Investigations into Applying the Transmission Simulator Method of Hybrid Modal Substructuring to Model an Electrodynamic Shaker

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THE UNIVERSITY of WISCONSIN MADISON

Masters Defense

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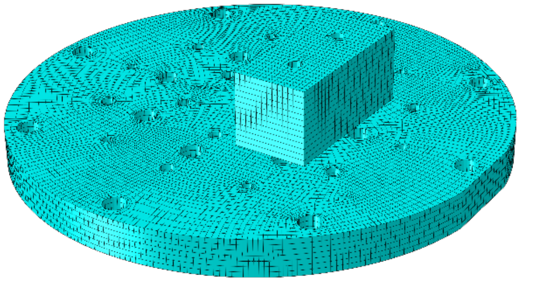
Outline

- Why Model a Shaker?
- Transmission Simulator Method
- Test Case 1: Circular Plate w/ Block
  - Subsystem Descriptions
  - Experimental Setup
  - Finite Element Modeling
  - Substructuring Results
- Test Case 2: Half Cube w/ Beam
  - ...
- Test Case 3: Half Cube w/ Block
  - ...
- Conclusions & Future Work

FEM



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Experiment

Electrodynamic Shakers are Used to Reproduce a Specific Vibration Environment

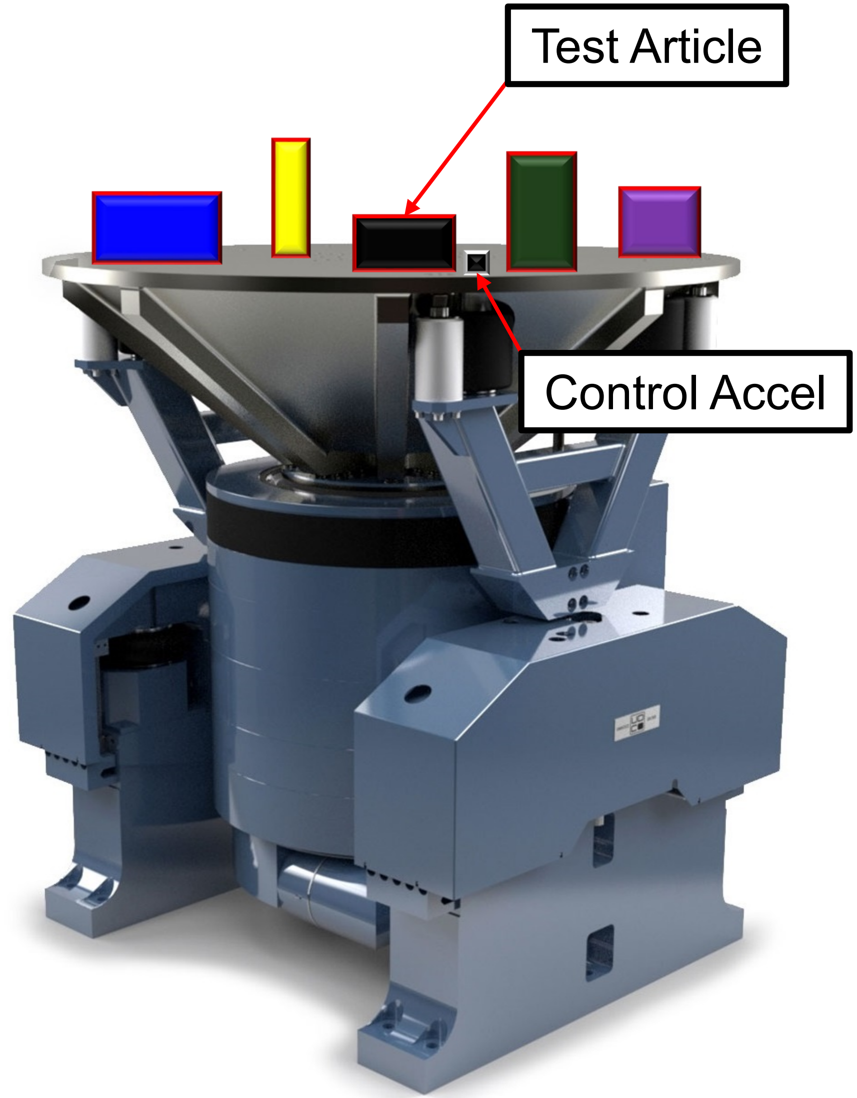
Measured Environment

Reproduced Environment

R. Rossarola, 2016, *Rocket Launch – motion design*

In Practice, Shaker Testing can be Tricky

- Test article attached to shaker fixture
- Control accelerometer used to monitor environment

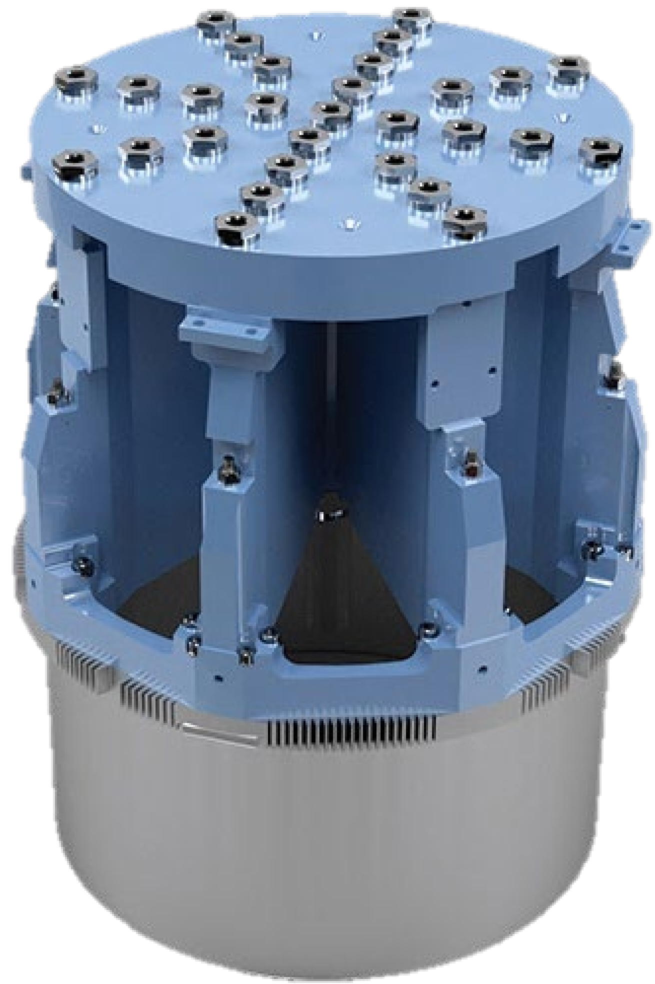


What if you want to test more than just one component?

Motivation to Create a Shaker Model

- An accurate shaker model allows for better pretest planning
  - Optimize component layout
  - Prevent over/under-testing and costly retests

- Creating completely analytical models has proven difficult [1],[2]
  - Unknown internal structure
  - Stiffness, damping and joint nonlinearity
  - Effective stiffness of EM field
  - Interaction with amplifier/control system

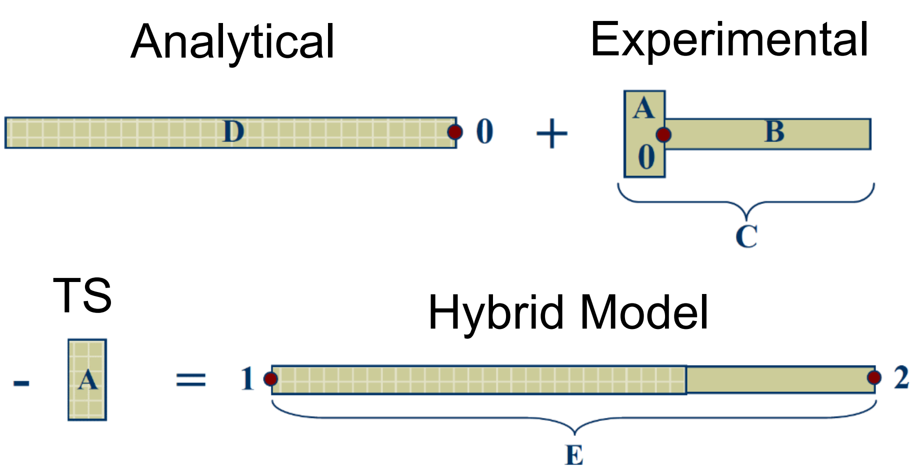


[1] DeLima & Ambrose, "Experimental Characterization and Simulation of Vibration Environmental Test," IMAC2015.

[2] Waimer-etal, "A Multiphysical Modelling Approach for Virtual Shaker Testing Correlated with Experimental Test Results," IMAC2016.

Transmission Simulator Method

- Hybrid Method of Modal Substructuring
- Combines Experimental and Analytical Subsystems
  - In physical domain, would require many measurements and is very sensitive to noise
  - Use Component Mode Synthesis → modal domain
    - Requires Modeshapes and Natural Frequencies of each subsystem



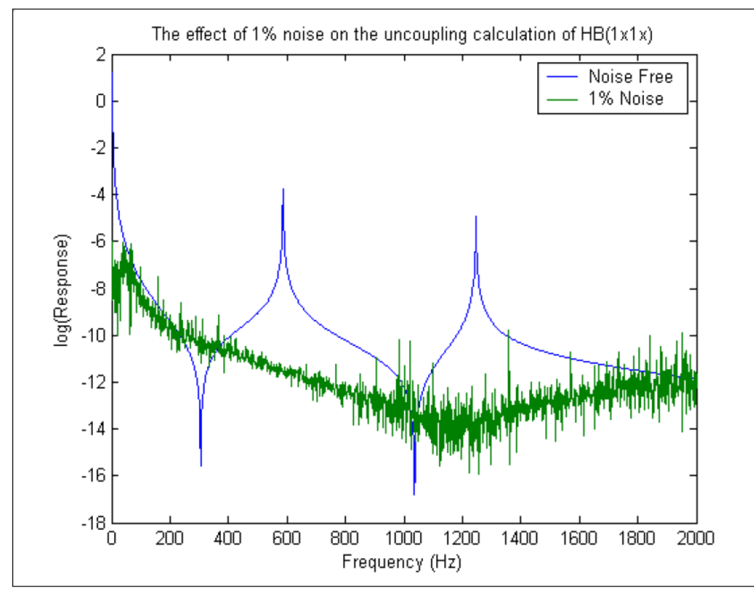


Figure 4.5.9. The effect of 1% "peak" noise on the uncoupling calculation.

M. S. Allen, R. L. Mayes, and E. J. Bergman, "Experimental Modal Substructuring to Couple and Uncouple Substructures with Flexible Fixtures and Multi-point Connections," Journal of Sound and Vibration, vol. 329, pp. 4891–4906, 2010, http://dx.doi.org/10.1016/j.jsv.2010.06.007.

Component Mode Synthesis

- Equations of Motion in Modal Coordinates

$$-\omega^2 \begin{bmatrix} \mathbf{I}_{EX} & 0 & 0 \\ 0 & -\mathbf{I}_{TS} & 0 \\ 0 & 0 & \mathbf{I}_{AN} \end{bmatrix} \begin{bmatrix} \boldsymbol{\eta}_{EX} \\ \boldsymbol{\eta}_{TS} \\ \boldsymbol{\eta}_{AN} \end{bmatrix} + \begin{bmatrix} [\omega_{n,EX}^2] & 0 & 0 \\ 0 & [-\omega_{n,TS}^2] & 0 \\ 0 & 0 & [\omega_{n,AN}^2] \end{bmatrix} \begin{bmatrix} \boldsymbol{\eta}_{EX} \\ \boldsymbol{\eta}_{TS} \\ \boldsymbol{\eta}_{AN} \end{bmatrix}$$

$$= \begin{bmatrix} \boldsymbol{\Phi}_{EX}^T & 0 & 0 \\ 0 & -\boldsymbol{\Phi}_{TS}^T & 0 \\ 0 & 0 & \boldsymbol{\Phi}_{AN}^T \end{bmatrix} \begin{bmatrix} \mathbf{F}_{EX} \\ \mathbf{F}_{TS} \\ \mathbf{F}_{AN} \end{bmatrix}$$

- Constraint Equations

$$\begin{bmatrix} \boldsymbol{\Phi}_{TS}^{\dagger} & 0 \\ 0 & \boldsymbol{\Phi}_{TS}^{\dagger} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Phi}_{EX} & -\boldsymbol{\Phi}_{TS} & 0 \\ 0 & -\boldsymbol{\Phi}_{TS} & \boldsymbol{\Phi}_{AN} \end{bmatrix} \begin{bmatrix} \boldsymbol{\eta}_{EX} \\ \boldsymbol{\eta}_{TS} \\ \boldsymbol{\eta}_{AN} \end{bmatrix} = 0$$

Transmission Simulator Method

Experimental Subsystem - Transmission Simulator

Transmission Simulator Method

Experimental Subsystem - Transmission Simulator

Transmission Simulator Method

Experimental Subsystem - Transmission Simulator + Analytical Subsystem = Hybrid Model

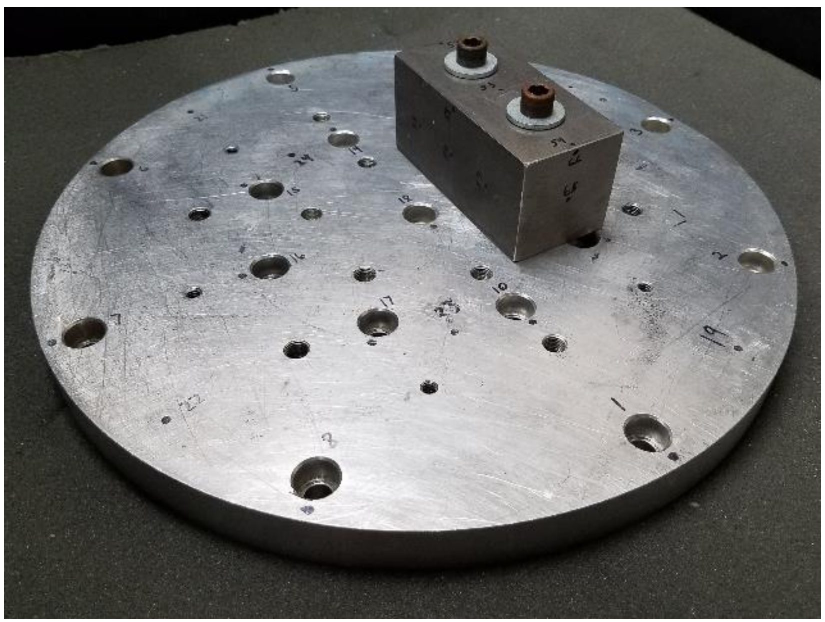
Case 1: Circular Plate & Steel Block

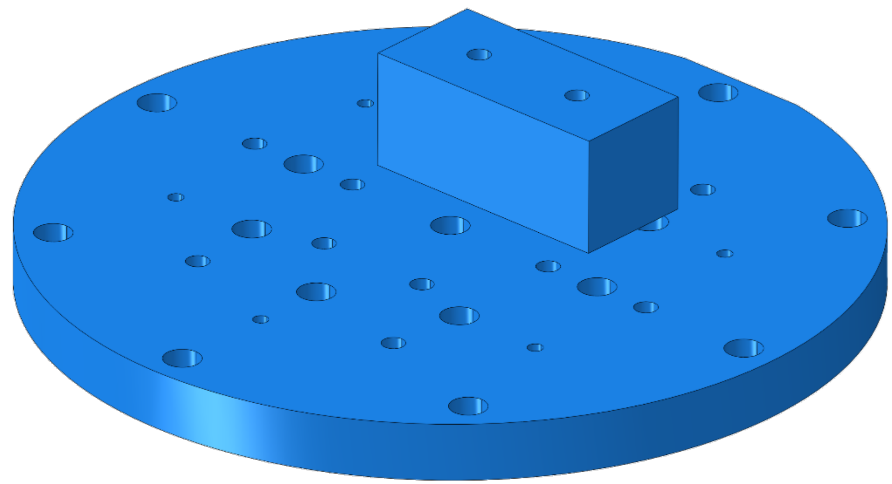
The Transmission Simulator

- Aluminum Plate
  - 13” diameter, 1” thick, 13.25 lbs

Analytical Subsystem

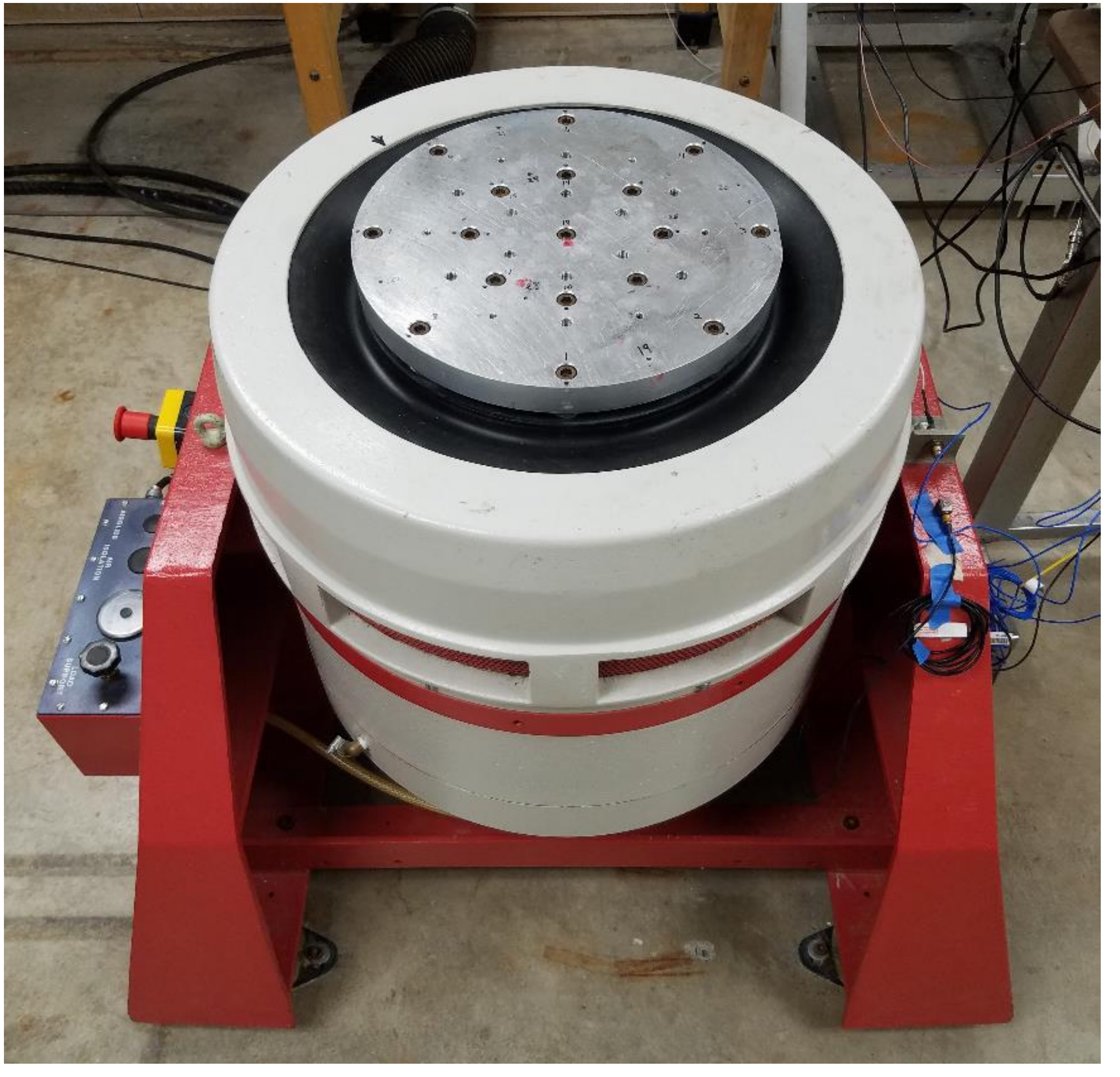
- The Transmission Simulator with an attached Steel Block
  - Steel Block: 4” x 2” x 2” & 4.5 lbs



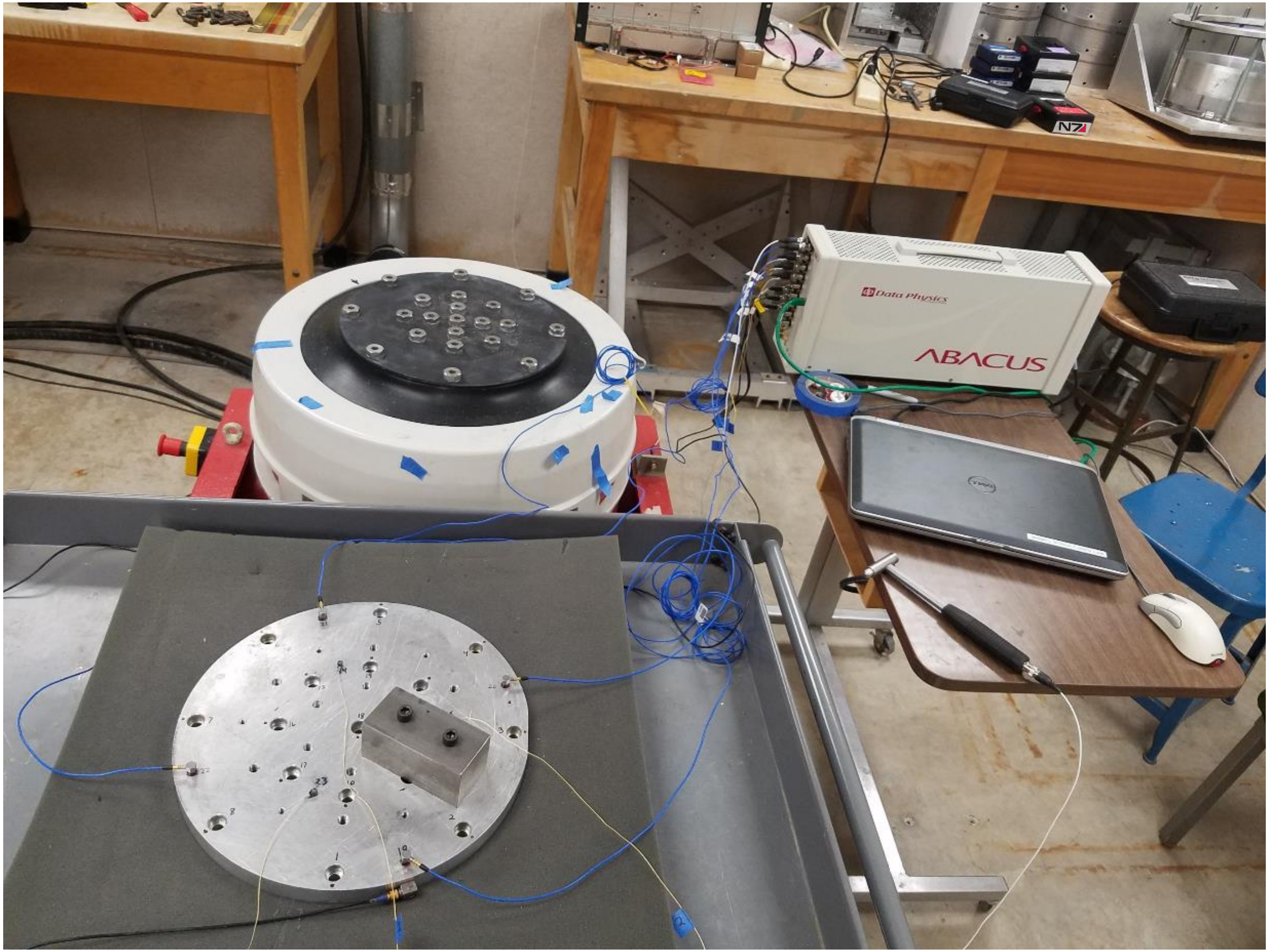


Experimental Subsystem

- LDS V830 Electromagnetic Shaker
- Operable Range: 0-3000 Hz

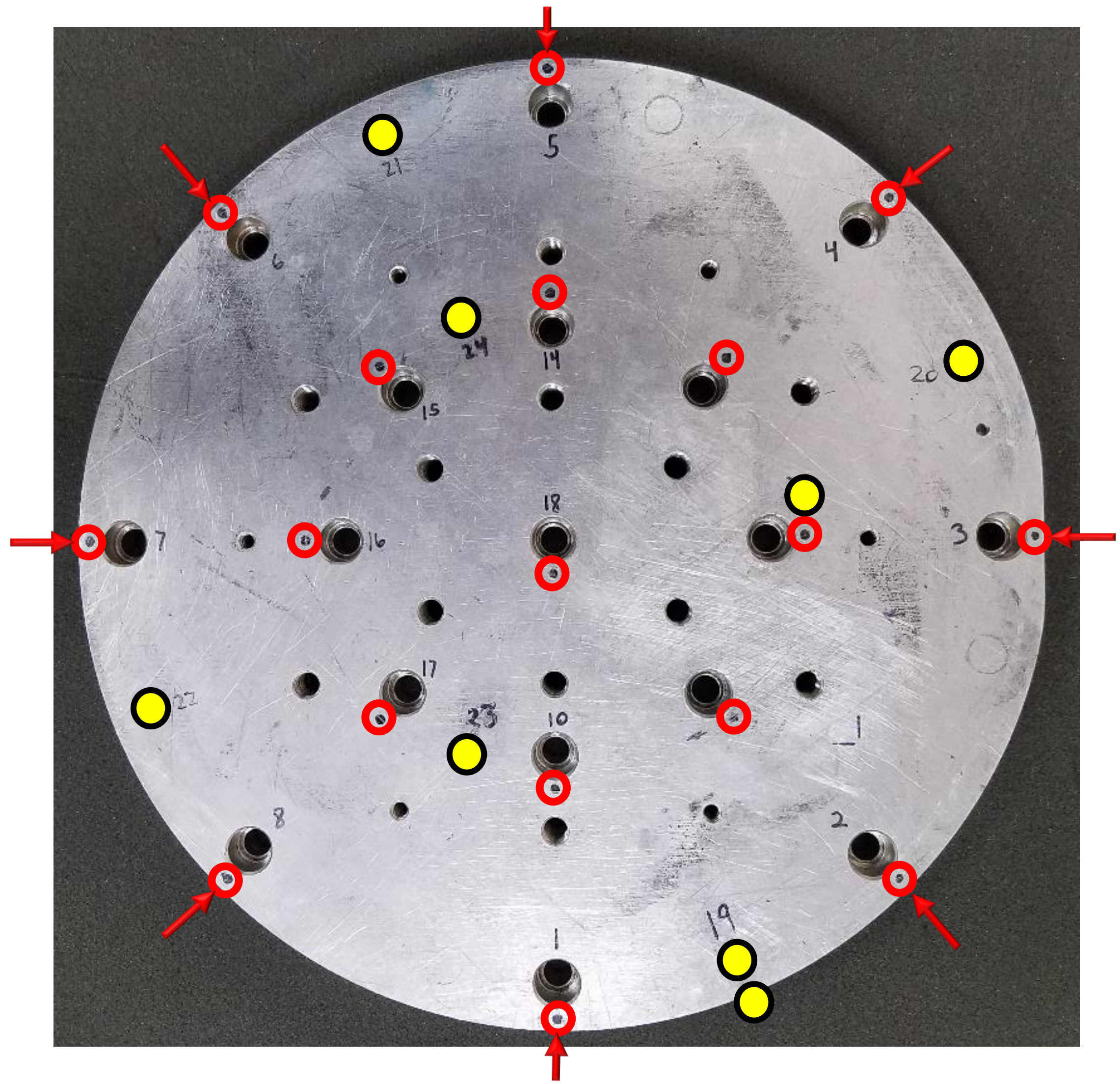


Experimental Setup

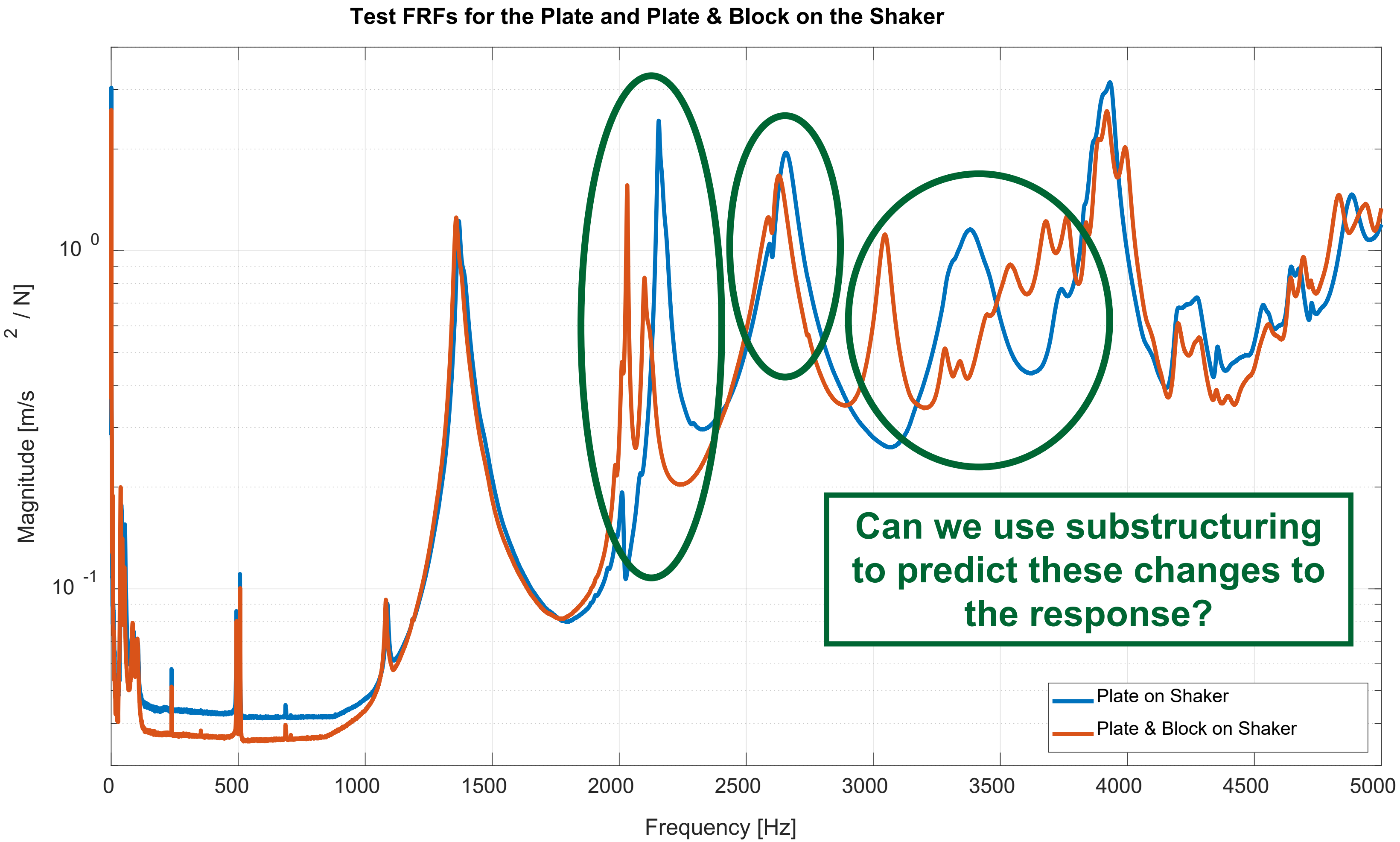


Modal Testing – Roving Hammer Test

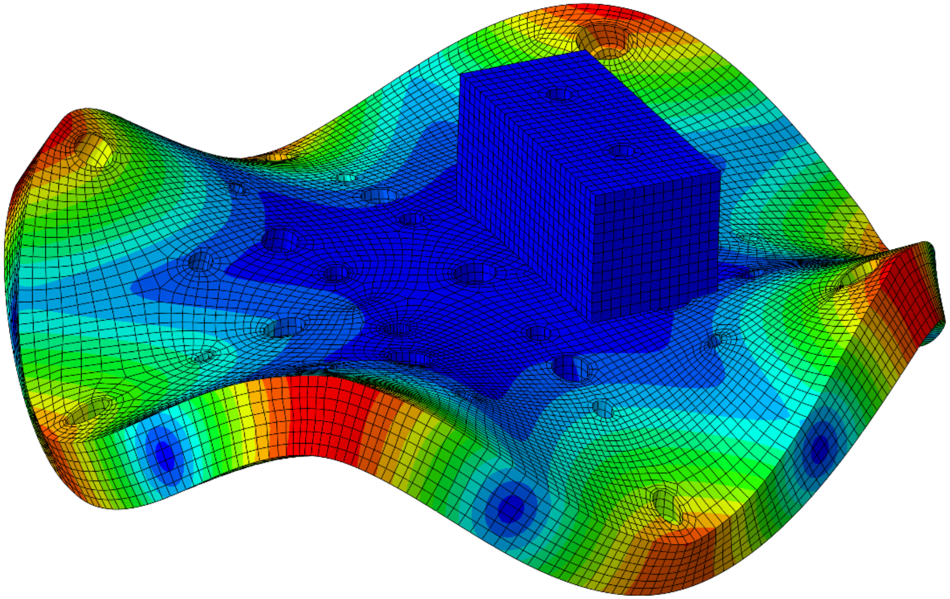
- 25 Hammer Locations
- 9 Accelerometer DOF
- Plate and Plate & Block tested on foam and on the Shaker

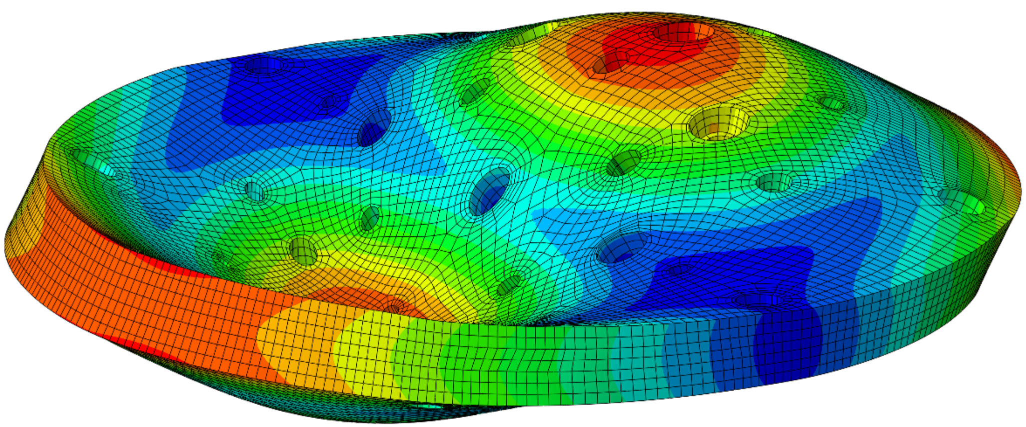


While the Shaker dynamics largely dominate, the Plate and Block give rise to differences at high freq



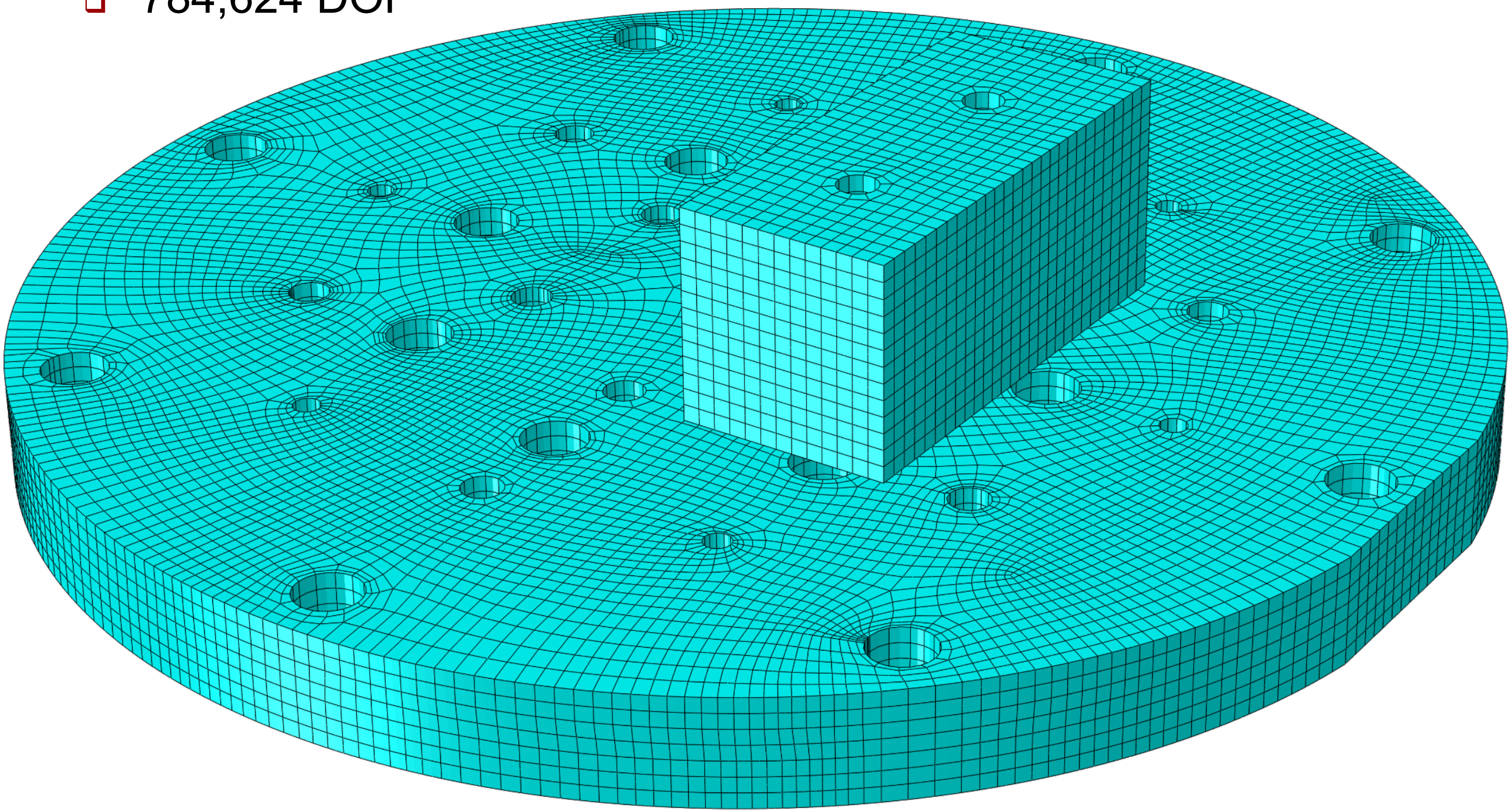
Finite Element Analysis



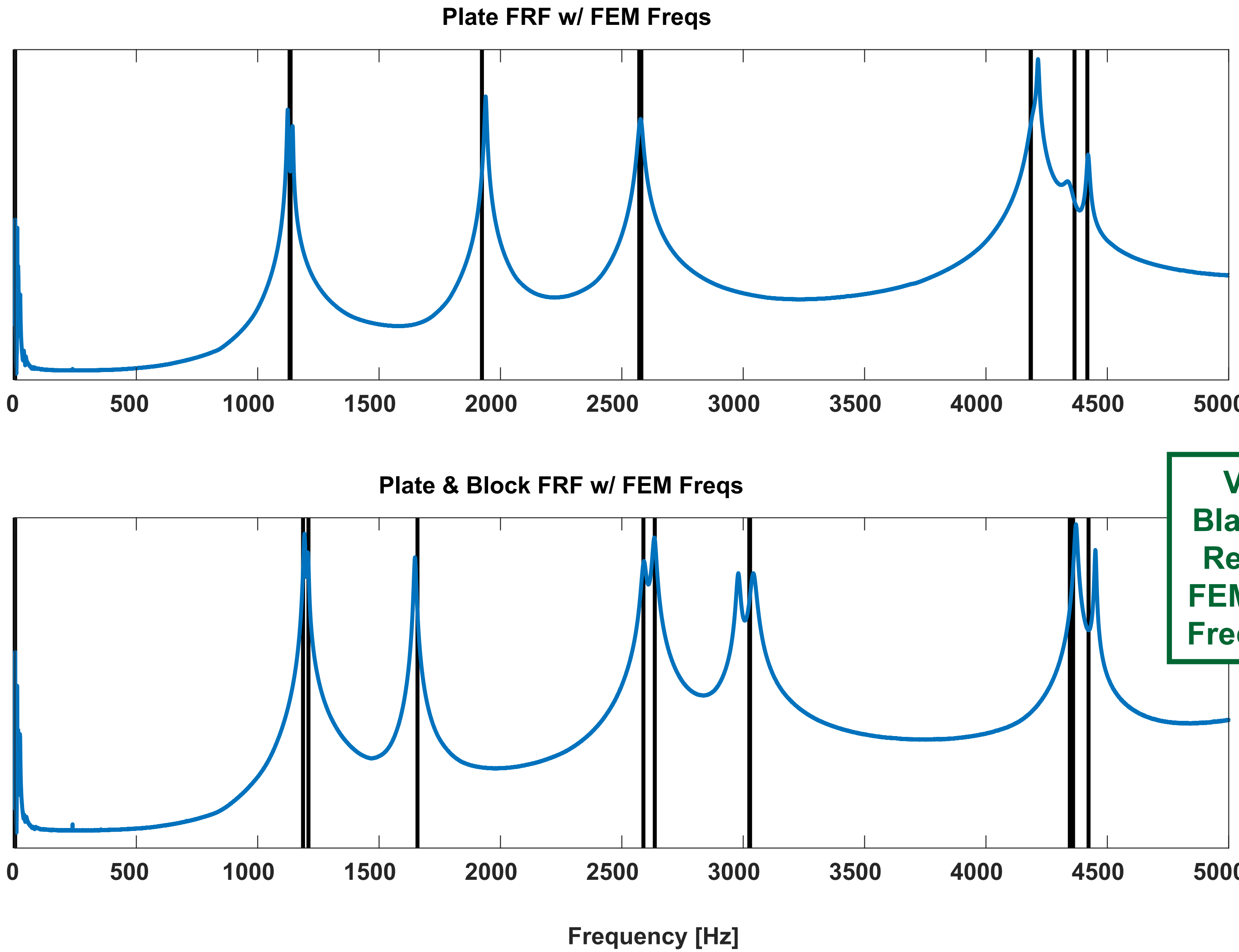


Finite Element Model

- Abaqus 20 Node Solid Elements
  - 239,034 Nodes
  - 784,624 DOF



Good Agreement Between FEM and Test

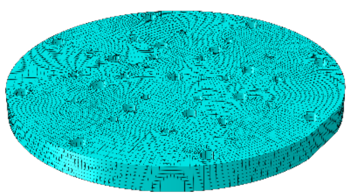


Vertical Black Lines Represent FEM Natural Frequencies

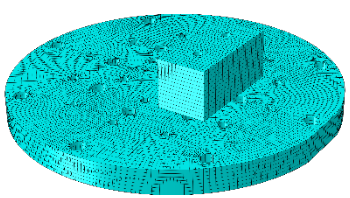
Substructuring Results

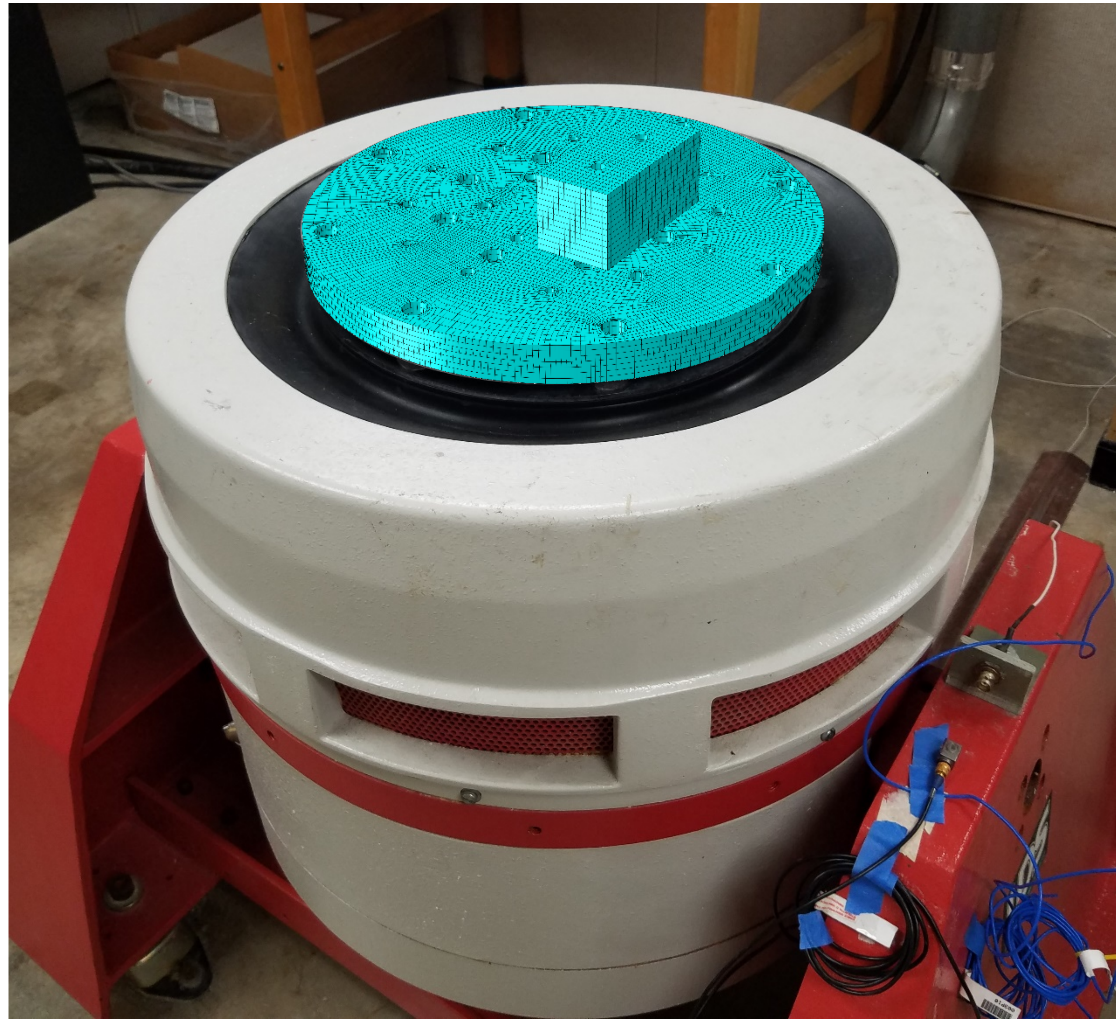
EXP: 18 Modes

TS: 23 Modes

\- 

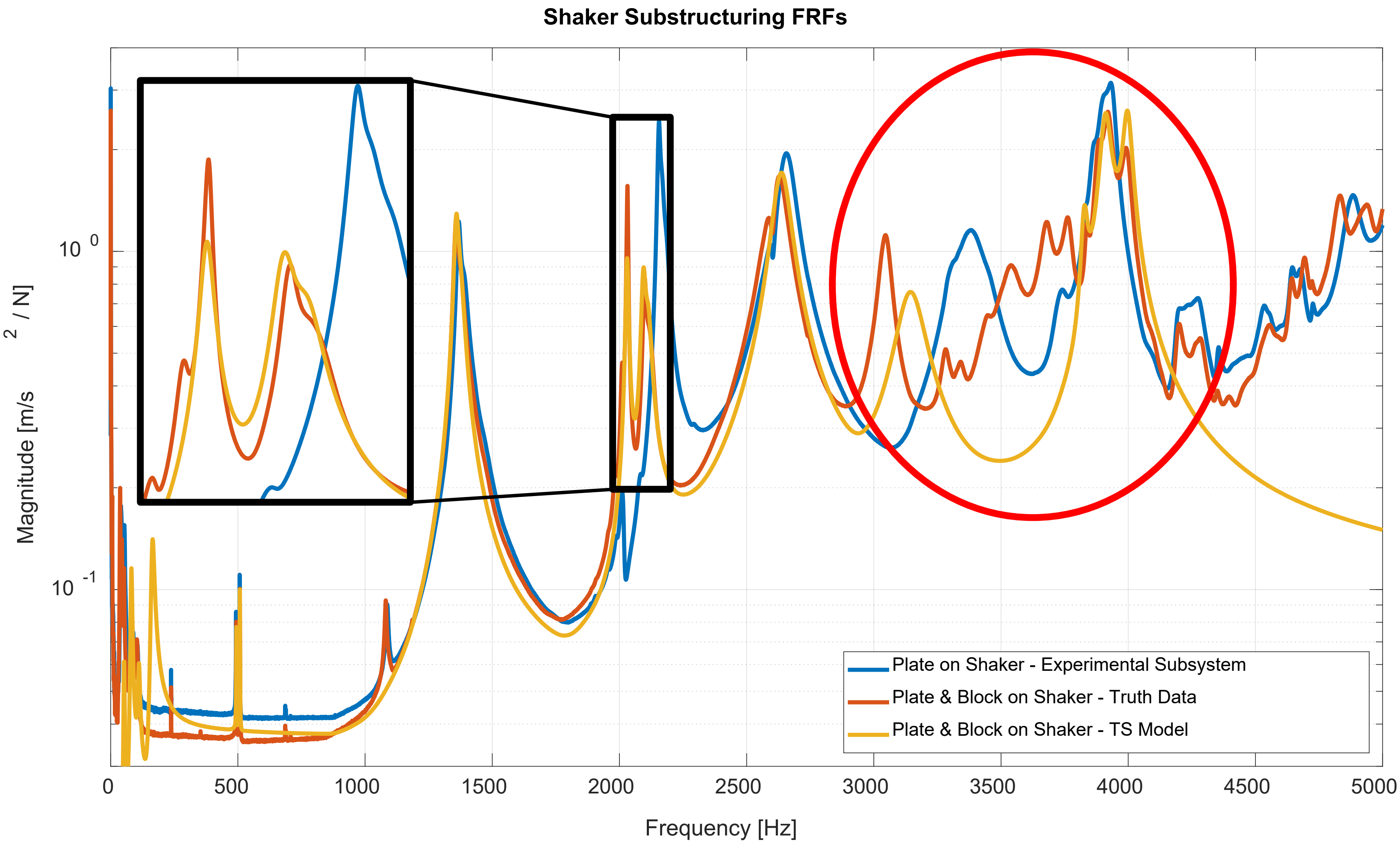
AN: 43 Modes

\+  =

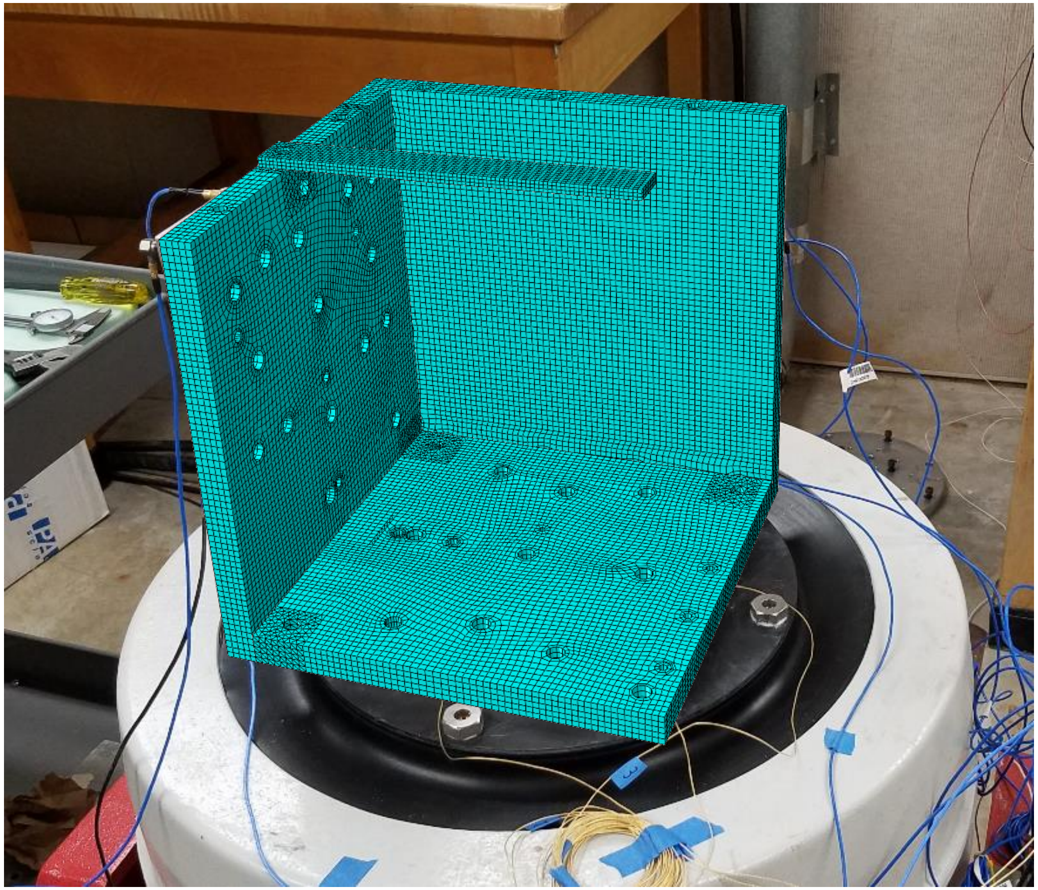


Reconstructed FRF from Substructuring Results

- Predicted freqs accurate to <1%, except for peak at 3000Hz

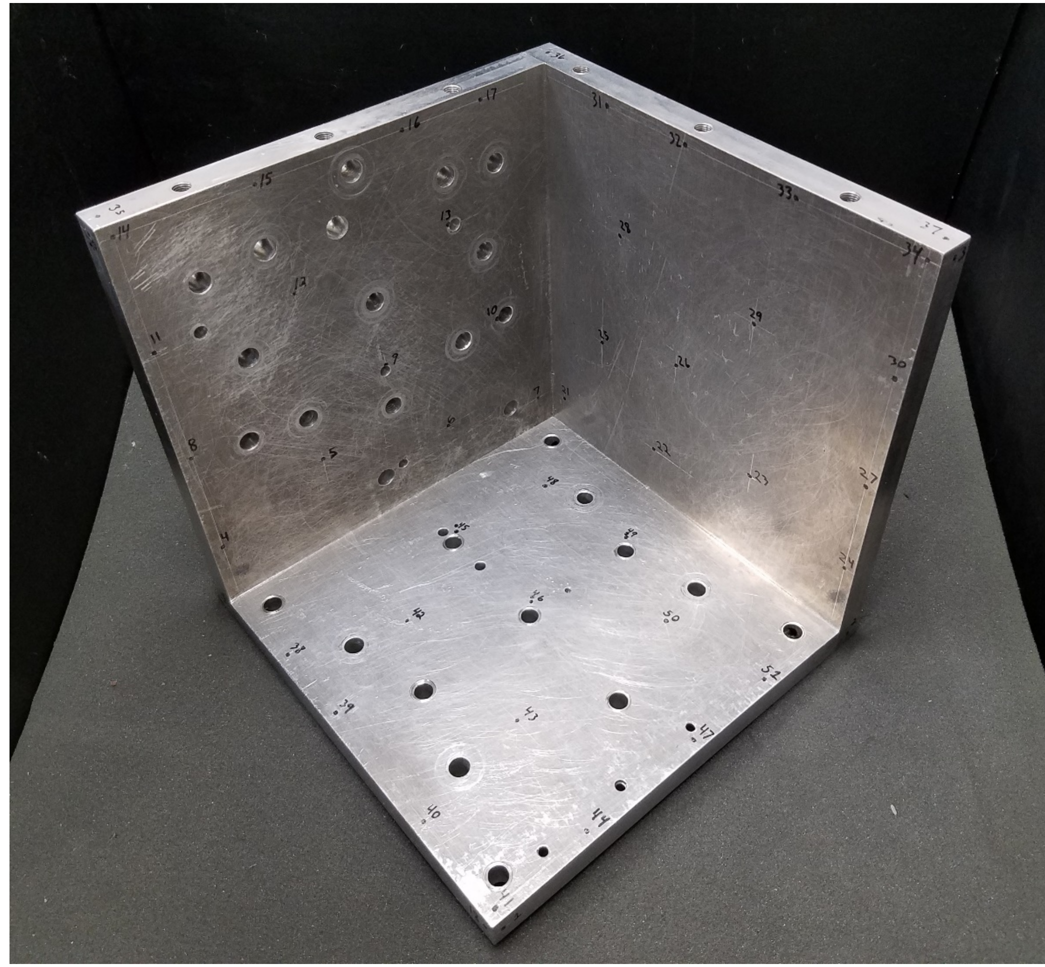


Test Case 2: Aluminum Half Cube with Cantilever Beam

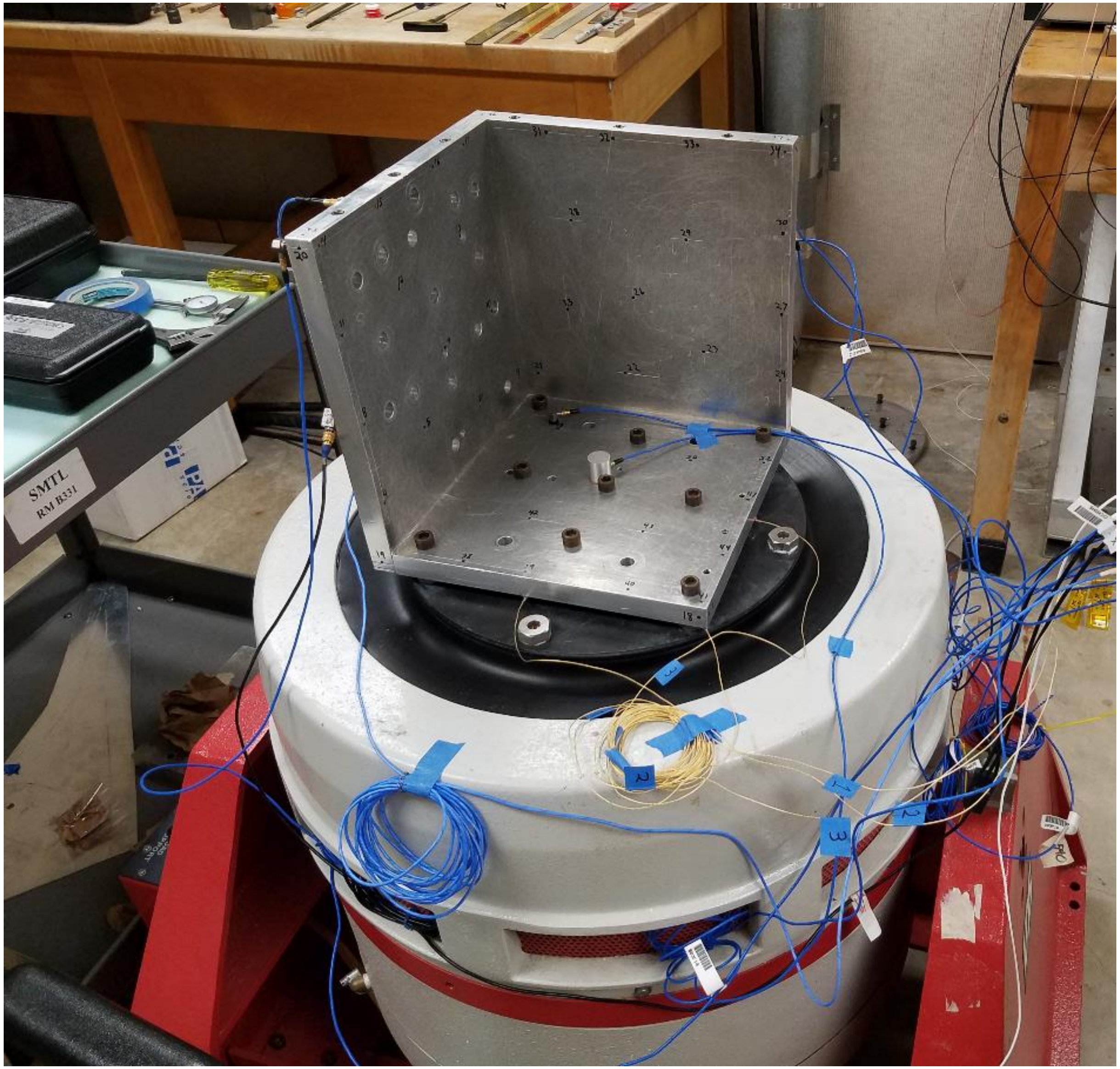


Transmission Simulator

- Half Cube
  - 10” interior cube
  - ¾” thick aluminum
  - 22.7 lbs

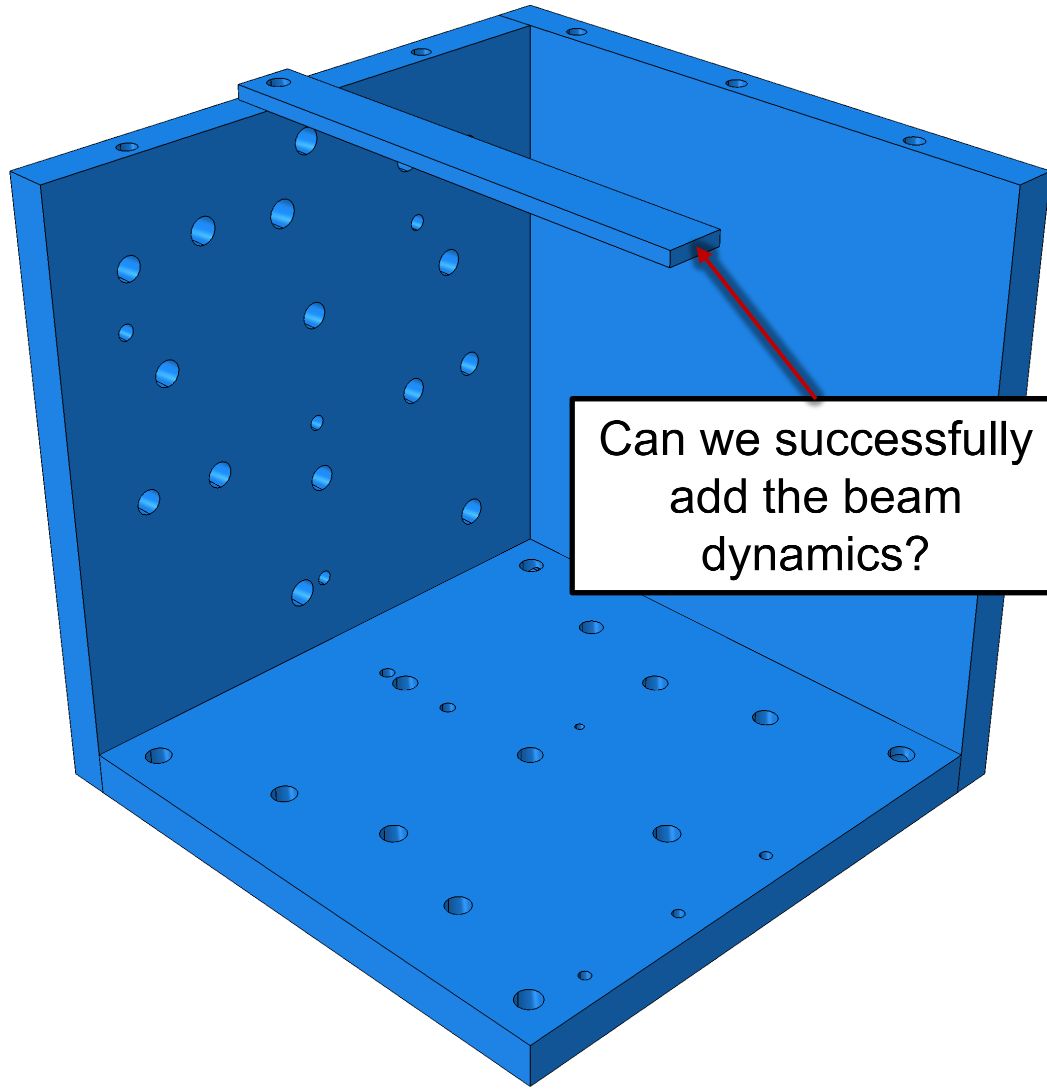


Experimental Subsystem



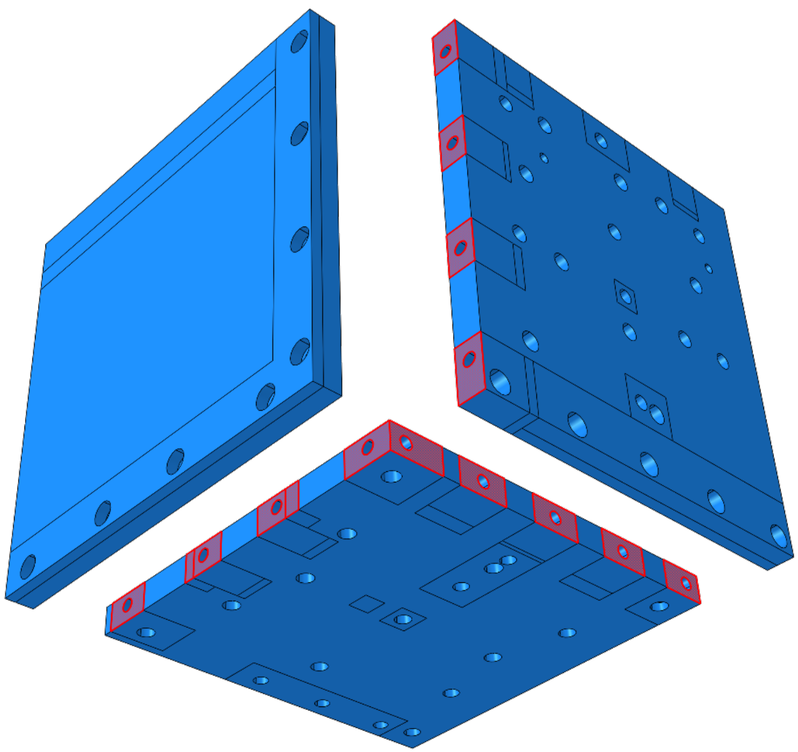
Analytical Subsystem

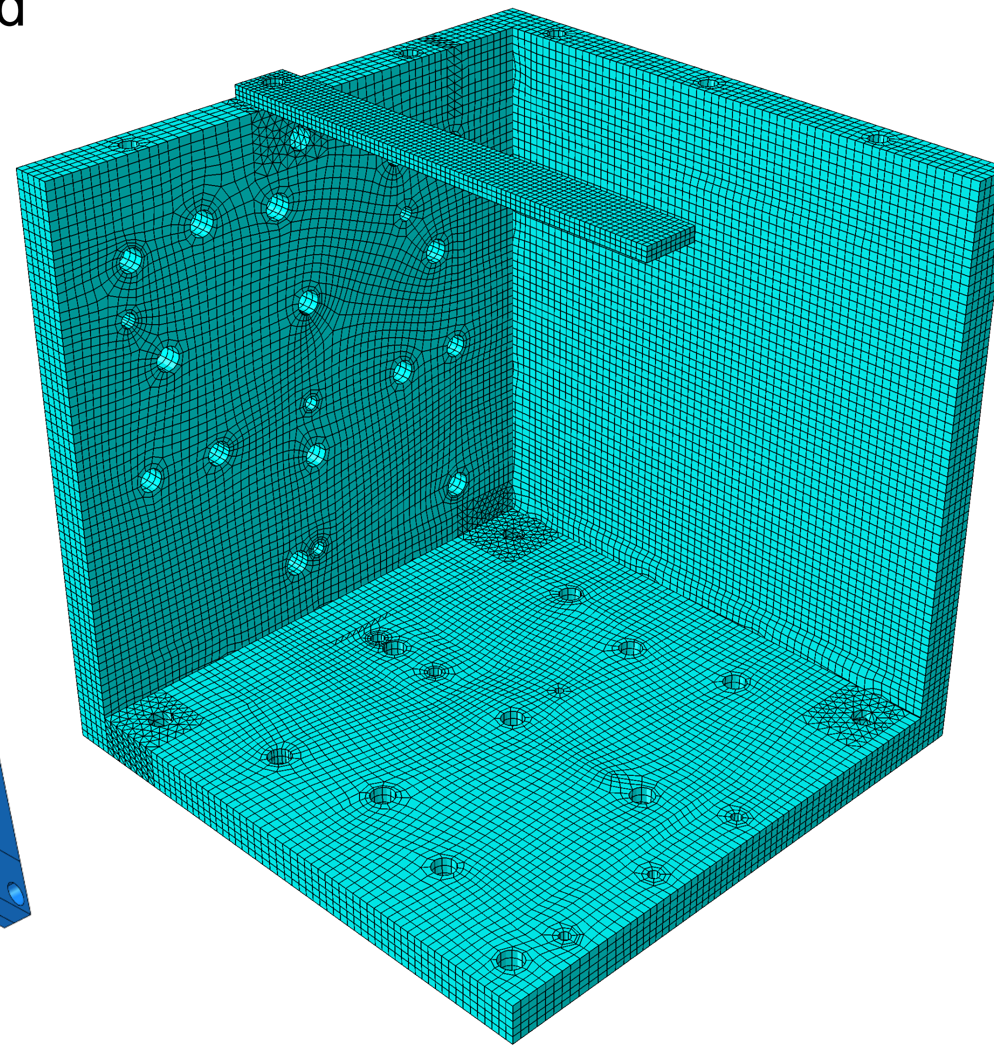
- Half Cube with a Cantilevered Beam
- Aluminum Beam
  - 8” x 1” x ¼”
  - .25 lbs



Finite Element Model

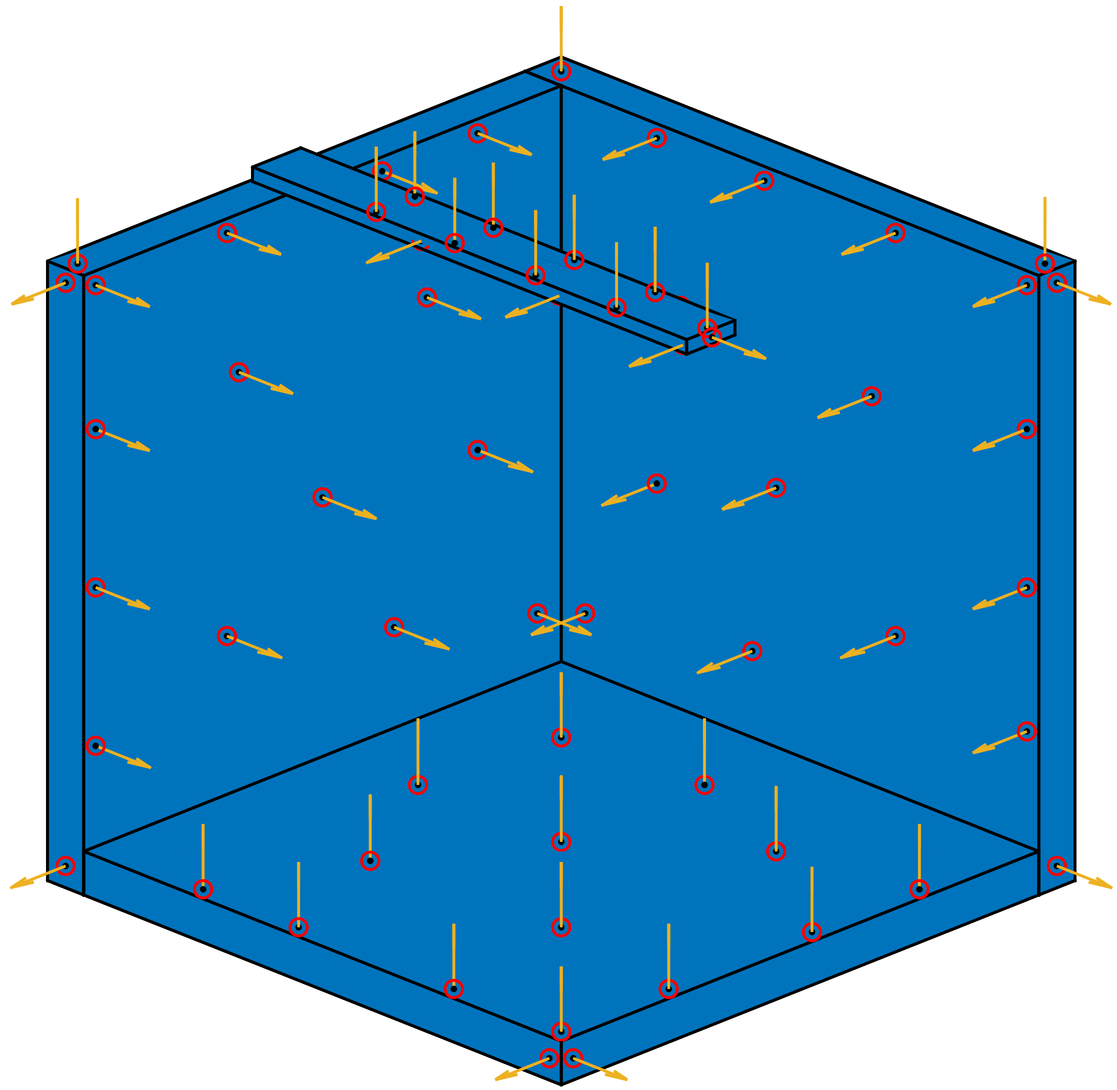
- Abaqus 20 Node Hex and 10 Node Tet Elements
  - 80,000 Elements
  - 340,000 Nodes



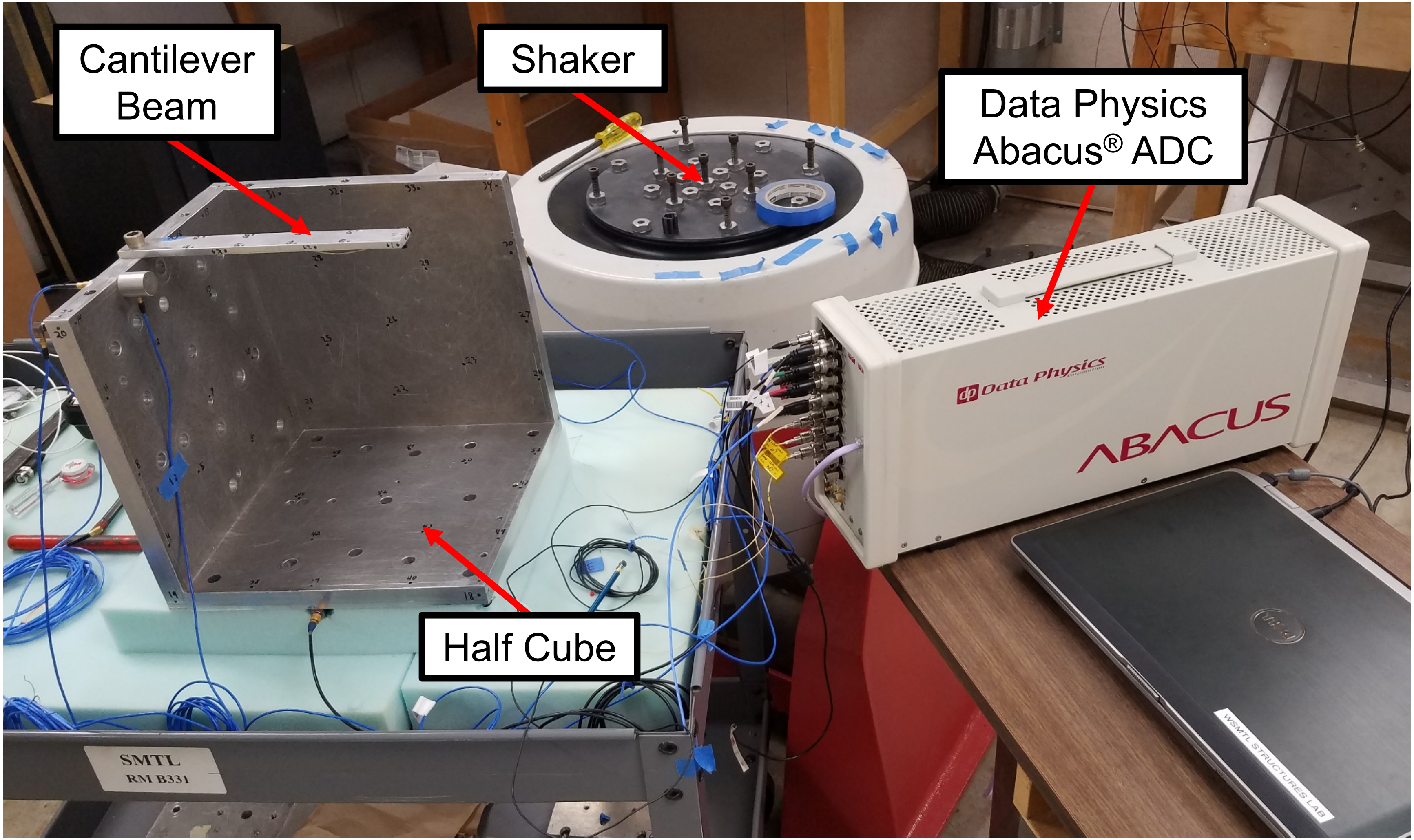


Used Effective Independence to Determine an Effective Set of Test Points

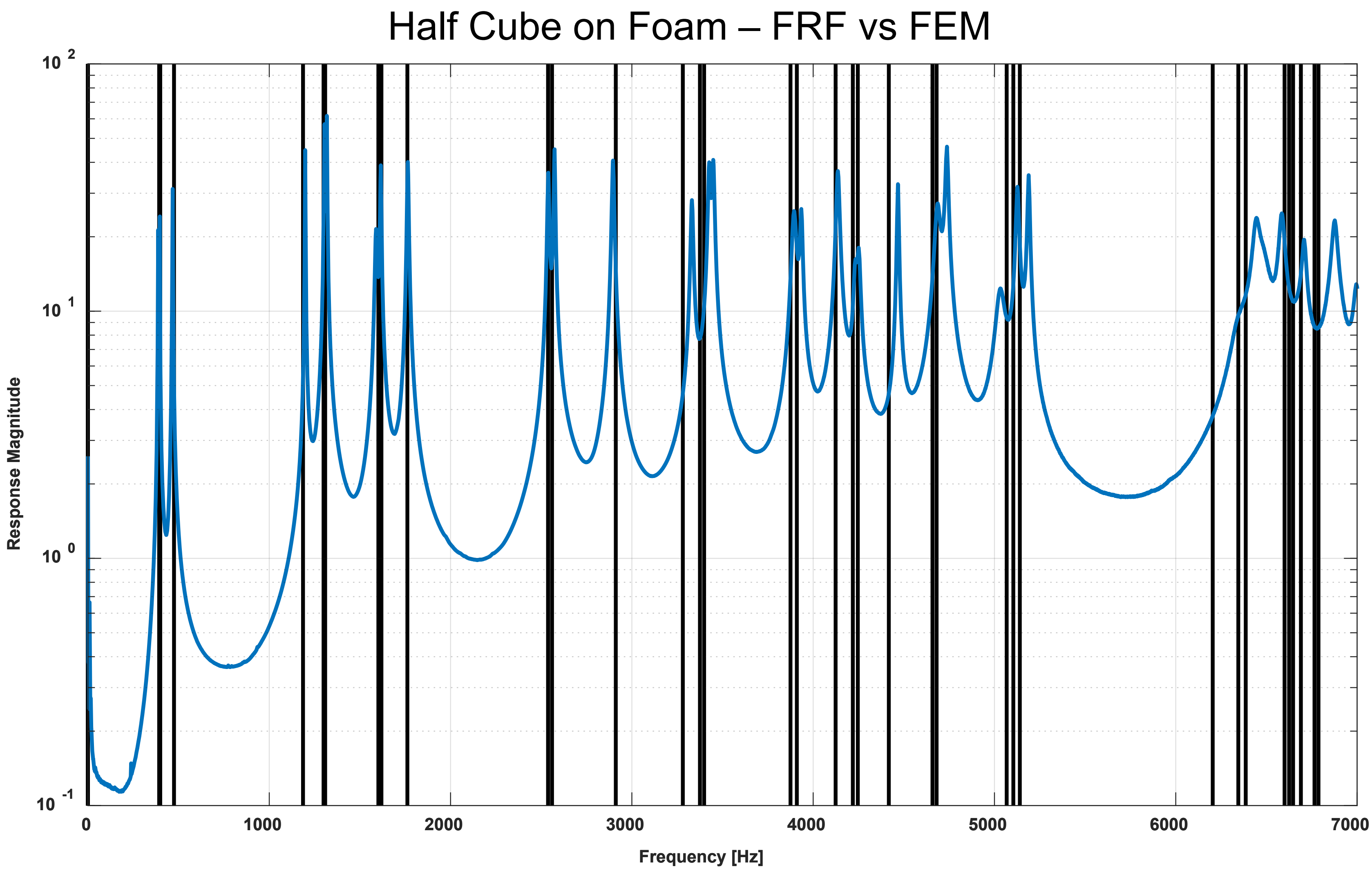
- Half Cube & Beam Test Point Layout
  - 64 Points
  - 17+1 X
  - 17+3 Y
  - 17+9 Z



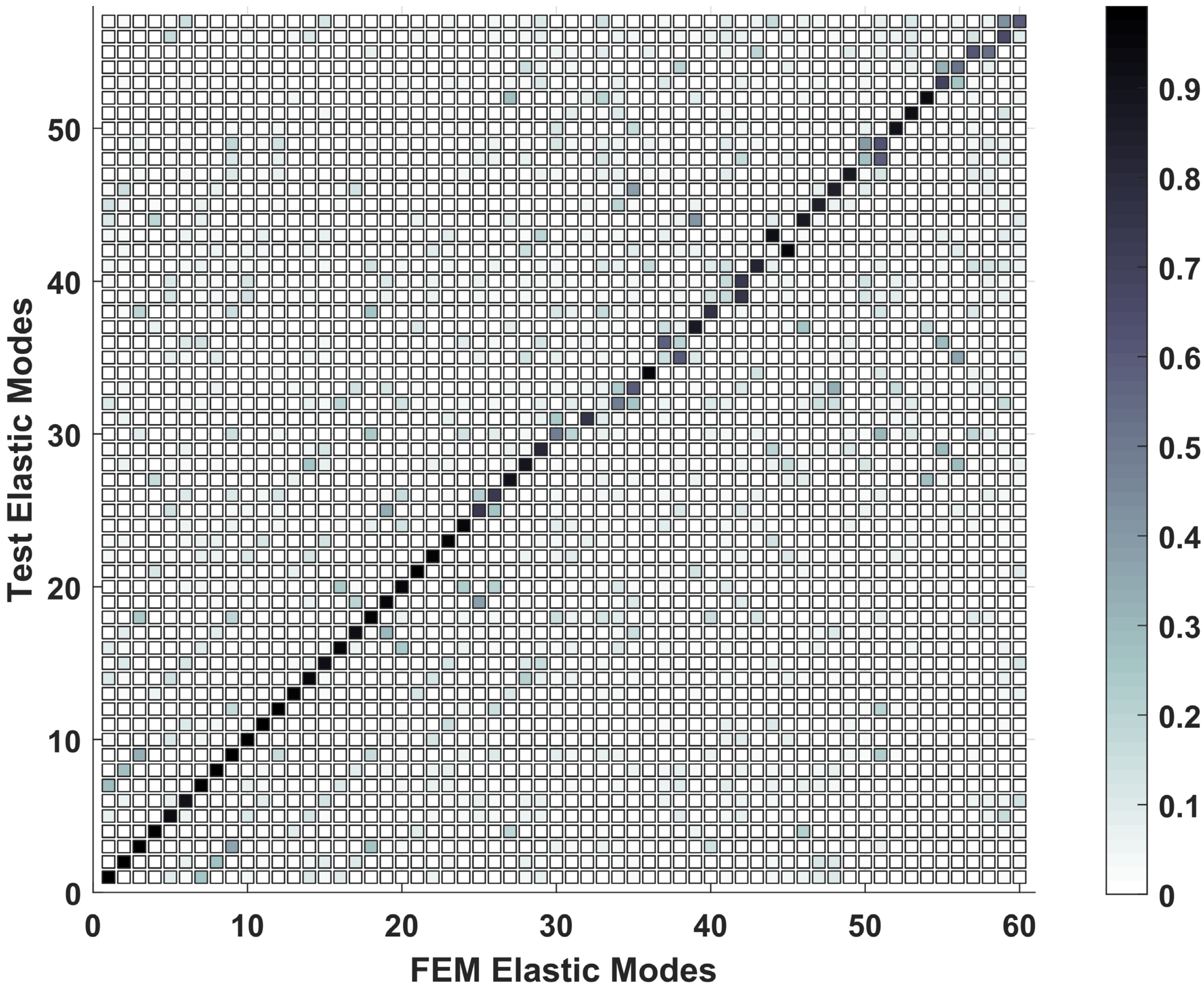
Similar Test Setup



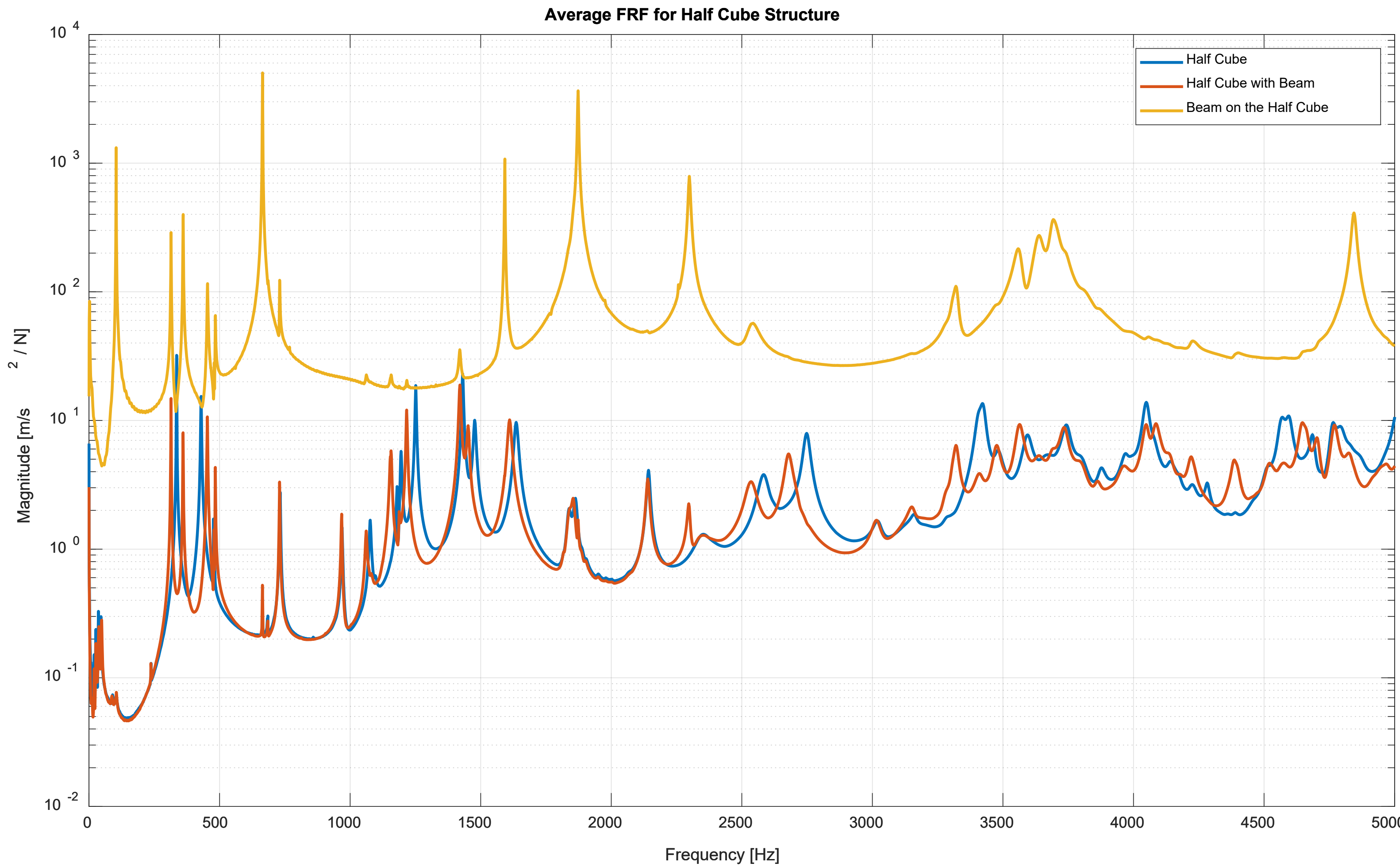
FEM in Good Agreement with Test Data



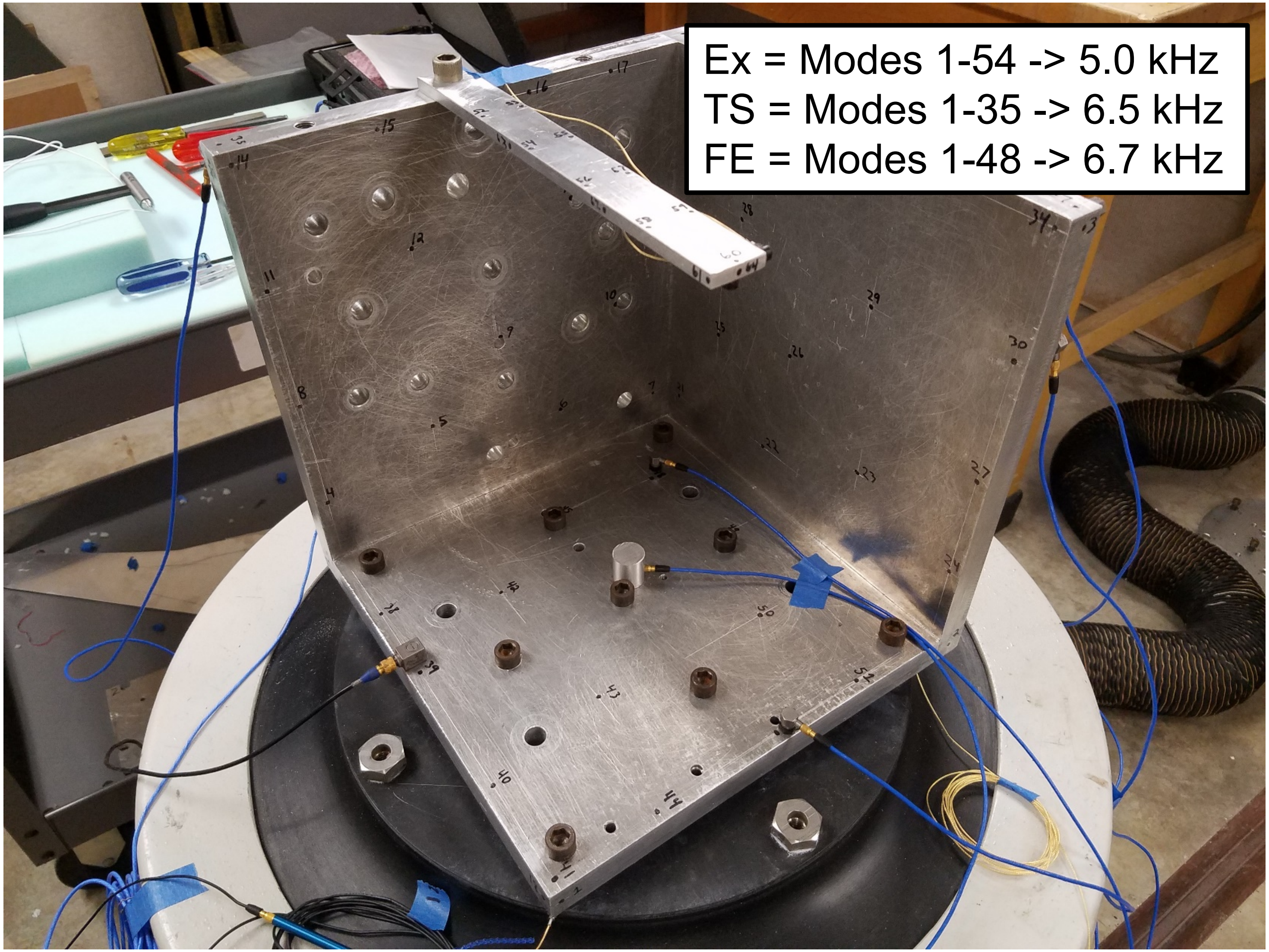
Cross-MAC for Half Cube



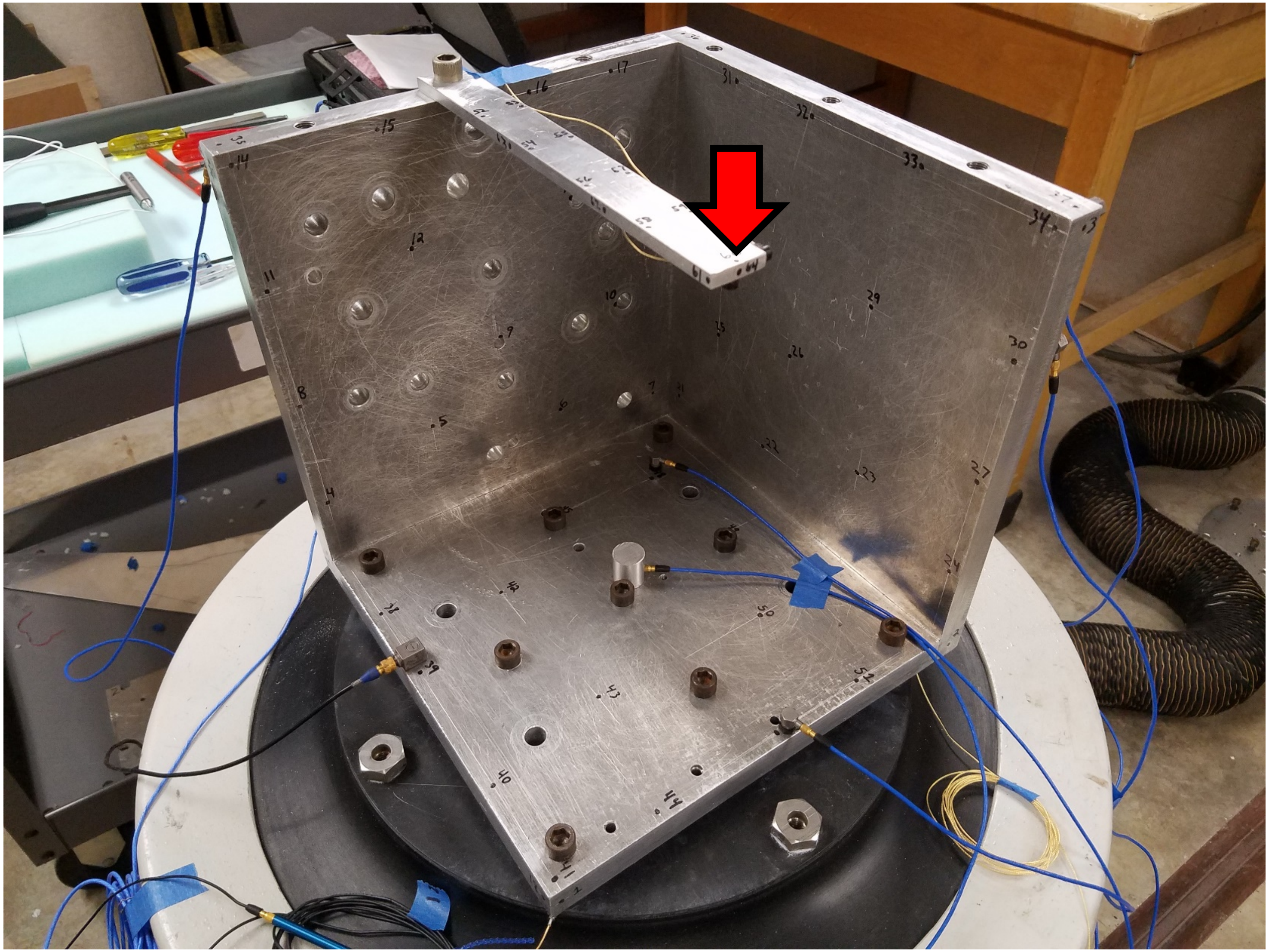
Half Cube on Shaker - Average FRF



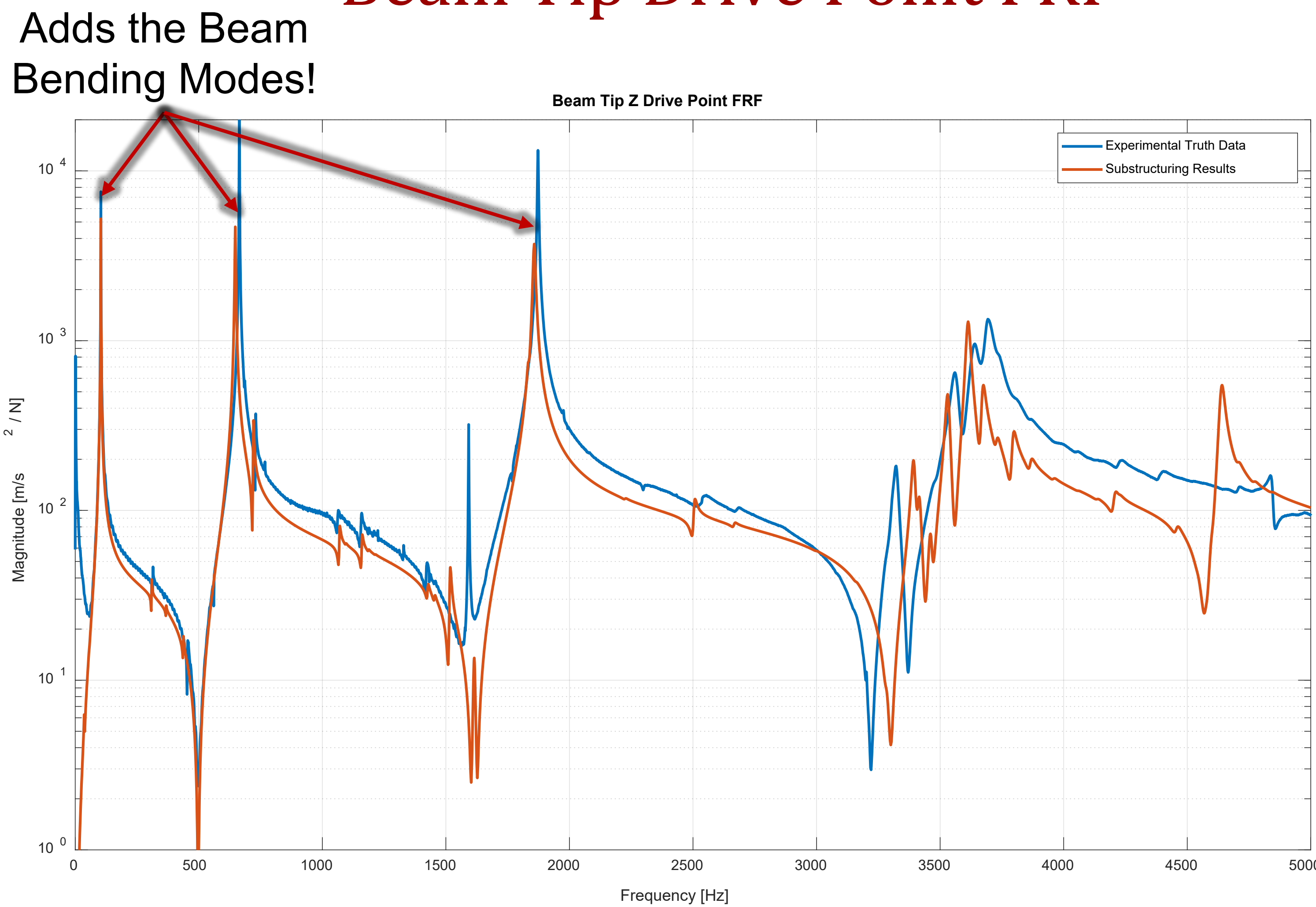
Substructuring Results



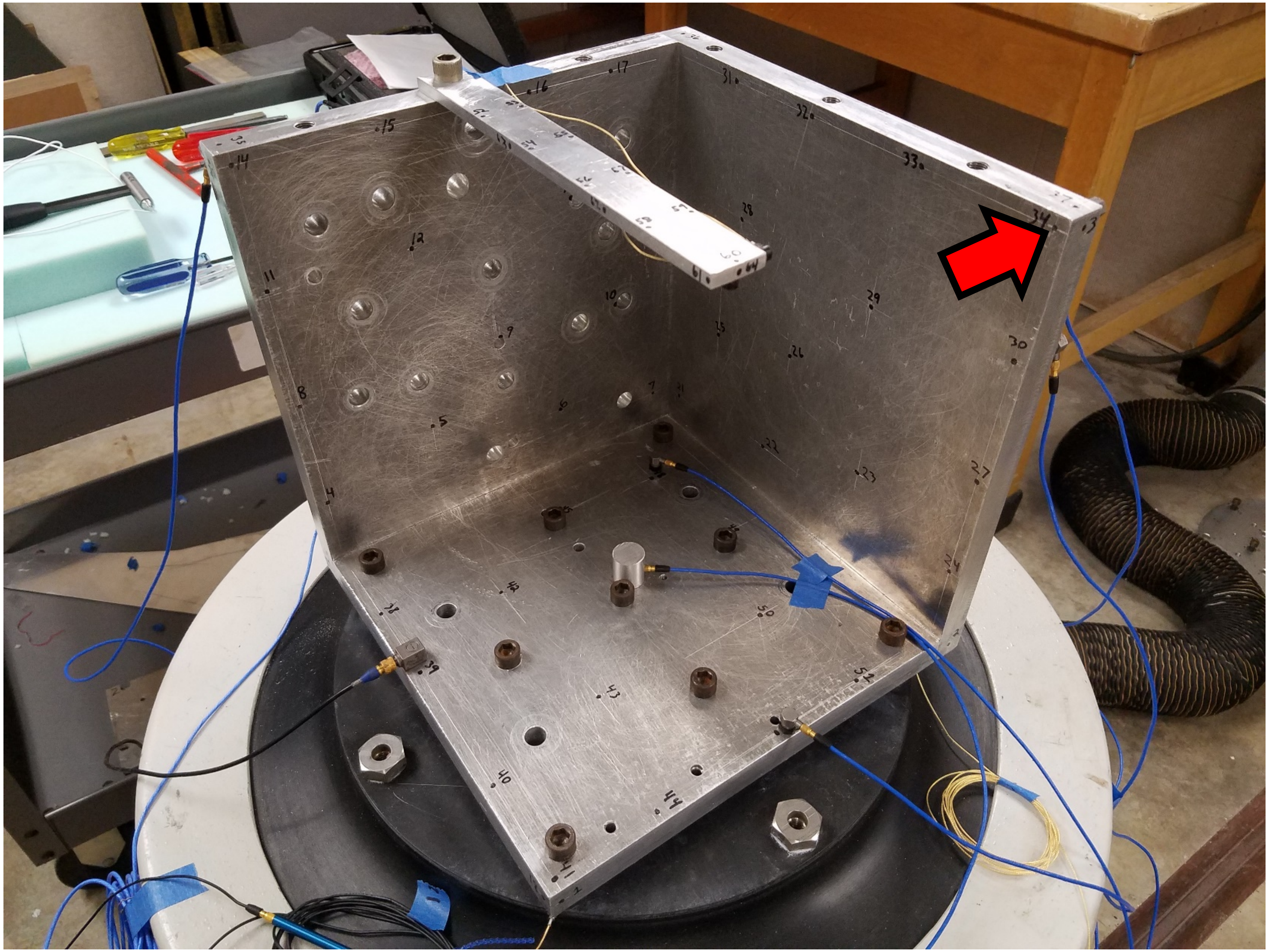
Beam Tip Drive Point FRF



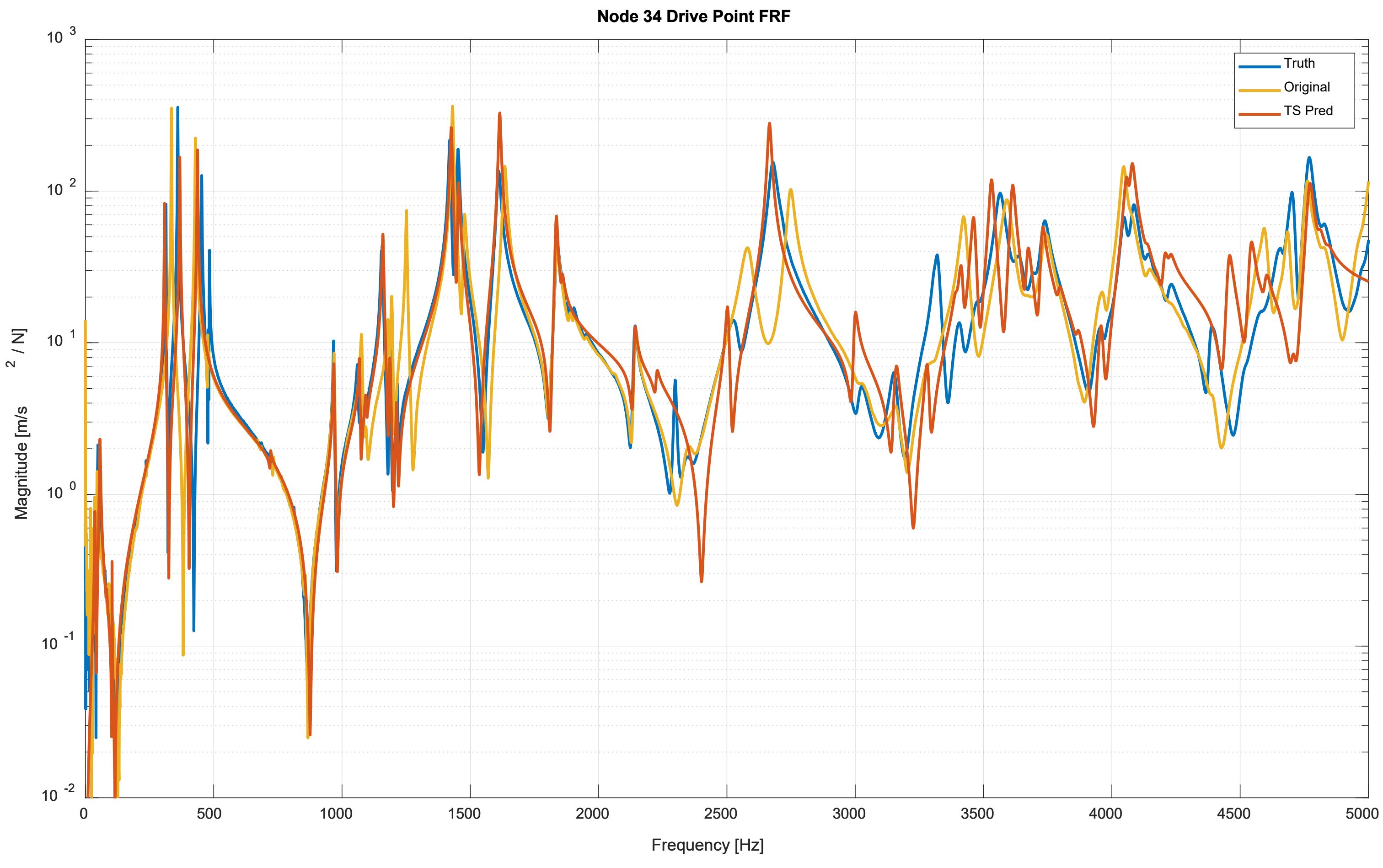
Beam Tip Drive Point FRF



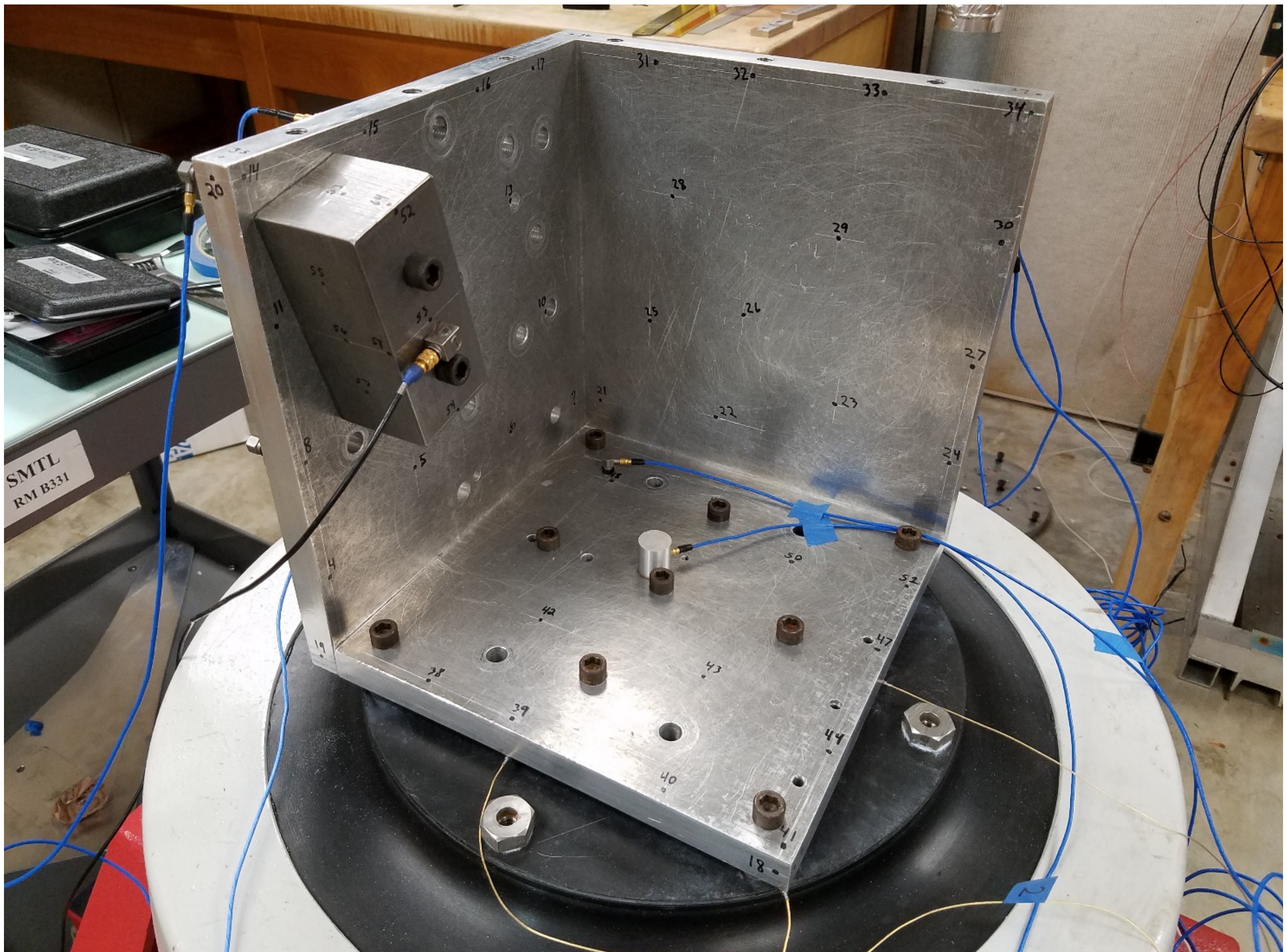
Top Right Corner Drive Point FRF



Top Right Corner Drive Point FRF

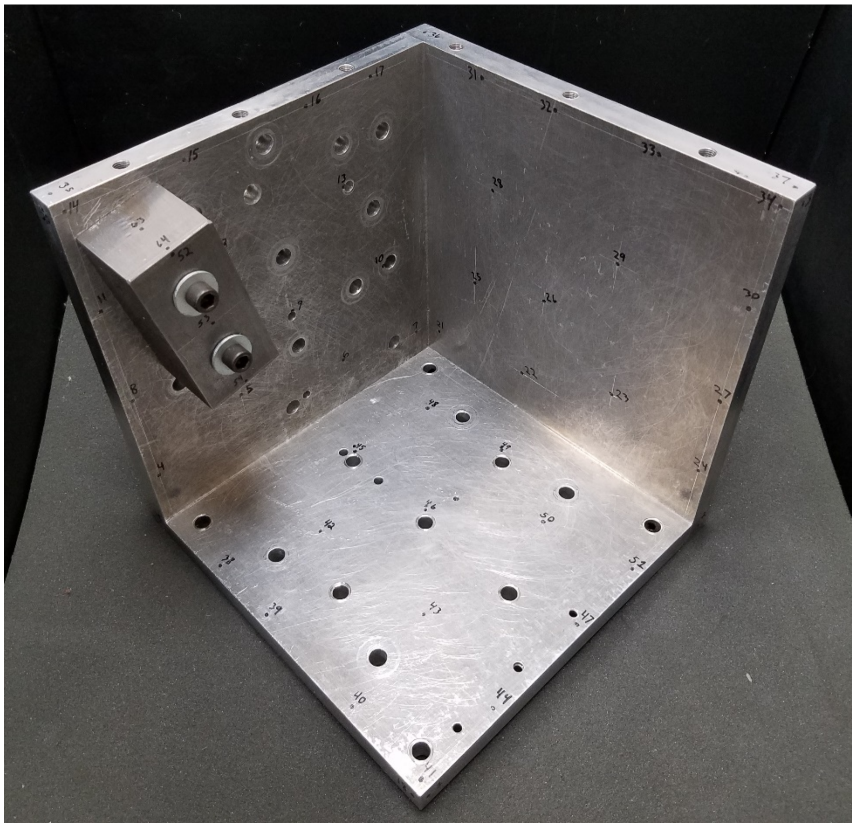


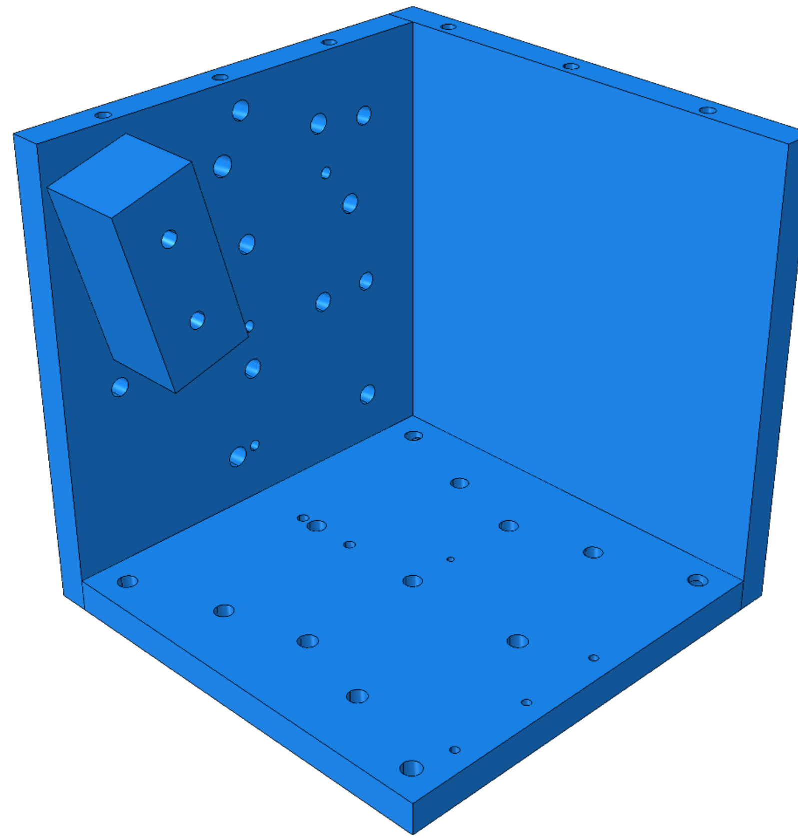
Test Case 3: Aluminum Half Cube with Steel Block



Subsystems

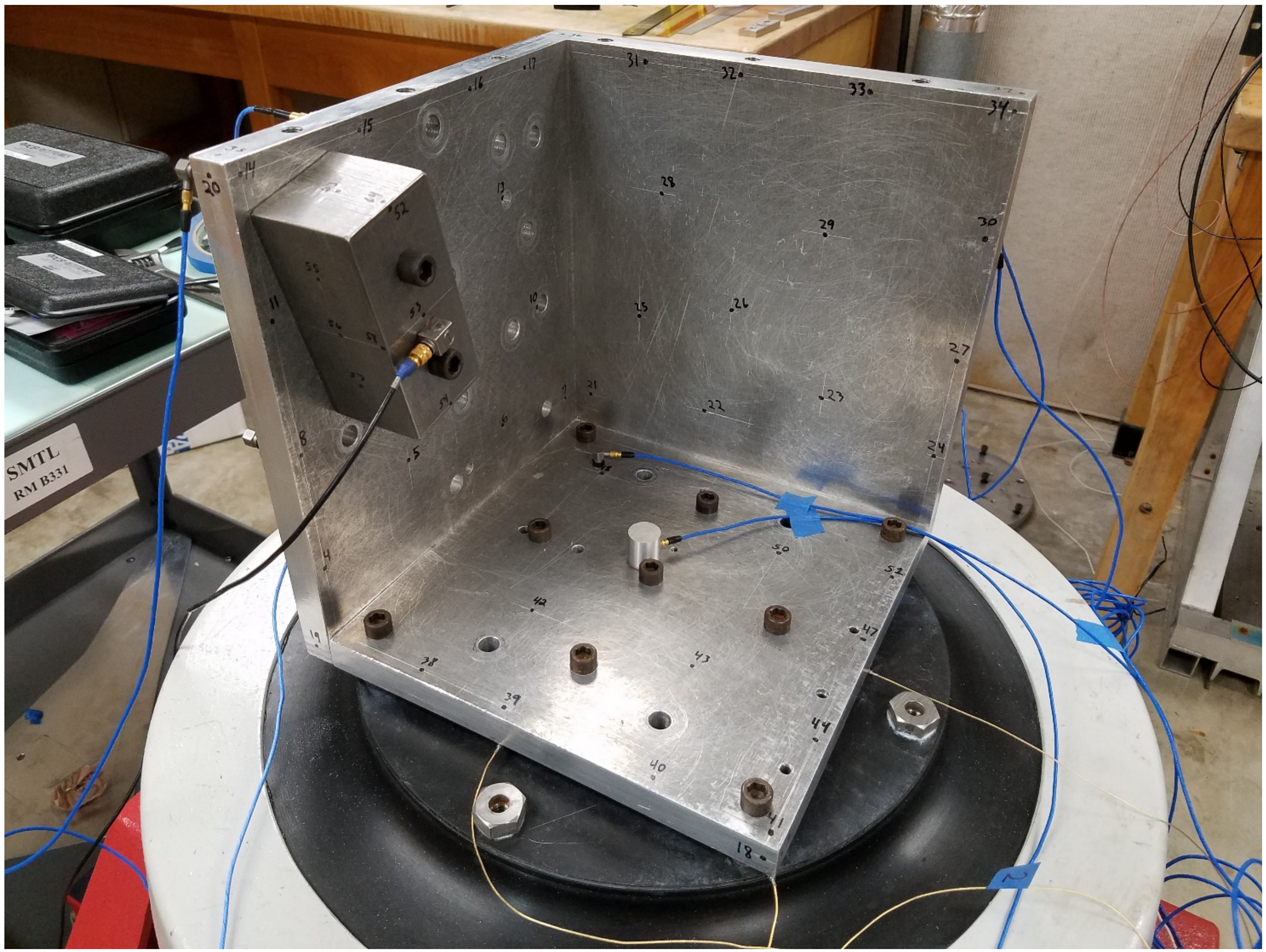
- Experimental Subsystem and Transmission Simulator are the same as Test Case 2
- Analytical Subsystem is now the Half Cube with the Steel Block



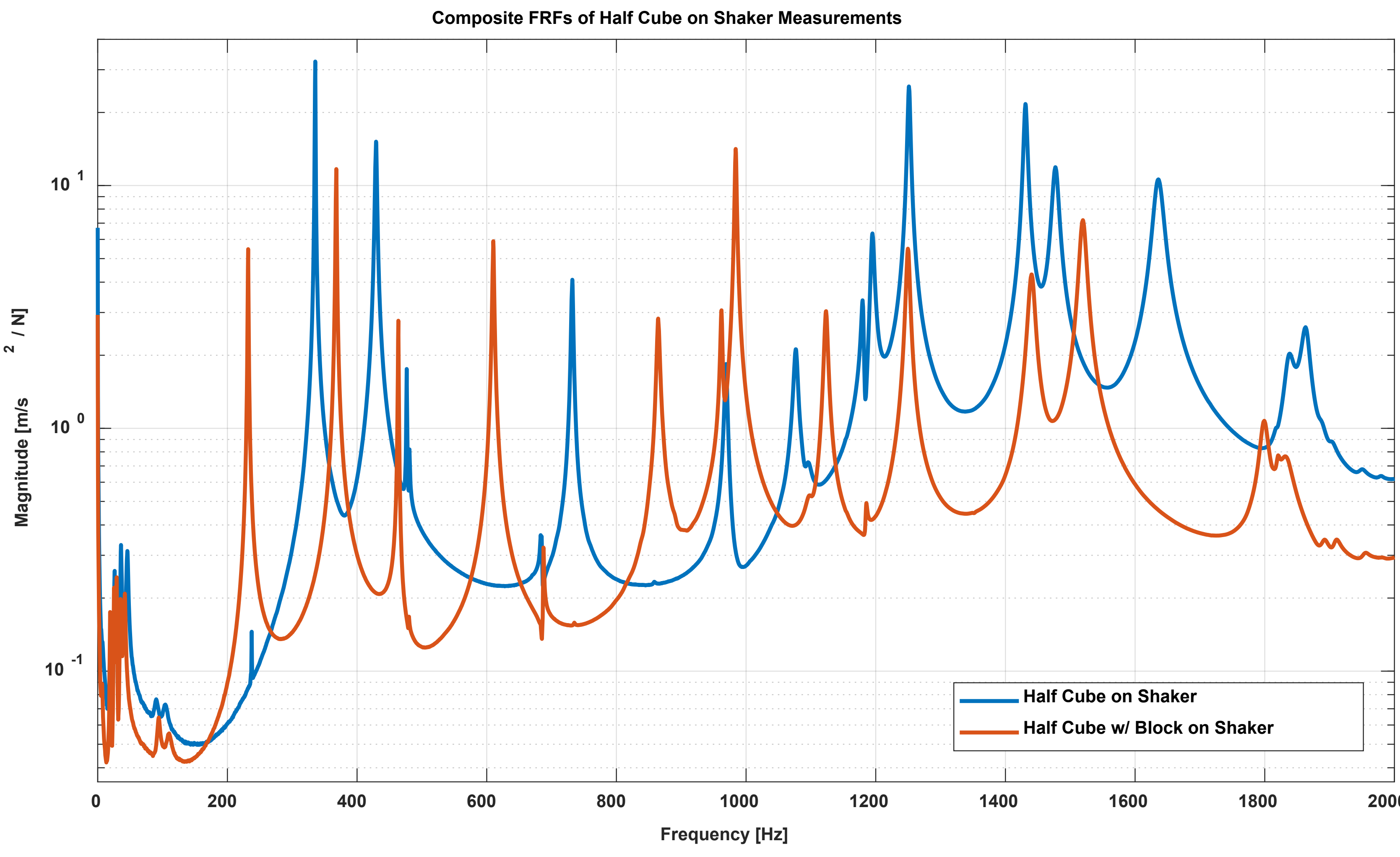


Experimental Setup

- Same test grid as previously
- Added tri-ax accelerometer to block

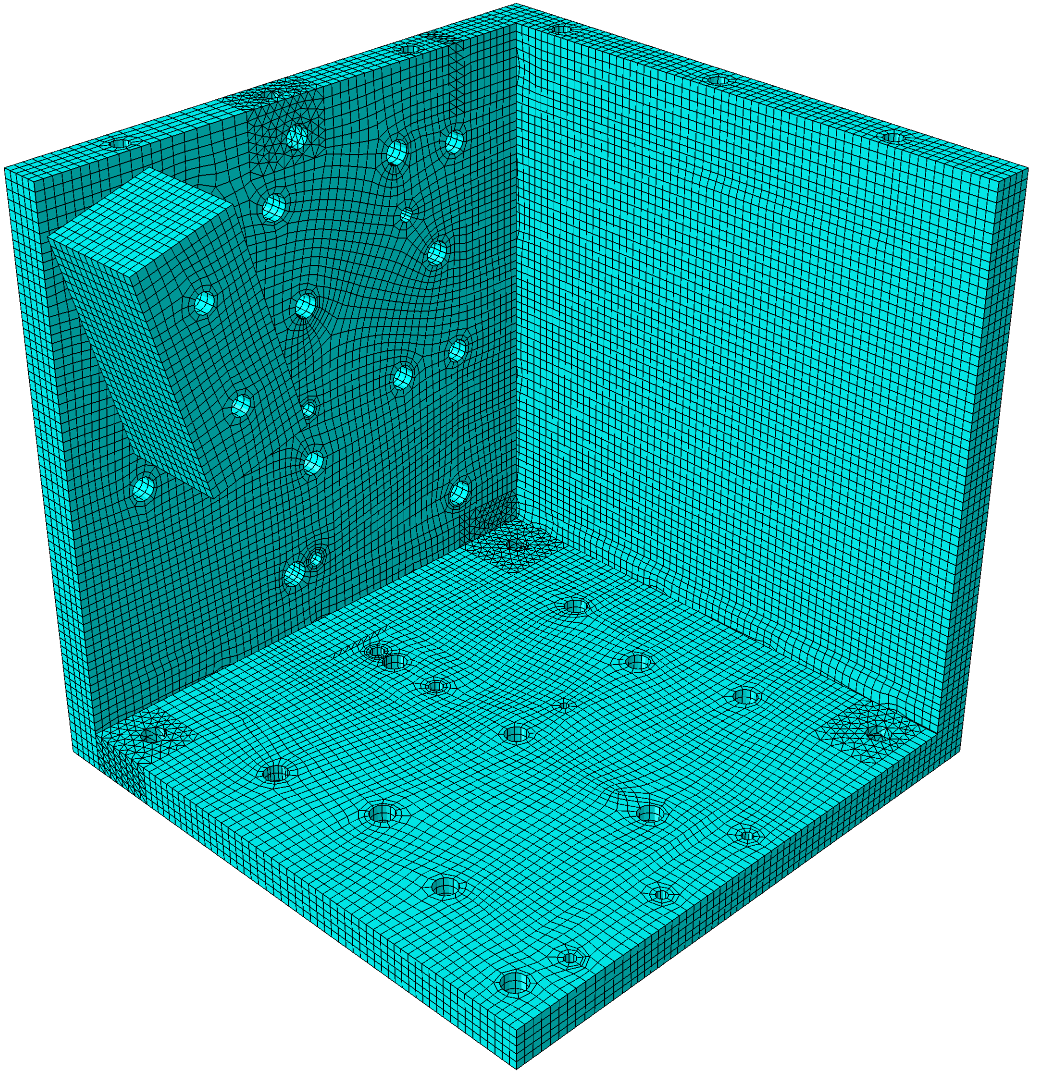


On Shaker Testing Shows Significant Changes

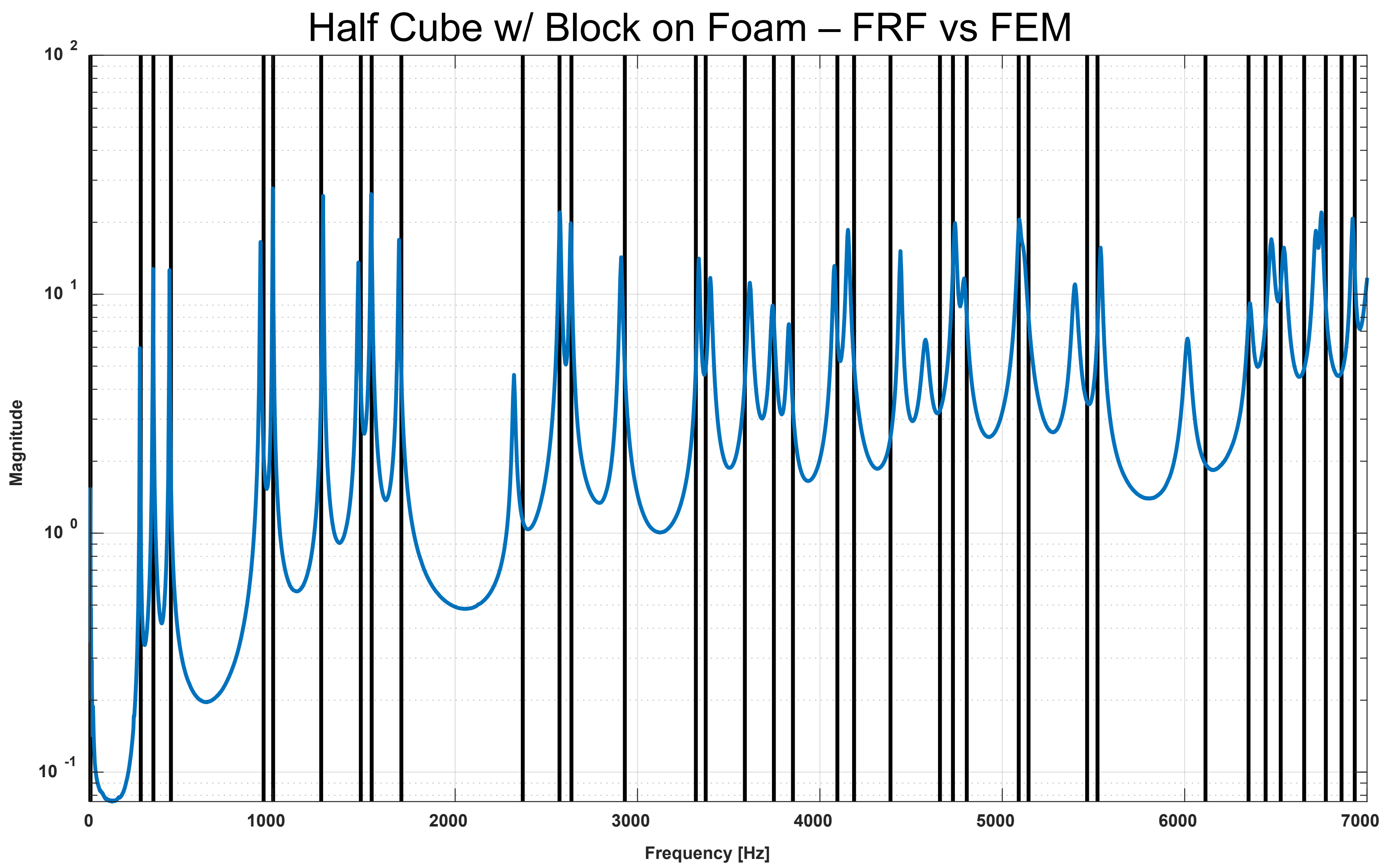


Finite Element Model

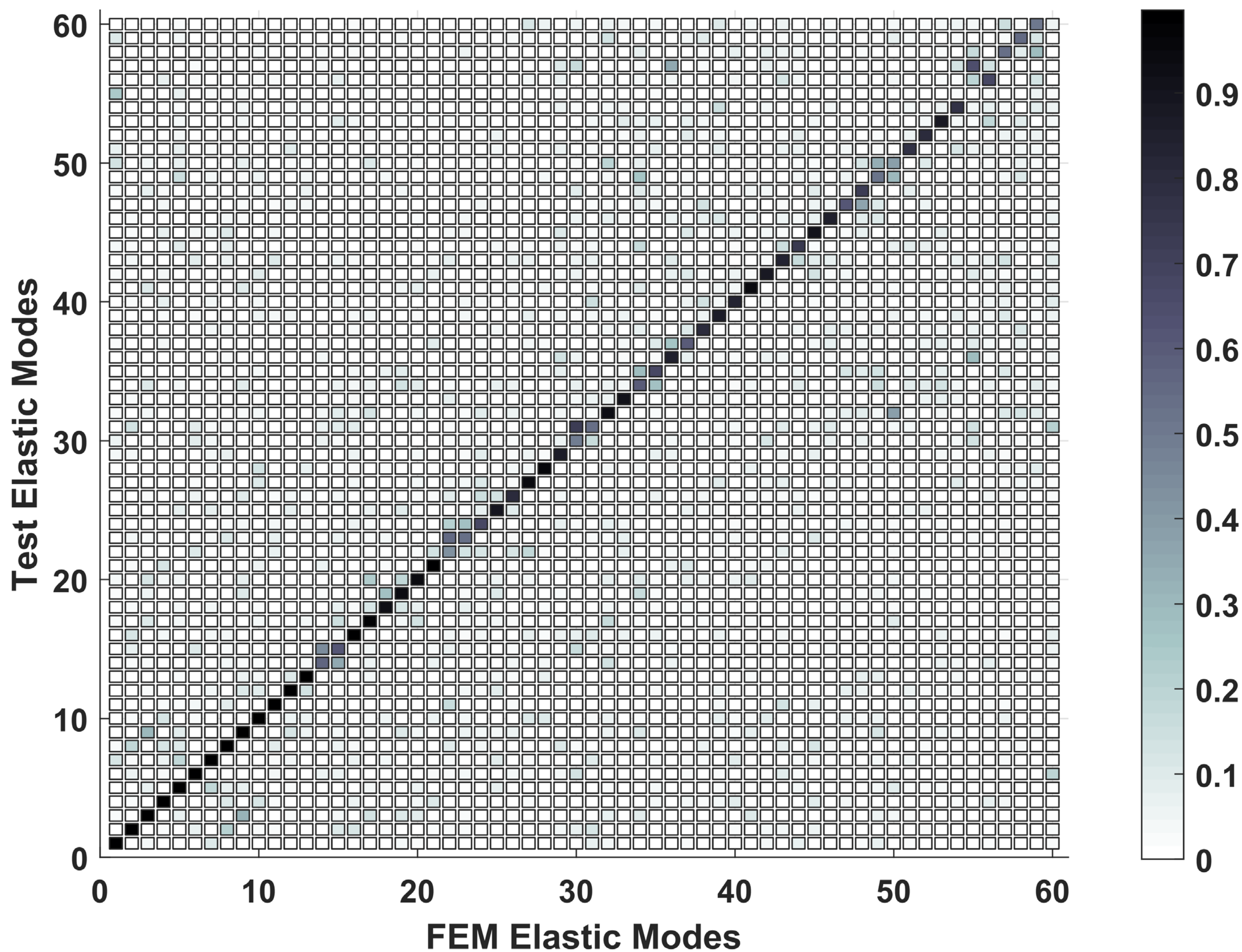
- Combination of existing Half Cube and Block models



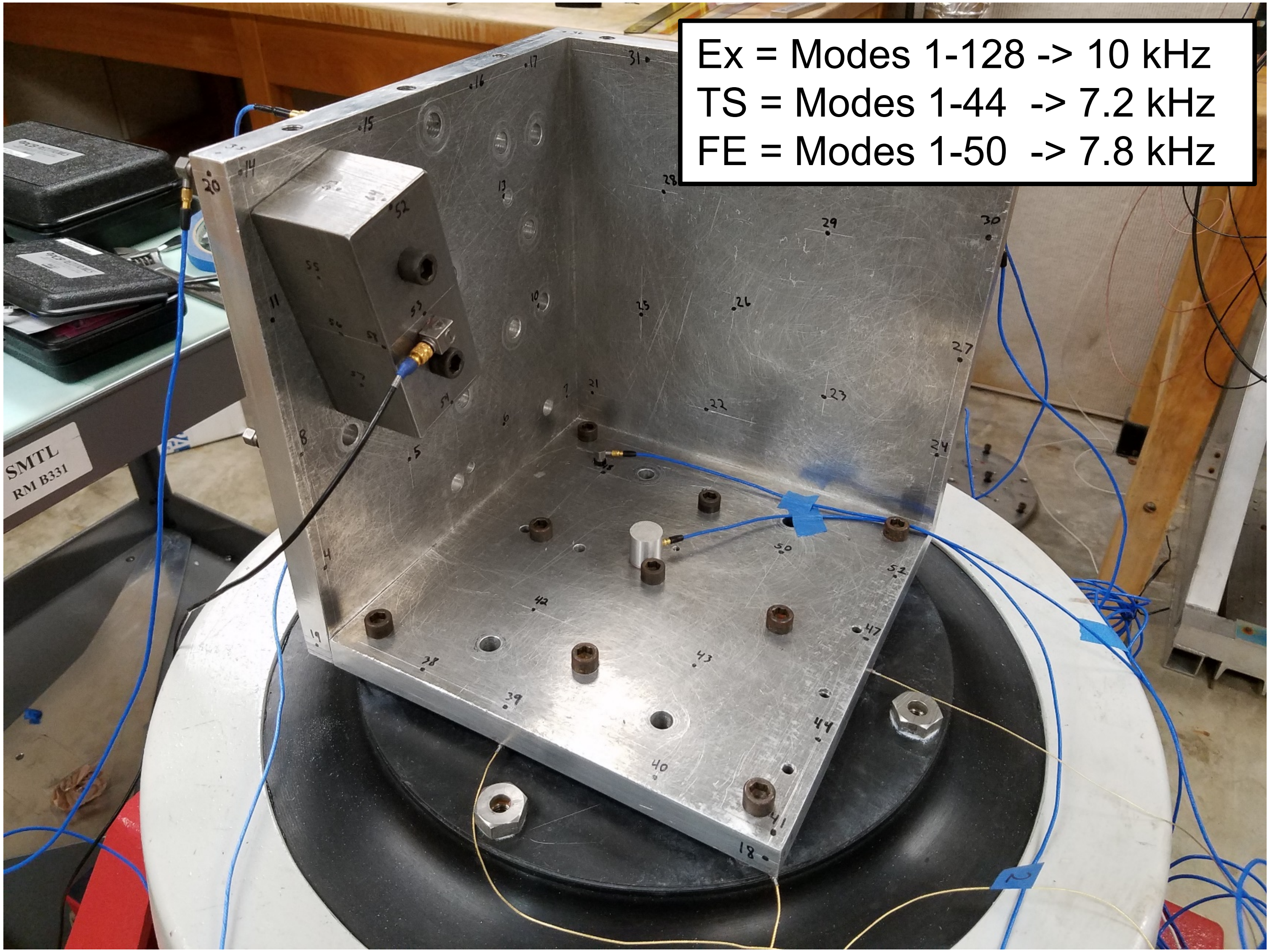
FEM is in Good Agreement with Test Data



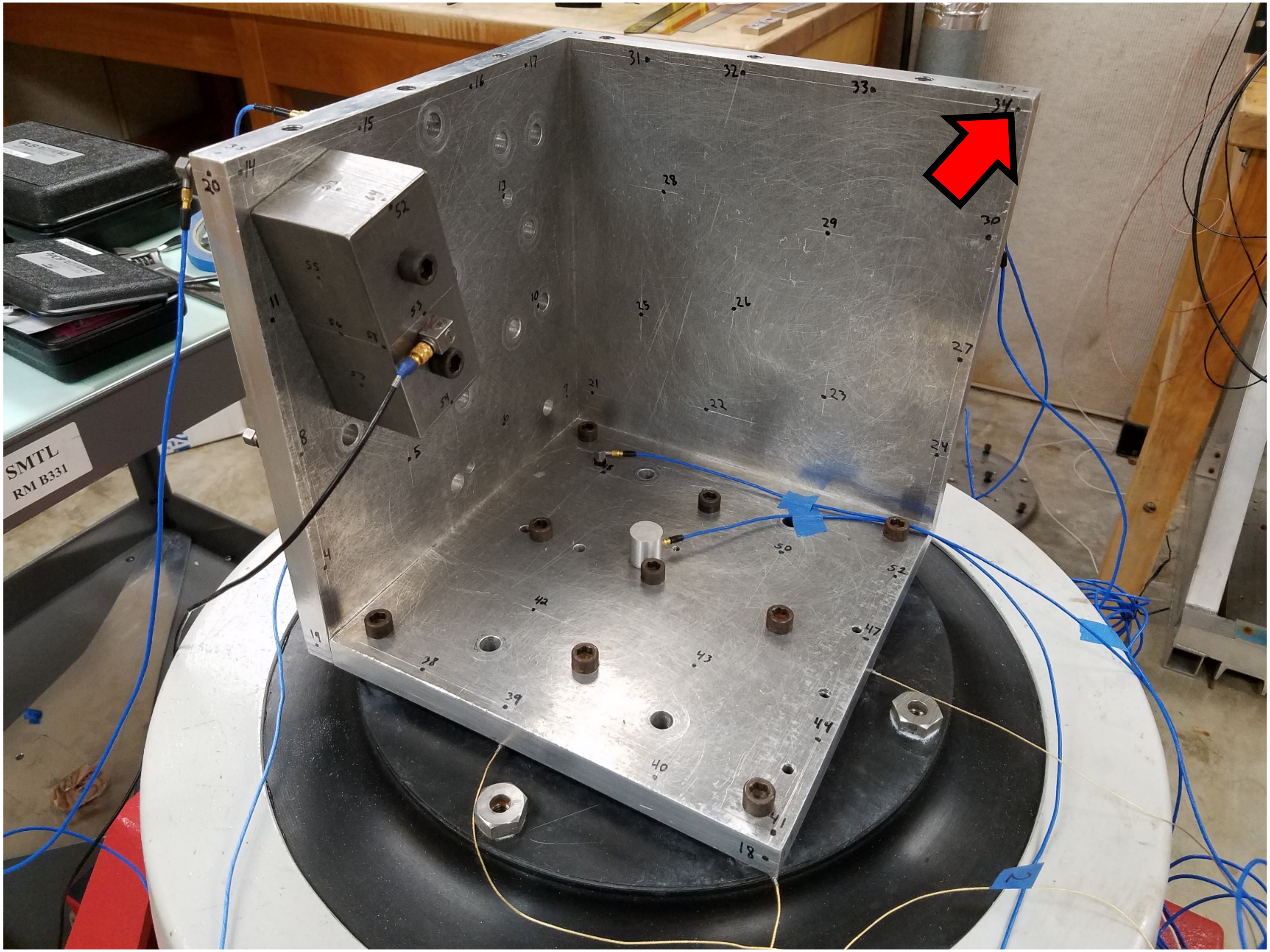
Cross-MAC Shows Agreement out to 6000 Hz



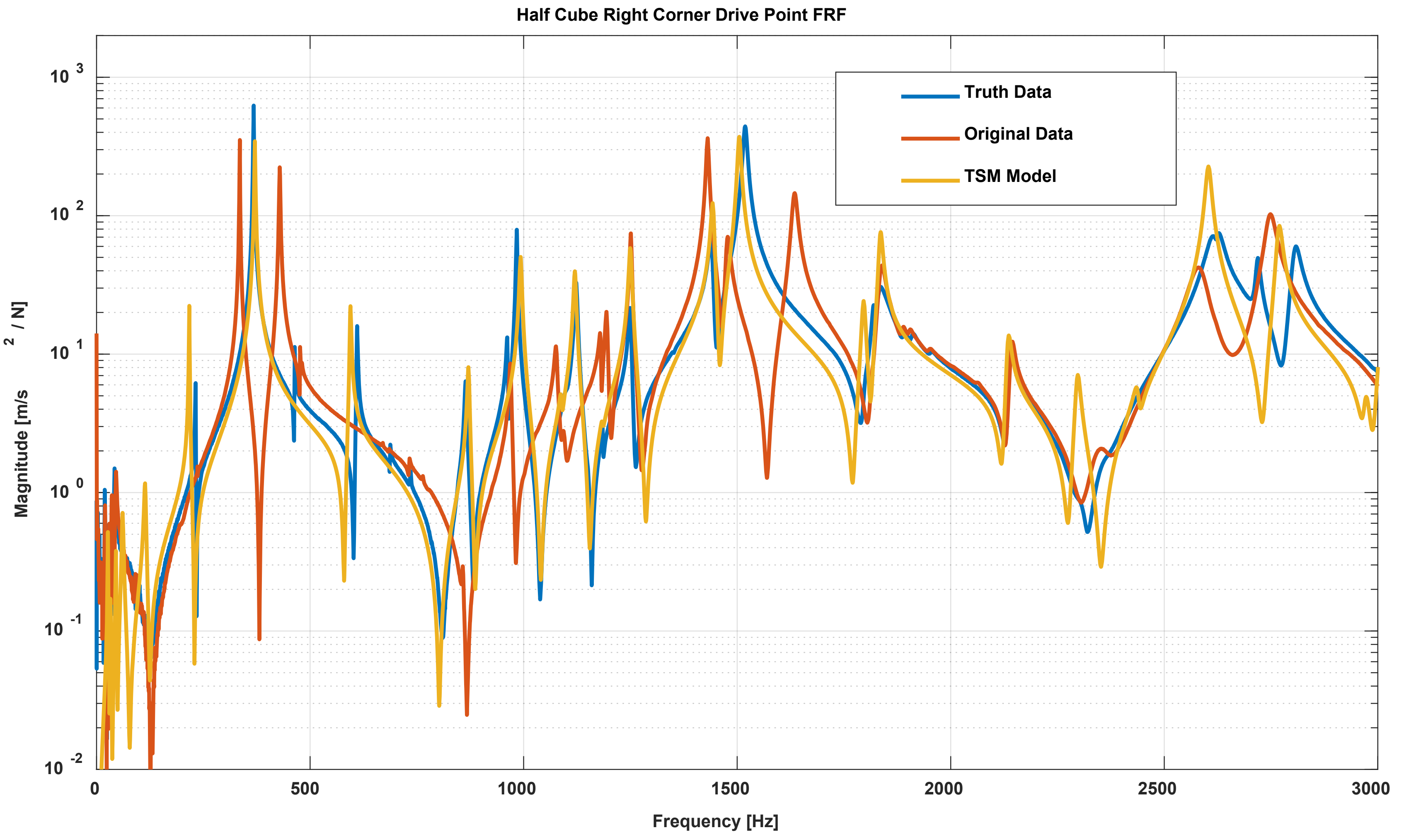
Substructuring Results



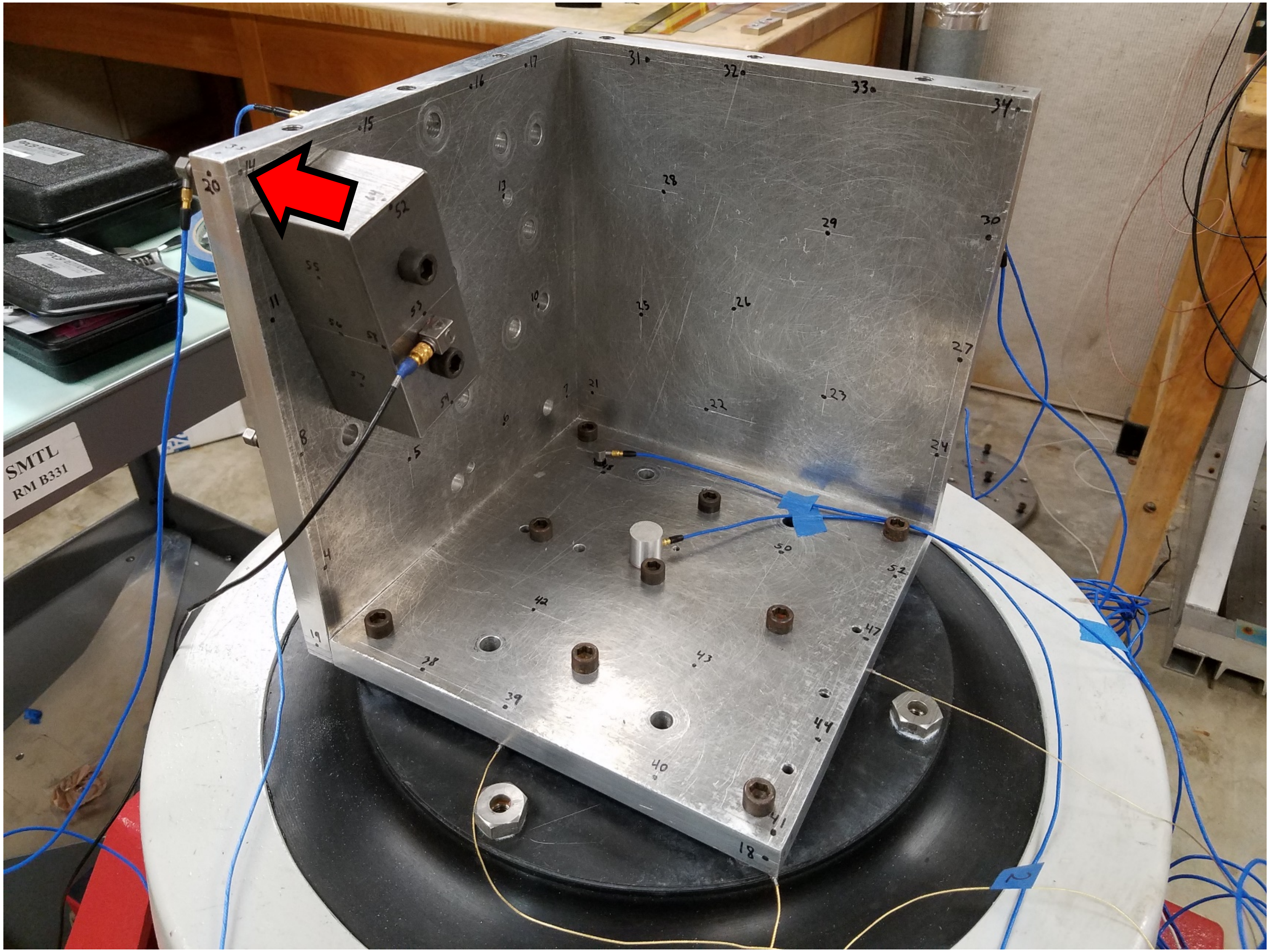
Top Right Corner Drive Point FRF



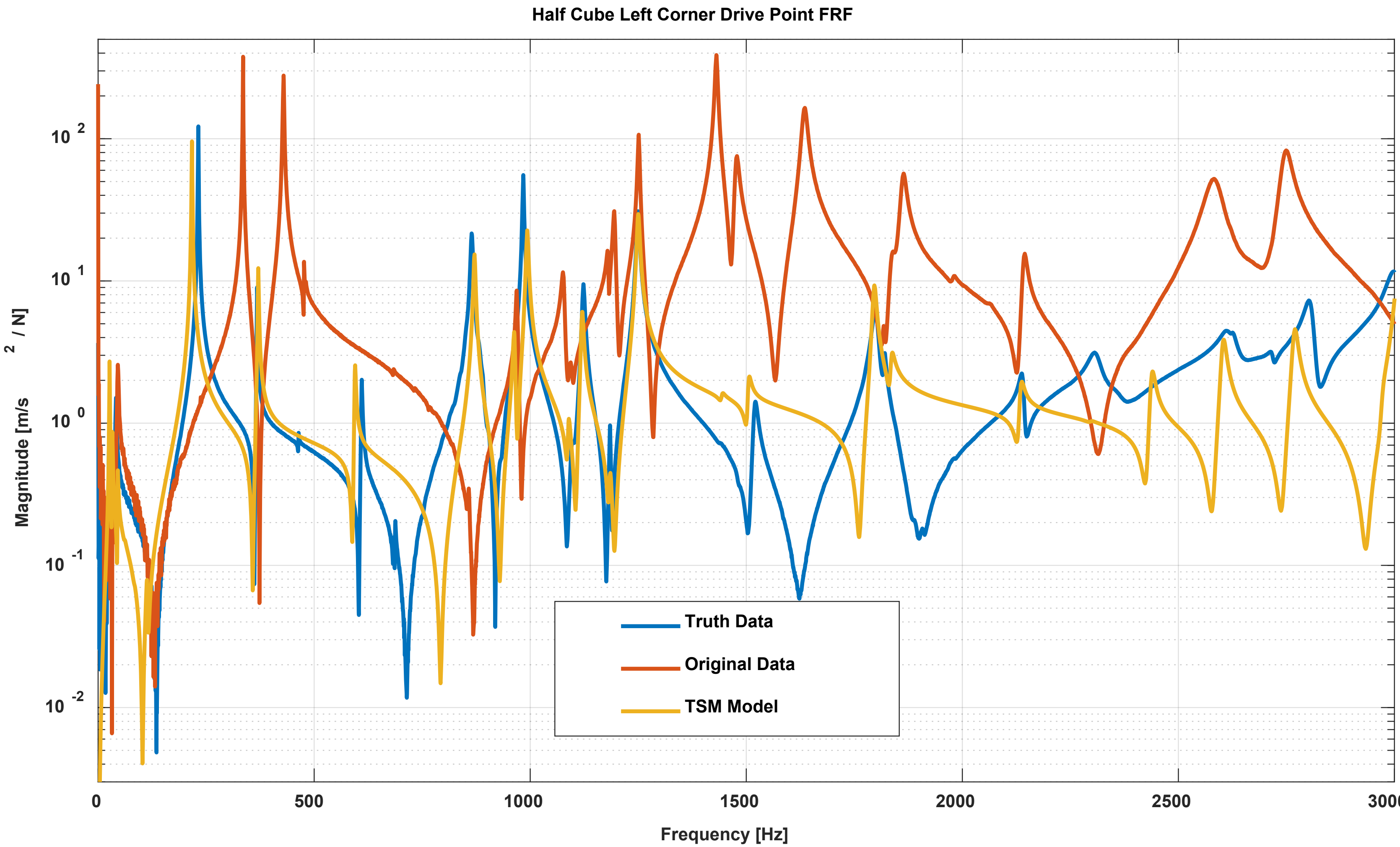
Top Right Corner Drive Point FRF



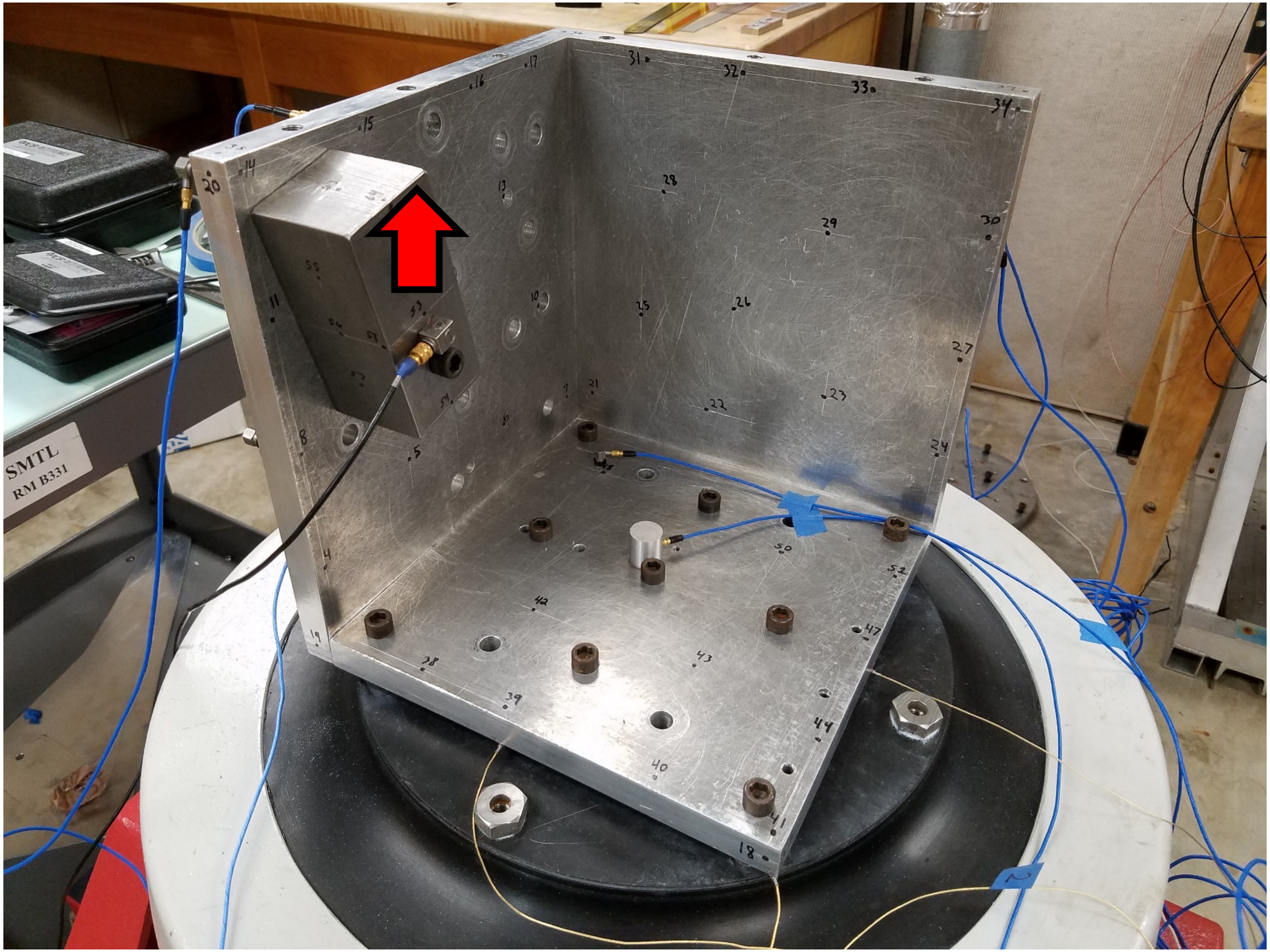
Top Left Corner Drive Point FRF



Top Left Corner Drive Point FRF



Block Face Response Due to Shaker Sin Sweep



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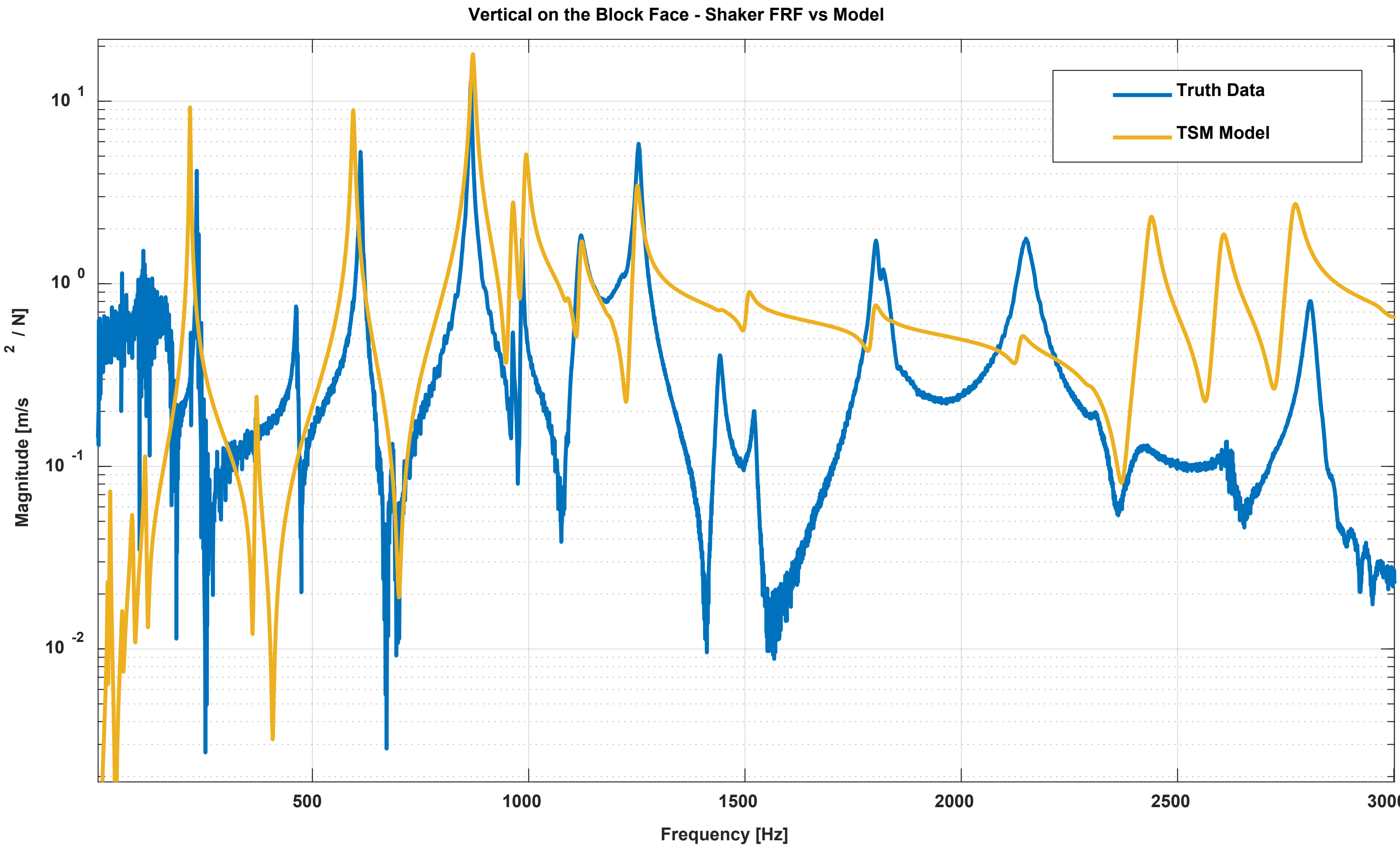

Conclusions

- The Transmission Simulator Method has been successfully implemented to create models of an electrodynamic shaker with mostly very accurate frequency predictions.
- While a shaker is difficult to model analytically, the important dynamics have been experimentally captured in the shaker's modal basis.
- Selecting a suitable test grid is essential, so that an adequate number of modes can be used in each basis set. Finite element models also need to be updated to match test data.
- Future Work includes: test even more complicated setups to check method robustness, determine how to best account for damping, and establish a metric so that model validity can be determined when truth data is unknow.

Acknowledgement

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