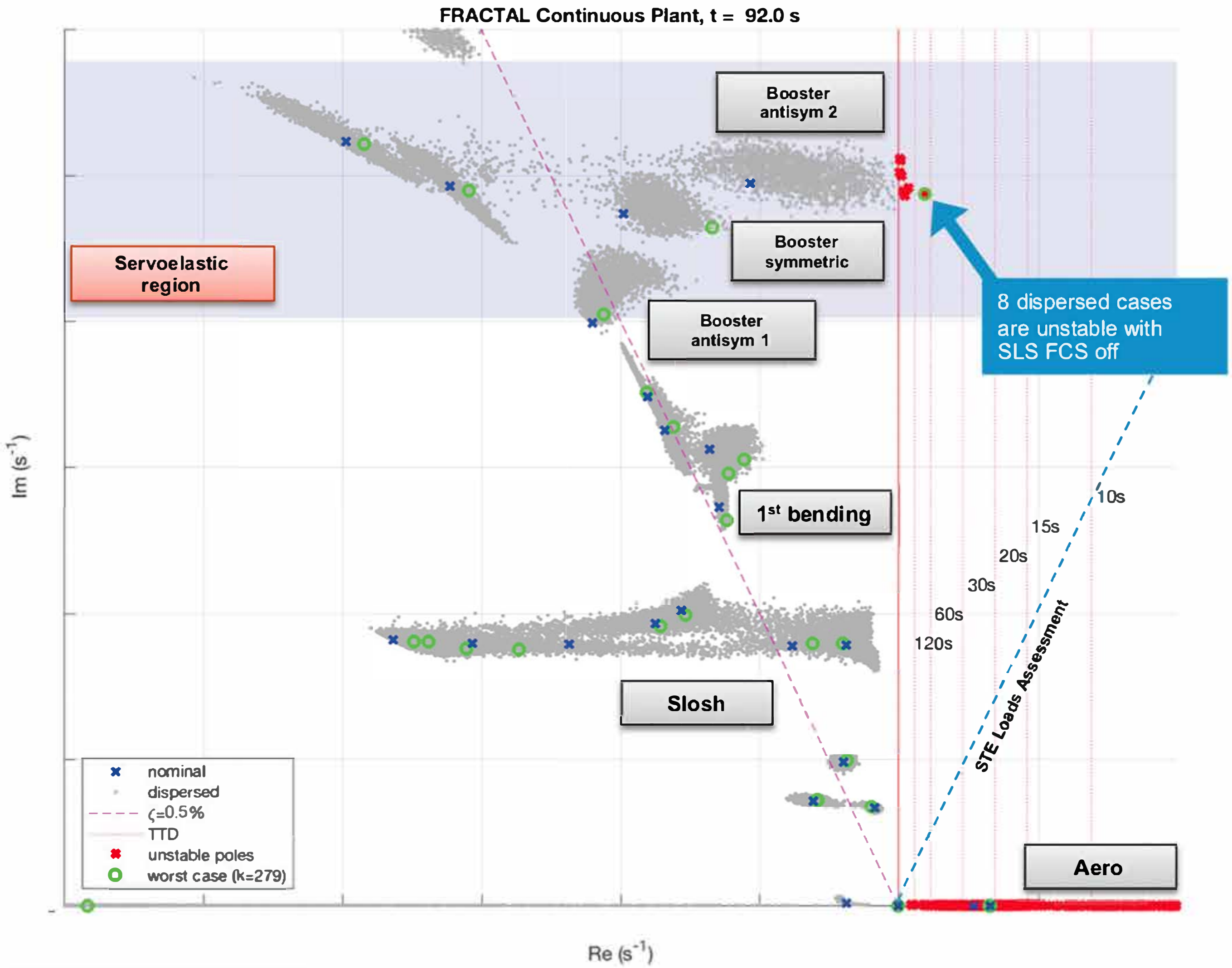
Dispersed System Damping – No Jet Damping, No Nozzle Ablation, FCS Off



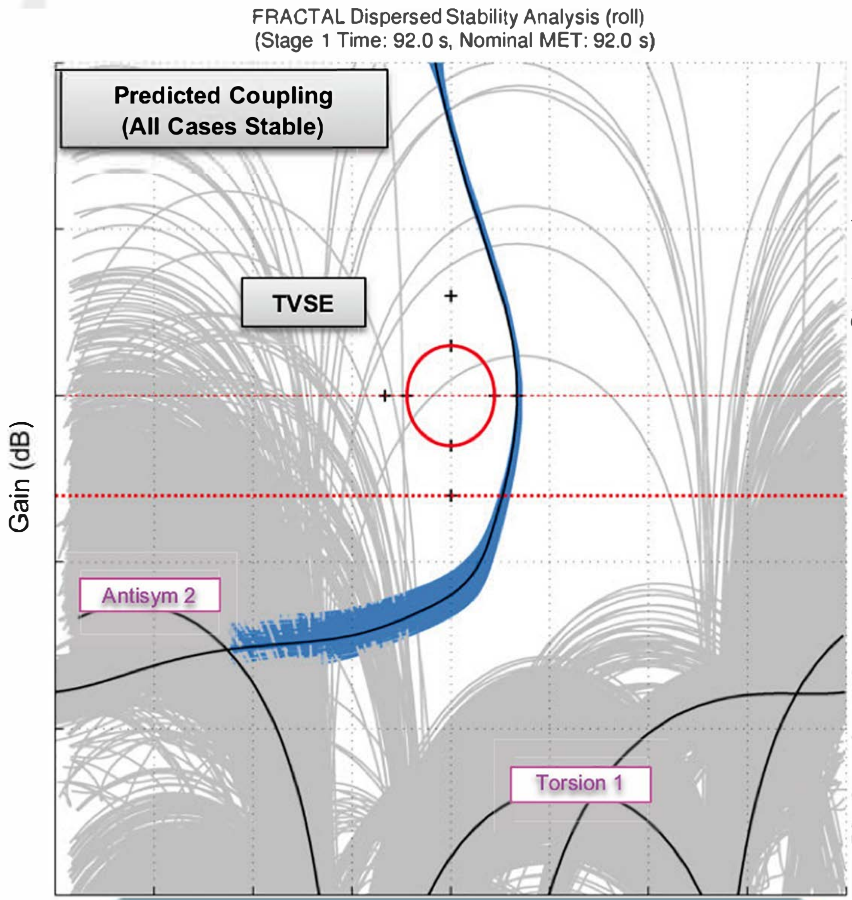
Dispersed System Damping – Jet Damping + Nozzle Ablation, FCS Off

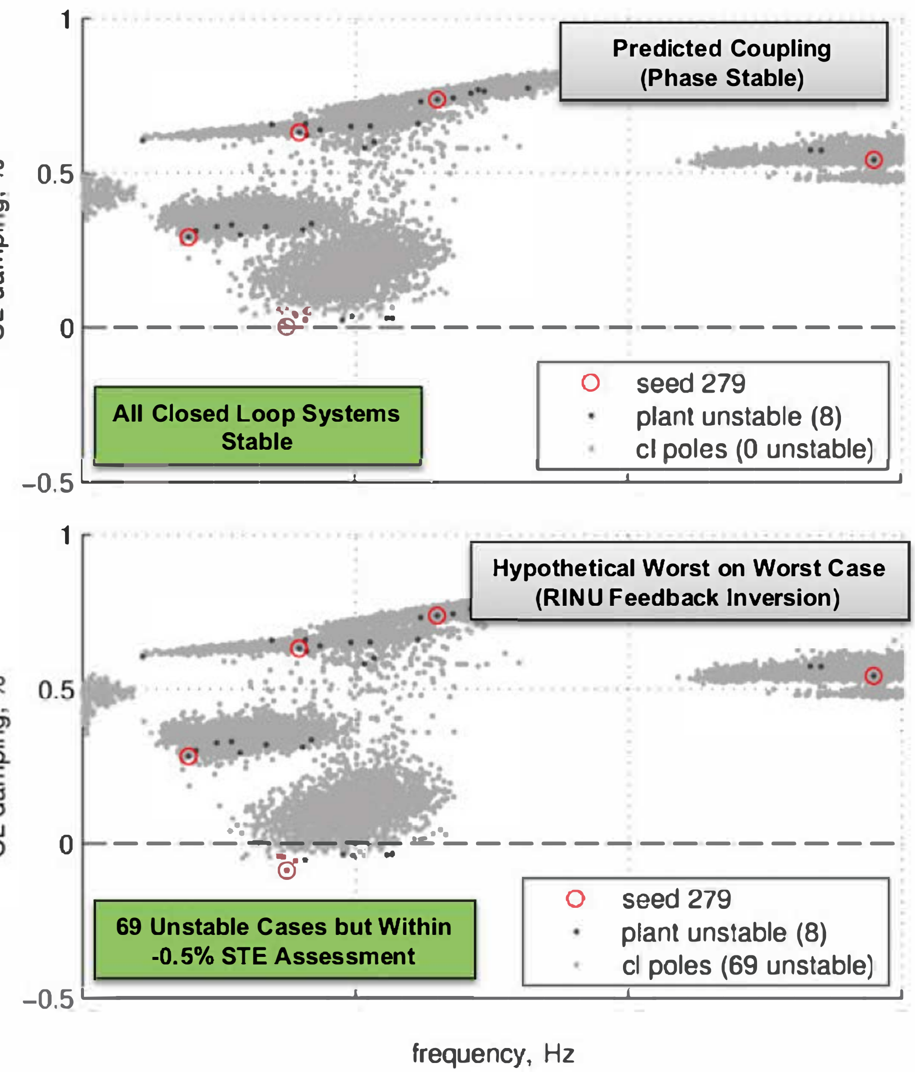
- **With STE damping, 8 cases unstable in Monte Carlo *without* FCS loop closure**
  - Benign response with TTD > 60 s and -0.05% damping



FRACTAL Analysis With FCS On

- **FCS roll feedback from RINU slightly enhances stability (phase stabilization)**
  - Torsion mode is strongly sign-definite at IMU location





FCS influence is modest but enhances stability

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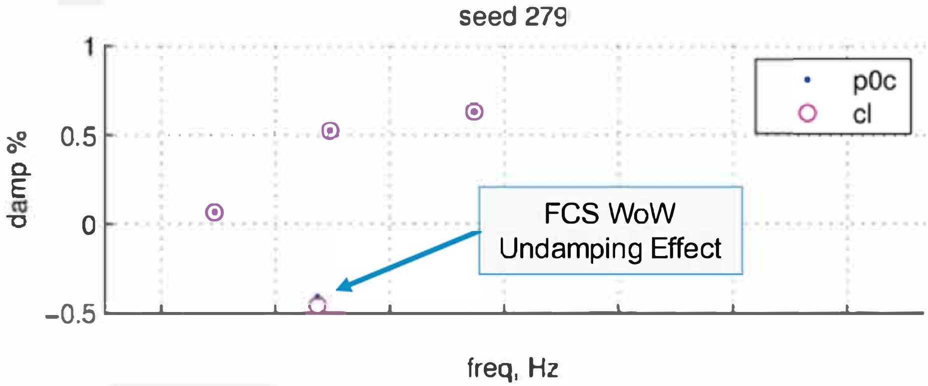
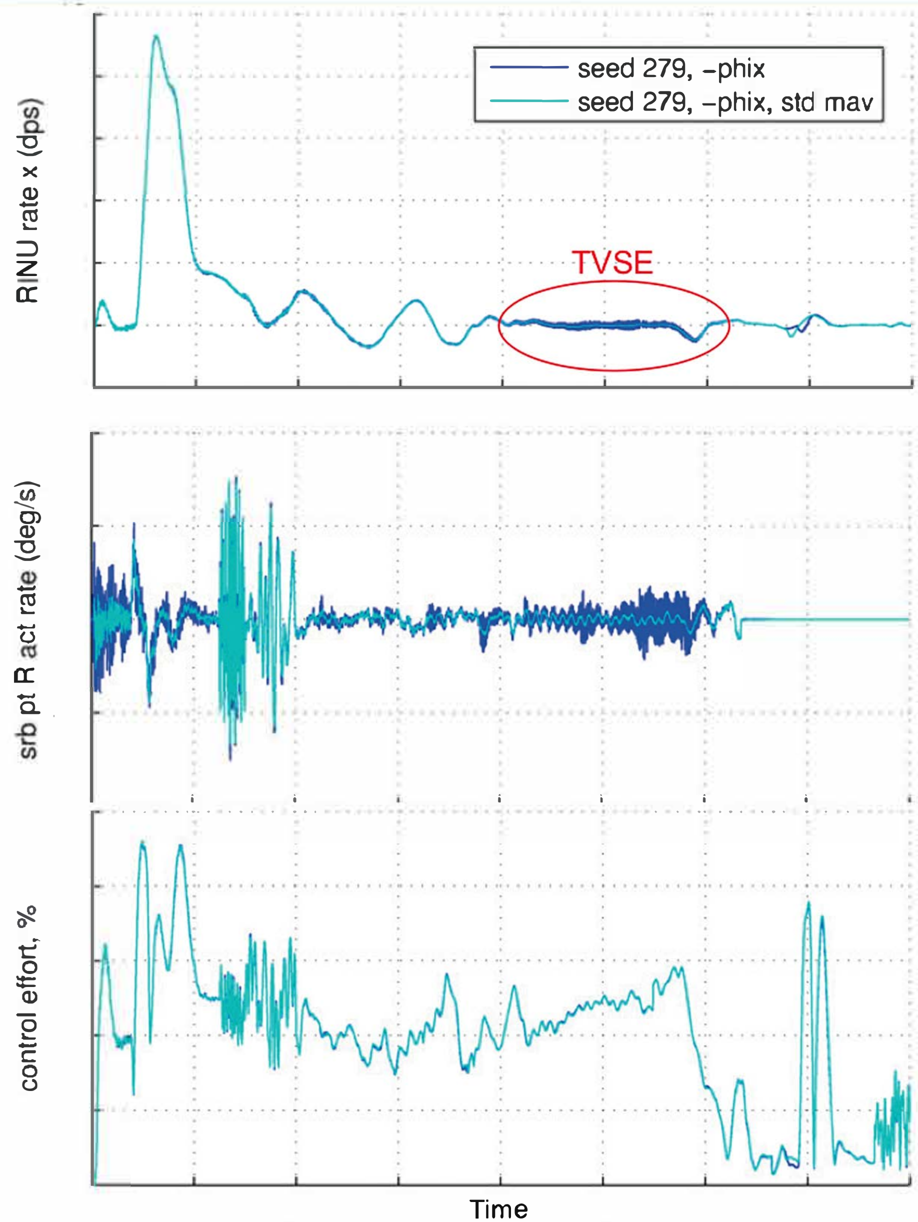
WoW: MAVERIC Time Domain RINU feedback inverted

- **Time Domain: worst case seed 279**
  - No jet damping
  - No nozzle ablation
  - Structural damping @ 0.5%
  - RINU mode slope sign inverted





Stressing case with intentional sign inversion shows inconsequential effects in nonlinear simulation

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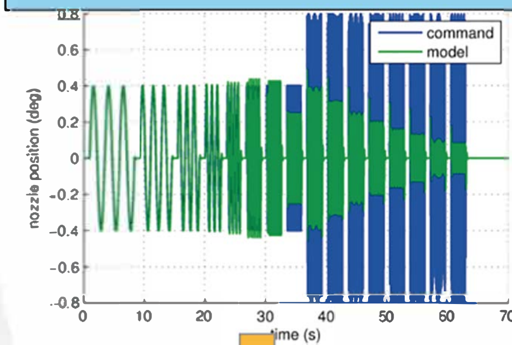
Summary and Insights

- **Beware of applications of heritage hardware to a new structure/configuration**
  - Uncovered unexpected global coupling phenomenon
  - Good example of a NASA lesson re-learned
  - Same actuator frequency response, different structure & nozzle inertia
- **TVSE effects are a credible concern for high-thrust/high-flexibility boost systems**
  - Fully-coupled servoelastic/inertial coupling model required to assess
  - Places additional constraints on FEMs (# modes, nozzles in/out, etc.)
  - Very high-quality actuators may be more likely to couple adversely
- **Modeling of moveable mass component of ablating SRM nozzle is challenging**
  - Historical data focuses on total mass/inertia of element
  - Ambiguity due to center of motion, disparate sources (FEM, MP, propulsion)
- **Still difficult to justify >0.5% damping for control-structure interaction analysis**
  - Contrast with 1% damping assumption for coupled loads analysis
  - Even with structural test data, STE/VM assumption is only slightly higher
- **Cautiously approach FCS phase stabilization of high-frequency dynamics**
  - Even with high-fidelity models, uncertainty in bending, latency, sensor dynamics, nonlinearities, etc.
  - Verify system is still good under grossly incorrect conditions (sign inversion)

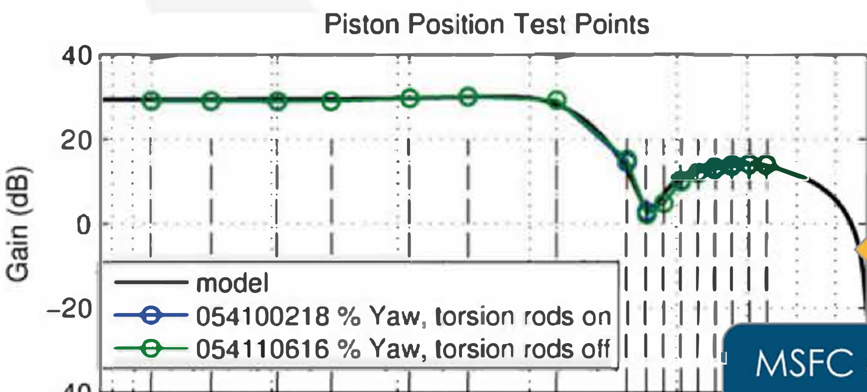
Backup: TVC Model Validation Example

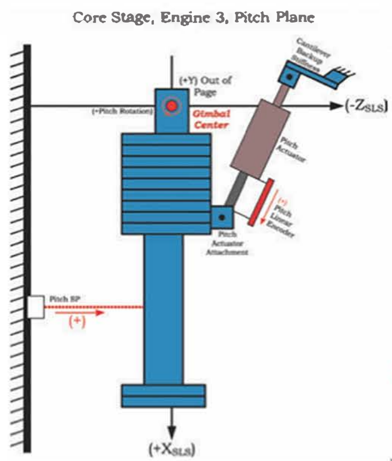
- **Booster and CSE TVC Simplex actuator models are accurate to at least 14 Hz**
  - 30+ year heritage of hardware and model development, test, and validation

2017 Feb 23 Test: CS GR FRT cmds



Simplex Model + stand stiffness mod





MSFC 4205 2-Axis TVC Simulator with Core Stage Actuator Shows Exceptional Match to CSE Simplex

Backup: Modeling Methods

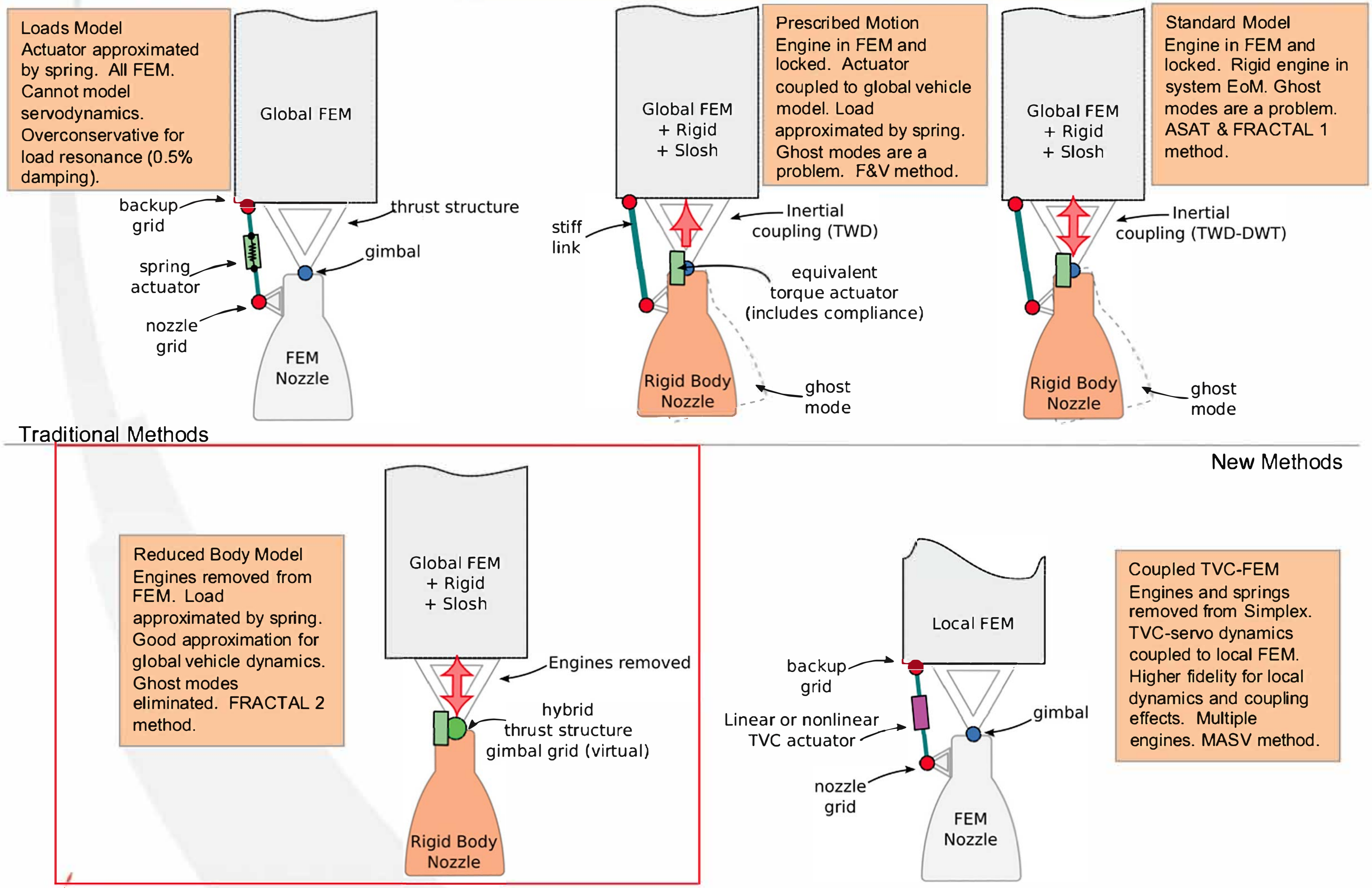
- **Prescribed Motion Model**
  - Output of TVC actuator is engine position and engine acceleration.
  - TWD coupling is modeled, but no DWT.
  - Used for early launch vehicle dynamic models, including Frosch and Vallely.

- **Standard Model**
  - System equations are written with the engine dynamics explicitly incorporated into the system as a set of angular degrees of freedom, under TVC actuator control.
  - The engine mass is included in the FEM but "locked," simplifying the formulation.
  - Challenging to determine engine constraint and the value of the backup stiffness.

- **Reduced-Body Model**
  - The engine mass is removed from the finite element model.
  - Avoids double-bookkeeping concerns on backup stiffness.
  - The TVC applies torques to a virtual grid, which may or may not use the backup grid eigenvectors.
  - This is the approach used for the study of global vehicle dynamics in FRACTAL.

- **High-Fidelity Local Structural Model**
  - Substructure finite element model contains all modes, including the engine.
  - The actuator dynamics are incorporated into the model as a force applied to the engine and backup grids.
  - Fully coupled local thrust structure dynamics.
  - High fidelity but requires typ. 500+ modes, plus static modes/residual modes.

Backup: Coupling Methods Review



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Backup: Engine Coupling Dynamics

- **Engine coupling in FRACTAL uses a torque-torque model**
  - Extension of classical methods for inertial-elastic coupling
  - Each rigid-body nozzle is included in the EoM and coupled to the thrust structure
  - EoM formulation supports "engines in" or "engines out" configurations
- **Elastic and inertial loads are coupled via modal accelerations at the gimbal point**
  - The "gimbal point" is the *thrust structure* including the actuators, which transfer loads between engine, backup structure, and thrust application point
  - Gimbal mode slope appears in rigid equations with no-engine FEM

$$\left(\mathbf{I}_k + \bar{\Gamma}_{ei} m_{ei} \Gamma_{ei} + \bar{\Psi}_{\mathcal{G}i}\left(\mathbf{J}^{\mathcal{G}}_{ci} + m_{ei}\mathbf{r}^{\times}_{\mathcal{G}ei}\mathbf{r}^{\times}_{\mathcal{G}ei}\right)\Psi_{\mathcal{G}i}\right)\ddot{\eta} + \mathbf{D}_{\eta}\dot{\eta} + \Omega^2\eta$$

$$= -\bar{\Gamma}_{ei} m_{ei}\delta\dot{\mathbf{v}} + \left(m_{ei}\bar{\Phi}_{\mathcal{G}i}\left(\mathbf{r}_{\mathcal{G}i} + \mathbf{r}_{\mathcal{G}ei}\right)^{\times} + \bar{\Psi}_{\mathcal{G}i}\left(\mathbf{r}^{\times}_{\mathcal{G}ei} m_{ei}\mathbf{r}^{\times}_{\mathcal{G}i} - \mathbf{J}^{\mathcal{G}}_{ci}\right)\right)\delta\dot{\omega}$$

$$-\bar{\mathbf{\Phi}}_{sj} m_{sj}\ddot{\rho}_{sj} - \left(\bar{\Psi}_{\mathcal{G}i}\mathbf{J}^{\mathcal{G}}_{ei} - \bar{\mathbf{\Phi}}_{\mathcal{G}i} m_{ei}\mathbf{r}^{\times}_{\mathcal{G}ei}\right)\dot{\omega}_{\mathcal{G}i}$$

$$+R_{ei}\bar{\Phi}_{\mathcal{G}i}\left(\mathbf{u}_{ei} - \mathbf{u}^{\times}_{ei}\Theta_{\mathcal{G}i}\right) + Q_{\text{jet}}$$

Orange	Generalized force due to thrust
Yellow	No-engine FEM
Green	TWD-Flex
Blue	Slosh

$\mathbf{I}_k$	Identity matrix	η	Elastic generalized displacement
m_{ei}, $\mathbf{J}^{\mathcal{G}}_{ei}$	Mass/inertia of engine	$\delta\dot{\mathbf{v}}$	Rigid-body acceleration
Γ_{ei}	Elastic coupling coefficient	$\delta\dot{\omega}$	Rigid-body angular acceleration
$\Phi_{\mathcal{G}i}$, $\Psi_{\mathcal{G}i}$	Mode shape/slope at gimbal	$\dot{\omega}_{\mathcal{G}i}$	Gimbal angular acceleration
$\mathbf{r}_{\mathcal{G}i}$, $\mathbf{r}_{\mathcal{G}ei}$	Location of gimbal, location of engine CG	ρ_{sj}	Slosh displacement
Φ_{sj}, m_{sj}	Sloshing mode shape and slosh mass	$\Theta_{\mathcal{G}i}$	Engine angular displacement
R_{ei}, $\mathbf{u}_{ei}$	Thrust and thrust unit vector (body)		

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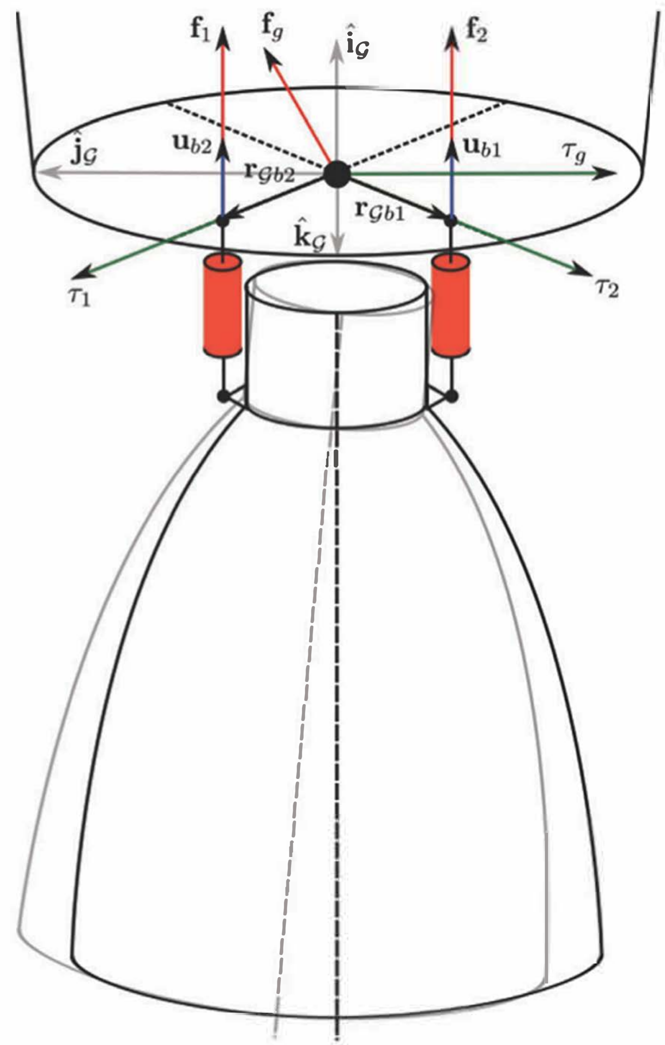
Backup: Force-Based Virtual Grid

- **Improved method constructs virtual grid $\Psi_{\mathcal{G}} \in \mathbb{R}^{3\times k}$ from static equilibrium problem**
  - Given applied torque τ_g, resolve torque into force components along actuator action lines $\mathbf{u}_{bi}$ and force $\mathbf{f}_g$ at gimbal
  - Gimbal torque component due to each actuator is $\tau_i = \mathbf{r}^{\times}_{\mathcal{G}bi} f_i \mathbf{u}_{bi}$
  - Forces must sum to zero: $\mathbf{f}_1 + \mathbf{f}_2 + \mathbf{f}_g = \mathbf{0}$
  - Let unknowns be $\mathbf{x} = \begin{bmatrix} f_1 \\ f_2 \\ \mathbf{f}_g \end{bmatrix} \in \mathbb{R}^5$
  - In matrix form,

$$\begin{bmatrix} \mathbf{r}^{\times}_{\mathcal{G}b1}\mathbf{u}_{b1} & \mathbf{r}^{\times}_{\mathcal{G}b2}\mathbf{u}_{b2} & \mathbf{0}_3 \end{bmatrix} \mathbf{x} = \mathbf{A}\mathbf{x} = \tau_{\mathbf{g}}$$

$$\begin{bmatrix} \mathbf{u}_{b1} & \mathbf{u}_{b2} & \mathbf{I}_3 \end{bmatrix} \mathbf{x} = \mathbf{C}\mathbf{x} = \mathbf{0}$$

  - This is a linearly constrained LS problem that has a unique solution.



SLS