Orion MPCV Nonlinear Dynamics Uncertainty

Adam Johnson[1], Paul Bremner[3]
Matt Griebel[1], Brent Erickson[1], Joel Sills[2]

[1]Quartus Engineering Incorporated
[2]NASA Engineering and Safety Center
[3]AeroHydroPLUS

Approved for Public Release

Background

- **Vibration testing of the Orion Multi-Purpose Crew Vehicle (MPCV) Configuration 4 (C4) Structural Test Article (STA) was performed in the reverberant acoustic chamber at Lockheed Martin**
  - **C4 = “full stack” launch configuration**
  - **Fixed base with varying stinger shakers**
- **Significant nonlinear behavior and response deviation from pre-test FEA predictions**
  - **Frequency and damping variations**
  - **Nonlinear FRF shapes**
- **MPCV Nonlinearities determined to be stick-slip in nature, sourced to multiple key joints**
  - **See “SCLV-2019_Quartus_E-STA_NL_Correlation.pptx"**

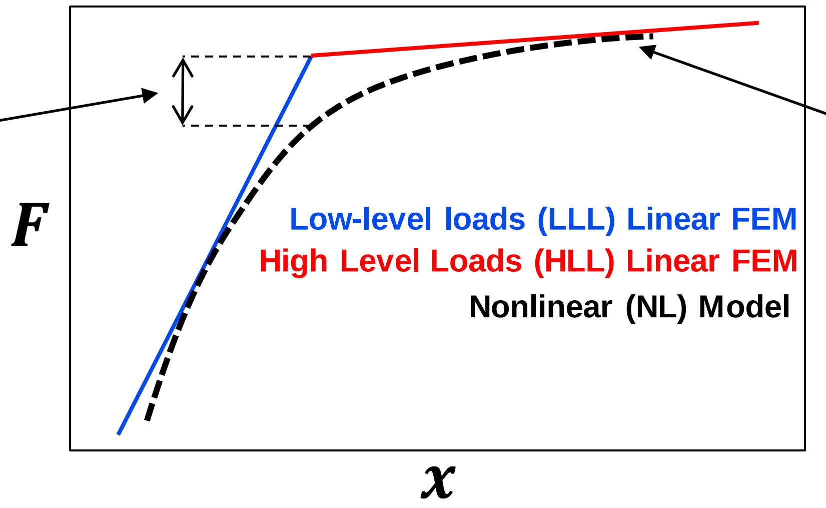
    and “SCLV_2021_MPCV_Nonlinear_Correlation_and_QSMA.pptx

Nonlinear Correlation Motivation

- **Performed nonlinear model correlation to…**
  - Further elucidate the source and type of nonlinearities present in MPCV joints
  - Capture MPCV nonlinear dynamics in a single model
  - Develop a method to quantify uncertainty introduced when linearizing a nonlinear system ← **Focus of this presentation**
- **Coupled Loads Analysis (CLA) typically performed using a linear model**
  - Current technique for nonlinear MPCV is to develop 2 separate linearizations:
    - FEM correlated to a High Level Loading (HLL)
    - FEM correlated to a Low Level Loading (LLL)

Illustration of Linearization Uncertainty

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

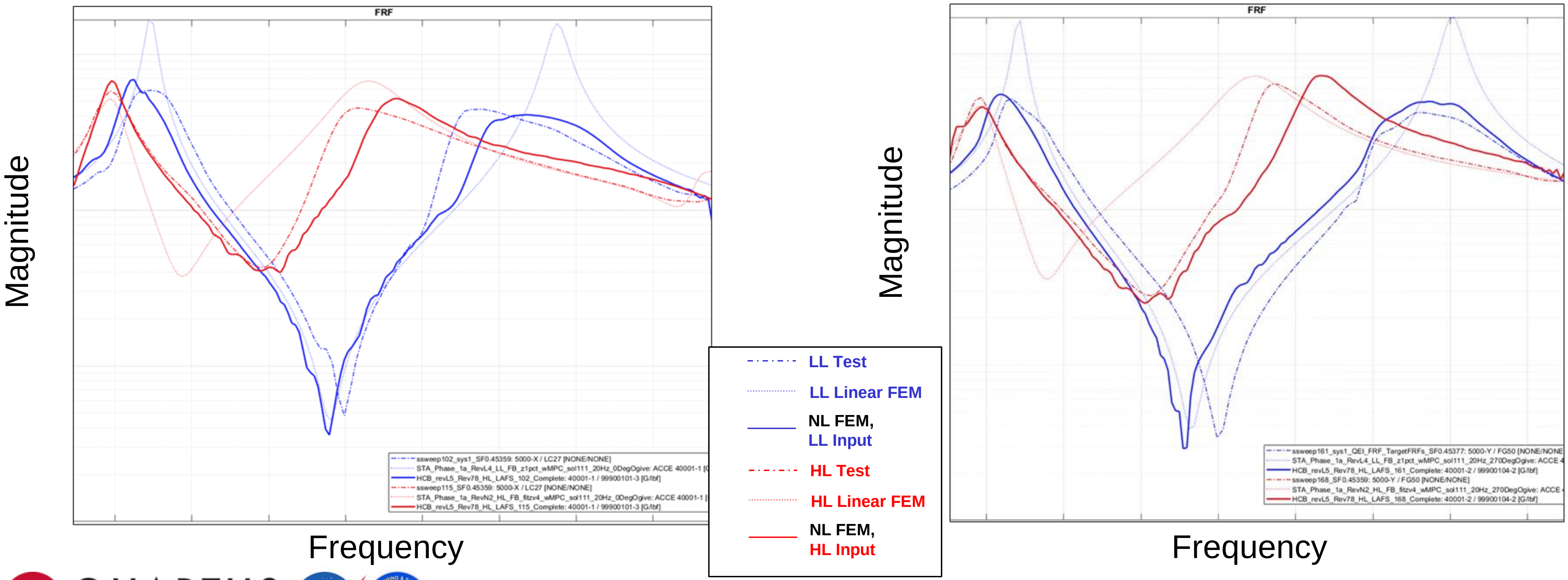


***Note:** Even at corresponding load levels, linear response cannot capture variations in response magnitude due to slipping joints*

C4 Nonlinear Correlation Example

- **Example FRF comparison below illustrates C4 nonlinear model correlation**
  - **Single model captures response to LLL loading as well as transition to HLL loading**
  - **Linear correlation cannot capture FRF shape**

Z Bending | **Y Bending**



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Comparative CLA Study

- **Performed a comparative CLA study to quantify Linearization Uncertainty**
  - **Developed flight-like NL "Truth" model from C4 correlation and LM flight FEM**
  - **CLA transient loads applied to all three models as base shake (MSA-SA interface)**

Models used in Comparative CLA study

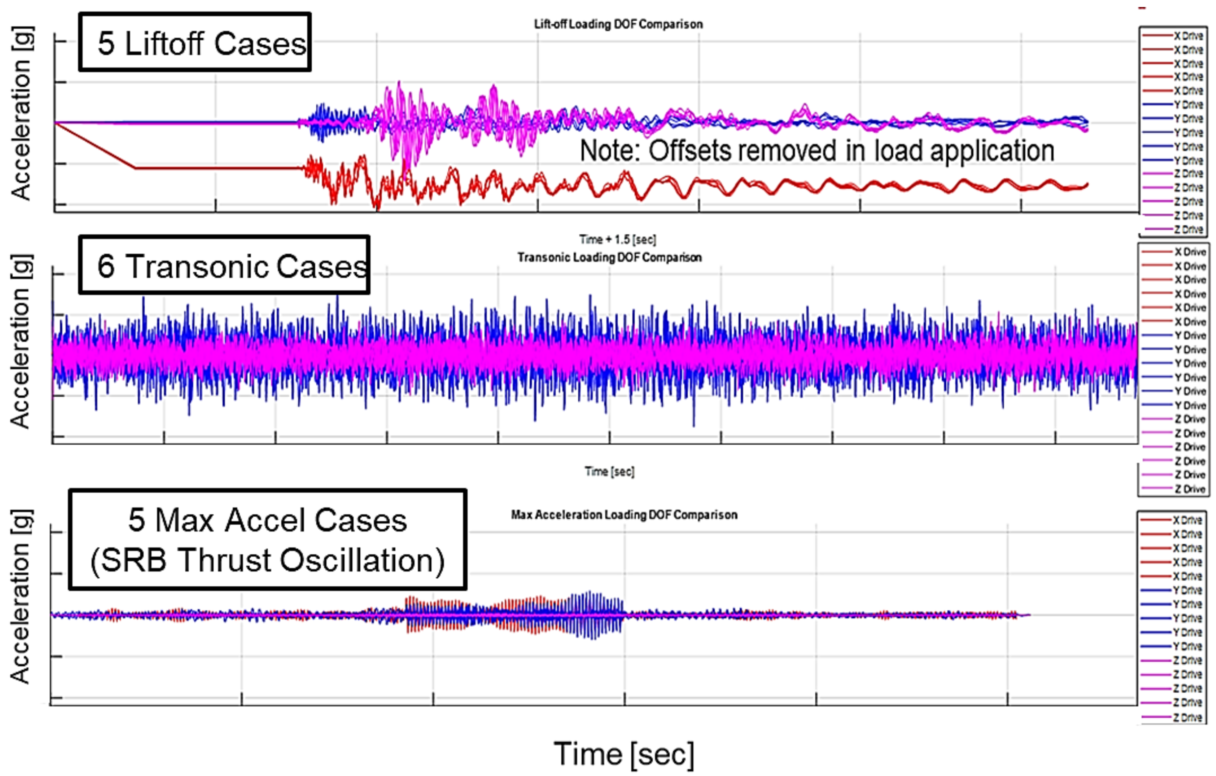
Developed from C4 correlated nonlinear joint properties → NL "Truth" Model

LM LL Linearization *(1% damping)*

LM HL Linearization *(1% damping)*

Flight Cycle CLA FEM

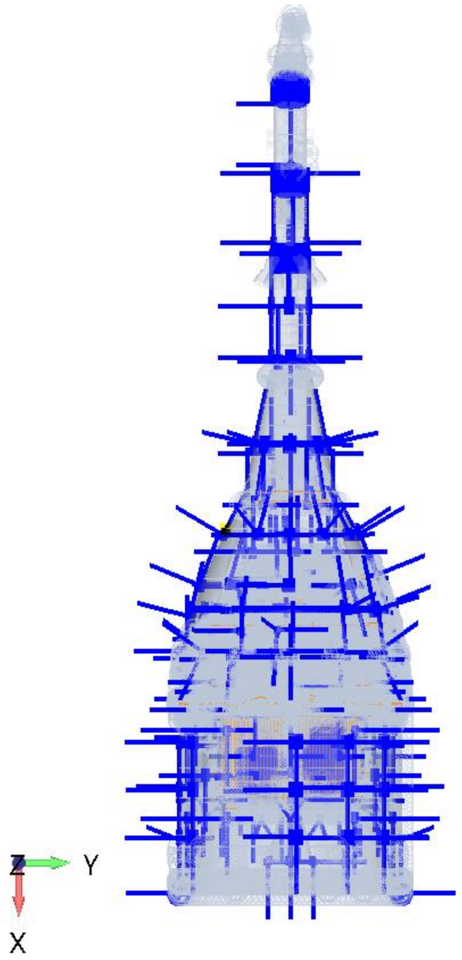
CLA Load Case Inputs (MSA-SA Base Shake)



Response Locations

- **Recovering grid response at 343 evenly distributed response locations**
  - Best immediately available response sample at the time
- **Known limitations of response sample**
  - Includes secondary structure that may not be of interest to stakeholders
  - Does not include assessment of forces, stresses or strains

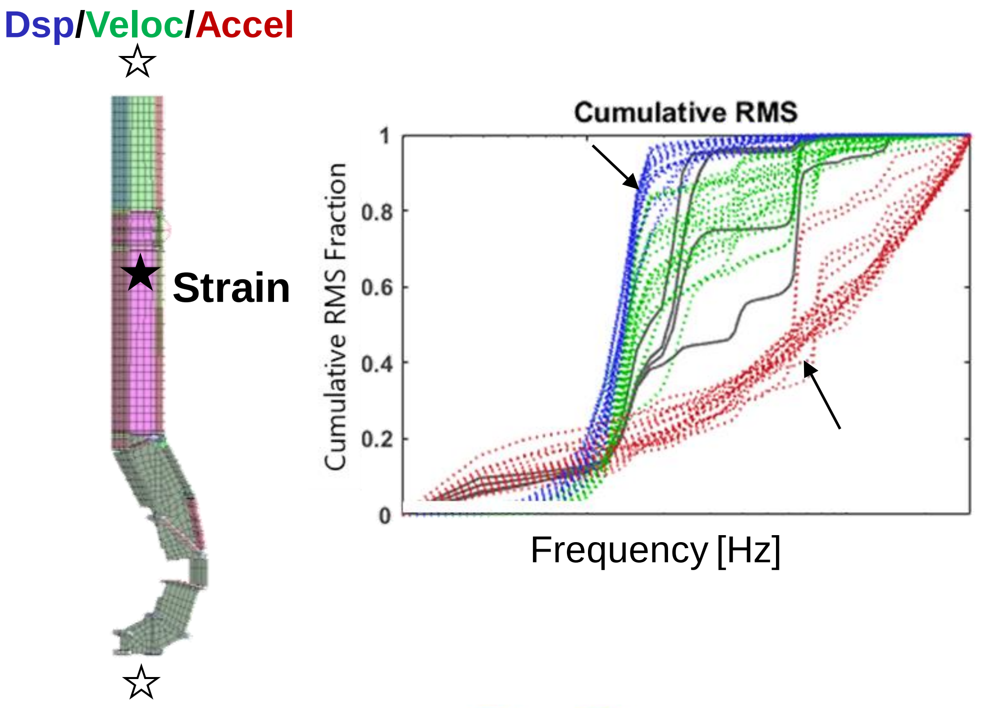
Response Recovery Locations Overlay



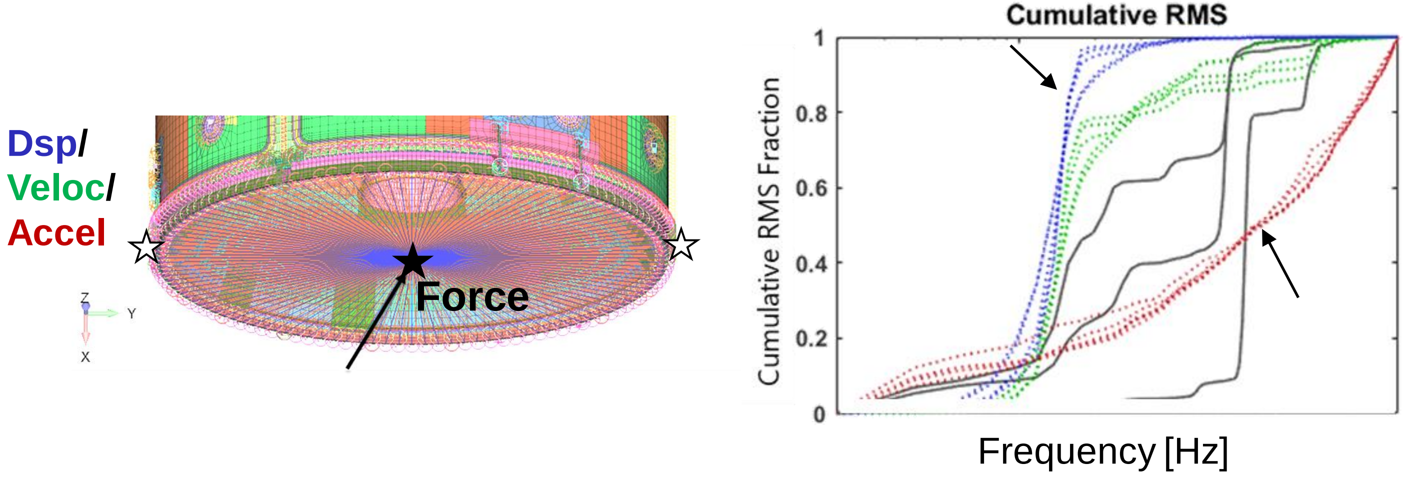
Response Metric Selection

- **Determined that velocity grid response is best proxy for structural loads and strains**
  - **Acceleration contains large amount of localized high-frequency vibration**
  - **Displacement under-represents vibration from second and third bending modes**

Longeron Output from NL Model (Transonic)



MSA-SA IF Output from NL Model (Transonic)

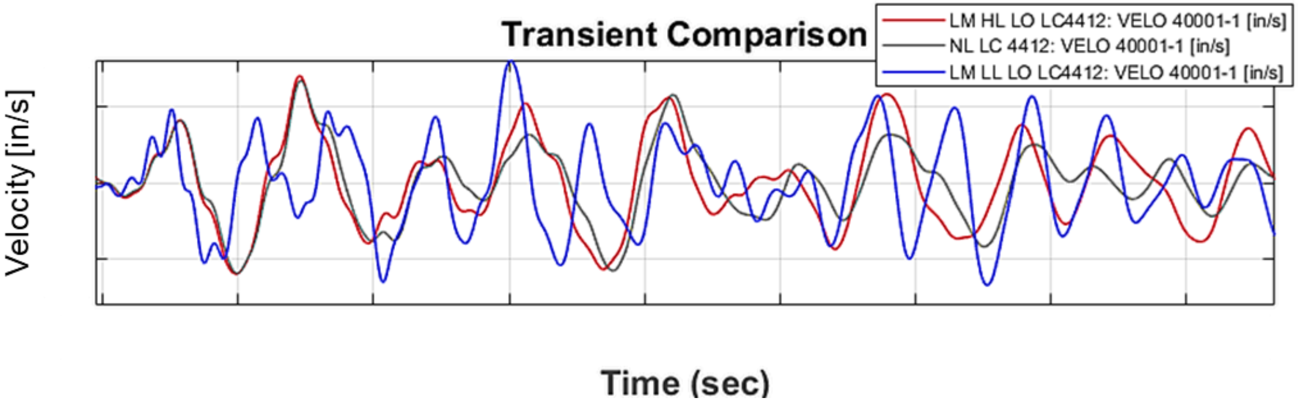


CLA Response Comparison Checks

- **How well are the linearizations approximating nonlinear flight transient response?**
- **Summarized comparison for each load case using Pearson correlation coefficients**
  - **1 => perfect match between transients**
  - **0 => transients have no linear relationship**
  - **Does not compare response magnitudes**

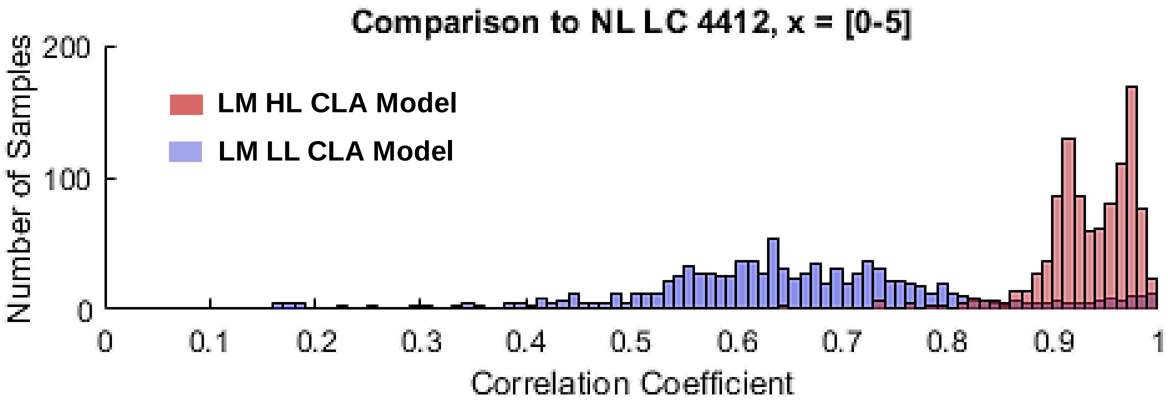
$$\rho(A,B) = \left| \frac{1}{N-1} \sum_{i=1}^{N} \left(\frac{A_i - \mu_A}{\sigma_A} \right) \left(\frac{B_i - \mu_B}{\sigma_B} \right) \right|$$

Liftoff Time History Comparison (LAS-Z)



Example Time History Correlation Coefficients

Liftoff LC 4412

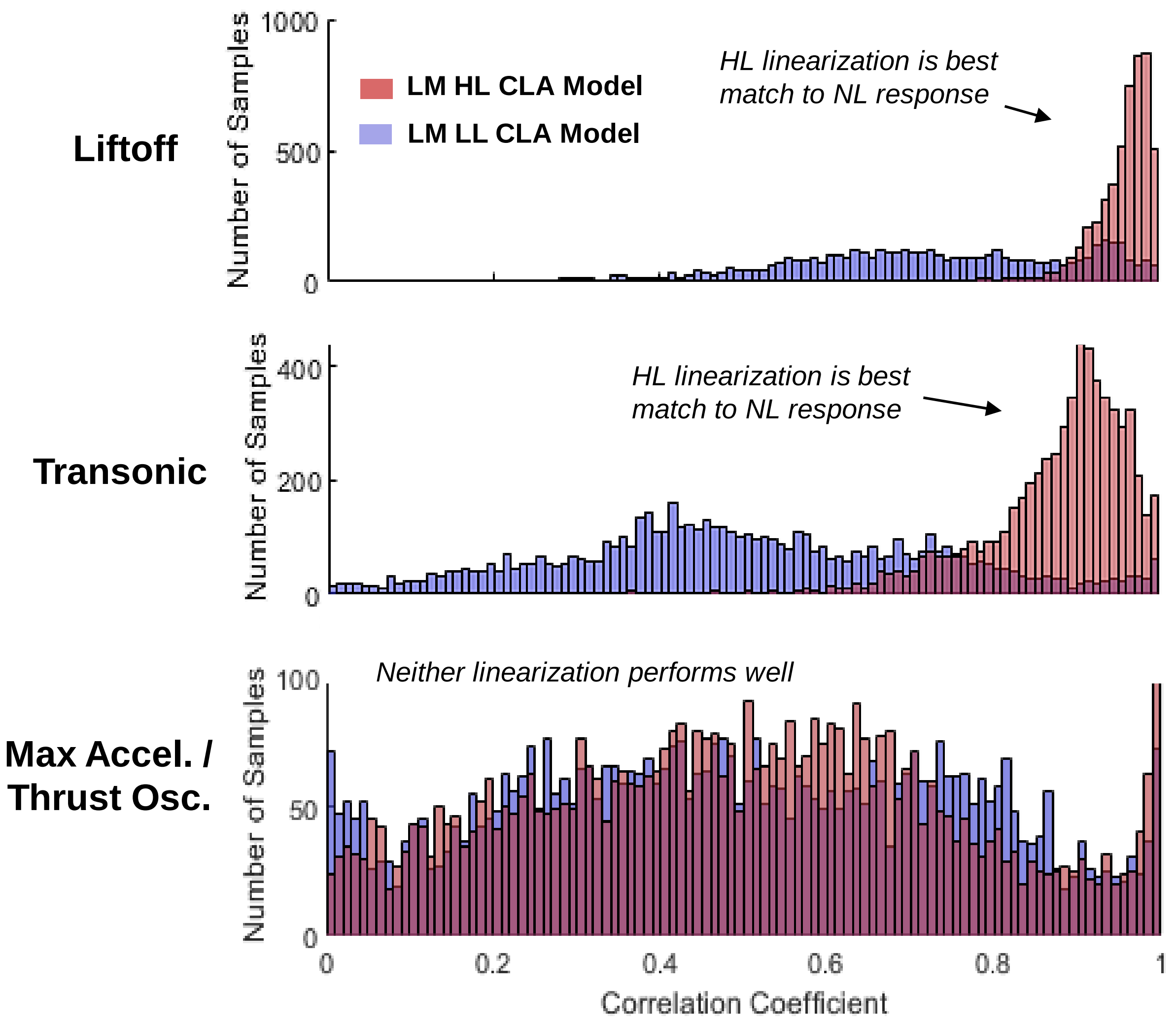


CLA Response Comparison Checks

- HLL linearization is a reasonable approximation for high-level flight loading
  - Liftoff and Transonic
- Need to compare response <u>magnitudes</u> (see next slide)

Correlation to NL Response

(Correlation coefficients for all responses and load cases)



Response Magnitude Uncertainty Parameter

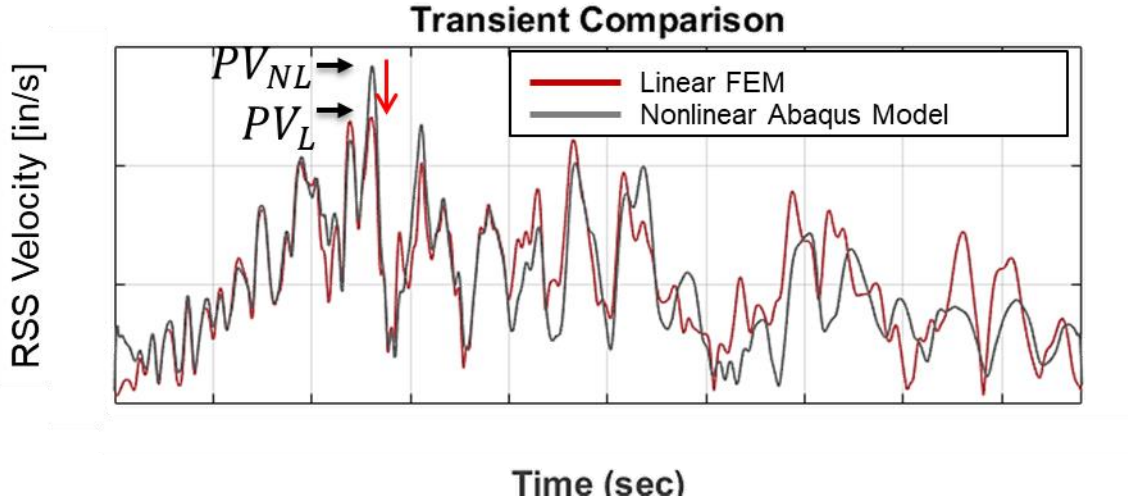
- **Linearization Uncertainty Factor (LUF) calculated at each response location for each load case:**
  1. **Combine XYZ by computing root sum squared (RSS) time history**
  2. **Find Peak Value (PV) of NL and linear FEM RSS time history**
  3. **LUF is NL PV normalized by linear FEM PV**
- **LUFs can be combined into probability distributions over all locations and a set of load cases (see next slide…)**

Linearization Uncertainty Factor (LUF)

$$LUF_n = \frac{PV_{NL}}{PV_L}$$

LUF>1 → Linear Model is Under-Predicting
LUF<1 → Linear Model is Over-Predicting

RSS Time Histories

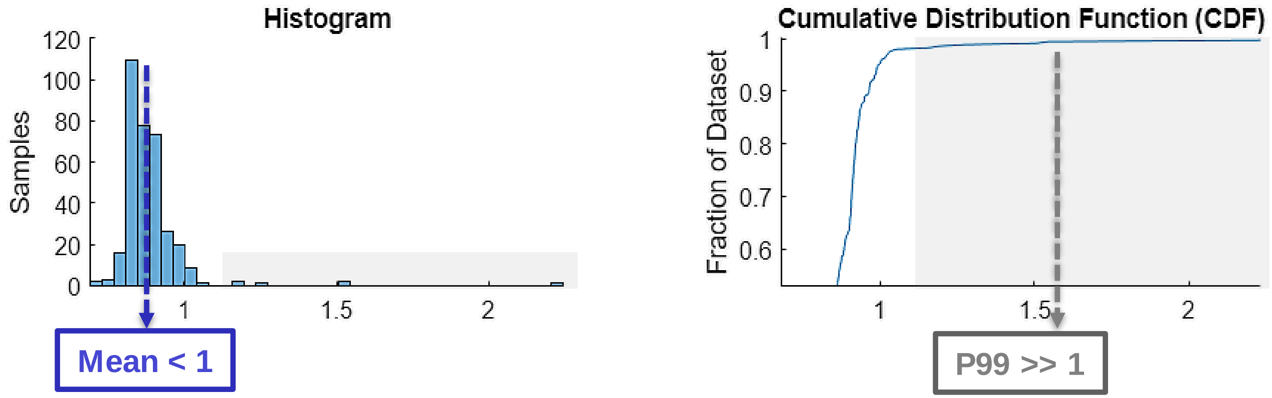


Trends in LUF Probability Distributions

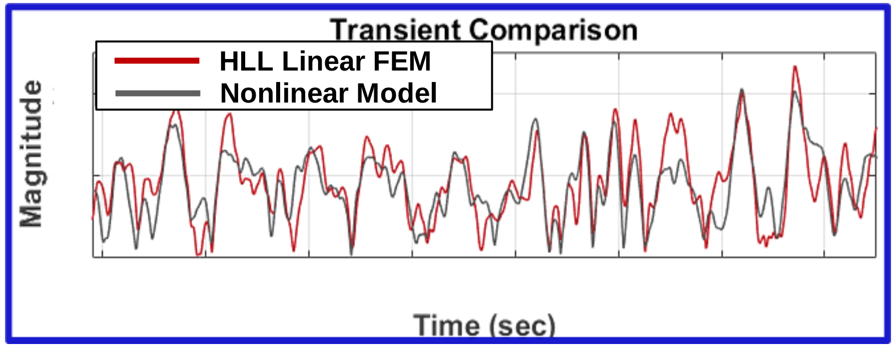
- Mean LUF <1 driven by conservative 1% damping in the linear model
- Highest 1% of LUFs driven by localized nonlinear transient "spikes"
  - Would likely be less pronounced in strains or integrated structural loads

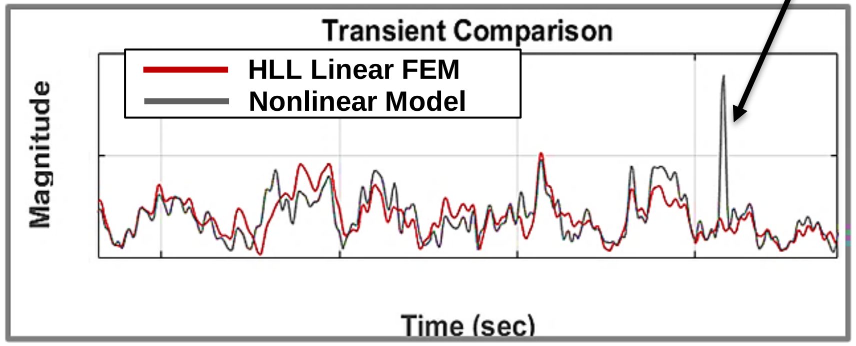
<u>Example LUF Probability Distribution</u>

Transonic Load Case



Linear model cannot capture localized nonlinear transient spikes

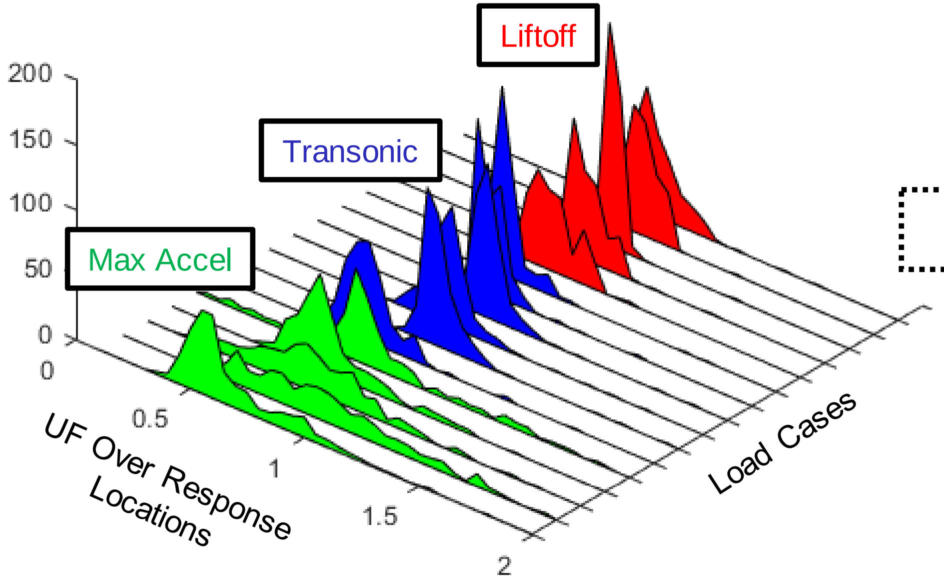




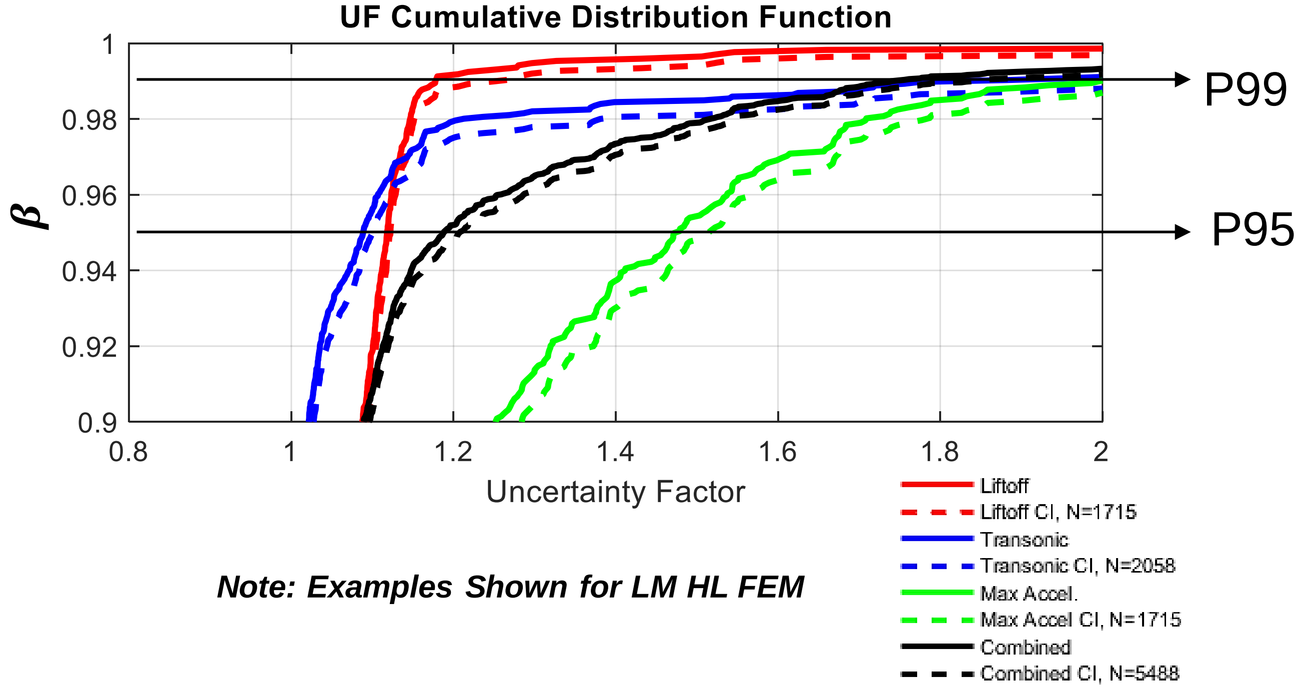
Maximum Expected UFs

- **Probability distributions shown for all load cases below**
- **Used Empirical Tolerance Limits (ETL) to estimate P95/50 and P99/90 LUF within each load class (NASA HBK 7005)**
  - **Probability level (β): determined directly from Cumulative Distribution Functions (CDF)**
  - **Confidence level (γ): computed from binomial confidence interval**

UF Probability Distributions



CDFs and Associated 90% Confidence Bounds



Note: Examples Shown for LM HL FEM

UF Summary – Velocities

- **LUF statistics shown below for HLL linear CLA model**
- **Applying P95 or P99 LUFs as a multiplicative factor existing estimate of P95/50 responses would be highly conservative**
  - Need to account for response reduction from mean LUF <1.0
  - Linearization uncertainty is an *independent* source of uncertainty (with respect to loads uncertainty, model uncertainty, etc…)
- **LUF <u>mean</u> and <u>standard deviation</u> should be correctly statistically combined with other sources of uncertainty to obtain the correct RSS-d uncertainty factor for P95/50 loads**
  - Details on the following slide…

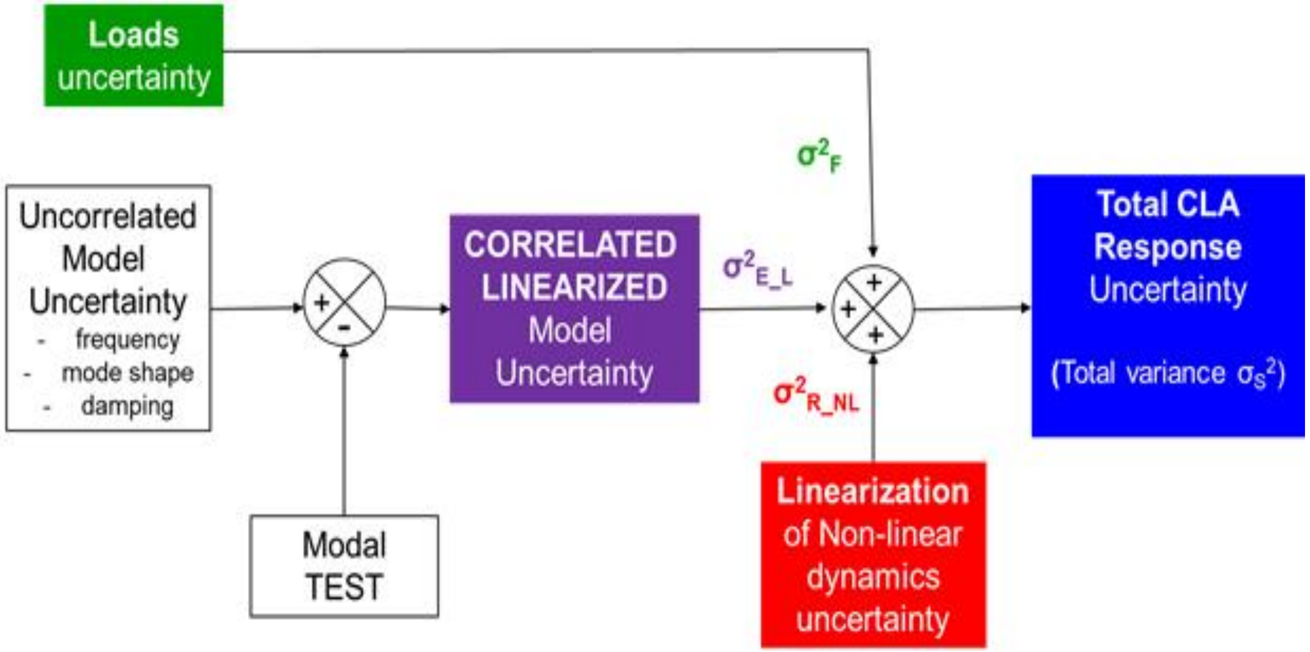
LM HLL FEM

Model Damping:	*1%*			
Statistic:	*Mean*	*Standard Deviation*	*P95/50*	*P99/90*
Liftoff	**0.98**	**0.10**	**1.1**	1.2
Transonic	**0.92**	**0.29**	**1.1**	2.1
Max Accel	**0.87**	**0.30**	**1.5**	2.1
Combined	**0.92**	**0.26**	**1.2**	1.7

P95 and P99 LUF should <u>not</u> be directly applied to existing estimate of P95/50 responses (see next 2 slides)

Total CLA Uncertainty [1 of 2]

- **CLA response (stress, loads, etc…) is a product of at least 3 Random Variables**
  - Loads (F), Linear Elastic Transfer Functions (E_L), Linearization Uncertainty Factor (R_{LUF})
- **Combined CLA response distribution will converge to a log-normal distribution**
  - Sum of statistically independent sources of uncertainty (central limit theorem)



CLA Response as a Product of 3 Random Variables

$$P(S) \sim P(F.E_L.\boldsymbol{R_{LUF}})$$

Log transform…

$$P(L_S) \sim P(L_F + L_{E_L} + \boldsymbol{L_{R_{LUF}}})$$

$$\rightarrow \ Normal\ Distribution$$

Total CLA Uncertainty [2 of 2]

- **Statistically combining LUFs with CLA response distribution results in modest increase from linear CLA P95/50 estimate**
  - **Incorporates mean LUF < 1.0 (slight reduction)**
  - **Linearization uncertainty RSS-d with other sources of CLA uncertainty**
- **Applying P95/50 LUF as scale factor to existing linear CLA P95/50 estimates exceeds true P95/50 (overly conservative)**

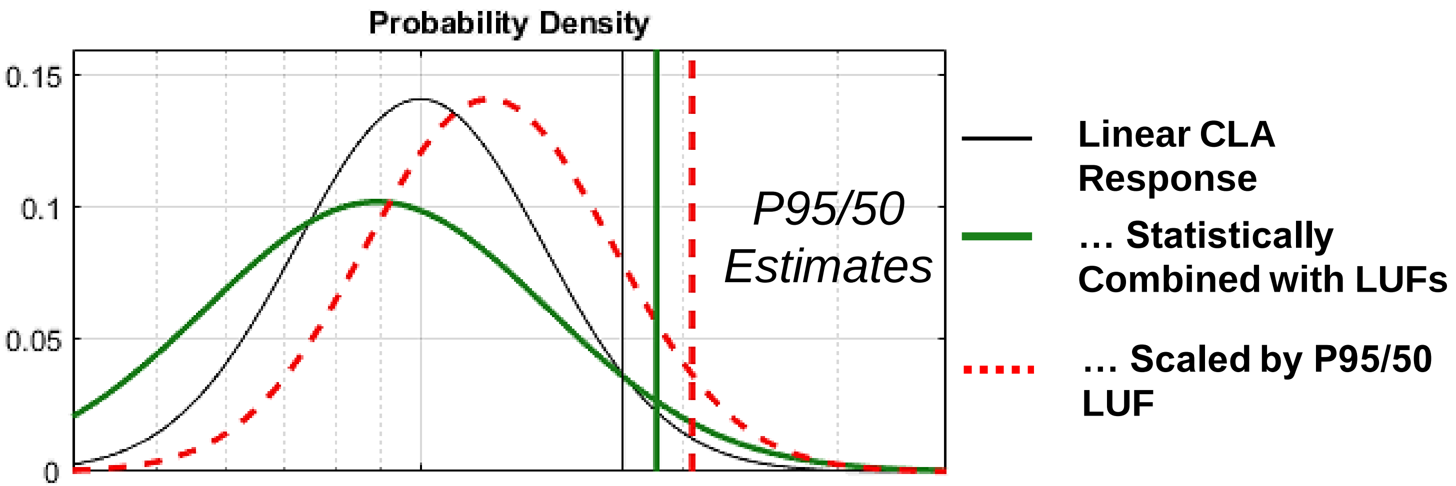
Mean LUF < 1.0

$$P95/50[L_S] = \langle L_F \rangle + \langle L_{E_L} \rangle + \langle \boldsymbol{L_{R_{LUF}}} \rangle$$

$$+k_{Normal}^{P95/50}\sqrt{\sigma^2(L_F) + \sigma^2(L_{E_L}) + \boldsymbol{\sigma^2}(\boldsymbol{L_{R_{LUF}}})}$$

CLA Uncertainty Margin

CLA Response Distribution (Illustration)



CLA Response
(Units are Arbitrary)

Considerations for Future Work

- **Future work should analyze targeted set of CLA outputs of interest**
  - Likely strains or integrated loads
  - This analysis used grid point velocities over entire vehicle as a proxy
- **Shock Response Spectrum could offer a more rigorous approach**
  - This analysis used time history peak value which give less insight into the dynamic sources of uncertainty