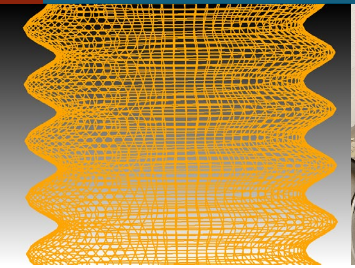
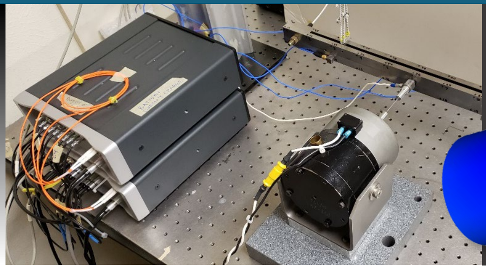
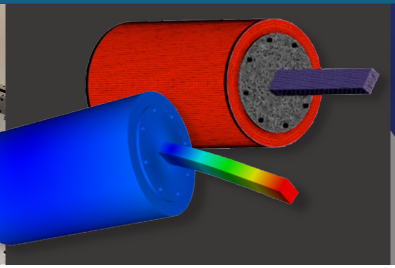
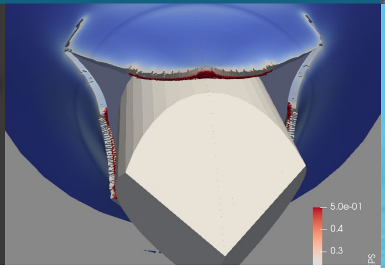
Nonlinear Transient Response of Electromechanical Assemblies

SAND2021-8886 PE









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Mentors:

Steven Carter, Deborah Fowler, Nathan Jackson, Robert Kuether, Andrew Steyer

Introduction

Background

Low-amplitude vibrations

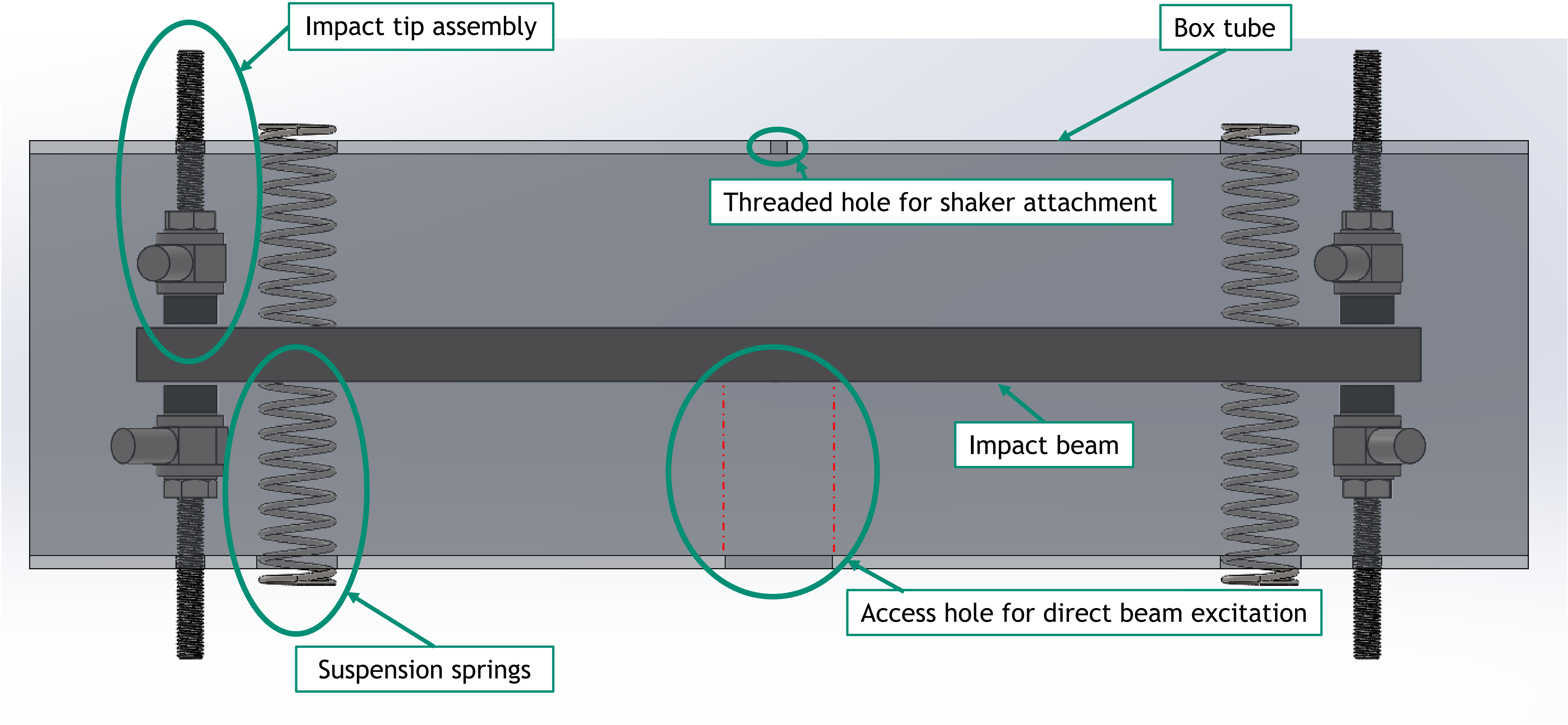
1. Long-duration random vibration
2. Linear responses produced
3. Classical modal analysis applicable

High-amplitude vibrations

1. Short-duration mechanical shock
2. Nonlinear responses produced
3. Classical modal analysis not applicable*

- Many electromechanical assemblies of interest to Sandia have sources of nonlinearity stemming from contact impacts
- This limits or invalidates the applicability of linear modal analysis techniques

Test Set Up


Impact tip assembly
Box tube
Threaded hole for shaker attachment
Impact beam
Access hole for direct beam excitation
Suspension springs

Project Description & Goals

Description

Understand how contact-impacts due to bearing clearances lead to nonlinear coupling between elastic and rigid body modes in rotor-bearing assemblies

Method

Study an idealized system that will imitate the essential physics

Task 1

Analyze physical test model

- Visualize the experimental linear modes
- Validate the linear modes via modal assurance criterion (MAC)
- Create a test plan to excite nonlinear modes
- Generate spectrograms for the nonlinear responses

Task 2

Develop detailed Sierra model

- Create simplified geometry and generate a hexahedral mesh
- Apply preload to the springs in Sierra SM
- Transfer the preload and run modal analysis in Sierra SD
- Replicate experimentally observed transient response

Task 3

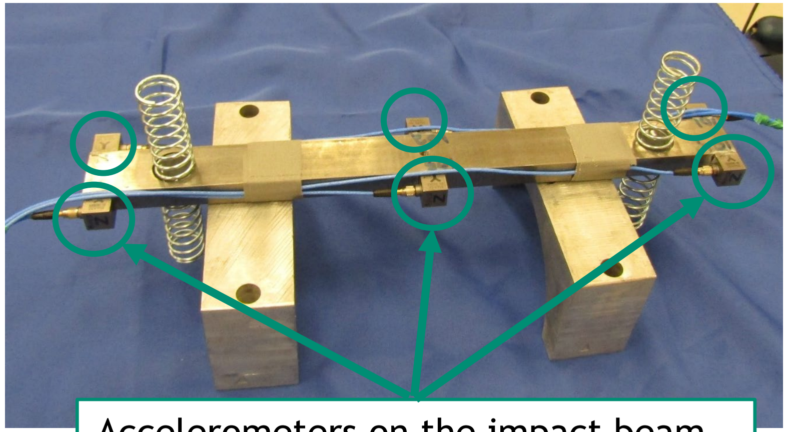
Develop simplified FE model

- Write implicit, transient finite element code in MATLAB
- Correlate model parameters to experiment
- Replicate experimentally observed transient response
- Contextualize transient response with NNM calculations

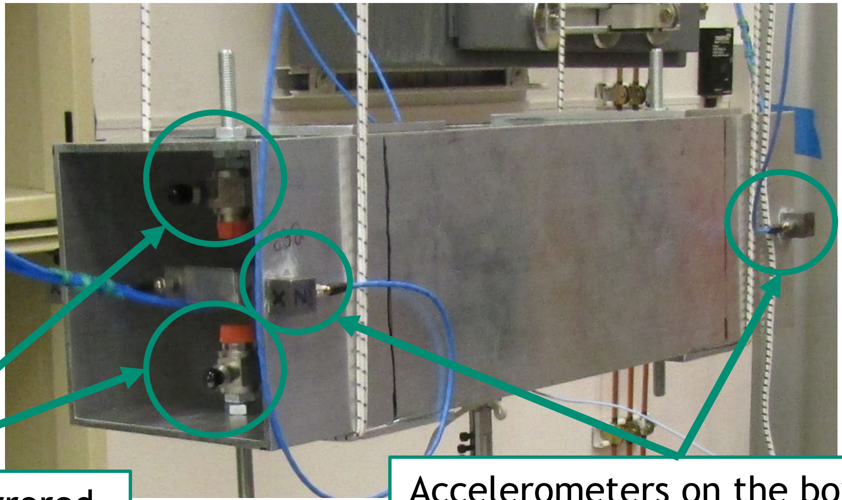
Physical Test Model

Linear Test Instrumentation & Plan

- 6 accelerometers were placed on the beam, 5 accelerometers on the box tube
- 4 impact load cells
- The system was excited with an impact hammer at a variety of locations on the box tube to excite the system in three orthogonal directions
- The system was tested in two configurations:
  - Impact gaps fully open
  - Impact gaps fully closed – The preload is unknown, but it was sufficient to ensure that the tips were in contact with the beam for all ranges of excitation.



Accelerometers on the impact beam

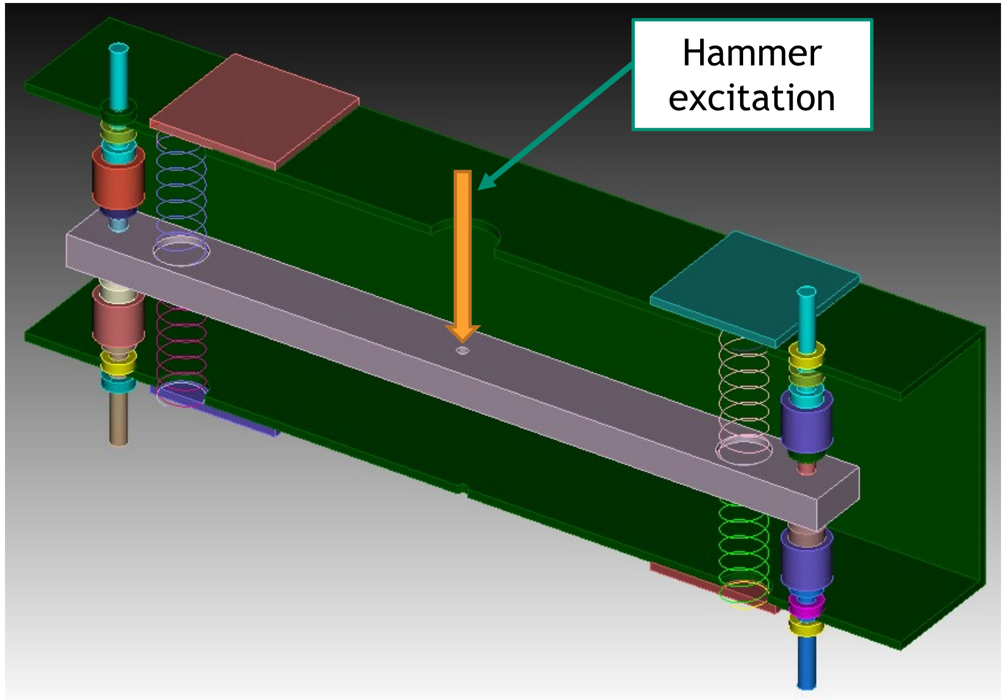


Impact load cells (mirrored on the other end)

Accelerometers on the box tube (mirrored on the opposite side)

Preliminary Nonlinear Tests

- Experiments were performed to measure transient response with impacts
  - Gaps set to approximately 0.01”
  - Beam excited by impact hammer at midpoint
- Data show large amount of damping
  - Likely due to accelerometer cables
  - Questionable applicability of short-time Fourier transform

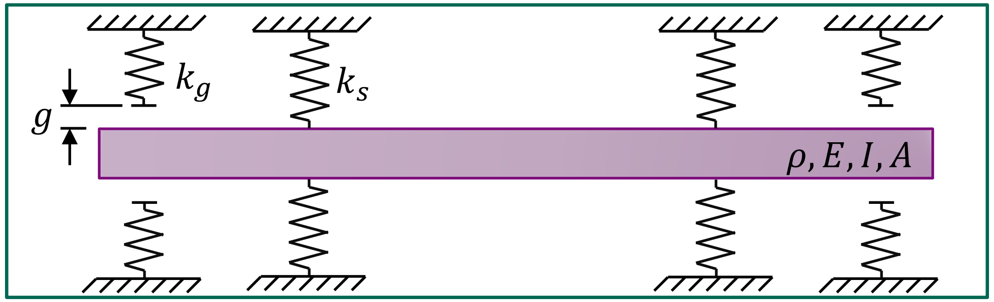


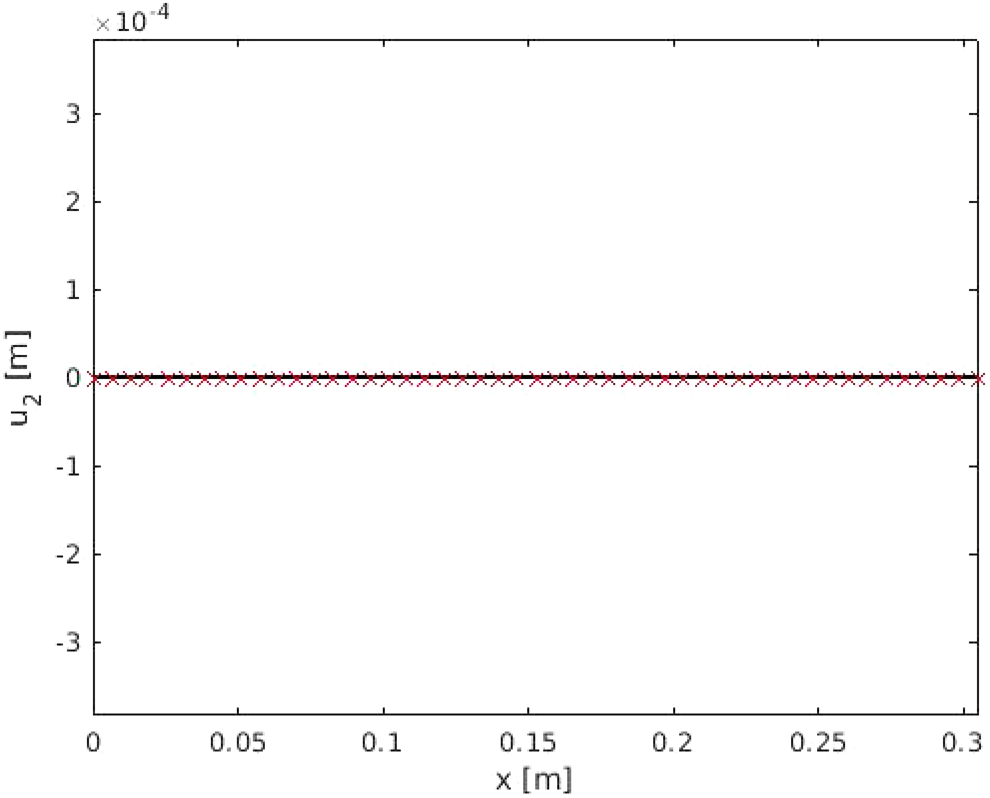
Simplified CAD model

Computational Capabilities

MATLAB Finite Element Code

- Implicit transient, accepts any time integrator
- Planar, 3-DOF Euler-Bernoulli beam elements
- Accepts easy-to-write input files
- Extensive validation against analytical solutions
- Also developed related codes to analyze nonlinear normal modes and forced response
- Model parameters k_g and k_s meticulously correlated to physical system

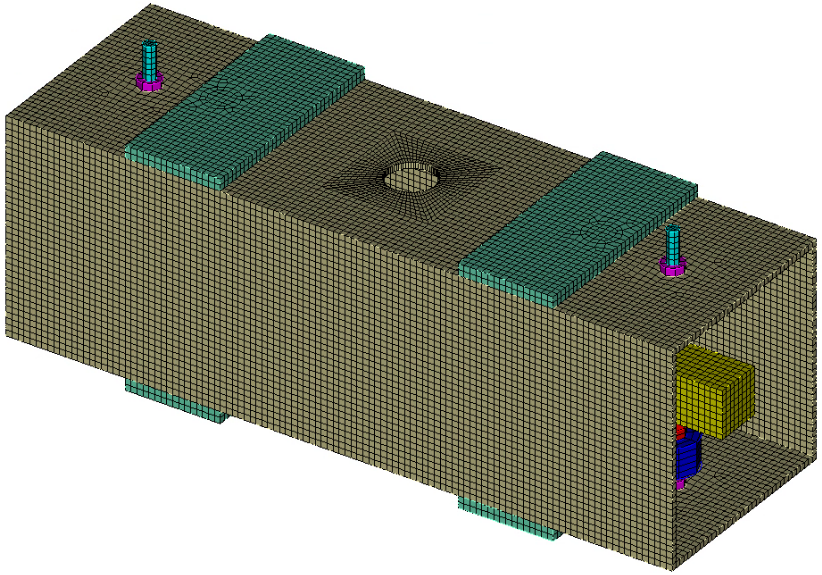


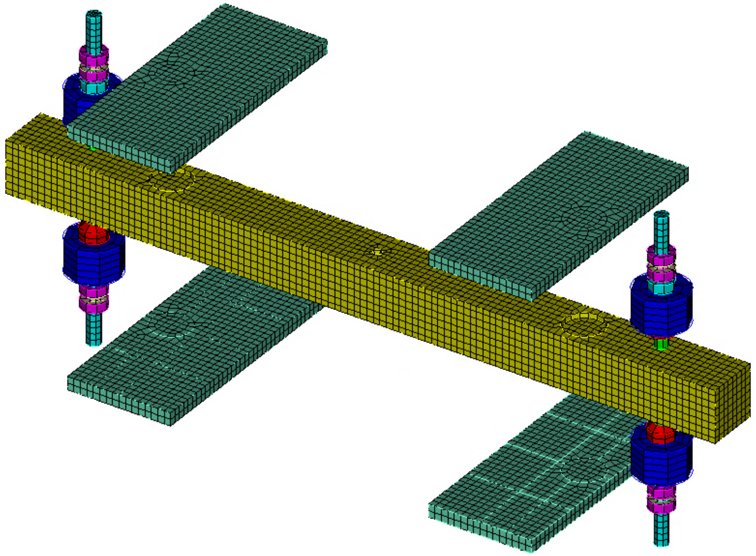


Automated Generation of Geometry and Mesh

- Created versatile CUBIT journal file
  - Input: various dimensions of parts
  - Output: CAD geometry and high-quality hex mesh
- Mesh is highly symmetric and regular
- Useful for future optimization studies

```
###########################
###   MESH PARAMETERS   ###
###########################
# Make this number bigger for a coarser mesh (1-10 range)
#{meshSizeFactor = 6}

# Unite all the volumes I webcut after mesh is created? (0 = no, 1 = yes)
# This operation can take some time, so be patient
#{uniteVols = 1}

# Unmerge backing plates from box tube, useful for doing preload in SM
#{unmergePlates = 0}

###############################
###   GEOMETRY PARAMETERS   ###
###############################
#{tol = 1e-5}

#{beamDepth = 1}
#{beamHeight = 0.5}
#{beamLength = 12}
#{beamCutoutRadius = 0.375}
#{beamCutoutDepth = 0.1}
#{beamDistFromCenterToCutout = 4.5}
#{beamCenterHoleRadius = 0.0795}

#{gap = 0.1}
#{distFromCenterToImpactPoint = 5.5}
#{impactTipRadius1 = 0.249}
#{impactTipRadius2 = 0.125}
#{impactTipRadius3 = 0.125}
##{impactTipRadius3 = 0.09375}
#{impactTipHeight1 = 0.2}
#{impactTipHeight2 = 0.1}
#{impactTipHeight3 = 0.16875}
#{impactTipHeight4 = 0.03125}
```

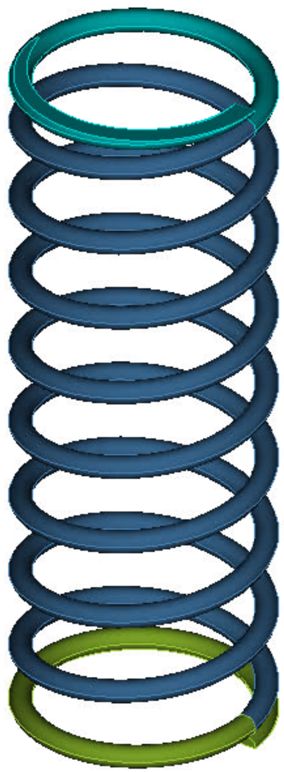




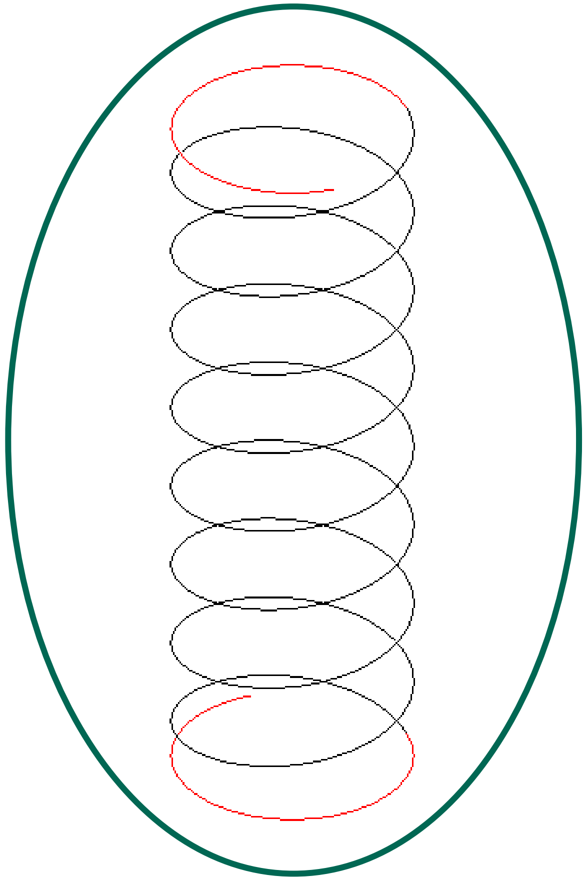
Spring Modeling

Parameters:

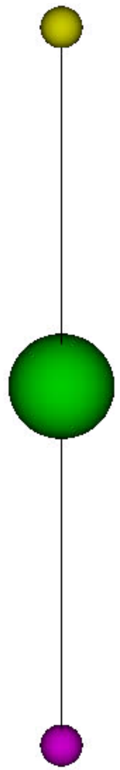
1. Meshing
2. Simulation
3. Fidelity



Solid elements (hex or tet)

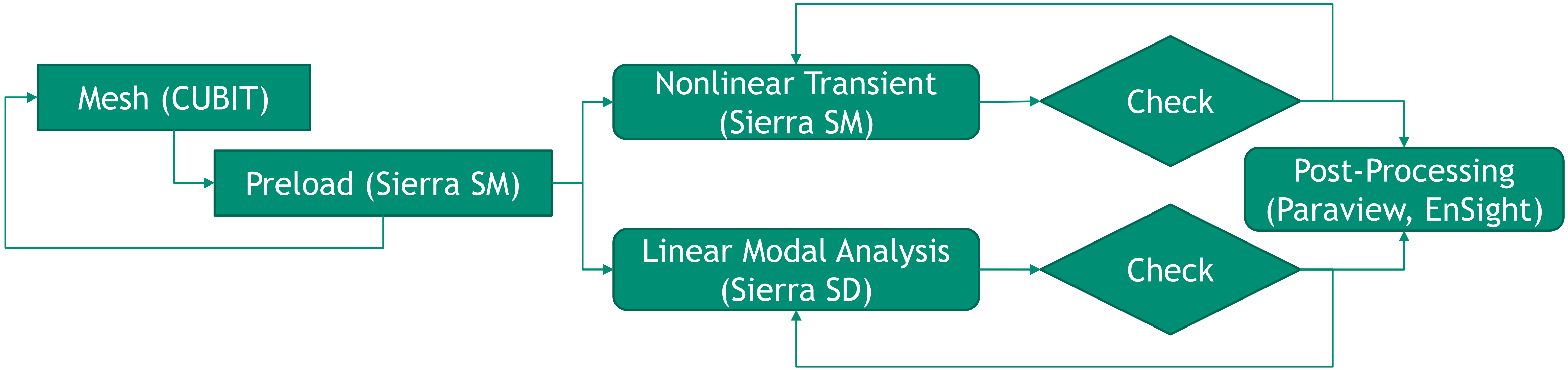


Beam elements

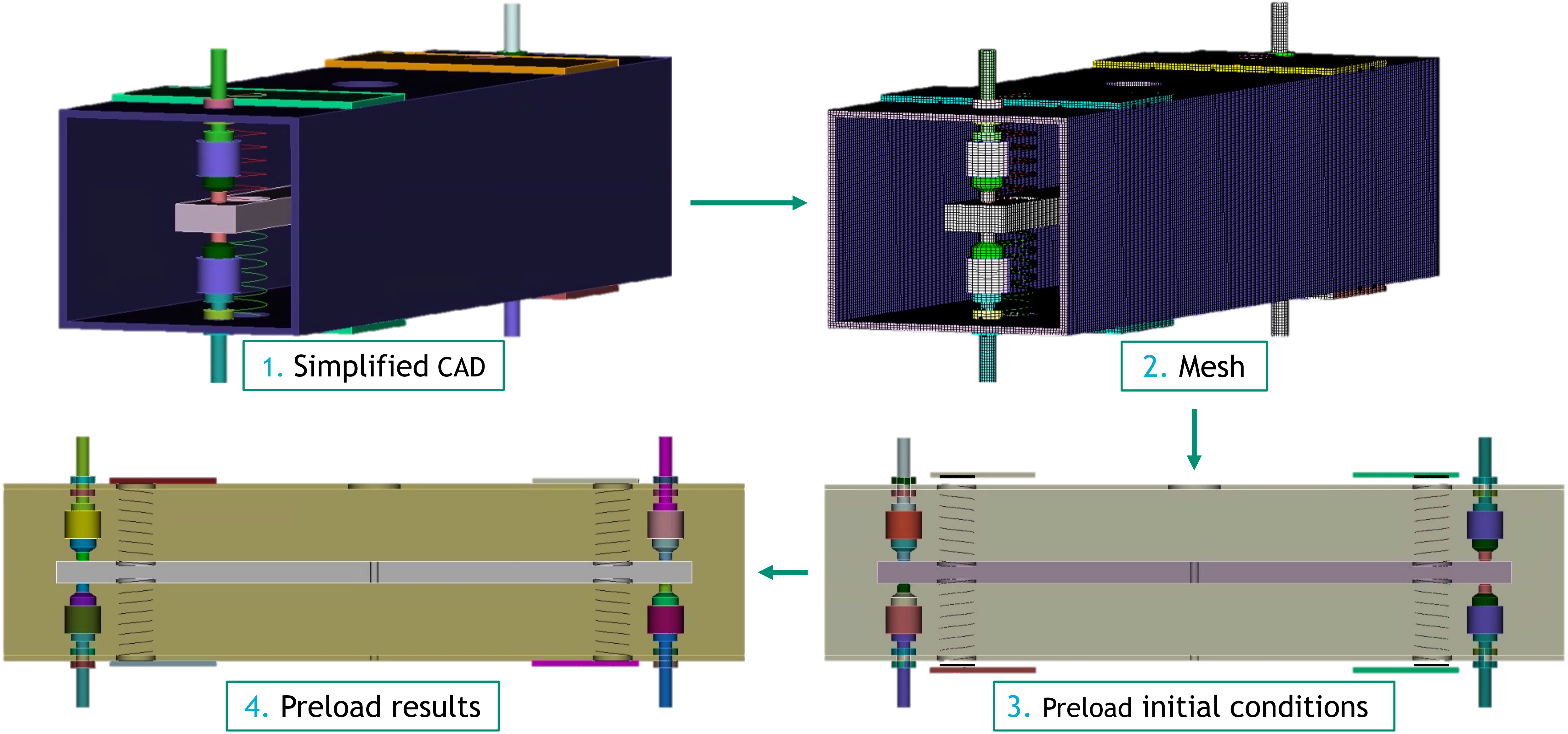


Spring elements w/ concentrated mass

Sierra Finite Element Model Workflow

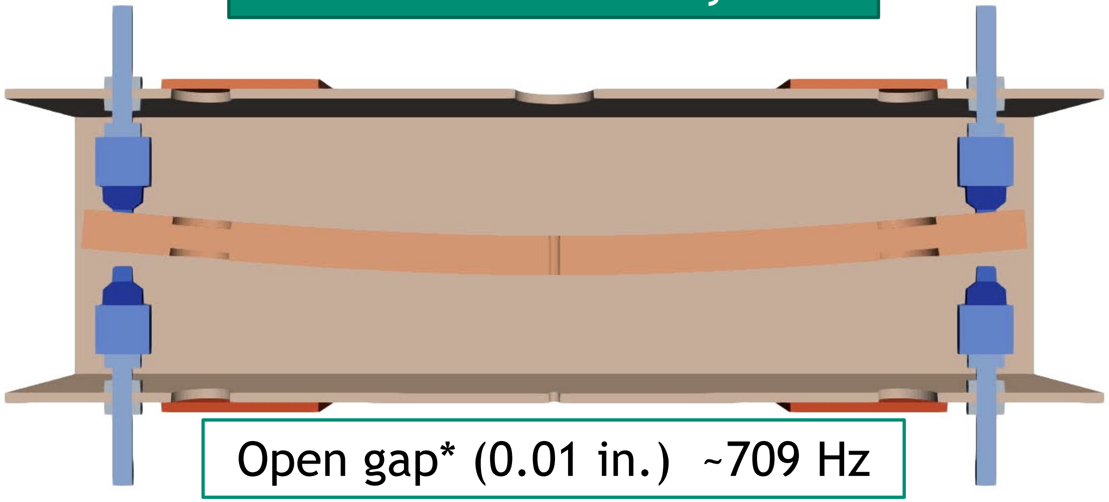


Sierra Model Workflow



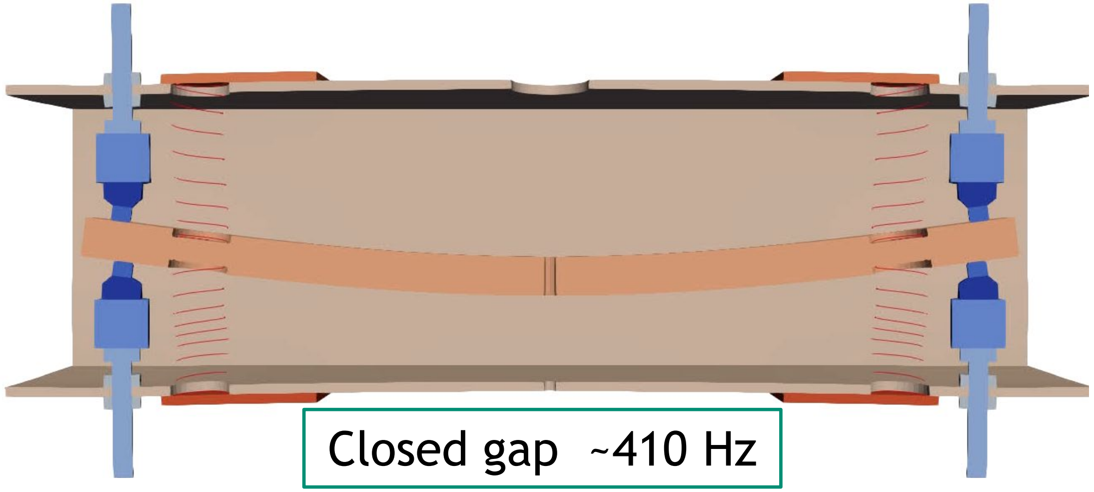
Linear vs. Nonlinear Response

Linear Modal Analysis



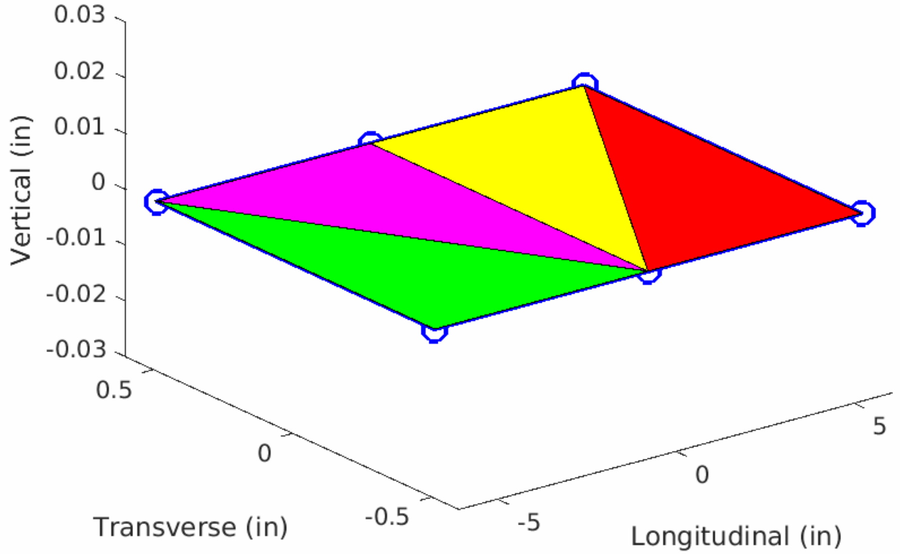
Open gap* (0.01 in.) ~709 Hz

*Springs not included in above animation



Closed gap ~410 Hz

Nonlinear Transient

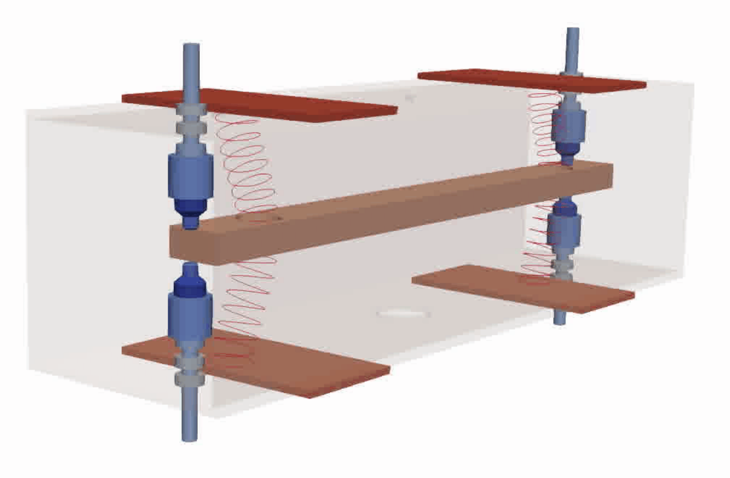


Open gap** (0.01 in.)

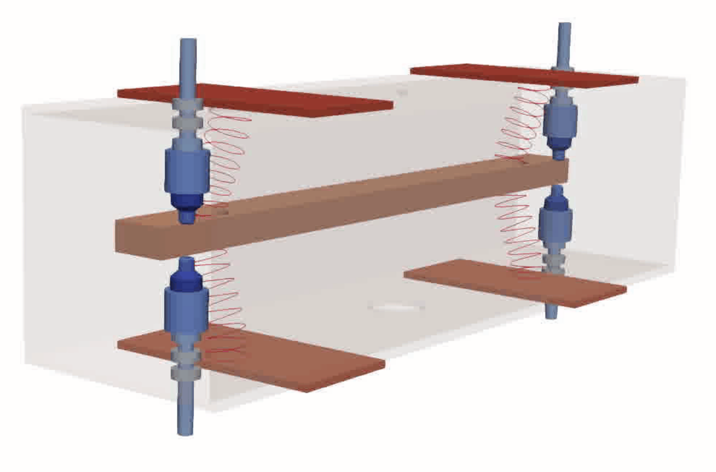
** Only beam represented in above animation

Outcomes

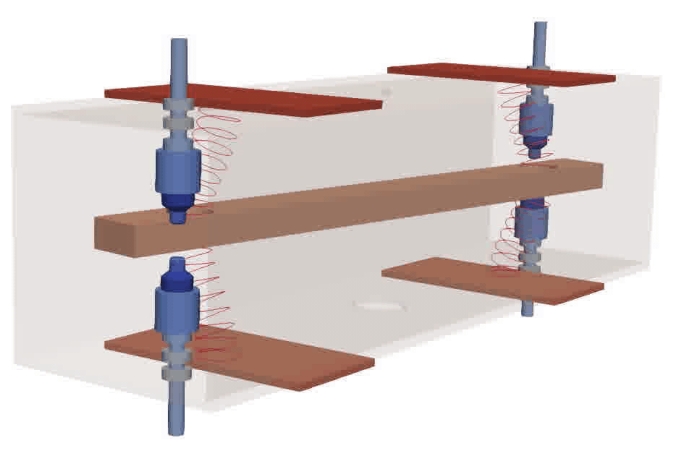
Pseudo-Rigid Body Mode Shapes (Fully Open Case)



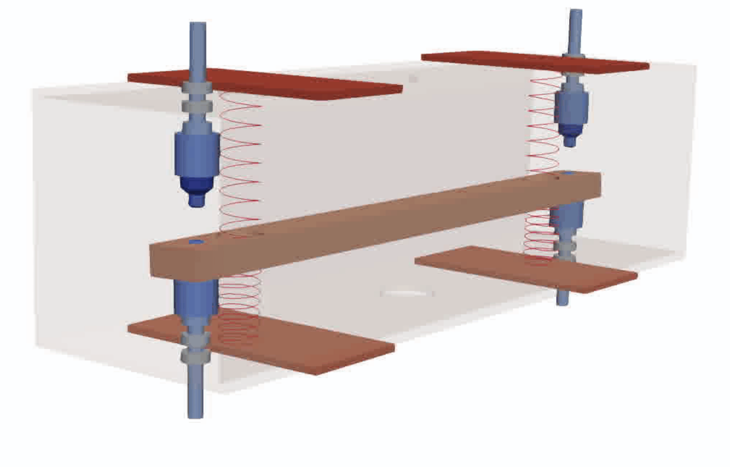
Longitudinal ~10.5 Hz



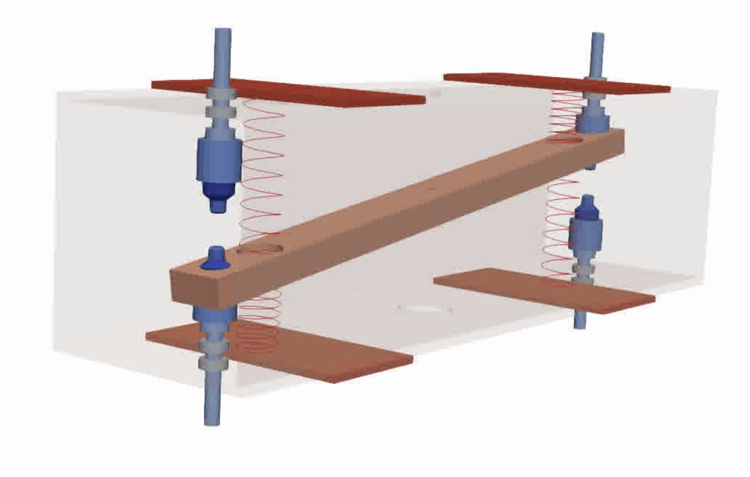
Lateral ~11.25 Hz



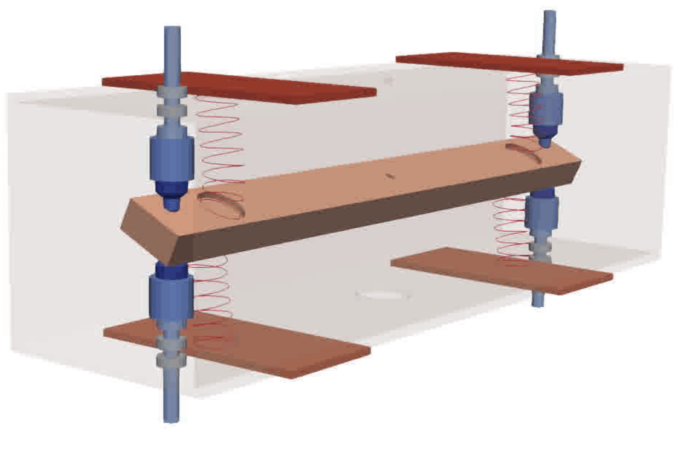
Yaw ~13.75 Hz



Bounce ~18.5 Hz

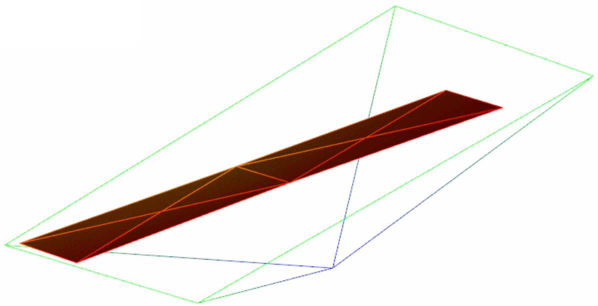


Pitch ~22.5 Hz

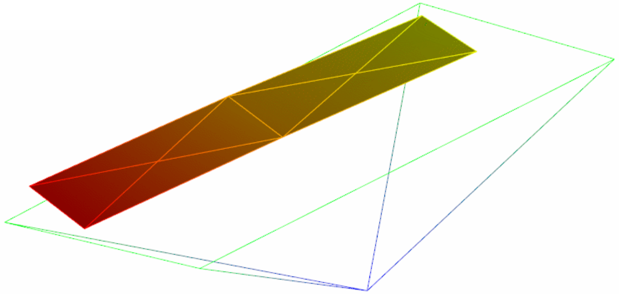


Roll ~34.75 Hz

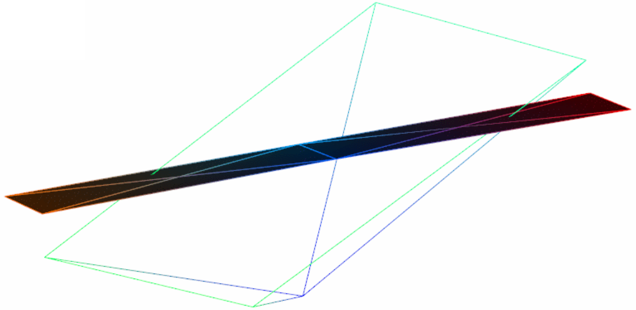
Rigid Body Mode Shapes – Fully Open Case



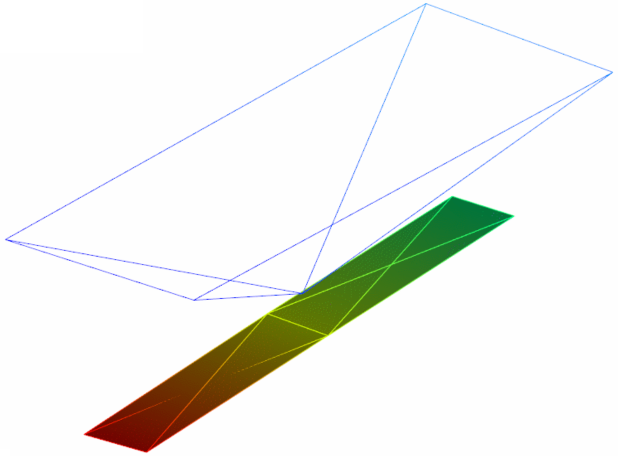
Longitudinal: 10.92 Hz



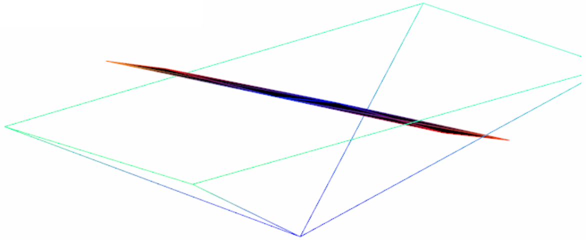
Lateral: 11.66 Hz



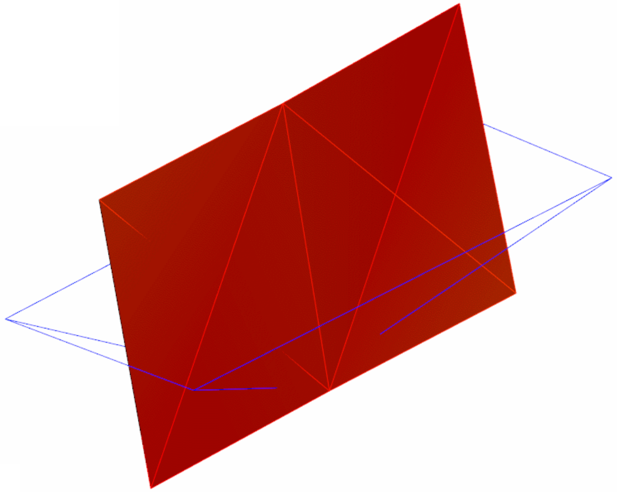
Yaw: 15.08 Hz



Bounce: 19.94 Hz



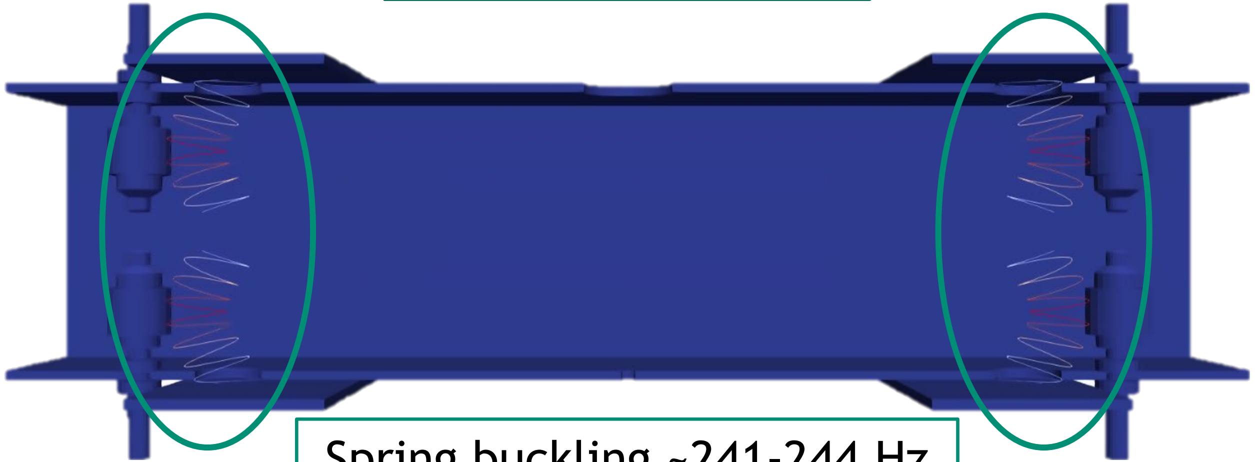
Pitch: 24.11 Hz



Roll: 33.69 Hz

Spring and Box Tube Mode Shapes

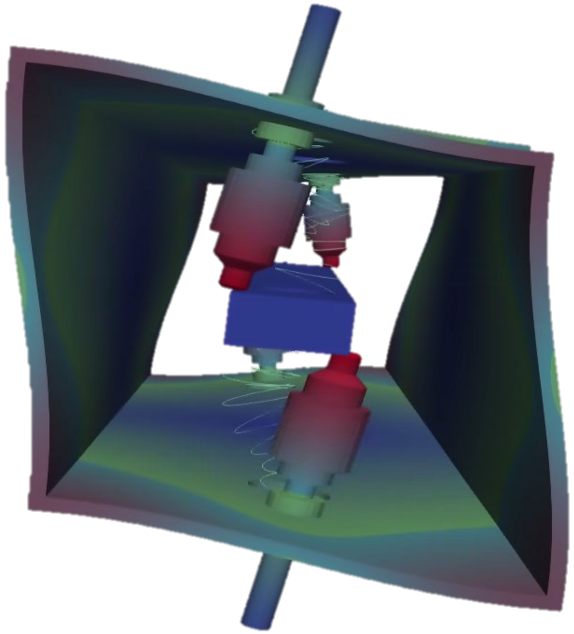
Spring Mode Shapes



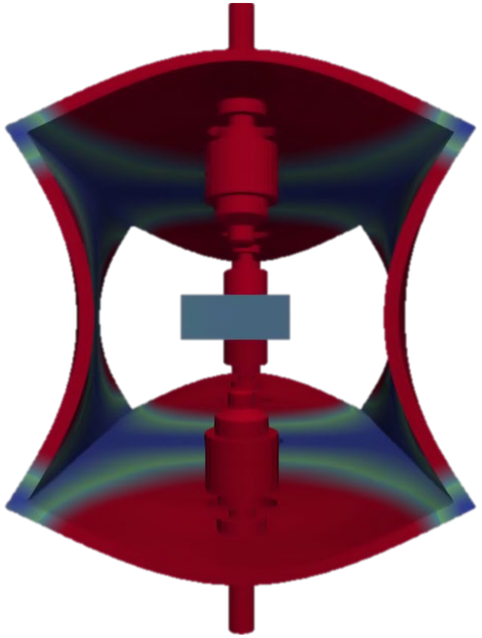
Spring buckling ~241-244 Hz

Spring barreling ~288 Hz

Box Tube Mode Shapes

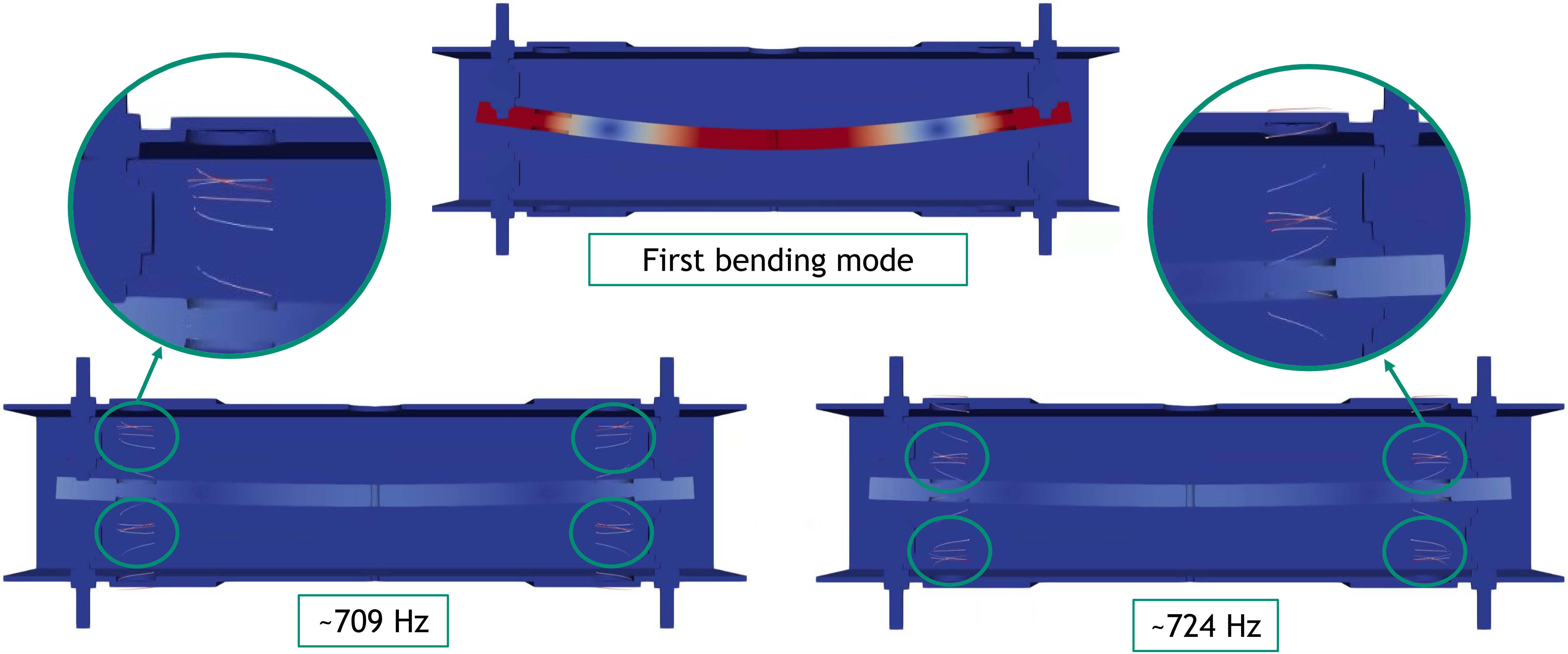


Matchboxing ~441-454 Hz

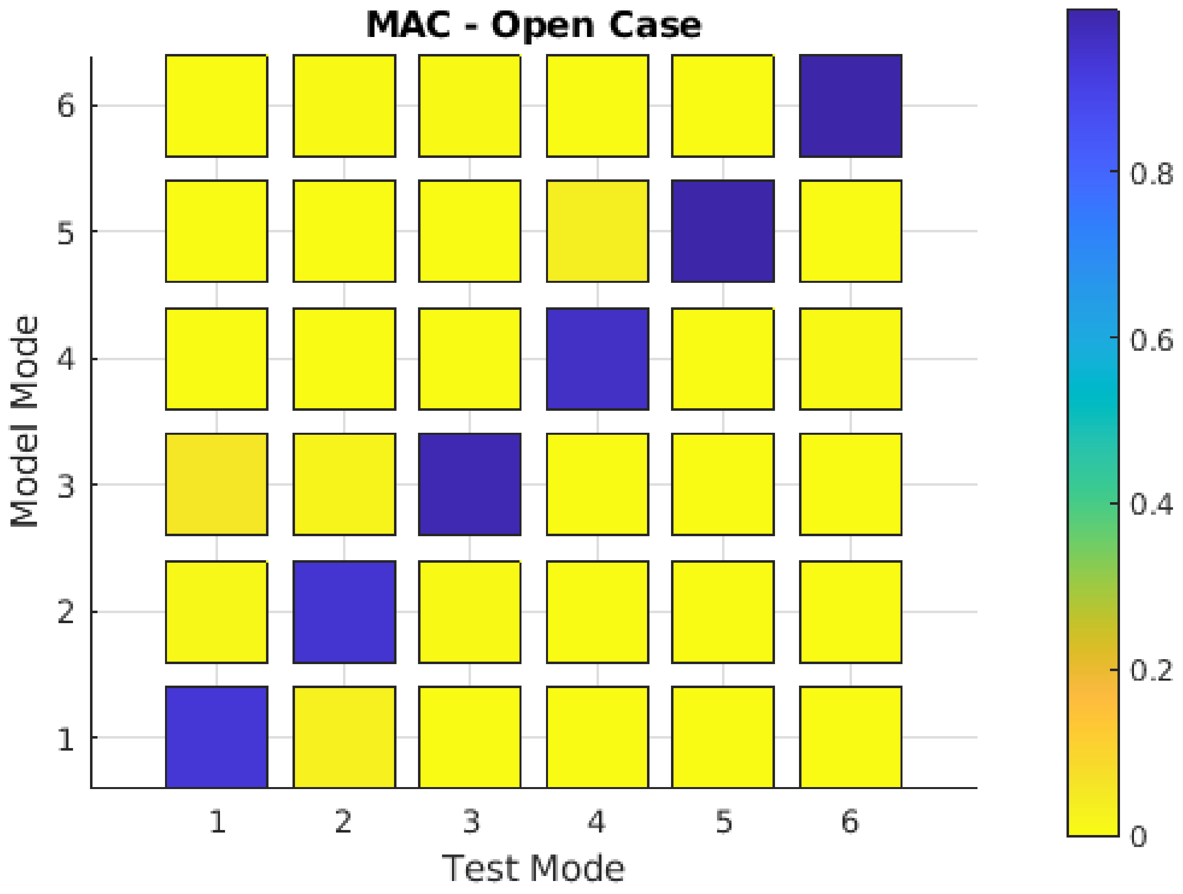


Buckling ~716 Hz

Coupling of Springs with Bending Modes

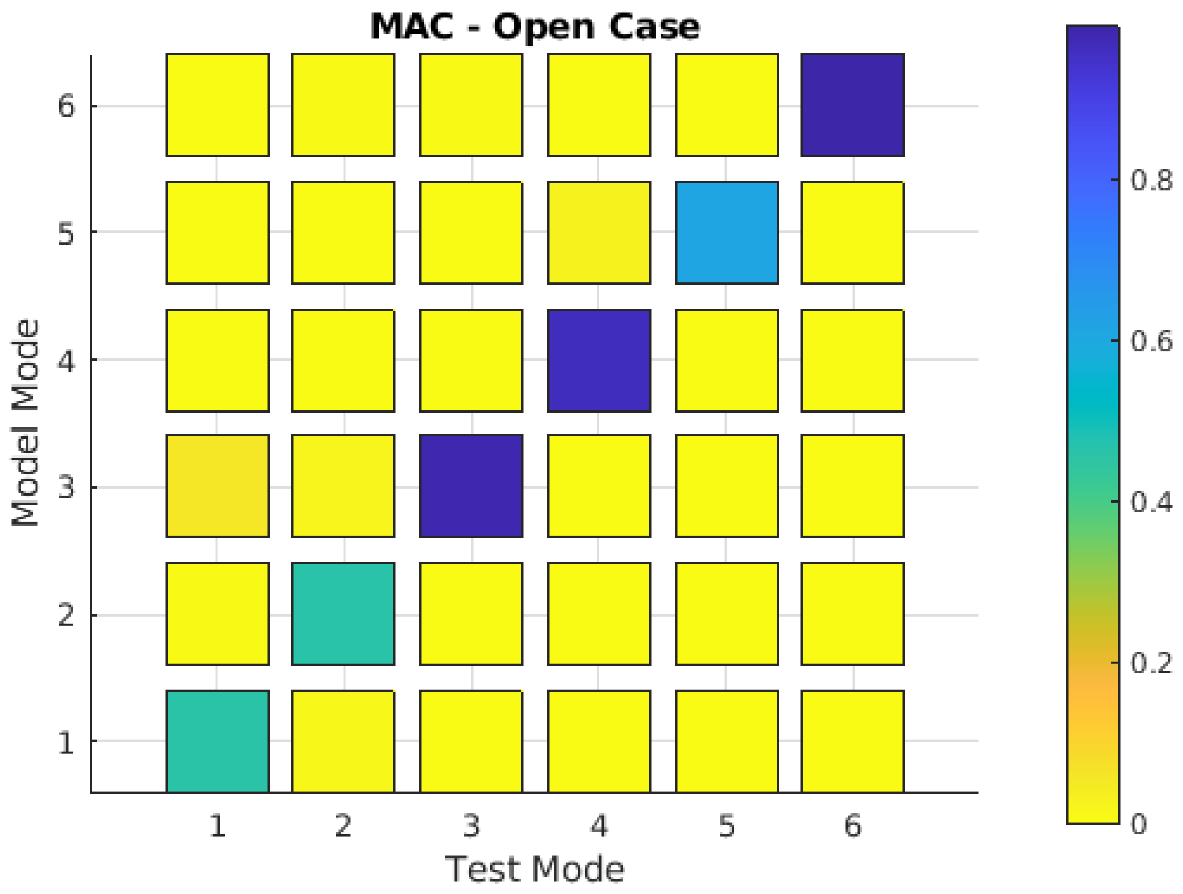


MAC for Linear Response of the Beam Accelerometers Only



Mode Number	Mode Name	MAC Value
1	Longitudinal	0.9348
2	Lateral	0.9414
3	Yaw	0.9834
4	Bounce	0.9567
5	Pitch	0.9943
6	Roll	0.9974

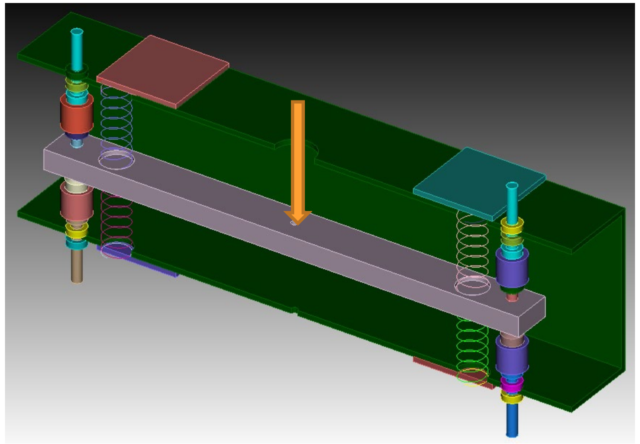
MAC for Linear Response of the Full System

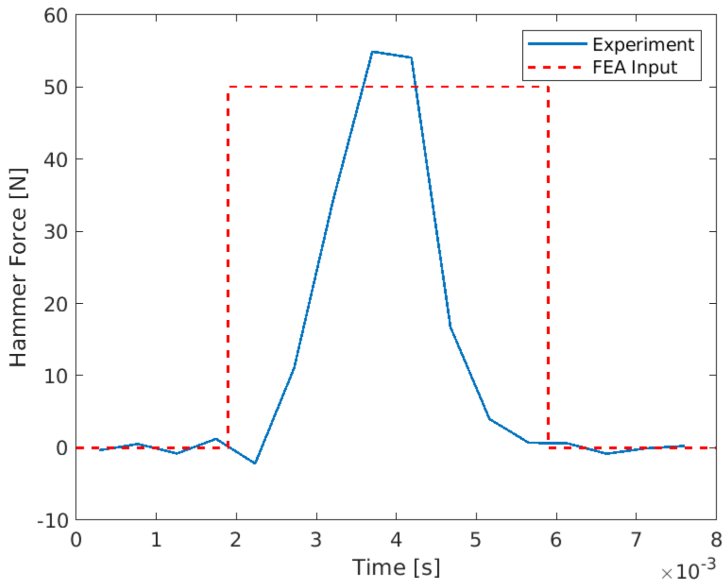


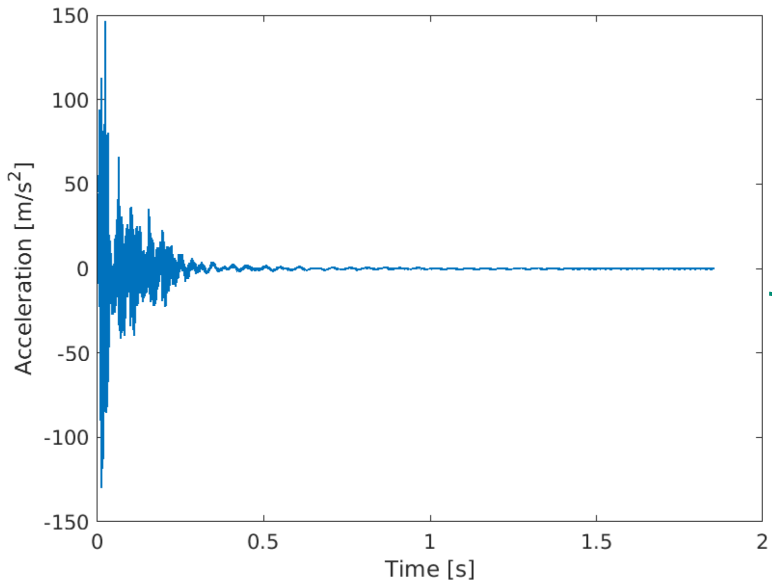
Mode Number	Mode Name	MAC Value
1	Longitudinal	0.4598
2	Lateral	0.4625
3	Yaw	0.9821
4	Bounce	0.9607
5	Pitch	0.6086
6	Roll	0.9913

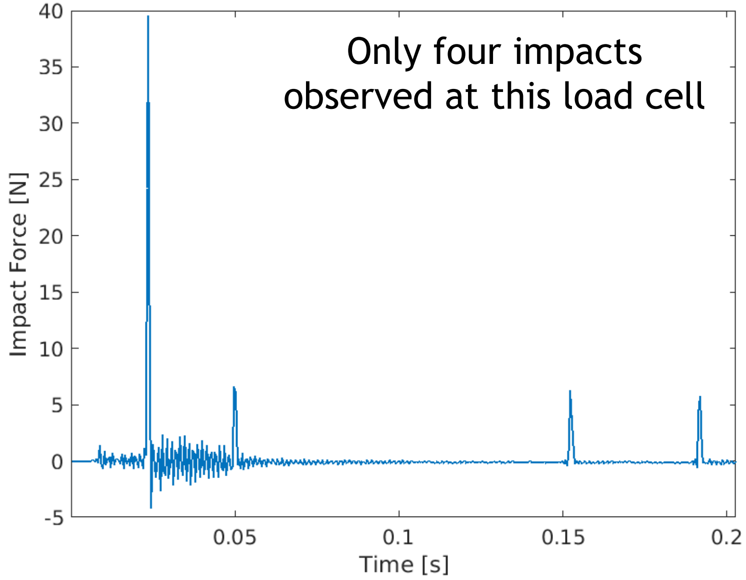
Transient Response - Experimental

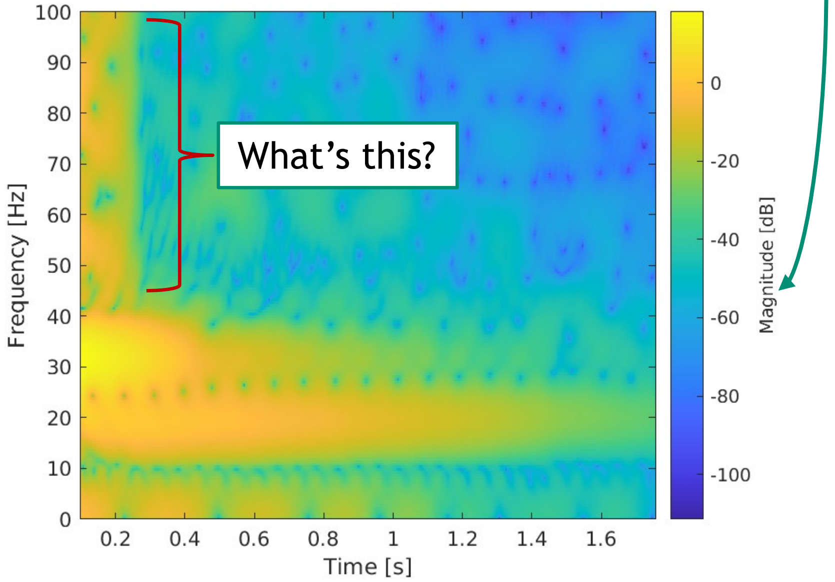
- Hit beam with impact hammer at mid-span
- Gap size 0.01”
- Several hammer hits with varying force
- Data is preliminary (damping due to cables, malfunctioning load cell, etc.)





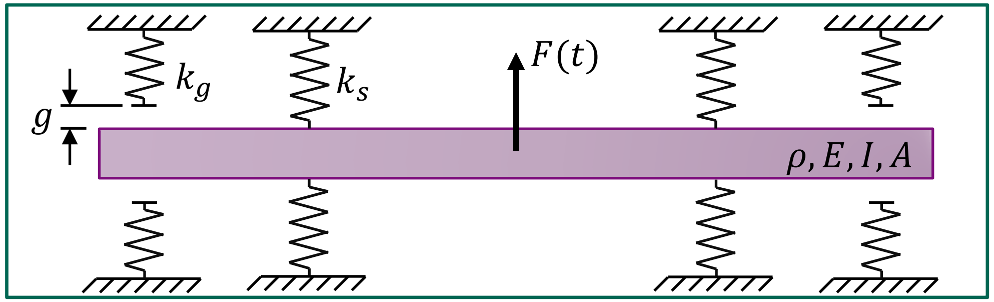


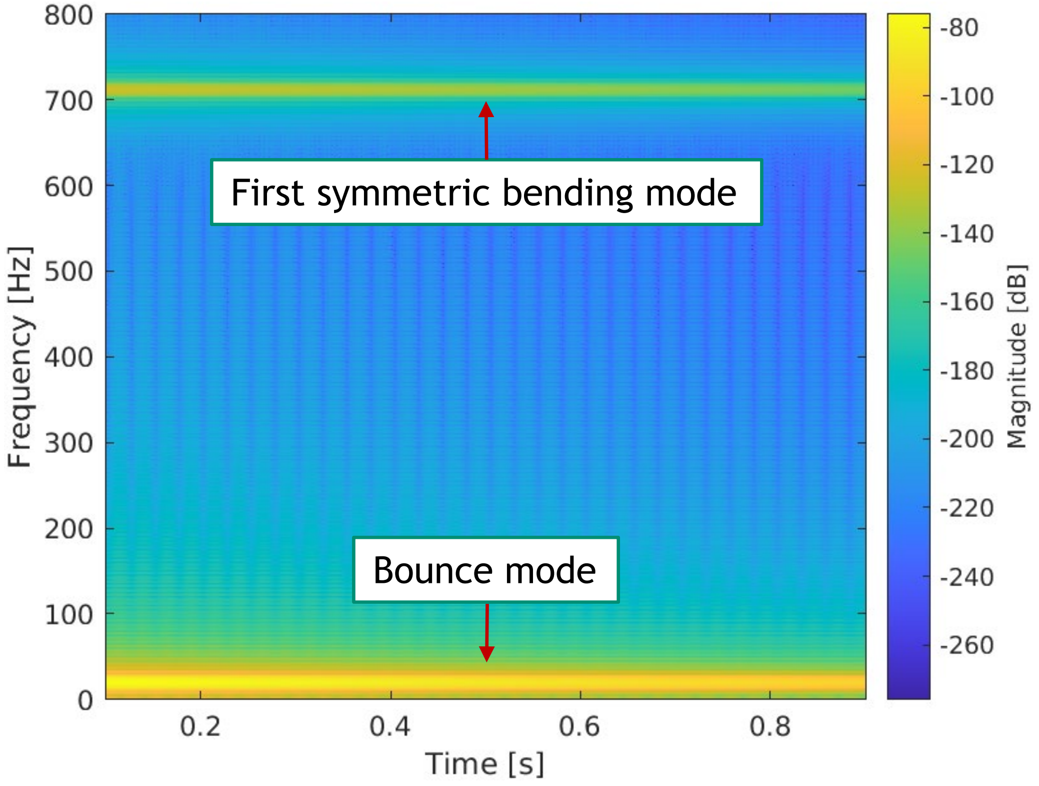


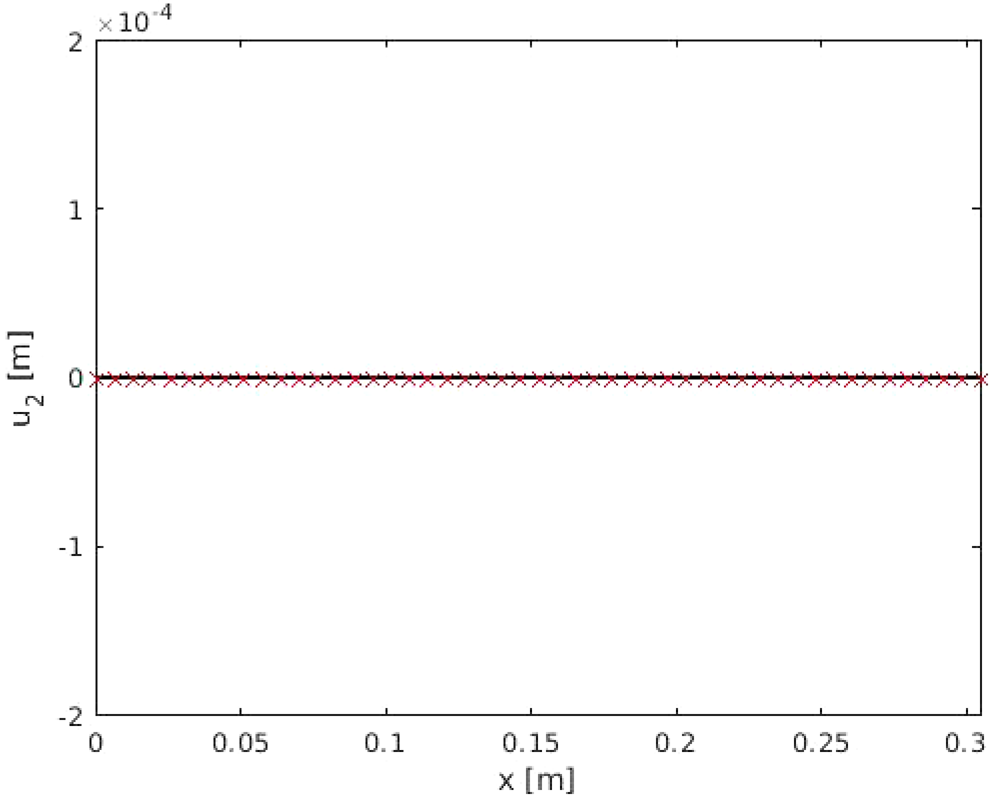


Transient Response - Linear Regime

- Emulate weak excitation with hammer
  - 5-N pulse for 4 ms at middle node
  - Best estimate of model parameters
  - Light Rayleigh damping

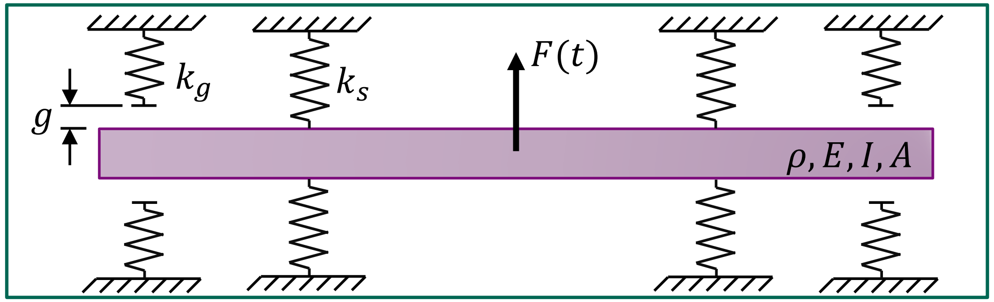


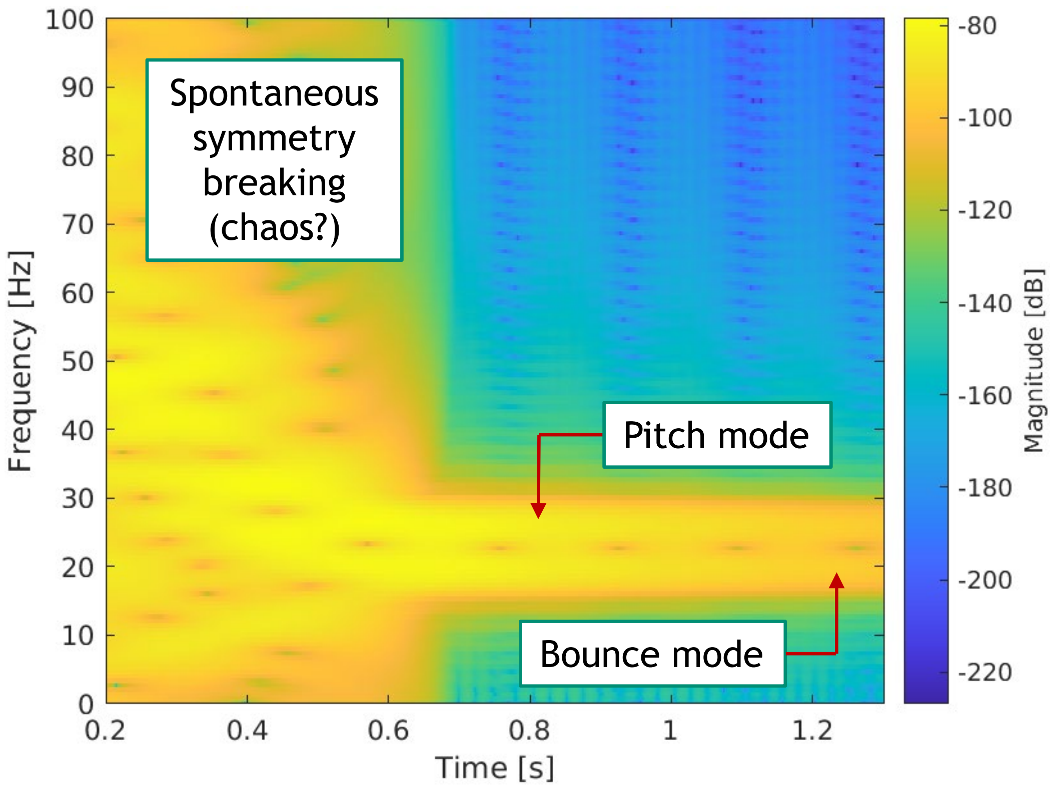


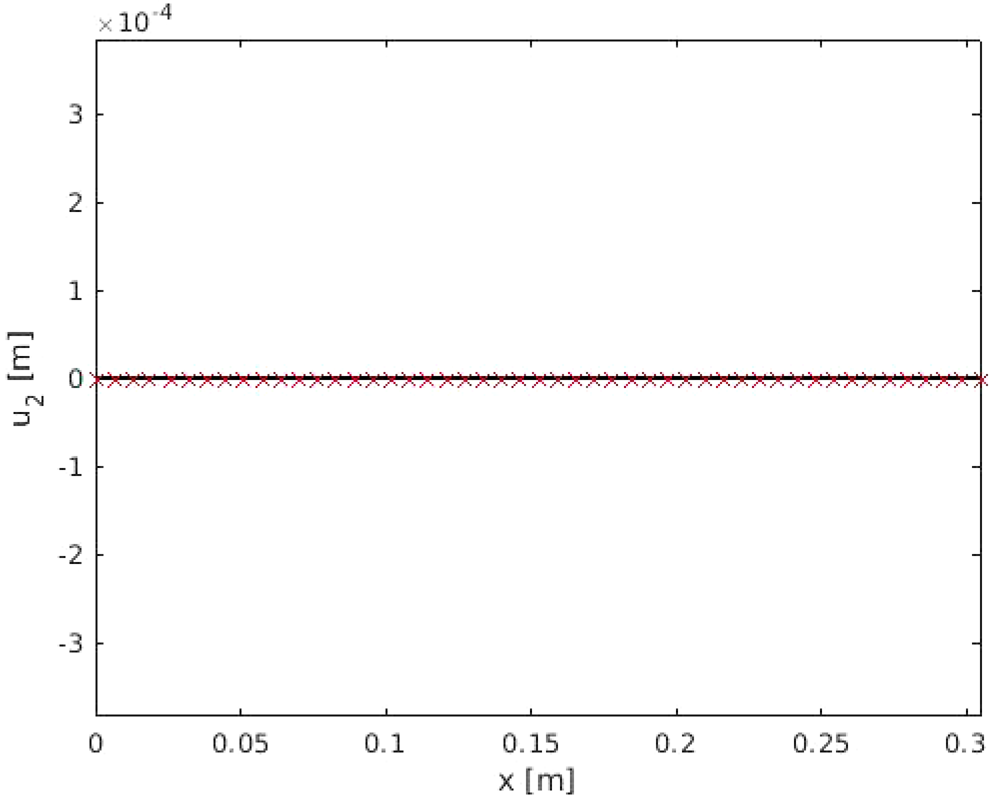


Transient Response - Nonlinear Regime

- Emulate <u>strong</u> excitation with hammer
  - <u>50-N</u> pulse for 4 ms at middle node
  - Best estimate of model parameters
  - Light Rayleigh damping

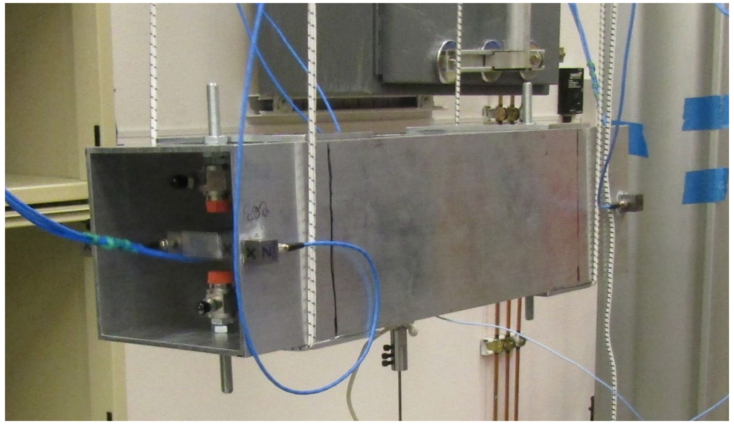


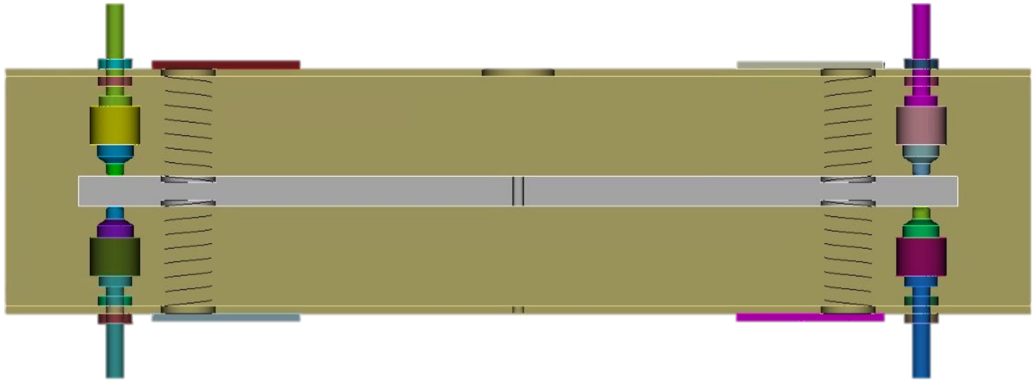


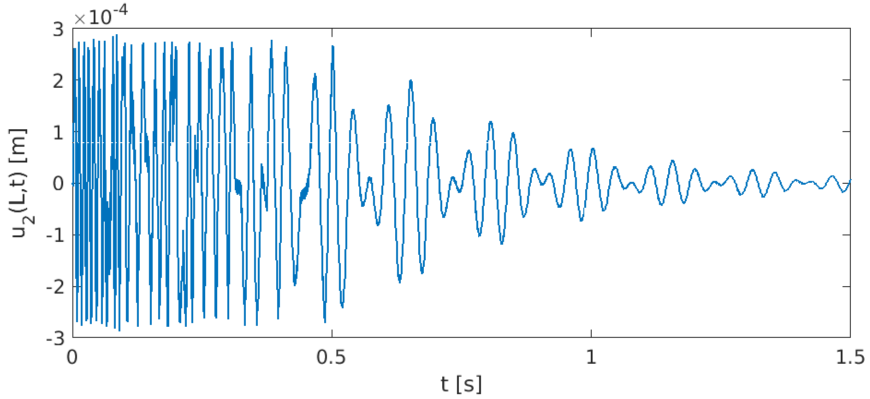


Outcomes

- Computational capabilities developed
  - Transient finite element code for simplified model
  - Multi-harmonic balance input files for nonlinear periodic response (free and forced)*
  - CUBIT input files for parametric CAD and hexahedral mesh generation
  - Sierra SD linear modal analysis input files
  - Sierra SM nonlinear transient input files
- Key conclusions
  - Linear modal testing and modal analysis techniques can successfully characterize the system when no impacts occur
  - Modal coupling may be difficult to observe due to instabilities and/or chaos
  - Highly discontinuous nature of contact complicates both modeling and experimentation







Future Work

Task 1
Analyze physical test model

- Generate a MAC for the linear closed-gap case
- Clarify testing plan to excite the nonlinear modes
- Possibly modify apparatus to decrease damping

Task 2
Develop Sierra model

- Vary the load type, and location
- Vary the gap size
- Change impact tip material

Task 3
Develop simplified FE model

- Incorporate more realistic damping mechanism
- Investigate potential instability/chaos
- Study nonlinear normal modes with MHB code

→ Get a clearer picture of the nonlinear normal modes and the effect of contact impacts

→ Relate this research back to the electromechanical assemblies of interest at Sandia

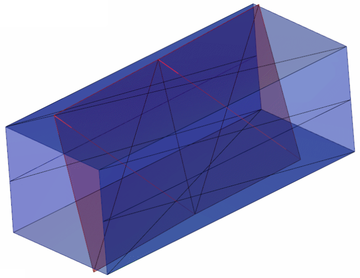
Acknowledgements

This research was conducted at the 2021 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.

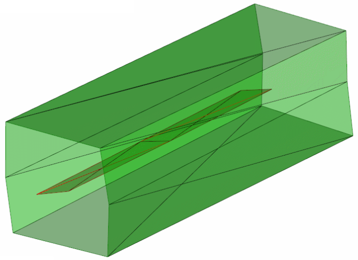
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Backup Slides

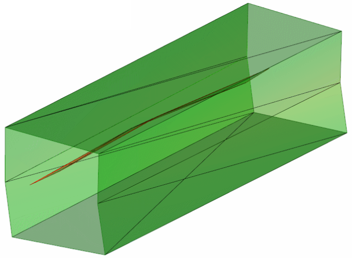
Rigid Body Mode Shapes – Closed Gap Case



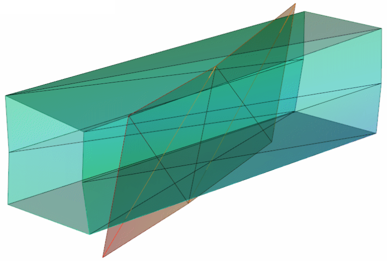
200.8 Hz



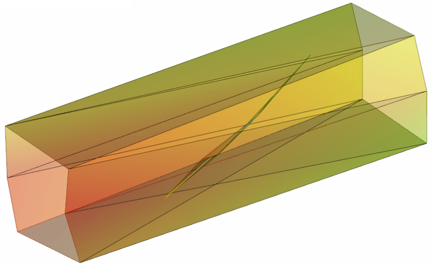
220.8 Hz



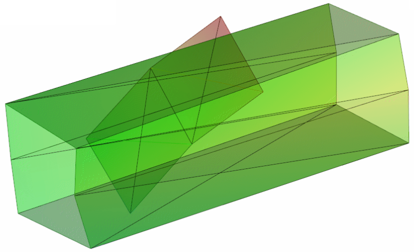
225.3 Hz



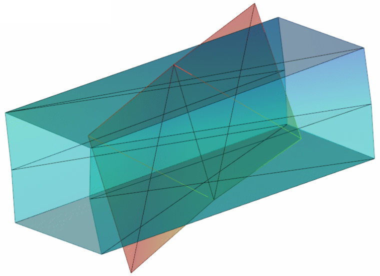
275.3 Hz



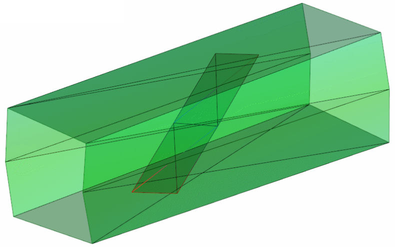
283.3 Hz



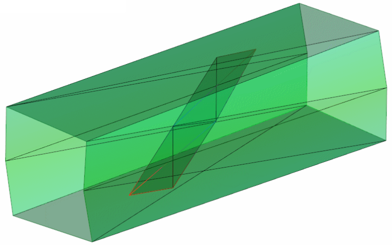
287.8 Hz



295.1 Hz

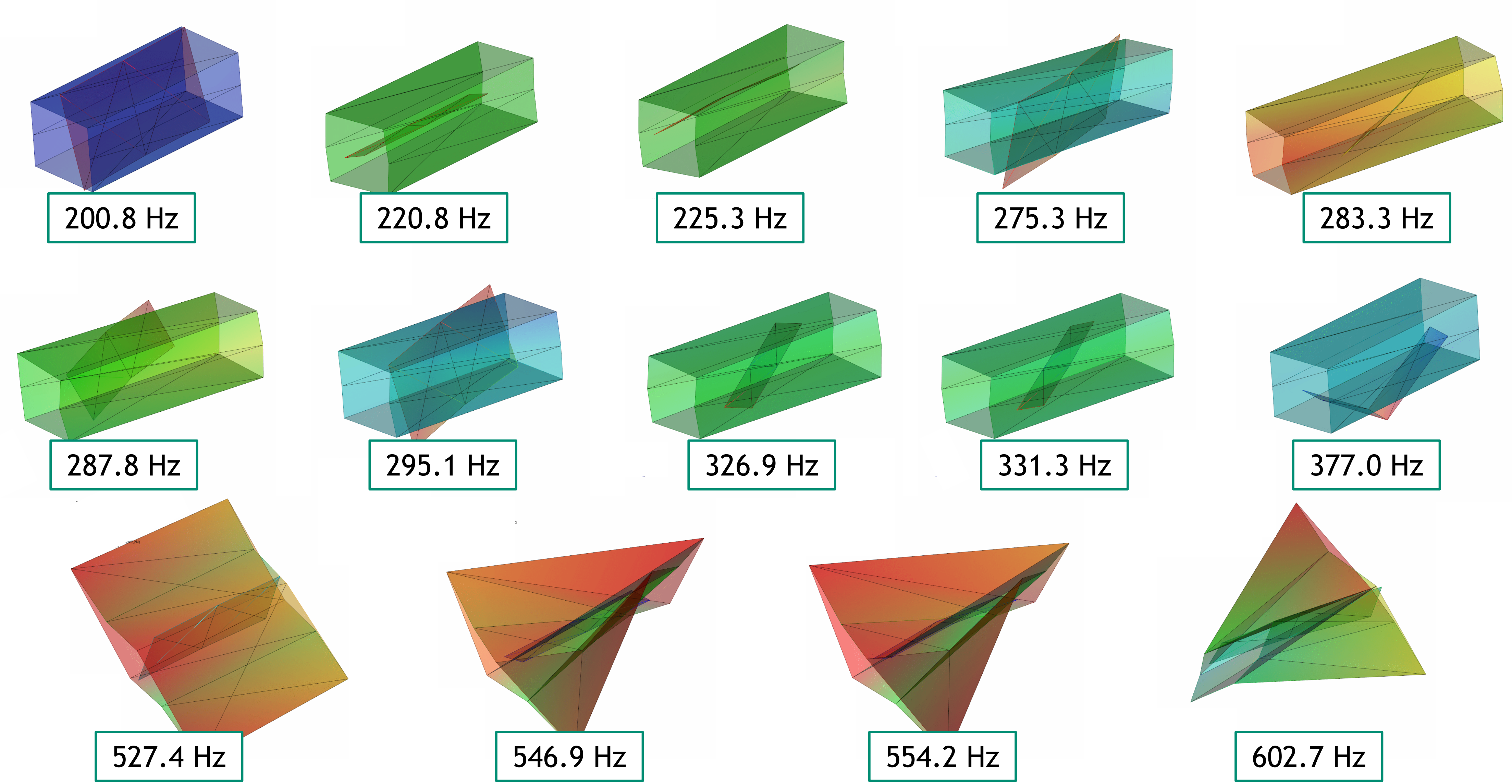


326.9 Hz

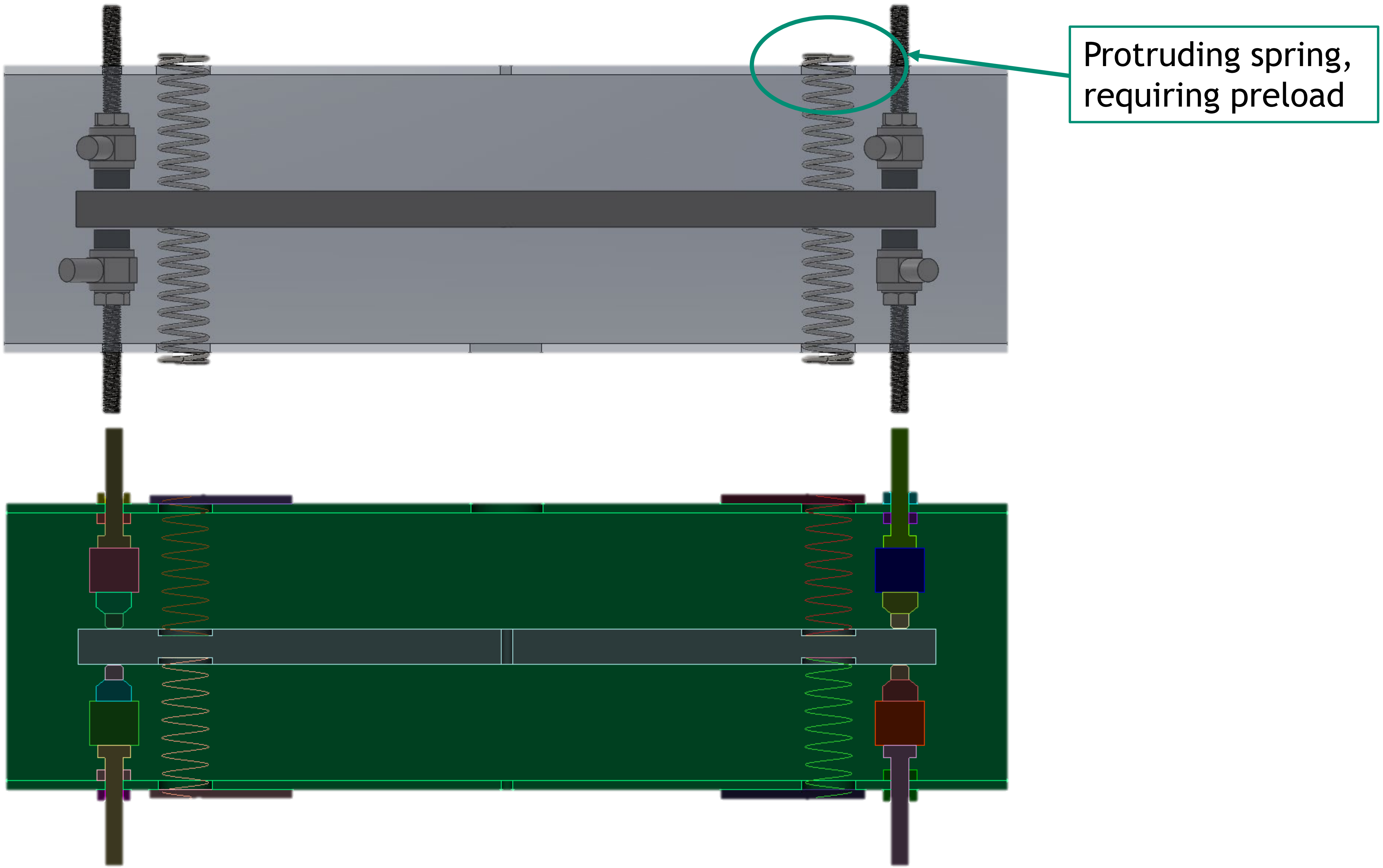


331.3 Hz

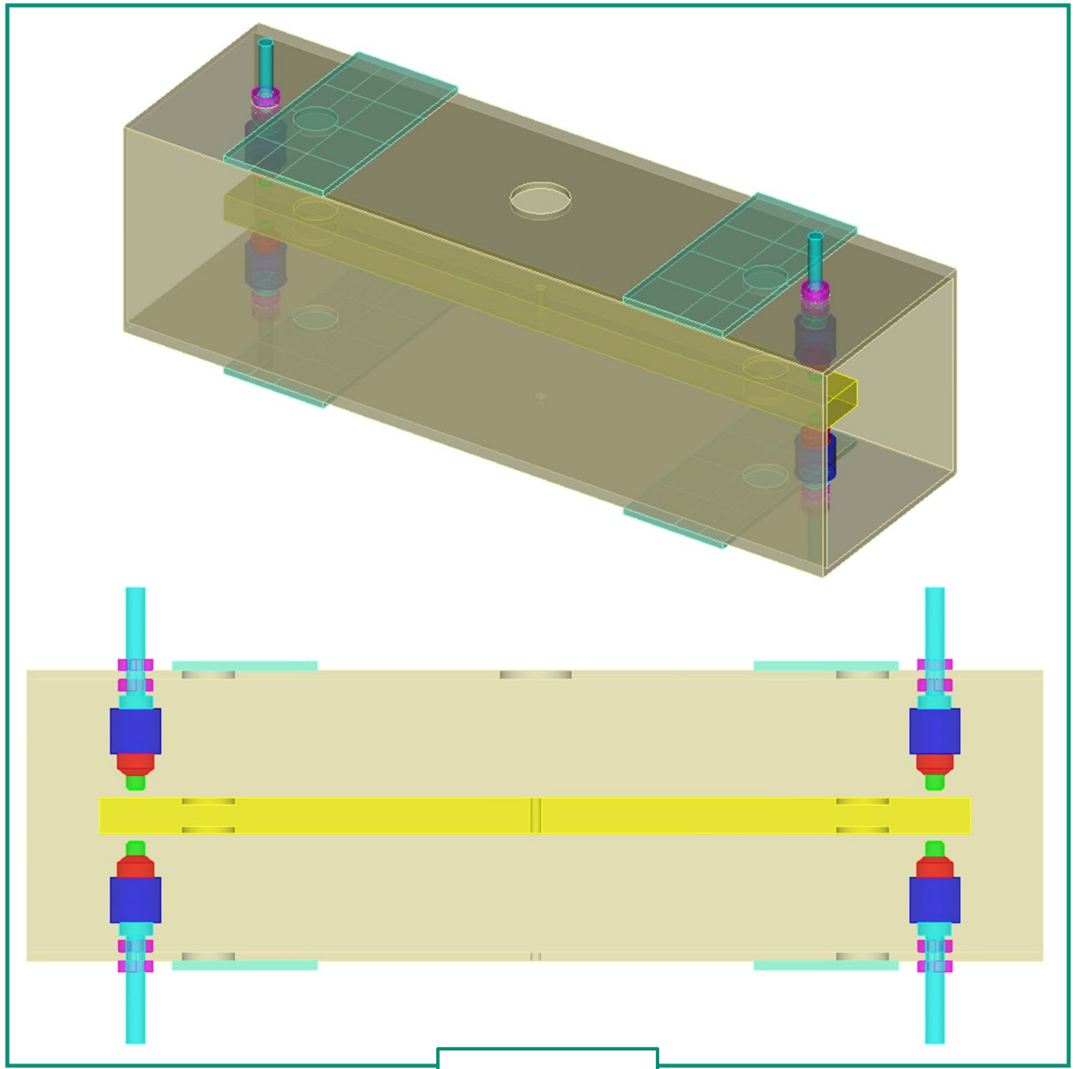
Mode Shapes – Closed Gap Case



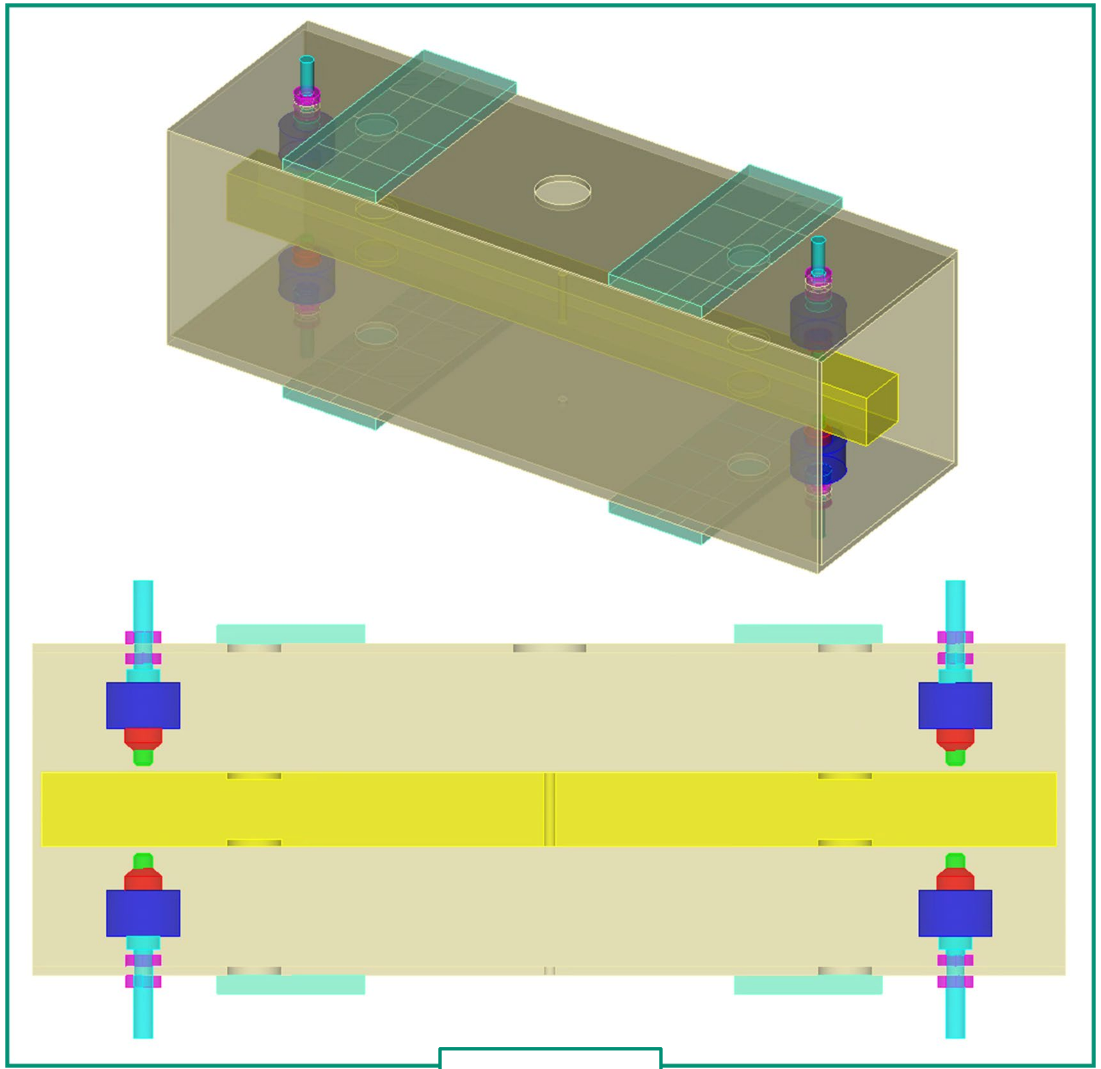
Mesh Generation



Automated Generation of Geometry and Mesh (cont'd)



Design A



Design B