Orion MPCV E-STA Nonlinear Dynamics Uncertainty Factors

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ABSTRACT

NASA vibration testing of the European Service Module (ESM) Structural Test Article (E-STA) for the Orion Multi-Purpose Crew Vehicle (MPCV) program demonstrated significant nonlinear behaviors and response deviation from pre-test finite element analysis (FEA). A linear FEA correlation effort, previously performed in 2017, resulted in the creation of two finite element models (FEM) – one correlated to high-load level swept sine responses and one correlated to low-load level swept sine responses. Additional work was required to quantify the uncertainty introduced when applying these linear models to non-sinusoidal flight load cases. To do this, an additional nonlinear dynamics model was developed and correlated with sine sweep test responses for low load level and high load level load cases. Results showed that, when the appropriate linearized model was selected for each specific Coupled Loads Analysis (CLA) loading type (i.e. Liftoff, Transonic, etc…), the linearized models closely matched predicted nonlinear responses with modest error (uncertainty factor). Results of this investigation have established a physics-based nonlinear dynamics approach that uses empirical test data to establish the credibility assumption for usage of linear FEM(s) in CLA. It is anticipated that the methodology employed can be extended for usage in correlation and flight loads analysis of subsequent spacecraft with major joint nonlinearities.

Keywords: Nonlinear Dynamics, Uncertainty, Orion MPCV, Coupled Loads Analysis (CLA)

INTRODUCTION

MPCV E-STA sine vibration testing was performed at various flight-like load levels. Significant nonlinear behaviors were observed as well as response deviation from pre-test FEA. These nonlinearities were observable as significant frequency and damping shifts between the low-load level test cases (20% flight level loads) and the high-load level test cases (100% flight level loads). Sample sine sweep frequency response function (FRF) results are shown in Figure 3. In addition, evidence of joint slipping onset was apparent in the test data FRFs, exhibited as nonlinear inflections in the ramp up to resonance.

A previous investigation by Quartus and NESC identified and limited the primary nonlinearities to three major interface joints. A linear FEA correlation effort resulted in the creation of two linear FEMs intended for use in a CLA study. The purpose of this study was to inform the use of correlated linear FEM(s) in a comprehensive linear CLA of a truly nonlinear system. One linear FEM was correlated to high level E-STA load cases (HLL FEM) and the other was correlated to low level E-STA load cases (LLL FEM). These two linear FEMs effectively represented linearizations of the true E-STA response about two specific load levels. Figure 1 illustrates how these linearizations might not necessarily predict accurate responses of a nonlinear system at load levels about which they were not correlated. Because of this, a single nonlinear FEM was created to help quantify the error (or uncertainty) introduced from utilizing linearized models in a linear CLA. This nonlinear "truth" model was developed from the previously correlated linearized models and correlated to the same E-STA sine sweep test results. It included detailed representations of the nonlinear joints – primarily through the inclusion of Coulomb friction stick-slip conditions. The results of both the linear and nonlinear model correlation efforts are briefly summarized in this report; additional details of these correlation efforts can be found in their corresponding references [1, 2].

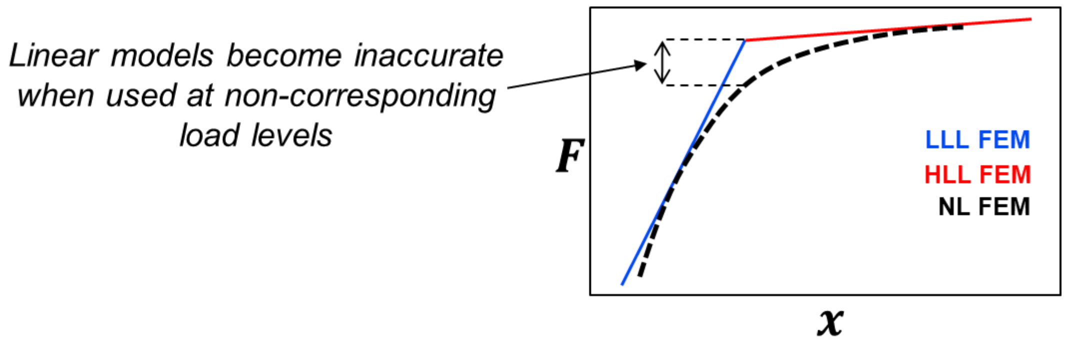

Figure 1: Illustration of Linearization Uncertainty – A single nonlinear "truth" model can help quantify uncertainty introduced when the correlated HLL and LLL linear FEMs are used under a loading about which they were not correlated

Figure 2 outlines the steps taken in a CLA study designed to assess the performance of the HLL and LLL FEM for a set of flight-like load cases. The study was performed using a subset of representative CLA load cases and compared the response of the HLL and LLL linearized models to the response of the nonlinear model. This subset of CLA load cases represented three distinct phases of flight:

- 5 Liftoff cases
- 6 Transonic cases
- 5 Max Acceleration cases

These CLA load cases (6 DOF acceleration time histories at the MPCV interface) were applied to all three models as a time domain base excitation (fixed base analysis). The HLL and LLL response time histories were then compared to the nonlinear response time histories and a best-fit linear FEM was selected to represent each CLA loading type. Linearization Uncertainty Factors (LUF) were then computed for each CLA loading type using the selected best-fit linear FEMs.

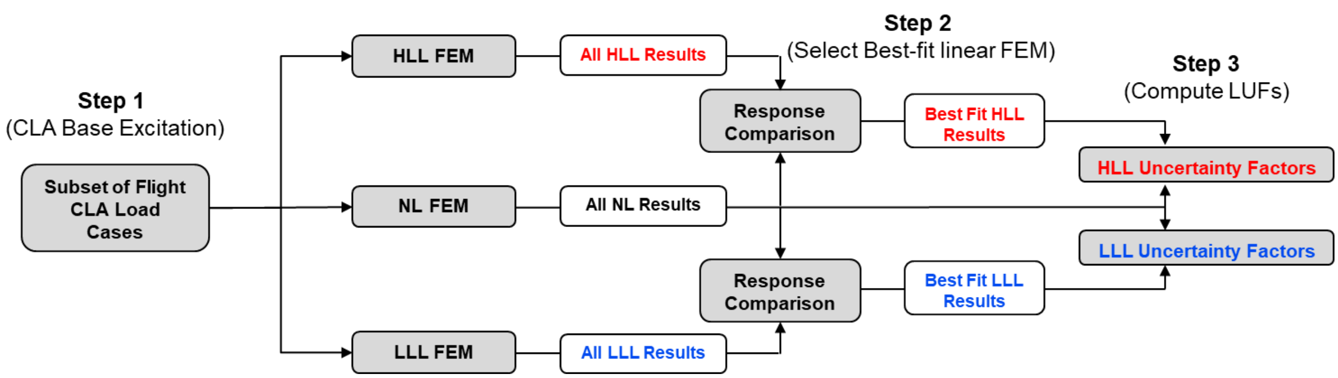

Figure 2: CLA Study Outline – CLA response was compared between the linearized models and the nonlinear model resulting in the selection of a best-fit linearized model and corresponding LUF for each CLA loading type

ANALYSIS

A previous investigation performed by Quartus and NESC resulted in the creation of three correlated FEMs for use in a CLA study:

- LLL linearized model: Linear NASTRAN FEM correlated to E-STA response at 20% flight load levels
- HLL linearized model: Linear NASTRAN FEM correlated to E-STA response at 100% flight load levels
- Nonlinear "Truth" FEM: Single nonlinear Abaqus model representing E-STA response at all load levels

The results of both the linear and nonlinear model correlation efforts are briefly summarized in this report; additional details of these correlation efforts can be found in their corresponding references [1, 2]. The nonlinear Abaqus model is a combination of nonlinear Abaqus joints and a Hurty-Craig/Bampton (HCB) reduced model of the majority of the E-STA structure (reduction performed on NASTRAN model and HCB matrices converted to Abaqus format).

One of the primary metrics used in the model correlation process was comparing E-STA FEM and test FRFs based on the E-STA sine test drive inputs. The linearized model FRFs were directly computed in the frequency domain using NASTRAN (sol 111). Figure 3 shows a comparison between the E-STA measured sine test FRFs and the linearized model FRFs at the Launch Abort System (LAS) simulator (considered a representative response location for gauging primary mode responses). Results are shown for the high-load level sine sweep (100% flight loading shown in red) and low-load level sine sweep (20% flight loading shown in blue) load cases. In the case of the linear correlation, the high load level sine sweep was applied to the HLL FEM while the low load level sine sweep was applied to the LLL FEM. The two linearized models approximated the frequency and damping shift observed during the E-STA test, however effects of slipping joints observable in the test responses was not captured.

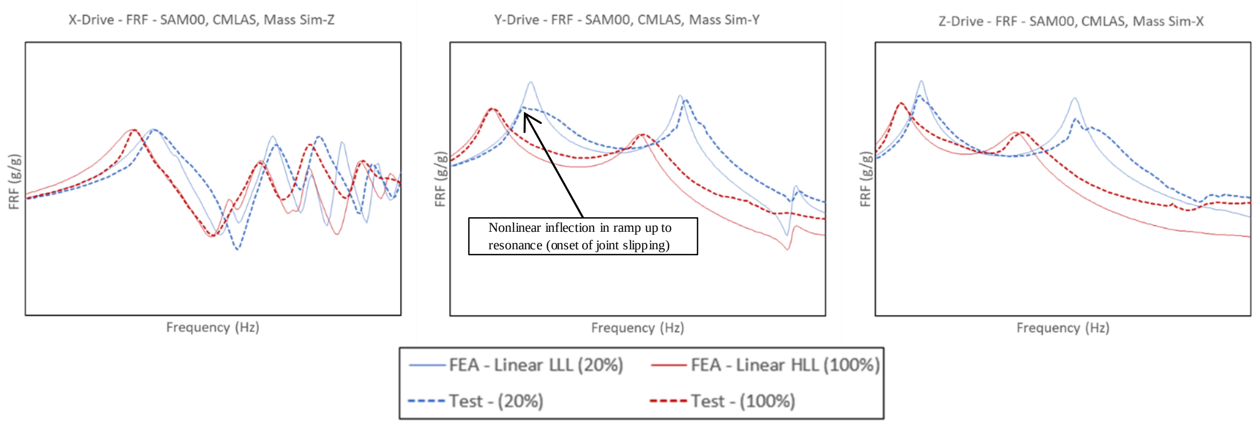

Figure 3: Linear FEM Correlation Results (LAS Simulator FRF) – Two linear FEMs were able to approximate the frequency and damping shifts observed in test; however effects of joint slipping (evident in some test FRF peaks) could not be captured using two correlated linear FEMs.

The nonlinear model FRFs were computed by post-processing time histories from a nonlinear direct transient simulation of the E-STA high level and low level sine sweeps. These simulations were performed using Abaqus implicit dynamics. Figure 4 shows the same comparison with E-STA test FRFs using only a single correlated nonlinear model. In this case, both the high-load level and the low-load level sine sweep transient inputs were applied to the same correlated nonlinear model in direct transient simulations in Abaqus. The use of this single nonlinear model showed improved correlation over the use of the two separate linearized models and captured the slipping onsets observed in the measured test FRFs. Because of this, the nonlinear model was considered a "truth" model and acted as a surrogate for the E-STA true nonlinear response.

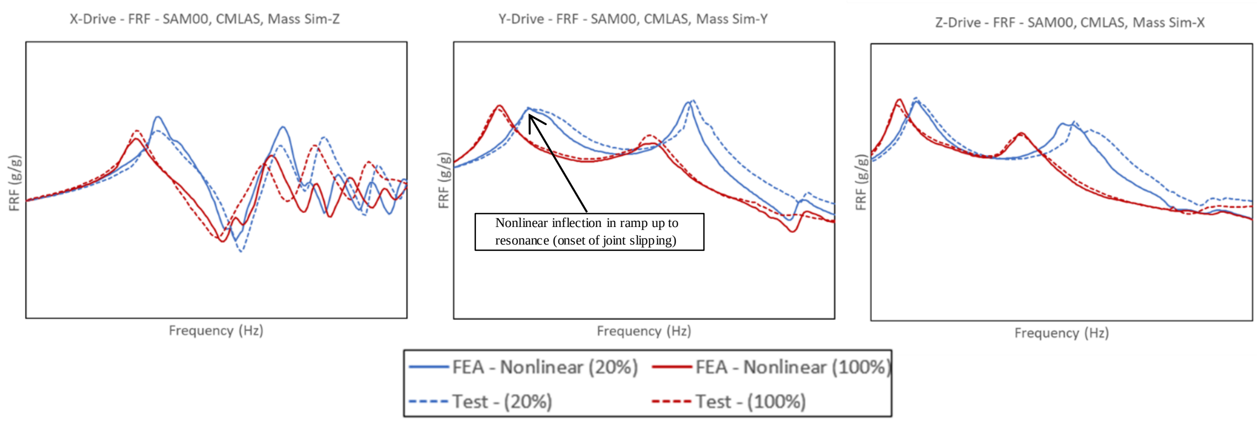

Figure 4: Nonlinear FEM Correlation Results (LAS Simulator FRF) – A single correlated nonlinear FEM was able to capture frequency and damping shifts as well as effects of joint slipping observed in test.

A CLA response study was performed using the three correlated models discussed above. The purpose of this study was to determine a best-fit linearized model for each CLA loading type (i.e. Liftoff, Transonic, Max Acceleration) by comparing the linearized model responses to the response of the nonlinear "truth" model. Figure 5 and Figure 6 show the ensemble of CLA response locations used in this study.

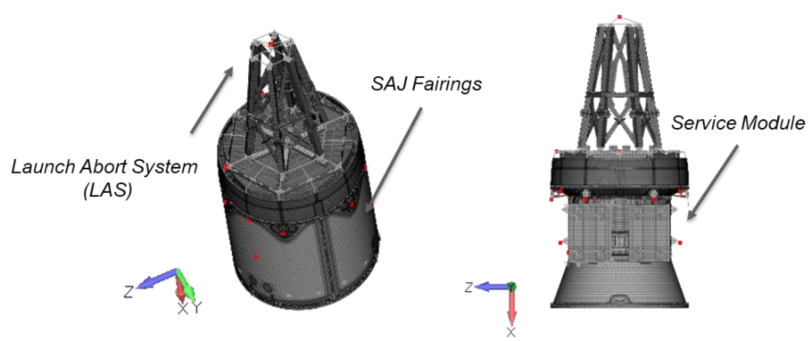

Figure 5: Nodal Response Locations – CLA transient acceleration response was recovered in all translation DOFs at 27 nodal locations for the HLL, LLL, and nonlinear FEM

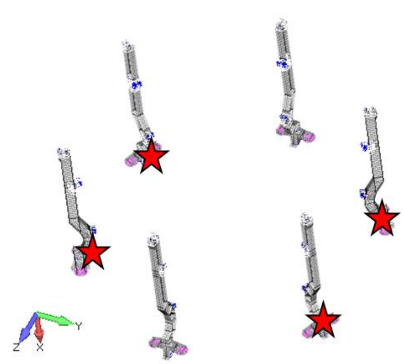

Figure 6: Strain Response Locations – CLA transient strain response was recovered at 4 elemental locations for the HLL, LLL, and nonlinear FEM

Due to the large number of response outputs (i.e. locations, degrees of freedom [DOF], and load cases), Pearson Correlation Coefficients were used to compare the response of the HLL and LLL model to the nonlinear model for each output. A Pearson Correlation Coefficient is a time-integrated measure of the linear dependence of two variables (Equation 1). When this is applied to two response time histories, it provides a high-level frequency and phase comparison. These are the most important metrics when determining which linearized model best represents the nonlinear response for any CLA loading type. It should be noted that the Pearson Correlation Coefficient is not sensitive to magnitude discrepancies between two time histories. These are accounted for in a subsequent computation of uncertainty factors after the best-fit linear models have been selected for each CLA loading type.

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

Equation 1: Pearson Correlation Coefficient – N: Sample Size, A&B: Random Variables, σ: sample standard deviation, μ: sample mean

Pearson correlation coefficients were calculated between each linearized model and the nonlinear model for all response locations over all load cases and grouped by their respective CLA loading types. Figure 7 shows histogram distributions of Pearson Correlation Coefficients representing the LLL and HLL acceleration response comparison with the nonlinear "truth" response. In addition, a representative sample transient response comparison is shown at a single node on the E-STA LAS simulator for each CLA loading type. For Liftoff and Transonic type load cases, a strong correlation was observed between the HLL linearized model and the nonlinear model. On the other hand, Max Acceleration load cases were a lower-level load case; therefore a strong correlation was observed between the LLL linearized model and the nonlinear model. The same trend was observed for strain response comparisons, but is not shown explicitly in this report. These trends informed the selection of the best-fit linearized models for each CLA loading type. The best-fit linearized model for Liftoff and Transonic CLA cases was the HLL FEM, while the best-fit linearized model for Max Acceleration CLA cases was the LLL FEM.

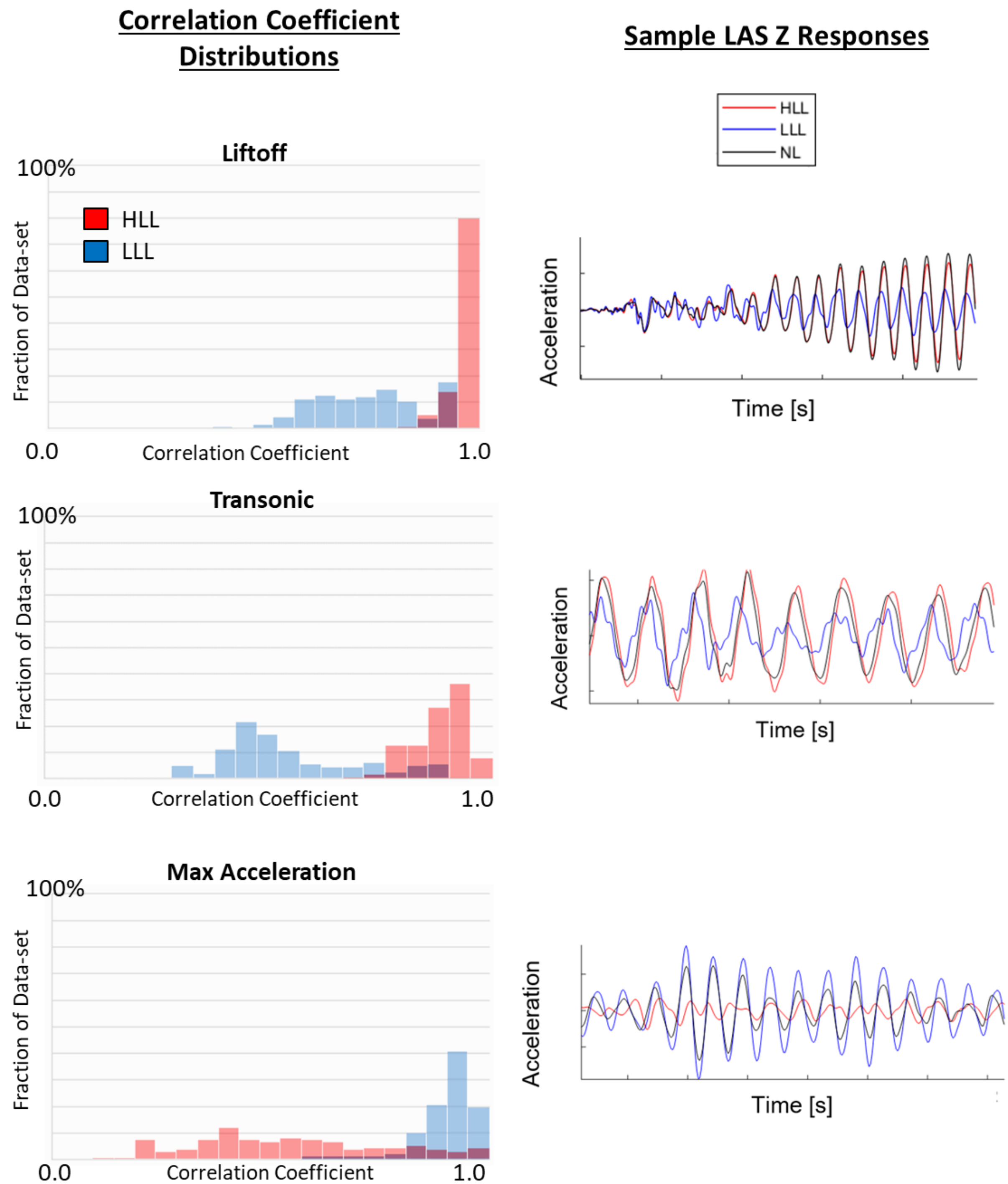

Figure 7: Pearson Correlation Coefficients for Acceleration Response – Pearson Correlation Coefficients were computed between each linear model (LLL and HLL) and the nonlinear FEM and represented by histogram distributions. This was done to determine the best fit linear model for each CLA loading type.

Following the response comparison, Linearization Uncertainty Factors (LUF) were computed to represent the uncertainty that would be introduced using the selected best linear models in a comprehensive CLA. LUFs were computed for each CLA response location as a ratio of response magnitude between the nonlinear "truth" model and the selected best-fit linearized model (Equation 2). Table 1 shows the selected response magnitude metrics for each CLA loading type. Because Liftoff and Max Acceleration load cases were non-stationary, peak-value was selected as the magnitude metric. Alternatively, since

Transonic load cases were primarily random buffet loadings, root-mean-squared (RMS) was selected as the magnitude metric for these cases.

$$\boldsymbol{LUF_n = \frac{R_{NLin}}{R_{Lin}}}$$

Equation 2: Linearization Uncertainty Factor – R_{Lin}: Linear response magnitude, R_{NLin}: Nonlinear response magnitude

Table 1: Determination of Response Magnitude Metric (R) for Each CLA Loading Type

	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*

By the definition in Equation 2, the maximum LUF for any loading type was of primary interest as it represented instances in which the selected linear model was under-predicting the true nonlinear response. However, since this study was performed on only a subset of CLA load cases, a measure of statistical significance was desired to help characterize how well the computed max uncertainty factors can generalize a comprehensive CLA consisting of hundreds or thousands of load cases. Figure 8 shows Probability Density Functions (PDF) computed using LUFs from all response locations (including acceleration and strain).

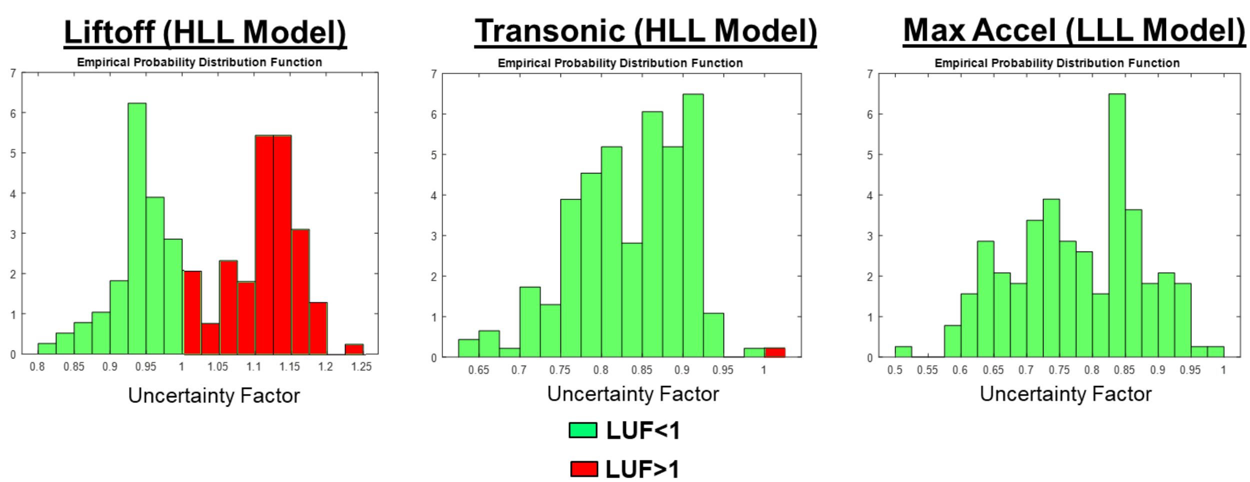

Figure 8: Probability Density Functions of LUFs Computed Using Best-fit Linear Models – Probability distributions were determined to be irregular (not Normal Gaussian distributions)

Statistical significance is typically given as a probability level (β) and confidence level (γ) associated with a particular maximum value. In this case, it was observed that the LUF distributions were irregular (not Normal Gaussian distributions) rendering the standard Normal Tolerance methodology unusable within the current analysis parameters [3]. Investigation revealed that the irregularities observed were primarily due to the use of peak value as a magnitude metric for non-stationary load cases. For example, the Liftoff load cases consist of two distinct events – one in which the HLL model over-predicts the true nonlinear response, and another in which the HLL model under-predicts true nonlinear response. This results in the bi-modal probability distribution observed in the Figure 8 Liftoff PDF.

A non-parametric, distribution-free methodology exists that does not assume any distribution of the sample [3]. The Distribution-Free Tolerance Limit (DFL) is defined as a value which exceeds all values for <u>at least</u> β fraction of a sample with a confidence γ defined by Equation 3. The primary limitation of the DFL methodology is that it does not permit independent selection of γ and β. Instead, $\beta < \beta_{max}$ is chosen to achieve desired confidence (where β_{max} is the fractional portion of the data enveloped by the max value). Since the LUF PDFs in Figure 8 were extremely irregular (particularly the Liftoff distribution), further development of this methodology should be done to arrive at more familiar LUF distributions. This would allow for a better estimation of statistical significance.

$$\boldsymbol{\gamma = 1 - \beta^N}$$

Equation 3: Confidence of Distribution-free Tolerance Limit (DFL) – Confidence associated with a DFL that envelopes β fraction of a sample (sample size = N)

Table 2 shows the max LUFs computed for each CLA loading type and an associated statistical probability and confidence (from the DFL methodology outlined above). Using the appropriate best-fit linear model for each loading type resulted in relatively modest maximum LUFs. It should be noted that inherent loads uncertainty as well as model uncertainty was not accounted for in this analysis. These additional sources of uncertainty would be combined with the LUFs to arrive at total CLA uncertainty.

Table 2: Max Uncertainty Factors for Each CLA Loading Type

	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%*

CONCLUSION

NASA vibration testing of the Orion E-STA demonstrated significant nonlinear behaviors and response deviation from pre-test analysis. Because of this, two correlated linear FEMs were developed that acted as linearizations of E-STA response about low-load level (LLL FEM) and high-load level (HLL FEM). Additionally, a single correlated nonlinear “truth” model was developed to act as a surrogate for the E-STA true nonlinear response. A CLA response comparison study revealed that the linearized models can approximate the true nonlinear response and informed the selection of a best-fit linearized model. To account for the uncertainty introduced from performing a comprehensive linear CLA on a nonlinear system, Linearization Uncertainty Factors (LUF) were computed for each loading type. Using the best-fit linear FEM for each CLA loading type, it was found that modest LUFs could be applied to a comprehensive linear CLA.

ACKNOWLEDGEMENTS

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