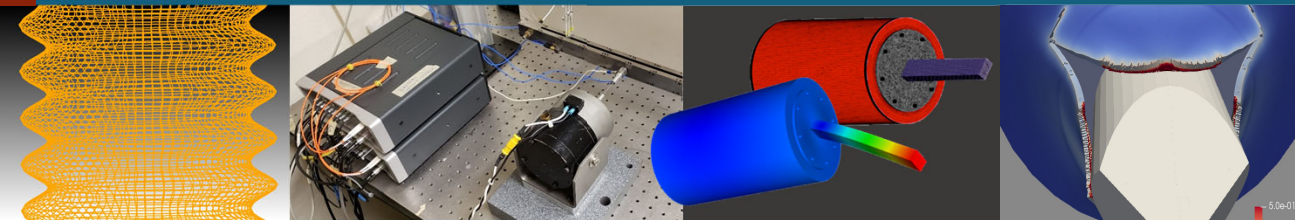# Investigation into Potential Modal Coupling in a Bolted Structure using a Nonlinear ROM and QSMA

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Background And Motivation – Previous Experiment

◦ During tension/compression fatigue testing of the bolt connecting a kettlebell to a fixture, a decrease in damping of Mode 5 was observed with increased excitation amplitude.

◦ Non-monotonic behavior such as this can be observed for a single mode in macro-slip, but this was not expected at these vibration levels

◦ Additionally, the contributions of Modes 4 and 5 were found to change (SVD shapes 1 and 2, respectively), indicating that the modes were interacting
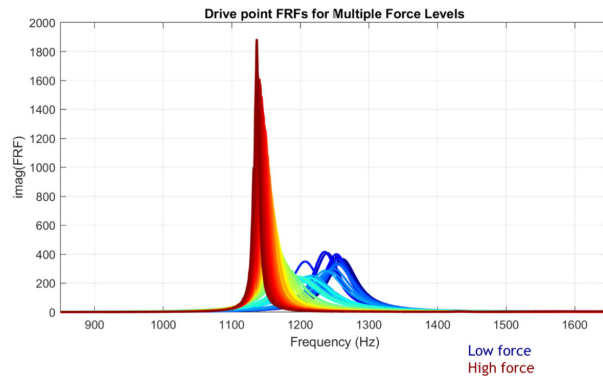
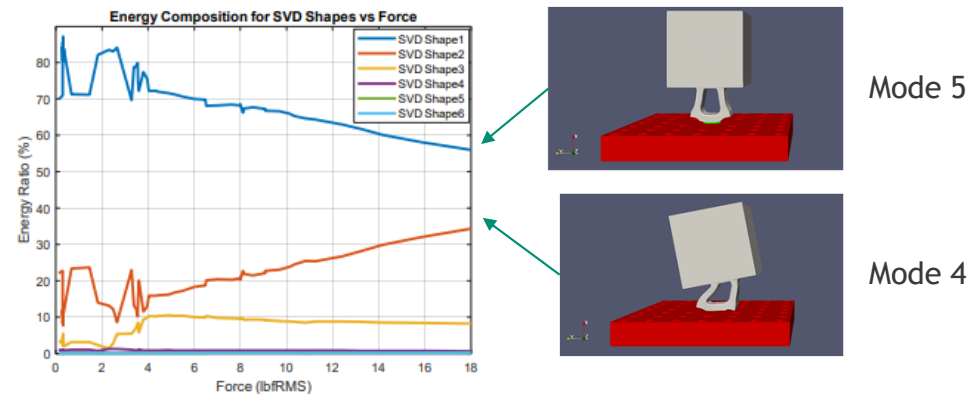Fig 1. FRFs for various forcing levels [1]

Fig 2. SVD shape energy composition [1]

◦ Motivating question: is the decrease in damping due to modal coupling, or a nonlinear characteristic of one of Mode 4 or Mode 5?

◦ Modal coupling definition: when the amplitude dependent frequencies and damping ratios are dependent on the modal amplitudes of other modes

[1] Khan, M., Hunter, P., Pacini, B., Roettgen, D., Schoenherr, T.: Evaluation of joint modeling techniques using calibration and fatigue assessment of a bolted structure. International Modal Analysis Conference (2020)

Project Overview

Project Goal: Determine if the decrease in damping observed in the bolted structure is caused by modal coupling of the axial and 2nd bending mode in Y and attempt to model this behavior

Structure of This Presentation:

1. Experimental system and setup

2. Results of linear and nonlinear testing

3. Nonlinear modeling approaches

4. QSMA results

5. Nonlinear reduced order model (ROM) results

6. Conclusion and future work

Experimental Setup

Location of Force Sensors

○ Node 1001: excites Mode 5

○ Node 1002: excites both modes

○ Node 1003: excites Mode 4

Mode 4   Mode 5

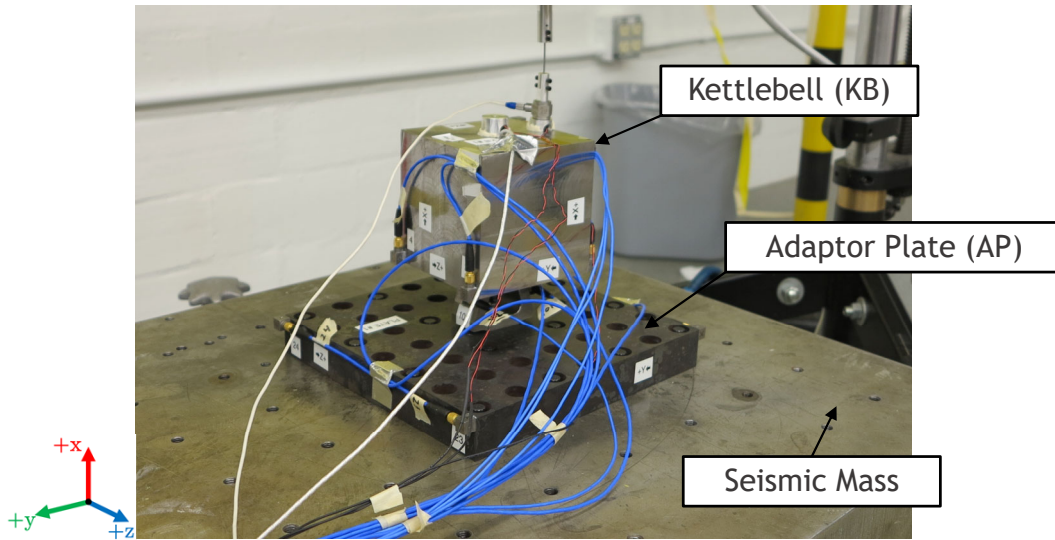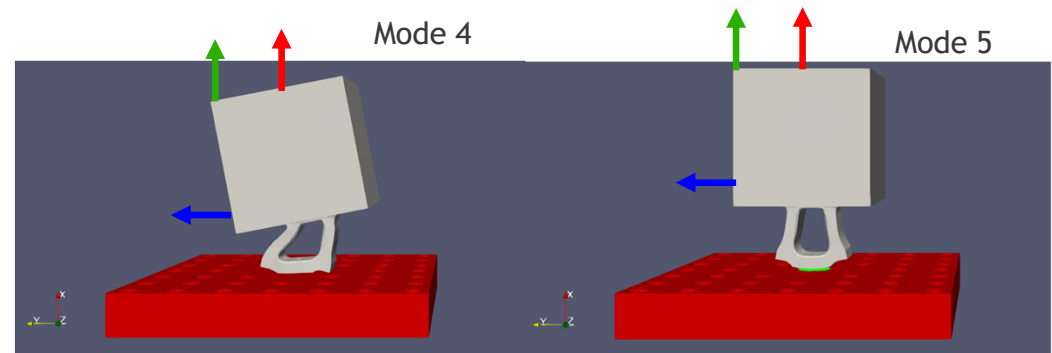Kettlebell (KB)

Adaptor Plate (AP)

Seismic Mass

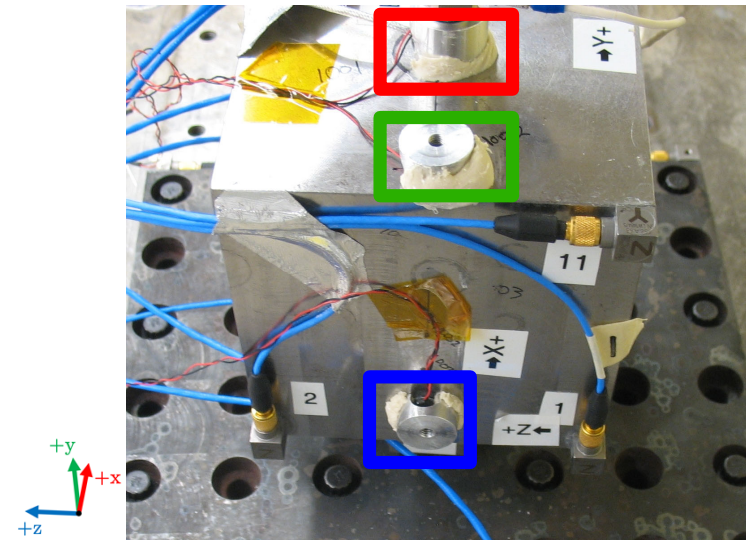Fig 3. Full setup for a shaker test

Fig 4. Close-up of kettlebell with reference node/drive point locations

Experimental System

- KB and AP are made from 4340 steel

- Boundary Conditions: Fixed base – Free end

- System is composed of two monolithic components

- The setup was originally devised for the purpose of studying fatigue failure of the bolt

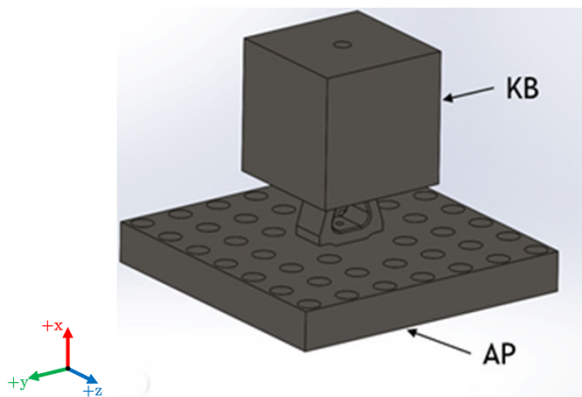- Linear and nonlinear testing was done through low-level and high-level impact testing, respectively
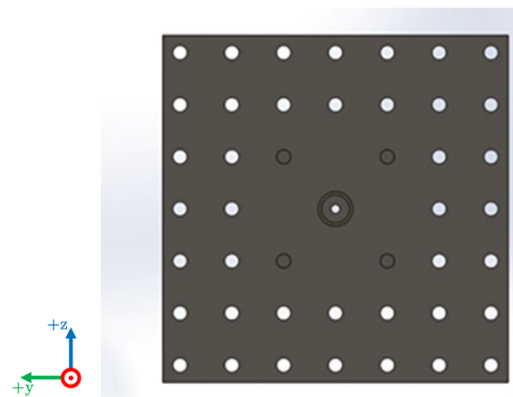

Fig 5. Isometric view of structure
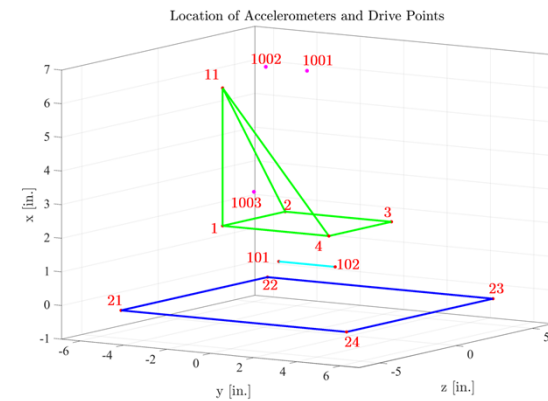

Fig 6. Bottom view of structure

Fig 7. Location of accelerometer, drive points and associated labels

Linear Testing Data

○ Linear (low level) impact testing was conducted for the system, and the following results were obtained

Table 1: Linear system parameters

| Mode	Description	Frequency [Hz]	Damping
1	1st bending in z	101.5	0.01072
2	1st bending in y	178.9	0.00423
3	1st torsion about x	348.1	0.00402
4	2nd bending in y	1137.3	0.00045
5	1st axial in x	1182.2	0.00266
6	2nd bending in z	1469.0	0.00290

○ The close spacing of Mode 4 and Mode 5 (4% difference), made analysis of the system difficult

Nonlinear Trends Extracted From Experiments

○ High level impact testing was conducted at the three drive points
- ○ 1001X: excites mostly Mode 5
- ○ 1002X: excites both Modes 4 and 5
- ○ 1003Y: excites mostly Mode 4

○ Nonlinear trend extraction procedure:
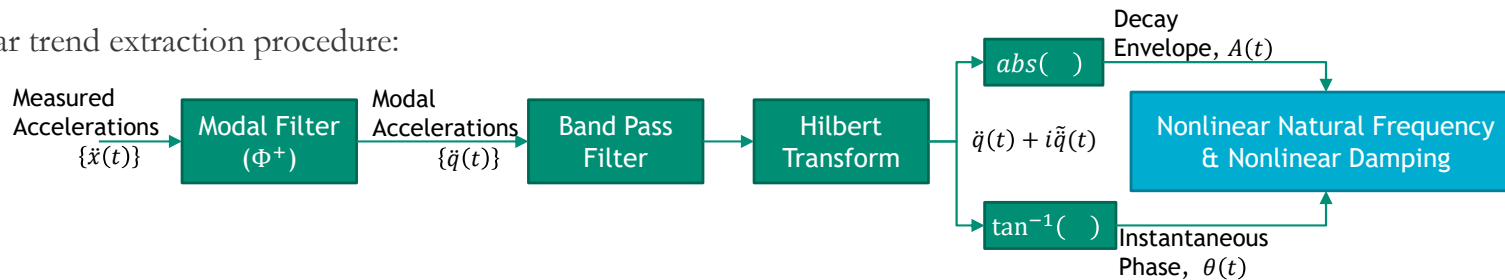
○ The Mode 5 response could not be adequately isolated without use of a narrow band pass filter (bandwidth = ±7% of frequency at peak response) → **Increased uncertainty in the extracted nonlinear trends for Mode 5**
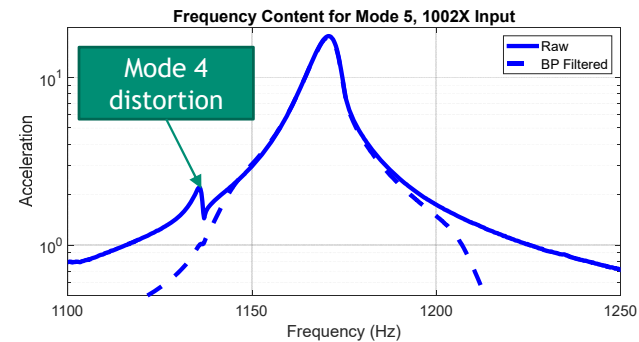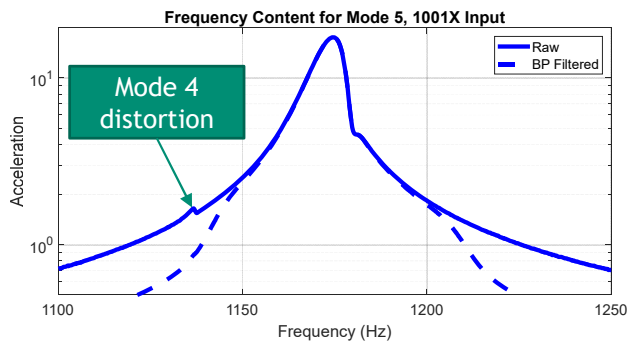
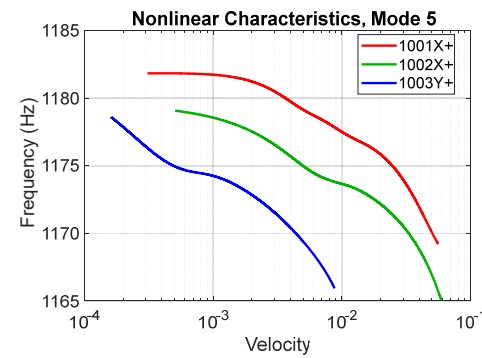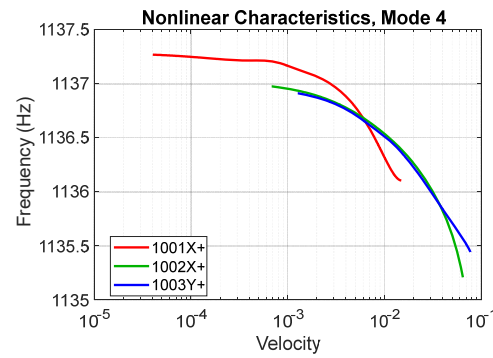# Nonlinear Testing Data and the Modal Coupling Hypothesis

- During the preparations for the live presentation, **an error in the results presented in the paper and video was discovered that changed the narrative of the work**
- The results in the paper and video indicated potential one-way modal coupling between Modes 4 and 5
- However, when processed correctly, modal coupling was not evident in the experimental data
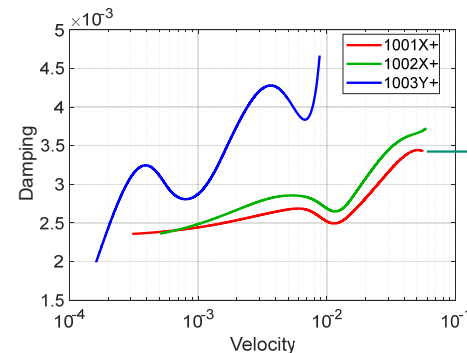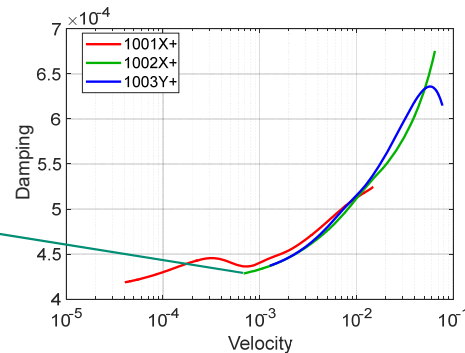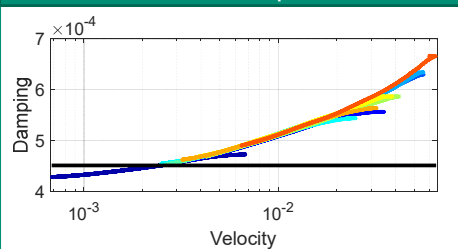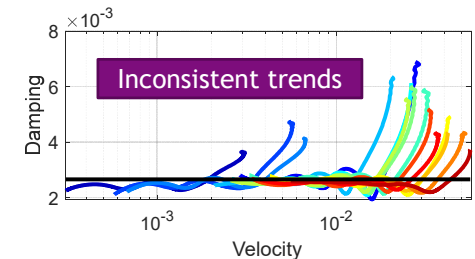
Nonlinear Modeling Approaches

The original intent of the modeling efforts were to capture the modal coupling trends previously thought to be seen in the experiment results

Even though modal coupling does not appear in the corrected data, the modeling techniques can be used to determine if coupling between any modes can be expected for this system and investigate the dynamics thereof

QSMA: The model is loaded with a force in the shape of a mode

- ◦ QSMA can be used to determine amplitude dependent frequency and damping
- ◦ By decomposing the response across a hysteresis cycle, modal coupling can be quantified in a novel approach

Nonlinear ROM: a 6-DOF spring with nonlinear elements is used to model the joint

- ◦ The model was dynamically substructured into two superelements: AP and KB
- ◦ Iwan joints were placed in rot-Z and linear-X directions to simulate slipping in these directions

Note: The models for each approach are different and were tuned to match the linear natural frequencies of the experimental system
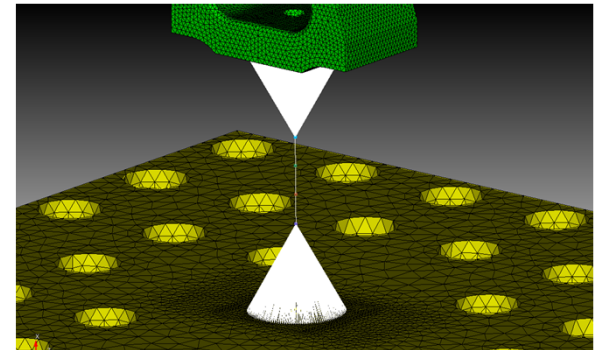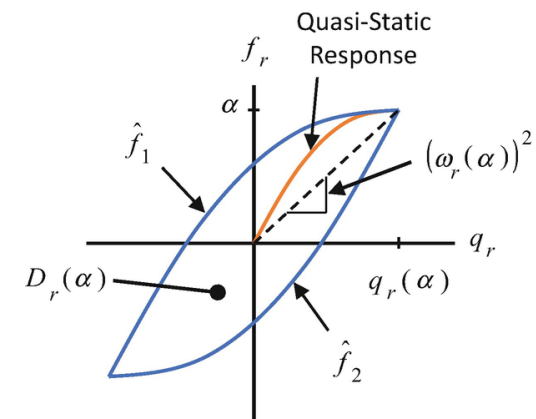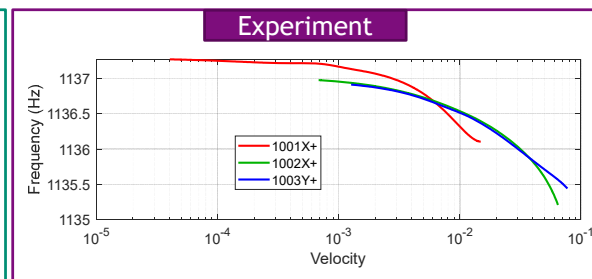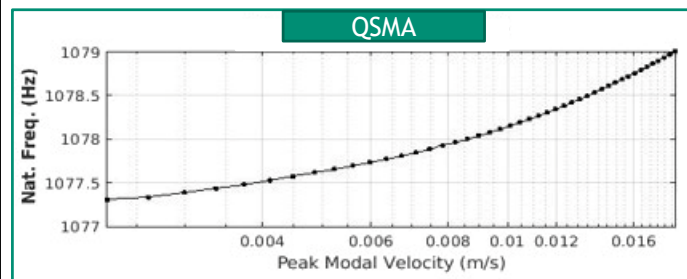

Fig 12. Substructuring approach

Fig 13. QSMA hysteresis curve generation

Preliminary QSMA Results

◦While there was not sufficient time to fully validate the nonlinear FEM, some initial results were obtained using QSMA
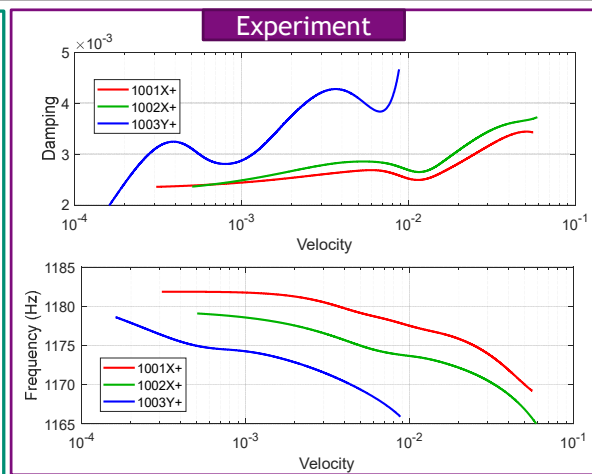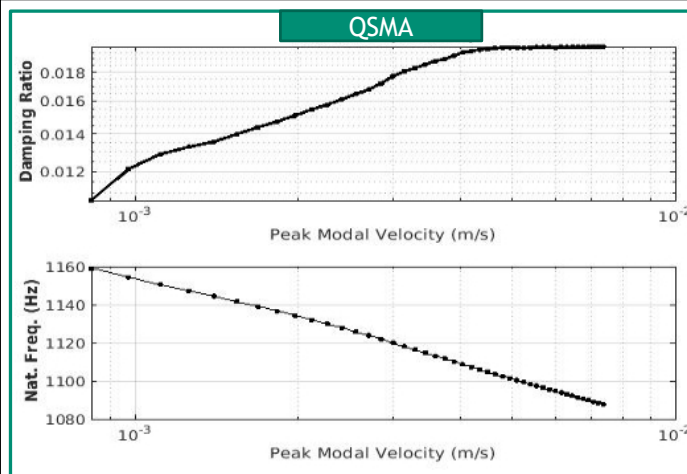
Preliminary Modal Coupling Results Using QSMA of FEM

○ QSMA was used in a preliminary study to evaluate the potential for modal coupling between Modes 4 and 5

  ○ These results represent initial steps in this evaluation, but more work is needed to produce results in which we are confident

○ Displacement of modes at amplitudes indicates activation and coupling

Loading in Shape of Mode 4

Mode 4 coupling with Modes 2, 3, and 5

Loading in Shape of Mode 5

Mode 5 coupling with Mode 2
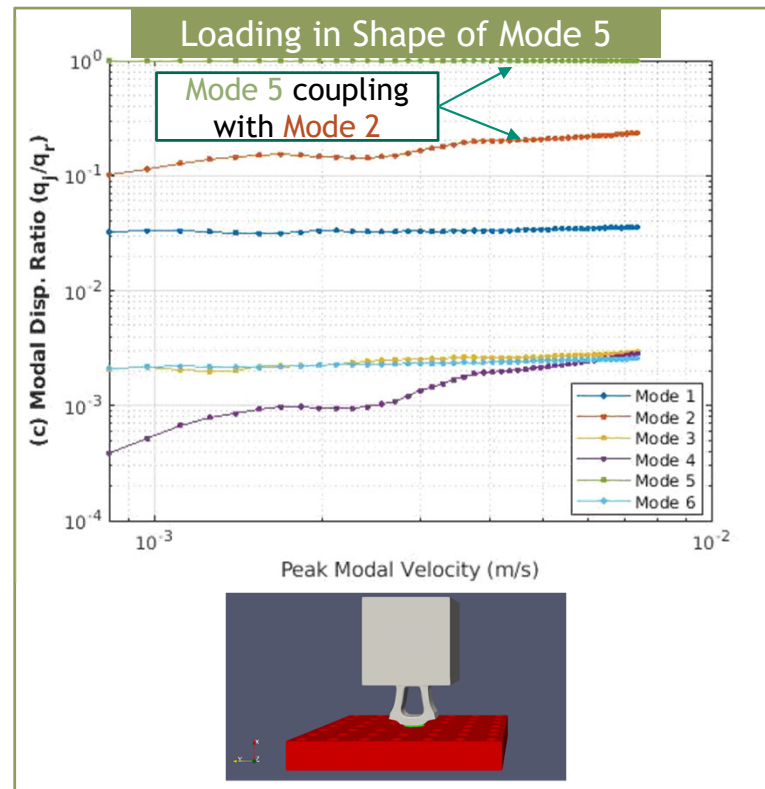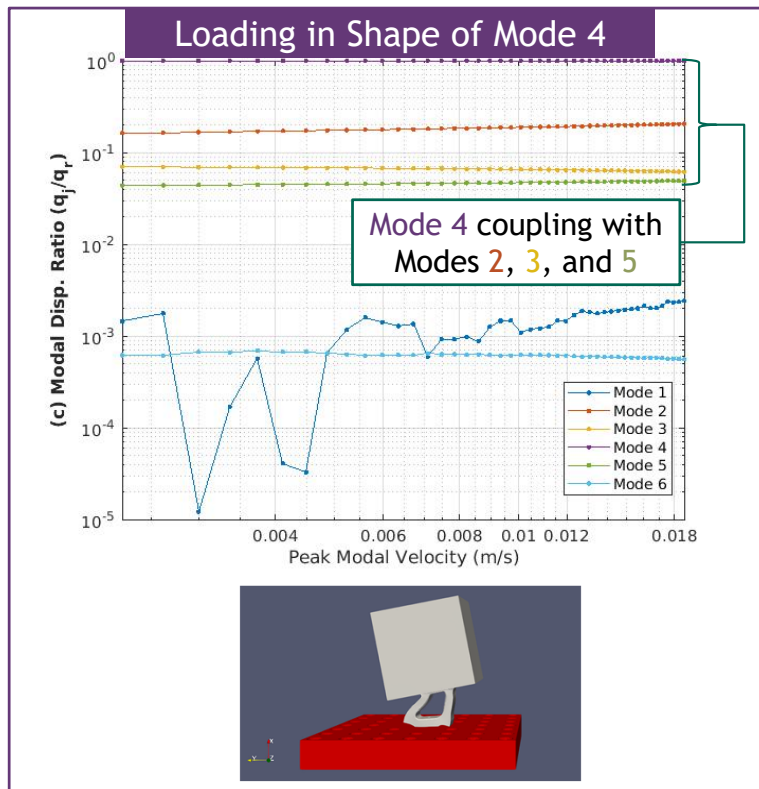
Nonlinear ROM Results

- A tuned nonlinear ROM could be used as another tool to investigate and understand modal coupling
- Time constraints for the project only allowed tuning the Iwan spring which connects the KB to AP to one set of experimental data, which was later found to be processed incorrectly.
- A nonlinear optimizer was used to tune Iwan parameters within MATLAB using QSMA

Spring	F_s	$\gamma \cdot K_T$	χ	β
Linear-X	4.9e5 lbf	3.16e7 lb/in	-0.98	0.6
Rot-Z	1.26e-1 lbf-in	1.30e7 lb/rad	0.33	0.25

- In seeking to update the model, it was discovered that this ROM could not capture coupling between axial and bending motions. The two Iwan joints are in different directions and there is no way to cause them to interact.
- To capture the physics that are of interest, the interface would need to be partitioned into left/right with separate Iwan elements for each.
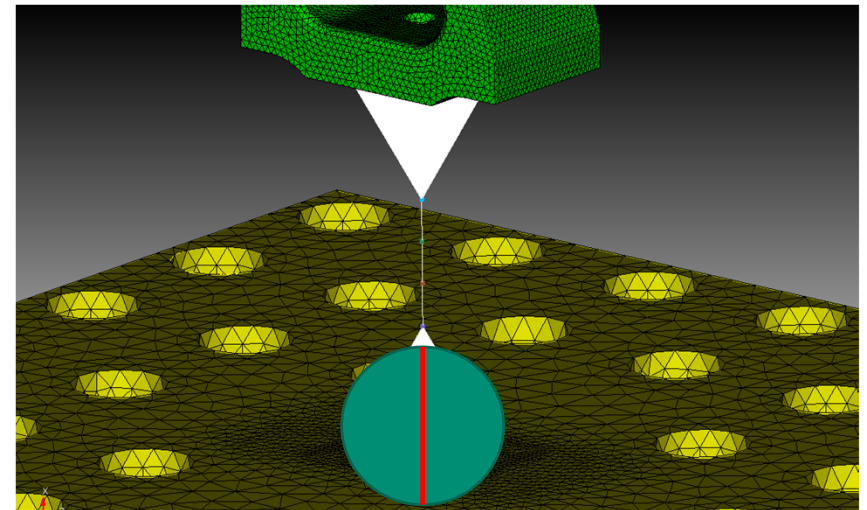
Summary and Conclusions

Six weeks proved to be far too little time to train a group of inexperienced students and tackle all that we wanted to in this project! As a result, we didn't thoroughly vet our results until preparing this talk.

Conclusions:

- Closely spaced modes remain a challenge in nonlinear dynamics testing and analysis

- Hammer impact testing should not be used for modal coupling studies, even if the modes can be individually excited with different drive points. It is recommended that other test methods (e.g. narrow sine beats) be used for future modal coupling studies.

  - Hammer testing excited modes that were not activated during motivating work

- QSMA can be an effective method for quantifying modal coupling

- To capture any potential modal coupling exhibited by this joint, it is probably necessary to capture the surface imperfections, so the contact pressure becomes asymmetric

- It became apparent that our Hurty/Craig-Bampton model could not capture bending-axial modal coupling unless the interface was divided into smaller regions

Acknowledgements