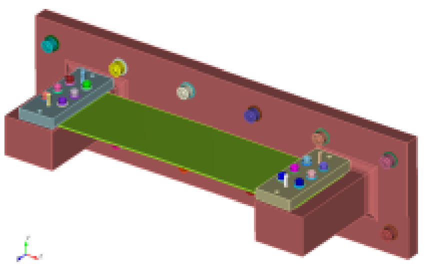
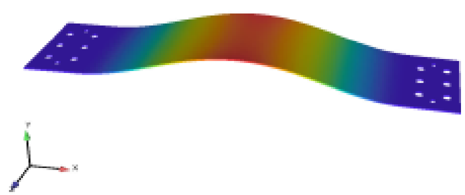
SAND2021-12915C

Sandia National Laboratories

2021 Tribomechadynamics Research Challenge: Sandia National Laboratories High-fidelity FEA Approach





Presented at IMAC XL in February 2022

Authors

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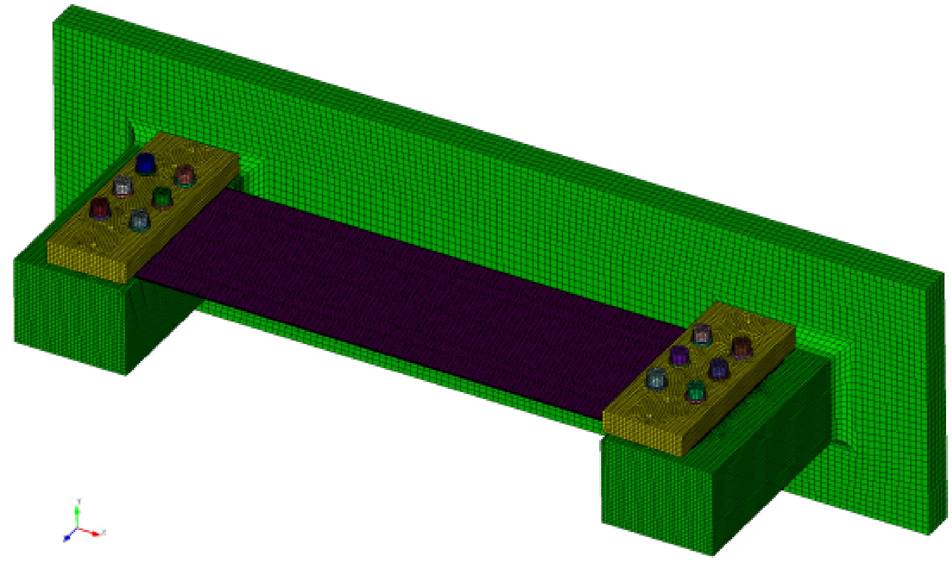
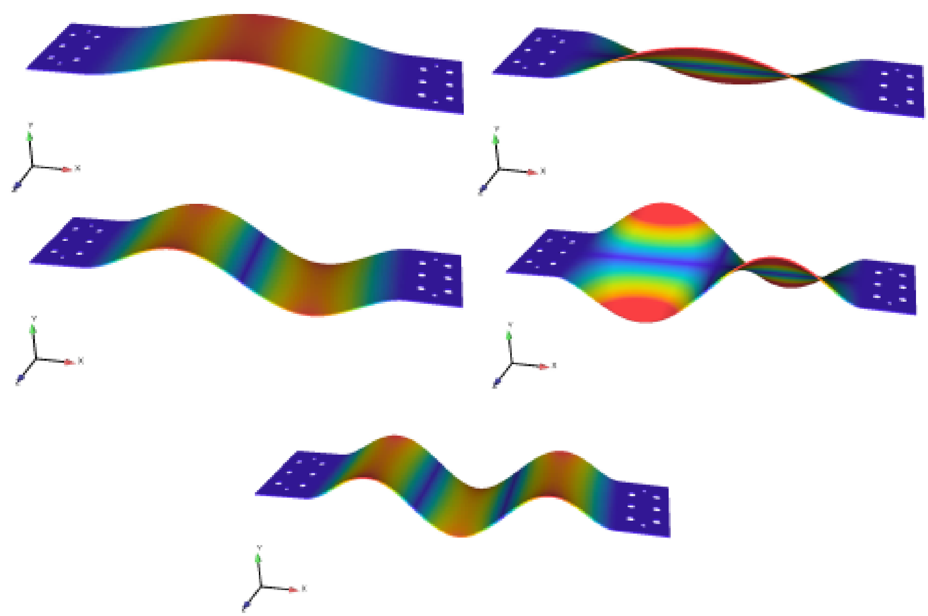
2021 Tribomechadynamic Research Challenge

Focus on blind predictions of nonlinear dynamic response
- How predictive are models with nonlinear physics?

Several participants (see talk by Krack et al.) exercise their modeling and simulation capability to address the challenge

Quantities of Interest:
- Linear natural frequencies of the first five vibration modes
- Amplitude-dependent frequency (normalized) and damping ratios of the lowest-frequency bending mode



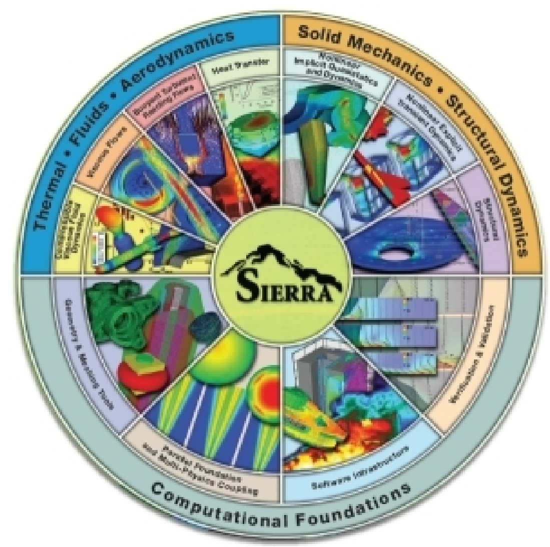


Methodology

Approach: develop a high-fidelity finite element model of the hardware and utilize time-stepping integration schemes available within most FEA packages to simulate the amplitude-dependent frequency and damping ratios

- **Advantages**: no specialized solvers required, able to leverage HPC platforms, widely accessible to industry, virtual test with parametric exploration

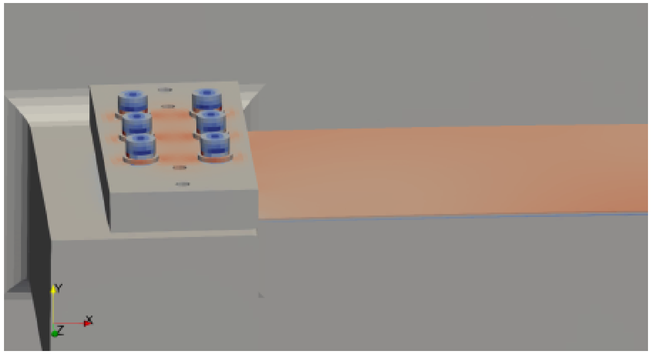
- **Disadvantages**: indirect approach to obtain quantity of interest, additional modeling effort for geometric complexity, numerical damping contaminates response, need access to computational resources, larger storage requirements and run times



Methodology

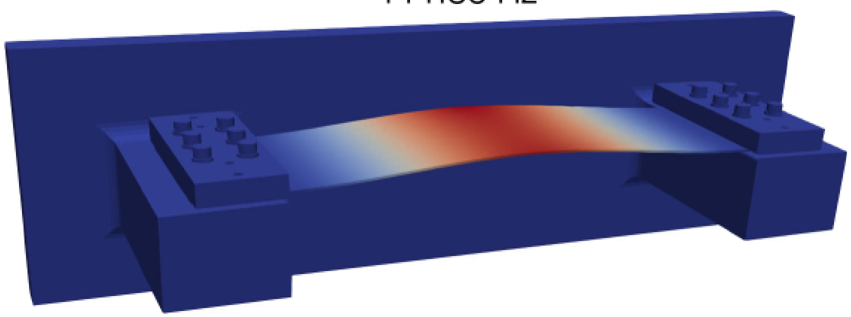
Step 1: Apply bolt preload that bends plate into place and calculate static equilibrium (Sierra/SM, quasi-static solve)

$$\mathbf{K}\mathbf{x}_{pre} + \mathbf{f}_{nl}(\mathbf{x}_{pre}) = \mathbf{f}_{pre}$$



Step 2: Linearize the solid mechanics model about preloaded equilibrium and calculate linear vibration modes (Sierra/SD, eigen solve)

$$\left(\mathbf{K} + \left.\frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{x}}\right|_{\mathbf{x}_{pre}} - \omega_r^2 \mathbf{M}\right)\boldsymbol{\phi}_r = \mathbf{0}$$



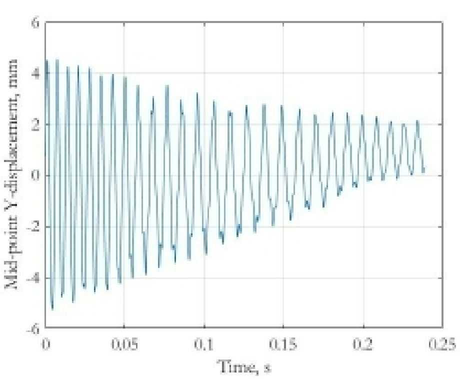
Methodology

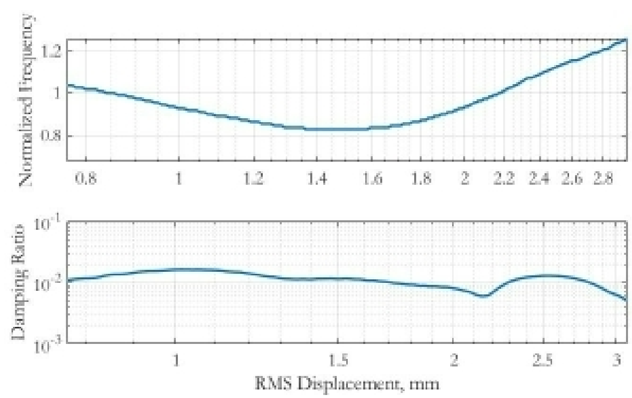
Step 3: Output a body force proportional to the mode shape of interest and apply to preloaded solid mechanics model (Sierra/SM, quasi-static solve)

$$\mathbf{K}\mathbf{x}_{mf} + \mathbf{f}_{nl}(\mathbf{x}_{mf}) = \mathbf{f}_{pre} + \alpha\mathbf{M}\boldsymbol{\phi}_r$$

Step 4: Release body force, integrate transient ring-down response, and fit frequency/damping curves using [1] (Sierra/SM, dynamic time integration solve)

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} + \mathbf{f}_{nl}(\mathbf{x}) = \mathbf{f}_{pre} \qquad \mathbf{x}_0 = \mathbf{x}_{mf} \qquad \mathbf{v}_0 = \mathbf{0}$$

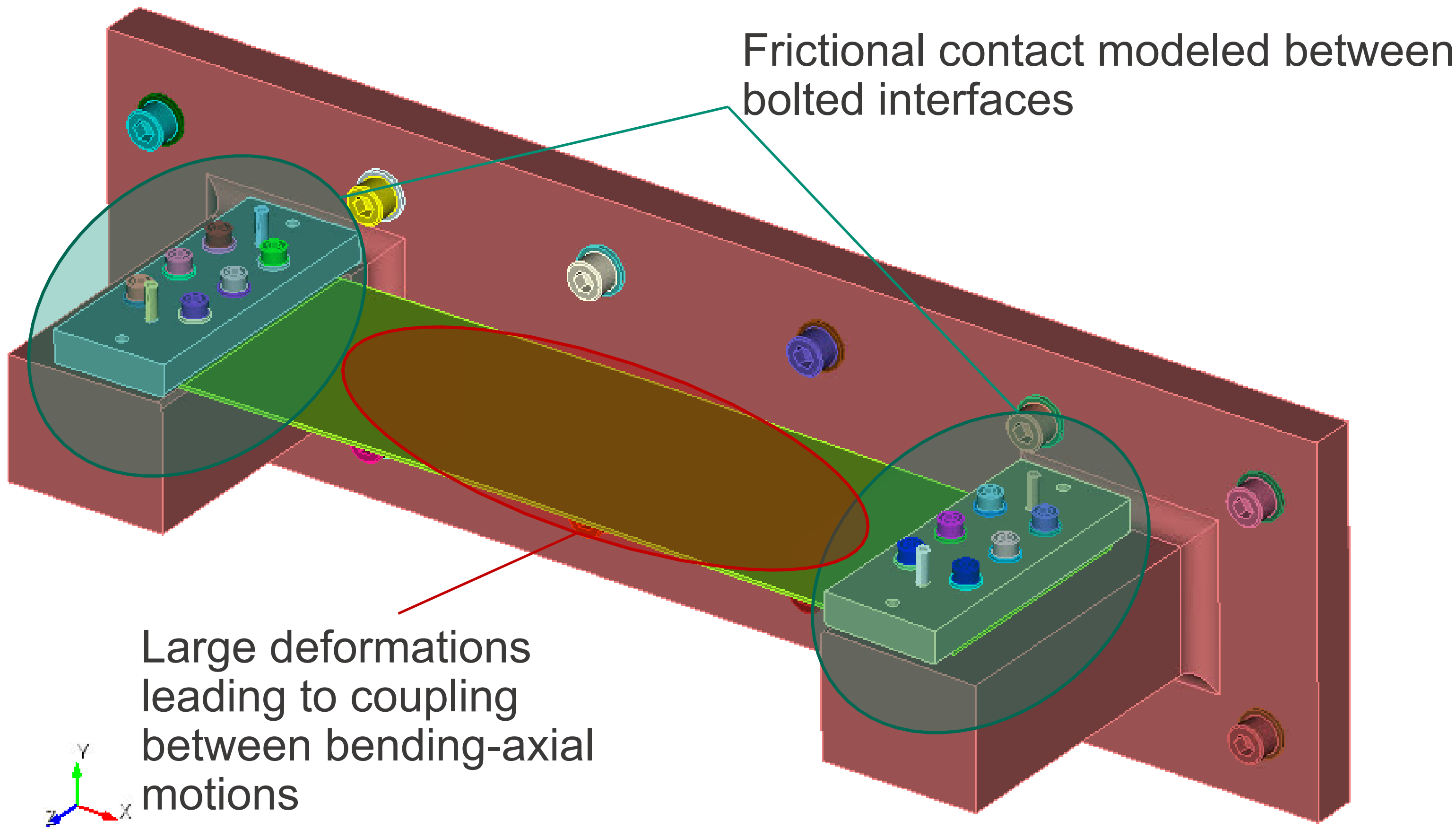




[1] Kuether, R.J. and M.R.W. Brake, "Instantaneous Frequency and Damping from Transient Ring-Down Data," in *34th International Modal Analysis Conference (IMAC XXXIV)*, Orlando, Florida, January 2016.

Model Overview

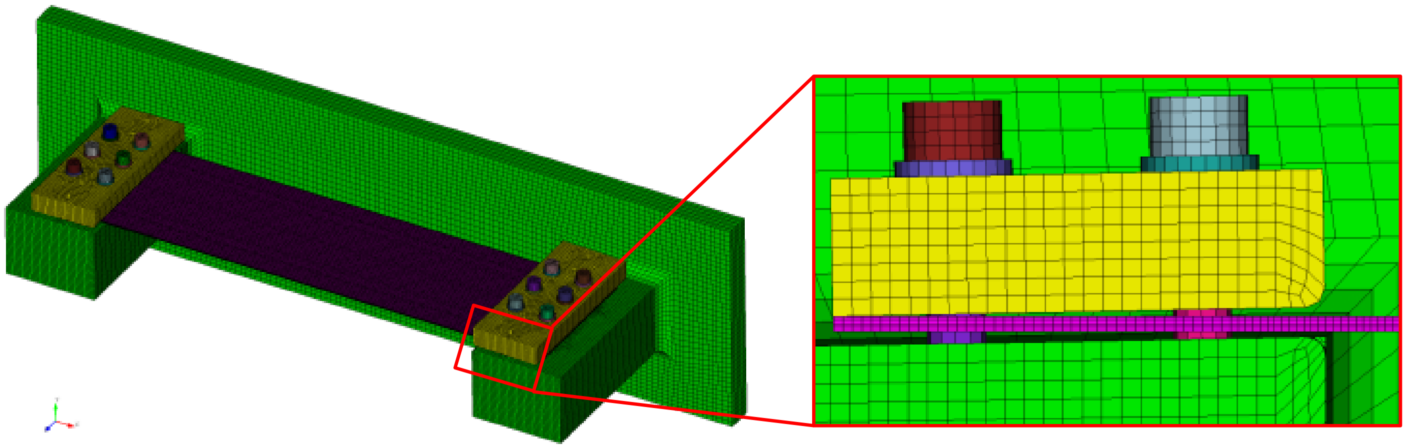
All materials assumed linear elastic



Model Overview

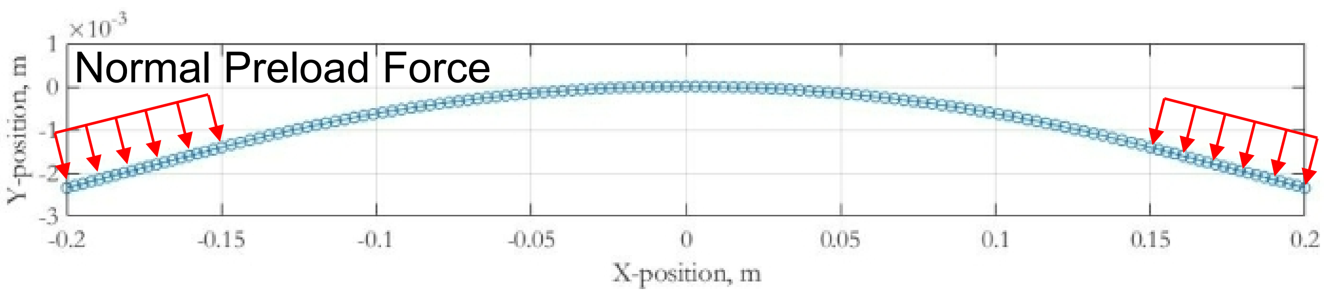
High-fidelity finite element model

- 431K Hex 8 elements (selective deviatoric, four through plate thickness)
- Plate initially flat
- Explicit central difference time integration scheme



Low-fidelity finite element model

- 136 two-dimensional co-rotational beam elements with Jenkins elements (constant normal load)
- Plate initially curved
- Implicit Newmark-Beta time integration scheme



Computational Time

Linux RHEL 7.7 computing environment

- Local machine: 8 cores, Intel Xeon E3-1585L 3 GHz, 64 GB RAM
- Cluster: 9 nodes/432 cores, Intel Cascade Lake 8268 2.9 GHz, 192 GB RAM per node
  - Selected # of cores to keep max run time < 48 hours

Pre-processing

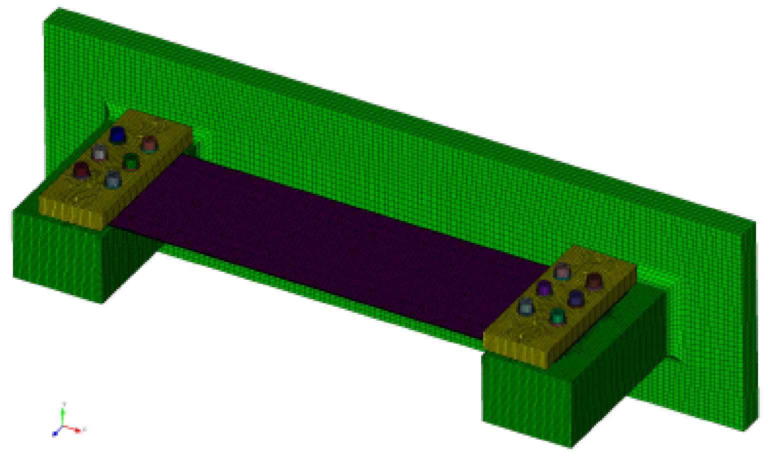
- Meshing and model development: 30 hours
- Mesh file run time: 5 min (local machine)

Processing

- SM preload: 3 hours (cluster)
- SD modal: 2 min (cluster)
- SM ringdown: 48 hours (cluster)

Post-processing

- MATLAB script: 2 min (local machine)
- Visualization: 5 hours (2 nodes cluster)



Windows 10 computing environment with MATLAB 2021a

- Intel(R) Core™ i7-8665U CPU 1.90 GHz, 32 GB RAM

Pre-processing

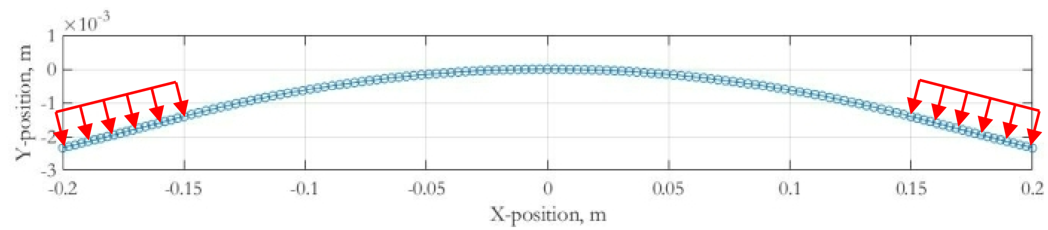
- Meshing and model development: 8 hours

Processing

- Preload: 2.5 sec
- Modal: 0.04 sec
- Ringdown: 33.3 min

Post-processing

- MATLAB Script: 0.9 sec



Linearized Vibration Modes - High-fidelity FEM

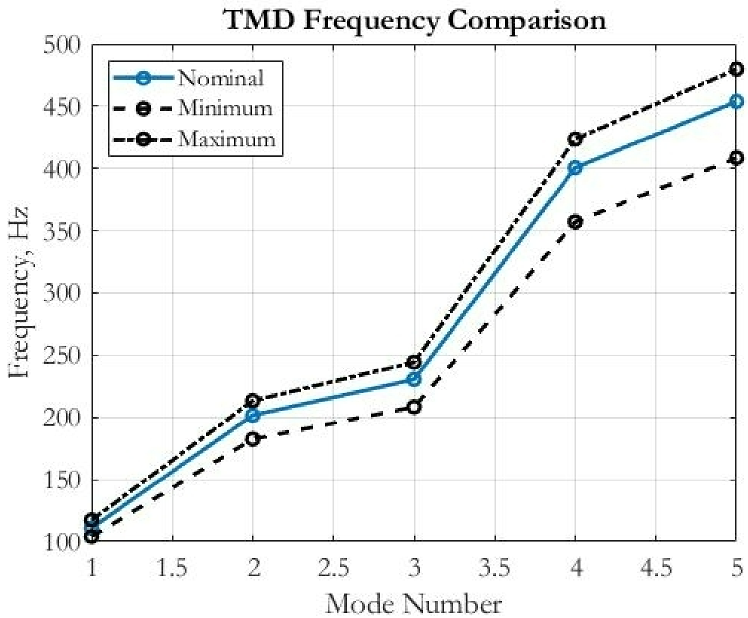
Linearized Modal Analysis UQ to study range of first 5 linear frequencies

Parameters

- Thickness: 1.5 ± 0.05 mm (from manufacturing tolerance)
- Modulus: 189.6 ± 10.5 Gpa (MMPDS and Thyssen Krupp data sheets - depending on heat treatment)
- Density: 7916.4 ± 38.8 kg/m^3 (GRANTA materials database range)
- Contact state: Fully tied or cutoff variable

Bounding cases

- Minimum frequency: Min thickness, min modulus, max density, cutoff variable
- Maximum frequency: Max thickness, max modulus, min density, fully tied



Mode	Description	Nominal Frequency [Hz]	Minimum Frequency [Hz]	Maximum Frequency [Hz]	Min/Max % Diff
1	1st bending	111.1	104.2	117.5	12.8
2	1st torsion	201.6	182.5	213.3	16.9
3	2nd bending	230.4	208.3	244.3	17.3
4	2nd torsion	400.7	357.1	423.6	18.6
5	3rd bending	453.8	408.5	480.0	17.5

Linearized Vibration Modes - Low-fidelity FEM

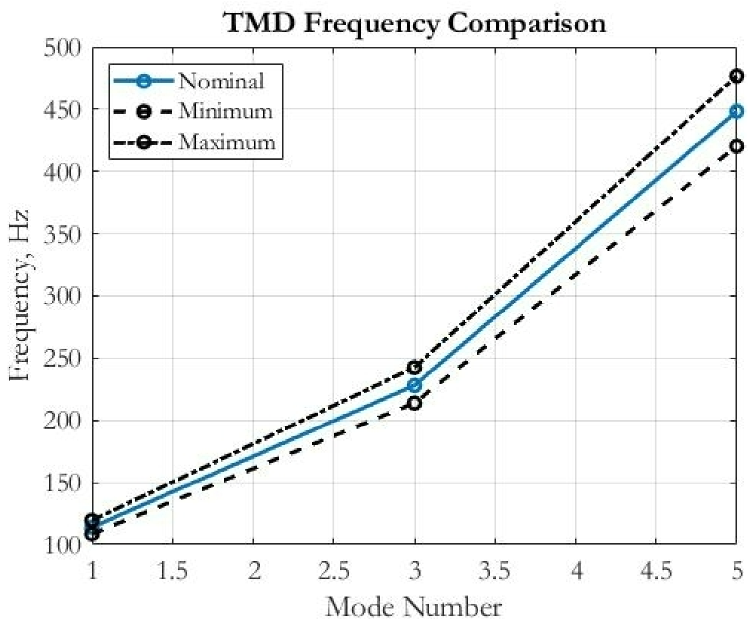
Linearized Modal Analysis UQ to study range of first 3 linear frequencies

Parameters

- Thickness: 1.5 ± 0.05 mm
- Modulus: 189.6 ± 10.5 GPa
- Density: 7916.4 ± 38.8 kg/m^3

Bounding cases

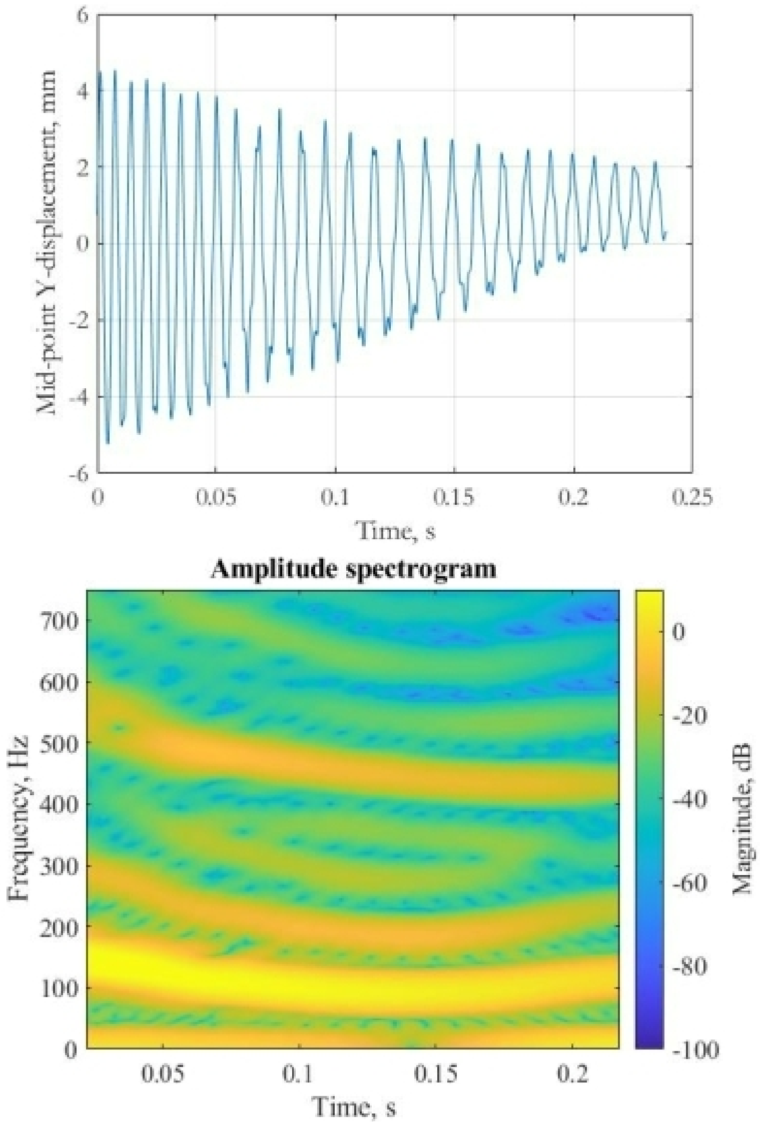
- Minimum frequency: Min thickness, min modulus, max density
- Maximum frequency: Max thickness, max modulus, min density



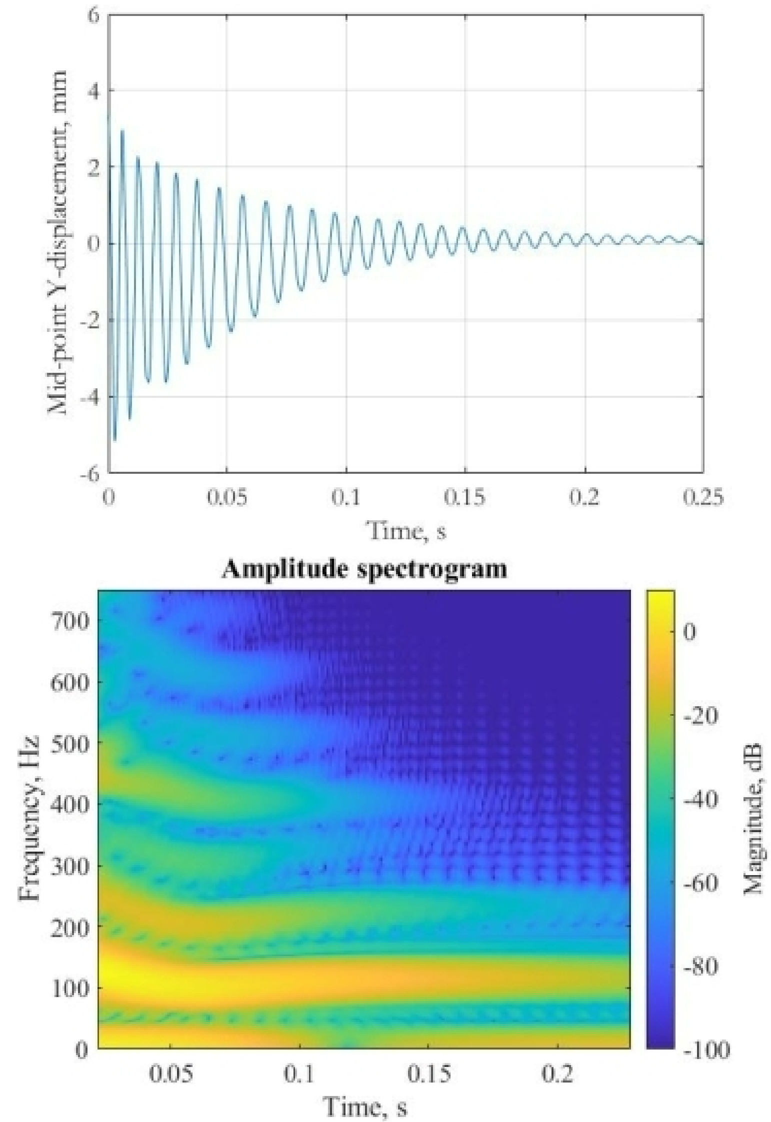
Mode	Description	Nominal Frequency [Hz]	Minimum Frequency [Hz]	Maximum Frequency [Hz]	Min/Max % Diff
1	1st bending	114.1	108.7	119.6	10.0
2	1st torsion	N/A	N/A	N/A	N/A
3	2nd bending	228.0	213.8	242.5	13.4
4	2nd torsion	N/A	N/A	N/A	N/A
5	3rd bending	448.3	420.4	476.8	13.4

Amplitude-dependent Frequency and Damping Ratio

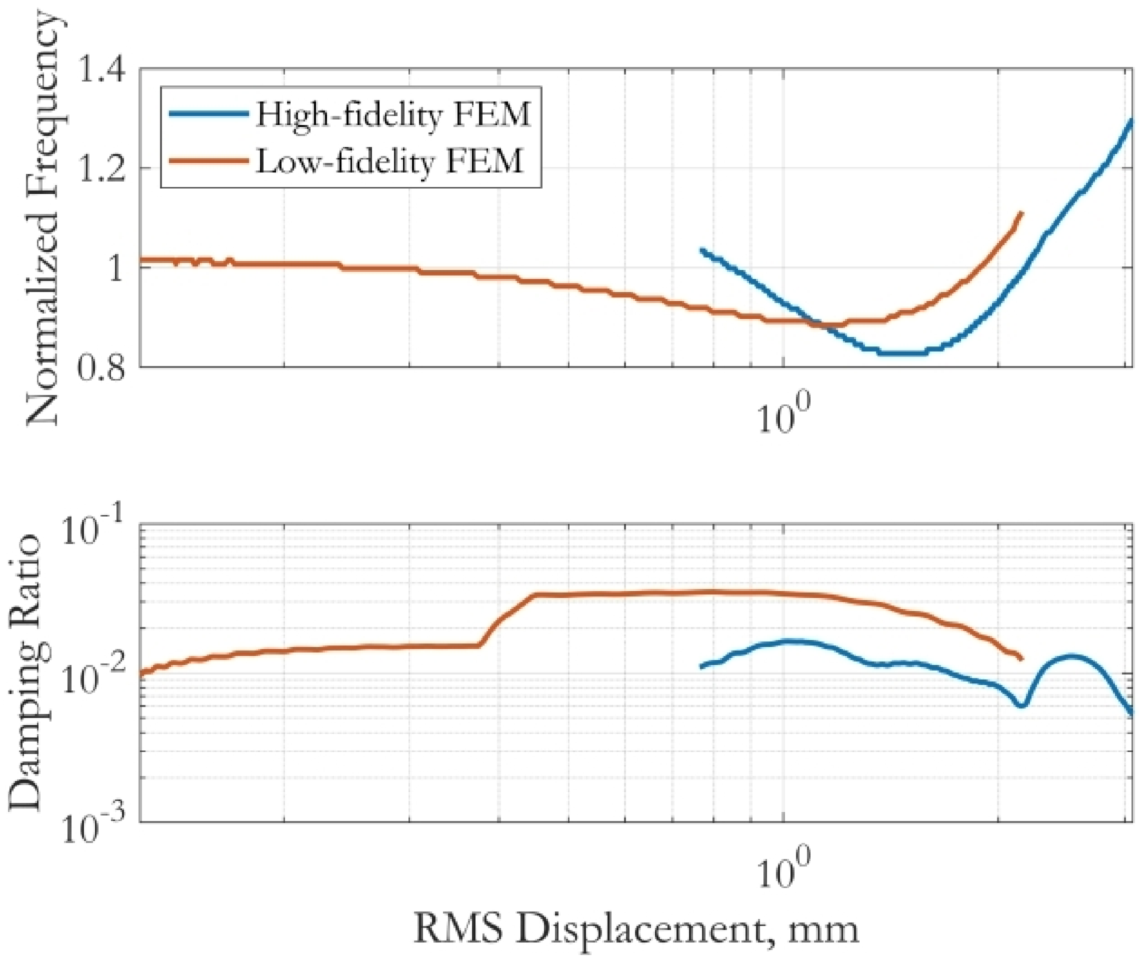
High-fidelity finite element model



Low-fidelity finite element model

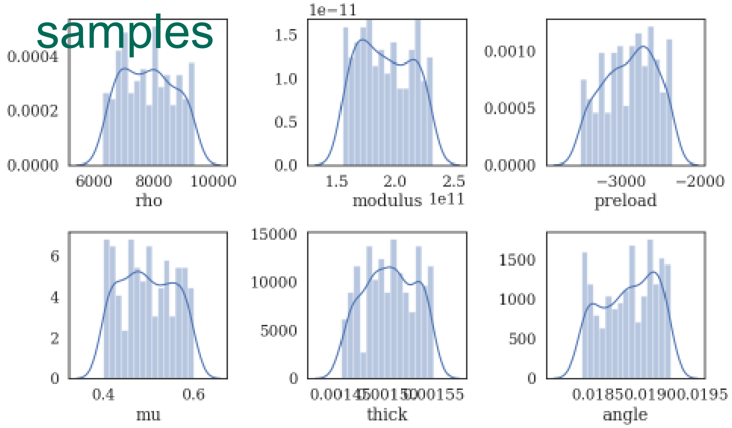


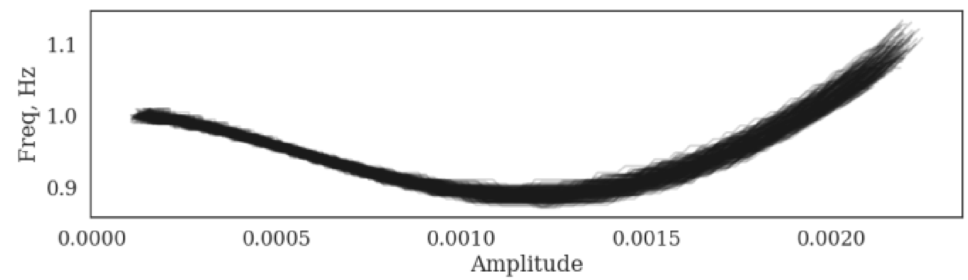
Amplitude-dependent Frequency and Damping Ratio

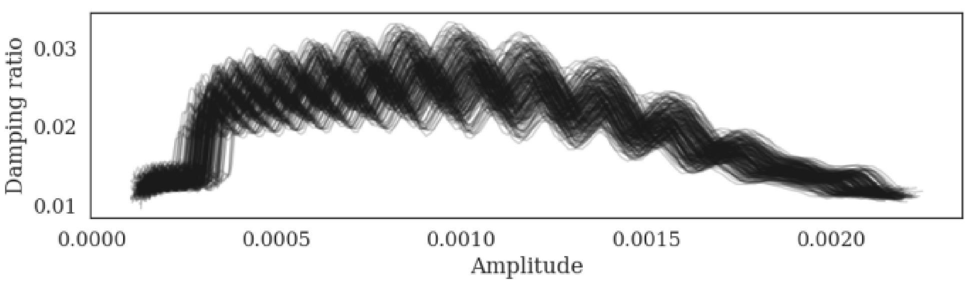


Low-fidelity FEM – Sensitivity Analysis

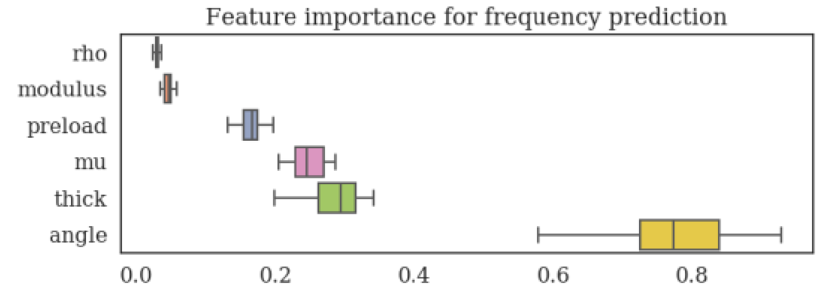
Random uniform parameter samples

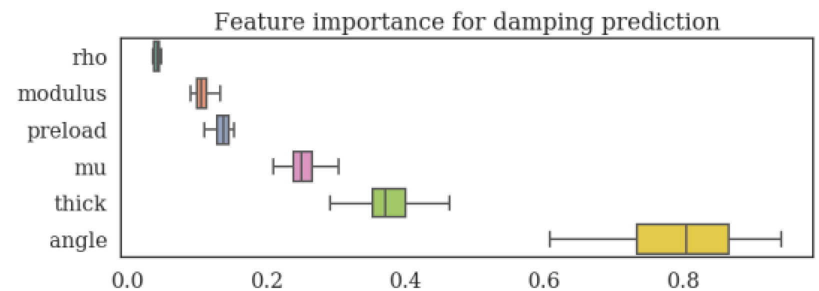






Feature importance computed from fitting a Random Forest regression algorithm to predict damping and frequency, and extracting influence from each parameter.





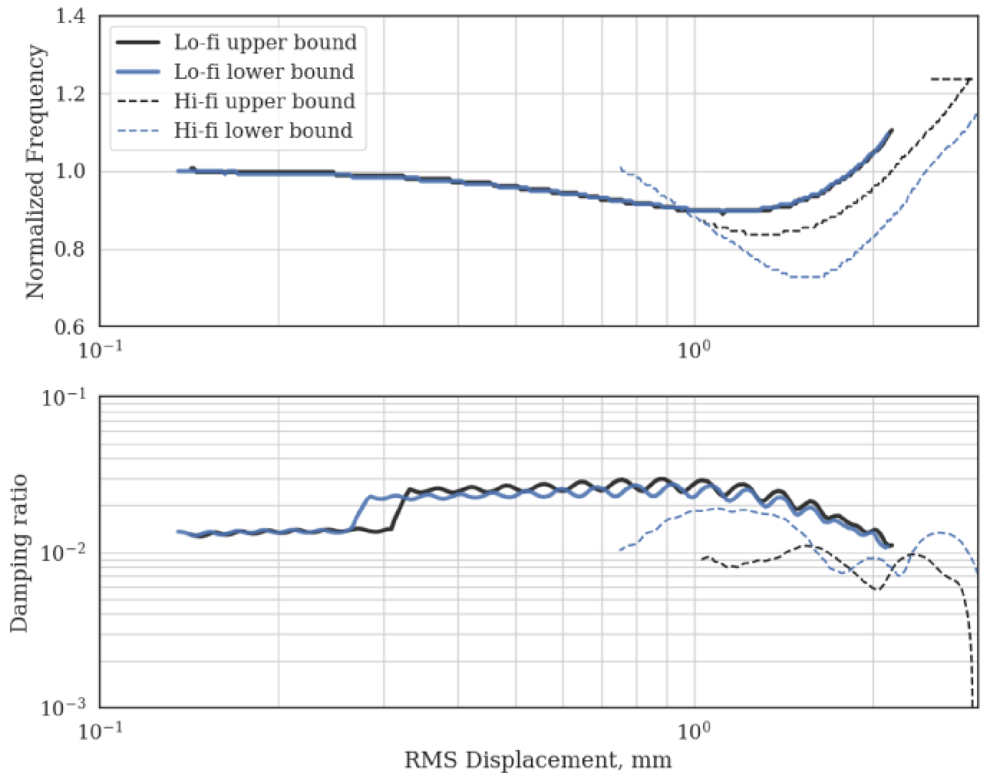
Angle, thickness, and friction coefficient were the most influential parameters.

High-fidelity FEM – Sensitivity Analysis

The low-fidelity model was used to determine the parameter sets that resulted in a lower and upper bound in the amplitude-dependent frequency and damping response. The parameter space was bounded by parameter value ranges that were determined from tolerances and uncertainty in the material, as shown in slid

Upper bound:
Modulus: 157 Gpa
Density: 8443 kg/m³
Friction coeff.: 0.45

Lower bound:
Modulus: 229 Gpa
Density: 6732 kg/m³
Friction coeff.: 0.60



These results indicates a certain amount of correlation between the low and high fidelity models as seen by the fact that certain trends are consistent between both sets of curves

Conclusions

A high-fidelity finite element modeling approach was deployed to predict the amplitude-dependent frequency and damping ratio of the 2021 TMD Challenge Problem

- Step 1: Apply preload to bolted interfaces
- Step 2: Linearize to calculate vibration modes about preload equilibrium
- Step 3: Calculate modal force
- Step 4: Apply modal force to preloaded structure, integrate transient free response and fit damping/frequency to simulated data

Structure showed an initial softening behavior, due to slip within the joint and geometric nonlinearity due to softening behavior of curved plate. Hardening behavior at higher amplitudes caused by geometric nonlinearity (bending-stretching coupling).

Sensitivity analysis on low-fidelity FEM reveals which parameters most influential to the frequency and damping curves – some correlation to sensitivities with high-fidelity FEM

Any Questions?

Contact information

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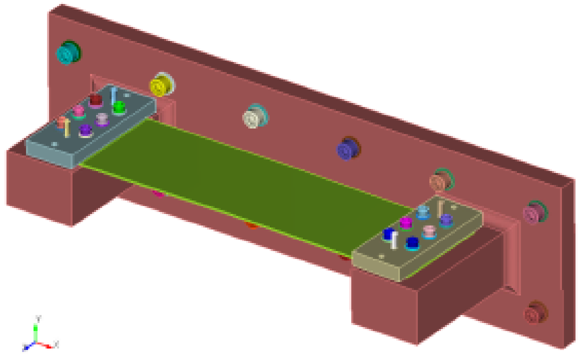

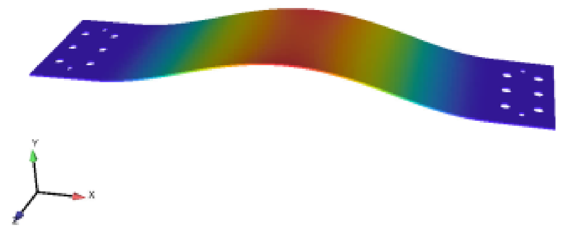

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