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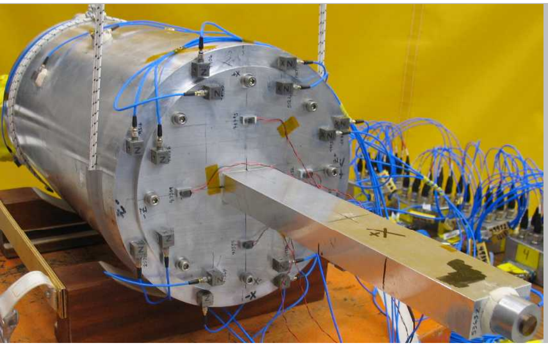

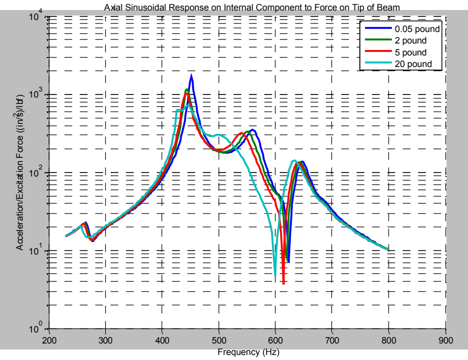

Nonlinear Model Updating: Experimental Nonlinear Modal Model Identification

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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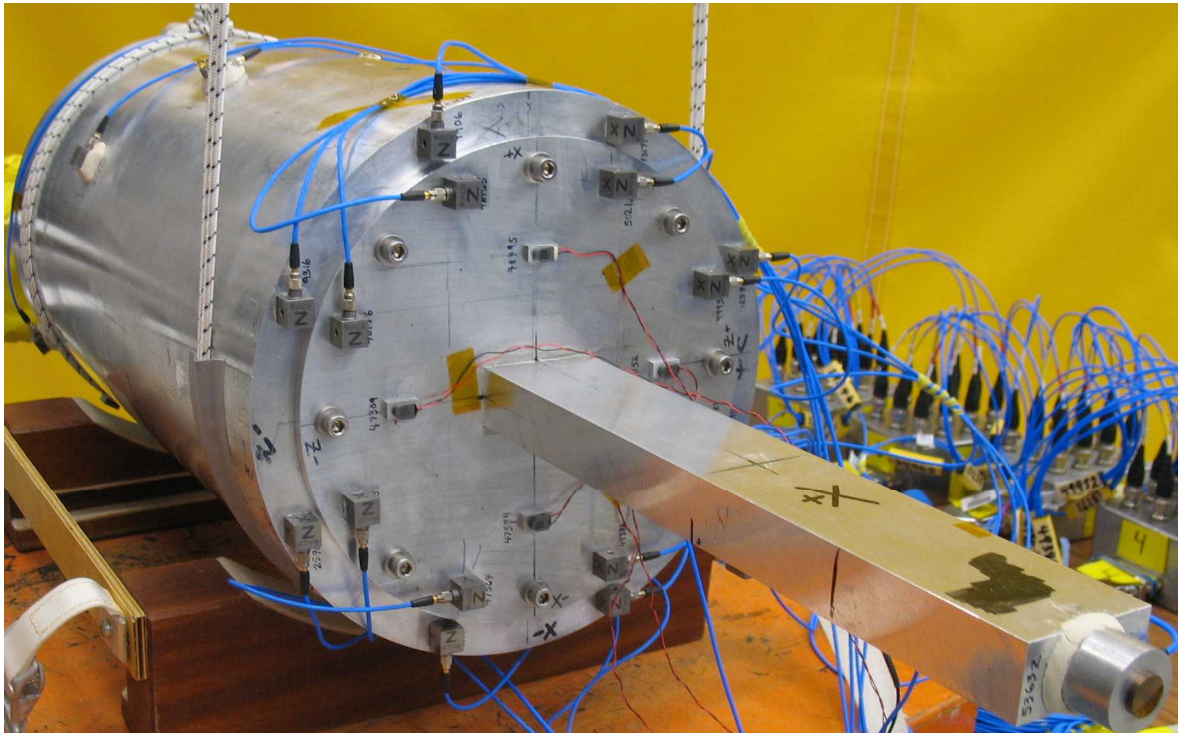
Motivation and Objectives

- Many systems are known to have mild stiffness/moderate damping nonlinearities which can reduce response by 50 percent from linear estimate
- It is difficult to model or validate local physical models for such nonlinearities because there are so many materials and interfaces with different degrees of nonlinearities
- The simulation approach, demonstrated last year, is to reduce the number of nonlinearities down to the number of modes active in the system. In this way, one nonlinear element captures many nonlinear effects on a single modal response
- **This project seeks to develop methodology to identify such nonlinearity experimentally and update a finite element model in a way to capture the nonlinear damping**

Hardware

- Nonlinear bolted joint between the plate and cylinder
- Potentially nonlinear bolted joint between beam and plate?
- No foam; cylinder is empty

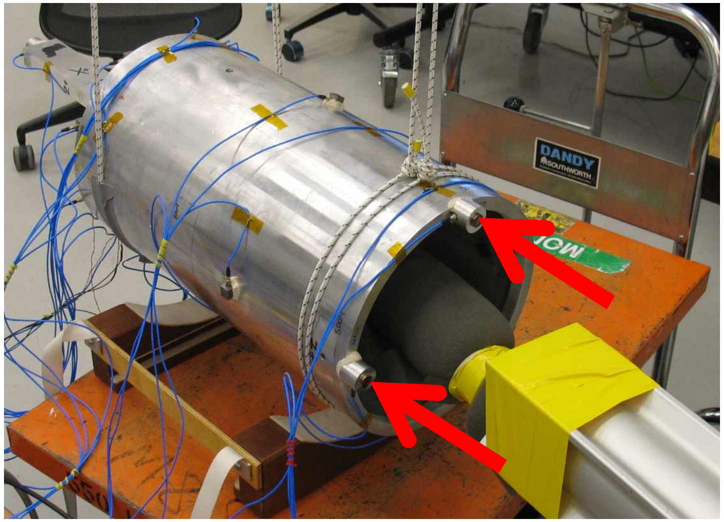


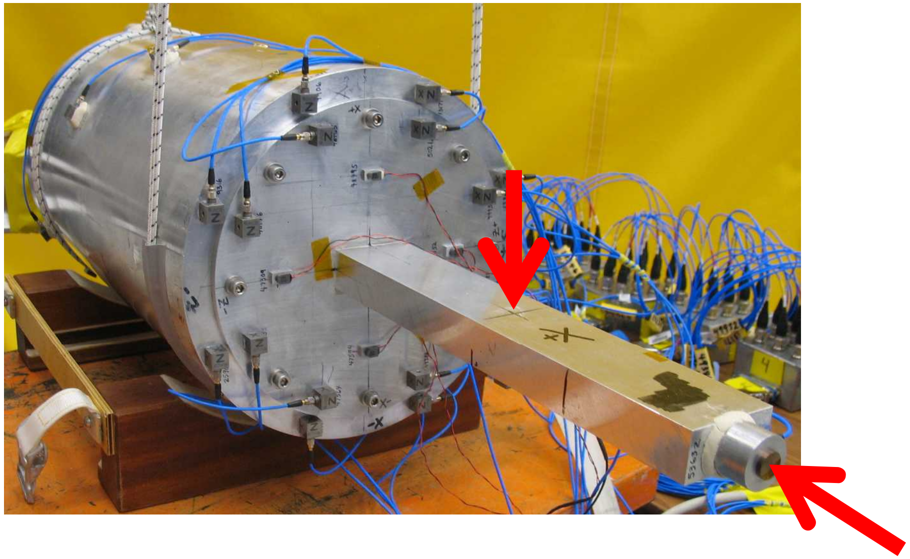
Testing

- Two phases: hammer and shaker
- Hammer
  - Low-level impacts to establish linear model for FEM calibration
  - High-level impacts for nonlinear parameter extraction
- Shaker
  - Low-level burst random to extract frequency and damping for modal filter
  - High-level blips focused at individual resonances for nonlinear parameter extraction

Hammer Test, Impact Information

- Impact degrees of freedom

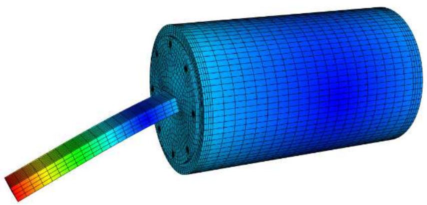


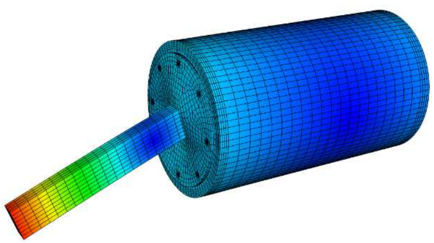


- Force levels
  - Low level
    - 5-10 lbf
  - High levels
    - 40 lbf
    - 90 lbf (55 lbf for lateral hit on beam)

Hammer Test, Linear Modal Analysis

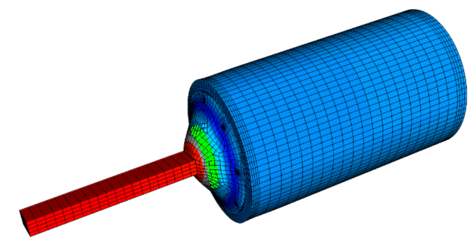
- Linear modal test results

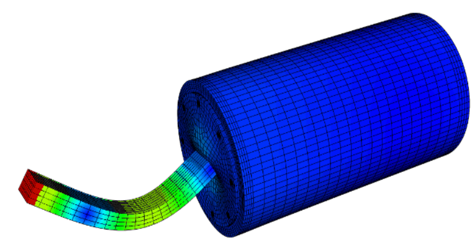




Mode Shape	Natural Frequency (Hz)	Damping (%cr)
*1st bend of beam, soft direction	125	0.45
*1st bend of beam, stiff direction	169	0.39
(2,0) ovaling	391	0.21
(2,0) ovaling	395	0.03
*Axial mode	560	0.31
(3,0) ovaling	957	0.11
(3,0) ovaling	958	0.09
*2nd bend of beam, soft direction	974	0.10
(2,1) ovaling	1280	0.12
(2,1) ovaling	1305	0.20
(3,1) ovaling	1408	0.17
(3,1) ovaling	1416	0.21

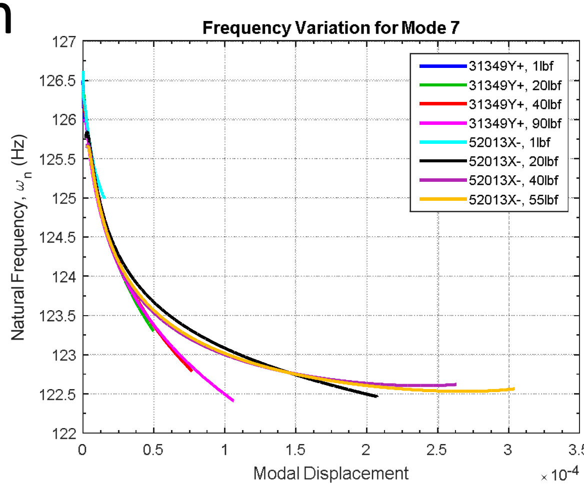
*Nonlinear modes

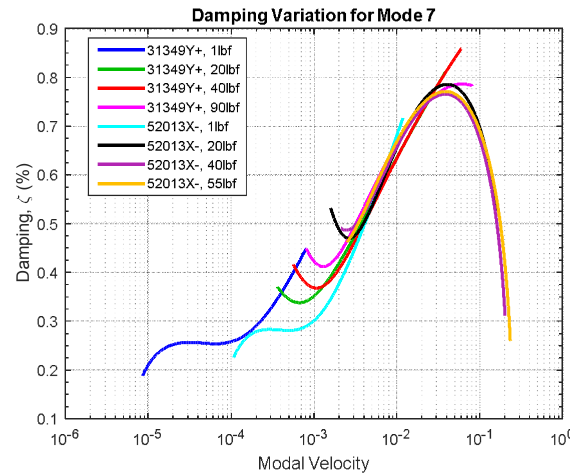


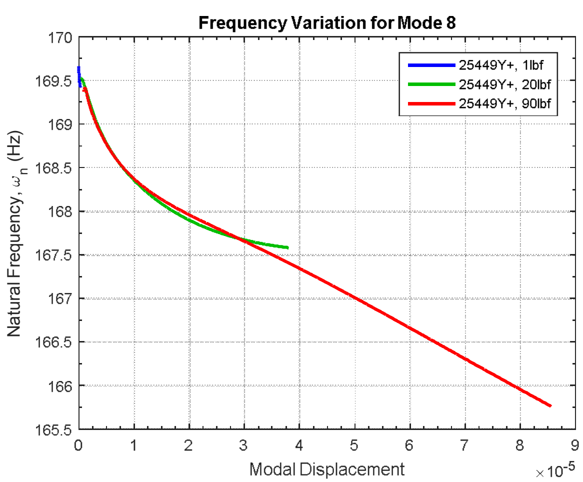


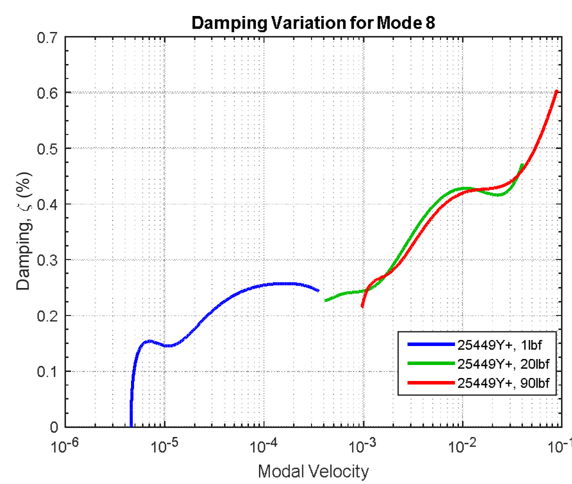
Hammer Test, Hilbert Analysis

- Natural Frequency and damping variations, 1^{st} bendings of beam



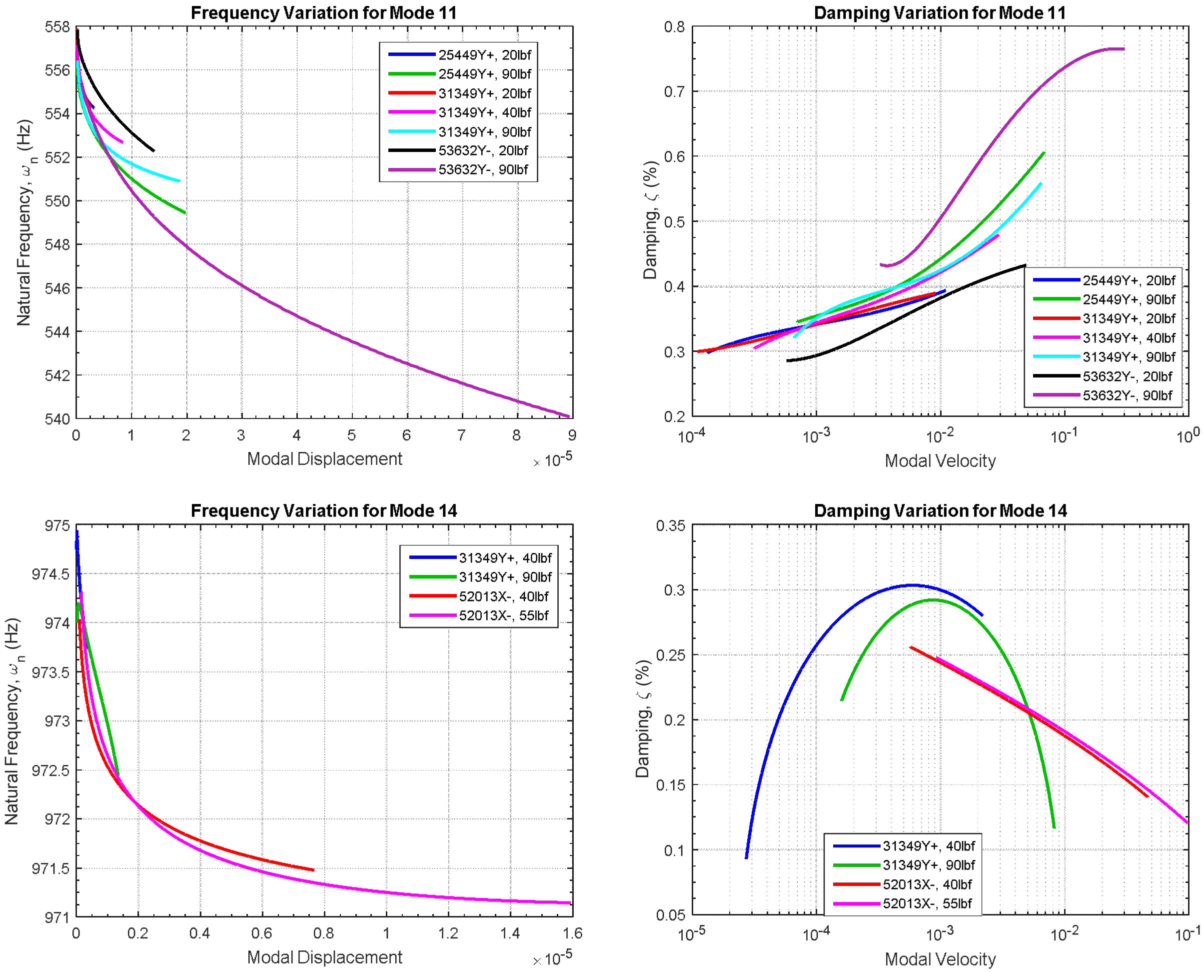






Hammer Test, Hilbert Analysis

- Natural Frequency and damping variations, axial mode and 2nd bending of beam



Hammer Test, Nonlinear Parameter Extraction

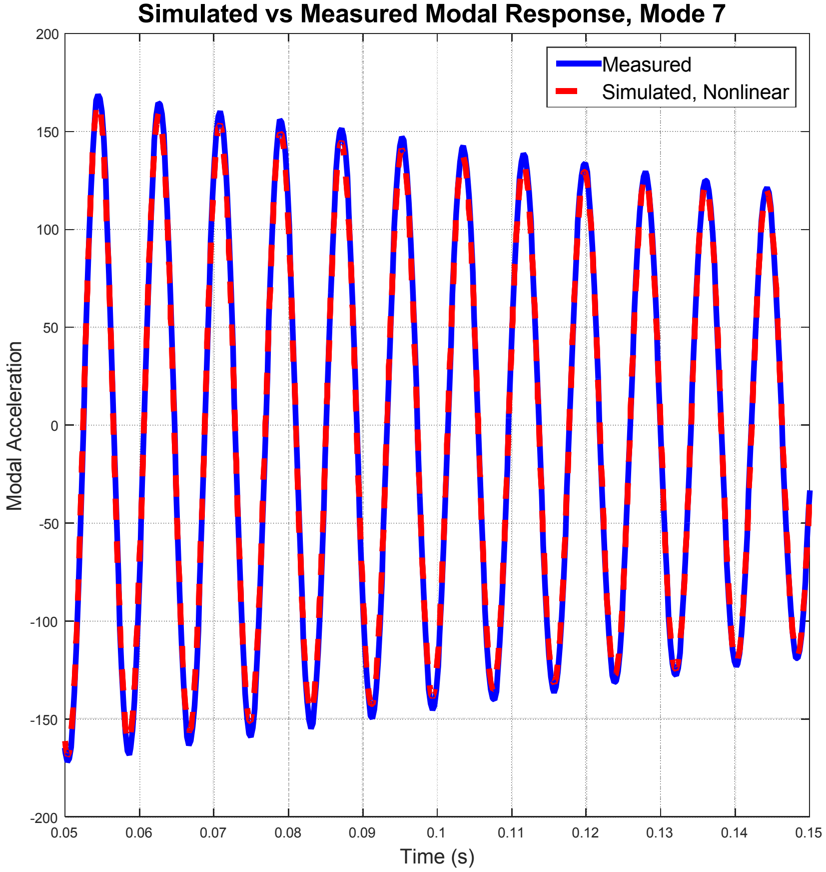
- Utilized Restoring Force Surface method

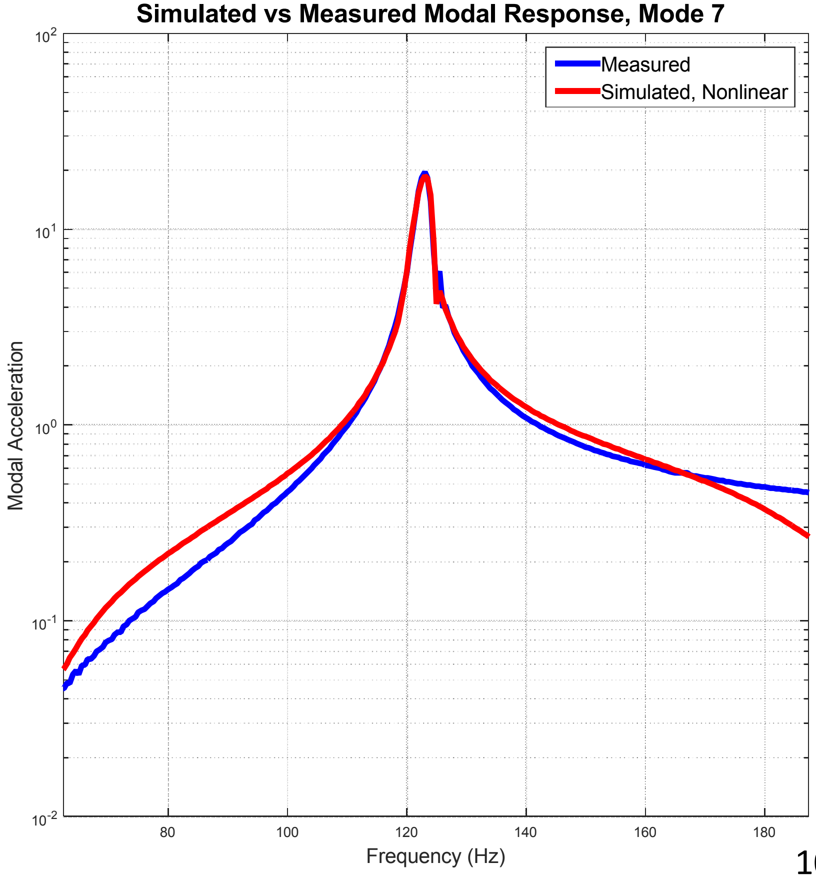
$$\ddot{q} + c_0\dot{q} + \underbrace{\sum_{i=1}^{n} c_i|\dot{q}|^i\dot{q}}_{\text{Nonlinear damping force}} + k_0 q + \underbrace{\sum_{i=1}^{n} k_i|q|^i q}_{\text{Nonlinear spring force}} = f$$

- All modes (except mode 7) used only a 2nd and 3rd order term for both damping and stiffness
  - Mode 7 also used a 4th order term in damping
    - Possibly to account for different damping trend?

Hammer Test, Simulation Results

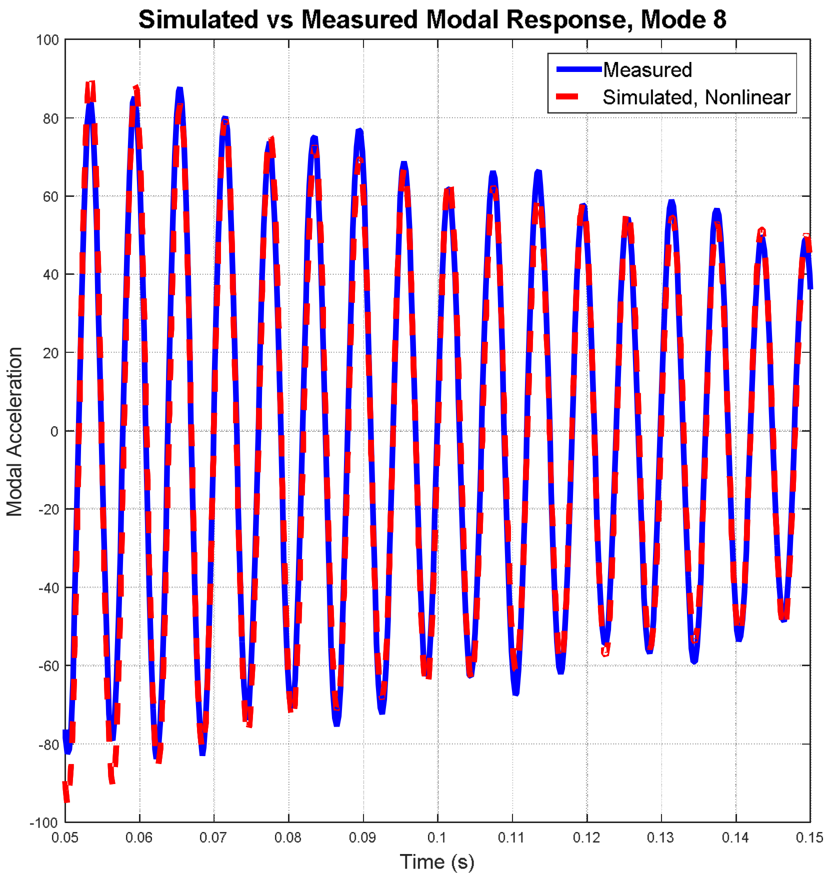
- Nonlinear parameter extraction and simulation results, 1st bending of beam in soft direction

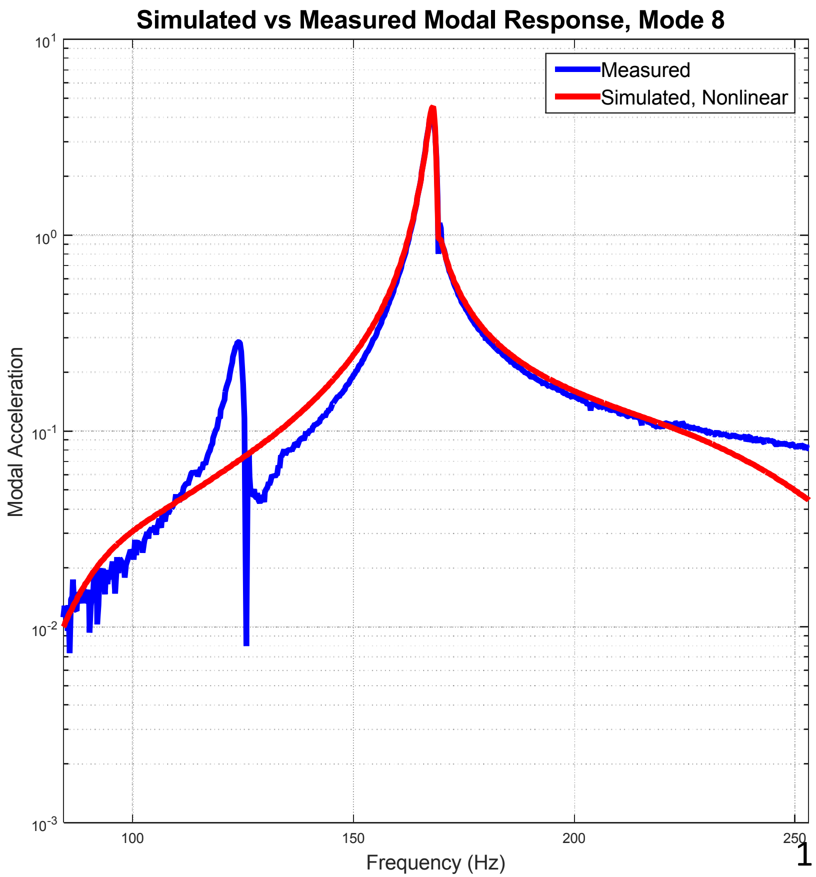




Hammer Test, Simulation Results

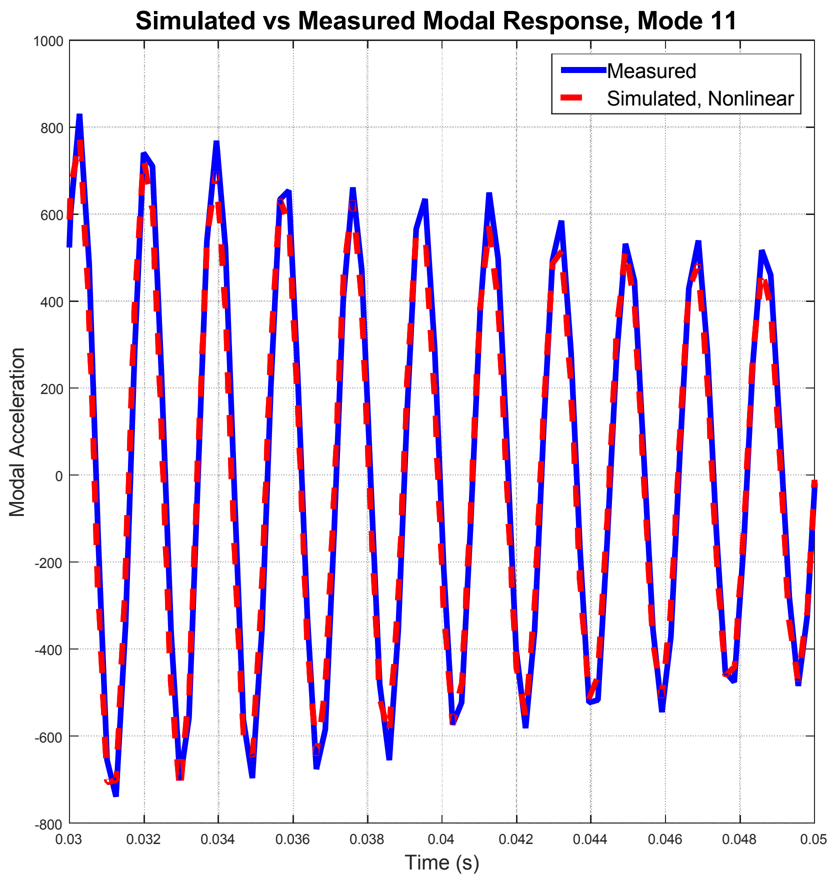
- Nonlinear parameter extraction and simulation results, 1st bending of beam in stiff direction

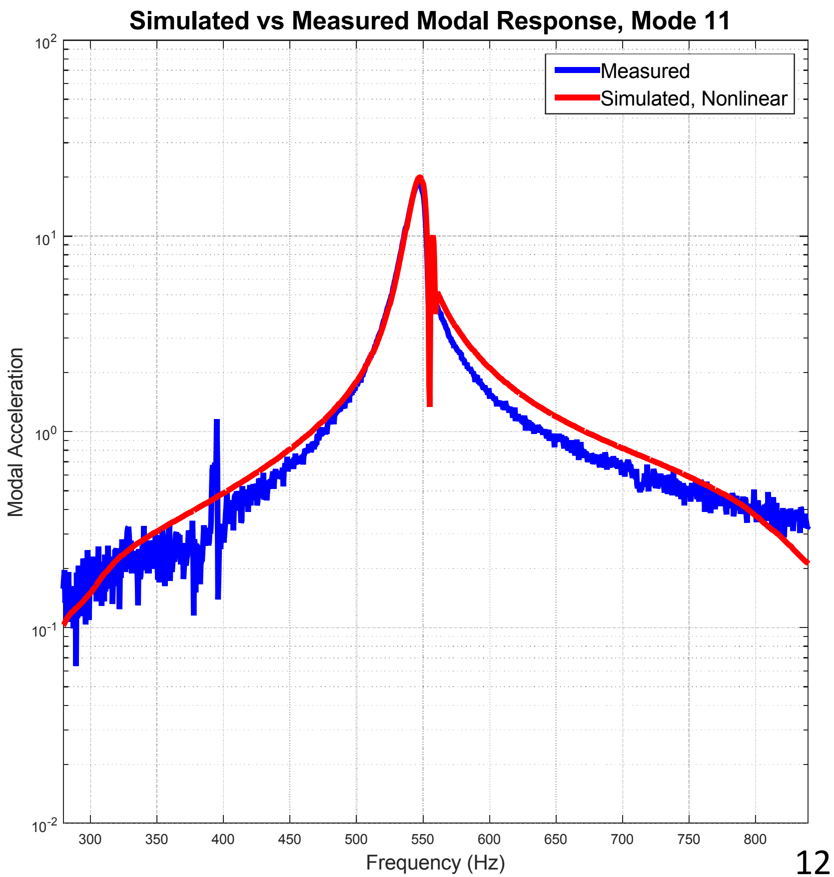




Hammer Test, Simulation Results

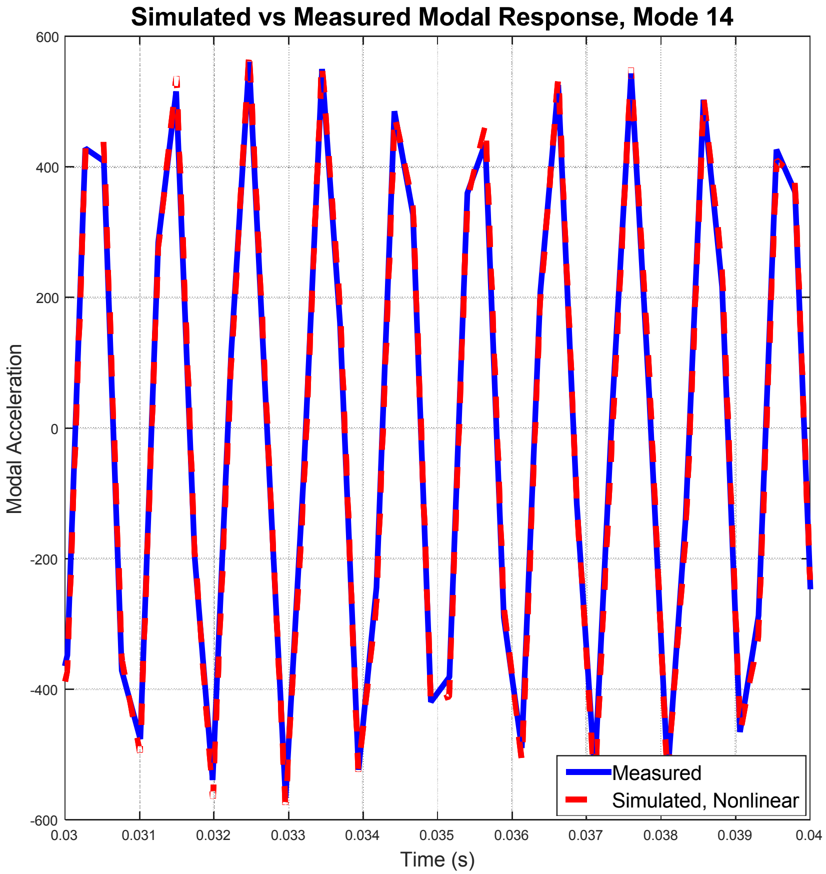
- Nonlinear parameter extraction and simulation results, axial mode

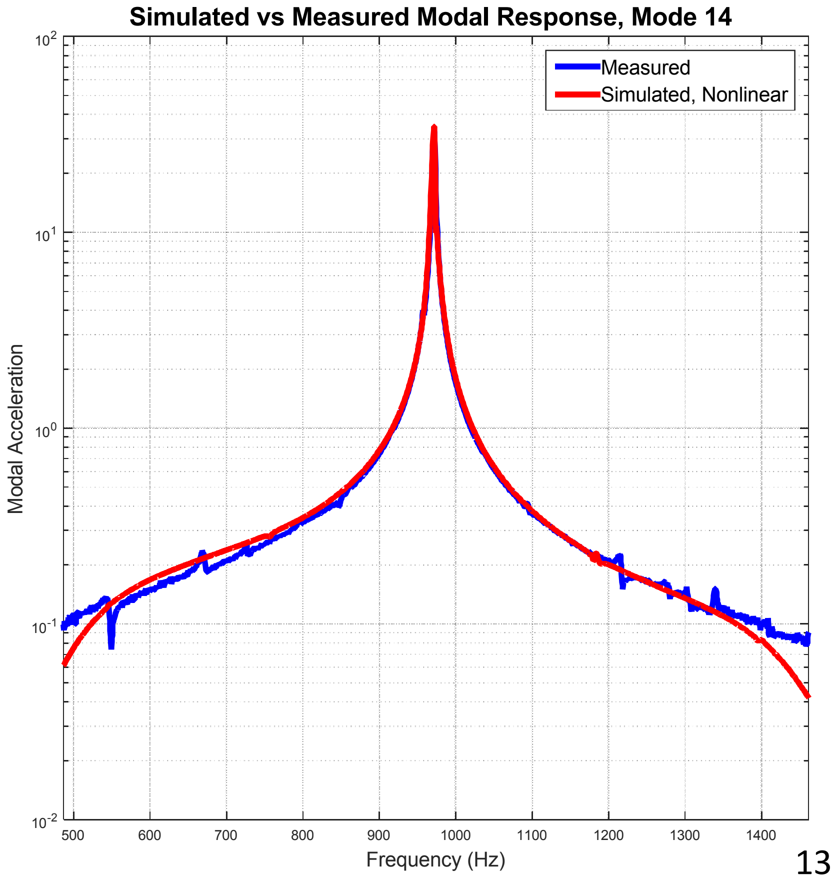




Hammer Test, Simulation Results

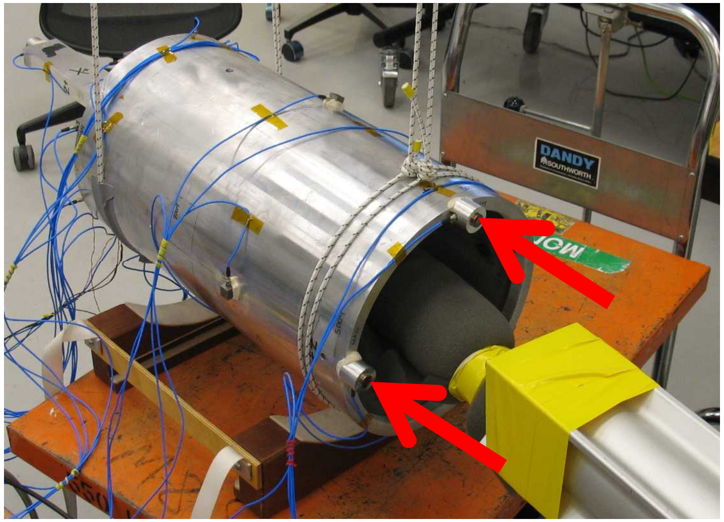
- Nonlinear parameter extraction and simulation results, 2nd bending of beam in soft direction

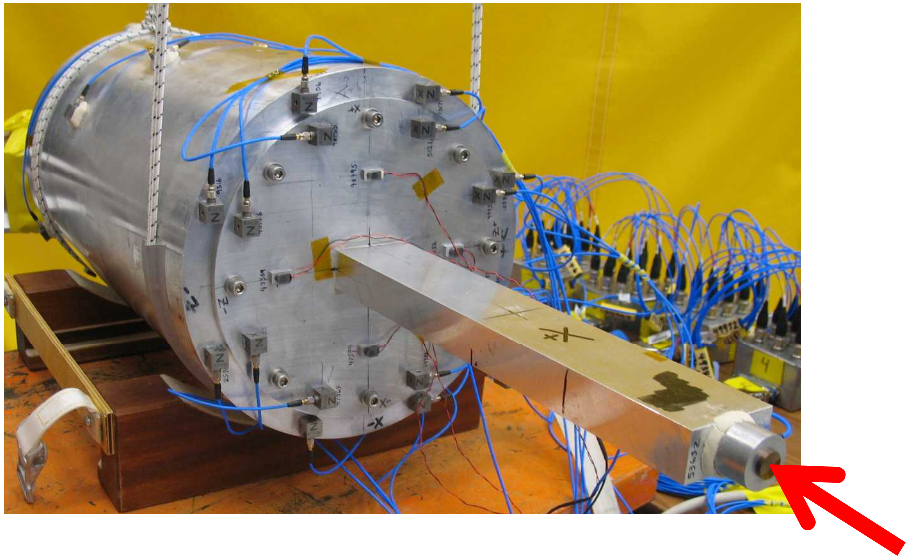




Shaker Test

- Input degrees of freedom





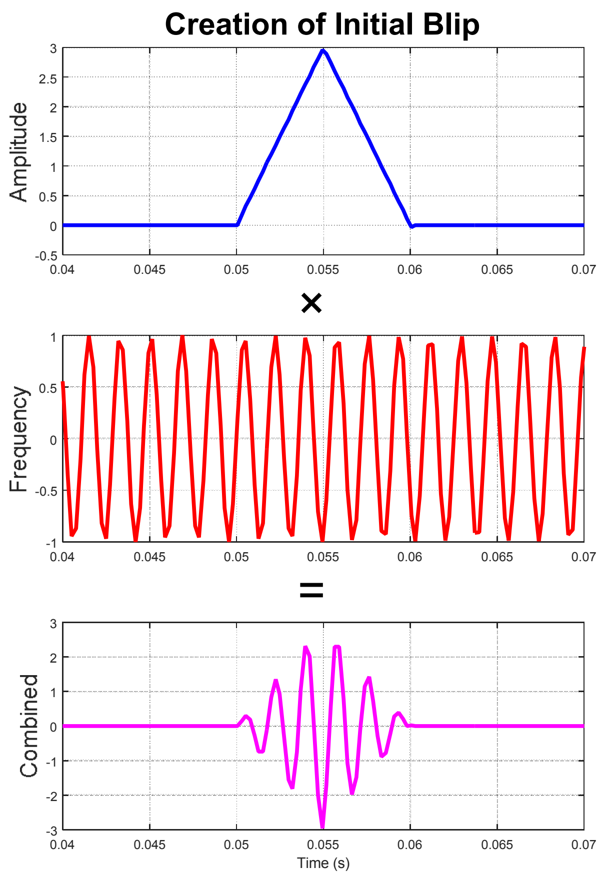
- Low level burst random tests (0.3 lbf RMS) were used to collect data for the modal filter
- High level excitation was accomplished using tailored inputs that concentrated the force around an individual resonance

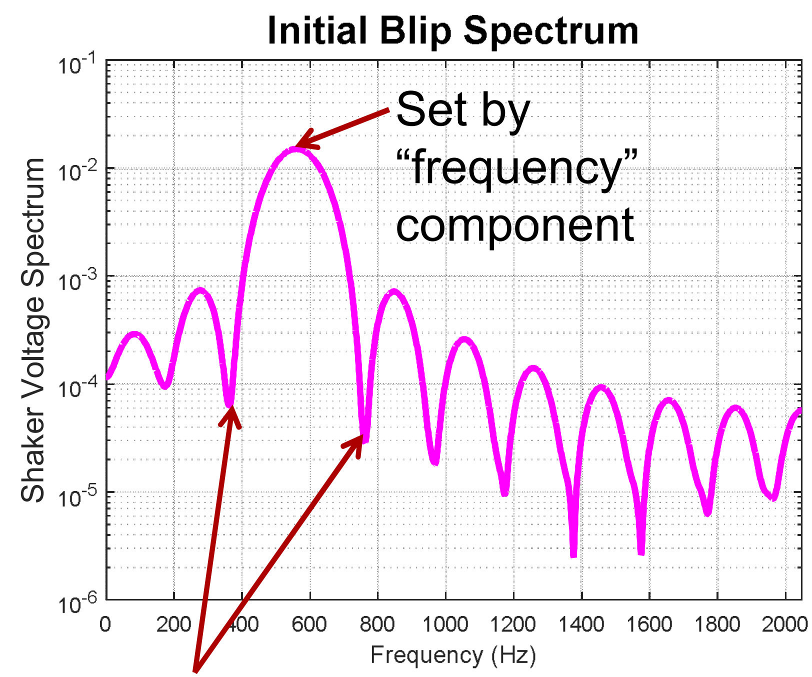
Shaker Test, High Level Input Development

- Hammer impacts excite all modes at once which can lead to premature saturation of accelerometers, limiting the level of excitation of a target mode
- Step sine tests are time consuming and difficult without closed loop control
- Therefore, it is desired to have a fast shaker test that concentrates energy around a single resonance

Shaker Test, High Level Input Development

- Need to create the voltage signal that is sent to the shaker amplifier in order to achieved desired excitation force profile

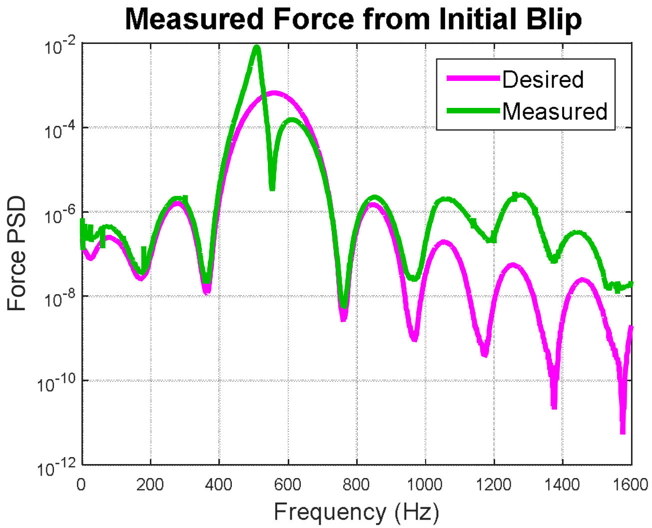




Set by the rise time of the "amplitude" component

Shaker Test, High Level Input Development

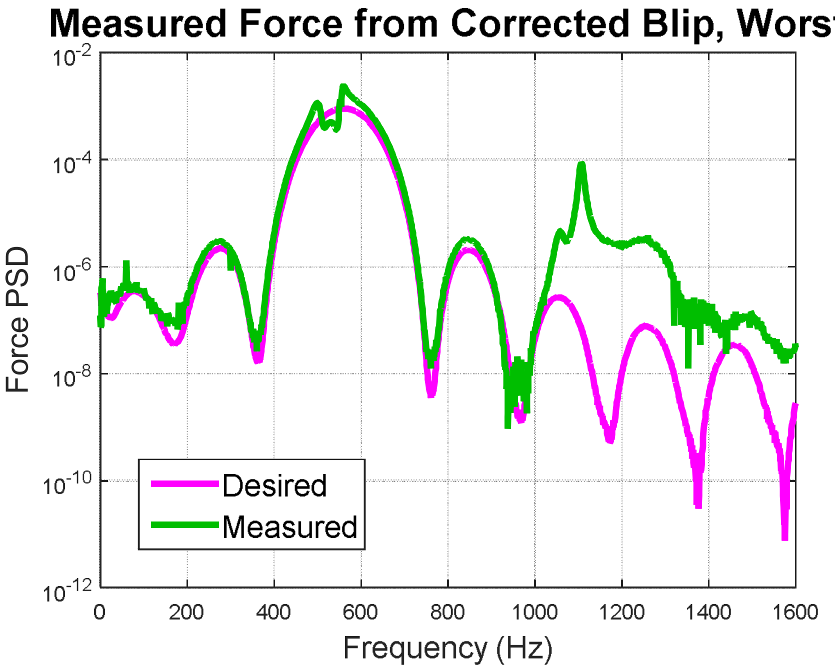
- However, due to the shaker-hardware interaction, the measured force does not match the desired near resonance

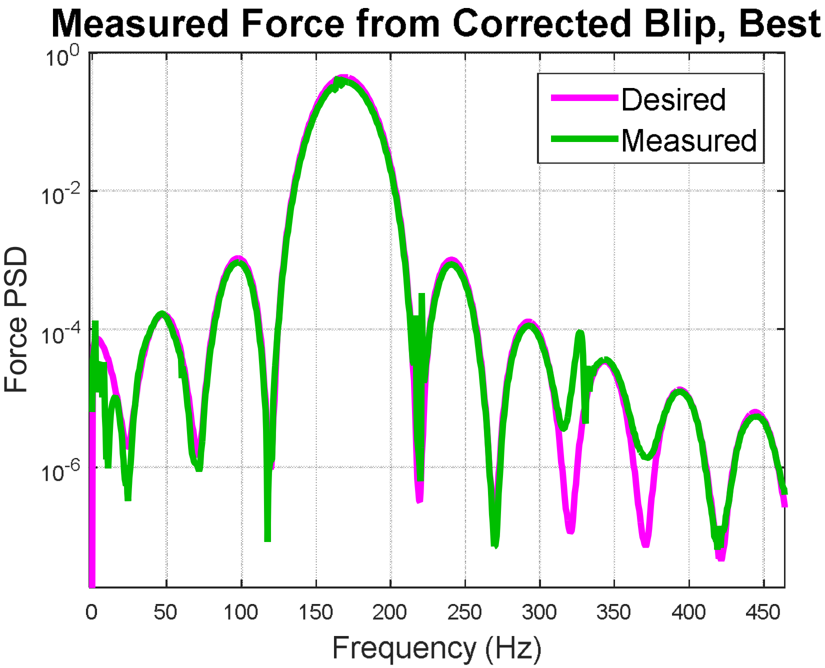


- To correct for this, the voltage-to-force transfer function is created using the data from the “initial blip” test
- This transfer function is then used in conjunction with the desired force profile to create a “corrected” shaker voltage signal

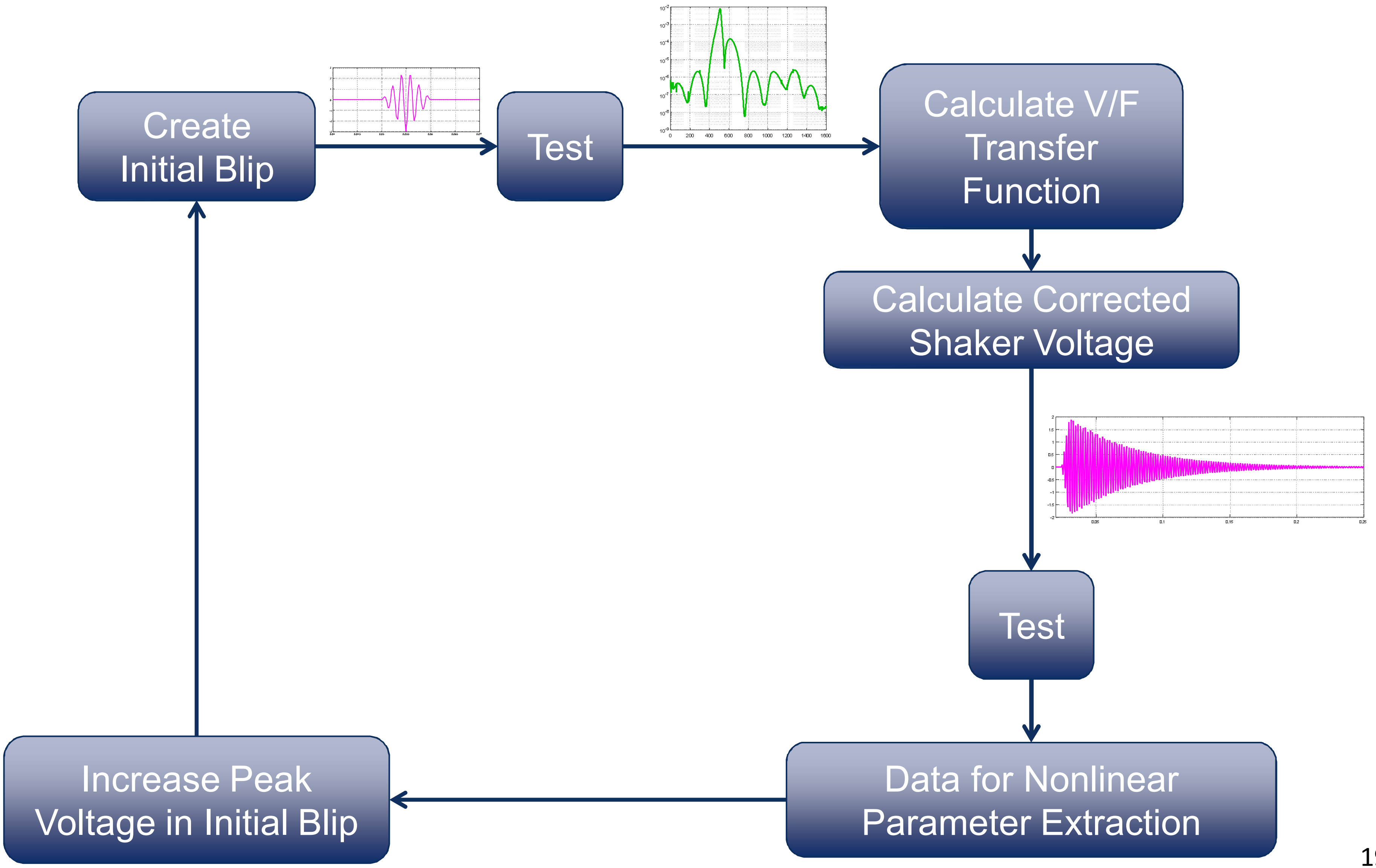
Shaker Test, High Level Input Development

- Since the TF is a linear operator and the hardware is nonlinear, the corrected shaker voltage does not exactly produce the desired force profile





Shaker Test, Procedure

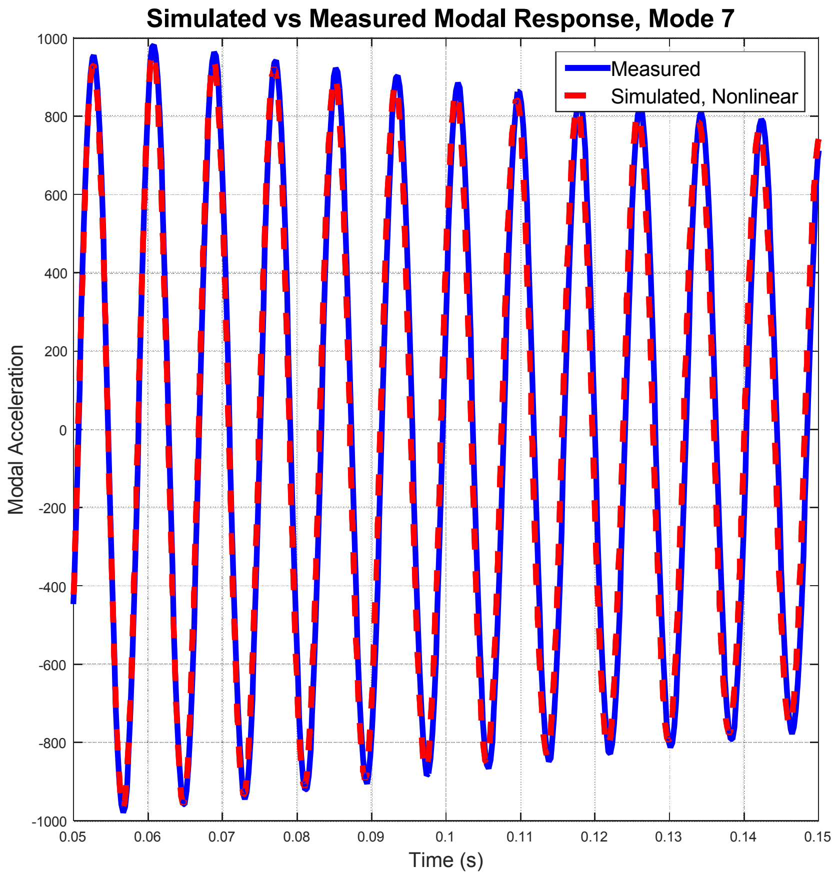


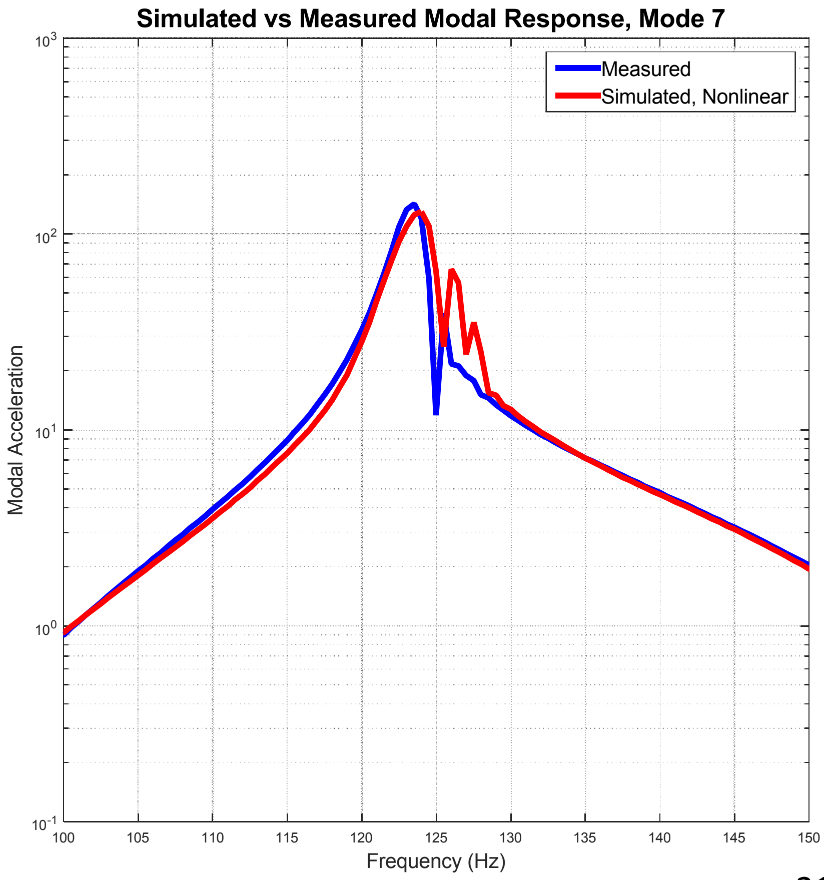
Shaker Test, Simulation Results

- Utilized Restoring Force Surface method to extract nonlinear model
- All modes were adequately fit using cubic polynomials for damping and stiffness

Shaker Test, Simulation Results

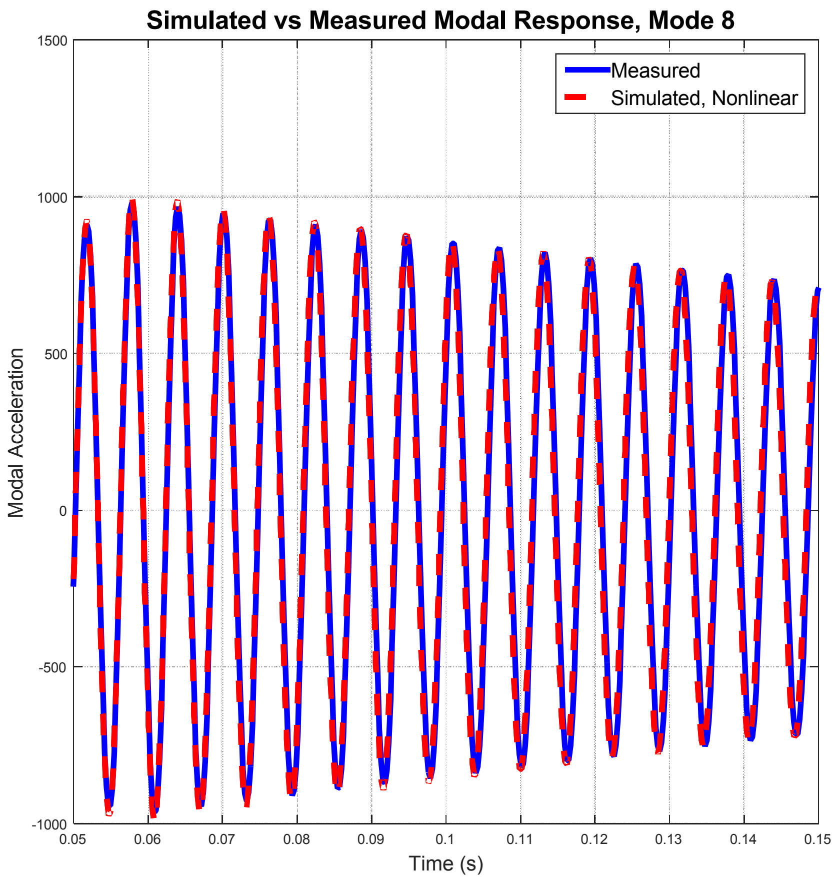
- Nonlinear parameter extraction and simulation results, 1st bending of beam in soft direction

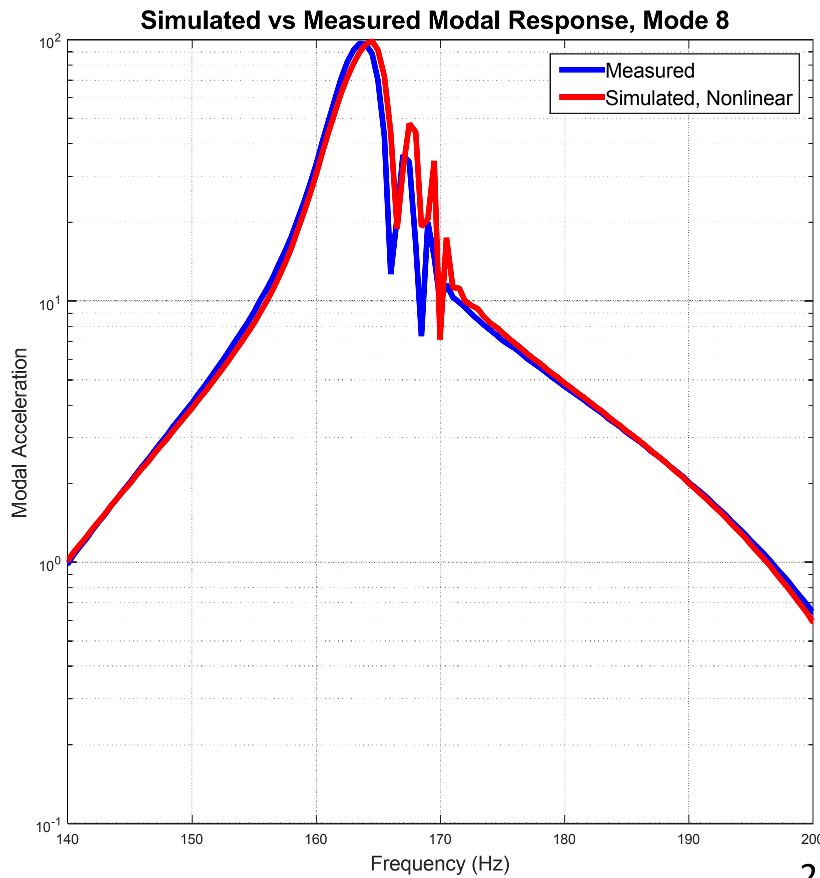




Shaker Test, Simulation Results

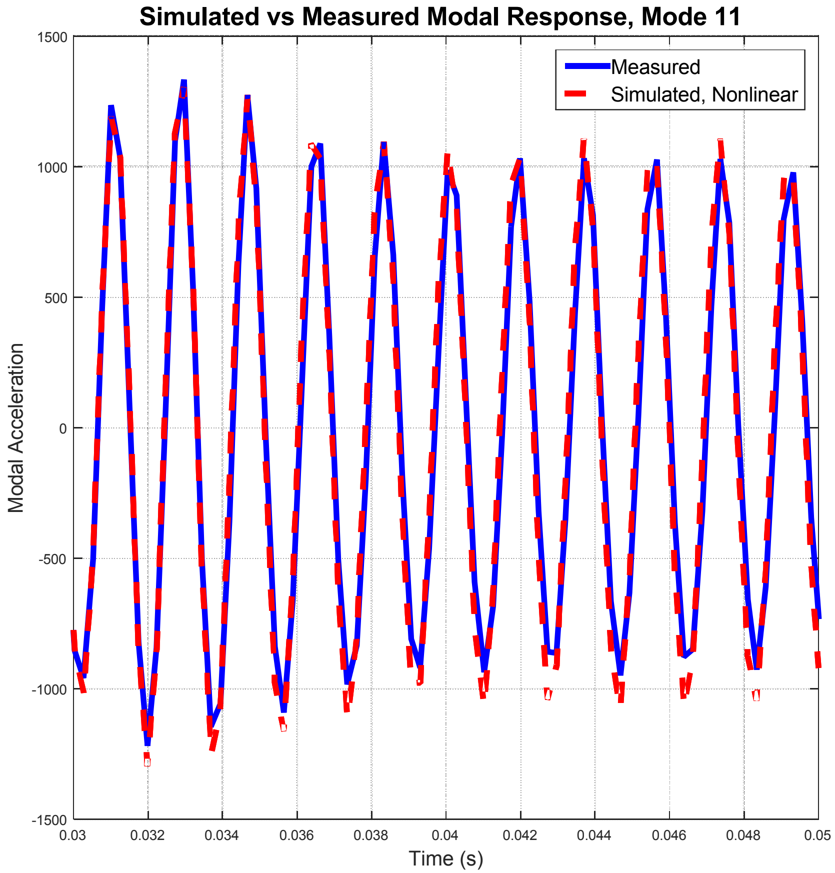
- Nonlinear parameter extraction and simulation results, 1st bending of beam in stiff direction

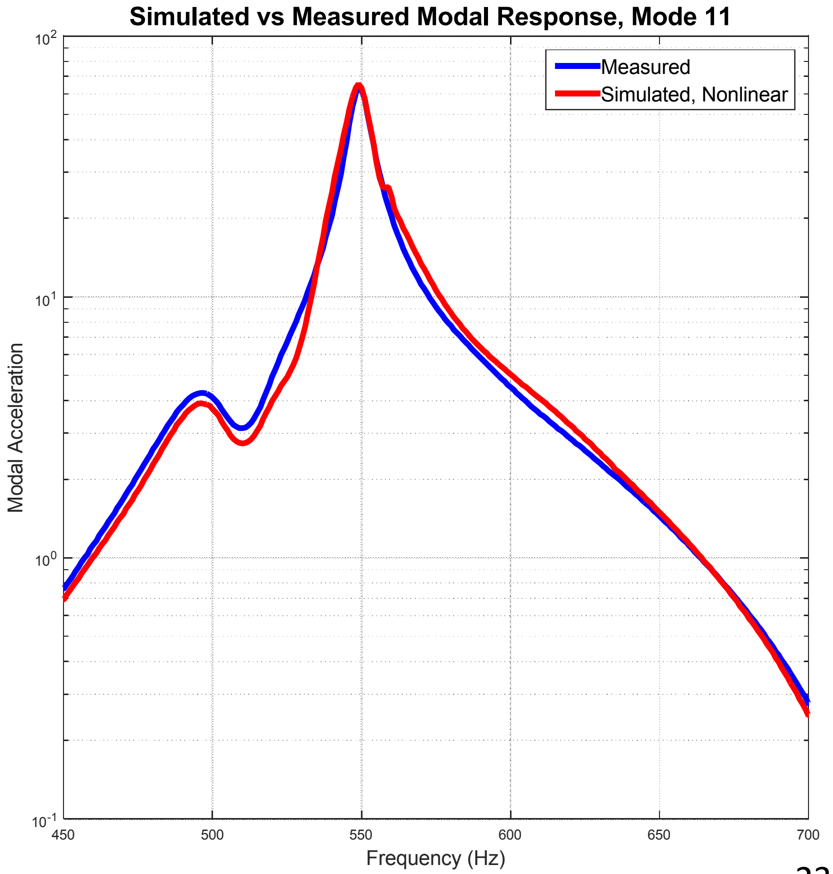




Shaker Test, Simulation Results

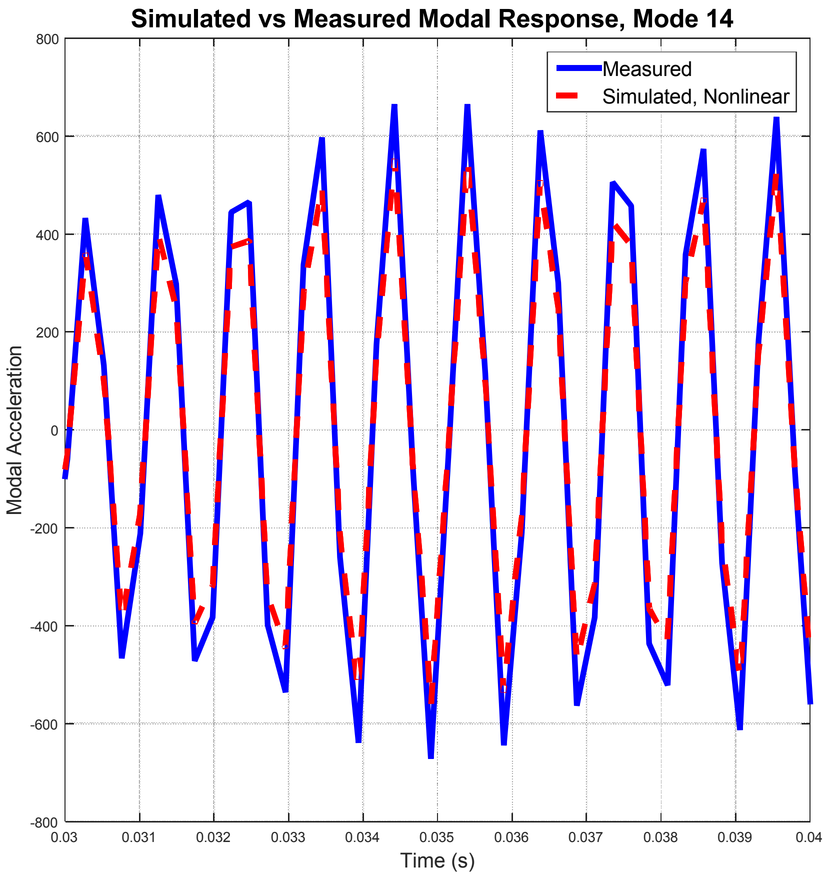
- Nonlinear parameter extraction and simulation results, axial mode

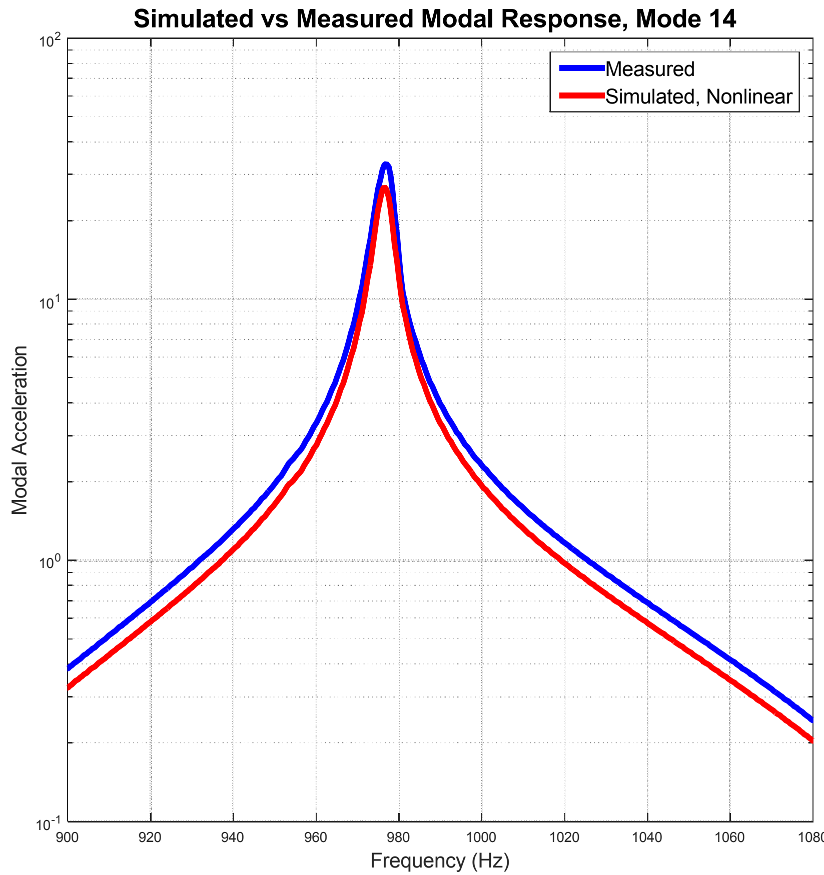




Shaker Test, Simulation Results

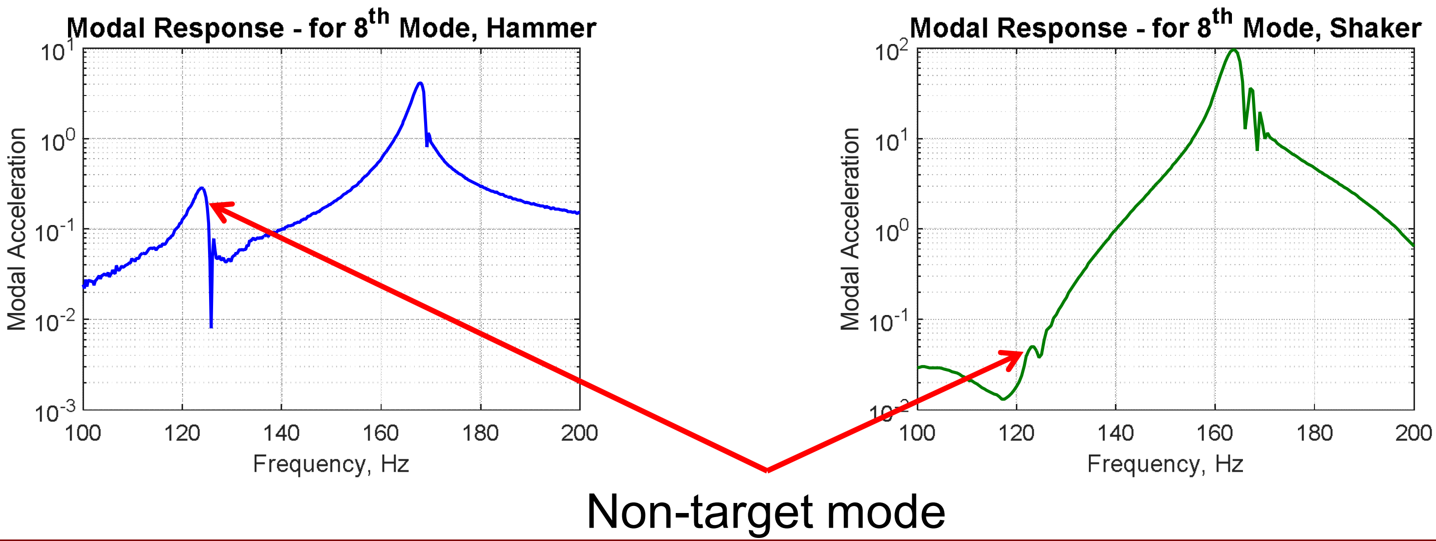
- Nonlinear parameter extraction and simulation results, 2nd bending of beam in soft direction





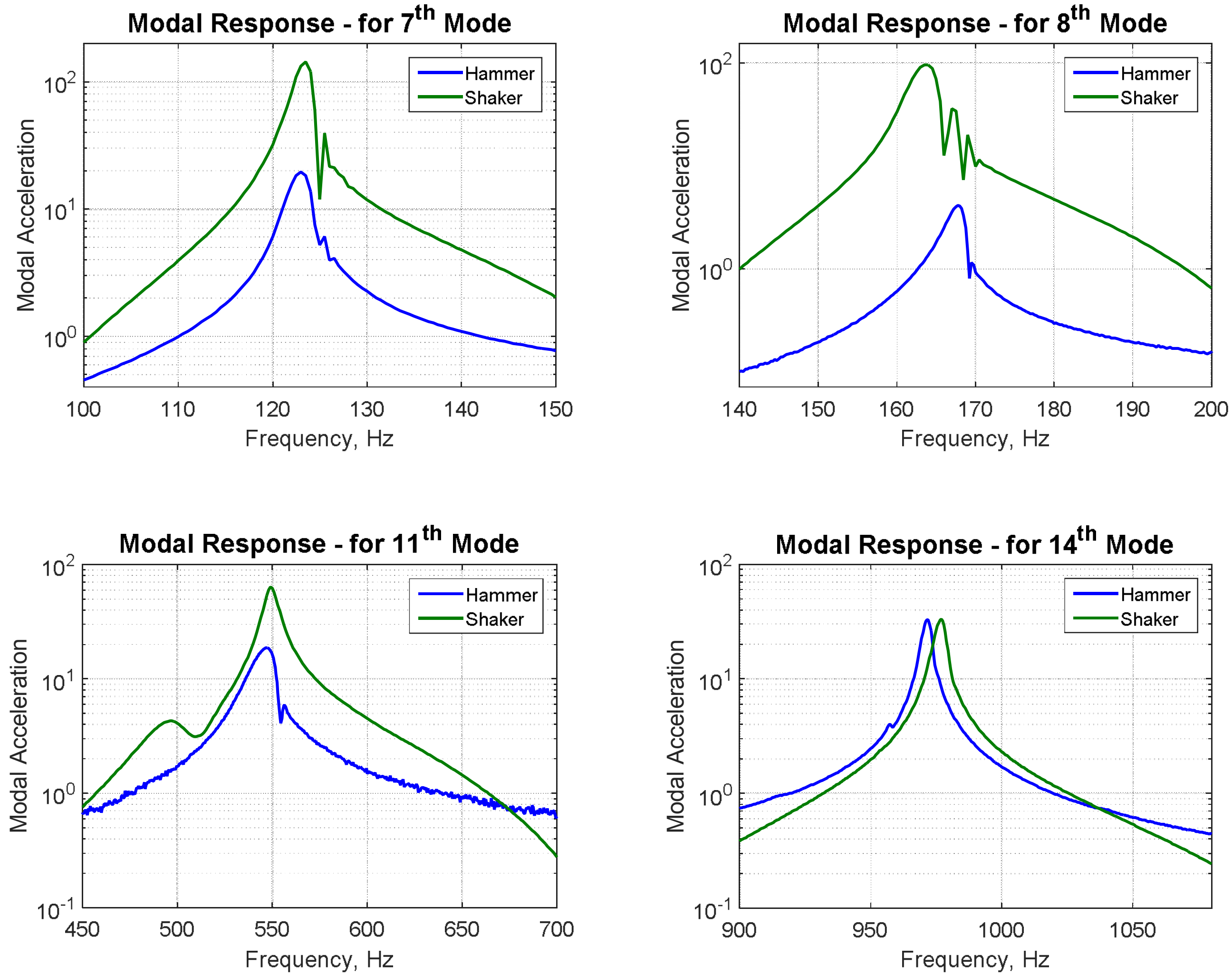
Remarks

- In approximately 1 hour, nonlinear data for a single mode could be collected with the shaker
  - Max voltage of initial blip is slowly ramped up so as to not saturate accelerometers/load cell. This requires many iterations which is the main reason for the “long” testing time. However, testing time will decrease with more experience with this process.
- Shaker testing assists in isolating the target mode which allows the modal filter to perform better



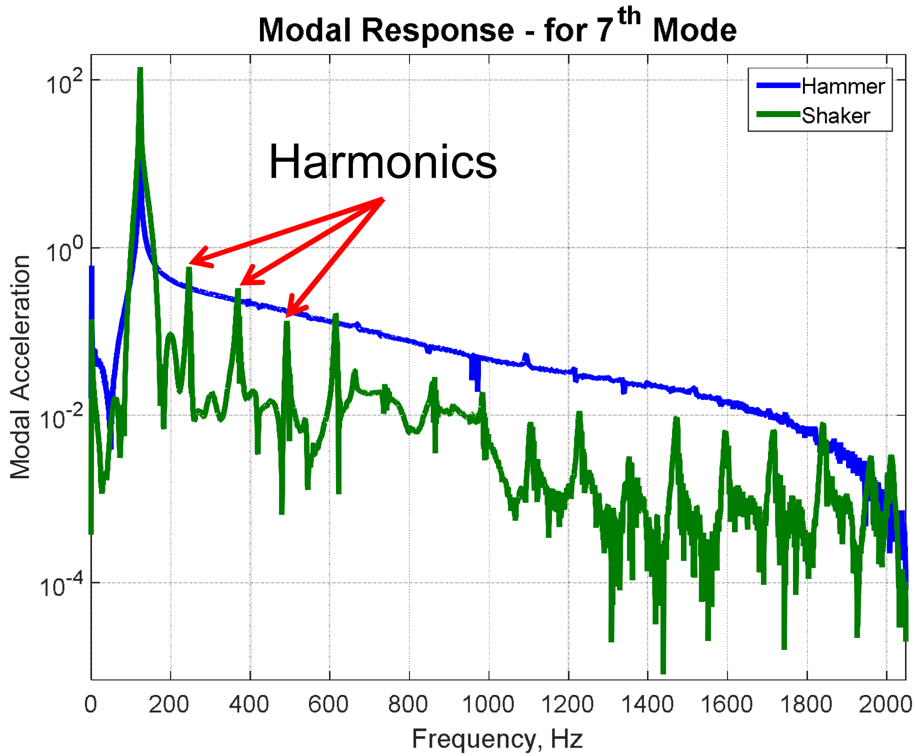
Remarks

- Generally, greater modal responses were achieved with the shaker



Remarks

- Shaker excited harmonics of the targeted mode and these harmonics passed through the modal filter
  - Allows evaluation of ability of nonlinear model to capture harmonic characteristics of nonlinearity.
  - Potential for studying modal coupling using modal methods?



Remarks

- Improved fits of shaker data was achieved with 5th order polynomials, but cubics were chosen for model simplicity and "computational safety" (i.e. simulation remaining stable)

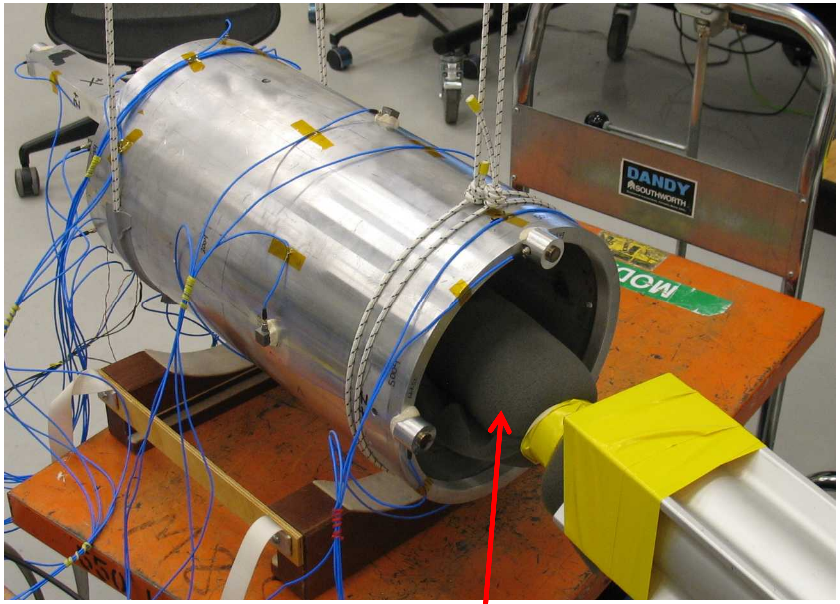
Future Work

- Implement nonlinear models in Finite Element framework
- Compare MATLAB modal simulation results with FEM modal results via recreating nonlinear response data
- Repeat comparison using a broad-spectrum chirp test

Backup Slides

Hammer Tests, Acoustic Modes

- Discovered acoustic modes of cylinder
  - To mitigate acoustic-structure interaction, foamed rod was inserted into the cylinder to absorb acoustic energy



Acoustic Energy Absorber