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ENGINEERING FORWARD

IMPROVED VIBRATION TEST PREDICTIONS LEVERAGING A PRE-VIBE MODAL SCREENING

SPACECRAFT AND LAUNCH VEHICLE DYNAMIC WORKSHOP 2024

Adam Johnson, Ivan Kurakin, Emily Kliewer, Andrew Doan

Special thanks to Dr. Matt Allen for Continued Technical Guidance

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Overview

- **Motivation:**
  - There is an increased need for qualification vibration test support of small satellites (pre-test and execution) due to a growing small-sat industry often subject severe test environments
  - Finite Element Model (FEM) predictions are critical for interface load control as well as understanding margins of sensitive components
    - Direct force limiting is ideal but increases cost and schedule
    - Response limiting is often preferred as a leaner option **but relies on a correlated FEM**
  - Discovery of significant model correlation errors on the day of a vibration test results in 2 significant issues:
    1. Schedule delays associated with live model correlation and re-evaluation of key margins
    2. Decision bias toward excessive conservatism
  - Problems often arise that could be informed by modal survey (e.g. correlation of critical subcomponents, verify 1st mode for LV, etc…)
  - However, standard approaches to modal testing typically fall outside of schedule & budget scope of small sat programs
    - Quartus historically performs modal testing & correlation in free-free or pseudo-fixed-base by explicit modeling of test fixture
    - Free free testing has limited sensitivity to modeling errors that impact fixed-base response
    - Explicit fixture modeling adds schedule and budget while reducing sensitivity to relevant modeling errors

- **Central Question:** Could a streamlined modal screening procedure provide sufficient value ahead of vibe or flight within the schedule and budget constraints of small sat programs?
  - This report compares approaches toward fixed base modal screening
  - Biggest challenge for small satellites is maintaining a lean approach
    - Fixturing approach must be easy to set up & non destructive
    - Clients must weigh cost of modal screening against risk reduction during vibe or flight
  - Results in this report are a part of an ongoing effort to streamline this procedure

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Comparison of Component Testing & Correlation Approaches

- The largest challenge in component modal testing is controlling the test article boundary condition so response can be compared to FEA
- Multiple approaches were considered for streamlining the component modal test & FEM correlation procedure
- This report covers a detailed assessment of two methods that appeared to be "low-hanging fruit"

Method 1: Free Free Testing & FEM Correlation

Method 2: Experimental Modal Substructuring (EMS) using a Lean Fixturing Approach

Approaches Reviewed Prior to This Study

#	Approach	Fixturing Approach	Post Processing Approach	Model Correlation Approach	Timeline	Ease of Test Execution	Sensitivity / Repeatability	Average Score (Weighted)	Specific Challenges
a	**Free Free Test**	*None*	*EMA*	*Correlate DUT Only*	5	4	1	**3.3**	Not sensitive to modeling errors in structure near LV attachment
b	**TAM Correction Methods**	*Any*	*Direct TAM Updating*	*Correlate DUT Only*	4	4	1	**3.0**	Numerically ill-posed without extremely large modal basis
c	**Include Fixture in Correlation**	*Any*	*EMA*	*Correlate Fixture & DUT*	2	3	2	**2.3**	Correlation is driven by fixture
d	**Frequency Based Substructuring [FBS]**	*Stiff*	*Freq. Domain Substructuring (SMURF, etc...)*	*Correlate DUT Only*	2	3	2	**2.3**	Extreme sensitivity to measurement noise & precision
e	**Experimental Modal Substructuring [EMS]**	*Stiff*	*Experimental Modal Substructuring*	*Correlate DUT Only*	4	3	4	**3.7**	Requires specific fixture design
f	**Build Custom Stiff Fixture**	*Designed High Impedance Fixture, bolted into floor*	*EMA*	*Correlate DUT Only*	4	2	4	**3.3**	Requires drilling into cement floor at customer facility
g	**Build Custom Massive Fixture**	*Seismic Table*	*EMA*	*Correlate DUT Only*	5	1	5	**3.7**	Seismic fixtures not available at most small sat facilities
h	**Fixed Base Correction Method [FBC]**	*Not Yet Investigated*	*FBS + Modal*	*Correlate DUT Only*	*Not Yet Investigated*				

Selected for ease of execution despite low sensitivity (→ a)

Relatively easy to execute with potentially improved sensitivity compared to free-free testing (→ e)

Sorted by Decreasing Ease of Execution

Many other approaches exist and may be as-good or better than a-g, however Quartus has not yet investigated them directly for this application.

Scores are qualitative with 1 being poor, 5 being best

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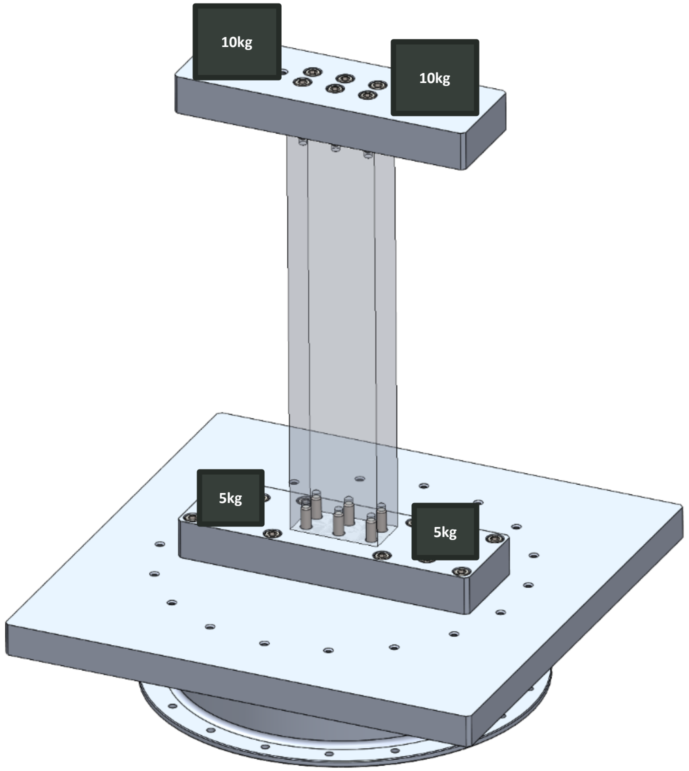
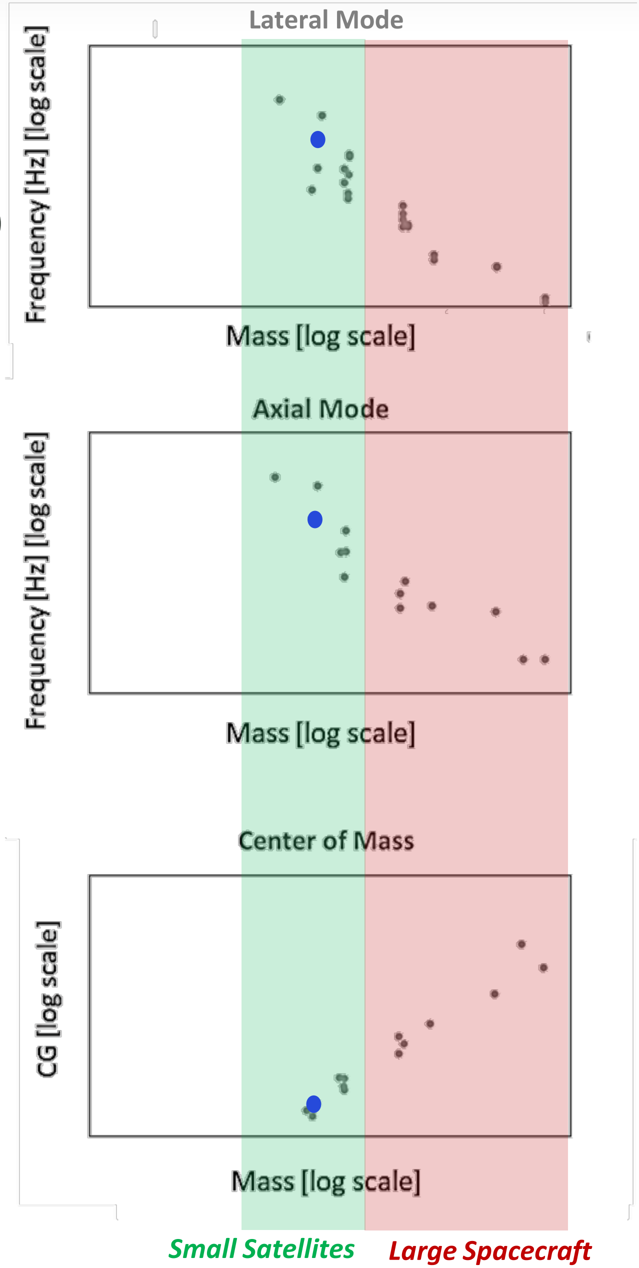
Test Article

- Quartus fabricated a small satellite dynamic simulator for multiple internal development studies
  - Mass = 18 kg + up to 30 kg of adjustable ballast
  - CG = 30 cm from base of sep ring
  - Primary modes and CG scale according to typical fixed-base spacecraft design trends (see trends on right)
- It was used for this study to compare the feasibility of various spacecraft testing approaches



Primary Test Article Dynamic Properties vs Typical Spacecraft Trends



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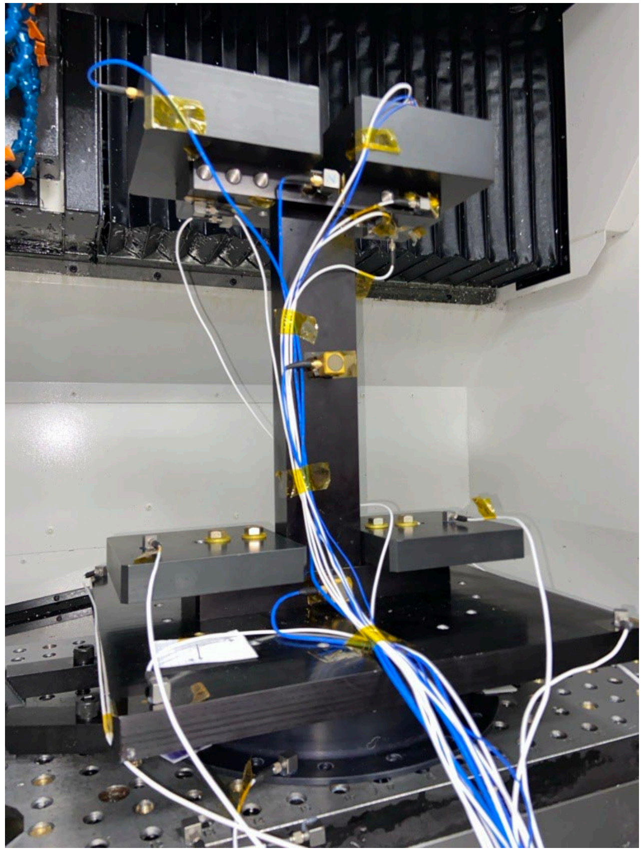
Sensor Placement

- Test article instrumented to fully characterize primary bending and axial modes
  - Additional instrumentation included for visualization of mode shapes during this study



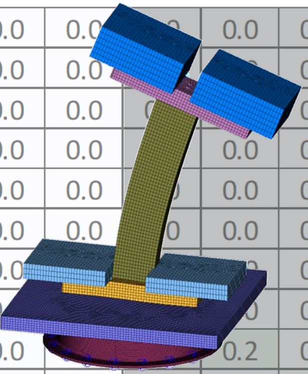
FEM vs TAM Cross Orthogonality

TAM Modes (columns) vs Full FEM Modes (rows)

Full FEM Modes	32.4	47.7	52.9	188.4	203.7	230.4	283.3	410.9	527.7	561.3	704.3	712.1	923.3
1BZ 32.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	[illegible]	0.0	0.0
47.6	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	[illegible]	[illegible]	0.0
1BX 52.9	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	[illegible]	[illegible]	0.0
169.9	0.1	0.0	0.0	0.8	0.1	0.0	0.0	0.0	0.0	0.0	[illegible]	0.0	0.0
1A 200.0	0.0	0.0	0.0	0.2	0.9	0.0	0.0	0.0	0.0	0.0	[illegible]	0.0	0.0
228.4	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	[illegible]	0.0	0.0
247.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	[illegible]	[illegible]	[illegible]	0.0
316.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.6	[illegible]	[illegible]	[illegible]	[illegible]	0.0
414.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0	[illegible]	[illegible]	0.2	0.0
429.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
469.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0
527.4	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.9	0.0	0.0	0.0
565.6	0.1	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.1	0.3	0.3	0.0
631.3	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.1	0.6	0.5	0.0
641.7	0.0	0.2	0.1	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.2	0.2	0.0
824.0	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.8
884.9	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0
916.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0
944.3	0.2	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.0	0.0	0.3	0.4	0.0
975.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Sensor set optimized for primary bending modes

Sensor set insufficient to characterize modes > 500 Hz



$$XOR = \phi^{T}_{GPart} M_A \phi_A$$

- ϕ^{T}_{GPart}: Partition of GSET mode shapes
- M_A: TAM Mass Matrix from Analytical Guyan Reduction
- ϕ_A: Analytical TAM Mode Shapes

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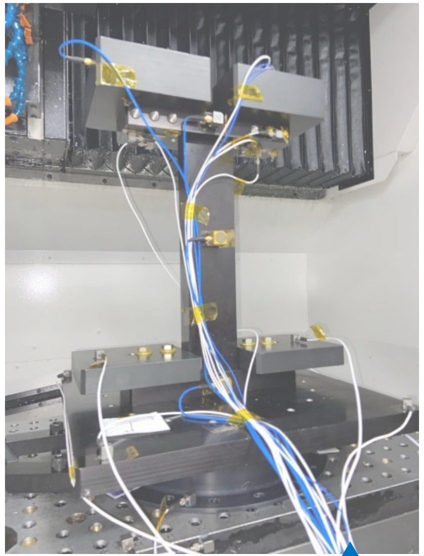
Test Article Fixturing

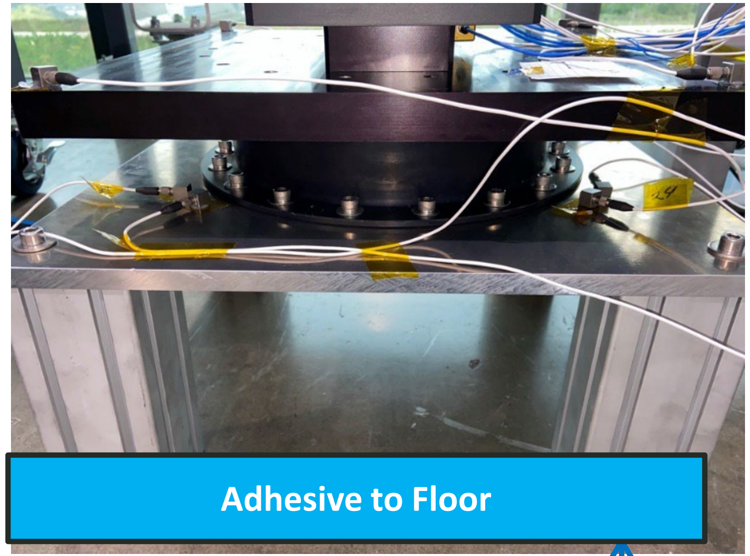
- The following lean fixturing approaches were considered throughout this study
  - Due to practical small sat customer constraints, and to exploit the robustness of the post process driven methods, Quartus intentionally avoided high LOE, expensive, or destructive approaches such as …
    1. Drilling into cement floor
    2. Purchasing / shipping large granite table
    3. Purchasing time on a vibe table

Clamped to Quartus CNC Machine & Mill Table



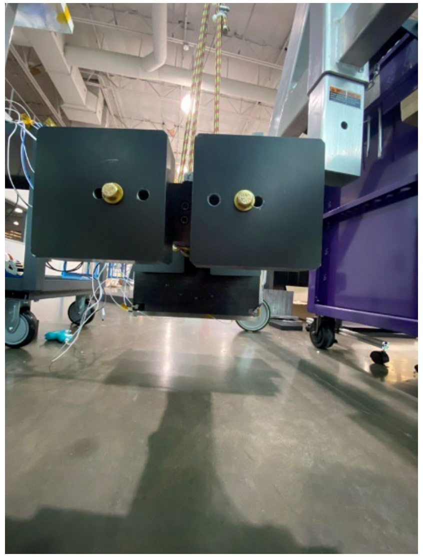
For this study, the results on the Quartus CNC table were used as a truth model as no fixture modes were measured in the frequency range of interest.

Flexible Fixture with Adhesive Boundary

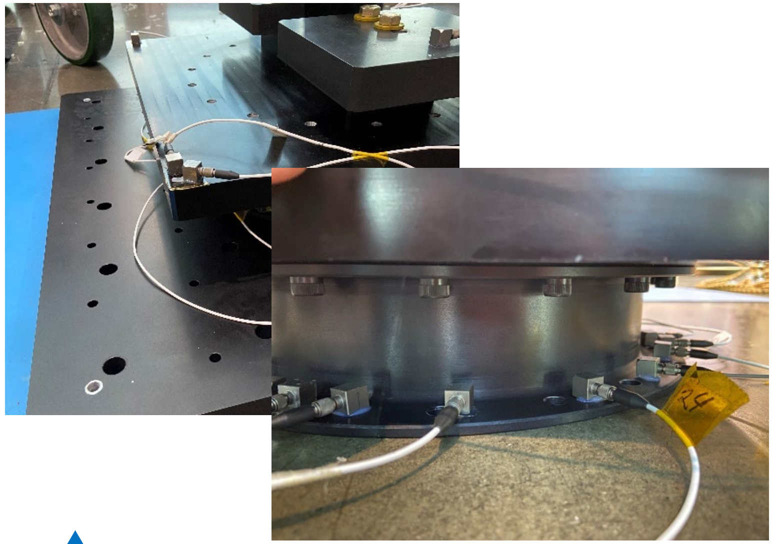


Hot glue can be used to create a soft, approximately linear boundary when drilling into floor is not desired

Free-Free using Bungees



Resting on Floor w or w/out Vibe Plate



Resting on an uneven floor generates nonlinear response peaks, but was included in the investigation due to its ease of implementation

General Baseline Response Comparisons

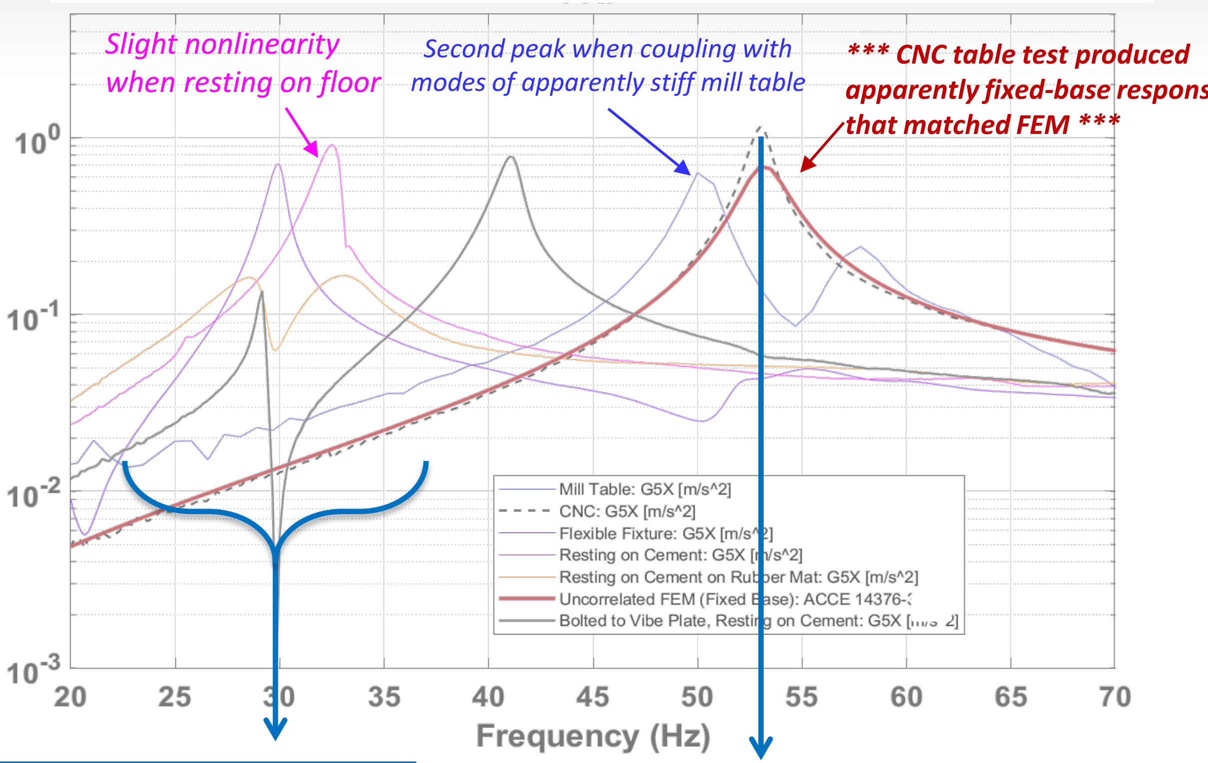
- Very lean (Low-LOE) fixturing approaches all result in insufficient boundary condition
  - Resting on floor is not sufficient even if test article is extremely heavy
    - Floor is not flat!
  - Large aluminum vibe plate resting on floor will improve constraint, but is not near a fixed condition

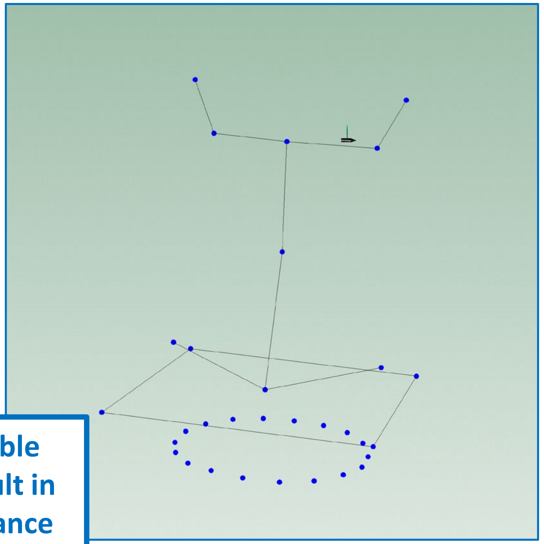
- Even apparently “stiff & massive” fixturing can produce coupled modes with test item (i.e. see Mill Table response)

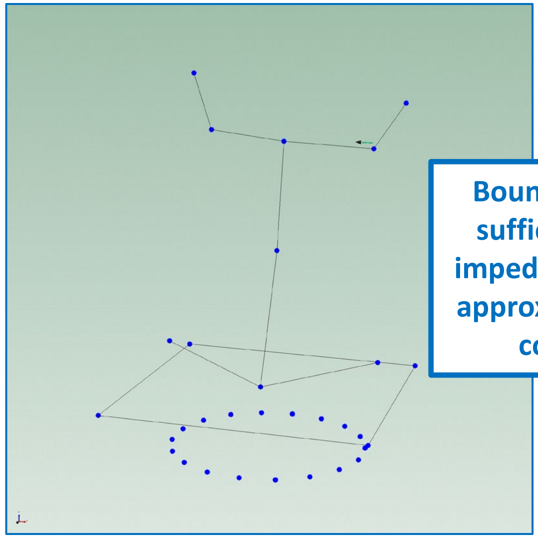
- Quartus was able to achieve apparent fixed base behavior when clamped to massive CNC table
  - <u>Always should be the first option considered if client has such a table available!</u>

X Bending Response w/ Various Boundary Conditions

$$\frac{\left(\frac{m}{s^2}\right)}{N}$$







Soft boundaries such as flexible fixture or resting on floor result in low frequency primary resonance

Boundaries with sufficiently high impedance achieve approximately stiff condition

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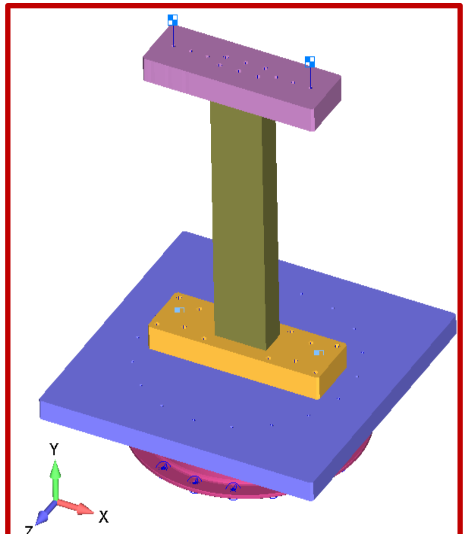
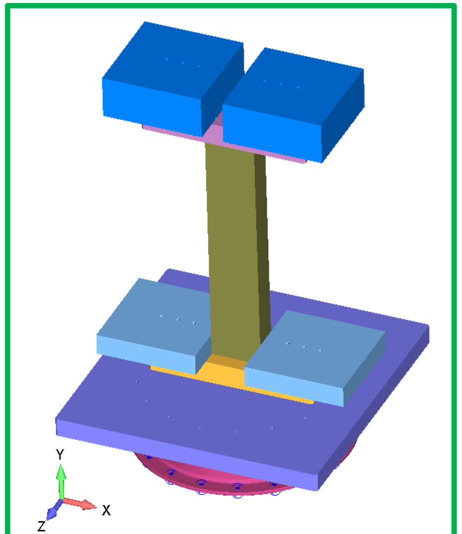
Method 1 – Free Free Correlation

- Quartus performed a free-free correlation on the test article to investigate its effectiveness on *fixed-base* correlation
- First, FEM was correlated to observed free-free responses
  - Primary update was explicit modeling of mass inertia and joints due to insufficient bolt pattern
- Example X drive point response comparison shown on right

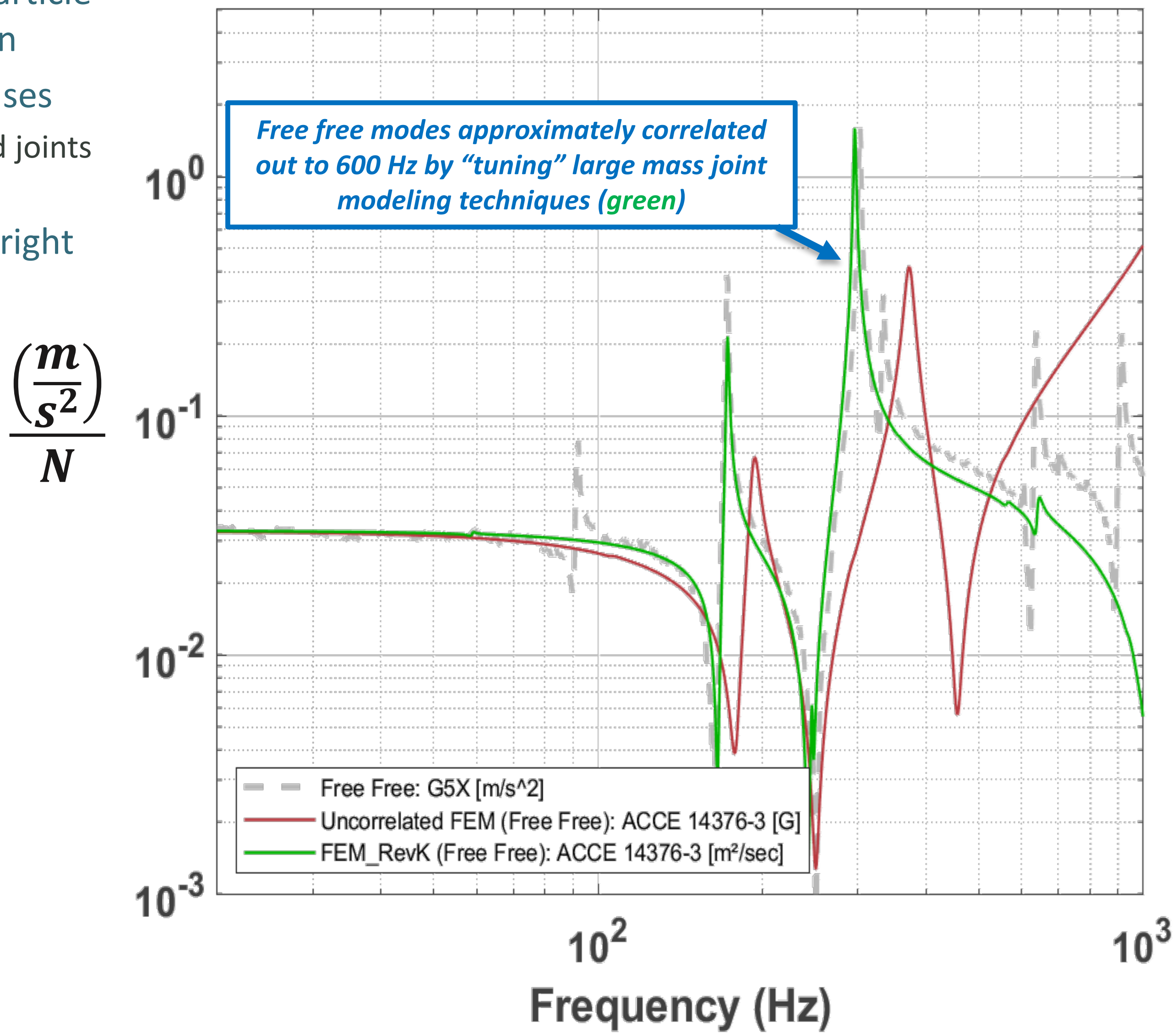


Uncorrelated FEM



Free-free Correlated FEM

Example X Drive Point Response Correlation



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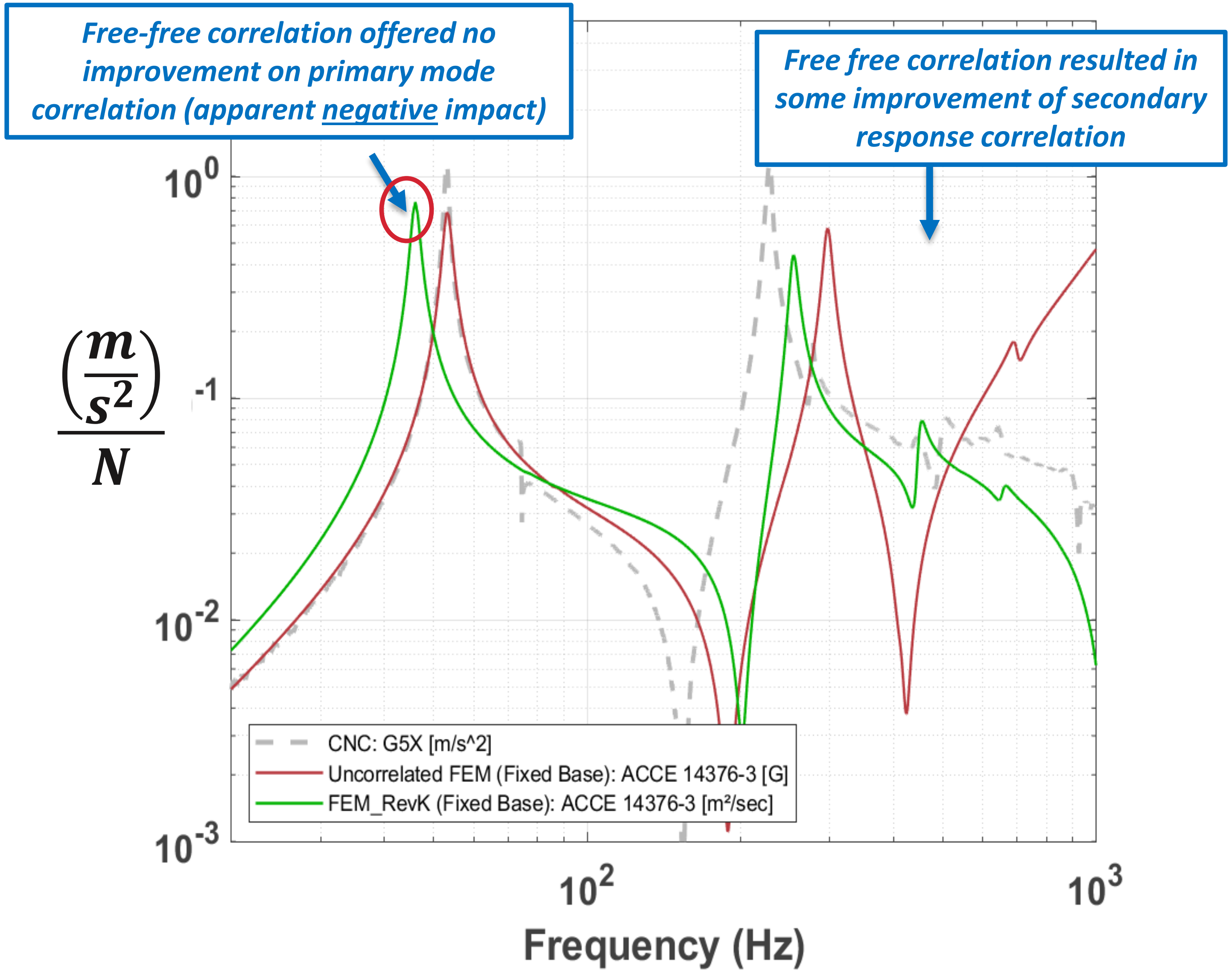
METHOD 1 – CORRELATION CHECK W/ FIXED BOUNDARY

- Uncorrelated and correlated FEM were constrained and compared to constrained test article "truth" model (clamped to CNC table)

- Free free correlation did not achieve net improvement for fixed-base response
  - Secondary / subcomponent responses show some improvement
  - Primary response is now overly compliant

- Free free correlation improved response of secondary / high frequency modes

Example X Drive Point Response Correlation



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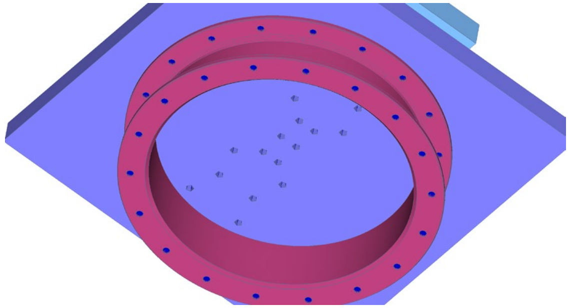
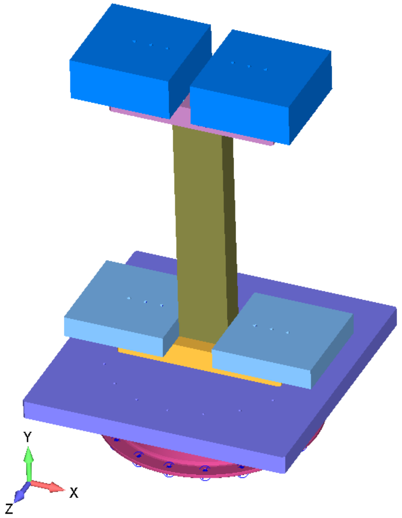
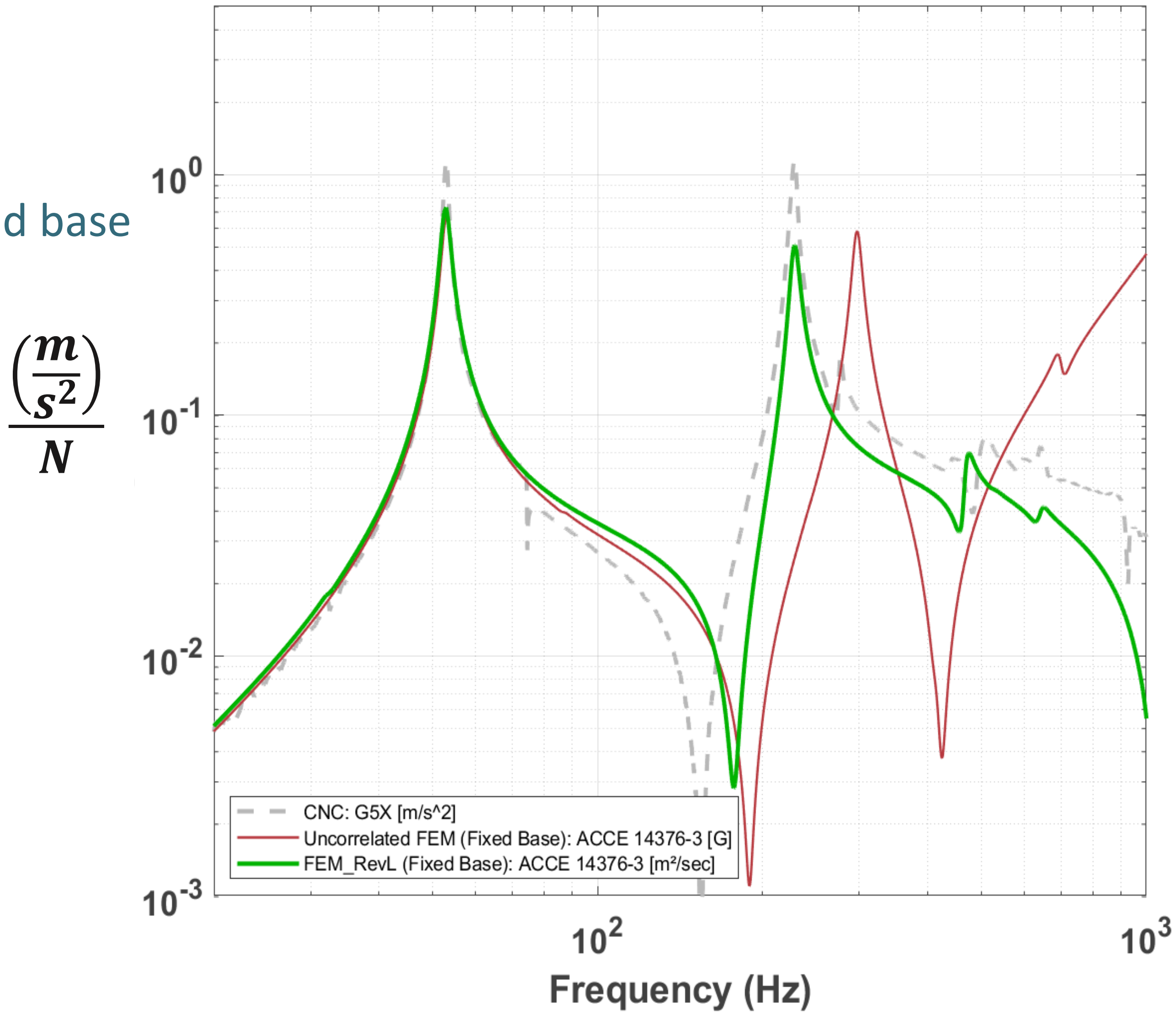
Comparison with Fixed-base Correlation on CNC Table

- Sufficient correlation required explicit mass modeling as well as expansion of RBE (rigid element) footprints at separation ring joint
- Only could be determined by measuring fixed base test modes





Example X Drive Point Response Correlation



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Method 1 - Summary

- Free free testing & correlation is known to be insensitive to modeling errors that impact fixed-base responses (verified by this study)

- However, free free modal testing of spacecraft or components can be used to improve correlation of *sub*components or secondary modal responses
  - Special caution should be taken to ensure that updates do not make overall responses overly compliant

Method 2 – Experimental Modal Substructuring (EMS) With Lean Fixturing Approach

- Experimental Modal Substructuring (EMS) reviewed as a method for easily correcting modal response from a test with an unconstrained boundary
  - FEA and test boundary conditions can be equated by enforcing a constraint on a modal model built from test data
- General principal [2,3]:
  1. A modal model can be constructed directly from extracted test modes (uncontrolled boundary)
  2. Analyst must find a modal transformation **B** that approximates the desired physical constraint
  3. Constrained modes calculated from transformed modal model

  Note: Methodology shown here based on work by Prof. Matt Allen (BYU)

$$M_c = B^T I B$$

$$K_c = B^T \omega^2 B$$

$$y = \phi B x_u$$

Constrained mode shapes and frequencies

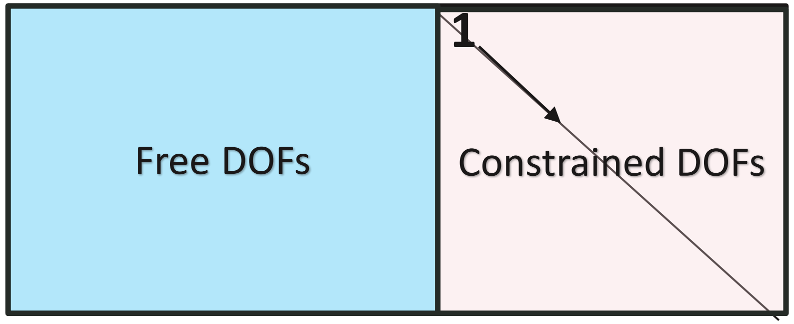
$$\omega_c^2, \hat{\phi}_c = eig(K_c, M_c)$$

$$\phi_c = \phi B \hat{\phi}_c$$

- Feasibility study on following slides:
  - Determine challenges associated with using EMS to estimate fixed base modes
  - Determine sensitivity of EMS when used with lean fixturing approaches.
    - i.e. Can it detect FEA error?

Constraint Definition

$a_p =$



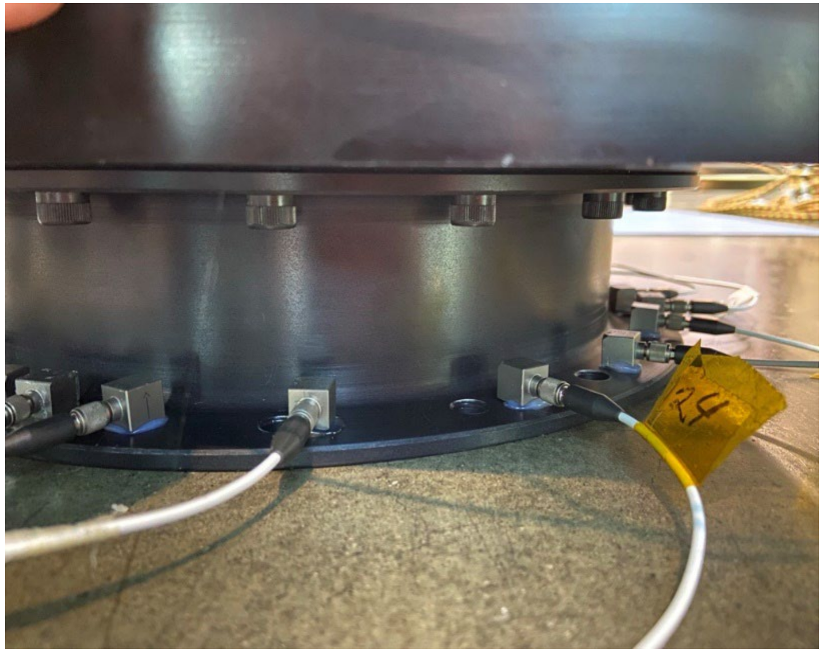
Matrix to define physical constraint equations or constraint shapes. In this case, setting boundary motion = 0. i.e. $a_p y_a = 0$

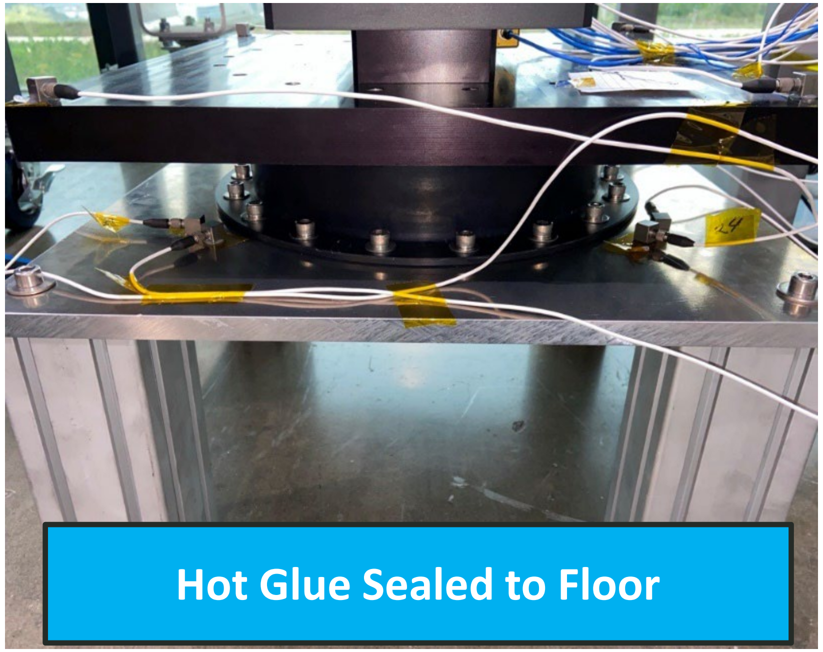
$$B = null(a_p \phi)$$

Challenge lies in identifying transformation from a general set of *unconstrained* modal coordinates

Method 2 –Test Setup

1. Instrumented Ring to Fully Characterize Boundary Shapes
2. Attached to simplistic aluminum standoff fixture hot glued to floor
   - Found that hot glue provided soft but linear boundary
   - Resulting fixture primary modes were simple shapes which are known to be advantageous for EMS method
   - This solution is logistically desirable to avoid drilling into cement floor or utilizing heavy / seismic table





Hot Glue Sealed to Floor

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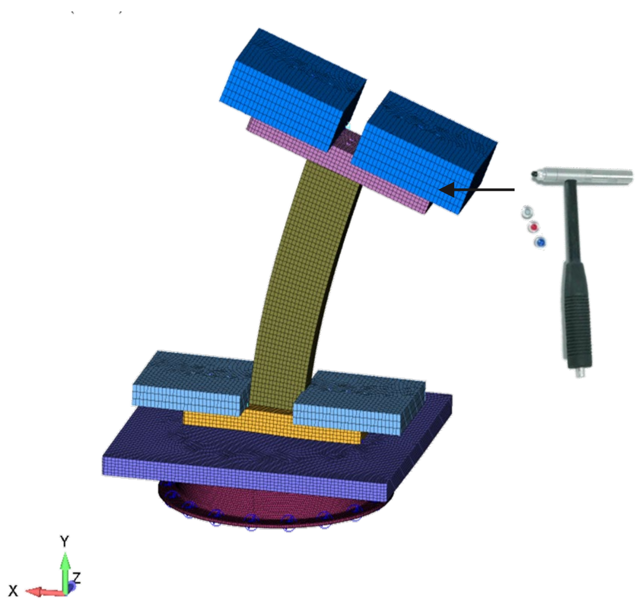
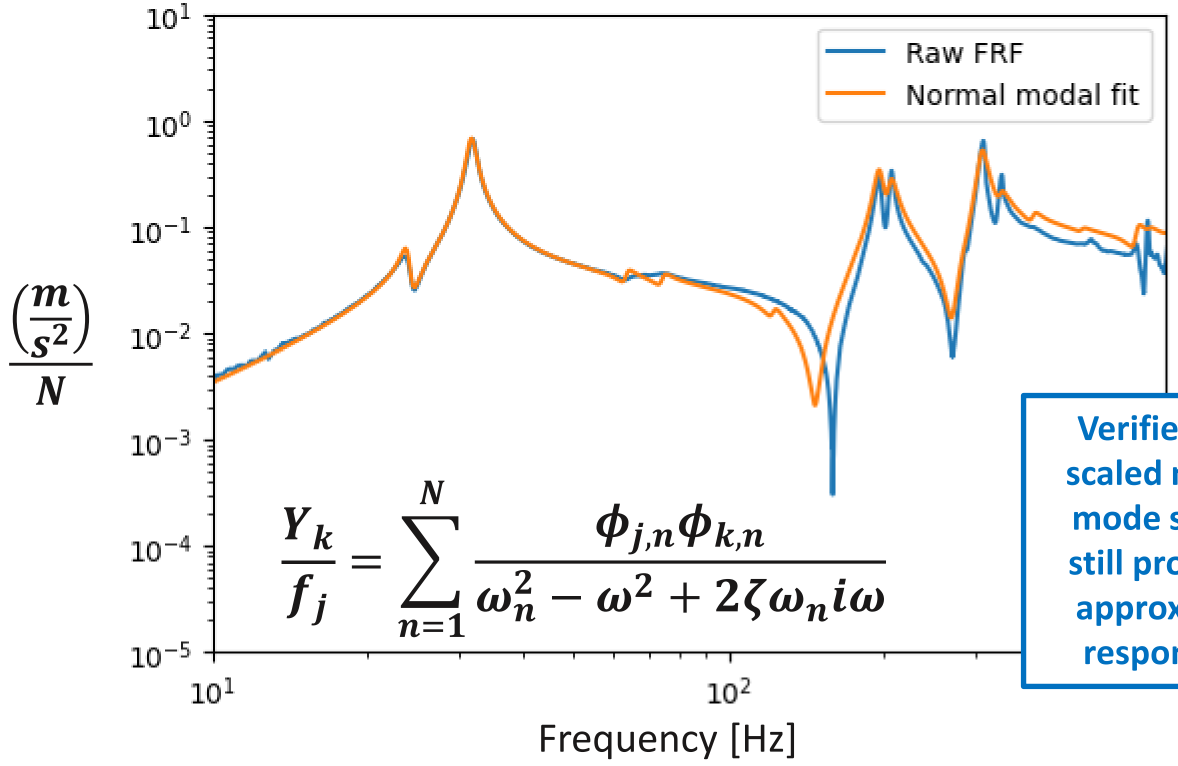
Method 2 – Test Execution & Modal Extraction

1. Test article was excited using modal impact hammer in 3 axes at indicated impact location
2. FRF curve fitting performed in BK connect using Polyreference Time algorithm
3. Mode normalization and scaling performed in BK connect, checked using modal FRF synthesis
   – Modes scaled to unity modal mass to construct modal model



Mode Shape Scaling & Normalization Validation (X Axis Ex.)



$$\frac{Y_k}{f_j} = \sum_{n=1}^{N} \frac{\phi_{j,n}\phi_{k,n}}{\omega_n^2 - \omega^2 + 2\zeta\omega_n i\omega}$$

Verified that scaled normal mode shapes still produced approximate response fit

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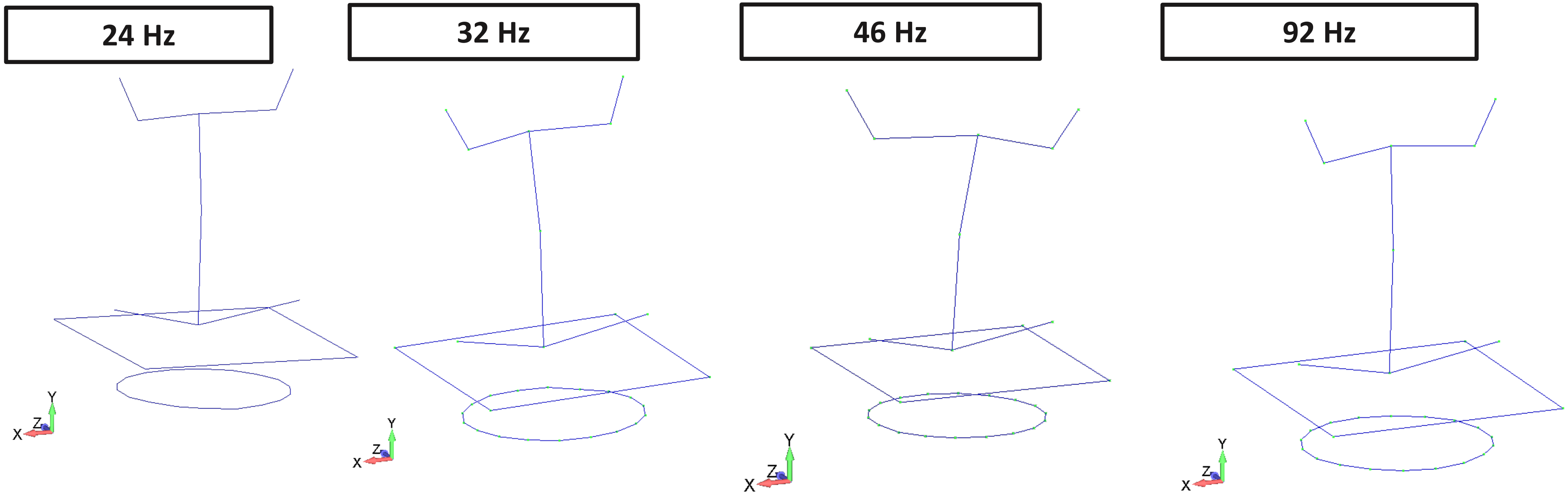
Method 2 – Fixture Dynamics

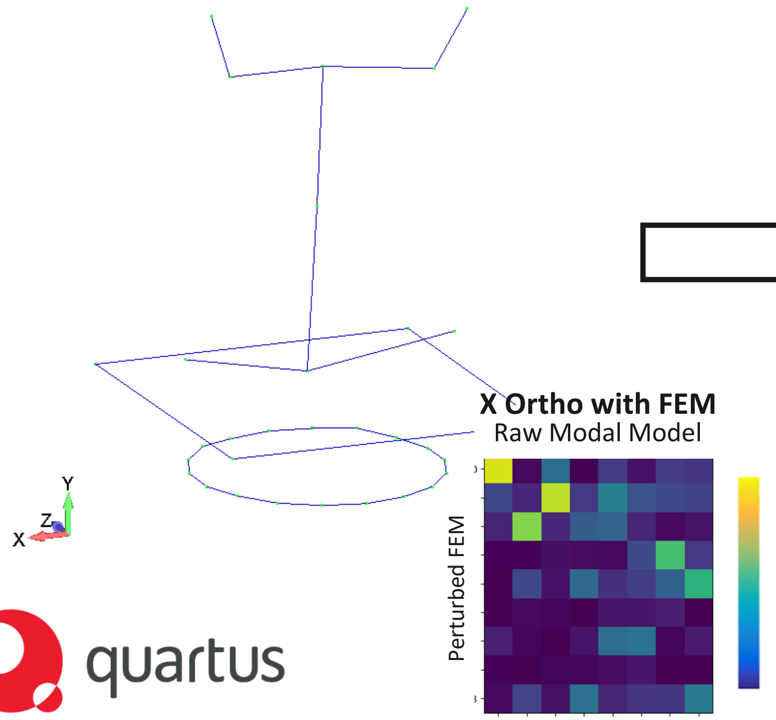
- Primary fixture mode shapes consisted of simple translations / rotations of interface
  - EMS known to struggle with high order interface mode shapes



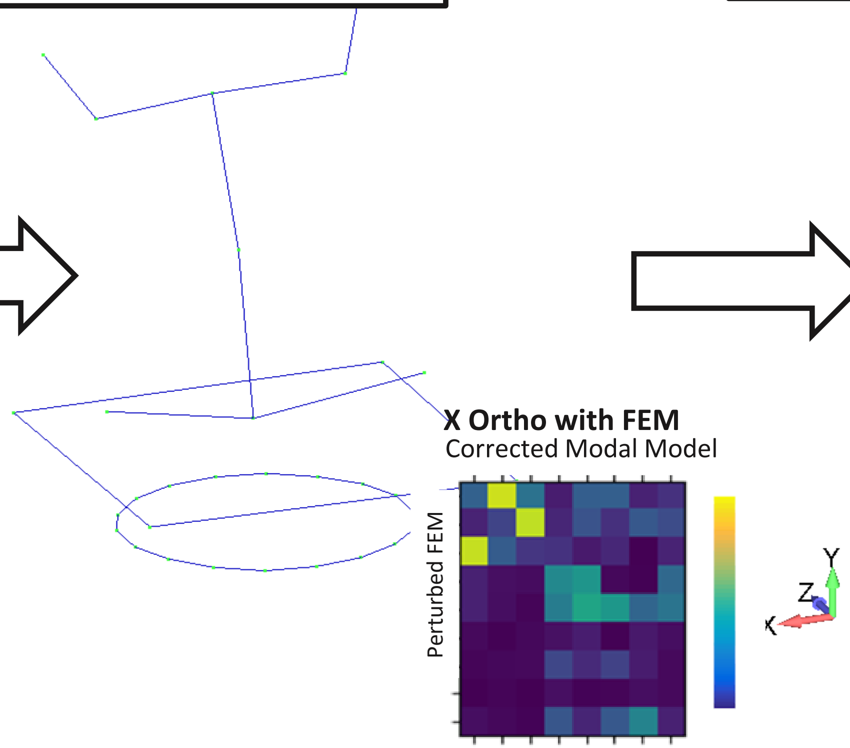
Method 2 – EMS General Procedure

- One option is to add degrees of freedom to constraint set until apparent constrained modal model is found
- Convergence can be difficult to detect but can be guided by…
  - Improved diagonalization of cross ortho with uncorrelated FEM (indicates appearance of fixed-base-like mode shapes)
  - Inspection of mode shape at boundary (should appear nearly fixed)
- Quartus generated a deliberately perturbed FEM to act as a control for this study
  - Emulates real-world situation in which analyst only has uncorrelated FEM to guide convergence
  - Introduced large mass error on top ballast

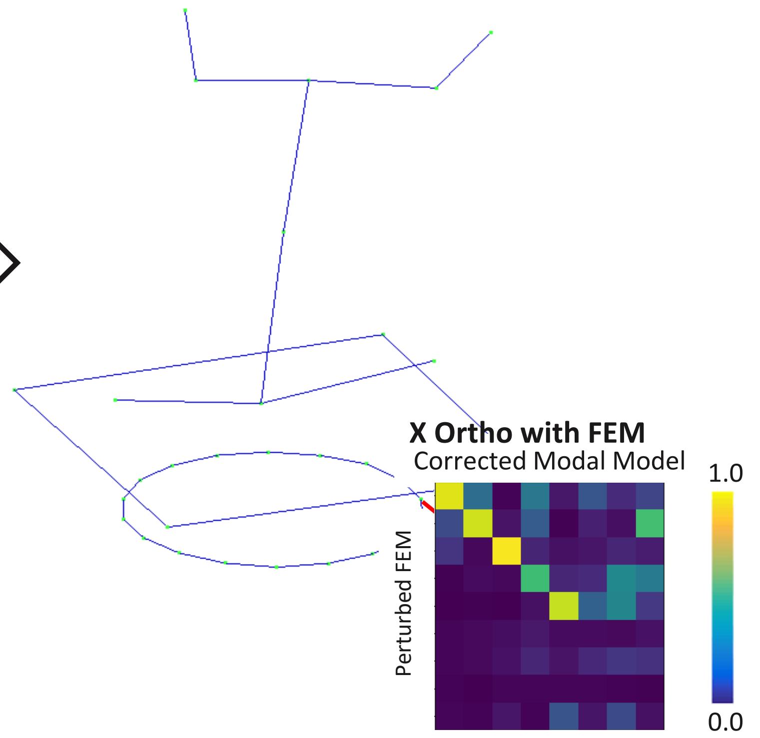
3DOF Constraint: 39 Hz



5DOF Constraint: 45 Hz



6DOF Constraint: 51 Hz



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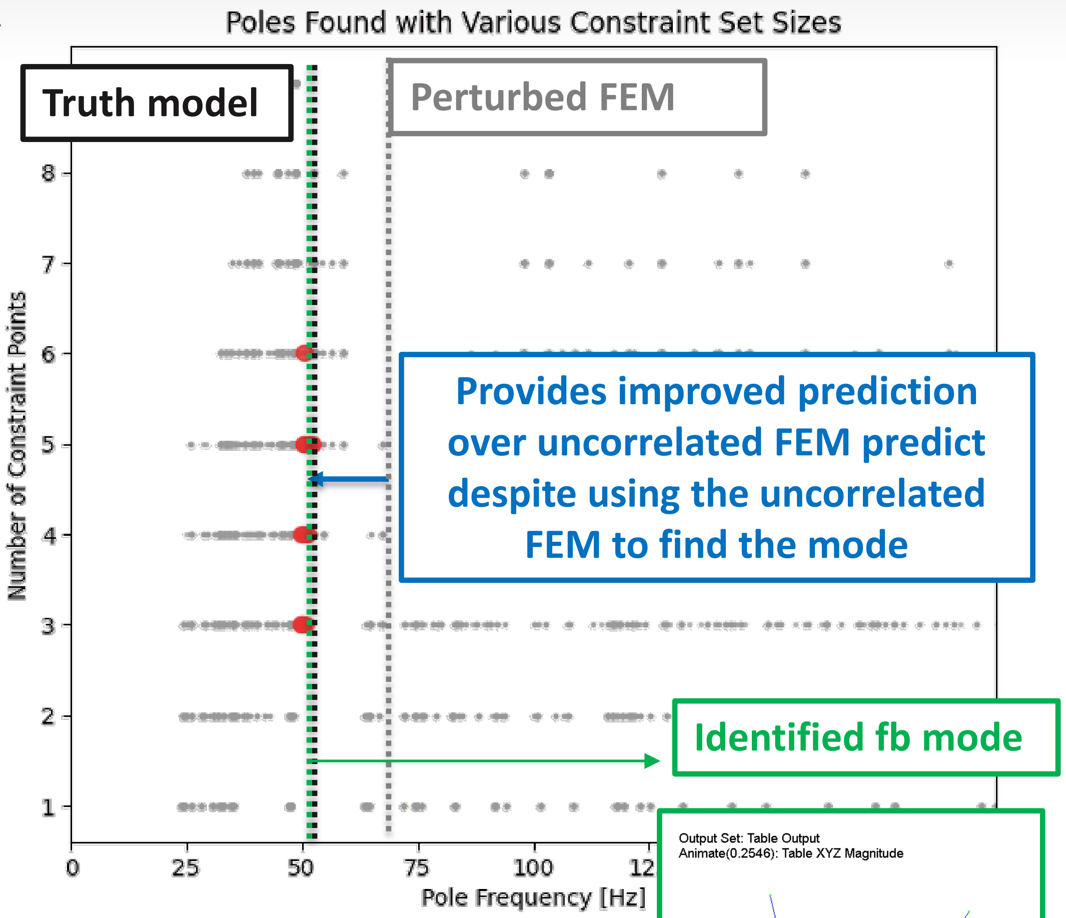
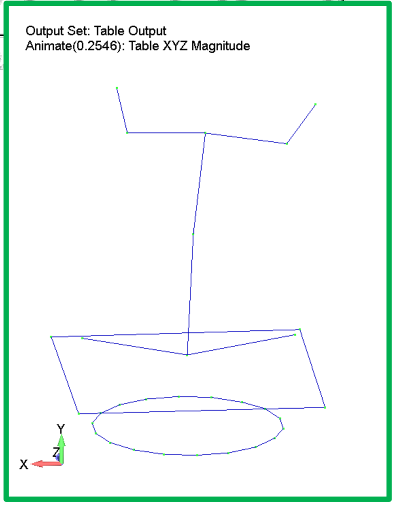
METHOD 2 – VALIDATION – X

- In this study, mode shape stabilization compared to *perturbed* FEM was used to aid in detecting convergence
  1. Generated plots of randomized constraint sets vs fixed-base pole frequency
  2. Highlighted poles that show maximum agreement with perturbed FEM target mode shape (in this case >95% cross orthogonality)

  – **Highlighted poles** are likely exhibiting fixed-base behavior in axis of interest
  – Poles not highlighted are either other converged primary modes or spurious modes (not fully constrained)
  – Mode shape comparison will never be perfect because FEM is not correlated (only looking for *relative maximum agreement to identify a mode*)

- EMS algorithm converged on good approximation of fixed-base X axis bending mode





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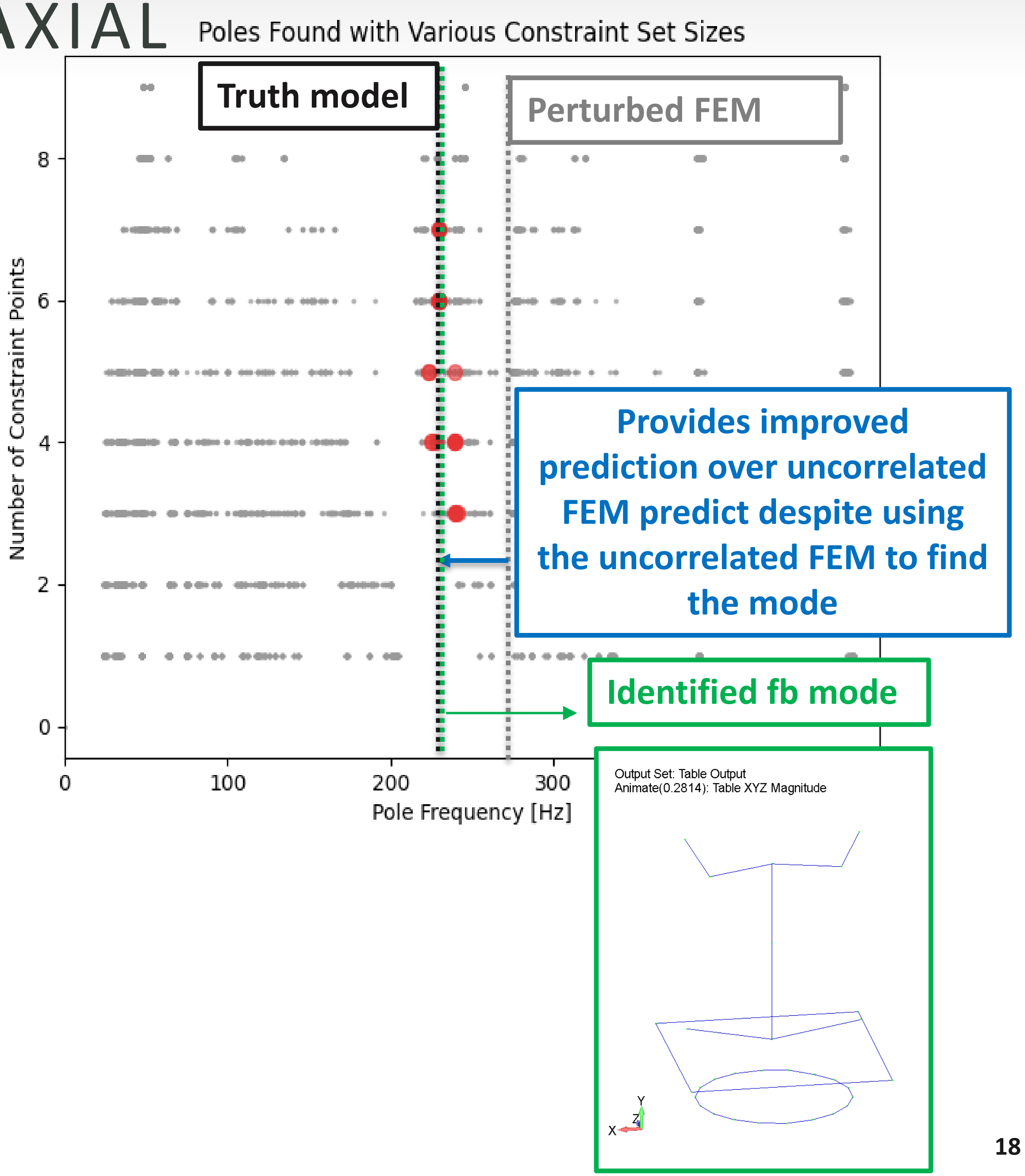
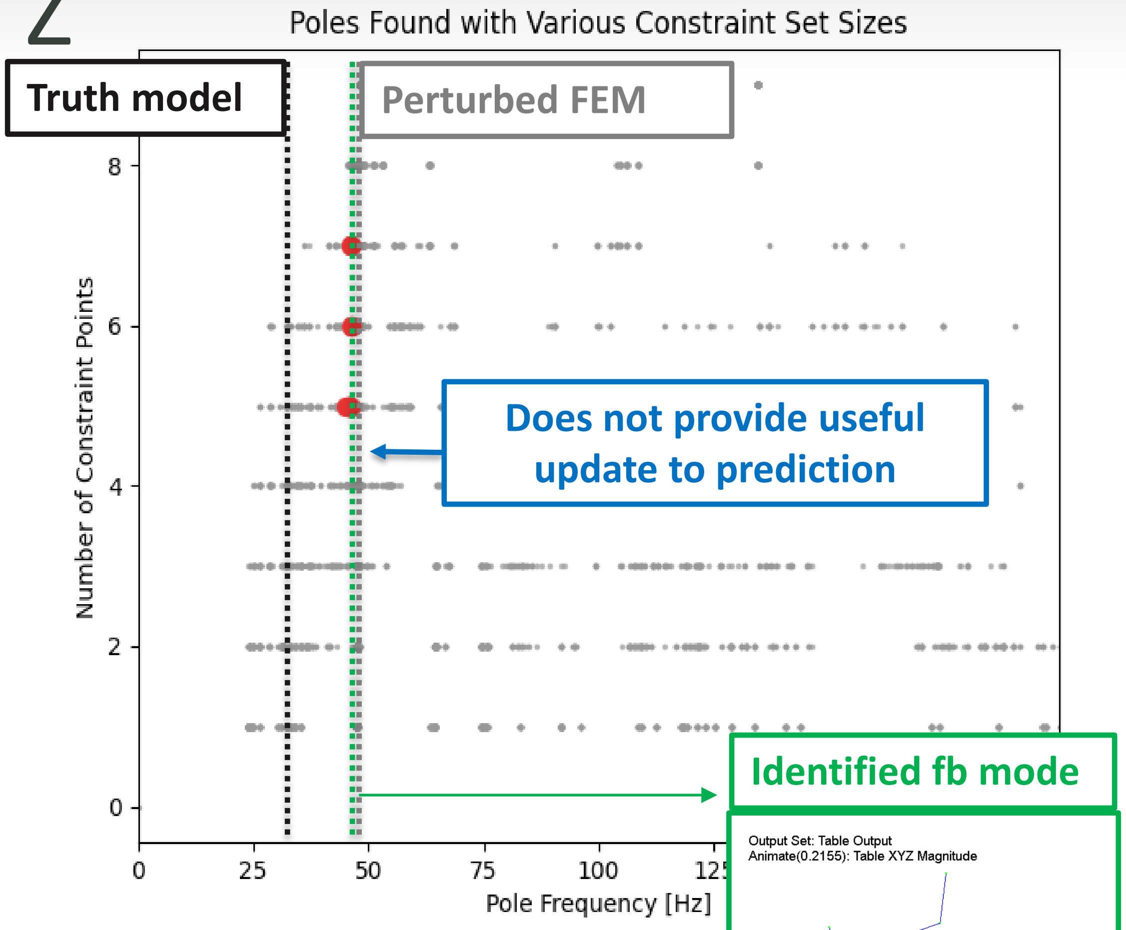
METHOD 2 – VALIDATION – AXIAL

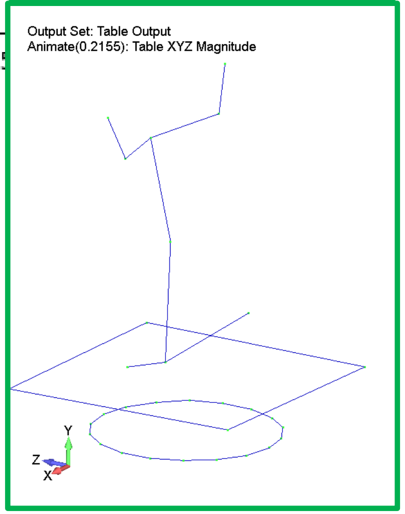
- EMS algorithm converged on good approximation of fixed-base Y axis axial mode



Method 2 – Validation – Z

- EMS algorithm converged on incorrect Z bending mode frequency
  - FEA predictions and CNC "truth model" test indicate fixed base mode should be around 32 Hz
  - EMS converged on 49 Hz, but with correct mode shape





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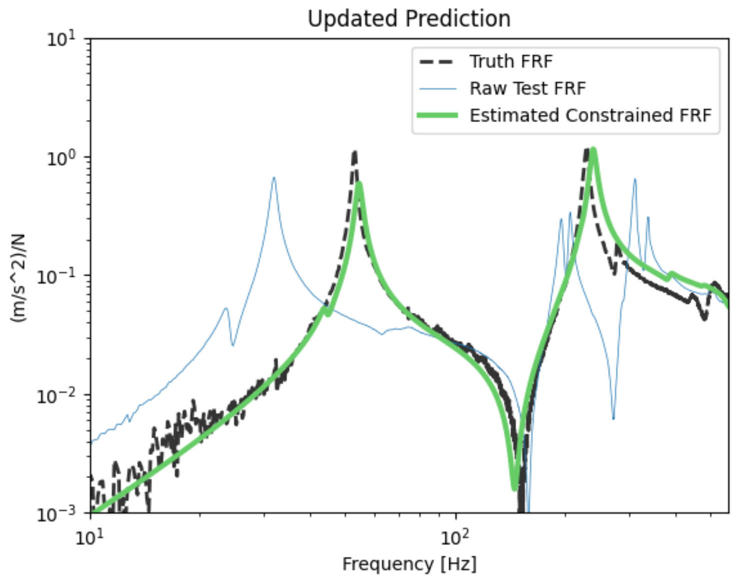
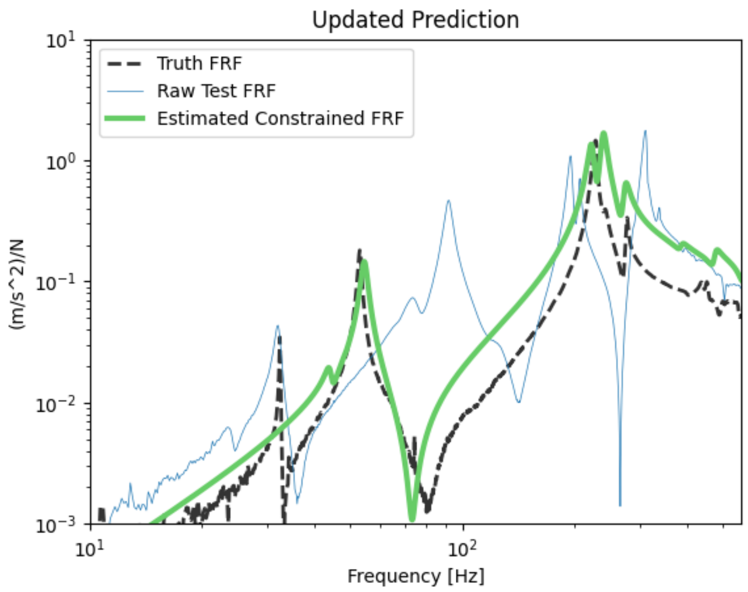
Converged Frequency Response Check

- Synthesized FRFs provide useful visualization of extracted fixed-base modal model
- Comparison shows reasonable agreement in X and Y axis, but poor convergence in Z axis

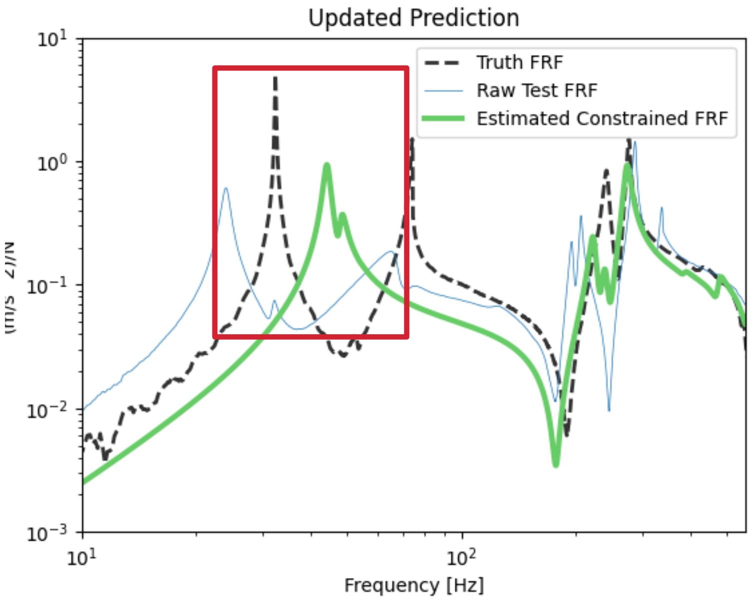
X Drive Point FRF Comparison



Y Drive Point FRF Comparison



Z Drive Point FRF Comparison



Corrected Test Response
Uncorrected Test Response
Truth Model (test item on CNC table)

Method yields poor predictions in Z axis

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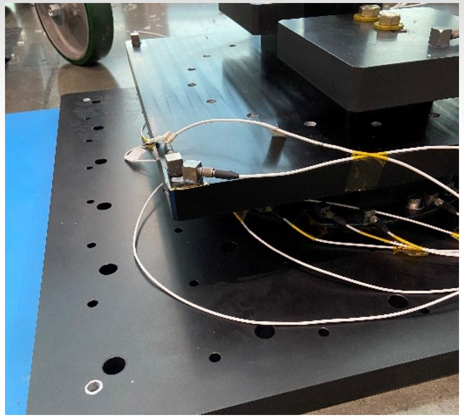
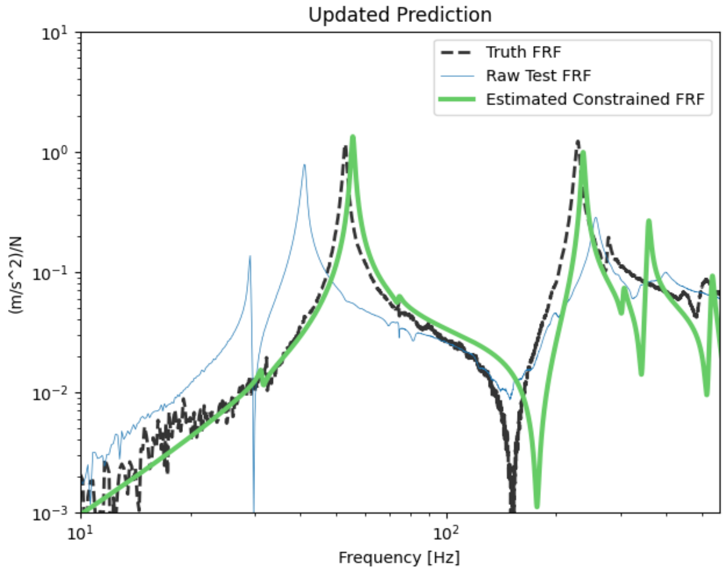
ALTERNATIVE FIXTURING TECHNIQUE

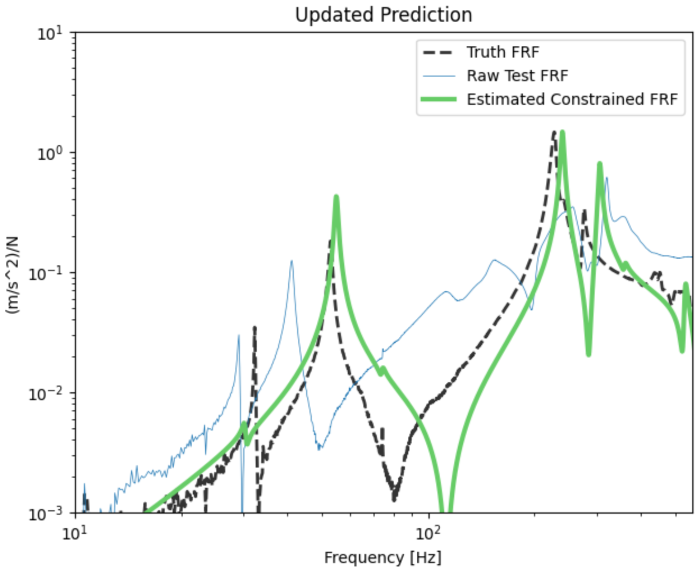
- Performed same procedure on updated fixture:
  - Test item bolted to vibe plate resting on cement floor (not flat / imperfect contact)
- Improved agreement in Z axis; slightly worse agreement in X and Y axes



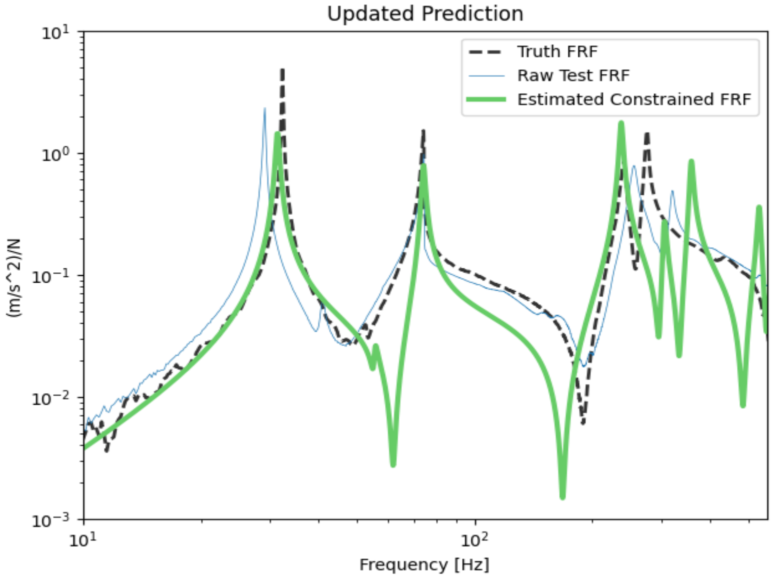
X Drive Point FRF Comparison



Y Drive Point FRF Comparison



Z Drive Point FRF Comparison



Corrected Test Response

Uncorrected Test Response

Truth Model (test item on CNC table)

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METHOD 2 - SUMMARY

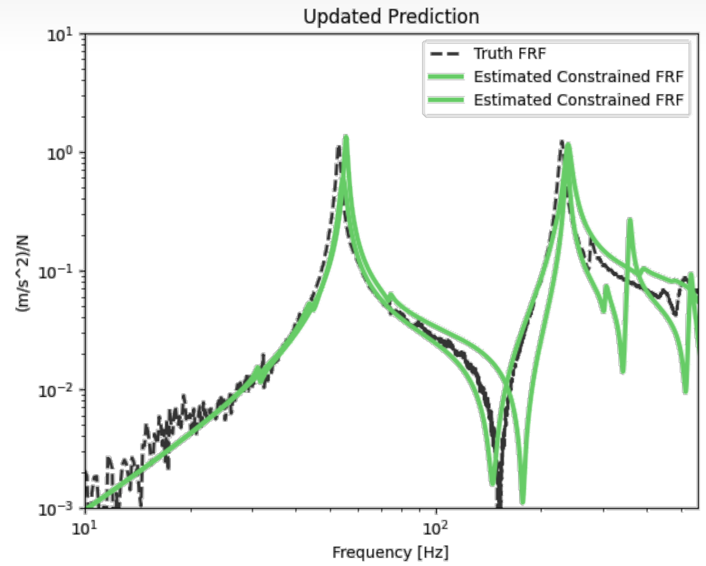
- EMS appears to be promising approach to reduce fixturing requirements & efforts for a constrained modal survey & FEM correlation
  - Preliminary results are sufficient to inform multiple FEM updates
  - Shows some improvement in sensitivity from free-free correlation approach even with low level of effort fixture design

- Preliminary study suggests further work is required to customize fixturing approach for best performance with EMS
  - Detected large FEM errors introduced in this study (see plot on bottom right)
  - Apparent uncertainty margin suggests current approach may be insensitive to small modeling errors
    - Results of 2 fixturing approaches agreed within +/- ¼ octave
  - Expect improved results upon customizing fixture design for use with EMS

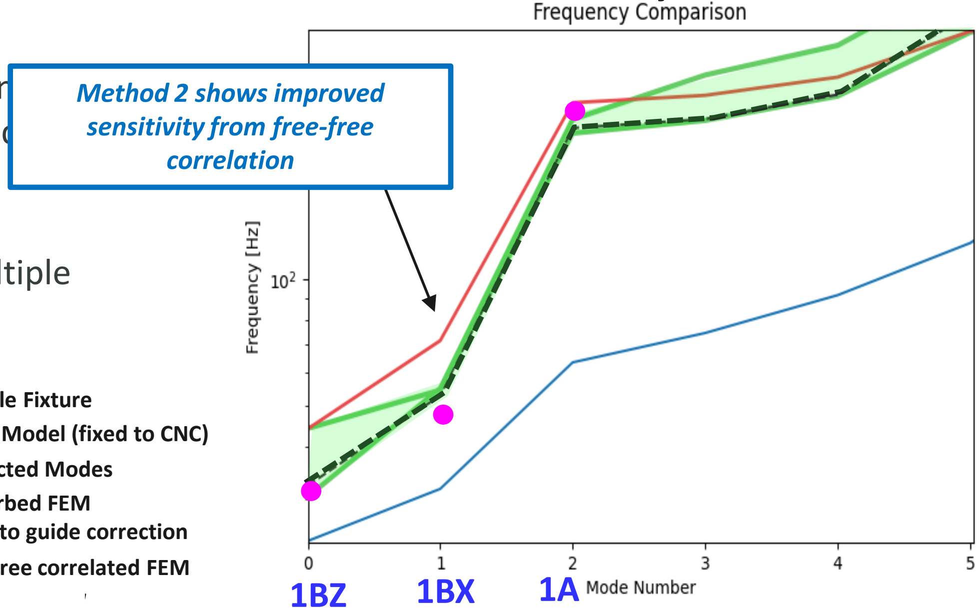
- Other challenges identified in this study:
  - Convergence of EMS can be difficult to detect without advanced analytical techn
  - Measured damping was heavily confounded with boundary condition in this stud

- Path forward:
  - Design simple portable fixture ***optimized*** for EMS method that will adapt to multiple interface types
  - Investigate ways of automating convergence & constrained model construction

X Response Synthesis of 2 Independent Attempts



Sensitivity Check



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Conclusions

- This study investigated the feasibility of incorporating a lean modal screening & model correlation of a component or small spacecraft ahead of a vibration test
- Many methods were reviewed, but the following were covered in this report:
  - **Free Free Correlation:**
    - Useful for correlating subcomponents and secondary responses
    - Insensitive to modeling errors that will impact constrained modes
  - **Experimental Modal Substructuring with Lean Fixturing Approach:**
    - Improved sensitivity to relevant modeling errors when compared to a free-free approach
    - Improved fixturing strategy required to detect smaller modeling errors
- Future Work:
  - Design simple, stiff, portable fixture optimized for EMS algorithms that will adapt to multiple small sat interface types
    - Fixture should have non-destructive attachment to floor (e.g. adhesive or similar…)

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3. Allen, Mayes, Bergman, *Experimental Modal Substructuring to Couple and Uncouple Substructures with Flexible Fixtures and Multipoint Connections*
4. Berman, *Mass Matrix Correction Using an Incomplete Set of Measured Modes,* Kaman Aerospace Corporation
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