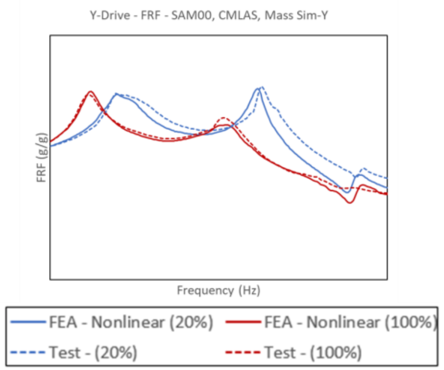
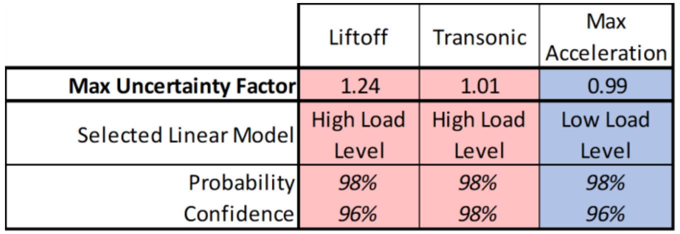
Background

- Vibration testing of Configuration 4 (C4) Structural Test Article (STA) for the NASA Orion Multi-Purpose Crew Vehicle (MPCV) modal correlation program 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

Motivation

- **Previous work by Quartus/NESC showed that a nonlinear correlation of the MPCV European Service Module STA (E-STA) could be used as a truth model for quantifying linearization uncertainty [1,2]**
  - Using a single linear FEM in coupled loads analysis (CLA)





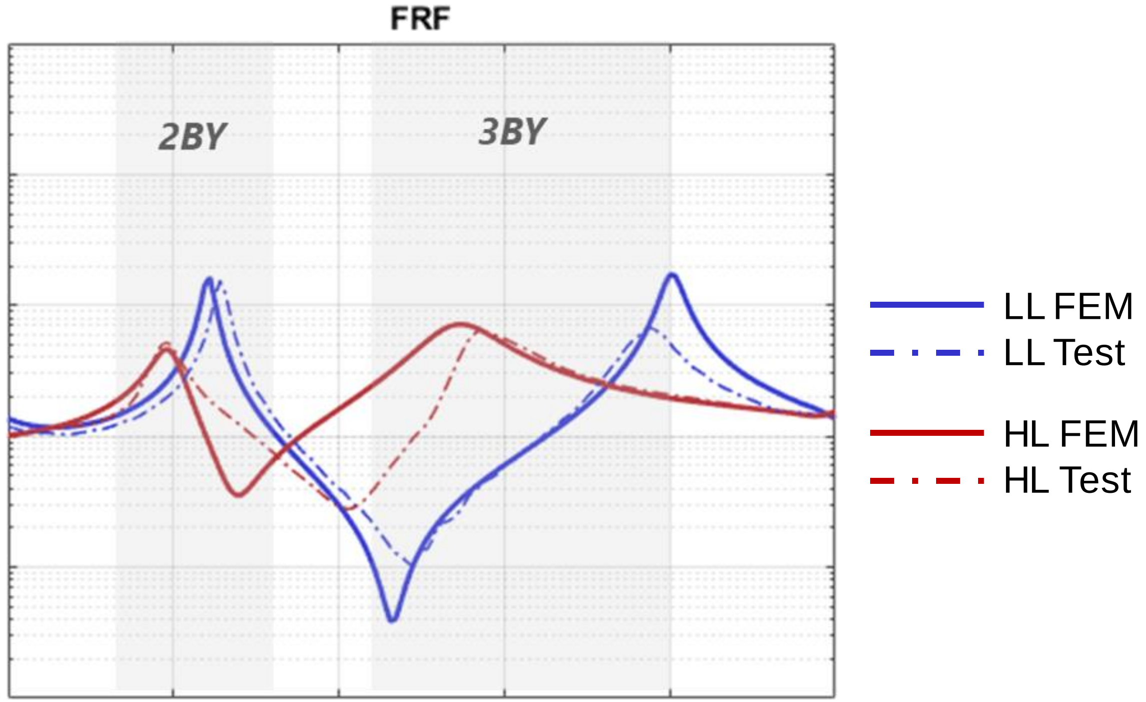
	Liftoff	Transonic	Max Acceleration
Max Uncertainty Factor	1.24	1.01	0.99
Selected Linear Model	High Load Level	High Load Level	Low Load Level
Probability	*98%*	*98%*	*98%*
Confidence	*96%*	*98%*	*96%*

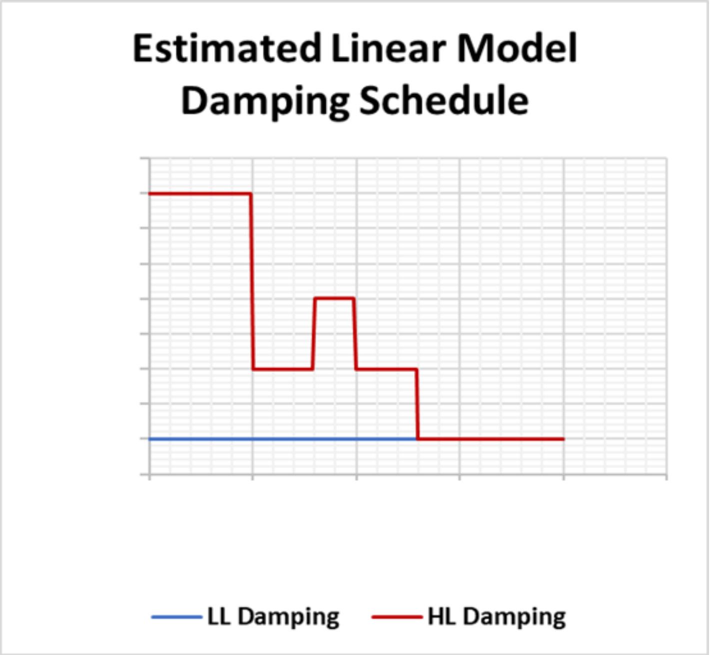
- **Allen et al. proposed that Quasi-Static Modal Analysis (QSMA) could be used to drastically decrease model updating time during the nonlinear correlation phase and QSMA + Bouc-Wen (BW) could extend the method into the time domain [3]**

[1] Griebel et al. "Orion MPCV E-STA Nonlinear Correlation for NESC," SCLV 2019.
[2] Griebel et al. "Orion MPCV E-STA Nonlinear Dynamics Uncertainty Factors," IMAC 2020
[3] Allen et al. "Leveraging Quasi-Static Modal Analysis for Nonlinear Transient Dynamics," SCLV 2019

Linear Correlation

- **Similar to E-STA, 2 linear FEMs were correlated to C4 STA**
  - Low-level (LL) and high-level (HL)
  - 7 joints identified as impactful through sensitivity studies
  - Linear correlation performed entirely in the frequency domain





Nonlinear Model Setup

- **Performed Hurty/Craig-Bampton (HCB) reduction of LL linear model**
  - Retain
    - Drive points, instrumentation locations, joint interfaces, modes
  - Includes nominal modal damping from LL linear correlation effort
    - Modal damping is converted to viscous damping
      - Since all DOF are CSET, except base constraint, component modes ≈ system modes
  - Converted Nastran HCB to Abaqus
- **Updated joints to Abaqus connector elements with Coulomb friction**
  - Started with stuck stiffness = LL linear stiffness and slip stiffness = HL linear stiffness
  - Frequency, x-ortho, and FRF checks done on Abaqus model to validate conversion

QSMA Overview

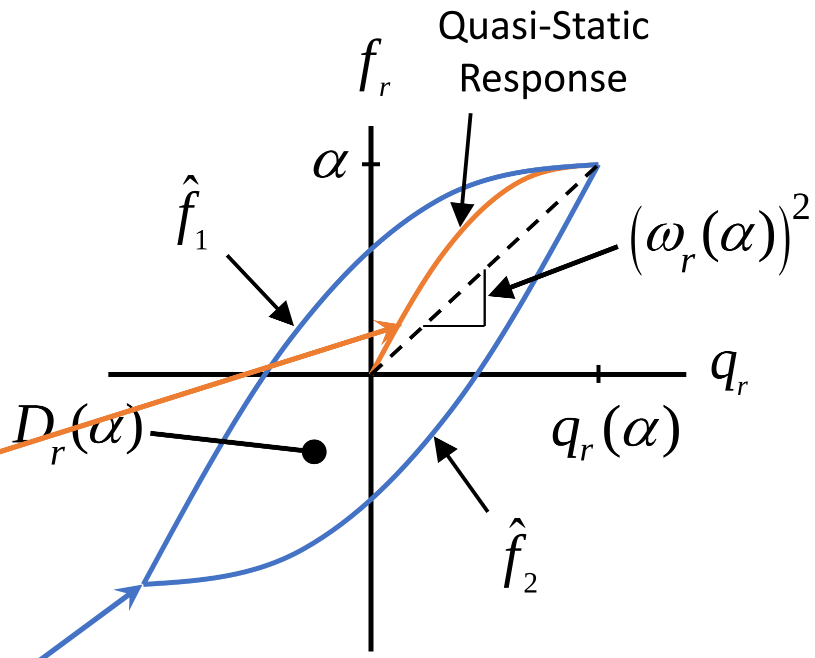
- **Deform a structure quasi-statically according the following loading**

$$\mathbf{f} = \mathbf{M}\boldsymbol{\psi}_r \alpha \rightarrow \mathbf{x}(\alpha)$$

  - $\boldsymbol{M}$ = Mass Matrix, $\boldsymbol{\psi}_r$ = rth mode shape
  - Apply static loading to enforce mode shape
- **Solve for modal response ($\boldsymbol{q}_r$) as α ramps to a user selected peak**

$$\boldsymbol{q}_r = \boldsymbol{\psi}_r^T \mathbf{M}\mathbf{x}$$

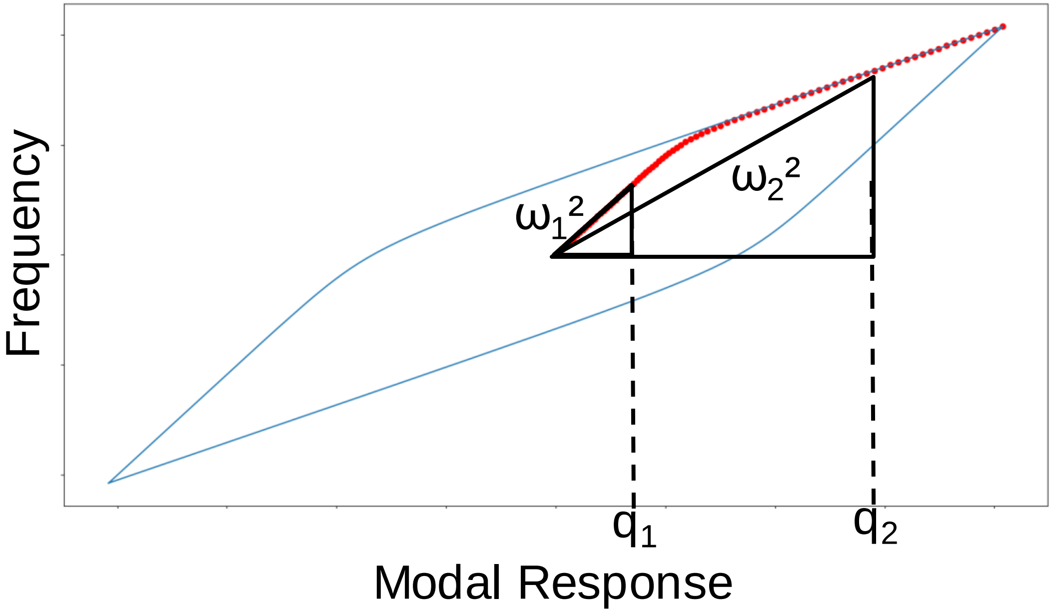
- **Expand to full hysteresis using Masing's rule**
- **Extract natural frequency (secant stiffness) and damping (dissipation per cycle)**
- **Key Assumption = modes are uncoupled**

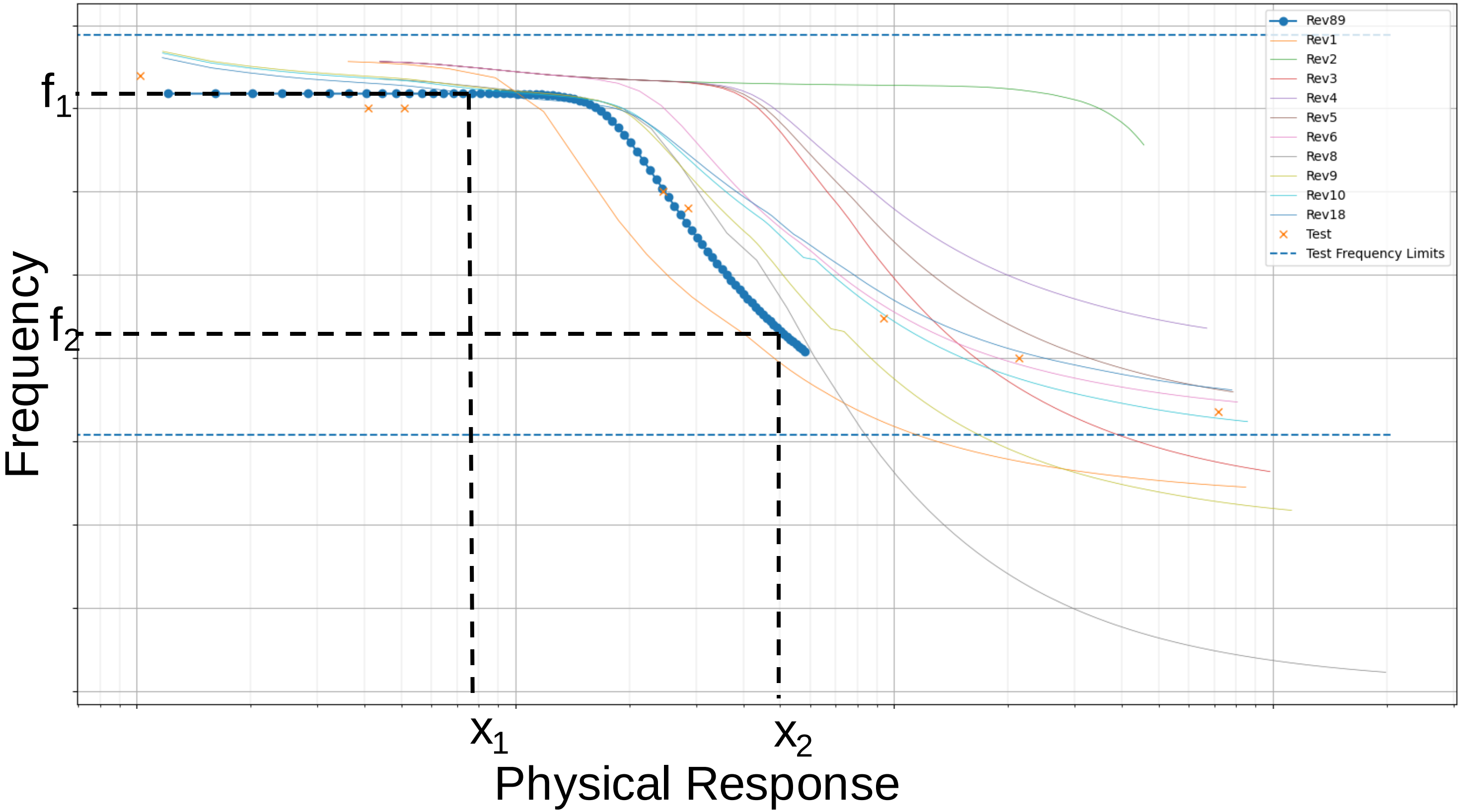


$$\zeta_r(\alpha) = \frac{D(\alpha)}{2\pi\left(q_r(\alpha)\omega_r(\alpha)\right)^2}$$

[4] R. M. Lacayo and M. S. Allen, "Updating Structural Models Containing Nonlinear Iwan Joints Using Quasi-Static Modal Analysis," Mechanical Systems and Signal Processing, vol. 118, 1 March 2019.

QSMA Workflow & Example Results

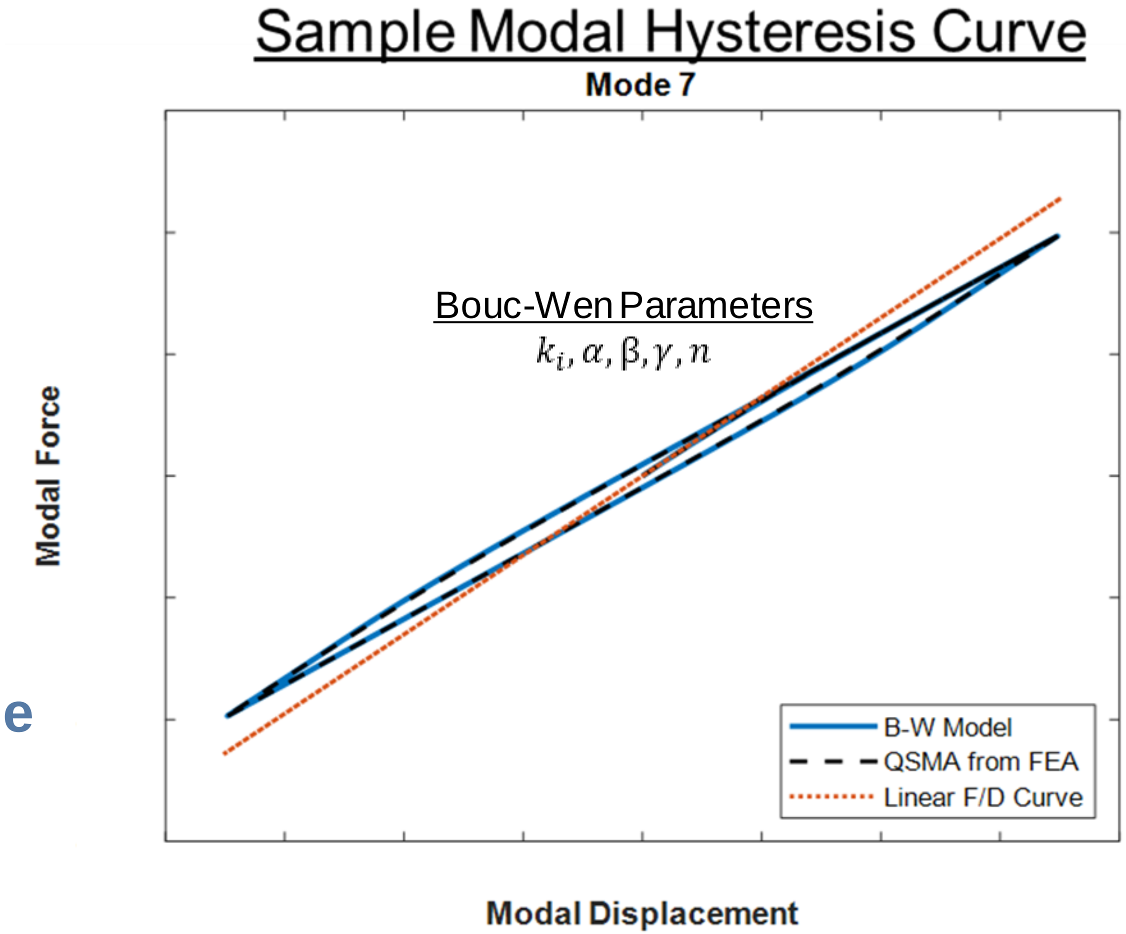




- **Workflow:**
  - Update Abaqus model parameters
    - Stick stiffness, slip stiffness, critical slip load
  - Run nonlinear static analysis
  - Convert force/displacement back to modal space and construct hysteresis
    - Calculate frequency and plot against physical response

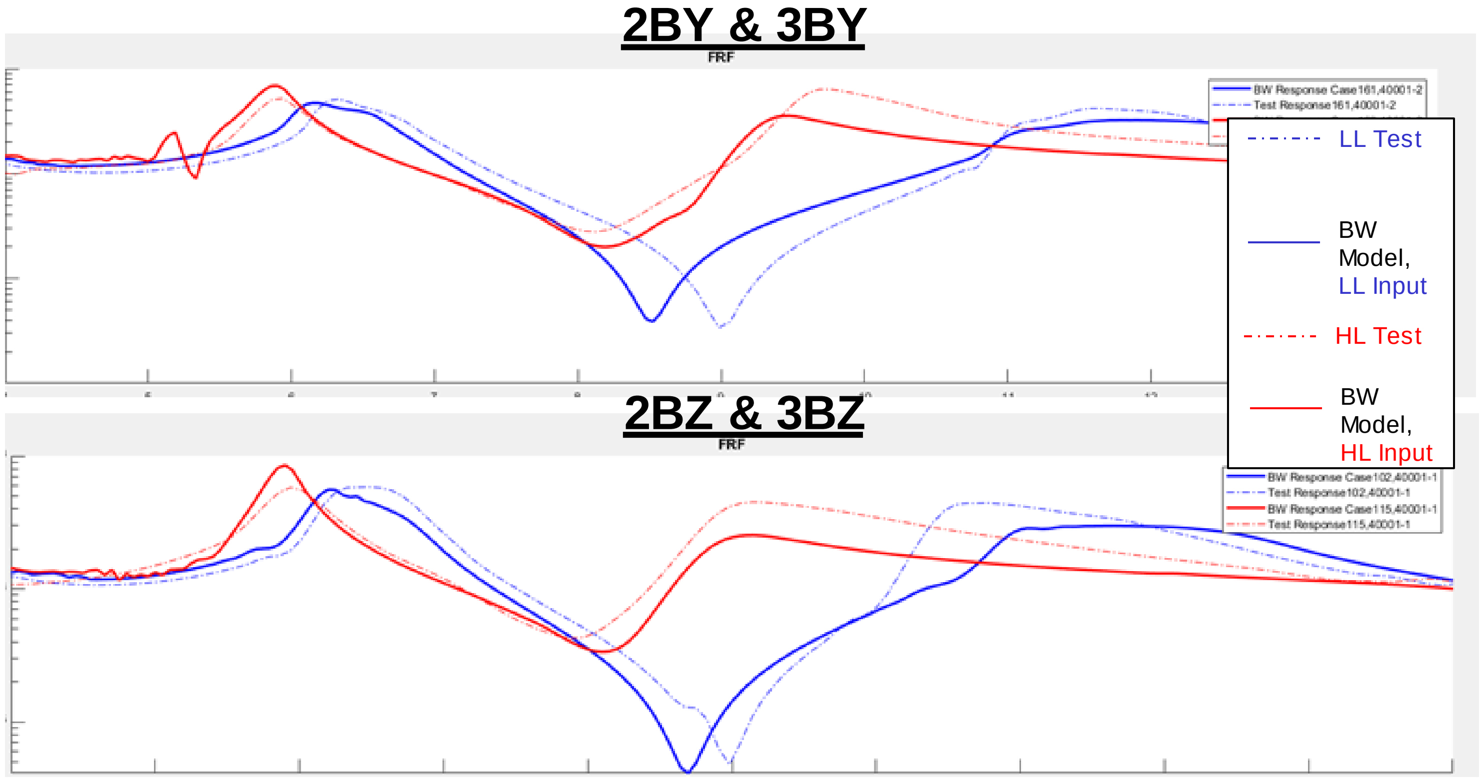
Bouc-Wen Overview

- **The BW model allows for time-domain simulations of nonlinear modes represented by hysteresis curves**
  - Adds a third state, z:
    - $\ddot{q} + 2\zeta\omega\dot{q} + f(q,z) = f_{ext}(t)$
    - $f(q,z) = \alpha k_i q + (1-\alpha)k_i z$
    - $\dot{z} = \dot{q} - \beta z|\dot{q}||z|^{n-1} - \gamma\dot{q}|z|^{n}$
  - where α, k_i , β, γ, n are parameters identified using a least squares fit to the hysteresis curve produced from QSMA



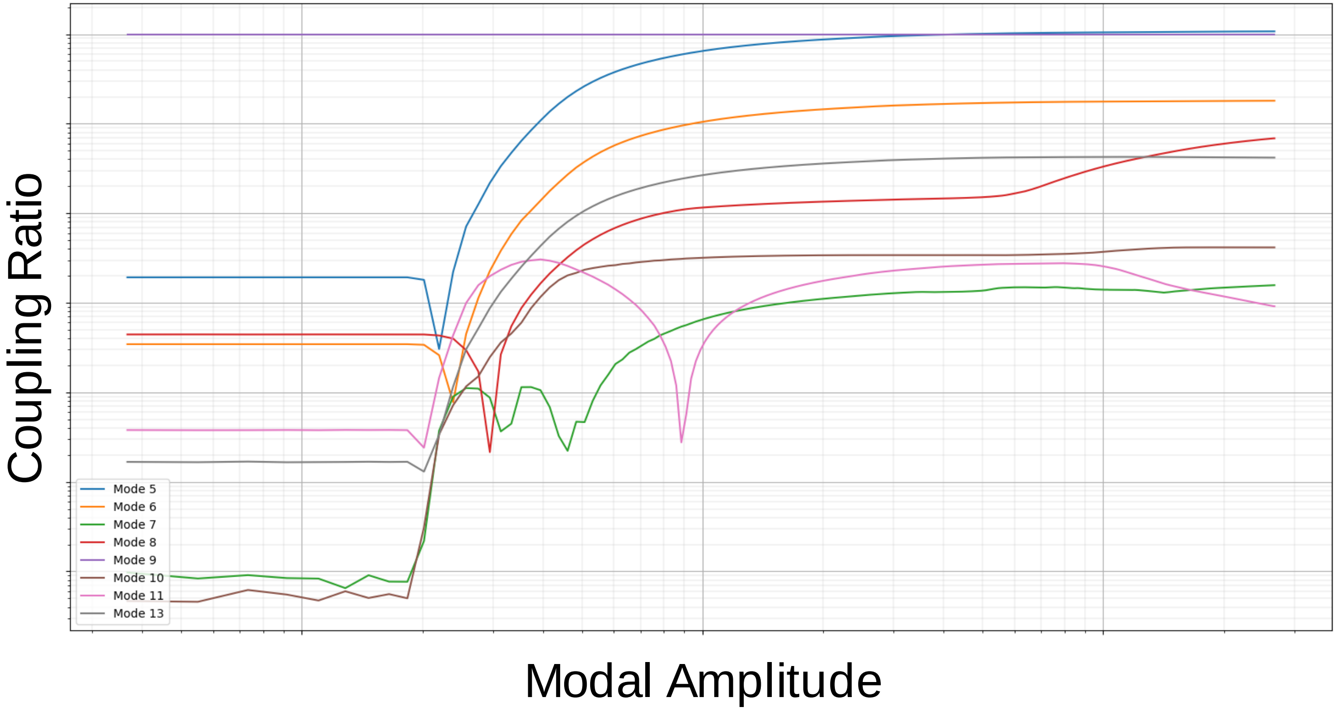
BW Workflow & Example Results

- **Workflow:**
  - Fit BW hysteresis to QSMA hysteresis
    - Mode being studied represented by hysteresis; other modes remain linear
  - Run modal transient and compute FRFs



Modal Coupling

- Current limiting assumption of both QSMA and BW is that each mode remains uncoupled
- Initial implicit dynamic correlation of the 3rd bending modes did not match the BW response
- Investigation of modal coupling showed significant coupling between the the 3rd (Mode 9) and 1st (Mode 5) modes
  - This would cause the QSMA/BW predictions of the response to be inaccurate.
- Efforts are underway to extend QSMA to account for modal coupling [5]



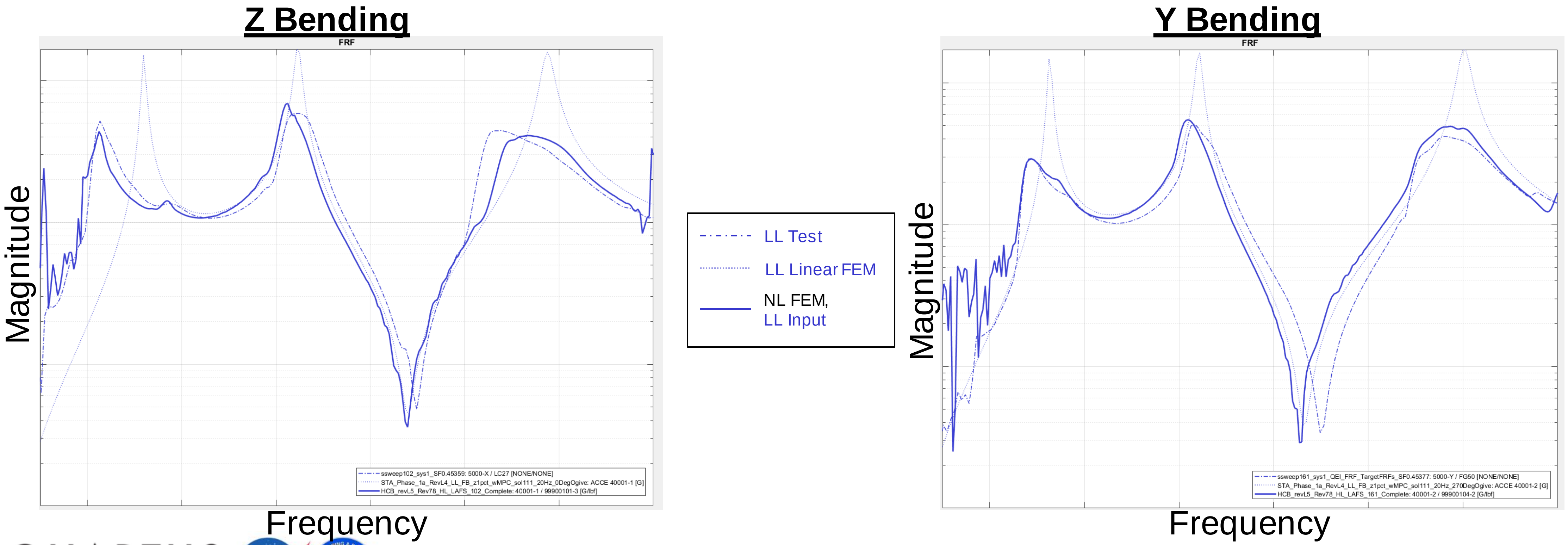
[5] Singh, Allen & Kuether, "Multi-mode Quasi-static Excitation for Systems with Nonlinear Joints," MSSP, (Submitted May 2021).

Implicit Dynamic Correlation – Overview

- Performed many iterations to improve joint parameters using QSMA + BW
- Nonlinear correlation finished using Abaqus implicit dynamics
- Time slices of transient test data used as input
  - Only analyzed slice of transient data exciting mode of interest to reduce run times
  - Transient responses were stitched back together when multiple modes were analyzed from a single test
- Spectral processing of transient responses performed to compare FRF
  - Due to the time slice/response stitching, spurious dynamic content outside the frequency range of interest and in between modes can be neglected

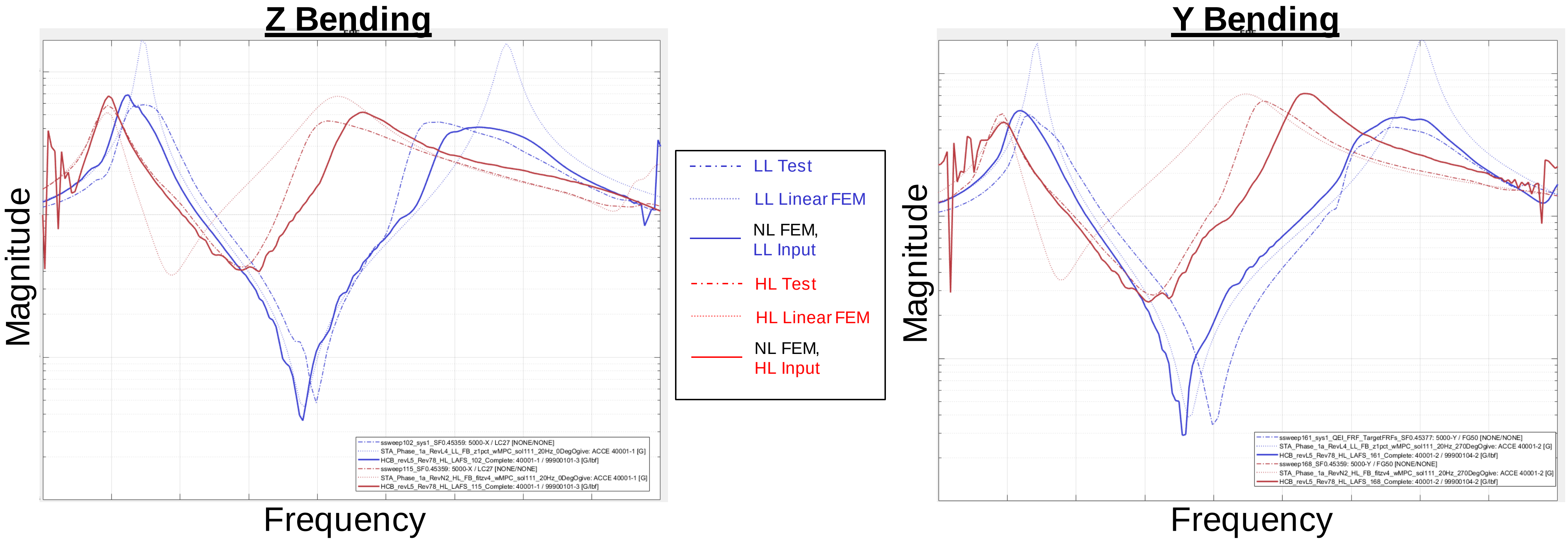
Final Nonlinear Correlation – 1B, 2B, 3B LL

- **NL model shows excellent frequency, damping, and shape correlation to the first three LL bending modes, especially compared to the linear correlation**
  - Even for relatively low-level inputs significant nonlinear behavior is exhibited in test
  - NL model accurately captures frequency shifts, changes in damping, and nonlinear transitions in primary resonant responses



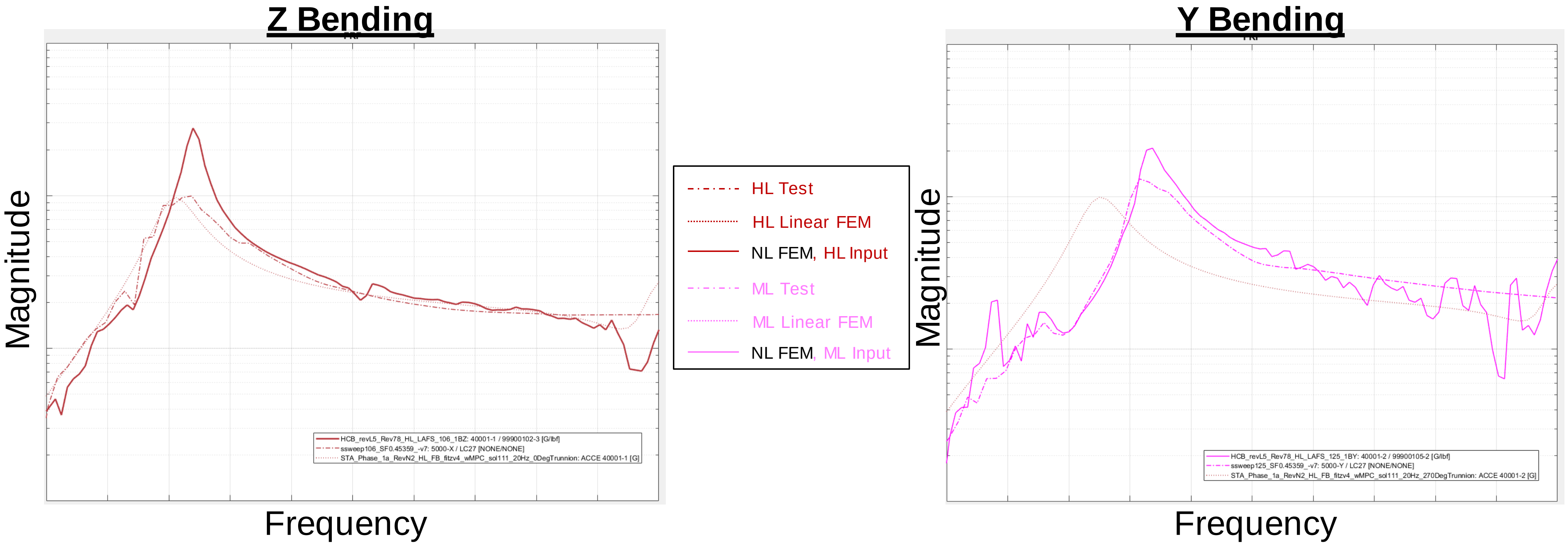
Final Nonlinear Correlation – 2B & 3B LL & HL

- NL correlation provides better amplitude and shape correlation to the LL and HL 2nd and 3rd bending modes, particularly the shape and transition of the 3rd bending mode, over the linear correlation
  - Low and high level responses captured in single model with increased accuracy for both (varying load level inputs)



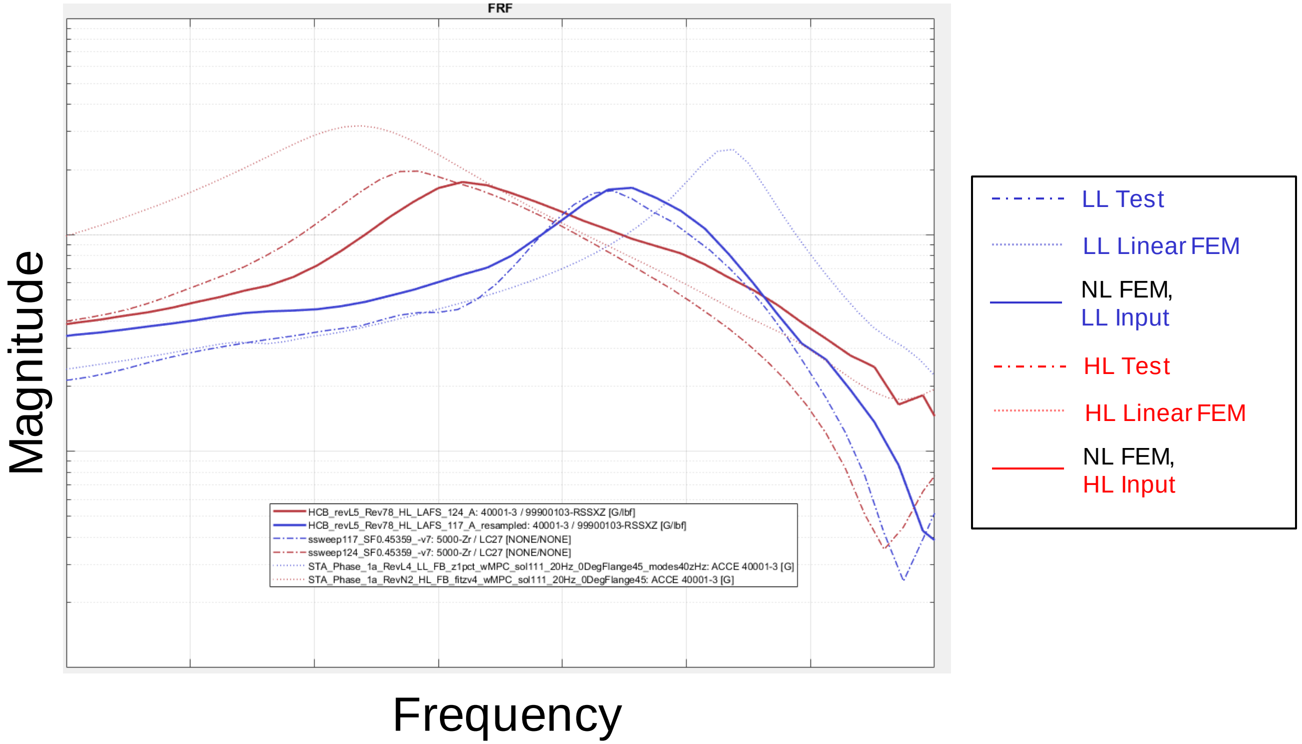
Final Nonlinear Correlation – 1B HL

- Due to time constraints, this effort proceeded with CLA/Uncertainty steps before 1B transient correlation runs were complete
- NL correlation provides accurate frequency correlation, but under-predicts damping for the first HL bending mode (over-predicts response amplitude)
  - Testing was not able to excite the 1BY mode at as high level as 1BZ, so correlation was performed to a "mid level" (ML) input
  - Since current model over-predicts high load level 1B responses, initial uncertainty factor calculations are conservative



Final Nonlinear Correlation – 1A HL & LL

- **Axial correlation was not explicitly performed in this effort**
  - Primary axial response exhibits minor nonlinearities compared to lateral responses
- **However, the final model parameters showed excellent correlation to frequency, damping, shape and transition from LL to HL**
  - Correlation driven by lateral response resulting in good predictions for axial



Conclusions

- QSMA + BW were successfully leveraged in nonlinear correlation and model updating for the current NESC MPCV C4 effort
  - QSMA + BW significantly reduced schedule and improved results
- Current QSMA and BW methodologies rely on the assumption that modes remain uncoupled
  - Modal coupling is present for this test article; full implicit dynamics simulations were required to finish nonlinear correlation
- Using modern computational tools (Hurty/Craig-Bampton Reduction, Abaqus, QSMA, BW) it is now possible to perform nonlinear modeling and model correlation within realistic computational/time constraints
- The final nonlinear correlated model was used as a "truth" model for subsequent CLA studies & uncertainty analysis