Orion MPCV E-STA Nonlinear Correlation for NESC

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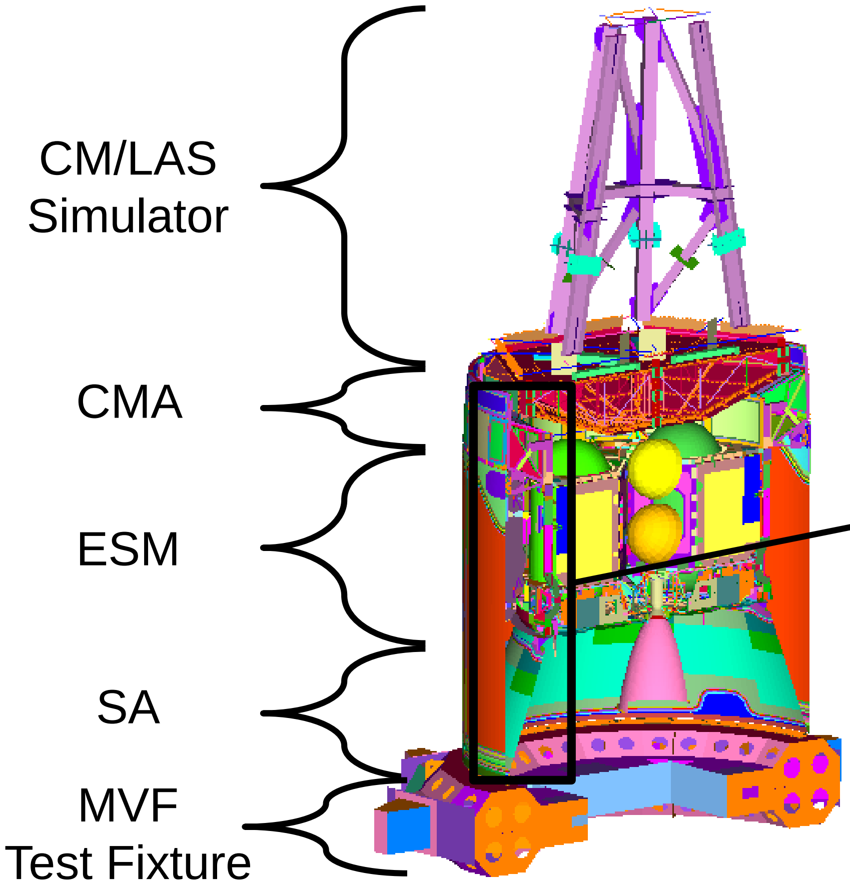
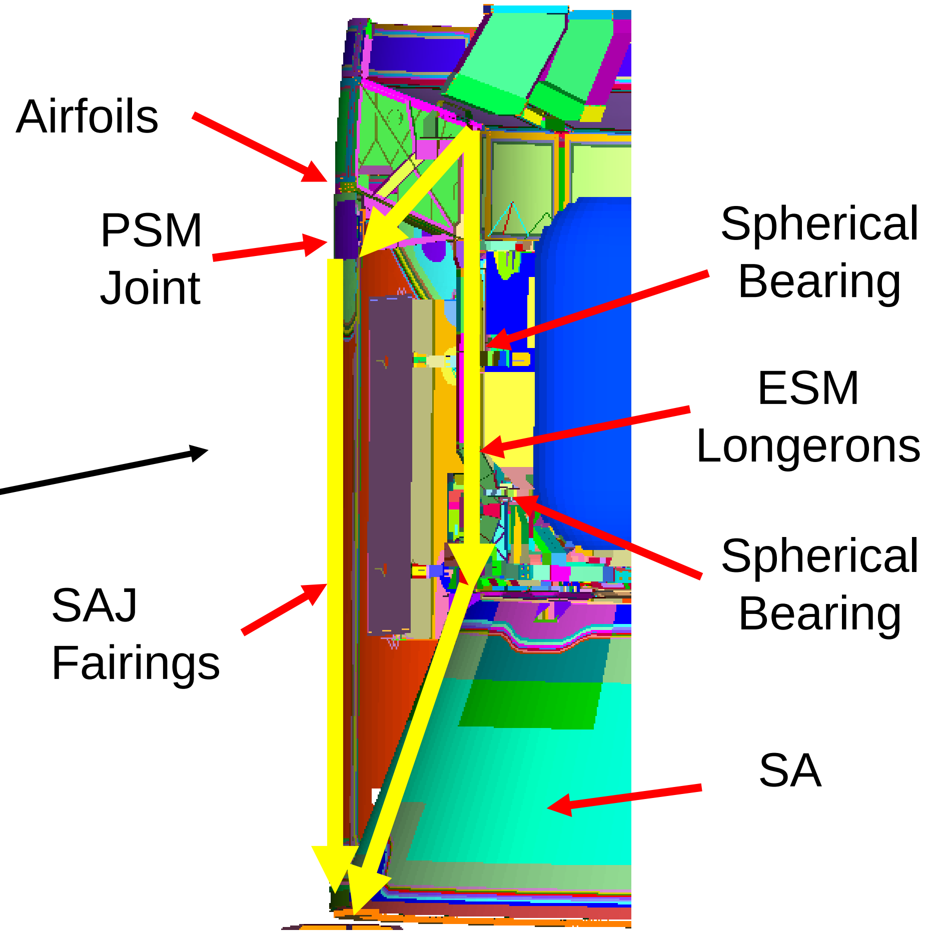
Background

- European Service Module (ESM) Structural Test Article (E-STA) vibration testing performed using the Mechanical Vibration Facility (MVF) at NASA Plum Brook Station
  - Verify structural integrity of near flight-specimen of ESM
- Large nonlinear behaviors observed
  - Frequency and damping vary widely between test cases
  - Nonlinear FRF shapes
- Previous low level modal/random tests at other facilities did not produce significant nonlinearities

E-STA Model Overview



Dual Load Path

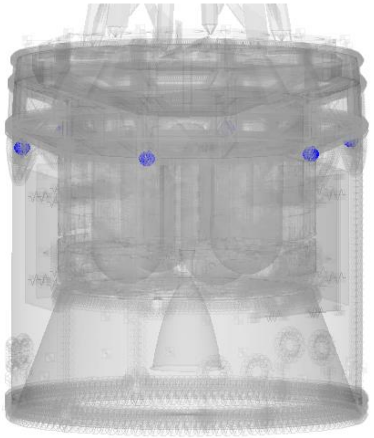


Linear Correlation Summary

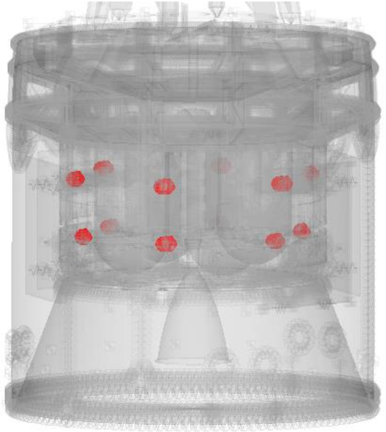
- **Previous effort by Quartus for NESC (presented at SCLV 2018) resulted in 2 correlated linear FEMs**
  - **Low load level (LLL) – 20%**
  - **High load level (HLL) – 100%**
- **Linear correlation performed in frequency domain**
- **Differences between FEMs reduced to properties at 3 joints (largest sources of nonlinearity)**
  - **Airfoils (SAJ to CMA), PSM, and ESM spherical bearings**

Airfoil Springs

PSM Springs



ESM SB Springs

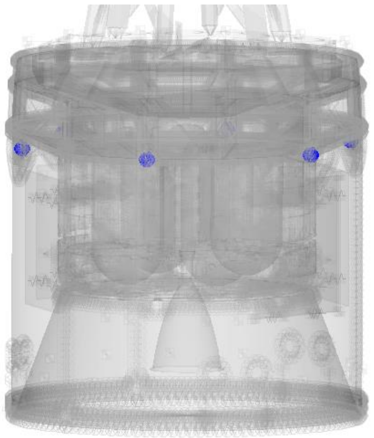


Location	DOF	LLL Stiffness Increase over HLL
Airfoil	1-3	1500
PSM	4	100
Spherical Bearings	1	1.5

E-STA Joints

Airfoil Springs

PSM Springs



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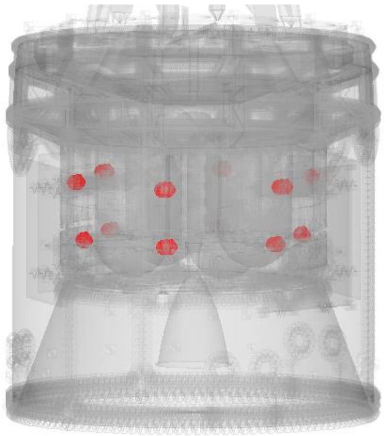

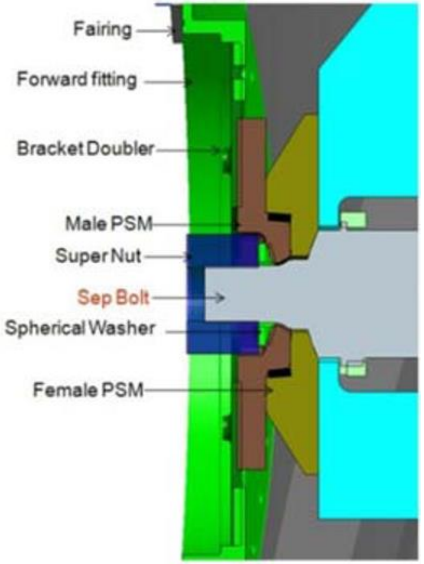

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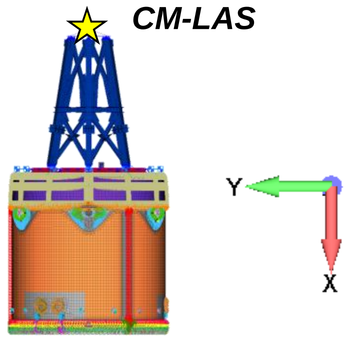
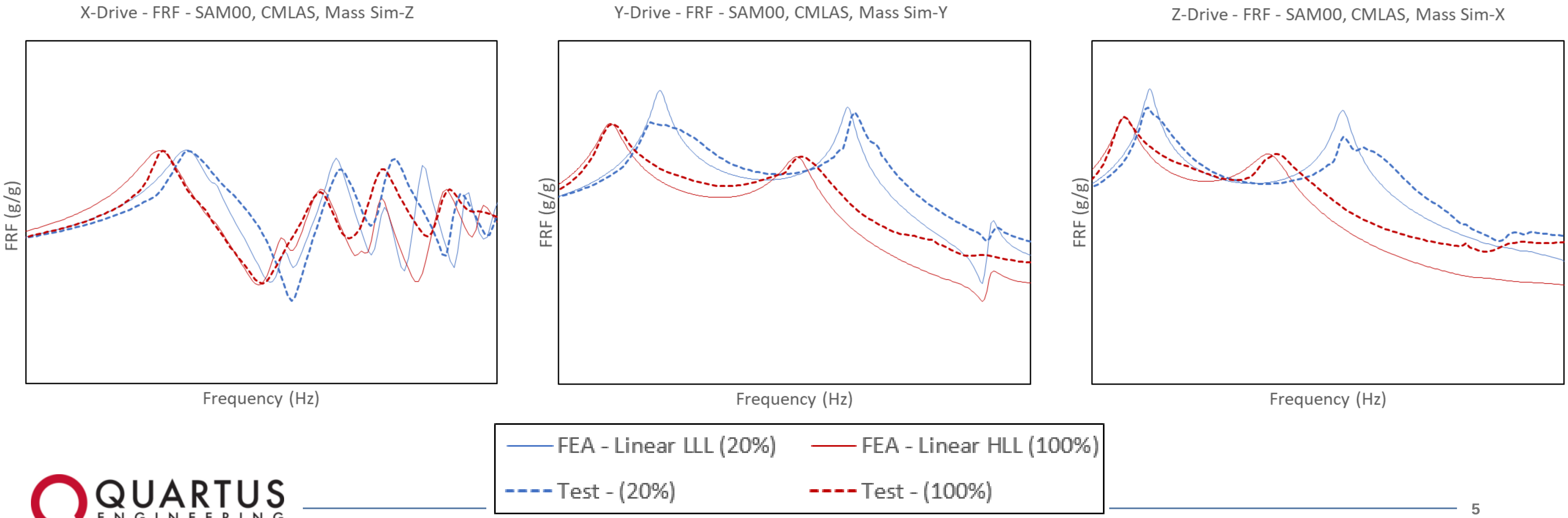
Linear Correlation Results – Acceleration

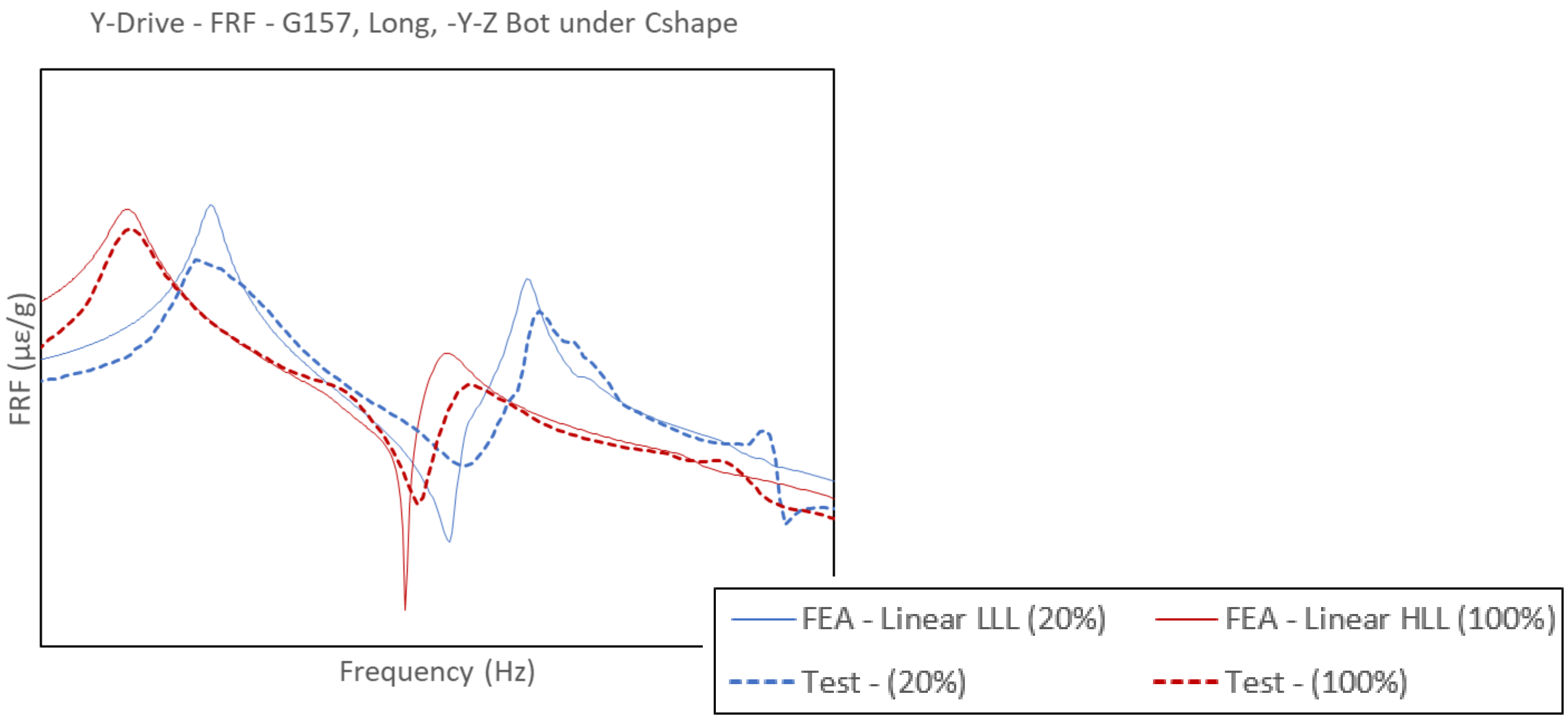
- **Representative location shown (CM-LAS)**
  - **Many more locations were examined/compared during the correlation process**





Linear Correlation Results – Strain

- **Representative location shown (inner load path longeron)**
  - Many more locations were examined/compared during the correlation process

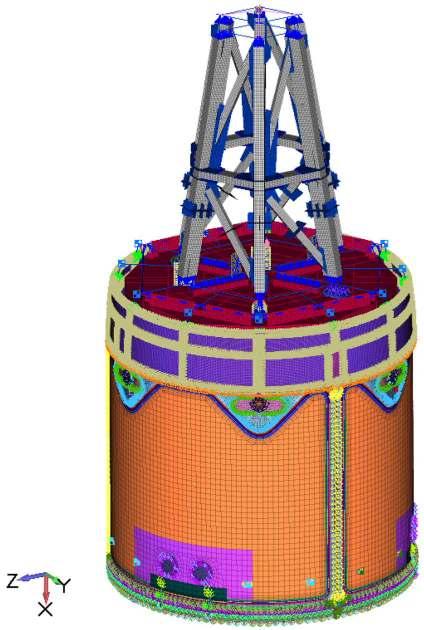


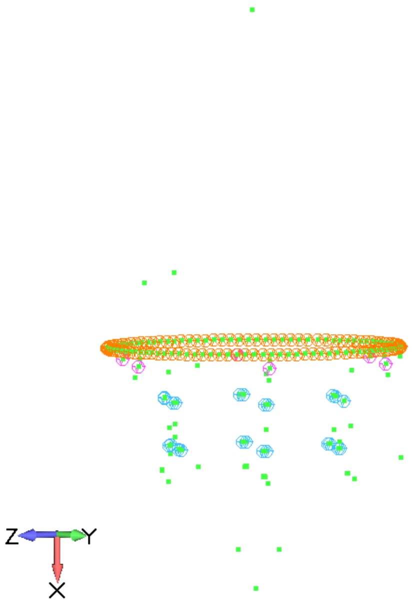
Nonlinear Correlation Motivation

- **Further elucidate the source and type of nonlinearity**
- **Capture extent of MPCV nonlinear dynamics in a single model**
  - Can correlate linear models to high or low loads conditions, but cannot ensure that analysis of those models will envelope responses
- **Inform the use of linear models in CLA** ***(not covered in this SCLV presentation)***
  - Can linearized models accurately predict MPCV flight responses?
  - What linearized models (HLL vs. LLL) should be used for different cases?
  - What uncertainty factors are required?

HCB Model Reduction

- **Hurty/Craig-Bampton (HCB) reduced model created from linear correlated LLL model**
  - Retained I/F, response, and nonlinear joint DOF
    - I/F grid BSET, all other boundary grids CSET (FEM: 4.4e6 DOF; HCB: 1218 DOF)
- **HCB matrices converted from NASTRAN to Abaqus**



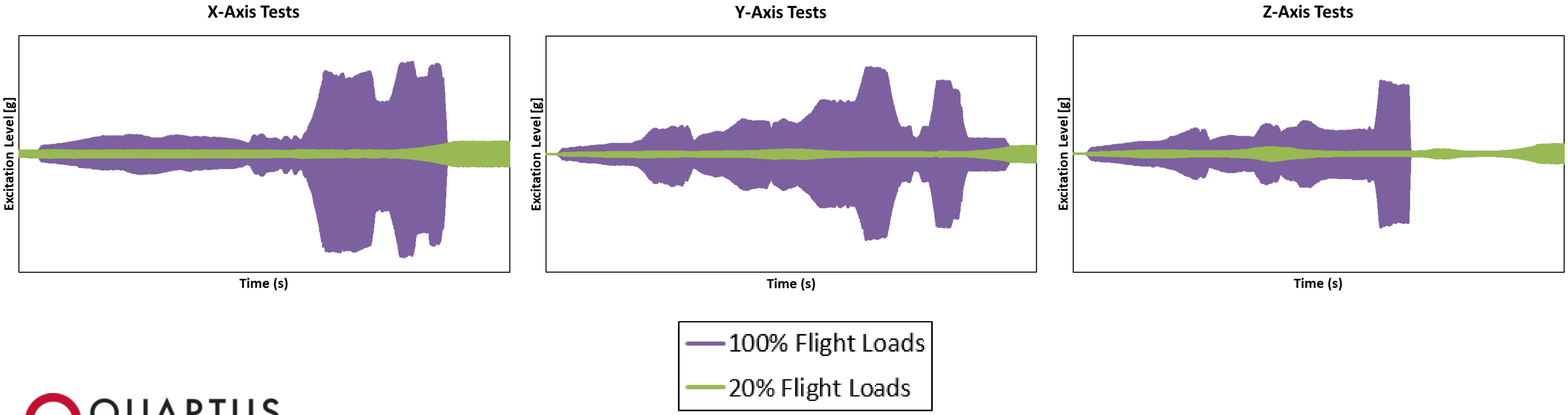


Nonlinear Transient Analysis

- Nonlinear implicit dynamic analyses performed using Abaqus/Standard
  - HHT time integration
- Recovered transient E-STA sine sweep test data used as inputs
  - Analyzed both 20% & 100% input levels for all three axes
- Nonlinear joints modeled using Abaqus connector elements
  - Lagrange multipliers allow for complicated reactions including Coulomb friction
- FRFs calculated from transient responses using spectral density estimation

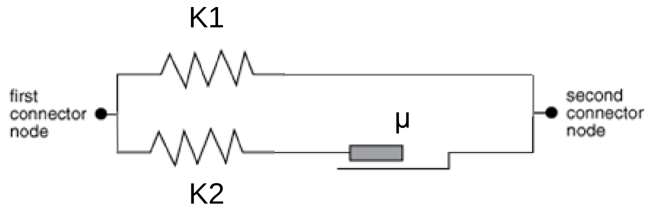
Transient Sine Sweep Inputs

- **Recovered transient E-STA sine sweep test data used as input**
  - Input levels vary (not a constant sine sweep)
  - All tests are sweeps up in frequency (frequency increases with time)



Nonlinear Joint Models

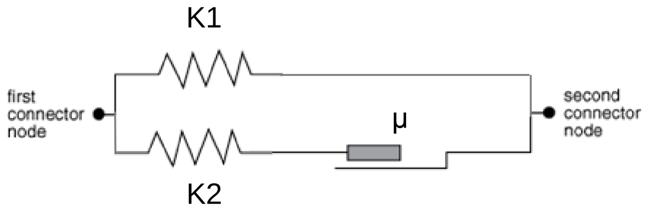
- **The airfoils and PSMs were modeled using regular Coulomb friction**
- **The spherical bearings used nonlinear stiffness/viscous damping in the axial direction**
- **Abaqus connector elements with friction have the following available variables**
  - K1 = slip stiffness
  - K1 + K2 = stick stiffness
  - μ = coefficient of friction
    - Critical slip load kept constant using constant internal generating normal force
      - $\tau = \mu F_{int}$



Nonlinear Correlation Summary

- **Table below summarizes the final nonlinear joint parameters in relation to their initial settings informed from the linear correlation**
  - $K1_i$ = HLL, $K1_i + K2_i$ = LLL, τ_i determined during LLL linear correlation

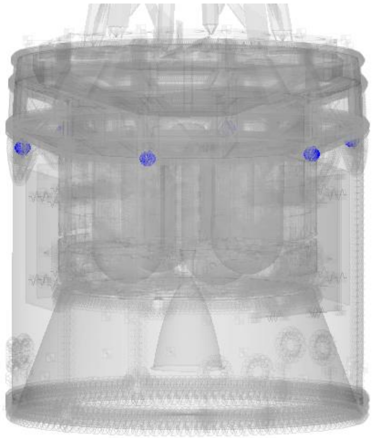
Nonlinearity Table				
Location	DOF	Nonlinear Correlated E-STA Model		
		K1	K1+K2	τ
Airfoil-to-CMA	2-3	0	8*LLL	2*LLL
PSM	4	HLL	LLL	LLL
ESM Spherical Bearings	1	0	33*LLL	LLL



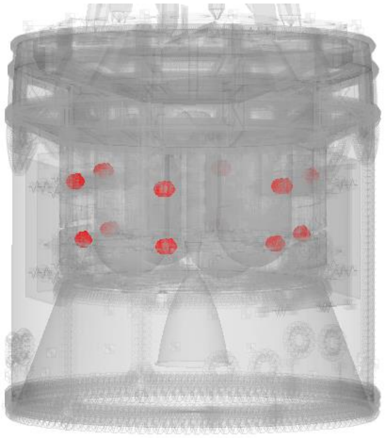
$$\tau = \mu F_{int}$$

Airfoil Springs

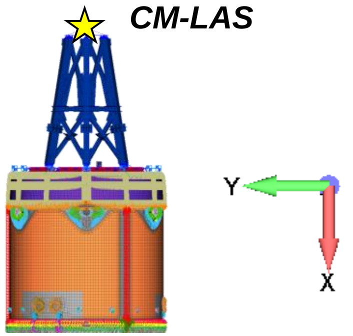
PSM Springs



ESM SB Springs



Nonlinear FEM Correlation Results – Acceleration



- **Representative location shown (CM-LAS)**
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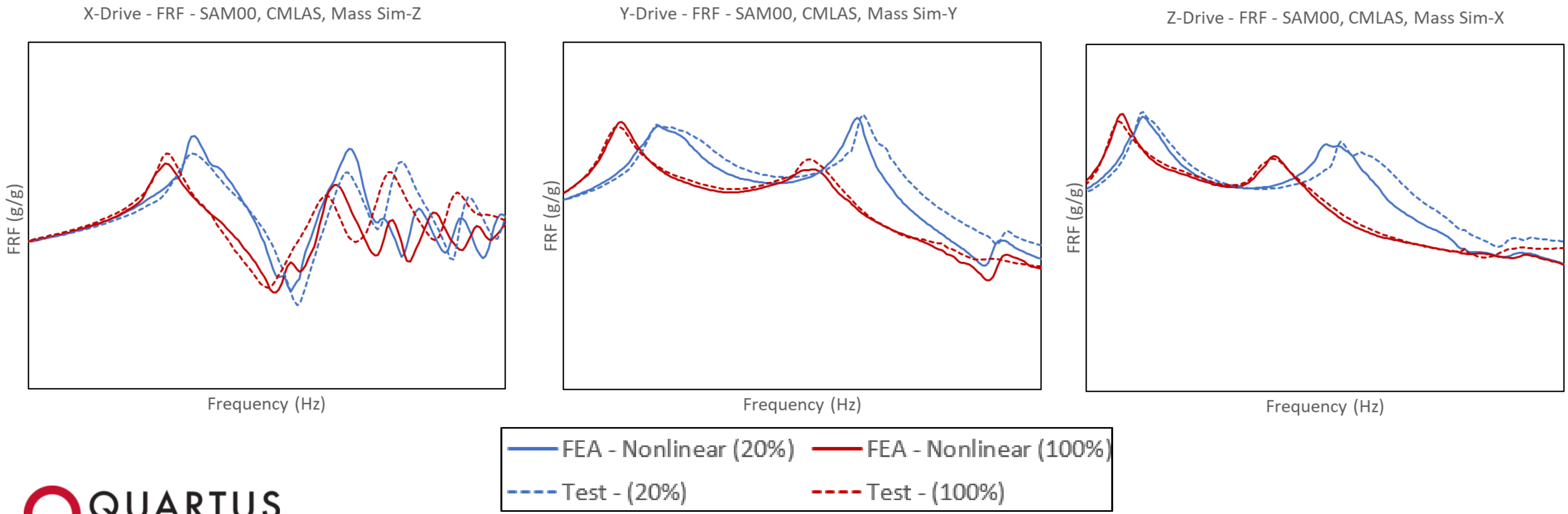

Nonlinear FEM Correlation Results – Strain

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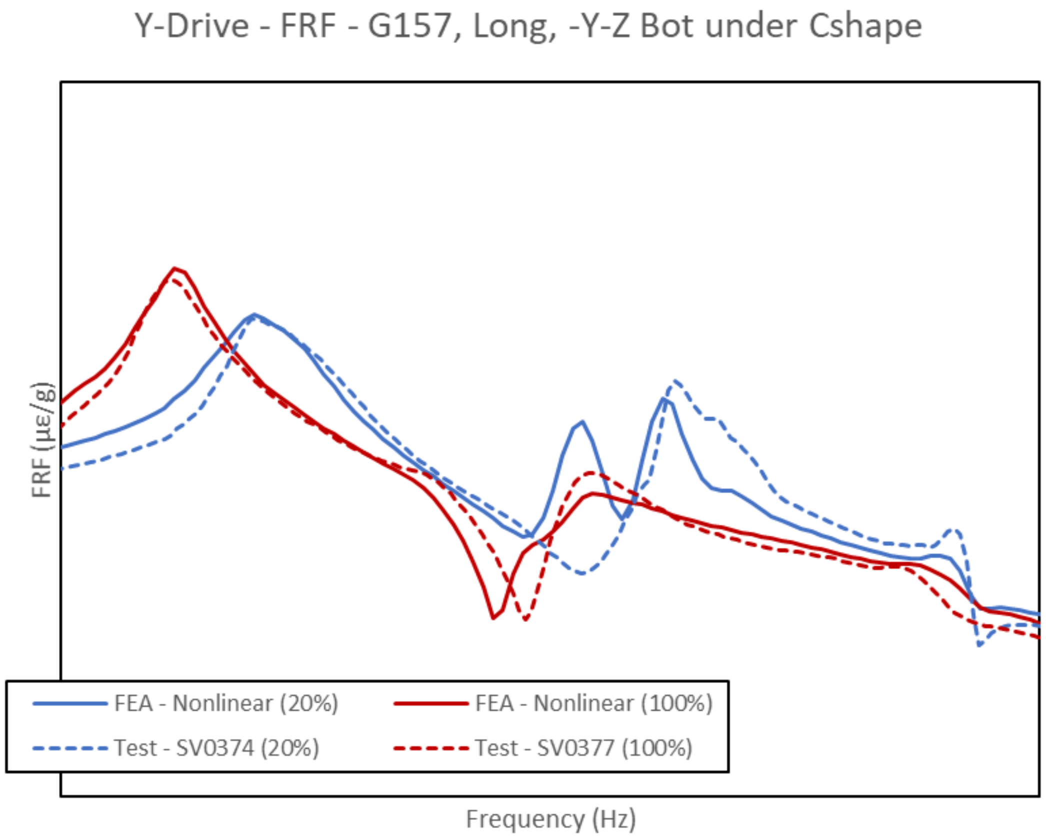


Summary & Recommendations

- **Nonlinear analysis can successfully capture MPCV nonlinear dynamic response**
  - Single model accurately captures response for all load levels
  - Excellent correlation achieved for primary lateral response
  - Very good correlation achieved for primary axial response
- **Subsequent analysis of select CLA load cases showed that the linear correlated FEM(s) match the nonlinear correlated FEM relatively well**
  - With modest uncertainty factors, HLL bounds for “high” load events while LLL bounds for “low” load events
- **Beyond a full nonlinear CLA, a dual linearized CLA may be appropriate to fully bound the response of MPCV**
  - Linear model selection & uncertainty factors informed by limited nonlinear CLA study

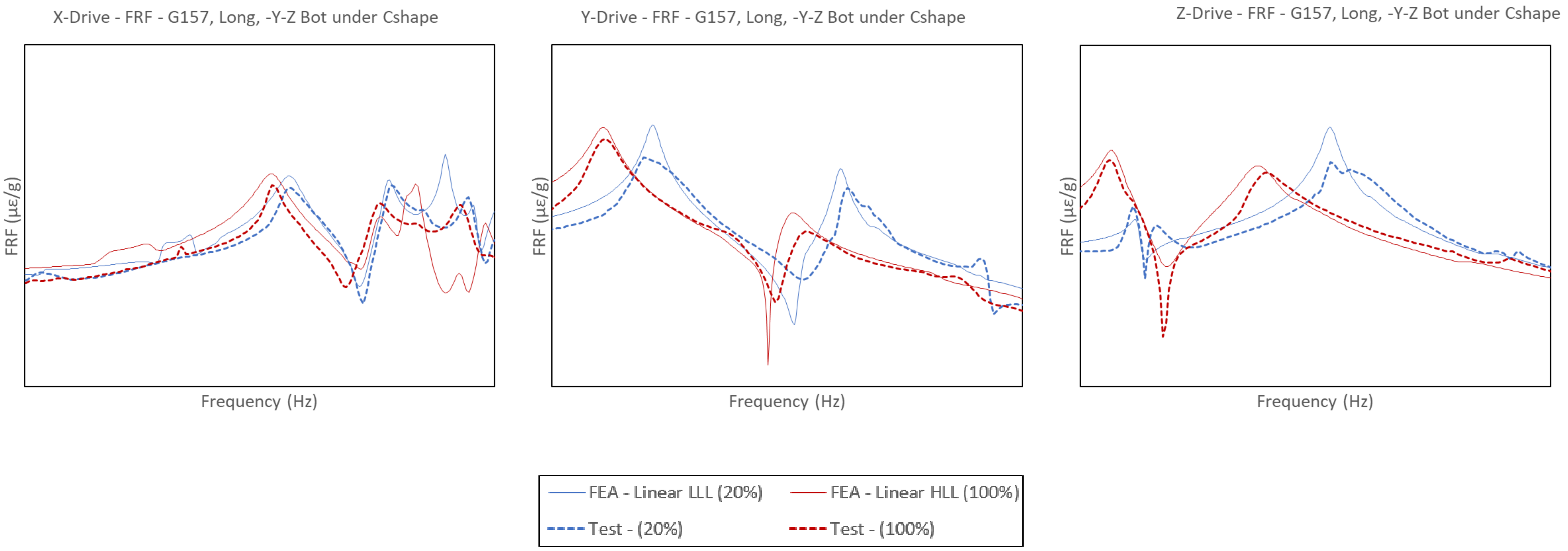
Future Work

- **Improve axial response**
  - Spherical bearing kinetic friction
  - Add friction regularization
- **Perform limited nonlinear full-vehicle CLA**
  - Correlated nonlinear MPCV model integrated into SLS
  - Determine if MPCV nonlinearities effect system modes or MPCV I/F levels
- **Perform linear and nonlinear correlation for future flight configurations**
  - Use breakout nonlinear CLA study to inform model selection/uncertainty factors

Questions?

APPENDIX

Linear Correlation Results – Strain



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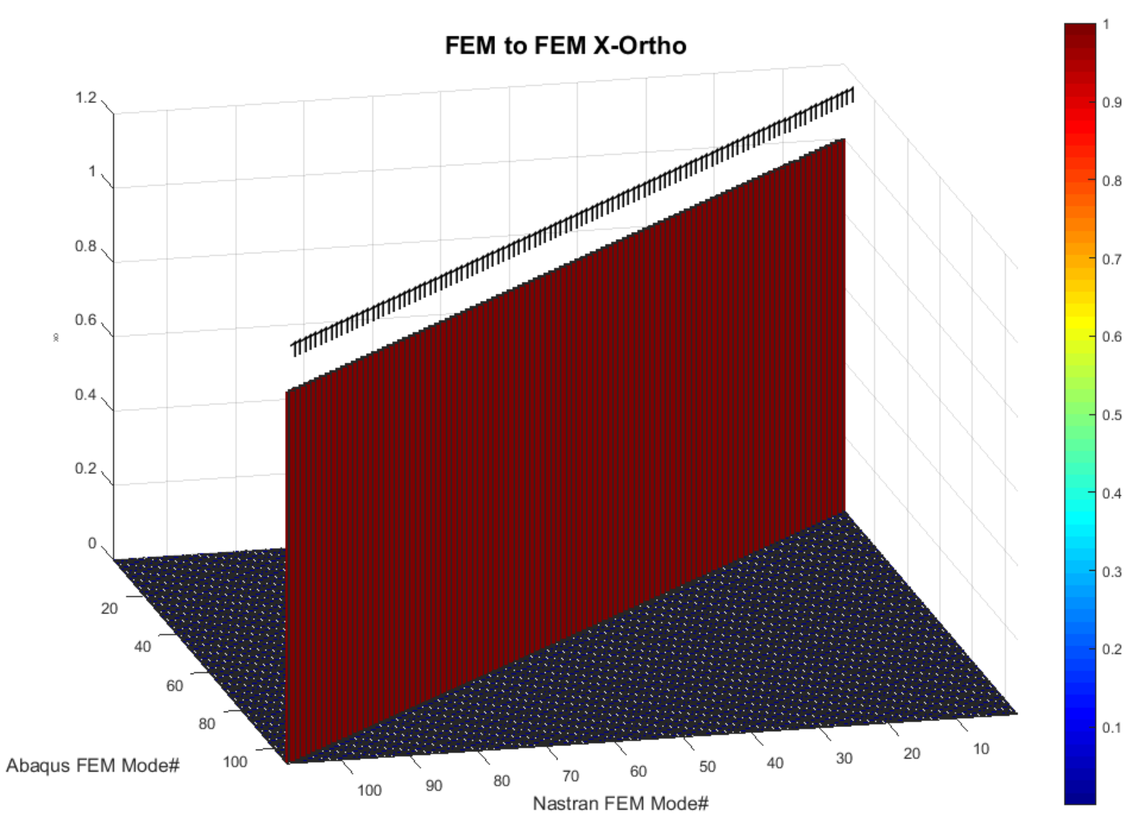
HCB Abaqus Conversion – Modes Check

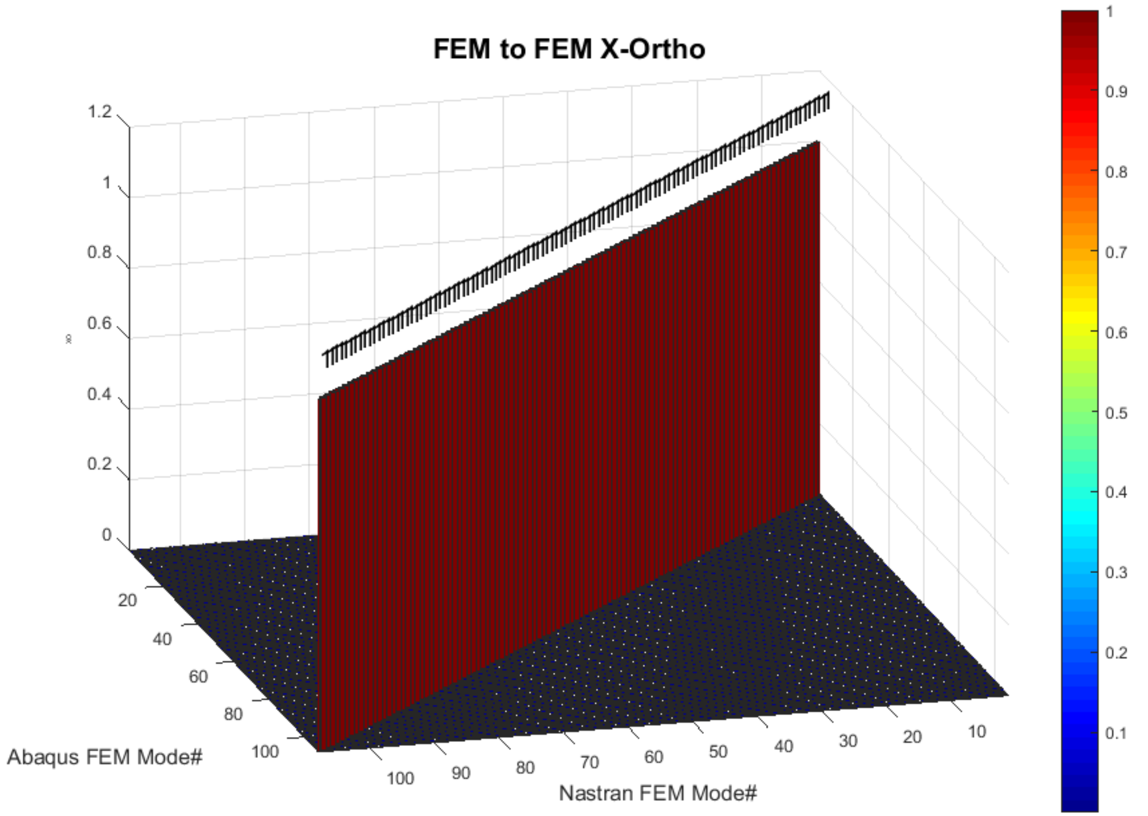
Mode	Nastran	Abaqus	
	HCB	HCB Only	HCB w/ Connector
	% Error	% Error	% Error
1	0.000%	0.000%	0.000%
2	0.000%	0.000%	0.000%
3	0.000%	0.000%	0.000%
4	0.000%	0.000%	0.000%
5	0.000%	0.000%	0.000%
6	0.000%	0.000%	0.000%
7	0.000%	0.000%	0.000%
8	0.000%	0.000%	0.000%
9	0.000%	0.000%	0.128%
10	0.000%	0.000%	0.097%
11	0.000%	0.000%	0.213%
12	0.000%	0.000%	0.260%
13	0.000%	0.000%	0.018%
14	0.000%	0.000%	0.438%
15	0.000%	0.000%	0.014%
16	0.000%	0.000%	0.039%
17	0.000%	0.000%	0.193%
18	0.000%	0.000%	0.119%
19	0.000%	0.000%	0.076%
20	0.000%	0.000%	0.057%
21	0.000%	0.000%	0.120%
22	0.000%	0.000%	0.114%
23	0.000%	0.000%	0.288%
24	0.000%	0.000%	0.000%
25	0.000%	0.000%	0.325%
26	0.000%	0.000%	0.081%
27	0.000%	0.000%	0.047%
28	0.000%	0.000%	0.088%
29	0.000%	0.000%	0.004%
30	0.000%	0.000%	0.055%
31	0.000%	0.000%	0.036%
32	0.000%	0.000%	0.004%
33	0.000%	0.000%	0.354%
34	0.000%	0.000%	0.413%
35	0.000%	0.000%	0.042%
36	0.000%	0.000%	0.014%
37	0.000%	0.000%	0.024%
38	0.000%	0.000%	0.000%
39	0.000%	0.000%	0.000%

HCB Abaqus Conversion – Cross-Ortho

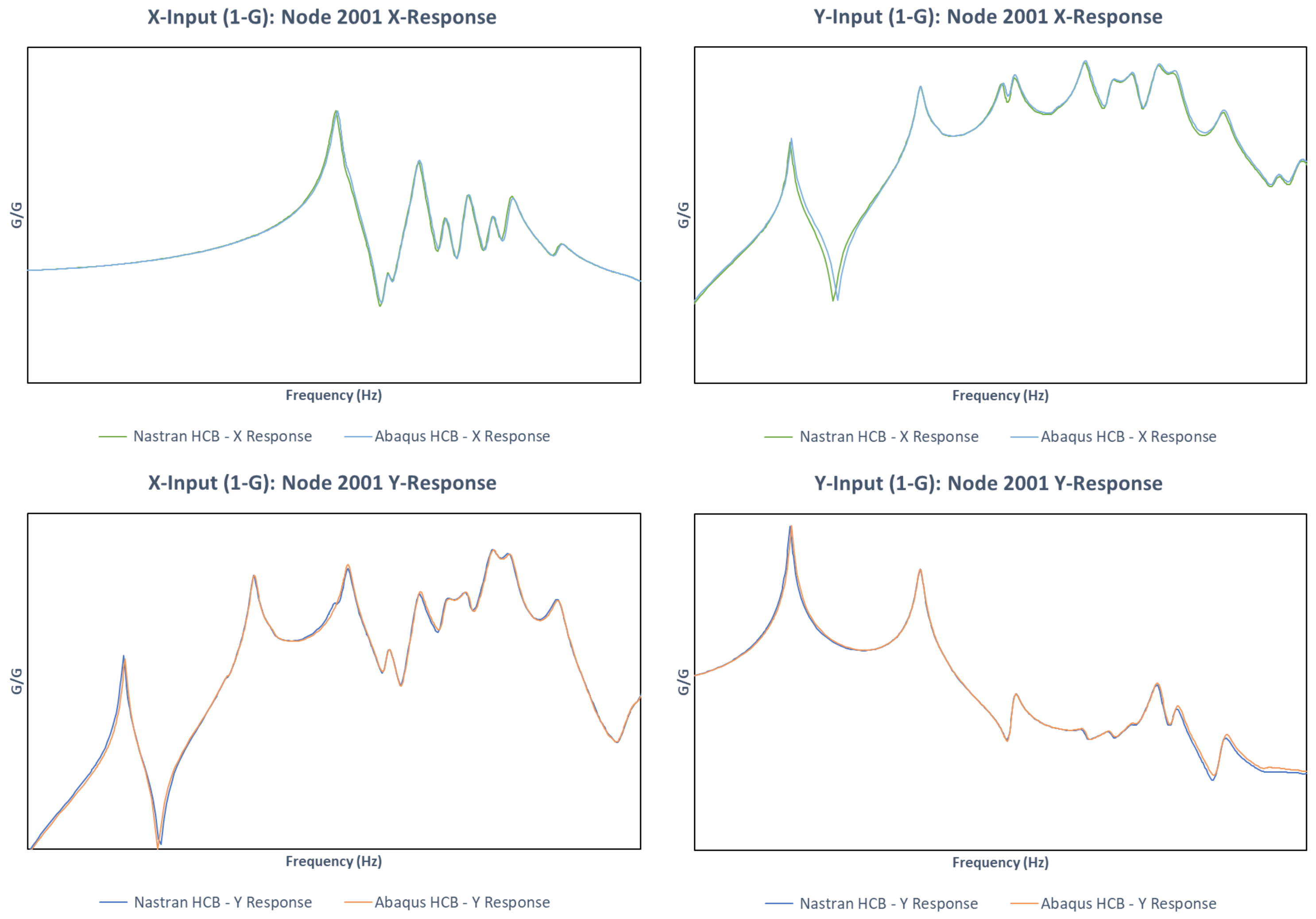
NASTRAN HCB to Abaqus HCB
(Matrices Only)



NASTRAN HCB to Abaqus HCB
(w/ Abaqus Connector Elements)



HCB Abaqus Conversion - FRF



HHT Time Integration – Numerical Damping

- **Abaqus defaults to $\alpha = -0.05$, $\beta = 0.275625$ and $\gamma = 0.55$ for "transient fidelity" applications**
  - If the time increment is 40% of the period of oscillation of interest, this results in a damping ratio < 2% due to numerical integration only
    - See "New Algorithm" curves

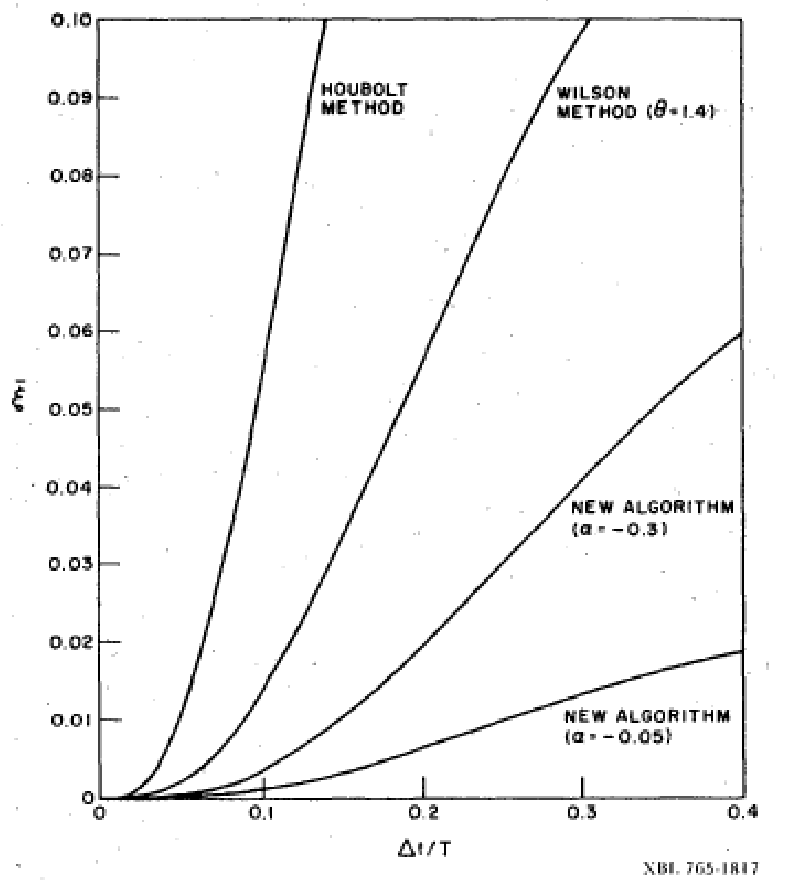


Fig. 5. Damping ratios versus $\Delta t/T$ for new methods and Houbolt and Wilson schemes

[1] Hilber, H. M., T. J. R. Hughes, and R. L. Taylor, "Improved Numerical Dissipation for Time Integration Algorithms in Structural Dynamics," Earthquake Engineering and Structural Dynamics, vol. 5, pp. 283–292, 1977.

Nonlinear FEM Correlation Results – Strain

- **Representative location shown (inner load path longeron)**
  - Many more locations were examined/compared during the correlation process