Orion E-STA Nonlinear Dynamic Correlation

Matt Griebel[1], Adam Johnson[1], Brent Erickson[1], Andrew Doan[1], Chris Flanigan[1], Jesse Wilson[1], Paul Bremner[2], Joel Sills[3], Erica Bruno[4]

[1]Quartus Engineering Incorporated

[2]AeroHydroPLUS

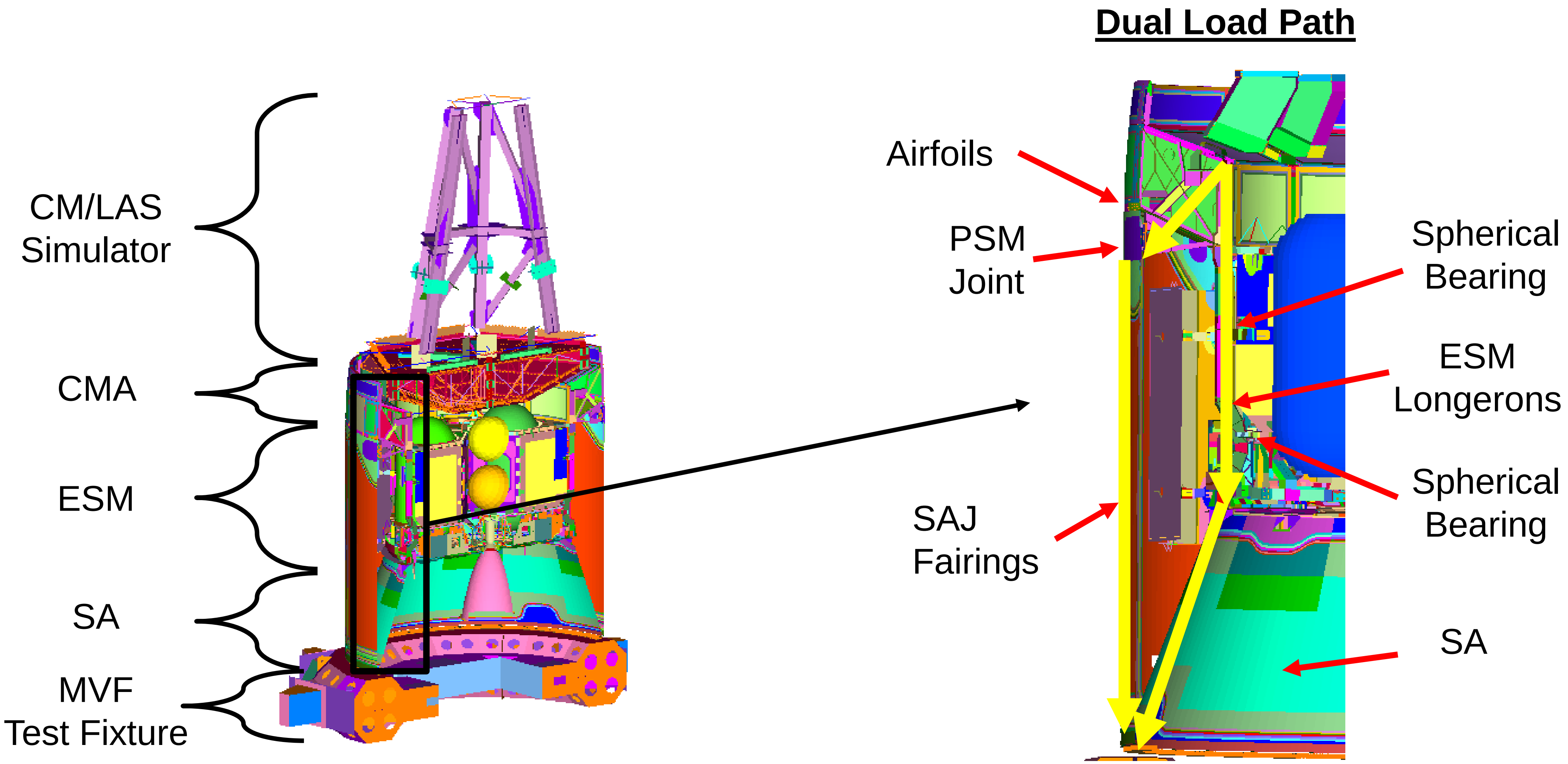
[3]NASA Engineering and Safety Center

[4]Analytical Mechanics Associates, Inc.

Background

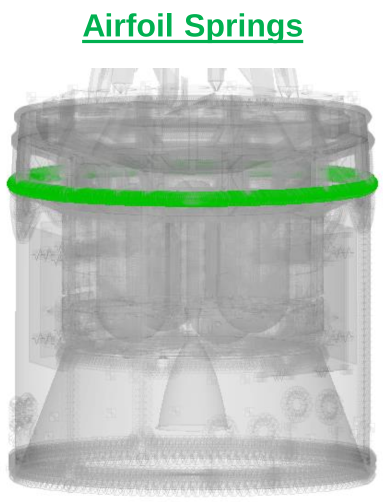
- **European Service Module (ESM) Structural Test Article (E-STA) vibration testing performed using the Mechanical Vibration Facility (MVF) at NASA Plum Brook Station**
  - Verify structural integrity of near flight-specimen of ESM (E-STA)
  - E-STA = One of several structural test articles in the NASA Orion Multi-Purpose Crew Vehicle (MPCV) program
- **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**
  - MVF capable of high load levels (flight)
- **Quartus performed independent E-STA model correlation (linear & nonlinear) for the NASA Engineering & Safety Center (NESC)**

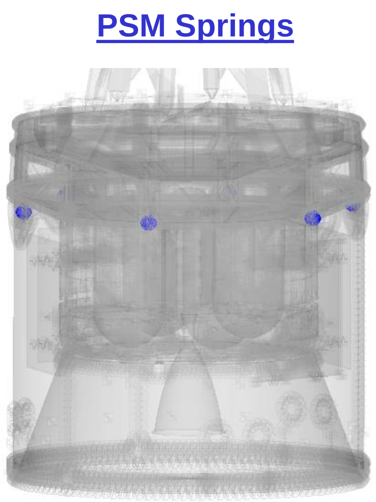
E-STA Model Overview

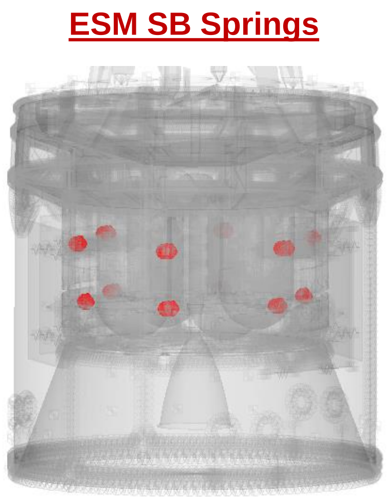


Linear Correlation Summary

- **Previous effort by Quartus for NESC resulted in 2 correlated linear FEMs (NASTRAN)**
  - Low load level (LLL) – 20% sine inputs
  - High load level (HLL) – 100% sine inputs
- **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





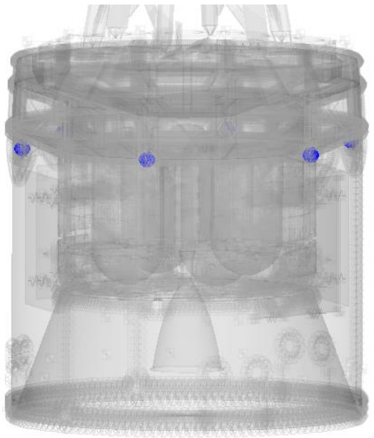


Location	DOF	LLL Stiffness Increase over HLL
Airfoil	1-3	1500
PSM	4	100
Spherical Bearings	1	1.5

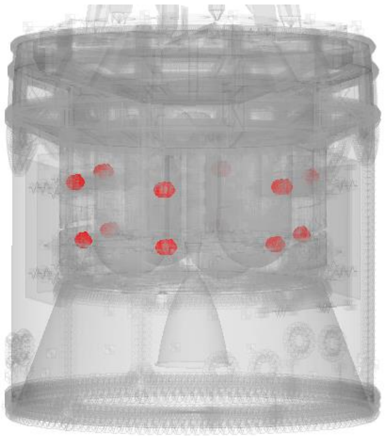
E-STA Nonlinear Joints

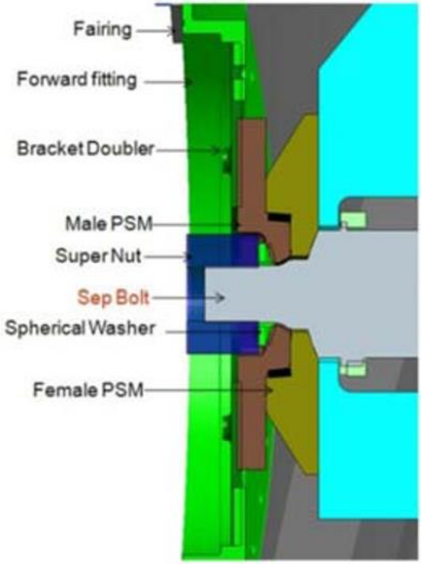
Airfoil Springs

PSM Springs



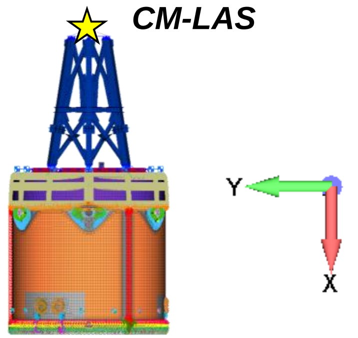
ESM SB Springs

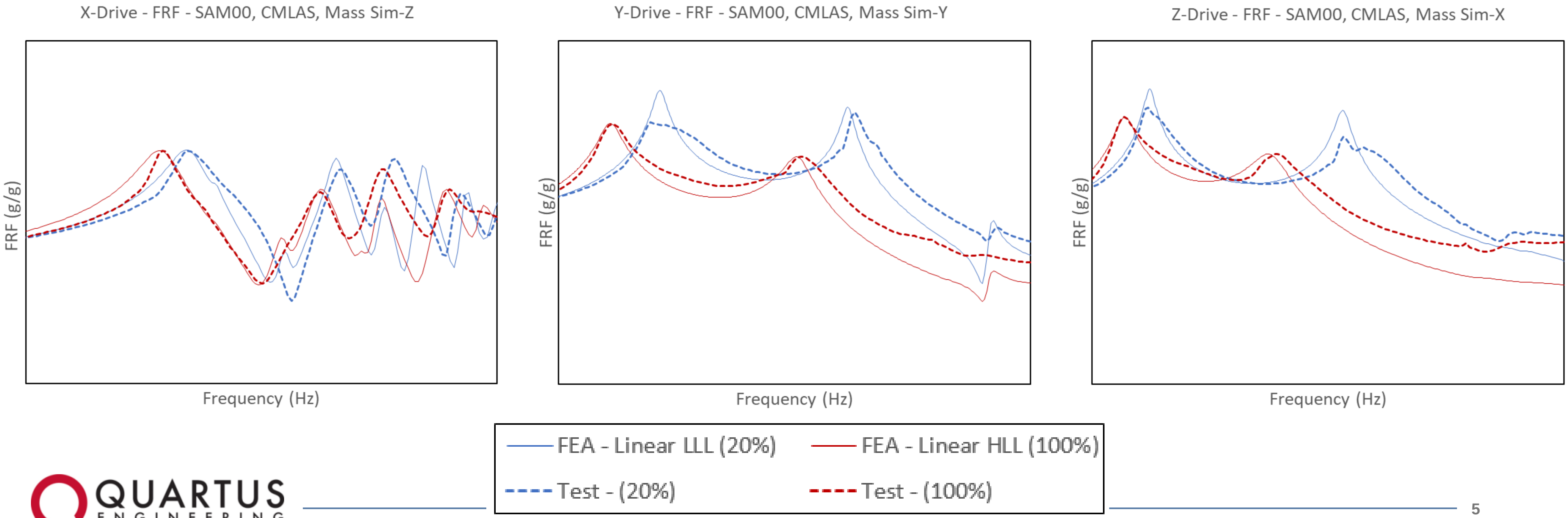




Linear Correlation Results – Acceleration

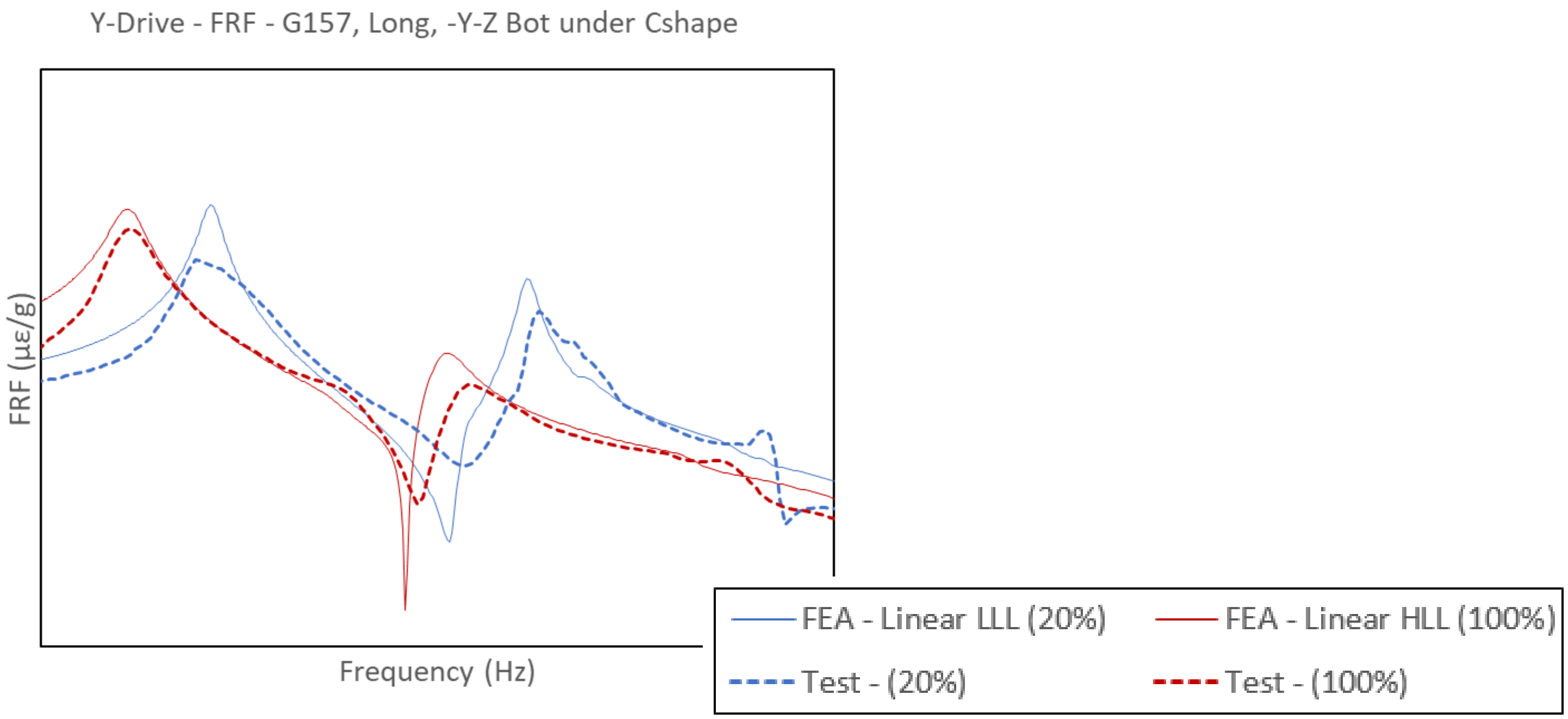
- **Representative location shown (CM-LAS)**
  - **Many more locations were examined/compared during the correlation process**





Linear Correlation Results – Strain

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



Nonlinear Correlation Motivation

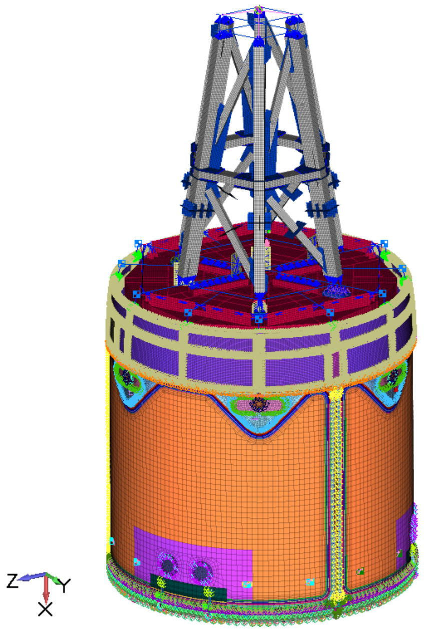
- **Further elucidate the source and type of nonlinearity**
- **Capture extent of MPCV nonlinear dynamics in a single model**
  - **Can correlate linear models to high or low loads conditions, but cannot ensure that analysis of those models will envelope responses**
- **Inform the use of linear models in CLA** ***(not covered in this 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?**

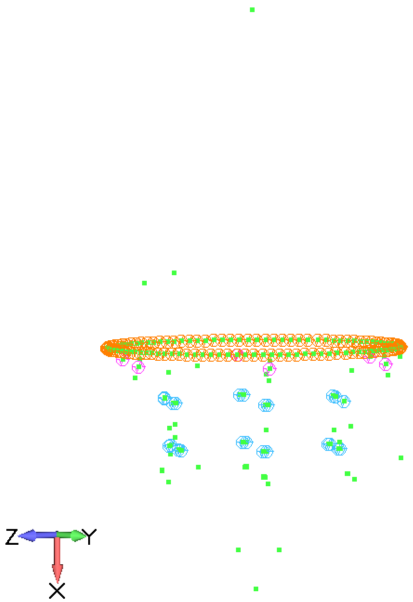
Nonlinear Correlation Steps

1. **Perform dynamic reduction of full Nastran model (Hurty/Craig-Bampton)**
   - Reduces model to mass/stiffness matrices and eliminates internal DOF
   - Modal DOF are retained in addition to selected boundary DOF to capture dynamic response
2. **Convert Nastran HCB model to Abaqus**
   - Check conversion (modes, cross-ortho, FRFs)
3. **Add nonlinear elements at identified interfaces**
   - Connector and flexible joint elements
4. **Perform nonlinear implicit dynamic iterations and correlate response to test**
   - Use FRF comparisons

HCB Model Reduction

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





HCB NASTRAN-to-Abaqus Conversion

- **NASTRAN HCB model (OP4 matrix format) converted to Abaqus *MATRIX INPUT**
  - NASTRAN uses SPOINTs and a DOF0 designation for modal DOF
  - Abaqus *used* to default to placing these on DOF9 which was sufficient for any modal solution, but for implicit dynamics, DOF9 is reserved for electric potential
    - Abaqus will now designate these DOF as internal and has developed an *internal=modal* parameter
      - Initial investigations have been unsuccessful – use with caution
  - After some FRF comparisons, DOF7 (beam warping) was selected
- **The built in NASTRAN-to-Abaqus converter was untrustworthy in converting HCB matrices, especially from OP4 format, so a custom Python script was written**

HCB Abaqus Conversion – Modes Check

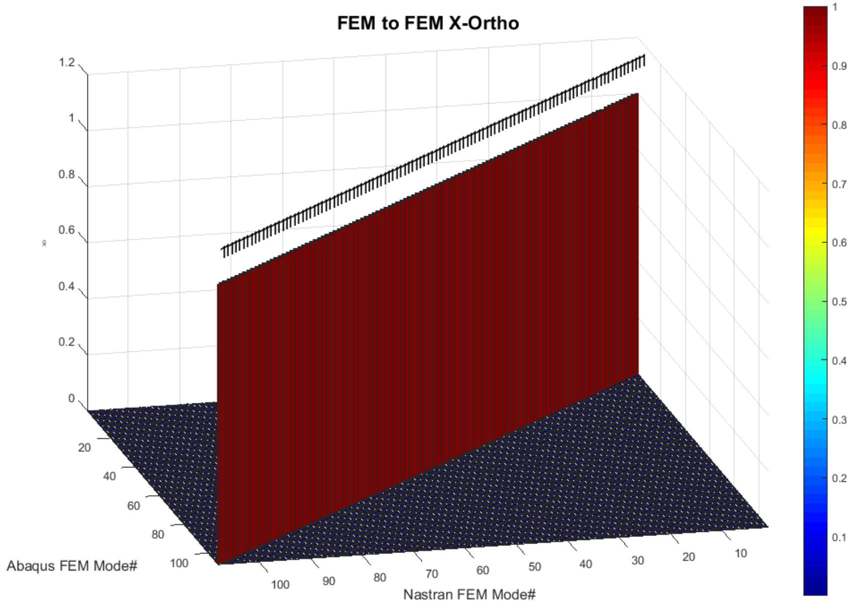
- **Modes of the HCB only match exactly**
- **Minor differences in frequency emerge after connector elements are included**
  - **Max difference = 0.438%**
  - **Likely due to Lagrange multipliers**

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%

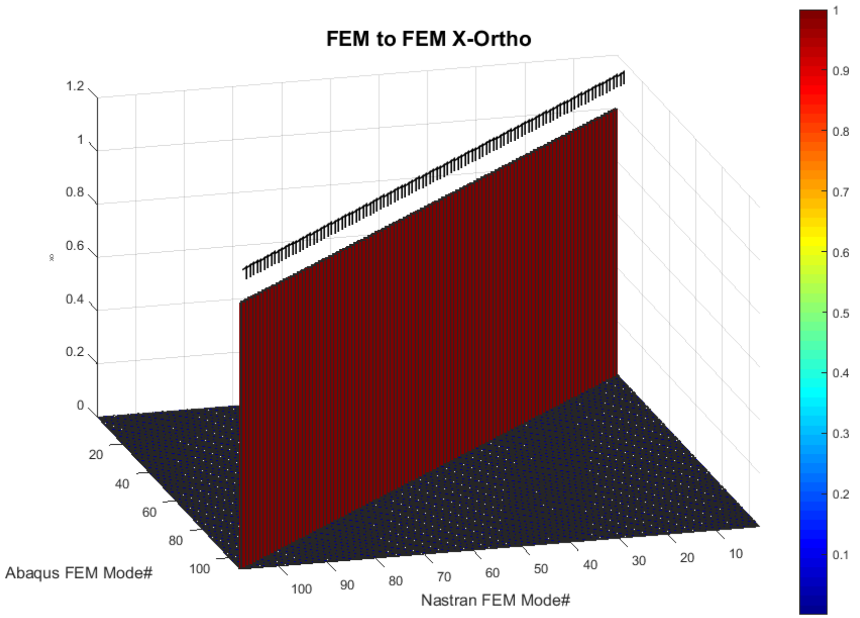
HCB Abaqus Conversion – Cross-Ortho

- **Cross-ortho (evaluation of mode shape) shows an exact comparison**
  - **i.e. – mode shapes are the same**

NASTRAN HCB to Abaqus HCB (Matrices Only)

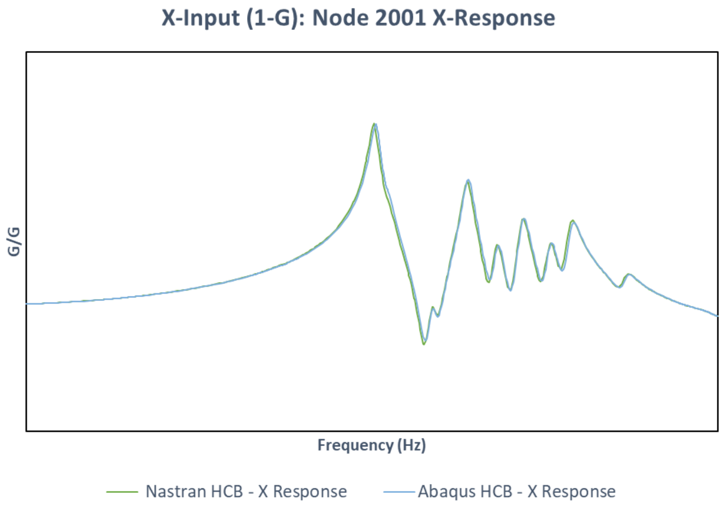


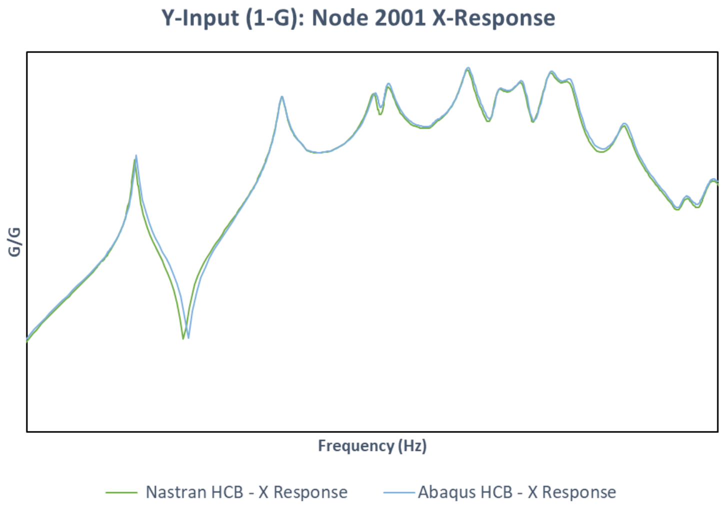
NASTRAN HCB to Abaqus HCB *(w/ Abaqus Connector Elements)*

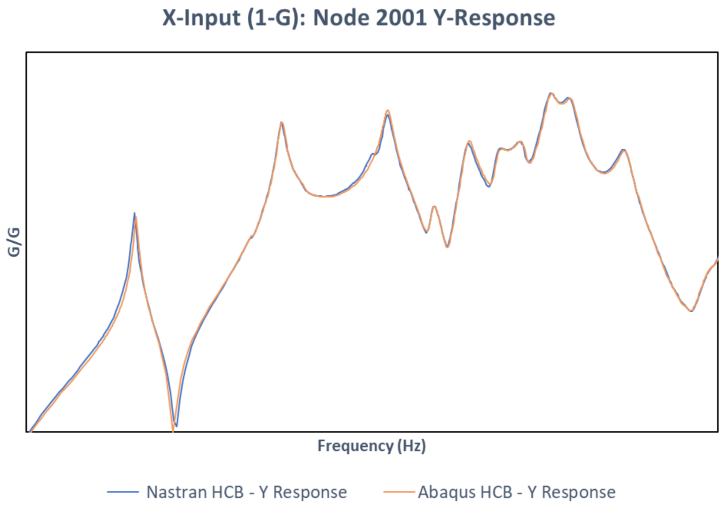


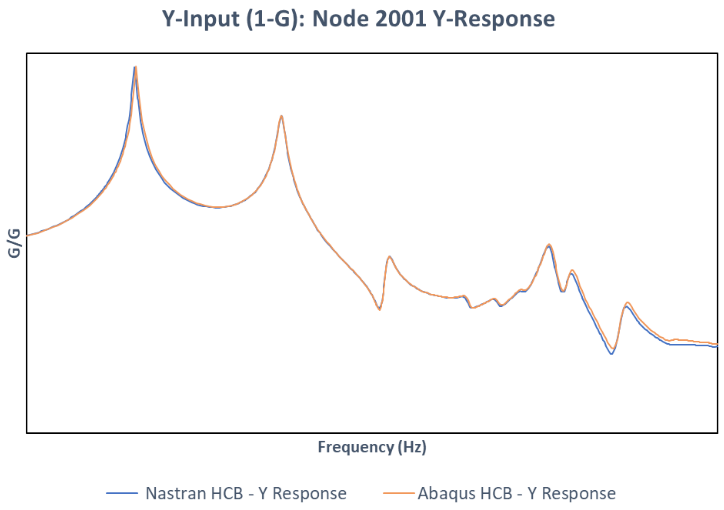
HCB Abaqus Conversion - FRF

- **Minor differences in FRFs**
  - Shape, frequency, and damping match well
  - Connector elements may again cause minor deviations
    - Where modal DOF are stored also had small affect









Nonlinear Transient Analysis

- **Nonlinear implicit dynamic analyses performed using Abaqus/Standard**
  - HHT time integration
  - Explicit avoided because of the relatively long duration of the simulation and because explicit time integration is not supported with direct matrix input
- **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 and flexible joint elements**
  - Lagrange multipliers allow for complicated reactions including Coulomb friction
- **FRFs calculated from transient responses using spectral density estimation**

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
- **Based on frequency range of interest, and time step selected, numerical damping is expected to be <<1%**

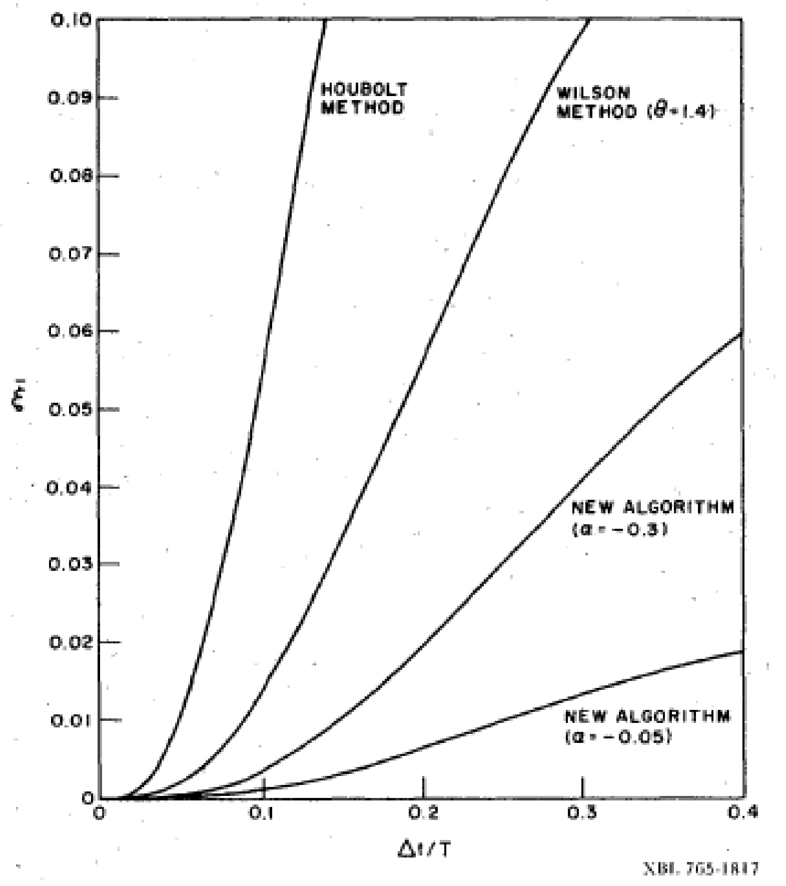
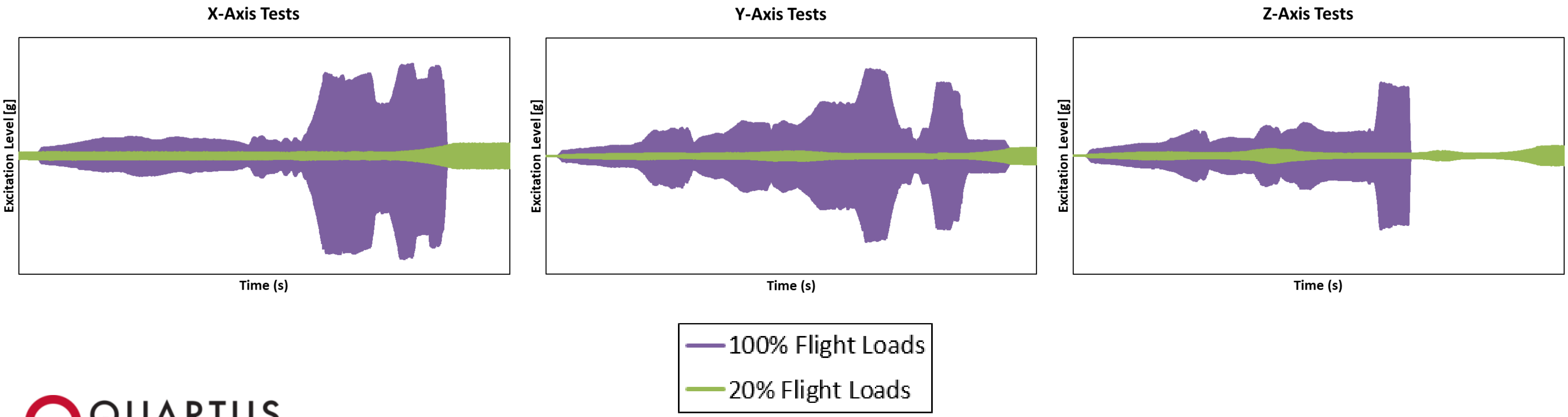


Fig. 5. Damping ratios versus $\Delta t/T$ for new methods and Houbolt and Wilson schemes

[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.

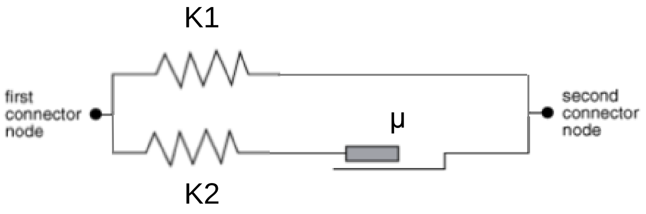
Transient Sine Sweep Inputs

- **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
      - $\tau = \mu F_{int}$
      - Some initial iterations tried keeping this a solution variable – too many variables



Implicit Dynamics – Damping

- Implicit dynamics allows for damping in the form of discrete viscous damping, friction, and Rayleigh damping
- Since Rayleigh damping has little physical significance, and is merely a numerical implementation of damping, avoiding/minimizing its use is desirable
- Nominal damping is included in the HCB model created from the correlated LLL linear model
  - During the model reduction in NASTRAN, the correlated modal damping table is converted to a HCB viscous damping matrix
  - Additional damping included in Abaqus through friction and discrete viscous damping

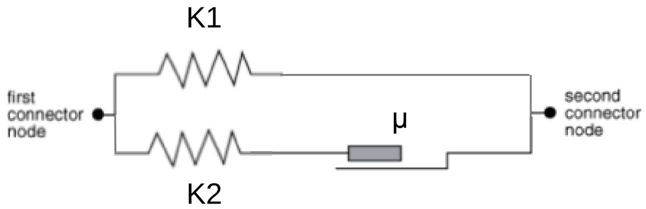
Nonlinear Correlation Strategy

- **Initialize nonlinear elements using linear correlation results**
  - e.g. K1 = HLL stiffness, K1+K2 = LLL stiffness, τ = LLL slip load
- **Iterate on properties to shift curves appropriately**
  - e.g. Increase K1+K2 to shift 20% responses up, decrease K1 to shift 100% responses down, iterate on τ to achieve appropriate slip point
- **Spherical bearings were correlated first on a reduced model**
  - Axial response primarily driven by spherical bearings; spherical bearings have small effect on lateral responses
  - Run times are long; breakout correlation allowed faster iteration and was tweaked only slightly after re-introduction to complete model

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**

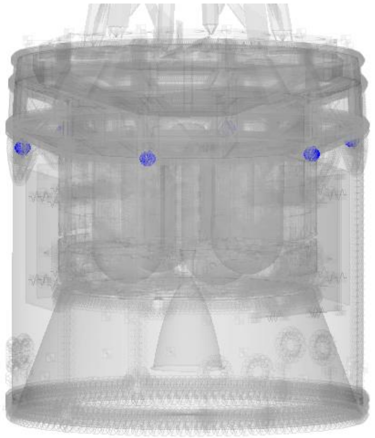
Nonlinearity Table				
Location	**DOF**	**Nonlinear Correlated E-STA Model**		
		K1	**K1+K2**	**τ**
Airfoil-to-CMA	2-3	0	8*LLL	2*LLL
PSM	4	HLL	LLL	LLL
ESM Spherical Bearings	1	0	33*LLL	LLL



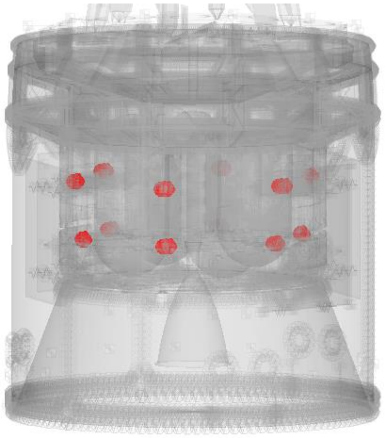
$$\tau = \mu F_{int}$$

Airfoil Springs

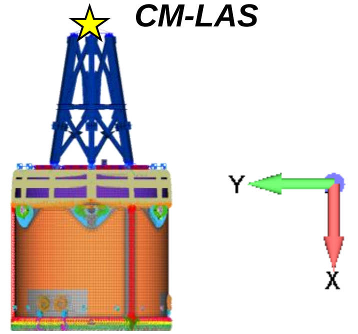
PSM Springs



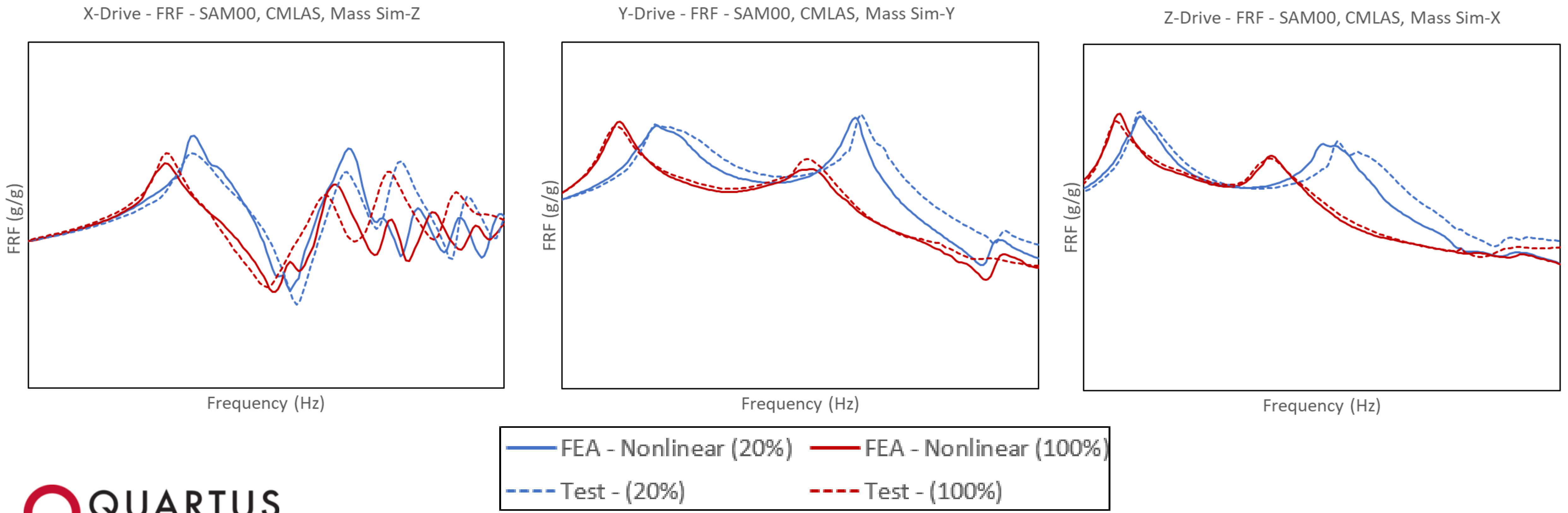
ESM SB Springs



Nonlinear FEM Correlation Results – Accel FRF



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



Nonlinear FEM Correlation Results – Strain FRF

- **Representative location shown (inner load path longeron)**
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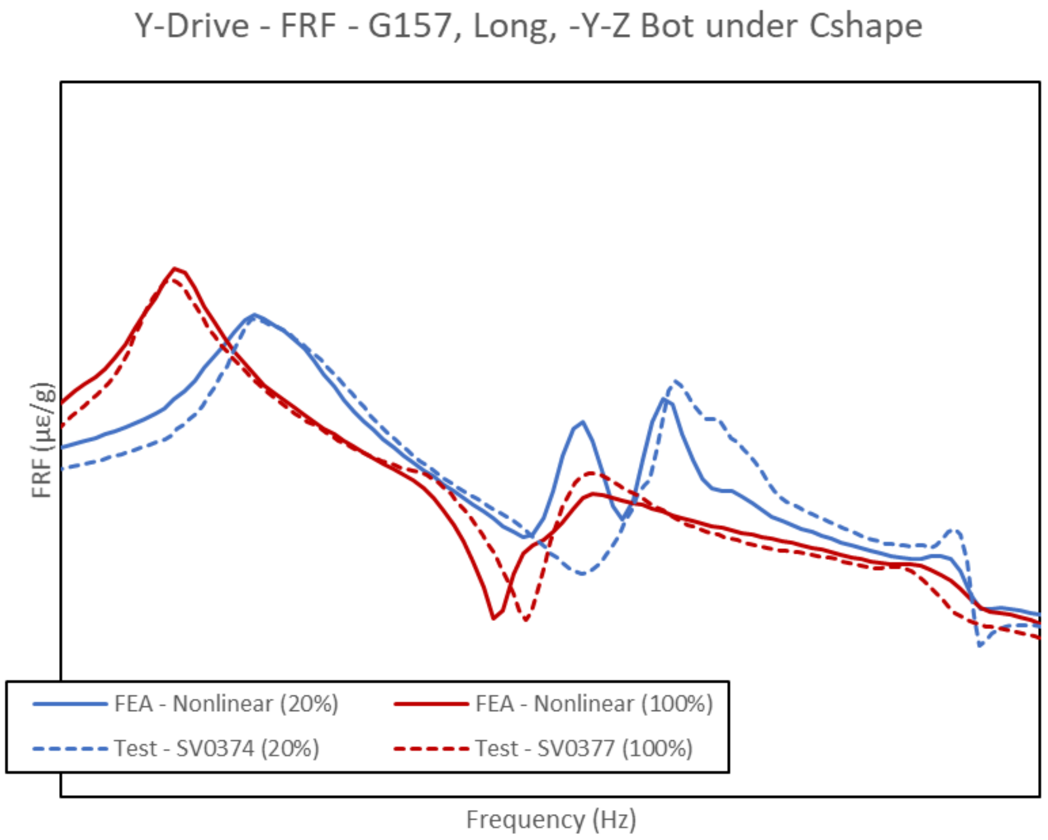


Summary & Recommendations

- **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

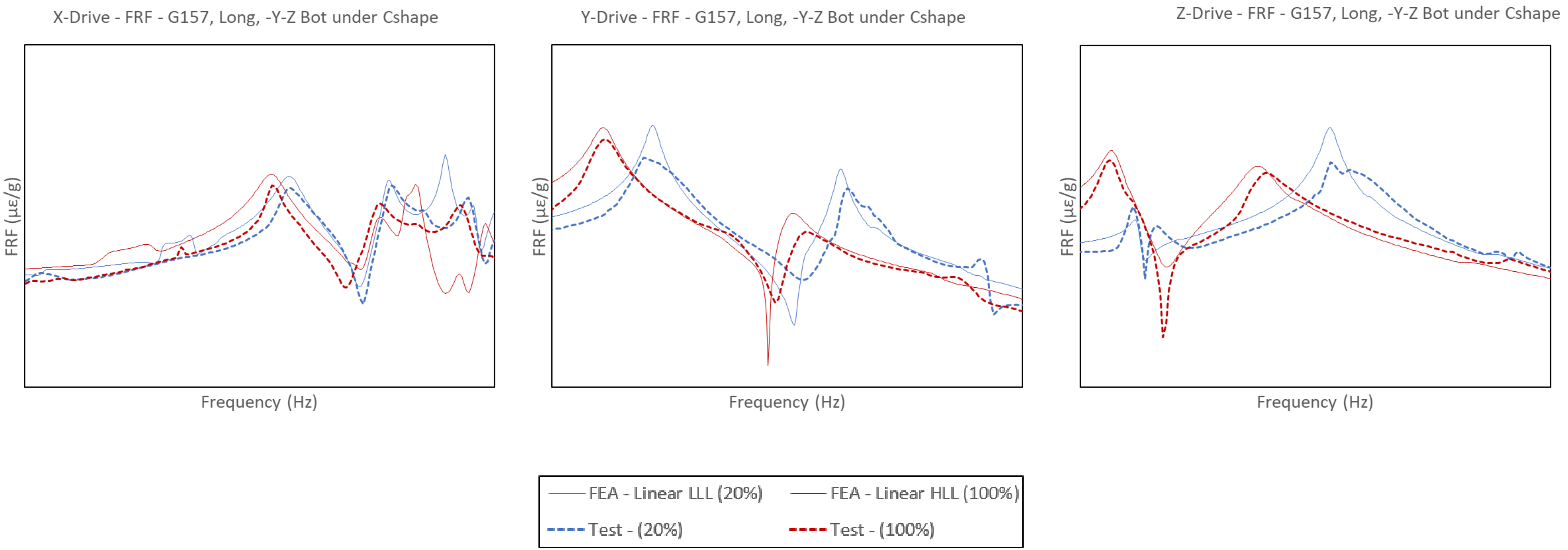
Abaqus & Methodology Summary

- Conversion of NASTRAN HCB, integration of nonlinear elements, use of modal response in implicit analysis
  - Connector elements introduce slight variation in stiffness matrix
  - No official support of SPOINT/modal DOF
    - Most displacement DOF seem acceptable
    - New “internal=modal” feature not reliable
- Viscous damping matrix used to implement baseline “modal” damping
  - Avoided use of Rayleigh damping
- Half-increment residual check
- Matrix input parallelization

Questions?

APPENDIX

Linear Correlation Results – Strain



Nonlinear FEM Correlation Results – Strain

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