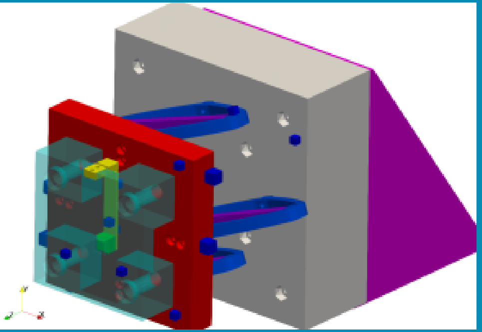
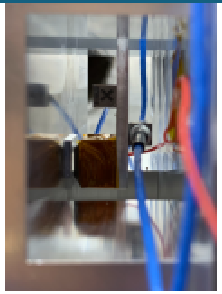
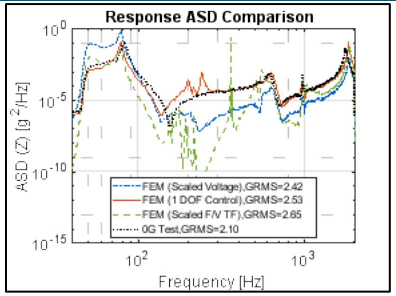
SAND2021-15725C

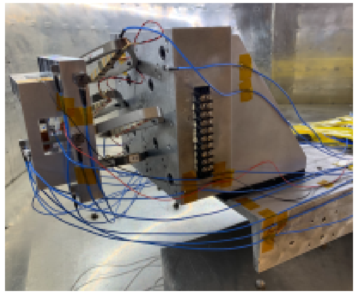
Sandia National Laboratories

Model Validation for Combined Inertial Acceleration and Vibration Environments









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IMAC-XL

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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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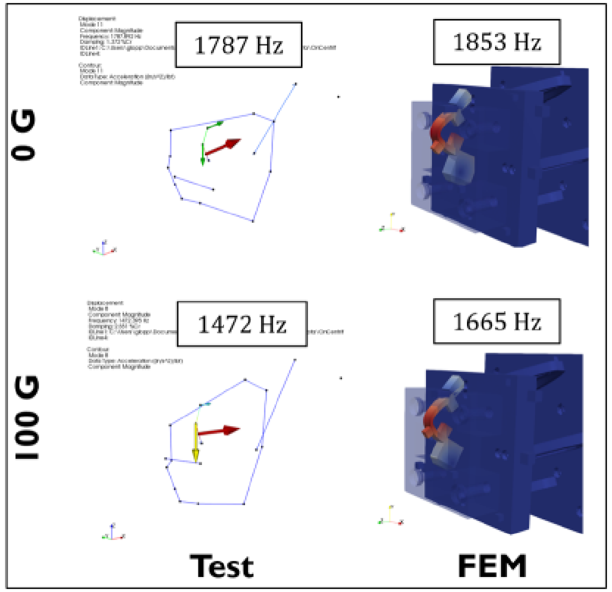
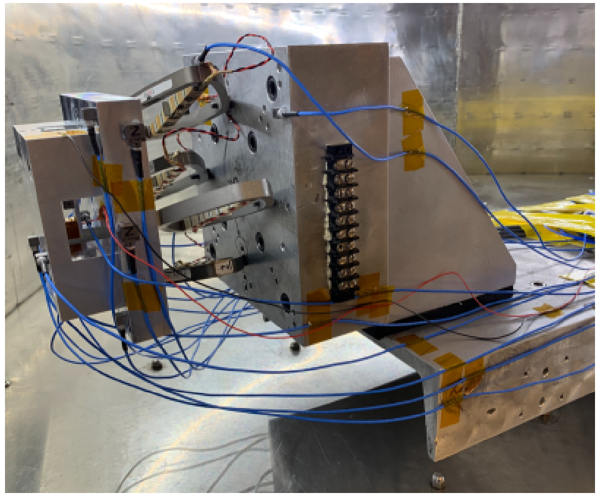
Summary

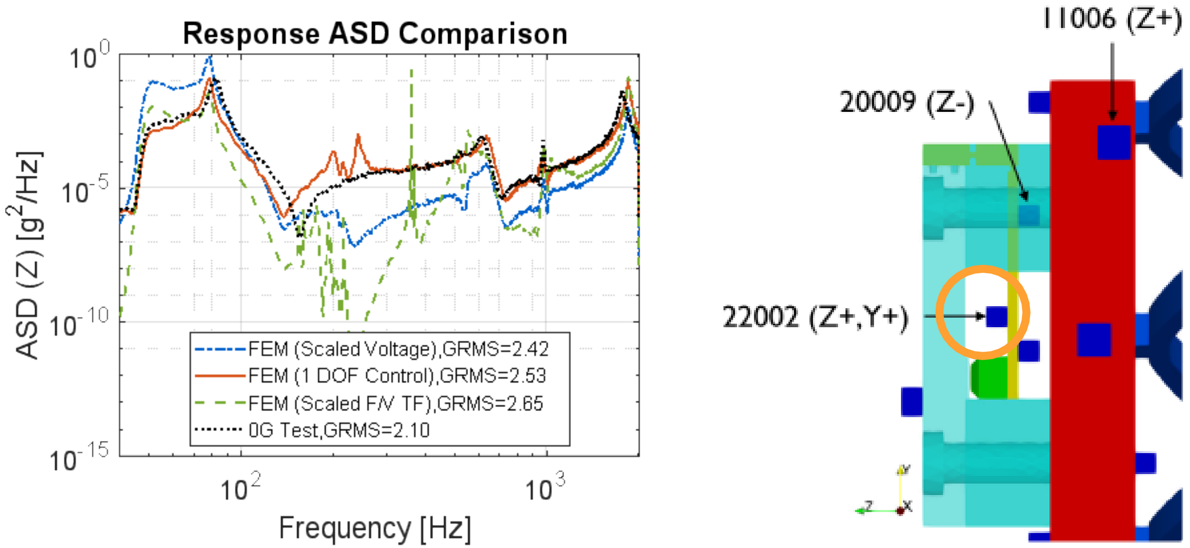
- Model validation was performed for a research structure subjected to combined inertial acceleration and vibration environments (vibrafuge)
- SIERRA coupled analysis was conducted to evaluate the effect of centrifuge acceleration combined with random vibration
  - Preloading the cantilever beam structure using SIERRA/SM
  - Updating the contact state, and evaluating the preloaded response using SIERRA/SD
- Results were validated with vibrafuge testing using piezoelectric actuators on a centrifuge
  - Comparisons to test data showed that the SM to SD handoff model was able to account for the updated dynamic response due to the inertial acceleration preload
  - Validation metrics were computed to quantify comparisons between model and test data
- This work demonstrates the development of an improved approach for combined mechanical environments analysis and model validation using SIERRA



3rd Bending Mode- 0/100 G Comparison



Test Article Vibrafuge Setup



Acceleration Response Results and Location

Outline

I. Introduction/Overview
   A. Unit Description
   B. Setup

II. Experimental Characterization
   A. Modal Testing
   B. Vibrafuge Testing

III. FE Modeling and Calibration
   A. Modal Analysis
   B. Code Coupling/Handoff Procedure
   C. Random Vibration Analysis

IV. Conclusion

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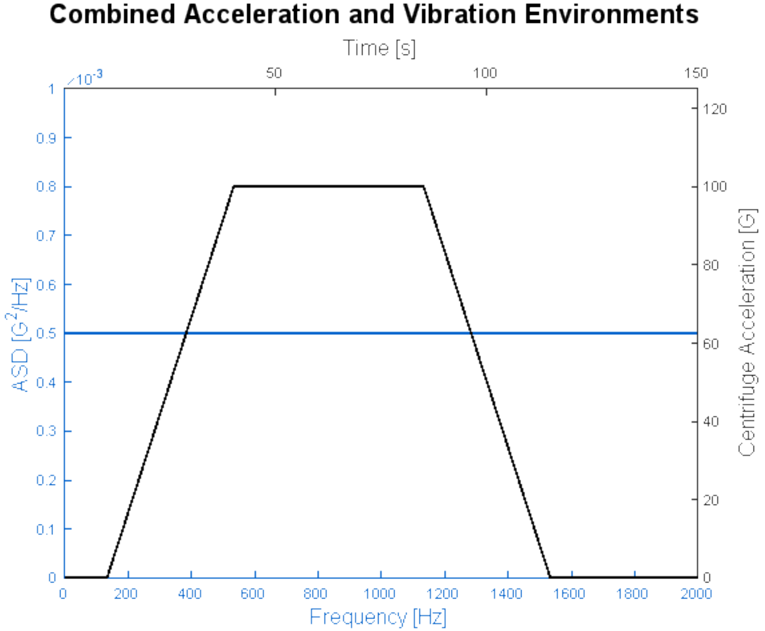
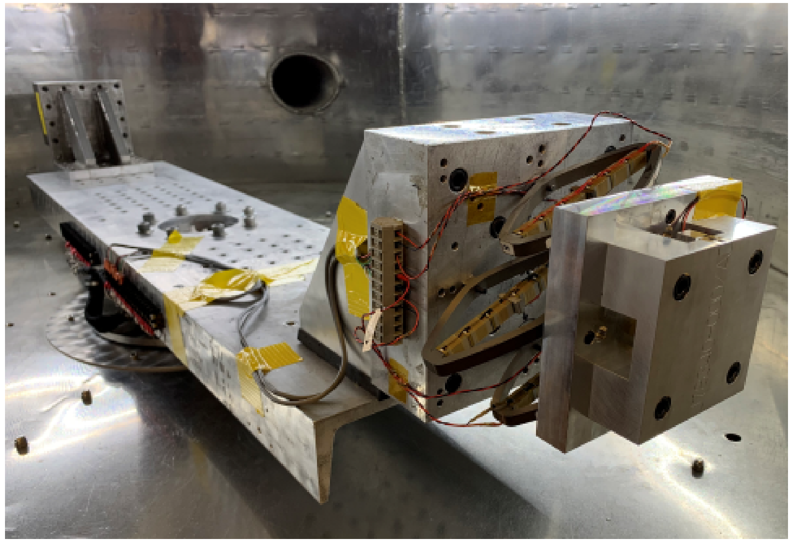
Introduction

- Aerospace structures are often subjected to combined inertial acceleration and vibration environments during operation
- Traditional test approaches independently assess a system under a sequence of inertial and vibration environments
  - Incapable of addressing couplings in system response under combined environments
- Considering combined environments throughout the design and qualification of a system requires development of both analytical and experimental capabilities
- Recent ground testing efforts have improved the ability to replicate flight conditions and aid qualification by incorporating combined centrifuge acceleration and vibration environments in a **vibrafuge** test
  - Modeling these loading conditions involves the coupling of multiple physical phenomena to accurately capture dynamic behavior



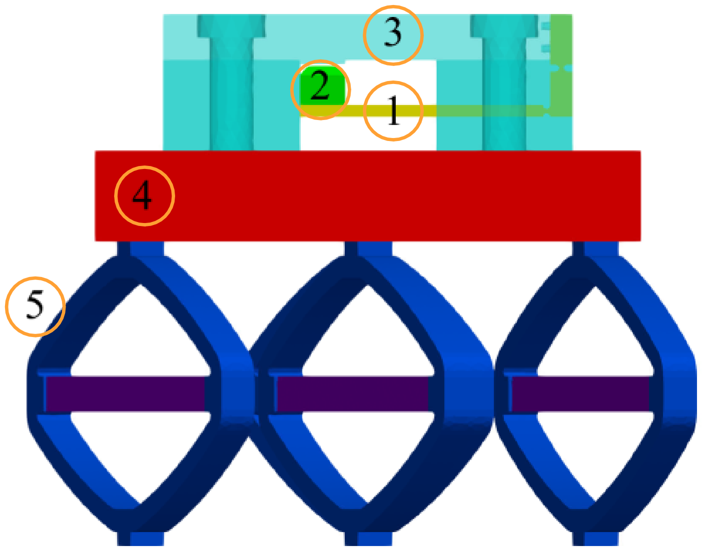


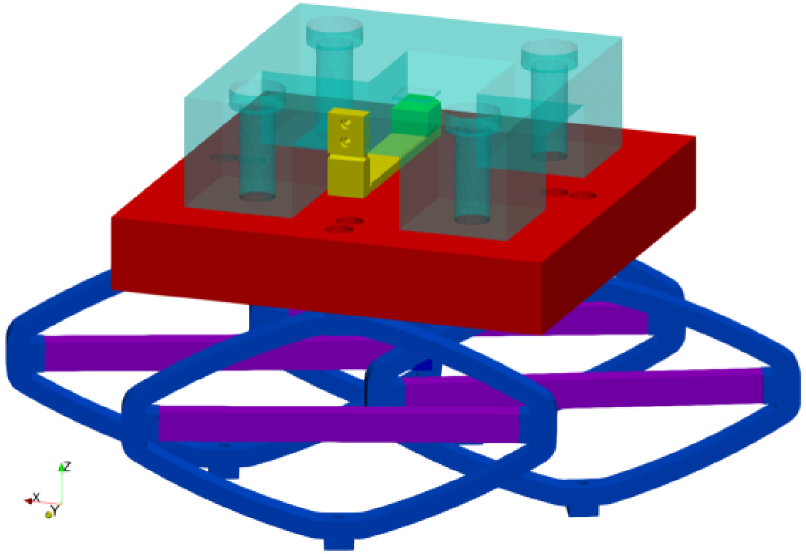
Vibrafuge Setup

Unit Description

- Vibrafuge capability demonstrated with research structure
  - Applied acceleration on centrifuge
  - Vibration using Cedrat Technologies APA230L amplified piezoelectric actuators (APA)
- Consists of an inverted cantilever beam
  - Functions as simple acceleration switch
  - Goal to study dynamics as tip contact state changes under vibrafuge environment
- Assembly consists of the following
  1. Aluminum beam
  2. Tungsten mass
  3. Aluminum support block
  4. Aluminum base block
  5. Piezoelectric actuators

Cantilever Beam Geometry

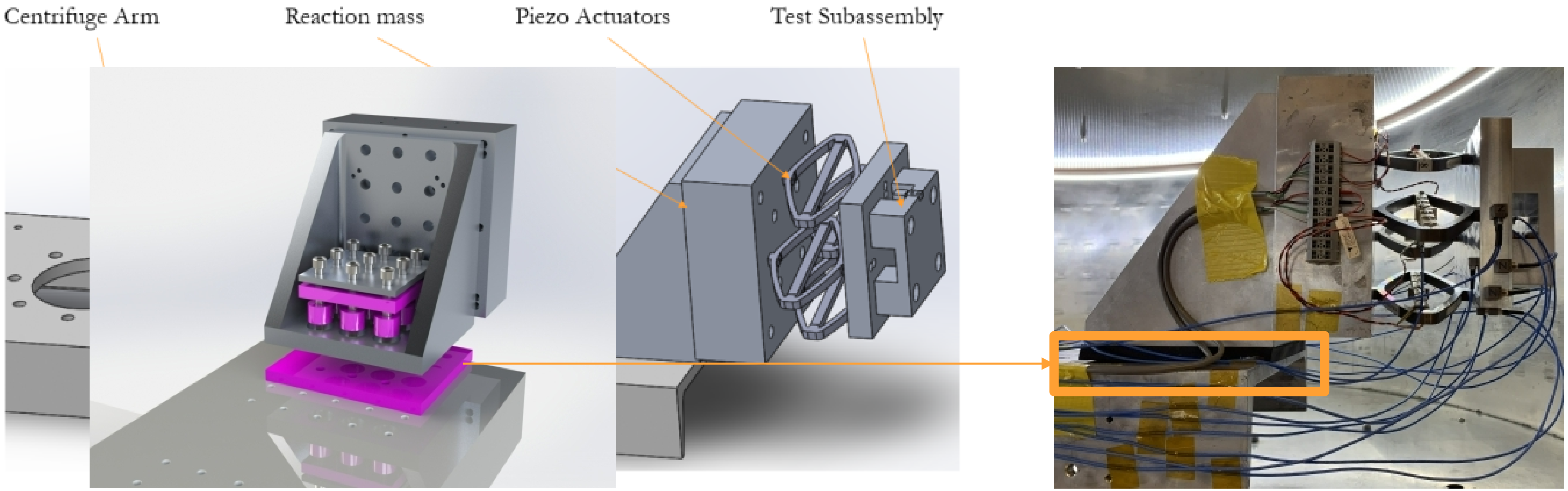




Test Subassembly

Vibrafuge Setup

- Combined inertial acceleration and vibration environments simulated using “vibrafuge” setup
  - Cantilever beam assembly and APA fixtured on centrifuge arm with reaction mass and angle bracket
- Test setup allows for dynamic characterization under simultaneous environments
  - Instrumentation set up through slip rings and routed to external controller and data acquisition
- Additional polyurethane rubber sheets and rounds used to isolate APA vibration to cer



Vibrafuge Description and Test Setup

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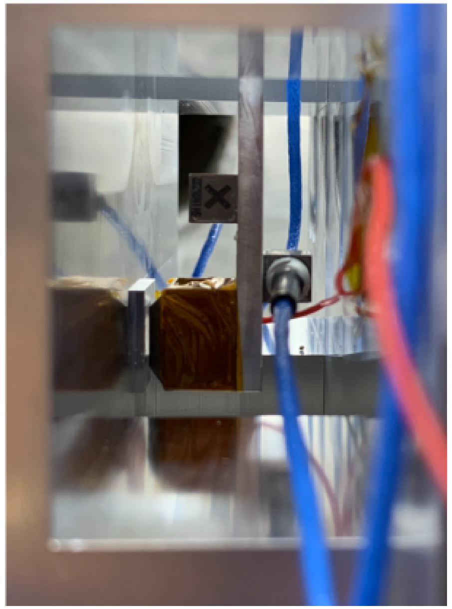
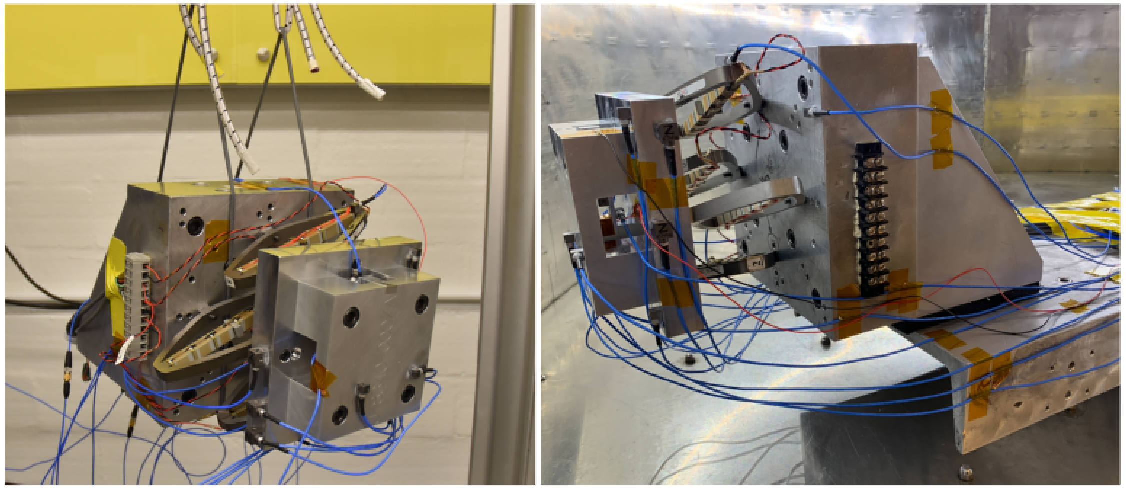
Modal Testing

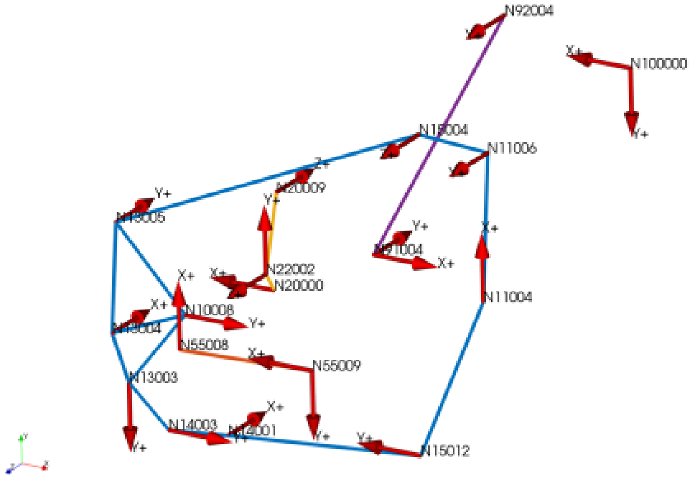
- Instrumentation designed to capture modes of interest
  - 18 accelerometers, 22 DOF total
- Modal testing performed in free-free and centrifuge boundary conditions
  - To evaluate effect of fixturing
- APAs also used to extract modal parameters during centrifuge testing
  - Modes and frequencies evaluated at various G-levels
  - Data used to later validate FE model



Beam Tip Instrumentation Closeup



Modal Test Setup



Instrumentation Layout

Modal Testing- Results

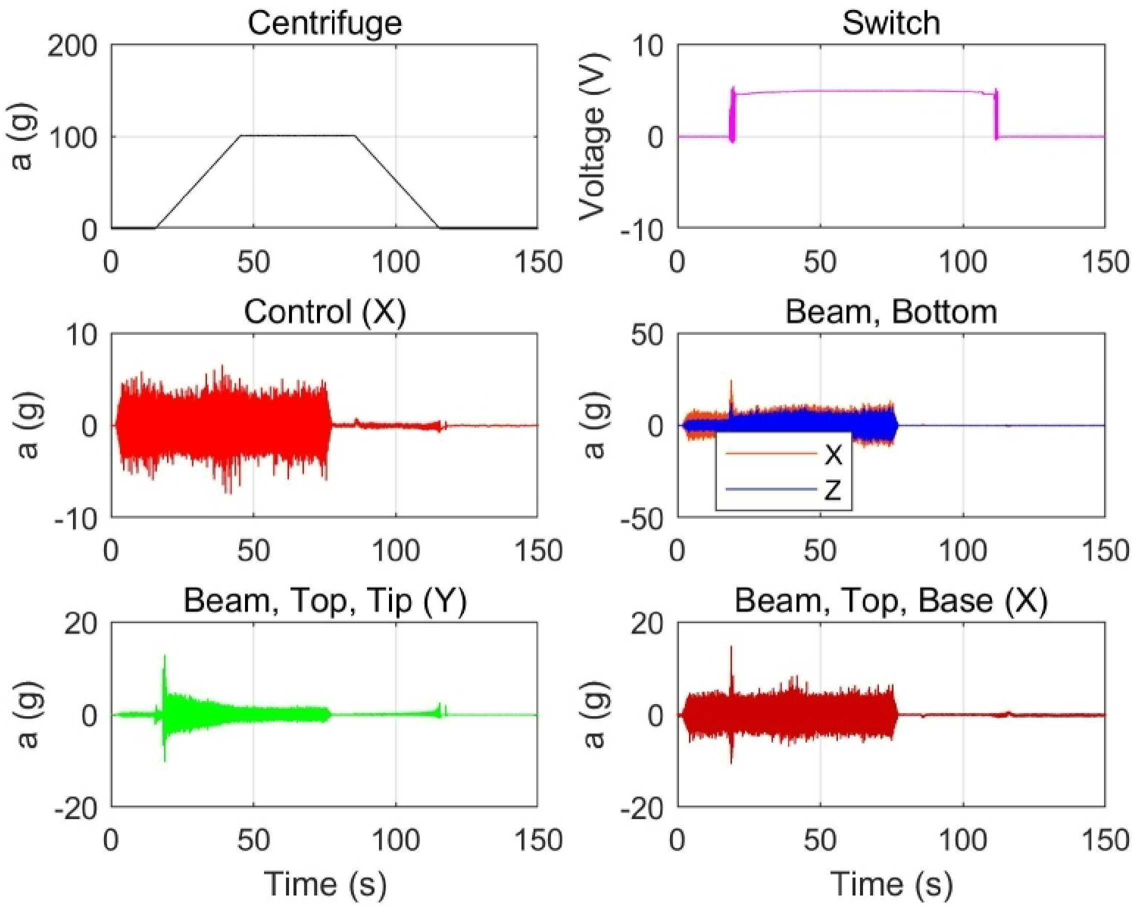
Test Mode	Description	Free-Free Modal Freq. (Hz)	Vibrafuge Modal 0G Freq. (Hz)	Vibrafuge APA 5G Freq. (Hz)	Vibrafuge APA 5G Freq. (Hz)	Free-Free Modal Damp (%)	Vibrafuge Modal 0G Damp. (%)	Vibrafuge APA 5G Damp. (%)	Vibrafuge APA 100G Damp. (%)
1	1st Beam Vertical Bending	79	84	75.3	-	0.4	2.0	2.4	-
2	1st Beam Lateral Bending	267	261	-	-	1.1	2.1	-	-
3	2nd Beam Vertical Bending	616	623	623	-	2.1	3.3	3.2	-
4	3rd Beam Vertical Bending	1784	1776	1788	1472.4	1.1	1.2	1.4	2.55

Frequency

Damping

Vibrafuge Testing

- Vibrafuge testing conducted with APA
  - 1 GRMS 50 to 2000 Hz
  - Range of acceleration from 5 to 100 G
- Vibration data measured at same accelerometers as modal testing
- Additional centrifuge acceleration profile
- Electrical contact measurement at beam tip
- Data used to validate FEM



100 G Vibrafuge Test Measurements

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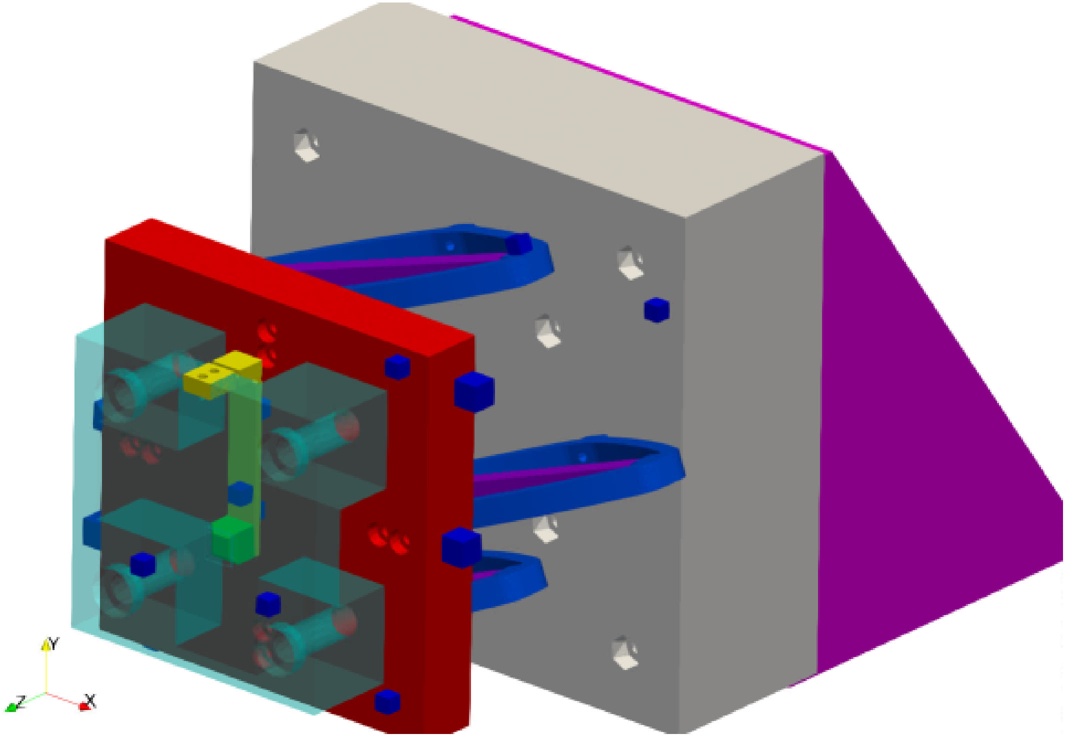
Finite Element Analysis

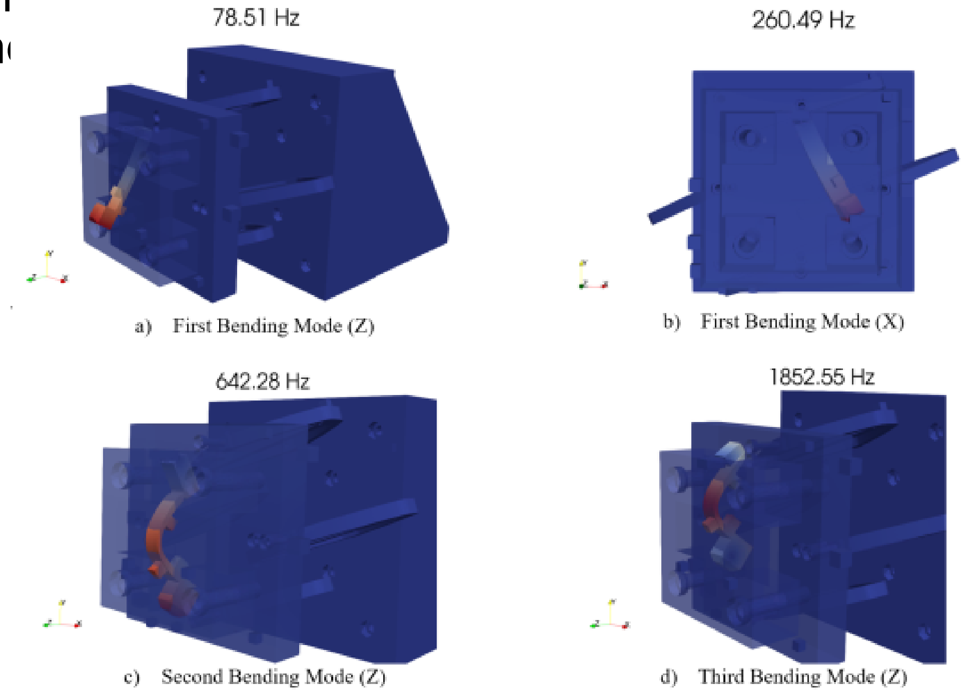
- FE modeling used to perform model calibration and validation
  - CUBIT meshing software and SIERRA codes
- Model assumptions
  - Elastic materials
  - Tied contact at joints/interfaces
  - Neglect rubber pads
- SIERRA Structural Dynamics used to perform initial calibration and updating to dial in modes and frequencies
- Followed by SIERRA Solid Mechanics preload analysis and handoff to SD
  - Coupled analysis used to pre-stress/stiffen cantilever beam and hand off state for a linearized modal analysis



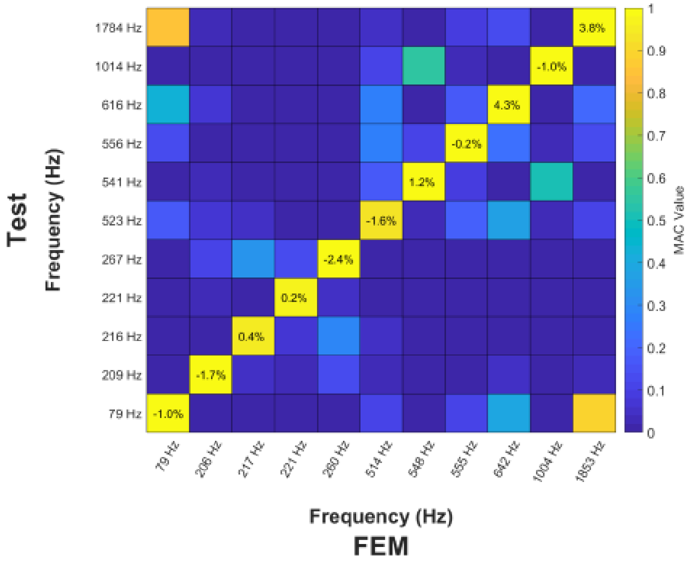
Vibrafuge Subassembly FEM

Modal Analysis

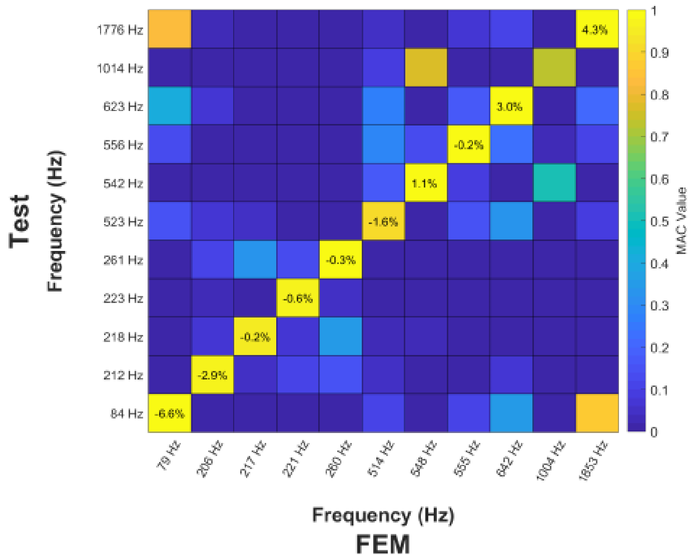
- Linear modal analysis using SIERRA/SD and model calibration with free-free test data
- Good match with frequency errors below 5% and MAC above 0.9
- Similar results for on-centrifuge (vibrafuge) data
  - Som ... mate boundary con



Free-Free Cantilever Beam Modes



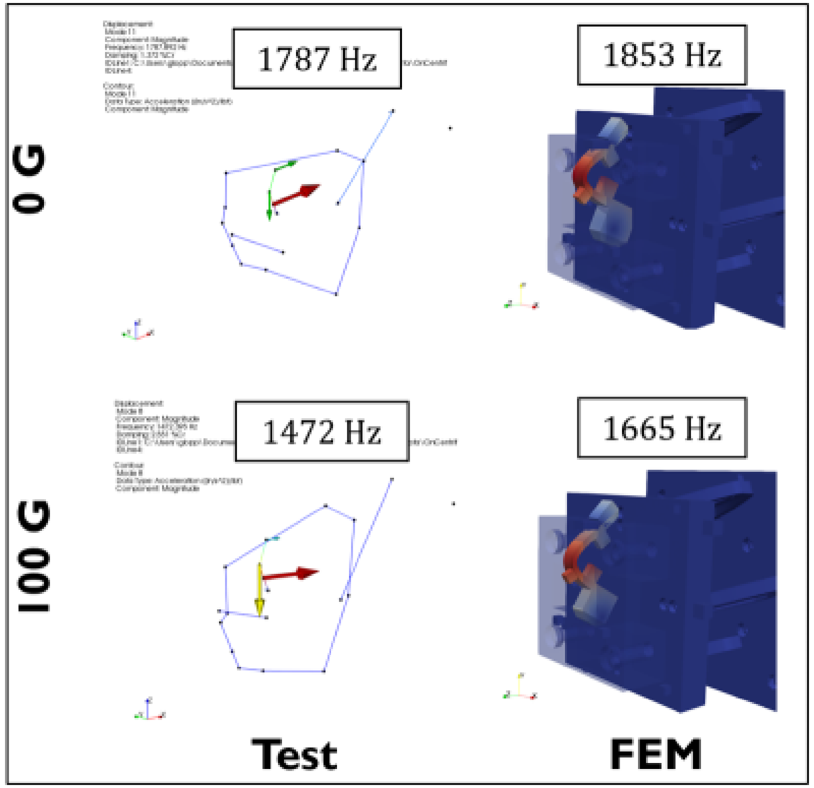
Free-Free MAC



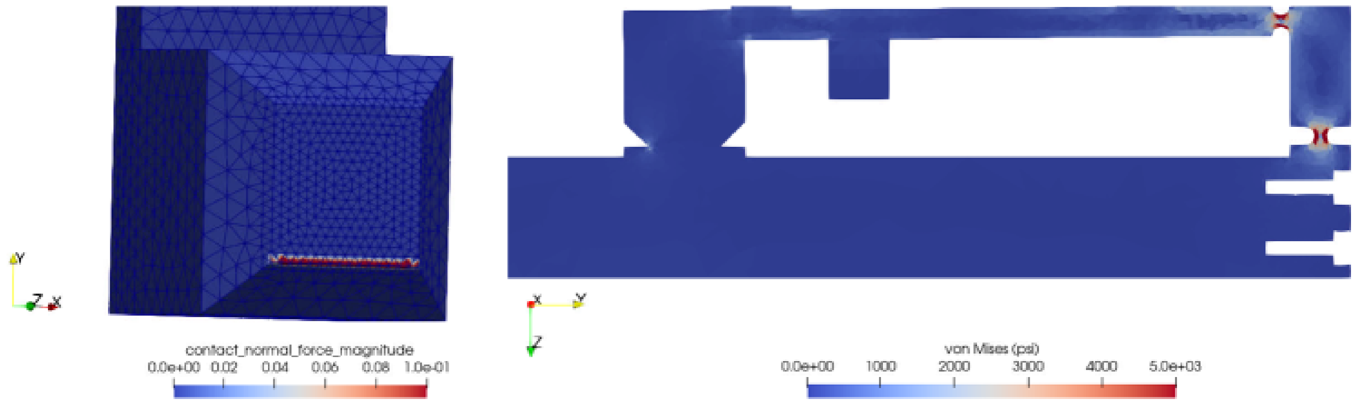
On-Centrifuge MAC

Code Coupling / Handoff

- After initial model calibration, the handoff analysis was performed
- Preload analysis in SIERRA/SM to determine contact state and update element tangent stiffness matrices
- Automatic conversion to tied contact based on threshold for linear modal analysis in SIERRA/SD
- Handoff model able to account of updated contact state and effect on dynamics
  - Updated modes consistent with test data



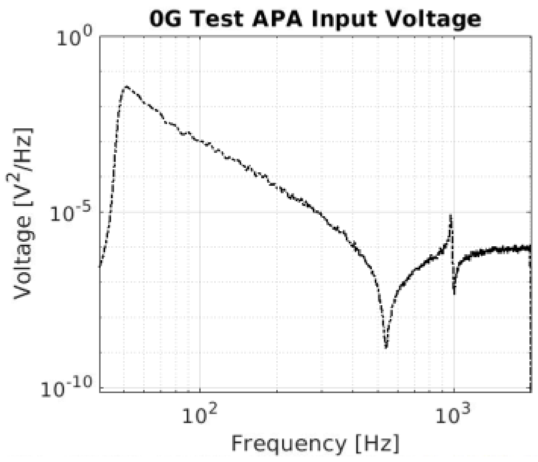
0 G and 100 G Comparison for 3rd Bending Mode



SIERRA/SM Preload Results

Random Vibration Analysis

- After model calibration and updated handoff model, random vibration analysis performed for same loading as testing
- Loading using input force at APAs
- Responses compared using 3 separate analysis approaches
  1. Scale APA voltage
  2. 1 DOF control
  3. Estimate APA voltage transfer function
- These approaches highlight the discrepancies with test data and impact of modeling assumptions



Method 1

$$S_{yy} = H_{yx} S_{xx} H_{yx}^H$$

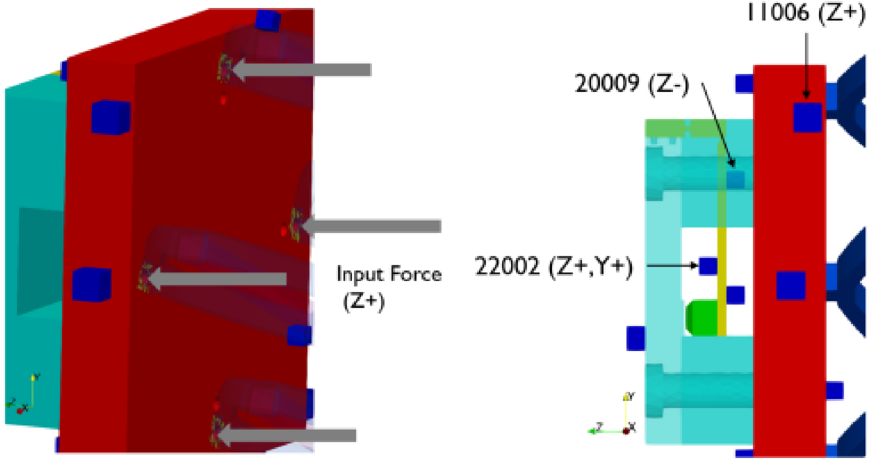
Method 2

$$F_p = k_p^E(u_2 - u_1) - \alpha V$$

$$\alpha = n d_{33} k_p^E \qquad k_p^E = \frac{Y_3^E A_p}{L_p}$$

$$\frac{F_p}{V} = \frac{\alpha}{k_p^E\left(\frac{u_2}{F_p} - \frac{u_1}{F_p}\right) - 1}$$

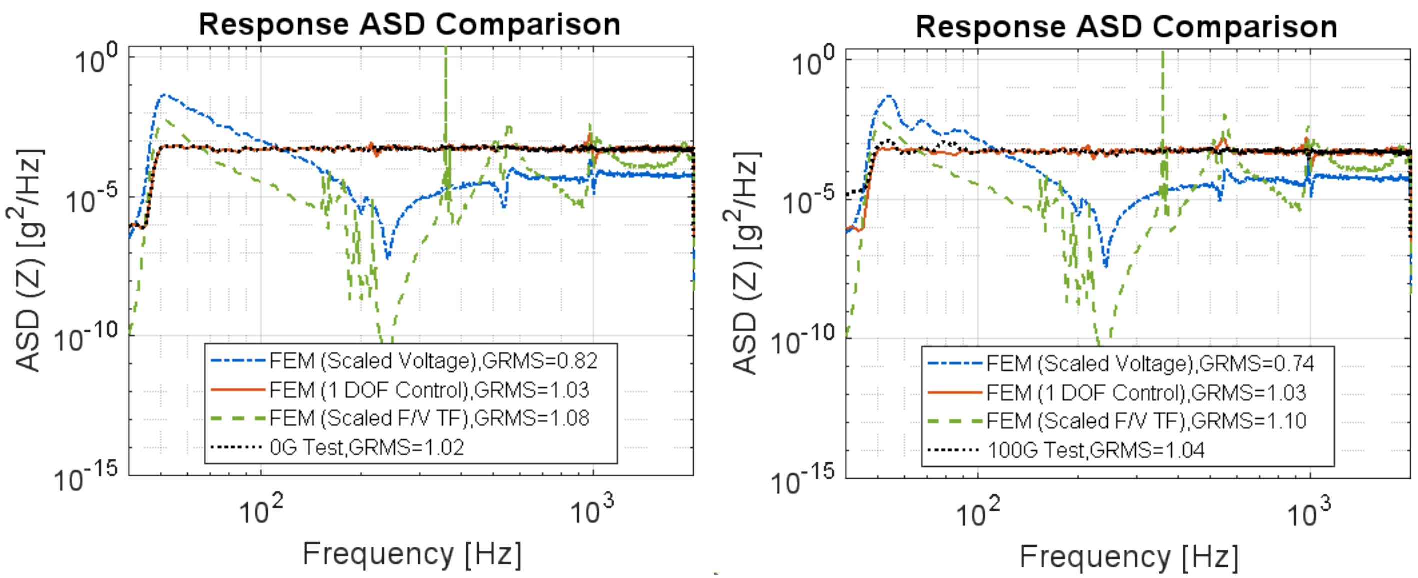
Method 3



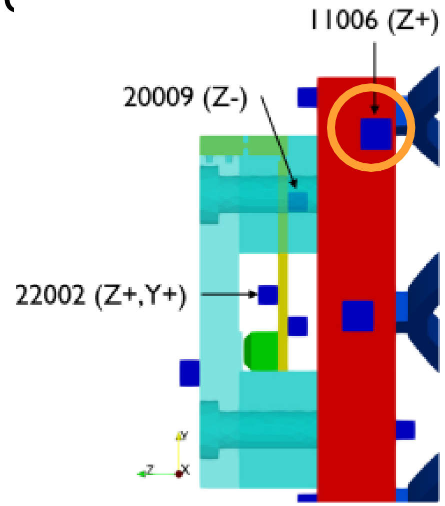
Random vibration loading and response location

Results- Control Accel

- 1 DOF Control (Method 2) matches control accelerometer exactly, as expected
- Computed APA FRF (Method 3) does better at some frequencies compared to scaled voltage (Method 1)
  - Still, both are poor matches
  - May be issues with FRF calculation causing discrepancies
- dB error high for methods 1 and 3 due to poor frequency match at certain bandwidths



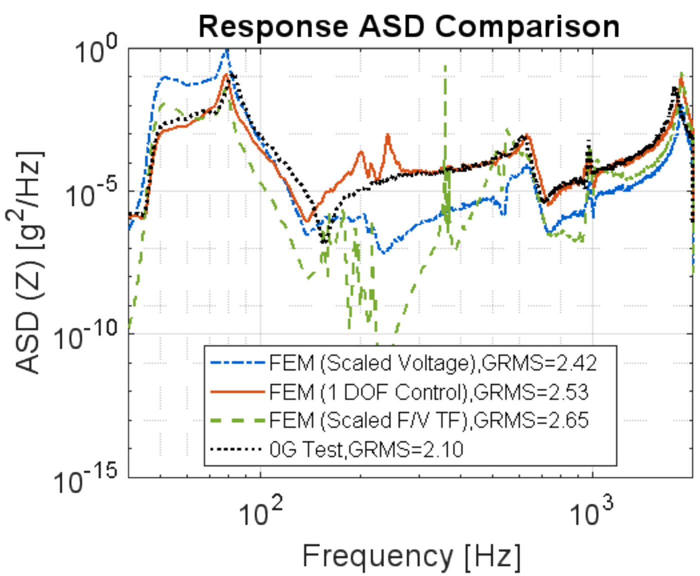
FEM/Test Comparison: Control Location 11006 (Z+)

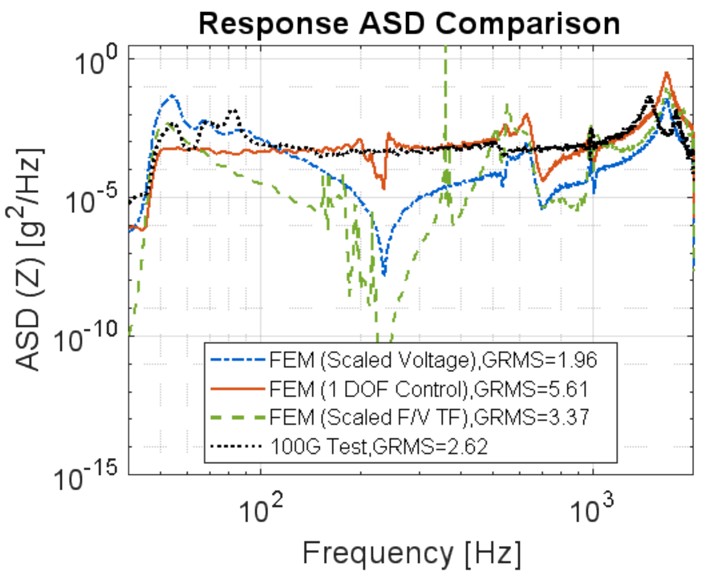


Case	Response GRMS	1/12 Oct Smoothed dB Error St. Dev.
0 G Test	1.02	-
0 G FEM Method 1	0.82	8.7
0 G FEM Method 2	1.03	0.2
0 G FEM Method 3	1.08	13.9
100 G Test	1.04	-
100 G FEM Method 1	0.74	8.3
100 G FEM Method 2	1.01	0.7
100 G FEM Method 3	1.10	13.9

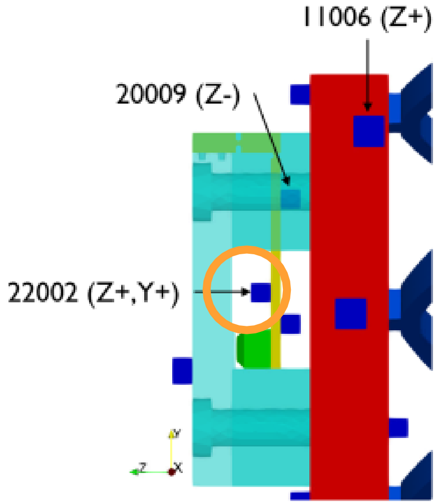
Results- Mid-Beam

- 1 DOF Control (method 2) once again best match
  - General trends match, good GRMS
  - Able to capture mode shifting
- Again APA FRF (method3) does better at higher frequencies compared to scaled voltage (method 1) are quite different
- dB error high for methods 1 and 3 due to poor frequency match at certain bandwidths
- Ideally APA scaled transfer function would perform better since it incorporates additional physics
  - Assumptions and simplified equations may not be valid (neglected stack mass)
- Need to improve loads and BC, but this method is able to qualitatively match trends such as mode and





FEM/Test Comparison: Mid-Beam Location 22002 (Z+)



Case	Response GRMS	1/12 Oct Smoothed dB Error St. Dev.
0 G Test	2.10	-
0 G FEM Method 1	2.42	7.8
0 G FEM Method 2	2.53	3.6
0 G FEM Method 3	2.65	13.2
100 G Test	2.62	-
100 G FEM Method 1	1.96	8.0
100 G FEM Method 2	5.61	4.1
100 G FEM Method 3	3.37	14.5

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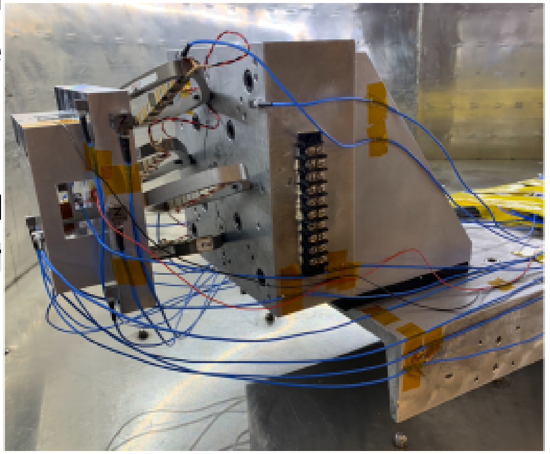
Conclusion

- Model validation was performed for a research structure subjected to combined inertial acceleration and vibration environments (vibrafuge)
  - SIERRA coupled analysis performed by preloading the structure, updating the contact state, and evaluating the altered structural response
  - Results validated with modal and vibrafuge testing using amplified piezoelectric actuators on a centrifuge
- Comparisons to test data showed that the handoff model accounts for the updated dynamic response
  - Mode frequency shift and elimination were observed under increased centrifuge acceleration
  - ASD trends consistent with test data, although the approximate BCs led to large errors in some frequency bands
- Modeling adjustments can improve the match to test data, but this work dem development of an improved approach for combined mechanical environme validation
- Future work can focus on improving model BC, adjusting the handoff param further work on force-voltage TF, and inverse solution methods to obtain be input loading



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[2]B. C. Owens and J. M. Harvie, "Combined Mechanical Environments for Design and Qualification", IMAC XXXVI, 12-15 February 2018, Orlando, Florida. doi:10.1007/978-3-319-74700-2_16.

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[6]G. K. Lopp, D. M. Siler, M. Khan, and B. C. Owens, "Modal Testing with Piezoelectric Stack Actuators", Paper to be presented at IMAC XL, 7-10 February 2022, Orlando, Florida.

[7]CUBIT Development Team, CUBIT Geometry and Mesh Generation Toolkit 15.8 User Documentation, 2021, SAND2021-5152 W.

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