Orion MPCV E-STA Nonlinear Dynamics Uncertainty Factors for NESC

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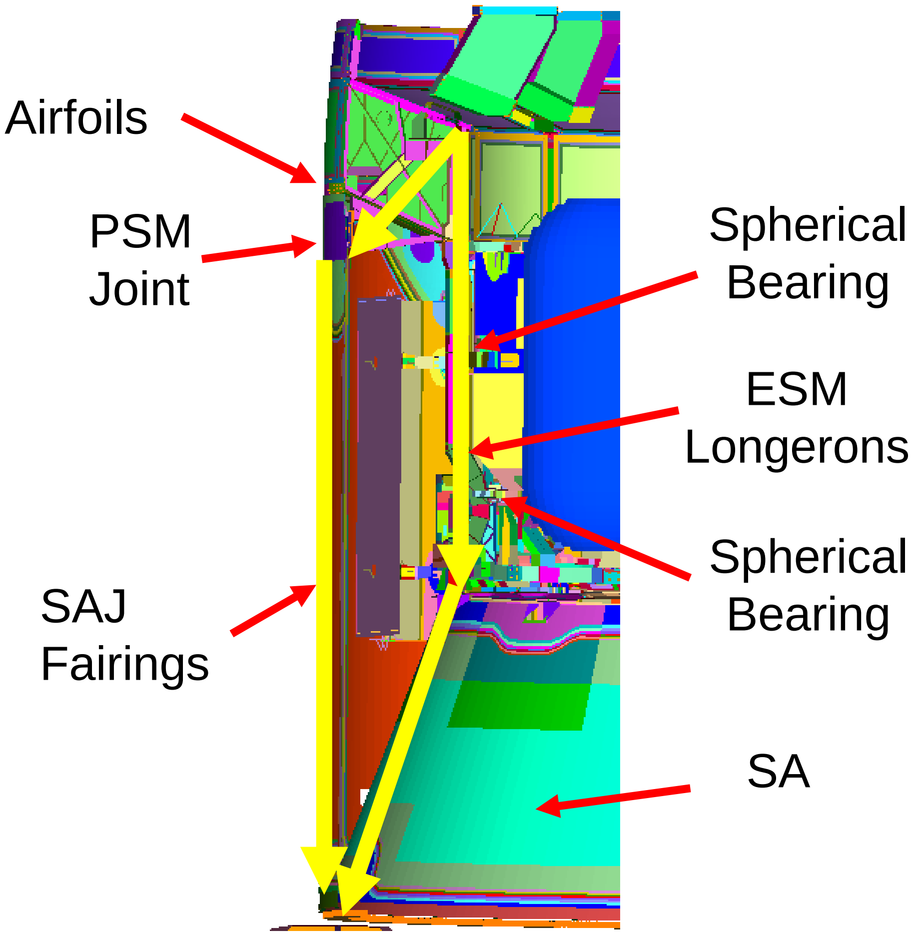
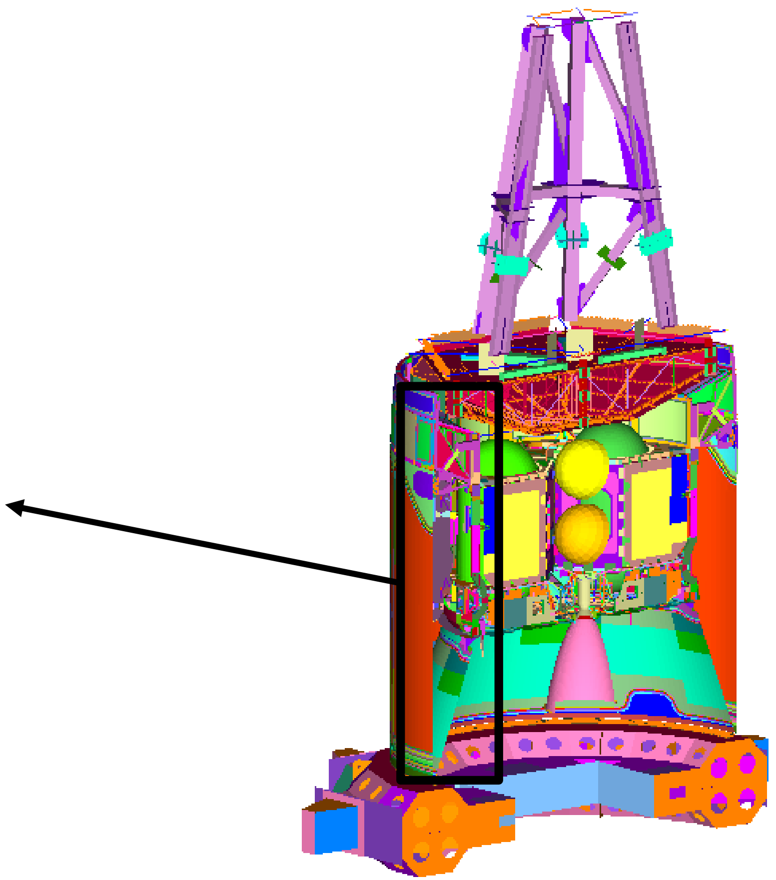
Background

- Vibration testing performed on European Service Module (ESM) Structural Test Article (E-STA)
  - Verify structural integrity of flight-like specimen of ESM near flight load levels
- Large nonlinear behaviors observed in primary dynamic responses
- Quartus performed independent E-STA model correlation (linear & nonlinear) for the NASA Engineering & Safety Center (NESC)
  - 1) Linear model correlation (see Appendix I)
  - 2) Nonlinear model generation & correlation (see Appendix I)
  - 3) CLA response study and uncertainty assessment

E-STA Model Overview

Dual Load Path





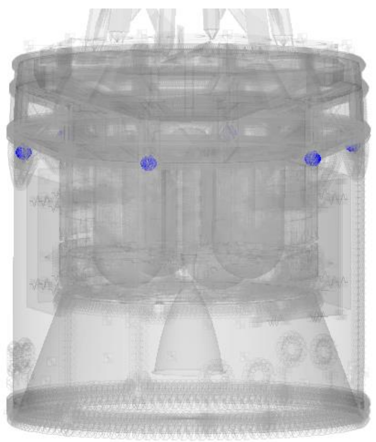
Linear Correlation Summary

- **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%**
- **Differences between FEMs reduced to properties at 3 joints (largest sources of nonlinearity)**
  - **Airfoils (SAJ to CMA), PSM, and ESM spherical bearings**

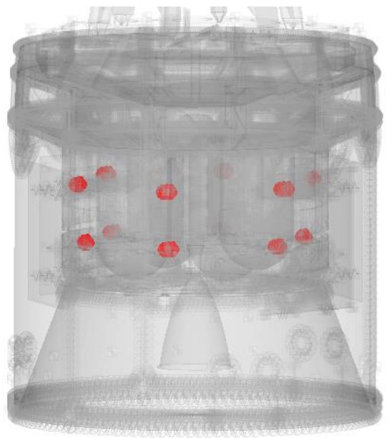
Location	DOF	LLL Stiffness Increase over HLL
Airfoil	1-3	1500
PSM	4	100
Spherical Bearings	1	1.5

Airfoil Springs

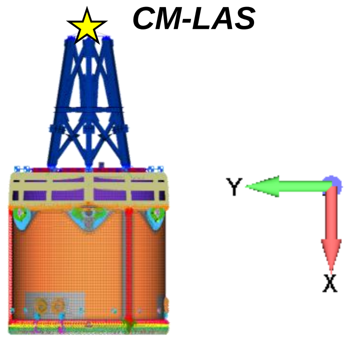
PSM Springs



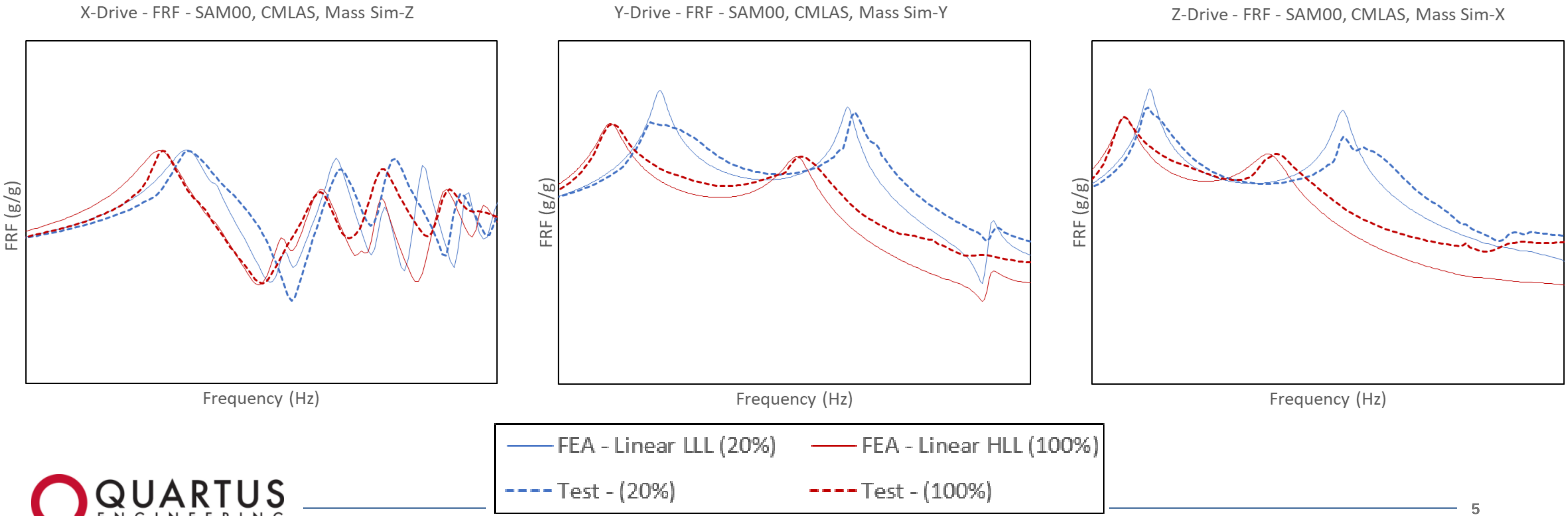
ESM SB Springs



Linear Correlation Results – Acceleration



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

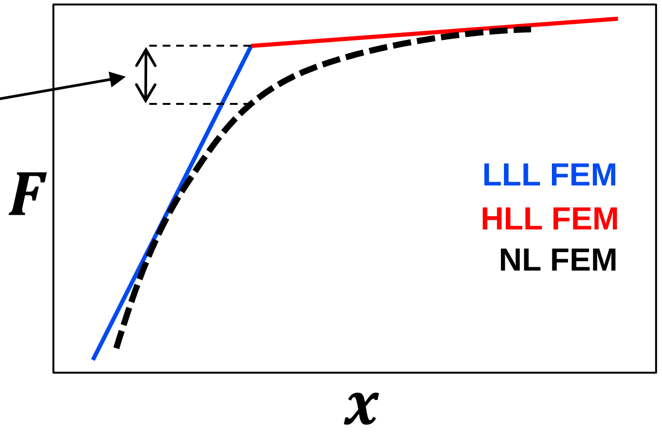


Nonlinear Correlation Motivation

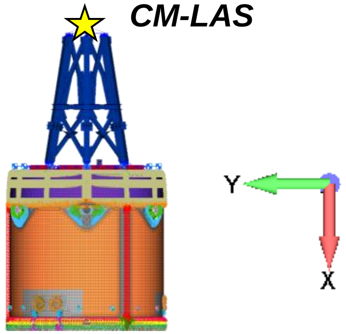
- **Further elucidate the source and type of nonlinearity**
- **Capture MPCV nonlinear dynamics in a single model**
- **Inform the use of linear FEM in CLA**
  - **Can linearized models accurately predict MPCV flight responses?**
  - **What linear FEM should be used with each CLA load type (i.e. liftoff, transonic, etc…)?**
  - **Uncertainty introduced from using linearization of nonlinear system**
    - **Linear FEMs represent linearization about two different load levels (HLL & LLL)**

Linearization Uncertainty Illustration

Linear models become inaccurate when used at non-corresponding load levels



Nonlinear FEM Correlation Results – Acceleration



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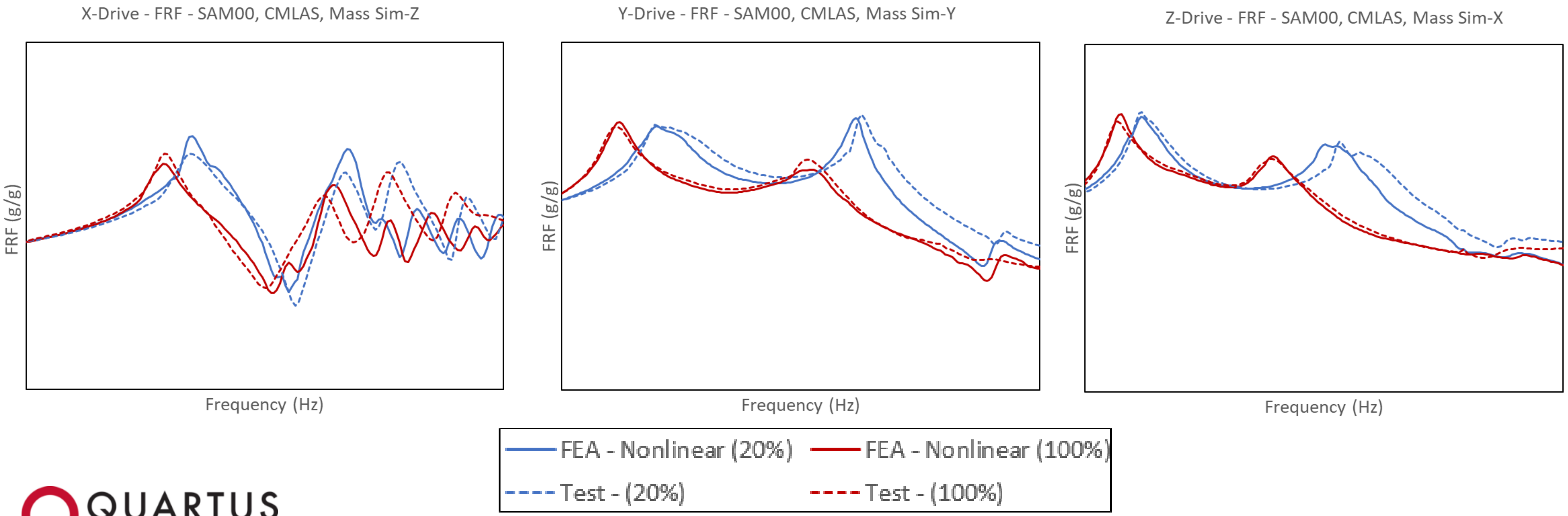
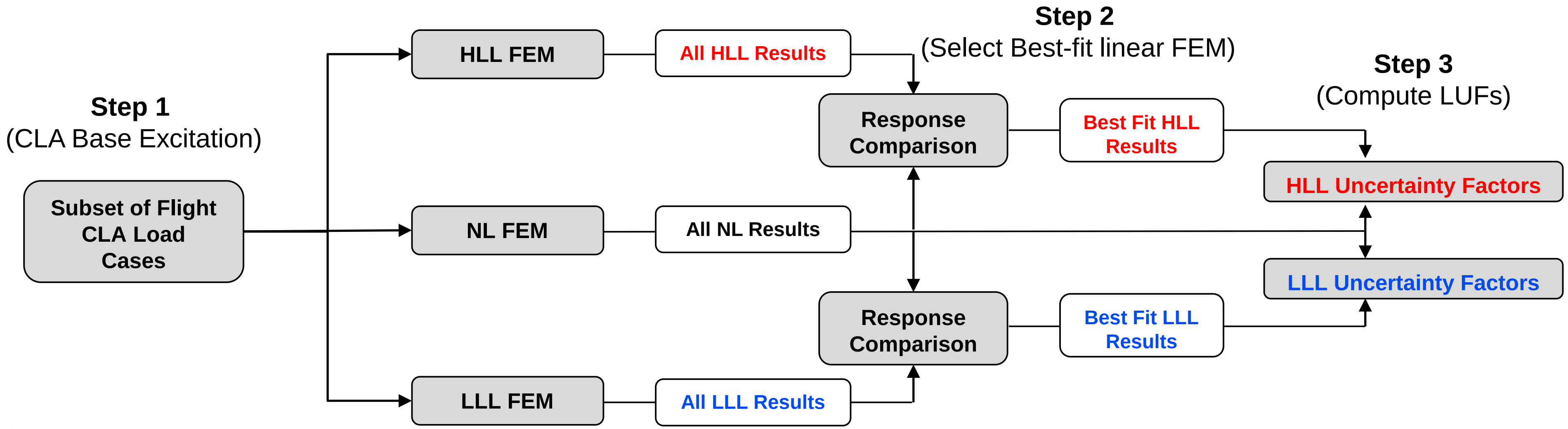


Uncertainty Factor Derivation

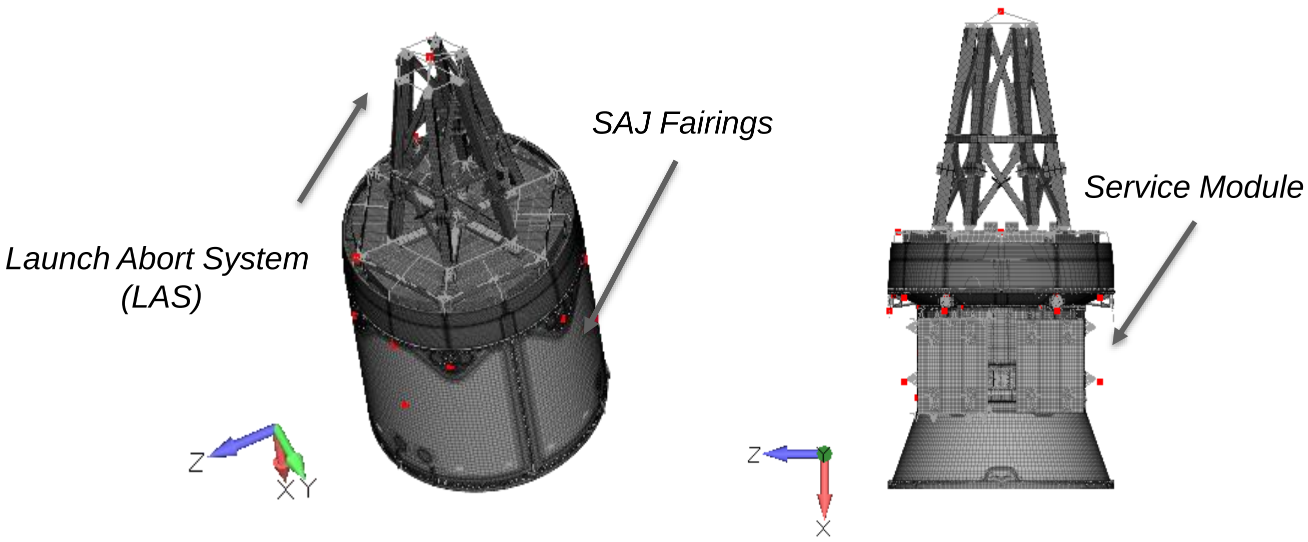
1. **Apply subset of CLA load cases to NL FEM and linear FEMs**
   - MPCV Base accelerations recovered from SLS/MPCV CLA
   - 5 X Liftoff
   - 6 X Transonic
   - 5 X Max Acceleration
2. **Characterize best-fit linear FEM for each loading type**
   - i.e. don't use LLL FEM for high-level load cases
3. **Compute Linearization Uncertainty Factors (LUF) using best-fit models**



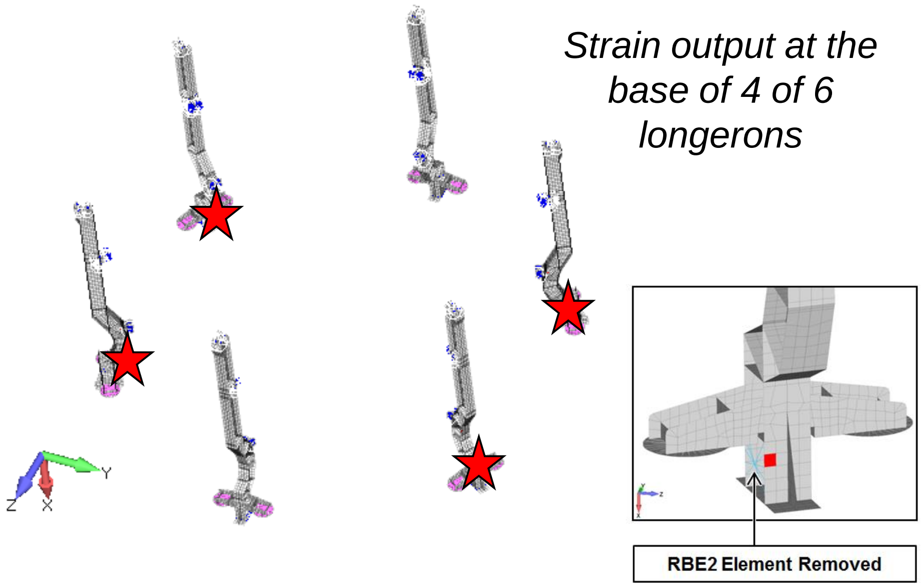
Model Output Post Processing

- **Response output locations:**
  - **27 nodal locations, 3 DOF each (LAS, CM, SM, SAJ Fairings)**
  - **4 elemental strain locations, 1 DOF each (longerons)**

Ensemble of Nodal Locations



Ensemble of Strain Locations



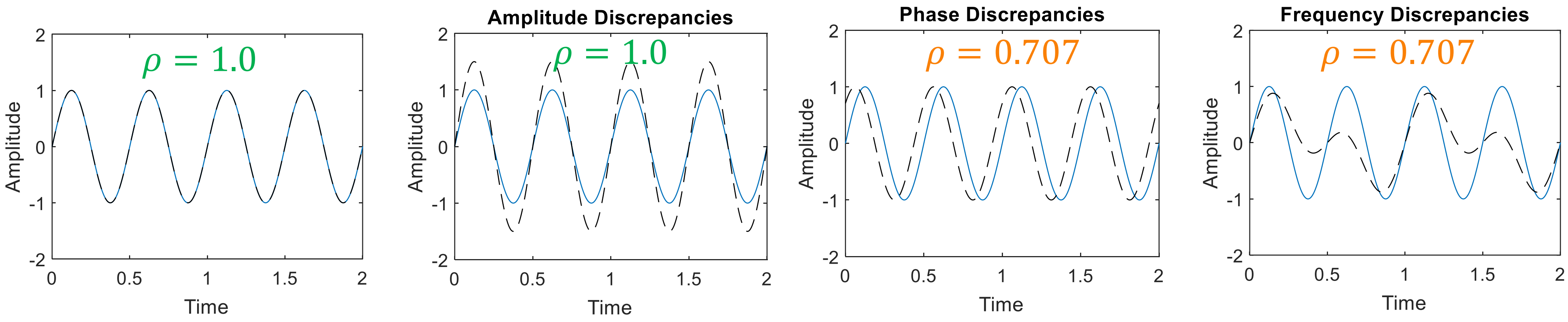
Response Comparison Methodology

- **Utilized Pearson Correlation Coefficient**
  - **Provides top-level frequency and phase comparison between two signals**
  - **Can help indicate which linear FEM best matches the true NL response**

Note: Pearson correlation coefficient is a time-integrated (averaged) measure of the linear dependence of two variables and does not compare magnitudes between time histories

$$\rho(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i - u_A}{\sigma_A}\right)\left(\frac{B_i - u_B}{\sigma_B}\right)$$

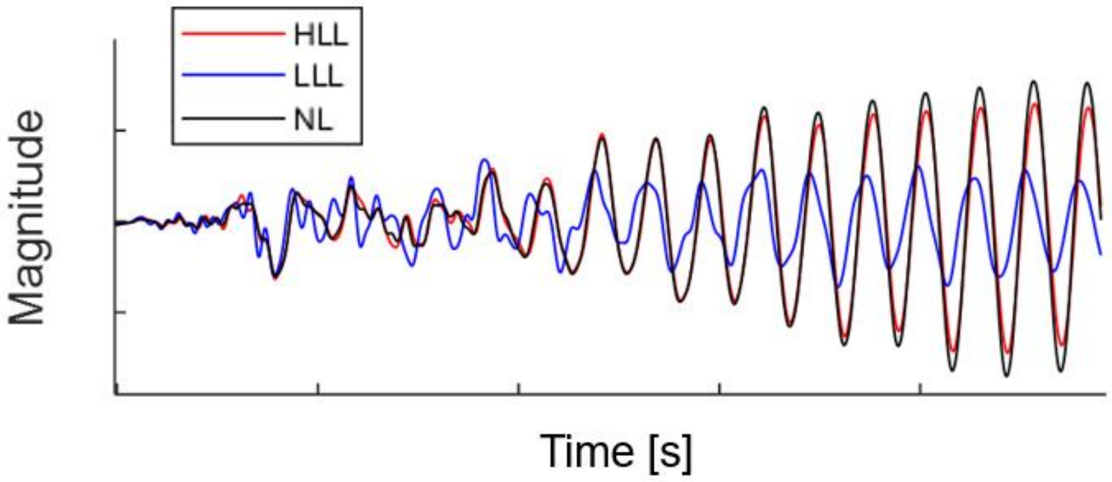
<u>Correlation Coefficient Example Application on Pure Sine Signals</u>



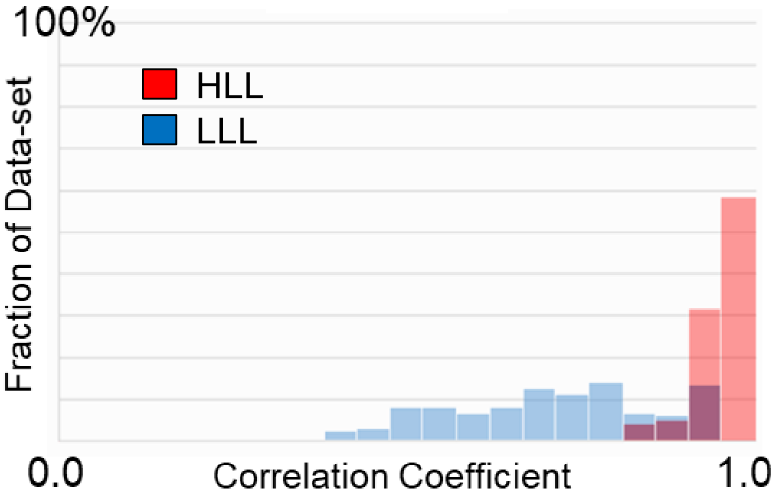
Response Comparison Example

- **Correlation Coefficient evaluated at all response locations**
  - Evaluated separately for each loading type (i.e. Liftoff, Transonic, Max Acceleration)
- **Summarized Correlation Coefficients using histogram of all locations and load cases**

Sample Response Comparison at LAS (Z)



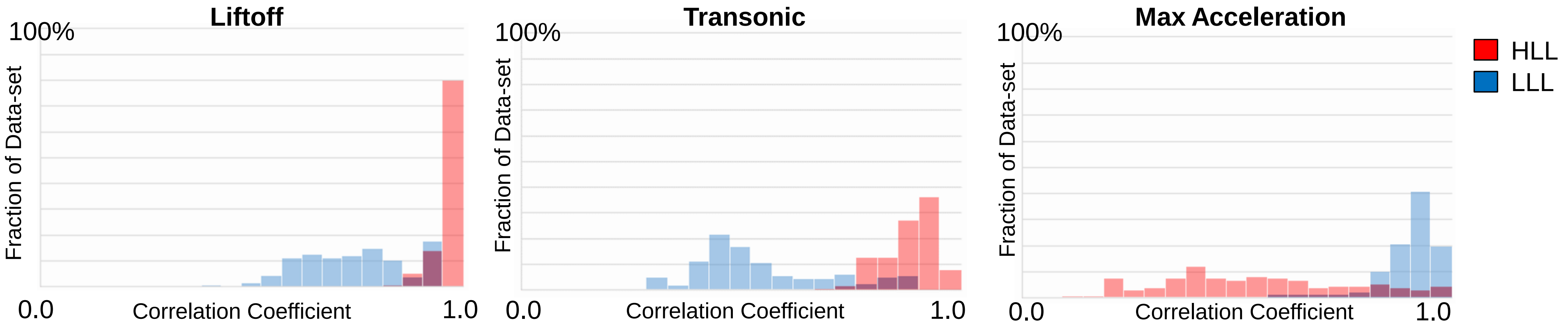
Liftoff Acceleration Response Comparison Summary

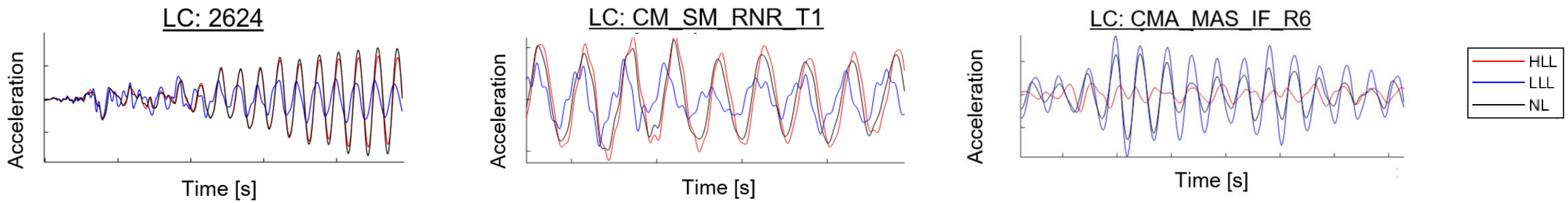


Acceleration Response Comparison Summary

- **Liftoff and Transonic load cases best represented by HLL FEM**
- **Max Acceleration load cases best represented by LLL FEM**

Correlation Coefficient Distribution By Load Type





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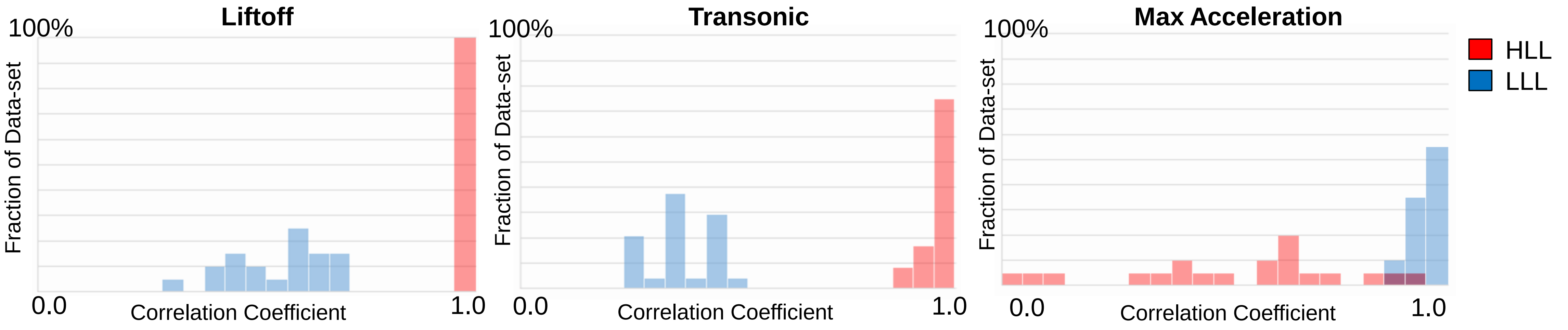
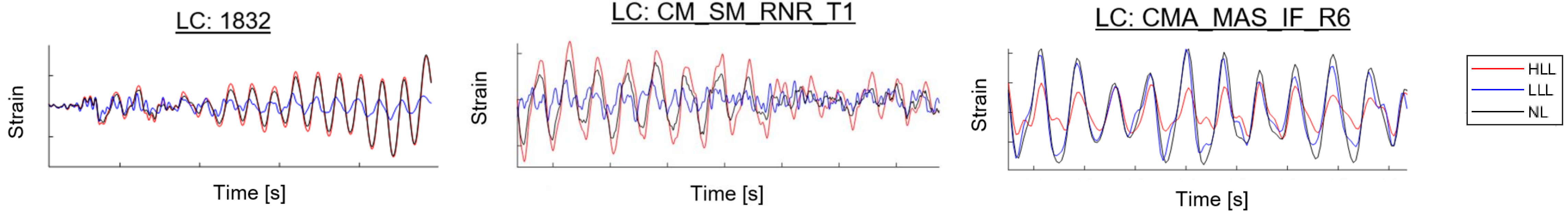
Strain Response Comparison Summary

- Liftoff and Transonic load cases best represented by HLL FEM
- Max Acceleration load cases best represented by LLL FEM

Correlation Coefficient Distribution By Load Type





Uncertainty Factor Calculation

- **Objective: determine uncertainty in HLL and LLL linear model response with respect to NL FEM response (Truth model)**
- **Uncertainty factor defined as scale factor between linear and nonlinear response magnitudes**

Uncertainty Factor

$$LUF_n = \frac{R_{NLin}}{R_{Lin}} \quad \text{(eq. 1)}$$

LUF>1 → Linear Model is Under-Predicting

LUF<1 → Linear Model is Over-Predicting

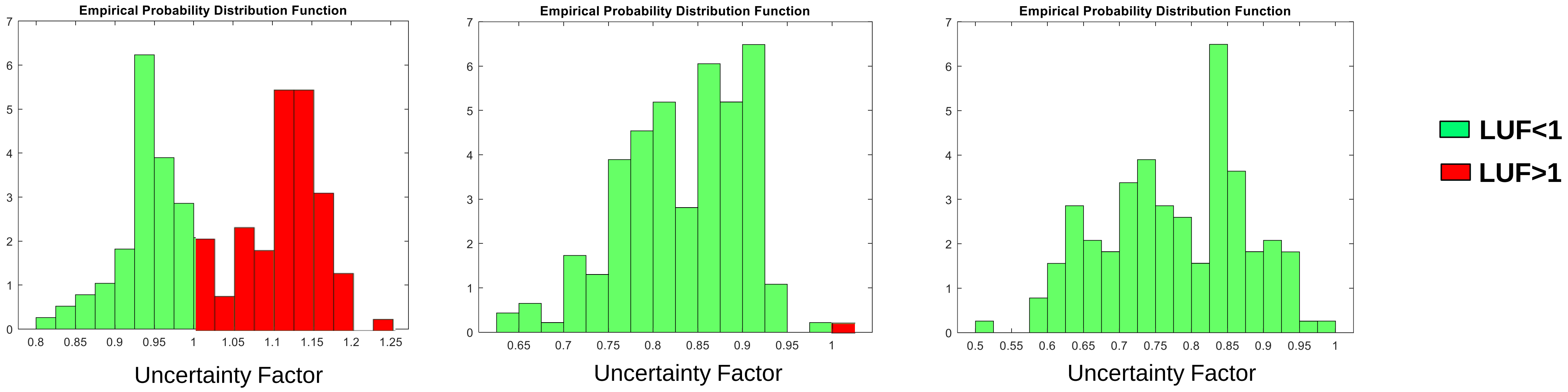
Determination of Response Magnitude (R)

	Type of Loading	Magnitude Metric	RSS DOFs
Liftoff	*Low Frequency*	*Peak Value*	*All*
Transonic	*Buffet + Thrust Osc.*	*RMS*	*YZ Lateral*
Max Acceleration	*Thrust Osc.*	*Peak Value*	*All*

Uncertainty Factor Ensemble

- **Uncertainty factors computed at all response locations for all load cases**
- **LUF probability distributions were generated for each loading type using the best-fit linear model**
  - **Concerned with statistical significance of max LUF**

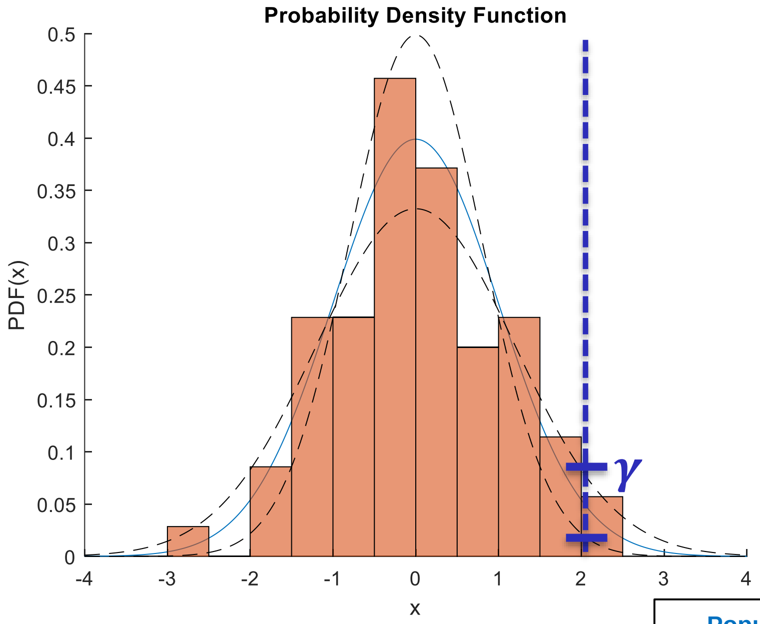
Liftoff (HLL Model) | **Transonic (HLL Model)** | **Max Accel (LLL Model)**



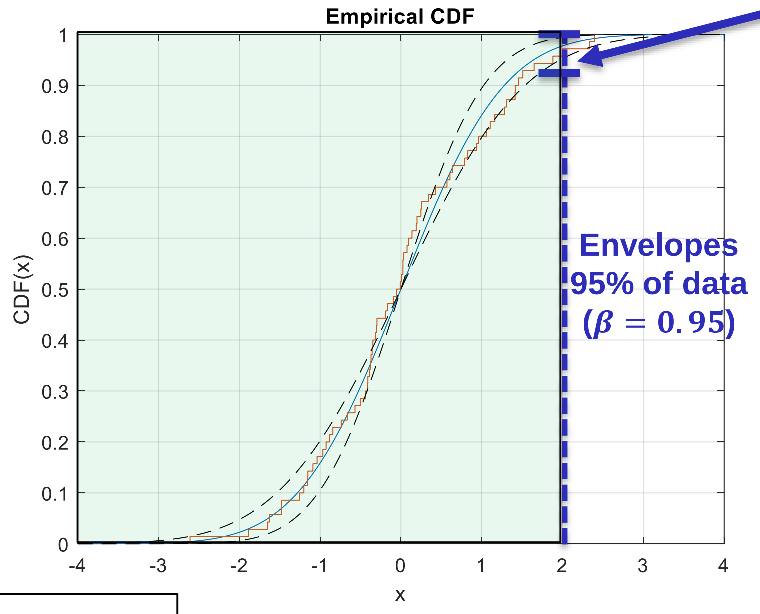
Max Uncertainty Factor Confidence [1 of 3]

- **Statistical significance provides context to max values:**
  - **How much data lies below this max value? – Probability Level (β)**
  - **How much would this distribution vary if more data was collected? – Confidence Level (γ)**
- **Example shown below for sampled *x* from a normally distributed population**

Probability Density Function (PDF)



Cumulative Distribution Function (CDF)



Confidence level (γ) characterizes uncertainty in distribution due to limited sample size

— Population
— Sample (x)
- - Distribution Uncertainty

Max Uncertainty Factor Confidence [2 of 3]

- **Since LUFs are not normally distributed, normal tolerance factors cannot be used**
- **Distribution-free methodology can be used (NASA Handbook 7005 – 6.1.3)**
  - **Does not assume normal or any standard distribution type**
- **Distribution-free tolerance limit (DFL) is defined as:**

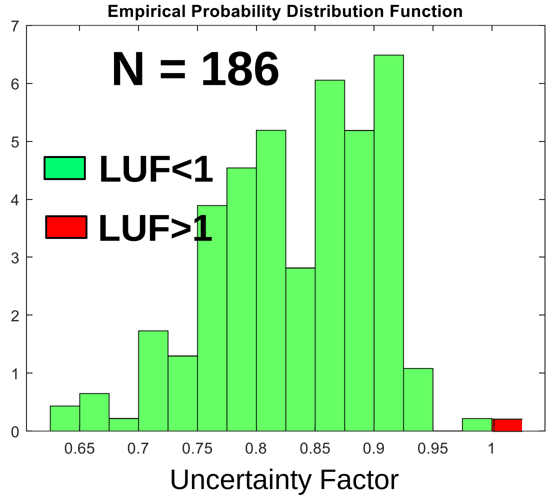
A value which exceeds all values for at least $\boldsymbol{\beta}$ fraction of the data with a confidence of $\boldsymbol{\gamma = 1 - \beta^N}$

  - **Let β_{max} be the fractional portion of data that lies below the DFL (max value)**
  - **Can choose $\beta < \beta_{max}$ to achieve desired confidence**
- **Primary limitation of DFL method: does not permit independent selection of β and γ**
- **Example calculation shown on next slide**

Max Uncertainty Factor Confidence [3 of 3]

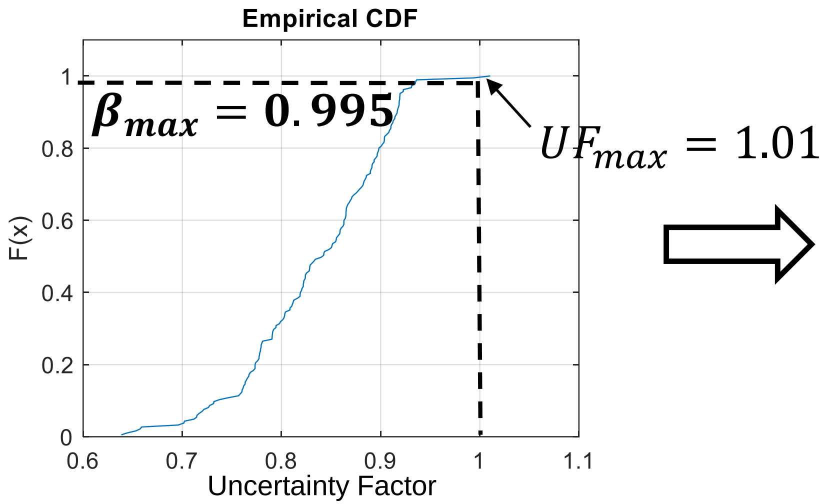
- **Example max uncertainty factor (LUF_{max}) determination for transonic load cases shown below:**

<u>Probability Density Function</u>



Step 1: Note that LUF distribution is not normal

<u>Empirical Cumulative Distribution</u>



Step 2: Calculate fractional portion of data β_{max} that lies below max value UF_{max}

<u>Probability and Confidence Calculation</u>

$$\beta = 0.98 < \beta_{max}$$

$$\gamma = 1 - 0.98^{186} = 98\%$$

<u>At least</u> 98% of data lies below 1.01 with a confidence of 98%

Step 3: Choose $\beta < \beta_{max}$ to achieve desired confidence level (98%) from $\gamma = 1 - \beta^N$

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Summary

- **Max uncertainty factors were computed for each loading type using the appropriate linear model determined by correlation coefficients**
- **When appropriate correlated linear model is used, uncertainty factors are small (<1.25)**
- **Note: Inherent uncertainty loads as well as the non-linear “truth” model not assessed in this report**

	Liftoff	Transonic	Max Acceleration
Max Uncertainty Factor	1.24	1.01	0.99
Selected Linear Model	High Load Level	High Load Level	Low Load Level
Probability	*98%*	*98%*	*98%*
Confidence	*96%*	*98%*	*96%*

Questions?

APPENDIX I: PREVIOUS REPORTS

Previous Reports

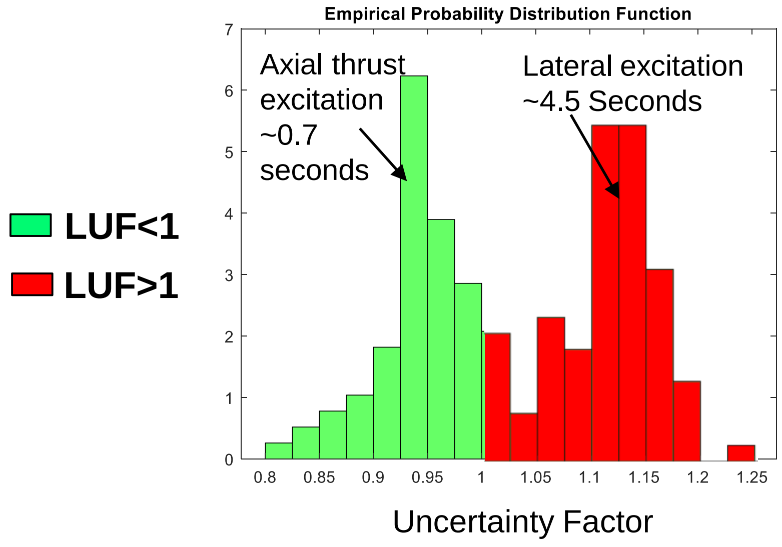
- **The following reports support the material presented in this report:**
  - **Orion MPCV E-STA Structural Dynamics Correlation for NASA NESC**
    - **https://www.quartus.com/assets/004/5377.pdf**
  - **Orion MPCV E-STA Nonlinear Correlation for NESC**
    - **https://www.quartus.com/assets/004/5404.pdf**

APPENDIX II: UNCERTAINTY FACTOR CHALLENGES

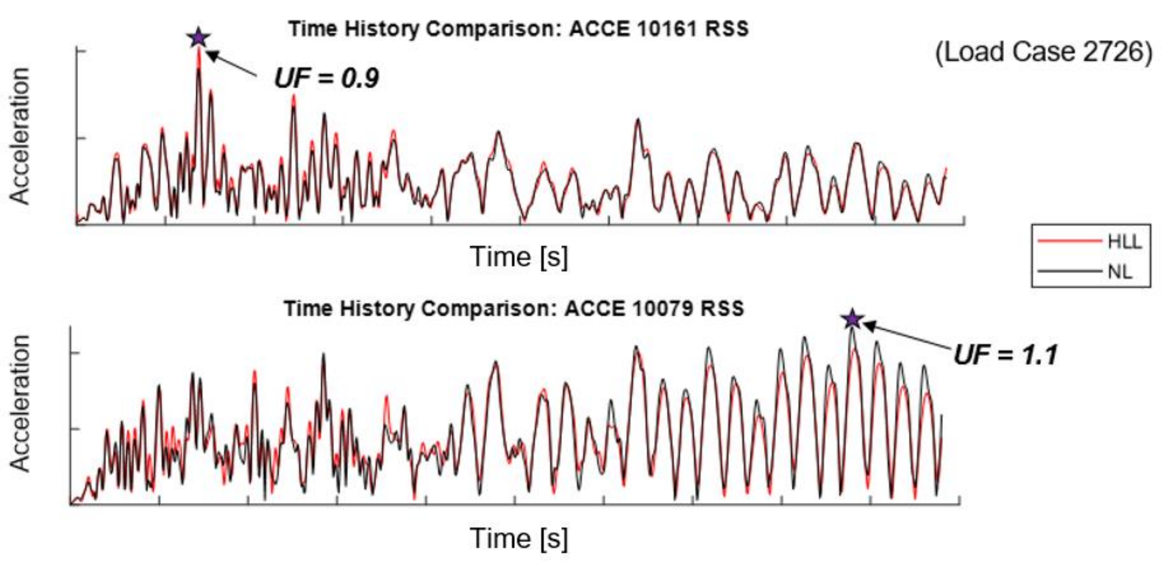
Uncertainty Factor Challenges

- Challenging to properly define statistical significance of max uncertainty factor
  - Must use distribution-free techniques
- Multi-modal distributions are an artifact of using peak value as magnitude metric
- Alternative methods could remove modalities

Liftoff (HLL Model)



Liftoff PV Modalities (Comparison at 2 Locations)



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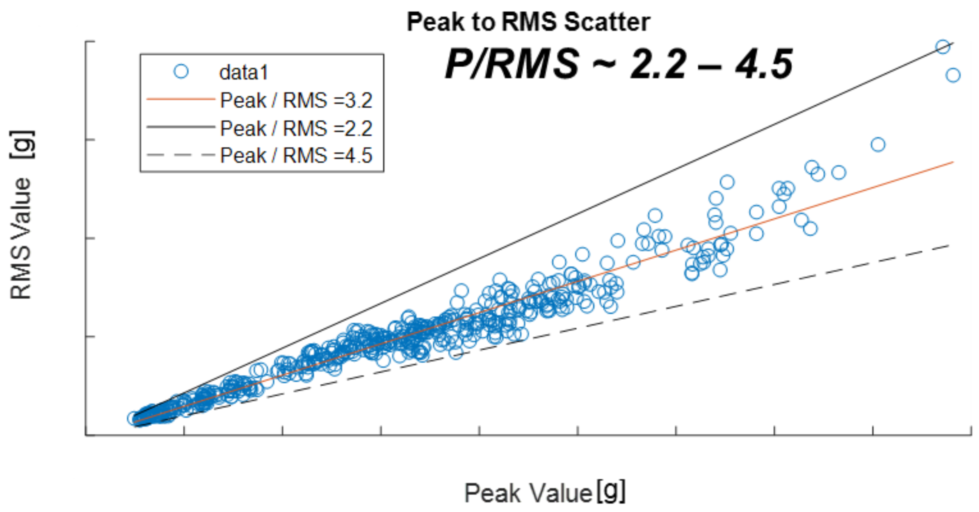
APPENDIX III: PEAK TO RMS RATIO (TRANSONIC LOADING)

Peak To RMS Ratio – Accel. Ensemble (TS)

- **Peak-to-RMS ratio checked for all response time histories in all DOFs**
  - **25 Hz Fwd Bwd LP Filter applied to only look at correlated, primary structural modes**
- **No significant change in response distribution in Nonlinear model response**

High Load Level Model



Nonlinear Abaqus Model