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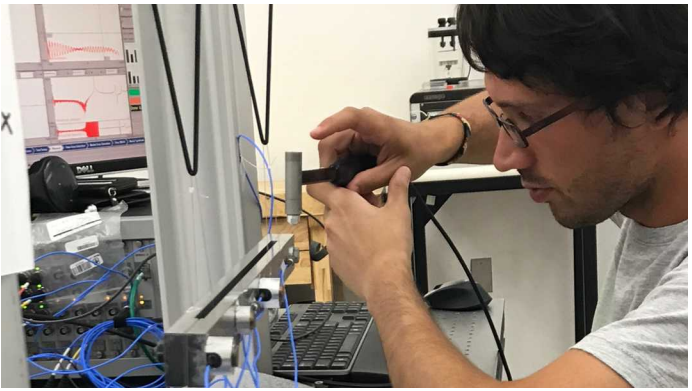

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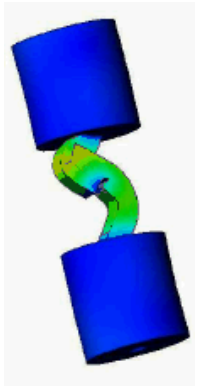

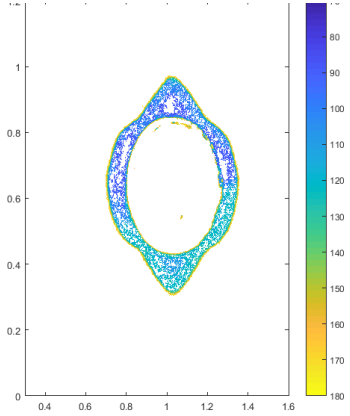


# Experimental Characterization of a New Benchmark Structure to Predict Damping Nonlinearities

Aabhas Singh, Matteo Scapolan, Yuta Saito

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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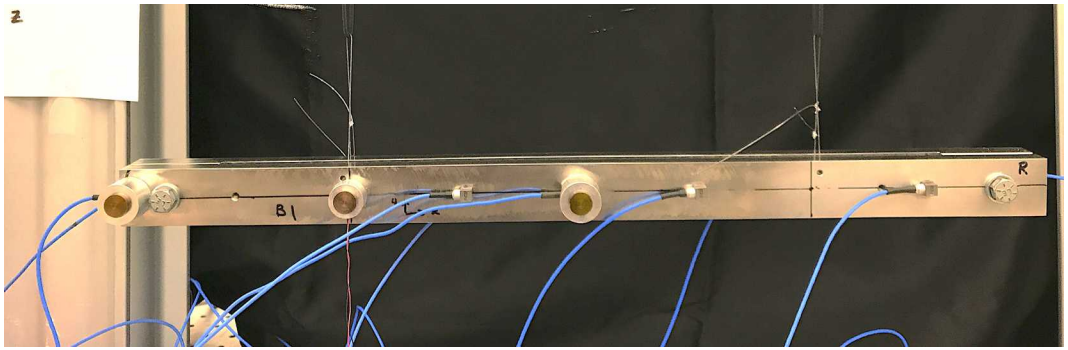
SAND2017-XXXX

# Agenda




1. Introduction
2. Project Overview
3. Joint Characterization
4. Experimental Methodology
5. Nonlinear Parameter Characterization
6. Conclusion

# Research Team

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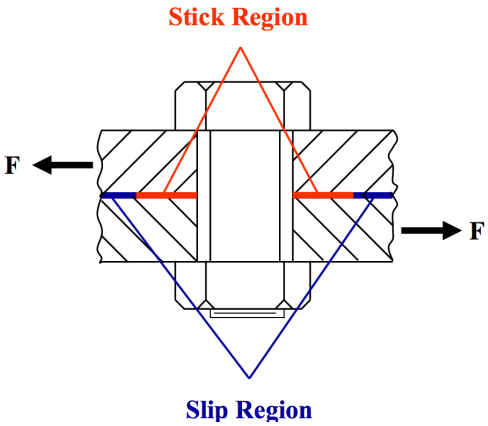
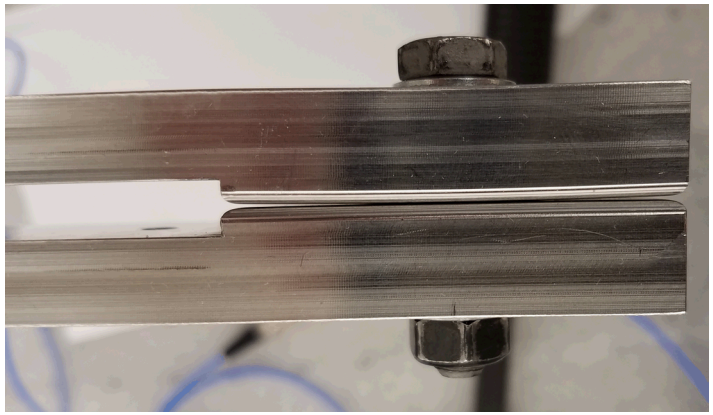
# Motivation

- Finite element models (FEMs) of interfaced structures leads to large uncertainties
  - Introduce nonlinearities
  - Difficult to predict stiffness and damping at the interface
- Bolted structures
  - Well tightened bolts still exhibit regions of slip at the edge of contact
    - Introduces hysteresis and an increase in damping

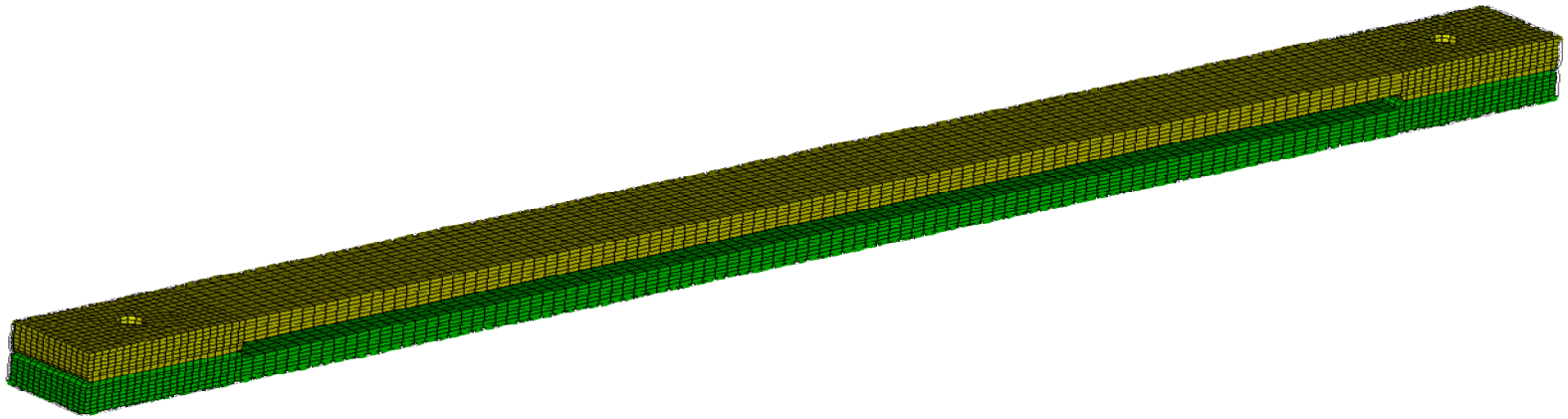


# Project Overview

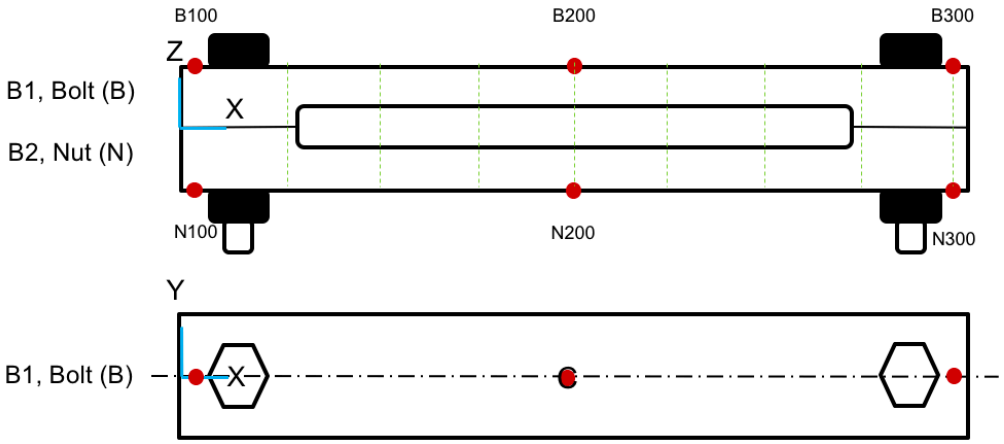
- Experimentally characterize a new benchmark structure
  - Designed such that the nonlinearities can be predicted with current simulation tools
  - Identify the degree of nonlinearity
  - Identify modes of interest

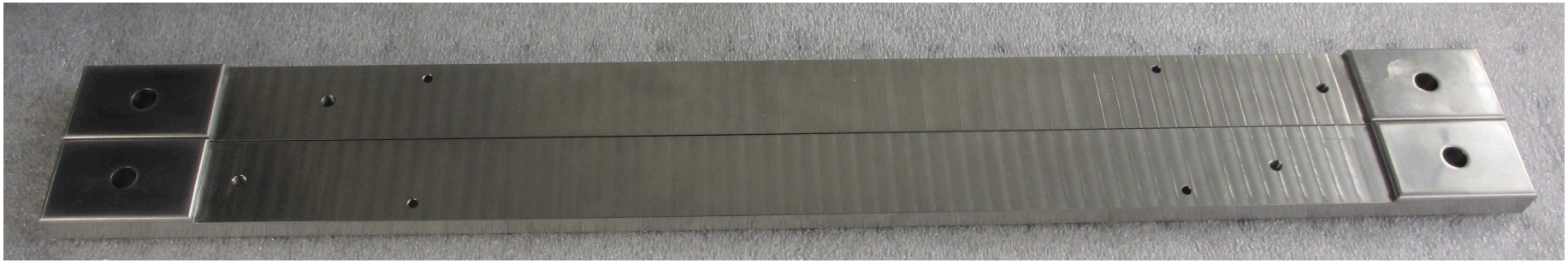
- Measure modal parameters as a function of amplitude
  - Help understand why predictive simulations are incorrect and begin to improve those methods



# Benchmark Structure – S4 Beam (S4B*)

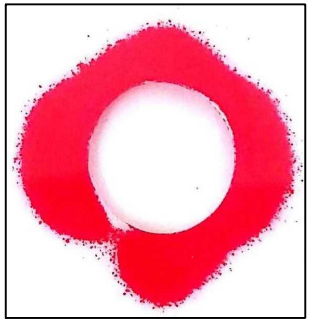
- Stainless Steel – 304
- Two bolted interfaces
- Four contact surfaces
- Nodes spacing every 2.5”
  - 20” Beam

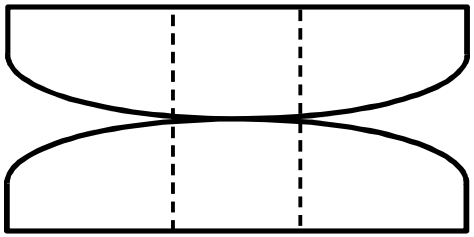


*Sandia – Singh – Scapolan – Saito (S4) Beam

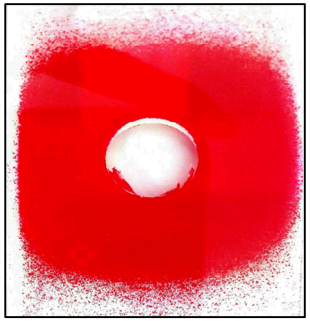
# S4B Variations

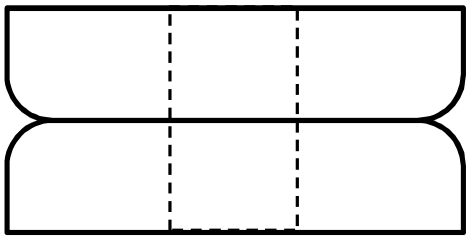




B1B2

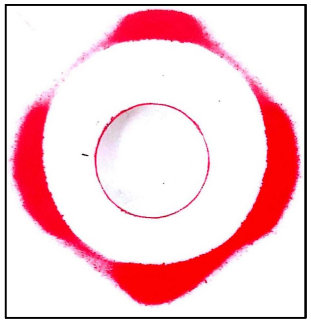
Curved – Curved Interface

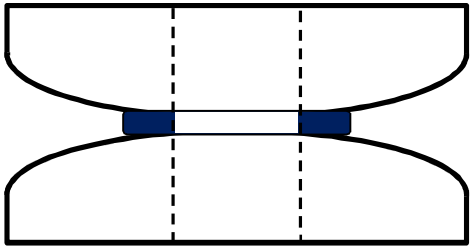




B5B6

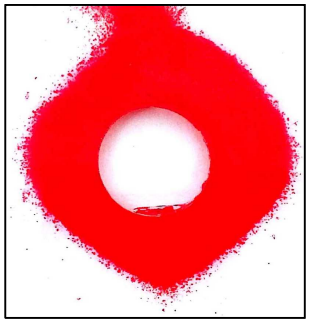
Flat – Flat Interface

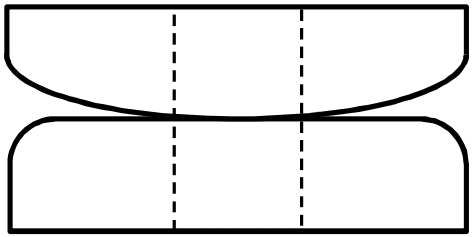




B1B2W

Curved – Curved Interface with SS Washer



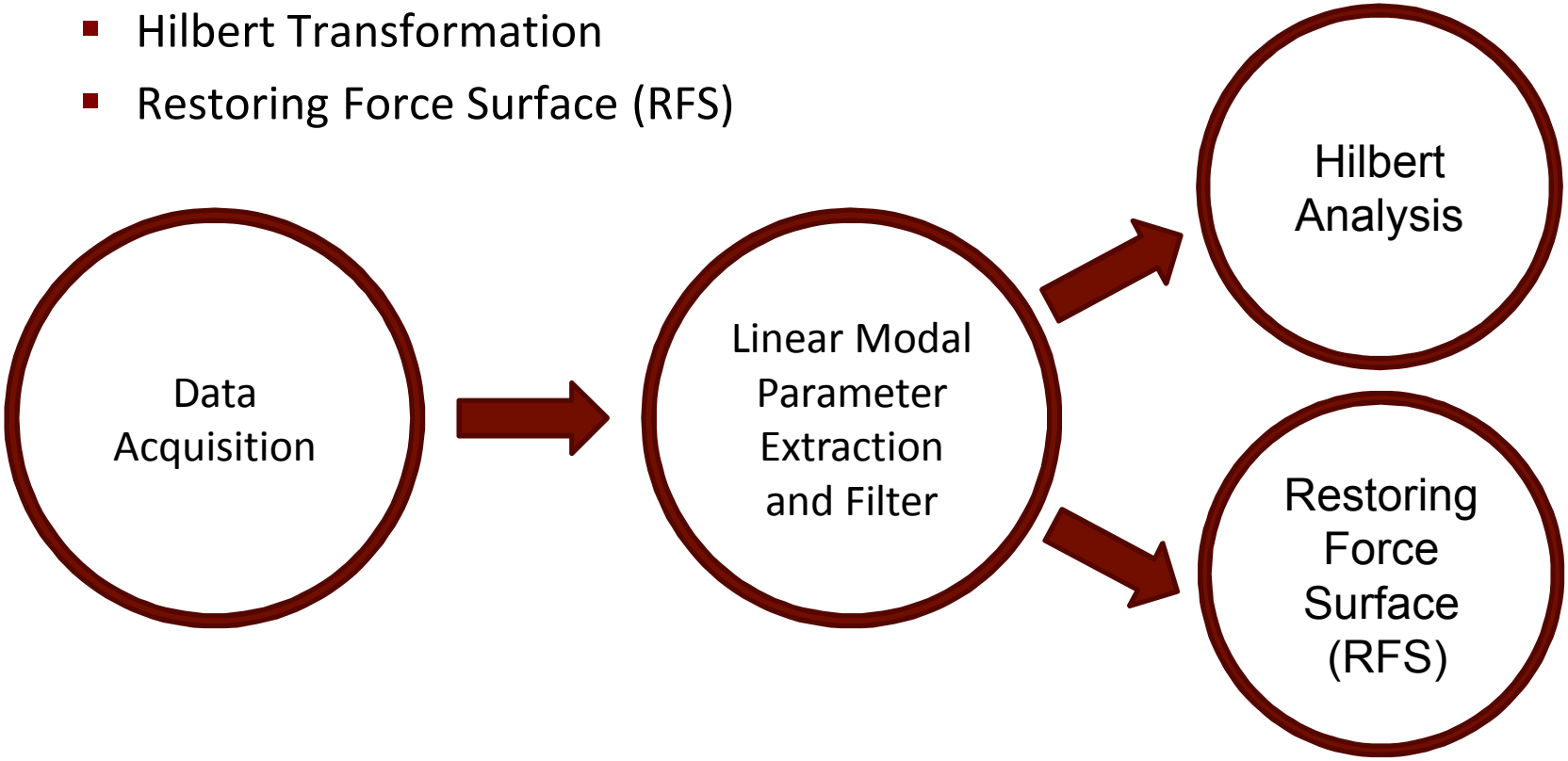


B1B6

Curved – Flat Interface

# S4B Characterization Methodology

- Characterize contact area of interface through pressure analysis
- Characterize nonlinear stiffness and damping through
  - Hilbert Transformation
  - Restoring Force Surface (RFS)



# Joint Characterization

**Objective:**
Have to find some way to “characterize’’ the joint to link the variance in the torque/contact surfaces to the change in the structural response (FRF)

In reality, the contact surfaces look like…

**Flat**

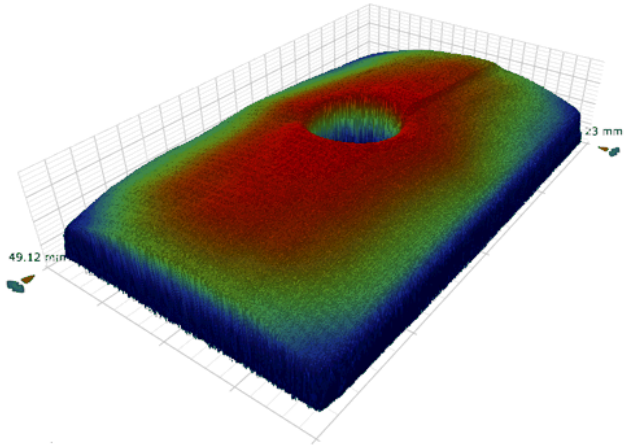
**Curved**

**Not flat nor curved**

**Take measurements of the contact surfaces to characterize the joints**

# Digital Imagery

Use a high resolution optical camera to obtain the three-dimensional profiles measuring nm (nano-meter) resolution.

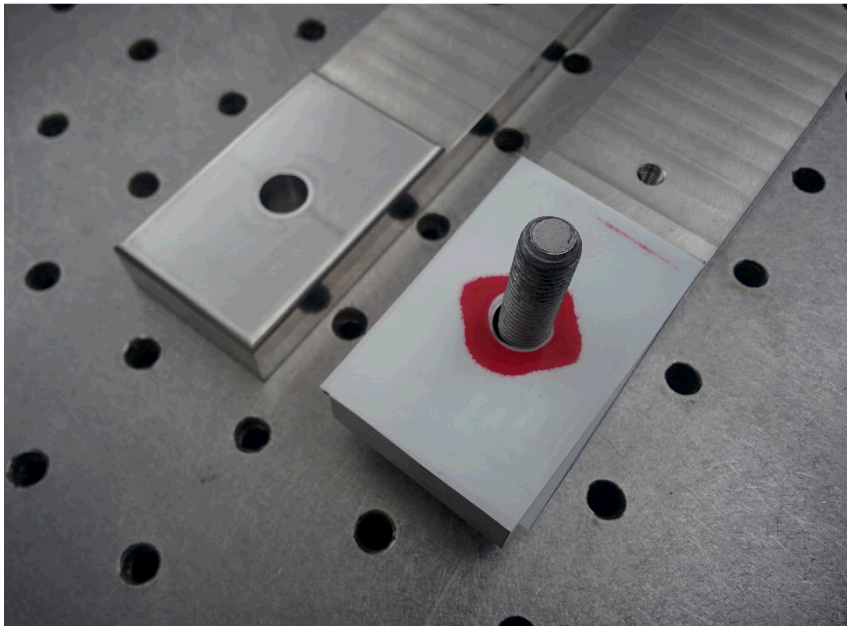


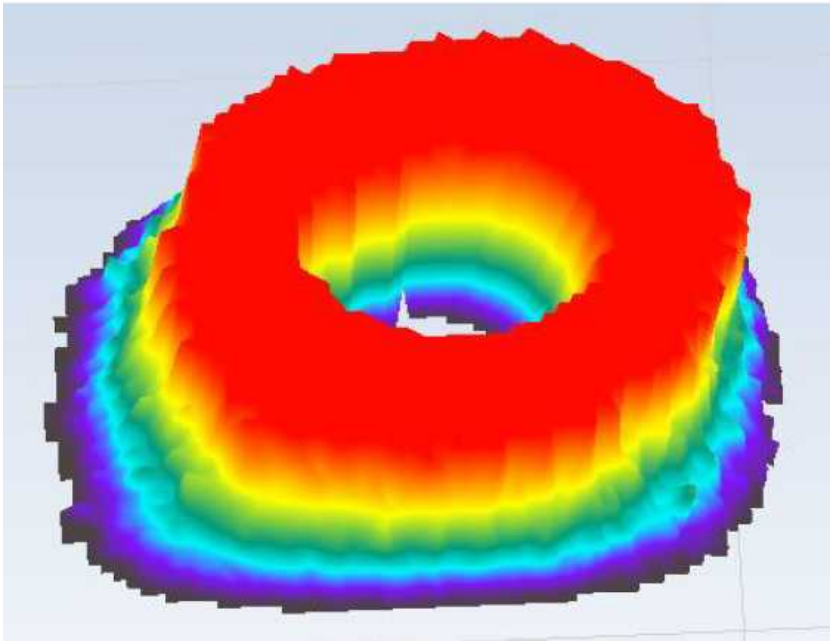


**Result:**
Extract surface roughness parameters (fractal dimension and fractal roughness parameter) and true geometry

# Pressure film

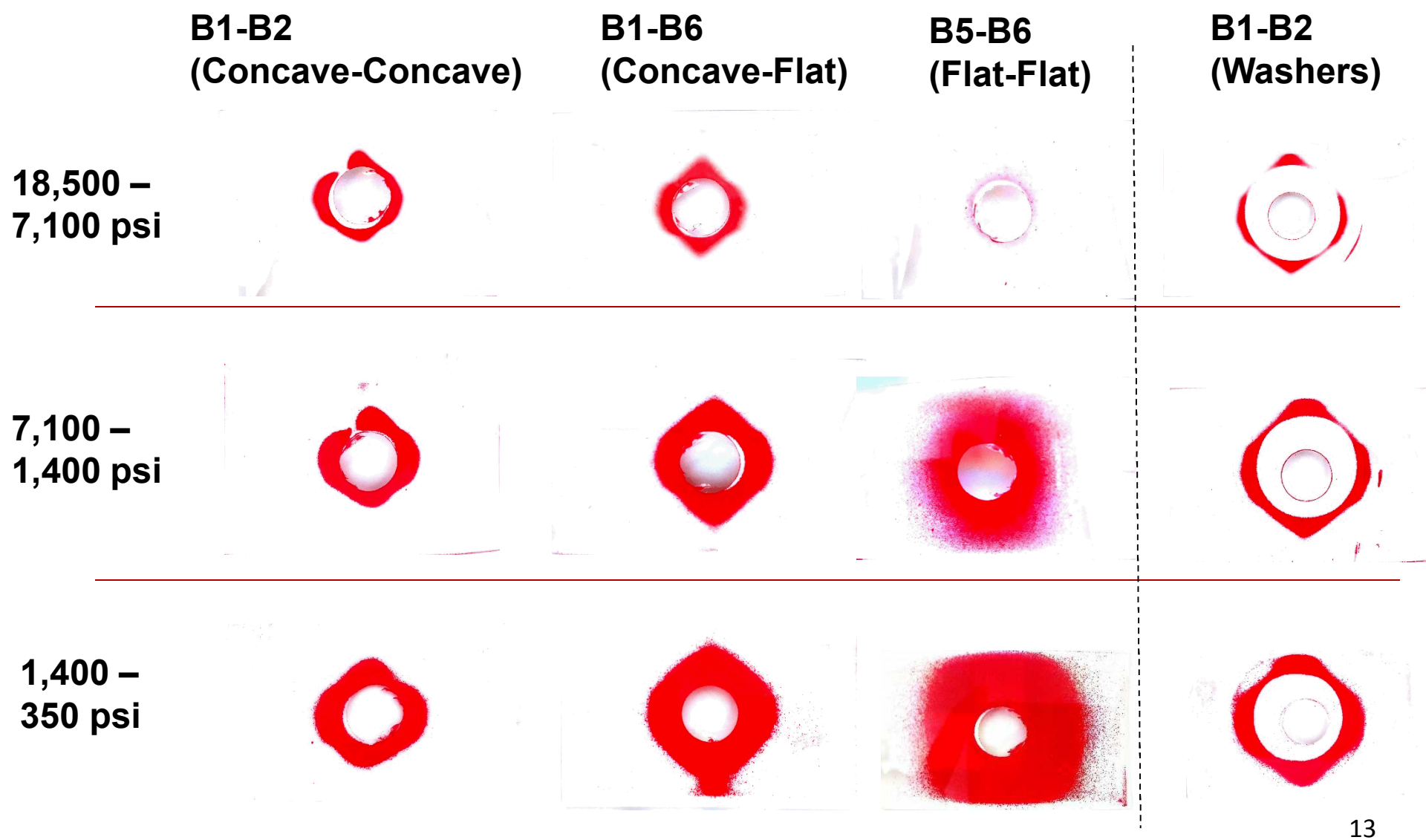
Use pressure films to extract the pressure along the surface of the interface for different torque levels.



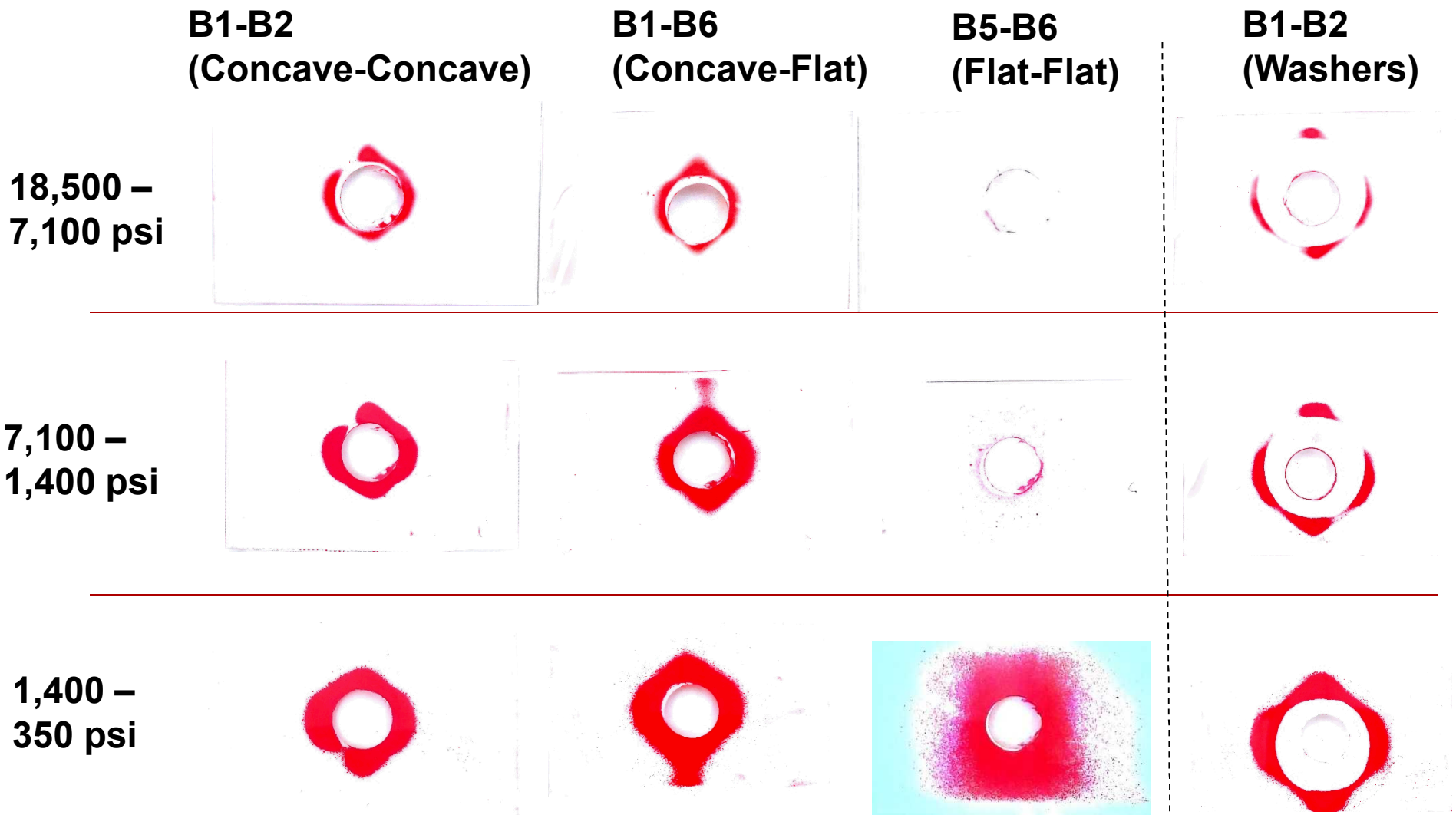


**Result:**
Extract the contact area and the normal/tangential force acting at different torque levels and combination of contact surfaces.

# Pressure Films (high torque)



# Pressure Films (low torque)



# Putting it together

**Pressure films**

- Find the pressure along the contact surface + surface area of contact
- Compute the contact area, normal/tangential force

**Digital Imagery**

- Find the high resolution surface contour
- Compute the surface roughness parameters

**Material Characteristics**

- Elastic moduli, hardness, mass. etc

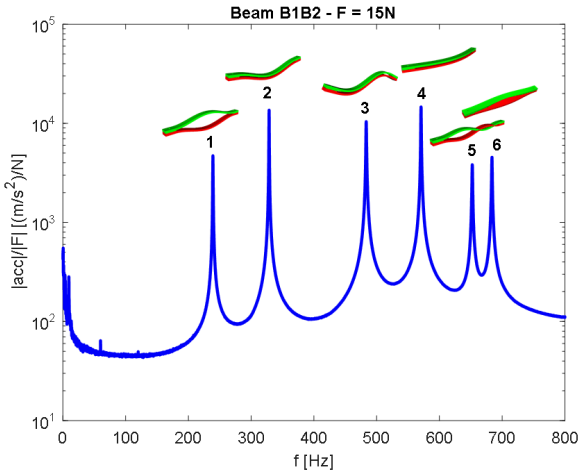
Find the “truncated area” i.e. the area of the contact after deformation in the interface

**Compute the normal/tangential stiffness and damping of the joint (eventually)**

# Experiment Design

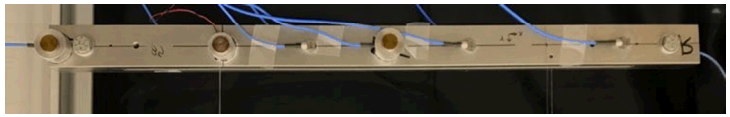
Modes identification

Roving Hammer




Optimal experimental setup

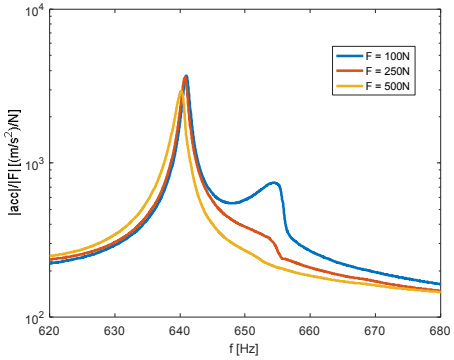
Minimum number of accelerometers and input points



Nonlinear modes evaluation

Increasing force levels

Increasing torque levels




Nonlinear time histories

| | Input Force | | | | |
|---|---|---|---|---|---|
| Torque Levels | | 15 N | 100 N | 250 N | 500 N |
| | 10.2 Nm | X | X | X | X |
| | 16.9 Nm | X | X | X | X |
| | 25.1 Nm | X | X | X | X |

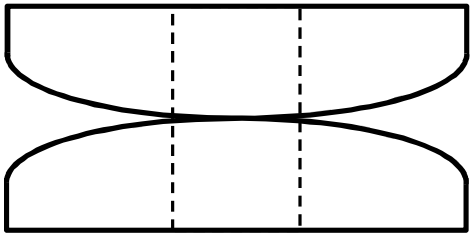
# Experiment Design

Nonlinear

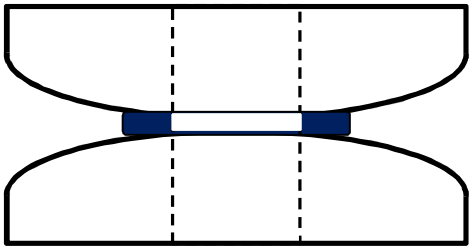
Nonlinear

| | Input Force | | | | |
|---|---|---|---|---|---|
| **Torque Levels** | | 15 N | 100 N | 250 N | 500 N |
| | 10.2 Nm | X | X | X | X |
| | 16.9 Nm | X | X | X | X |
| | 25.1 Nm | X | X | X | X |

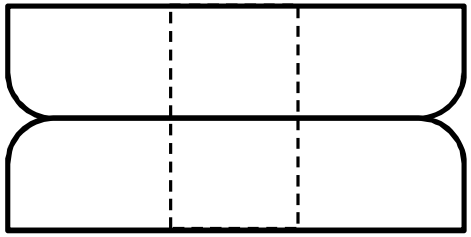
- 3 torque levels
- 4 force levels
- 4 interfaces



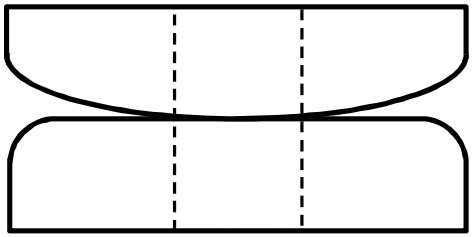
**B1B2**



**B1B2W**

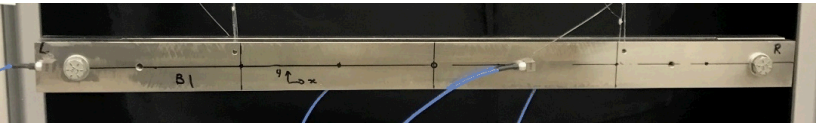


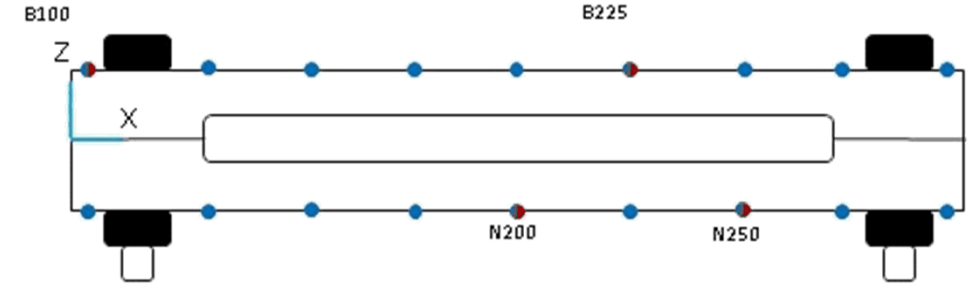
**B5B6**



**B1B6**

# Linear Modeshapes Identification

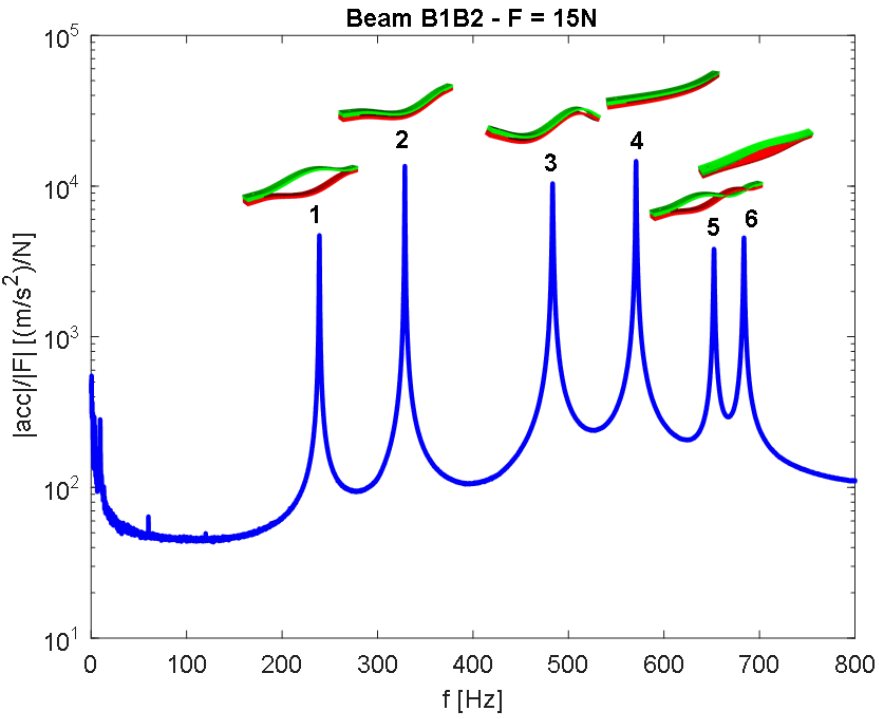





B1, Bolt (B)

B2, Nut (N)

B1, Bolt( B)




Outputs

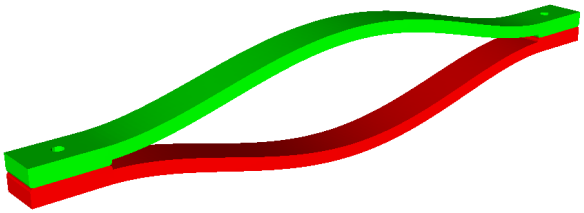
Inputs

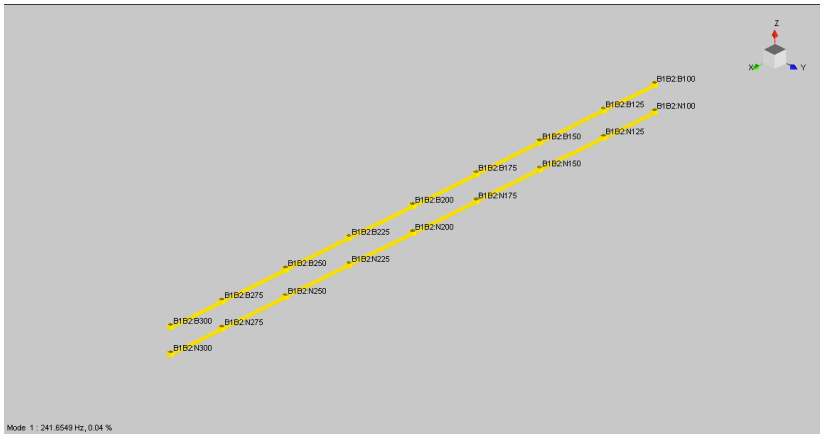
- Roving Hammer
- Minimum number of accelerometers
- Low amplitude impact

**Linear Modeshapes**

# Modeshapes

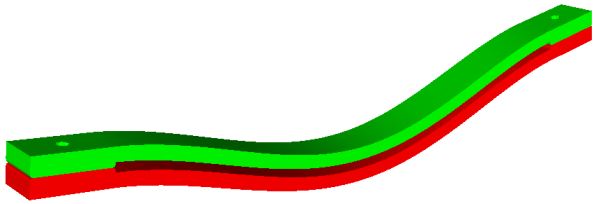
Mode 1
$f_n$ = 241.89 Hz, $\zeta$ = 0.00024

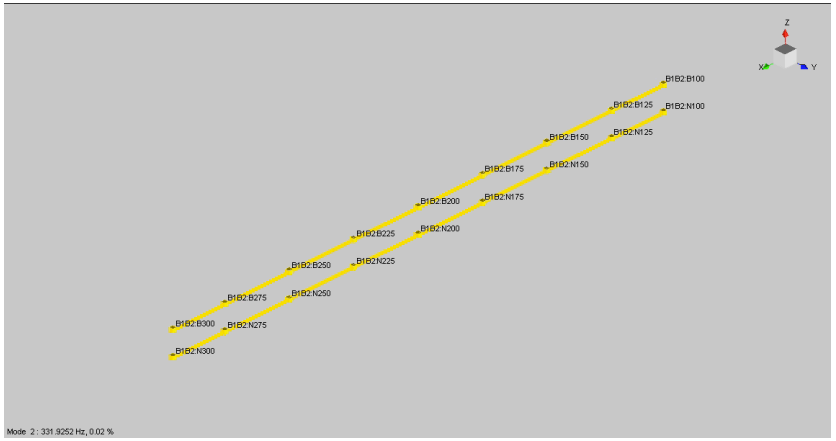





First z bending, clapping

Mode 2
$f_n$ = 332.09 Hz, $\zeta$ = 0.00012

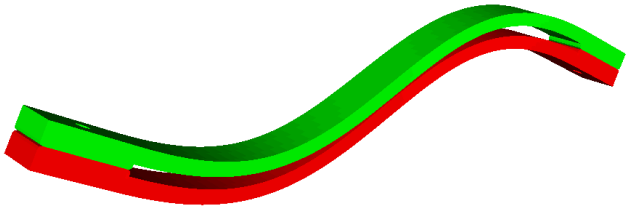


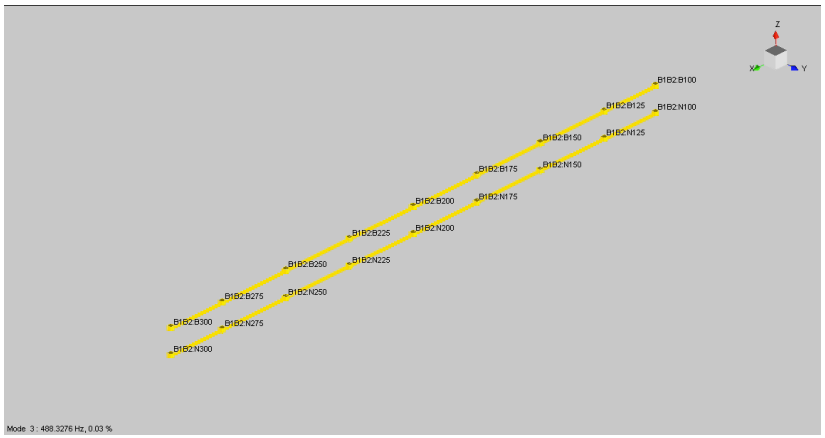



First z bending

# Modeshapes

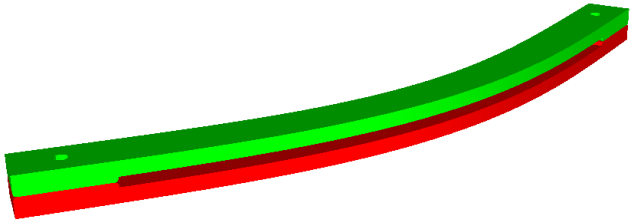
Mode 3
$f_n$ = 488.76 Hz, $\zeta$ = 0.00028

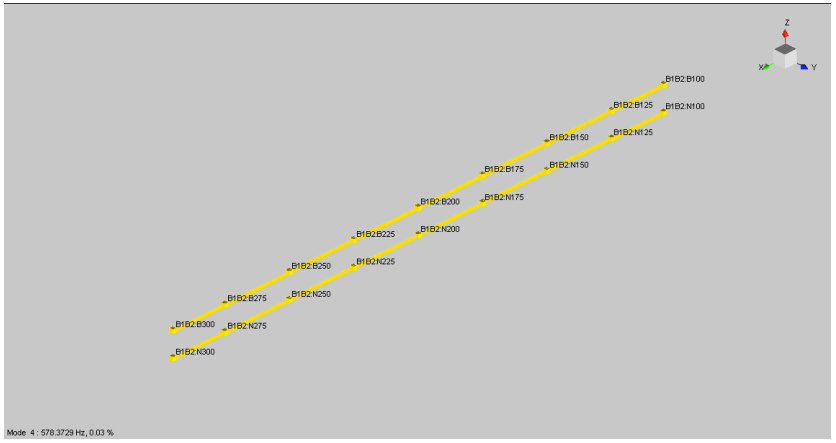





Second z bending

Mode 4
$f_n$ = 578.24 Hz, $\zeta$ = 0.00031

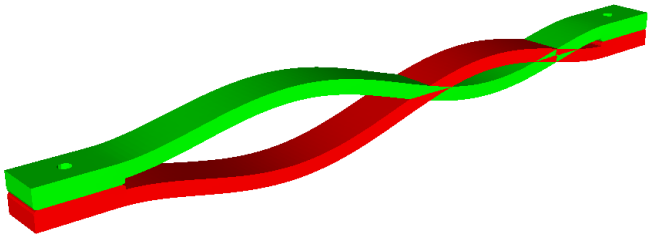


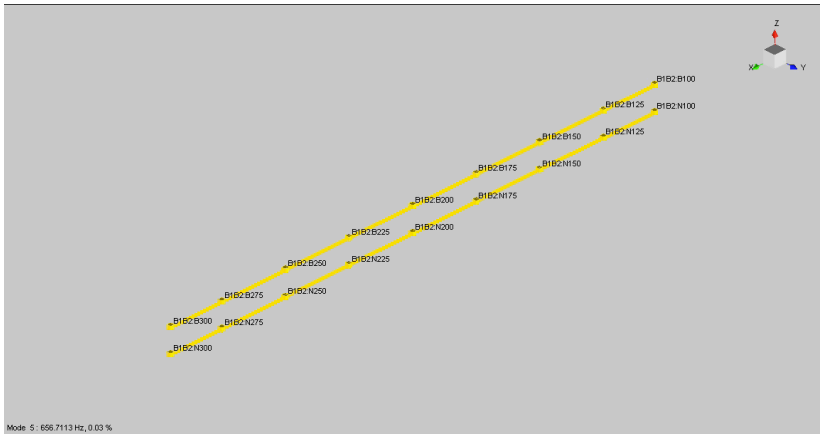



First y bending

# Modeshapes

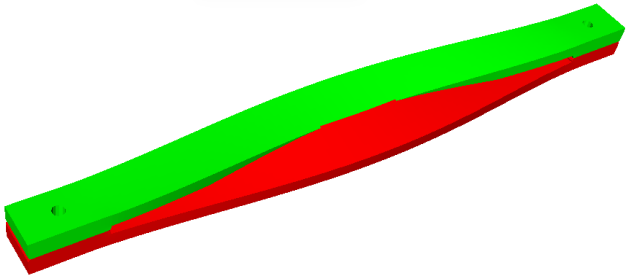
Mode 5
$f_n$ = 657.38 Hz, $\zeta$ = 0.00021

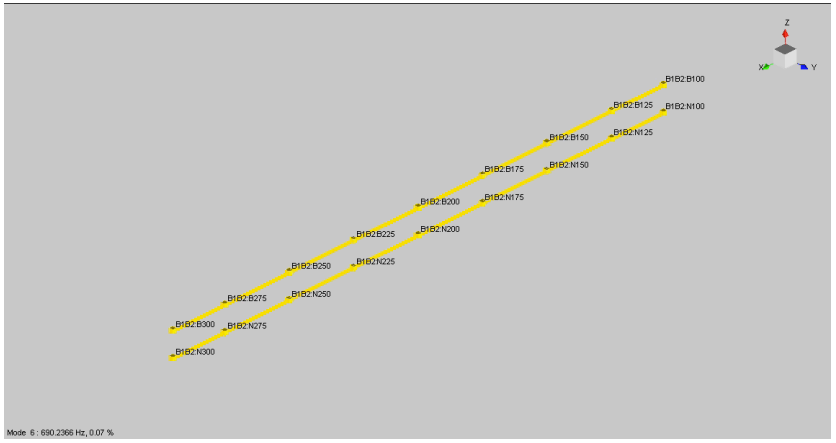





Second z bending, clapping

Mode 6
$f_n$ = 689.95 Hz, $\zeta$ = 0.00071



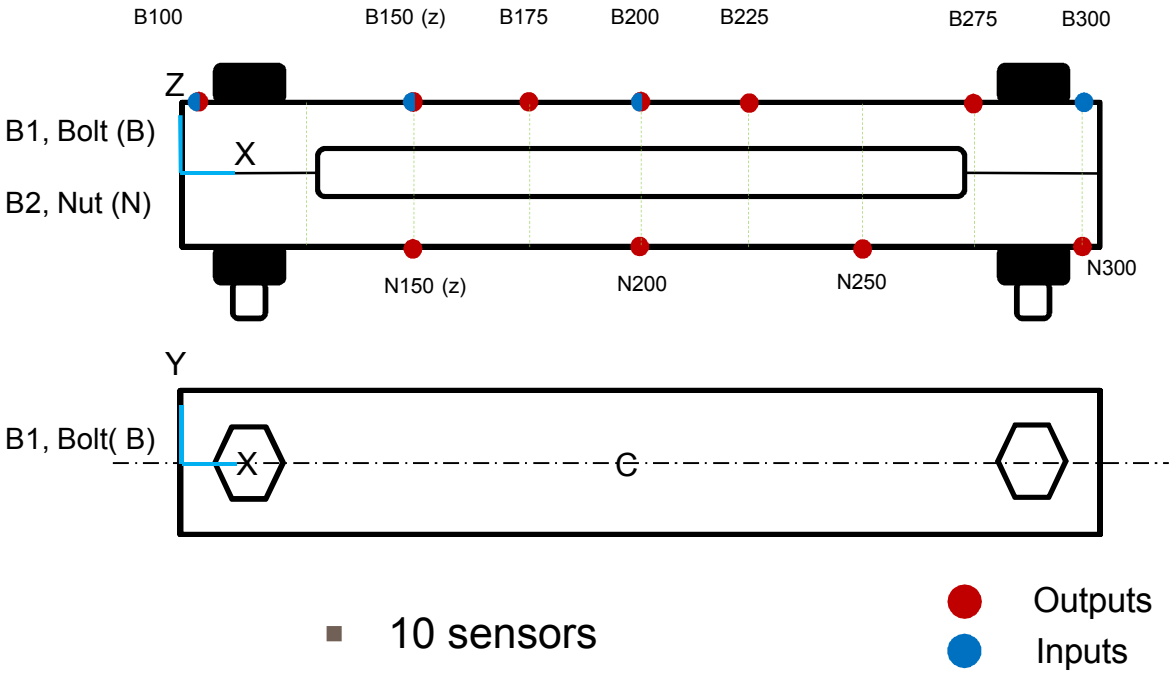



First y bending, clapping

# Experimental Setup

**7 input – 28 output setup**

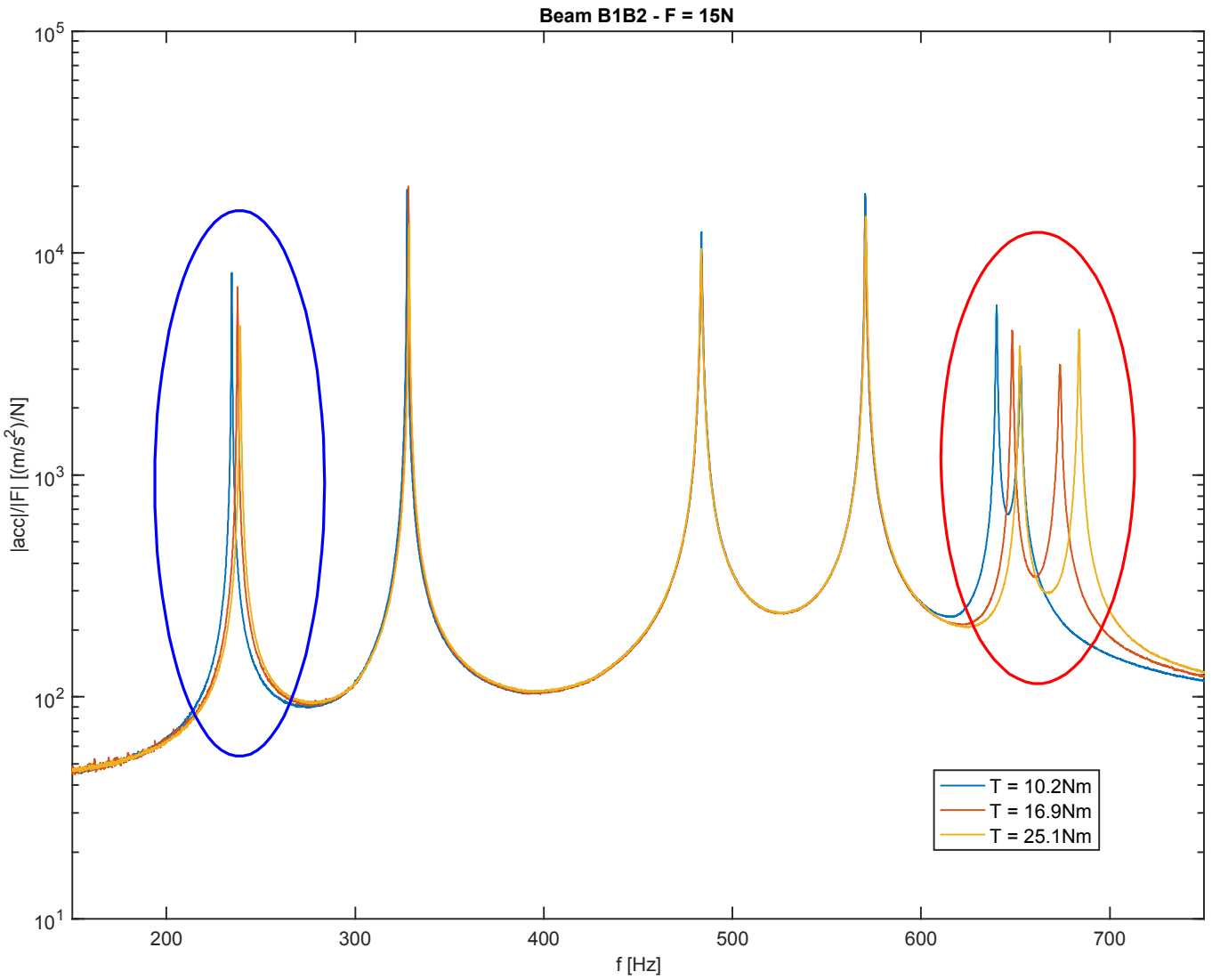
- Outputs:
  - Triaxials (X,Y,Z)
    - B200, N200
    - B100, N300
    - B175, B225, B275
    - N150, N250
  - Uniaxials (Z)
    - B150
- Inputs:
  - B300 z,y
  - B200 z,y
  - B100 z,y
  - B150 z



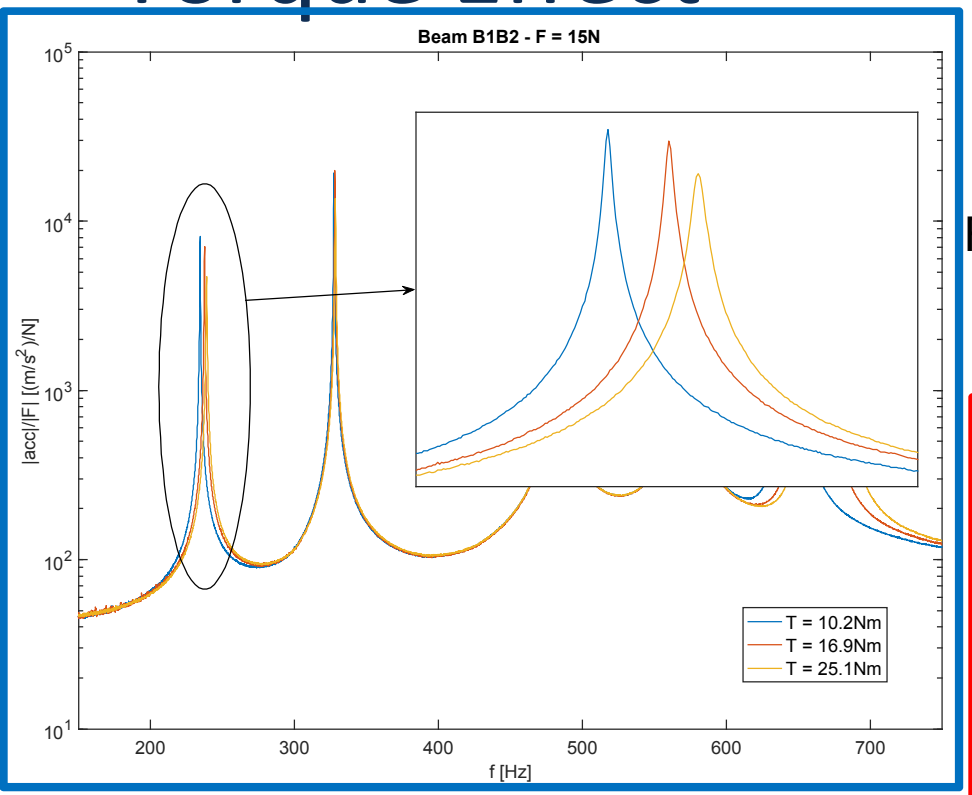

- 10 sensors
- 28 Channels (19 without X)
- 7 input points

**Nonlinear analysis and time histories**

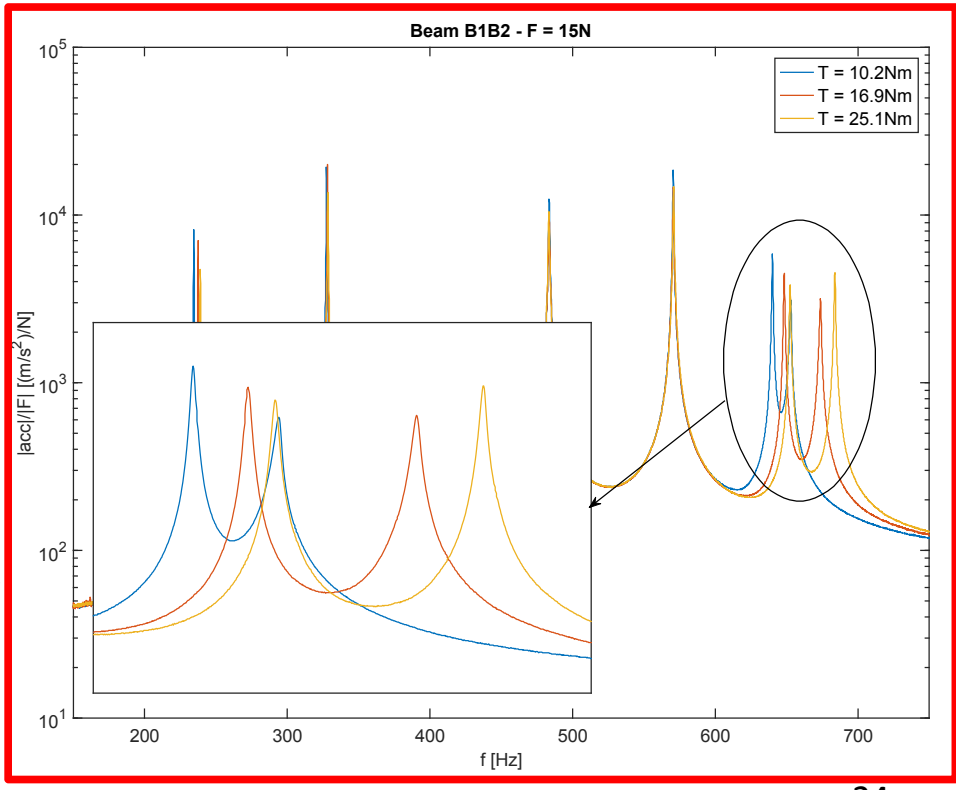
# Torque Effect



# Torque Effect

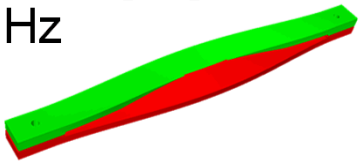



Frequency shift of **Mode 1**
234.6 Hz → 239.1 Hz

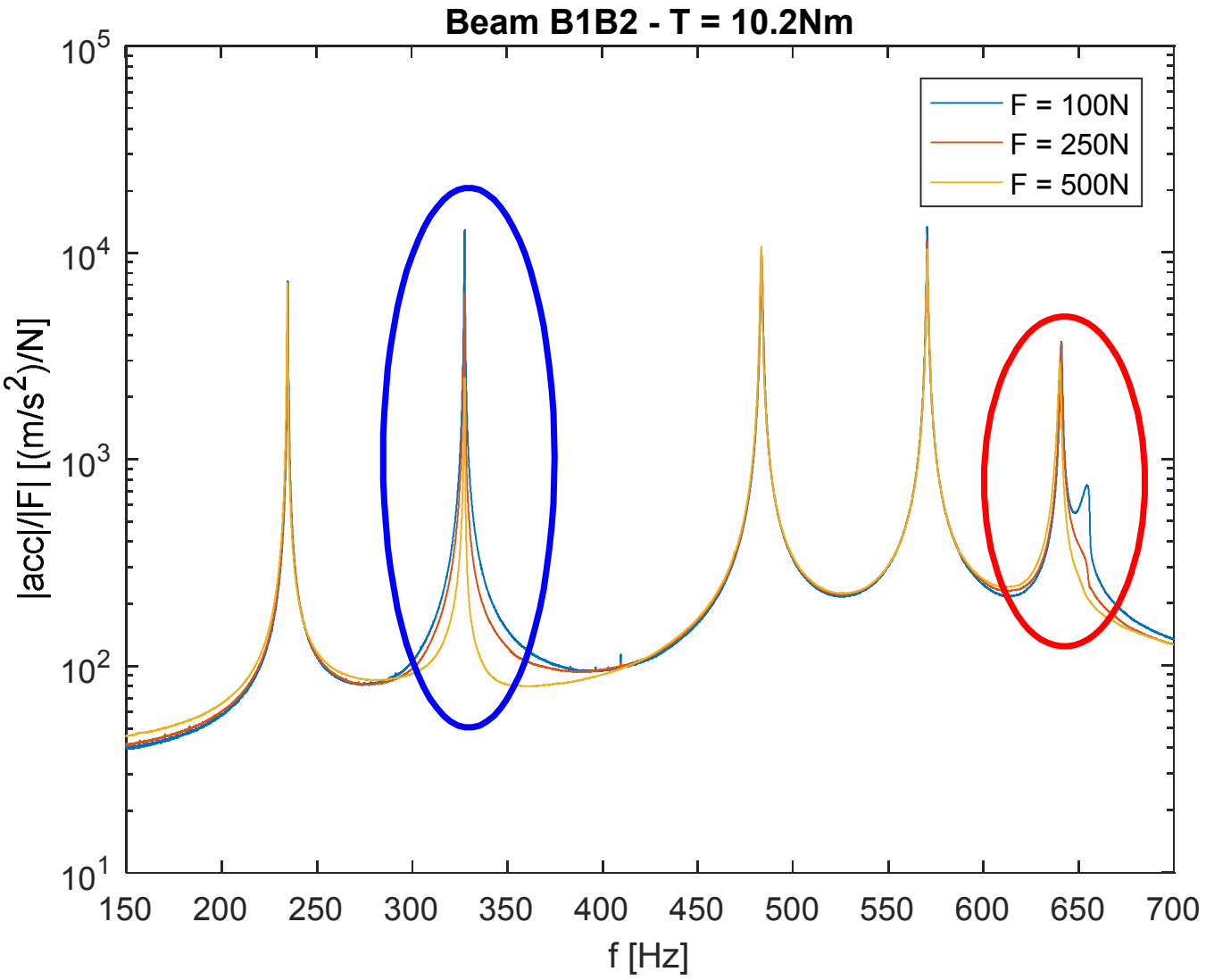



Frequency shift of **Mode 5**
640.0 Hz → 652.3 Hz

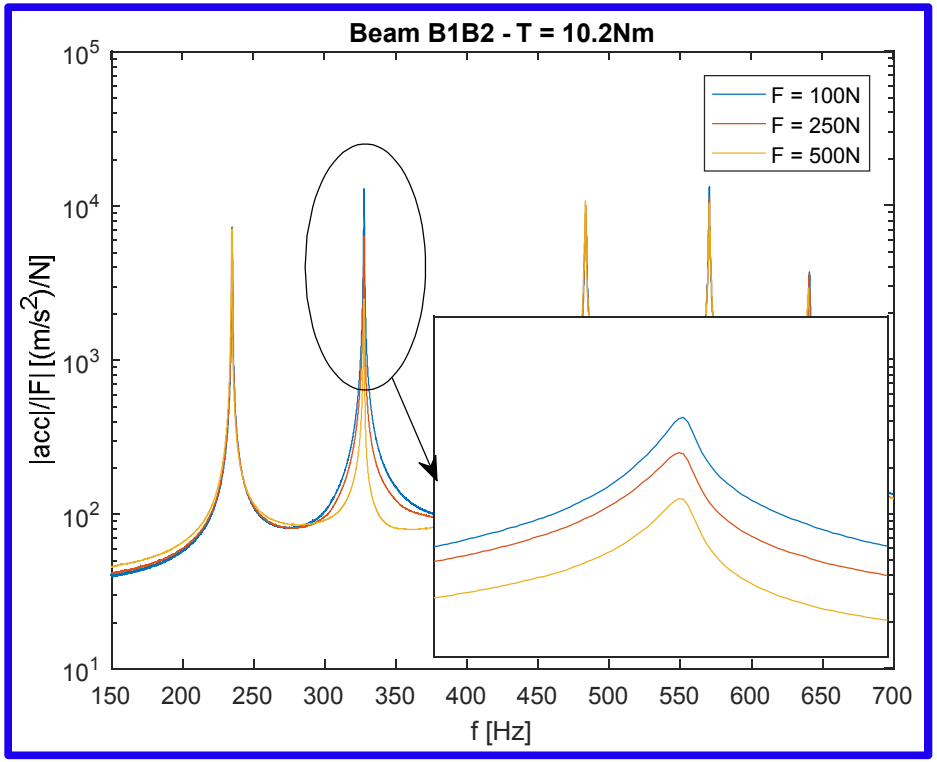
and **Mode 6**
652.9 Hz → 683.8 Hz



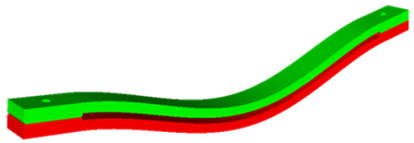
# Force Effect

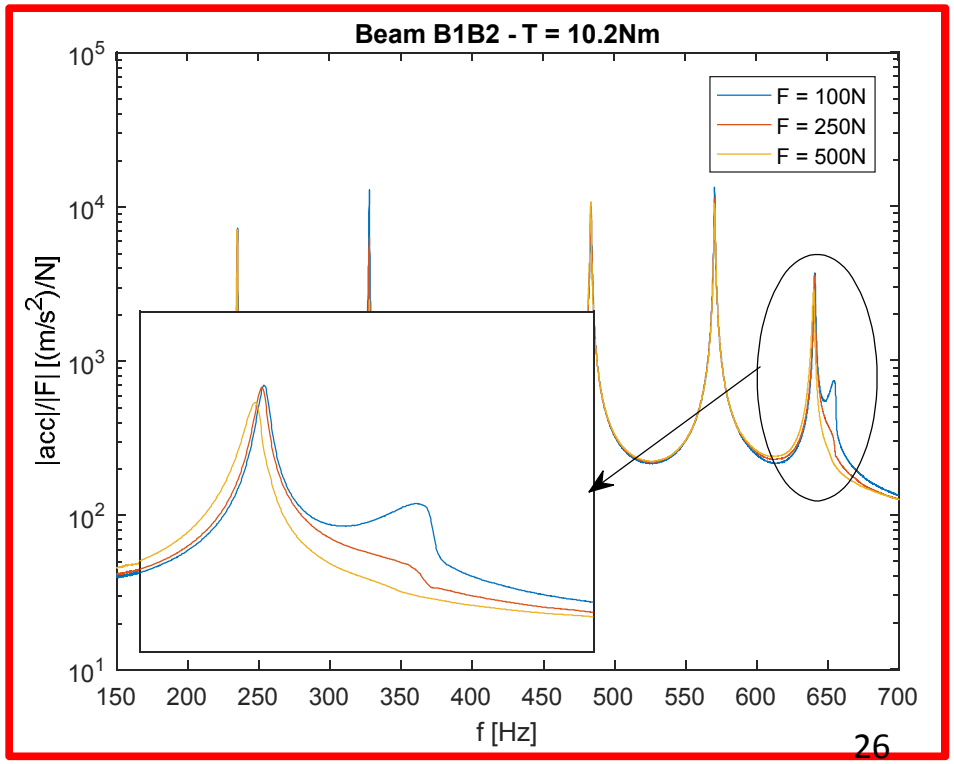


# Force Effect

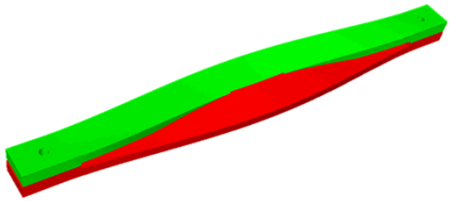



Slight increase in damping for **Mode 2**

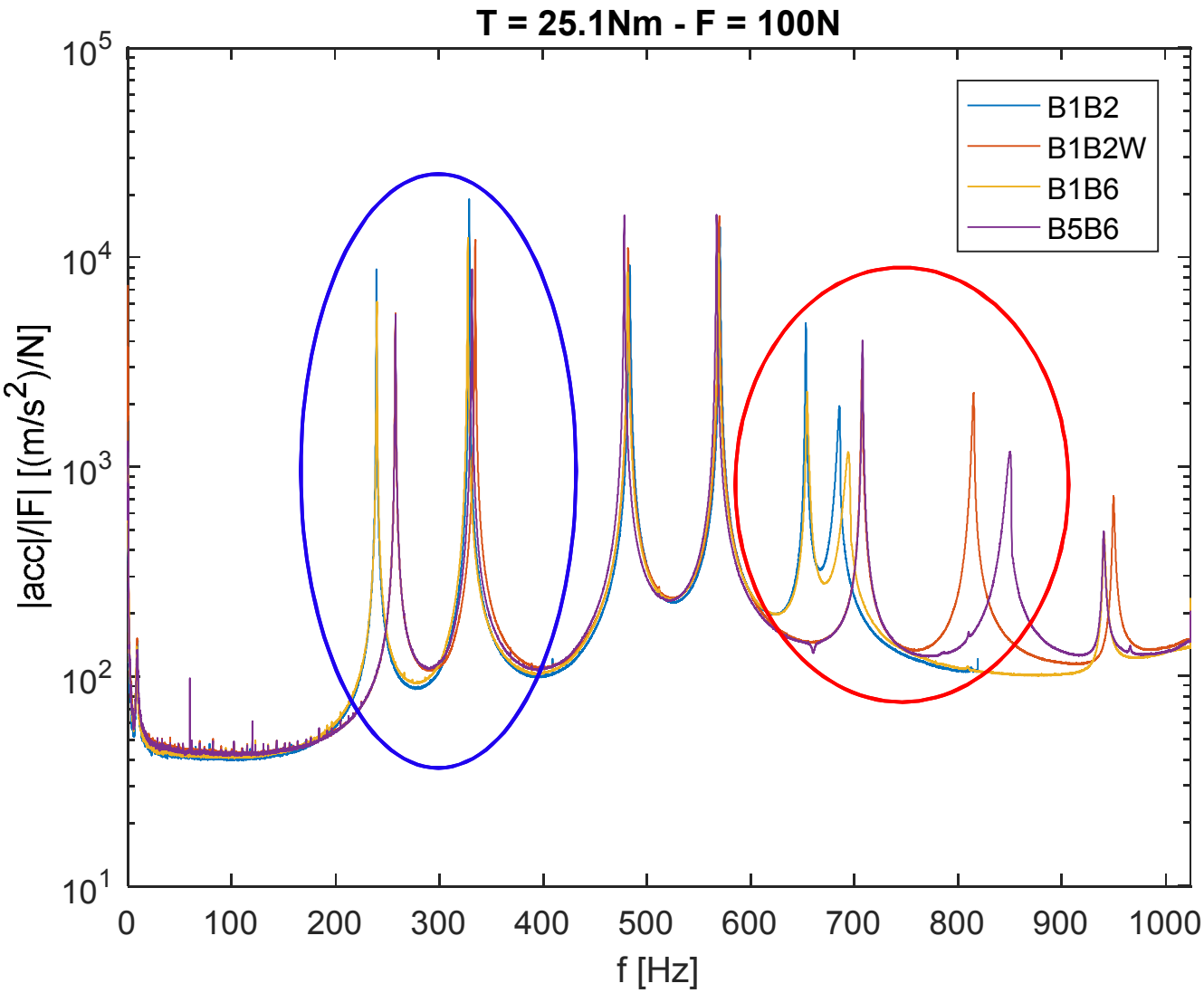




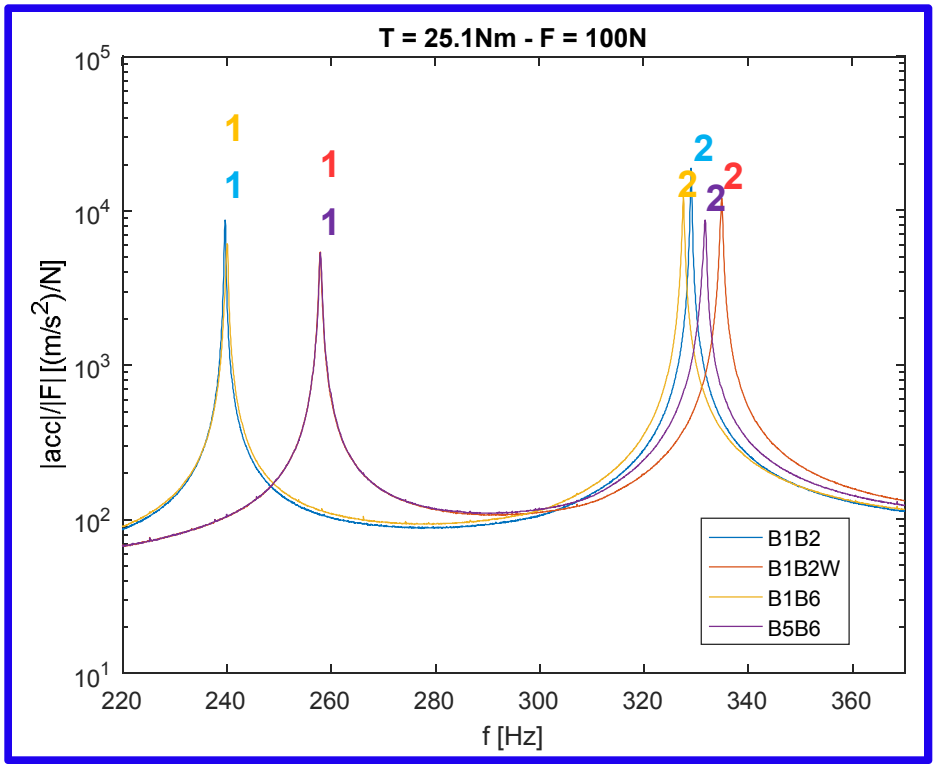

Large increase in damping for **Mode 6**



# Beams Comparison



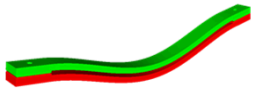
# Beams Comparison



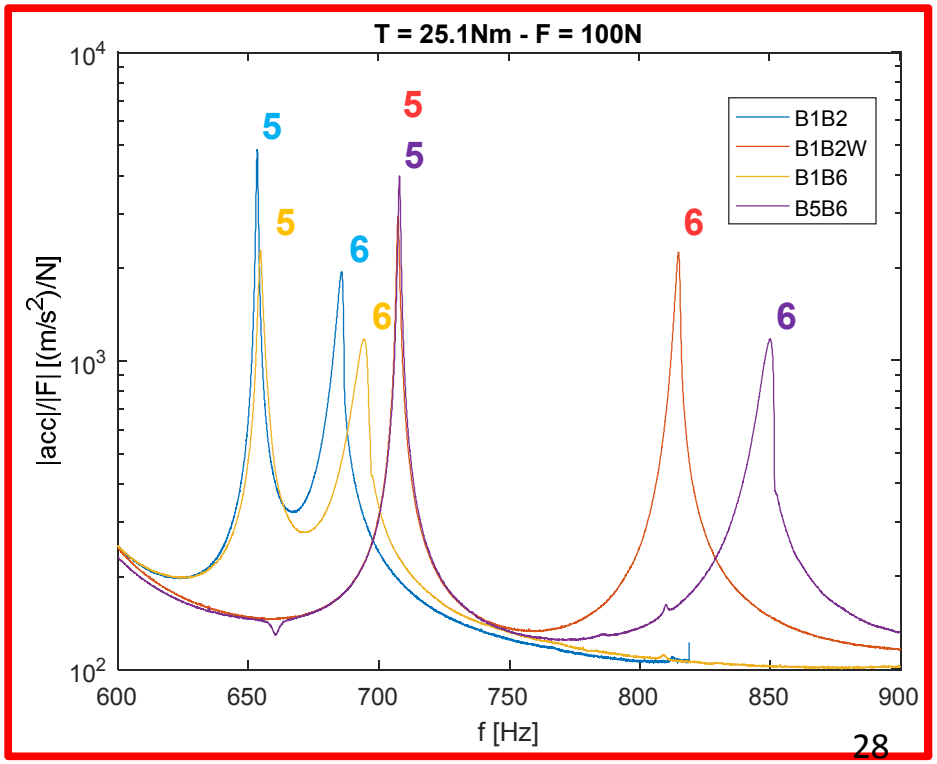

**Mode 1:**

- B1B2 & B1B6 ~240 Hz
- B1B2W & B5B6 ~258 Hz

**Mode 2:**



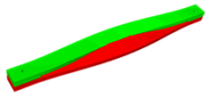
- B1B2, B1B2W, B1B6 & B5B6 [328 – 335] Hz




**Mode 5:**

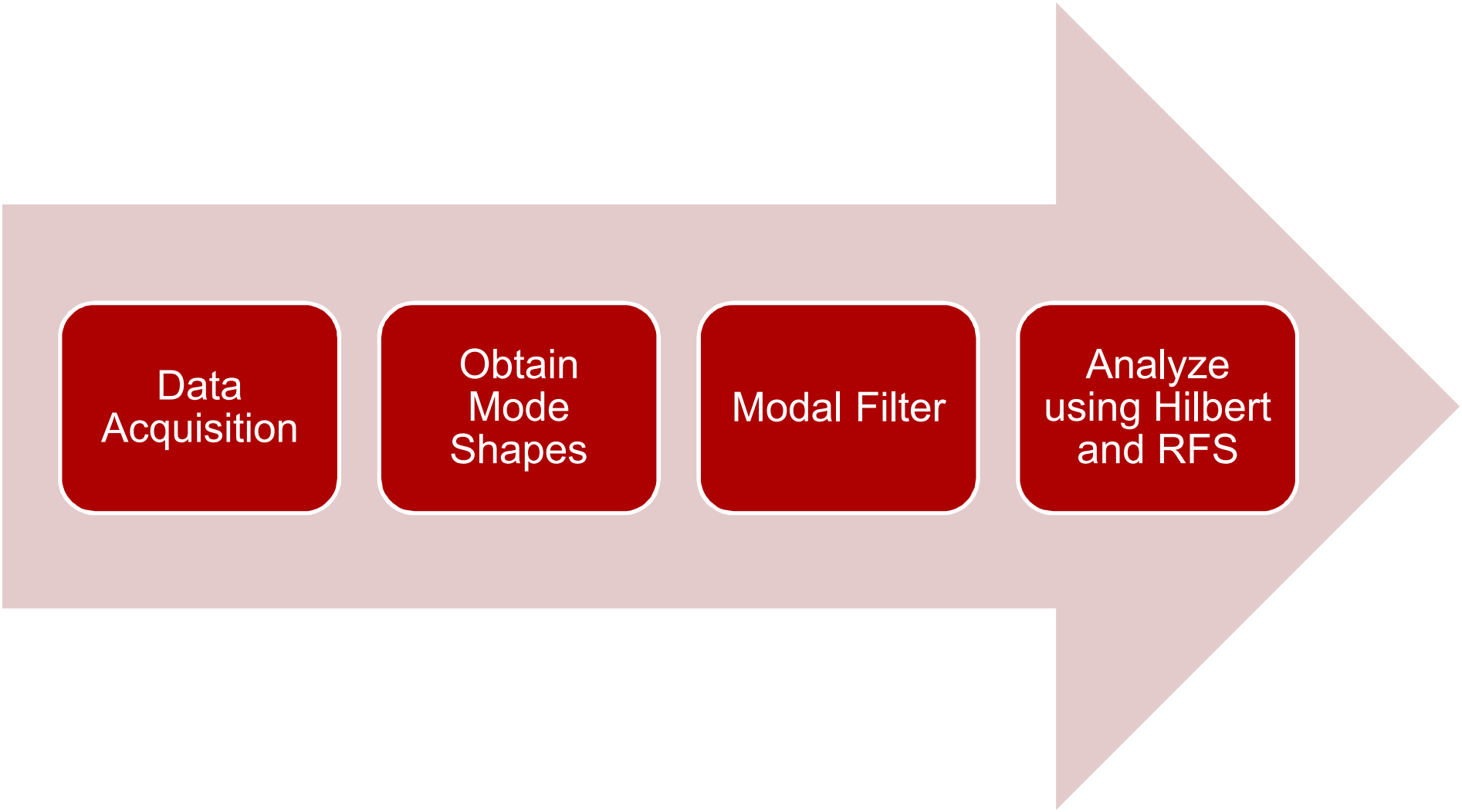
- B1B2 & B1B6 ~654 Hz
- B1B2W & B5B6 ~707 Hz

**Mode 6:**



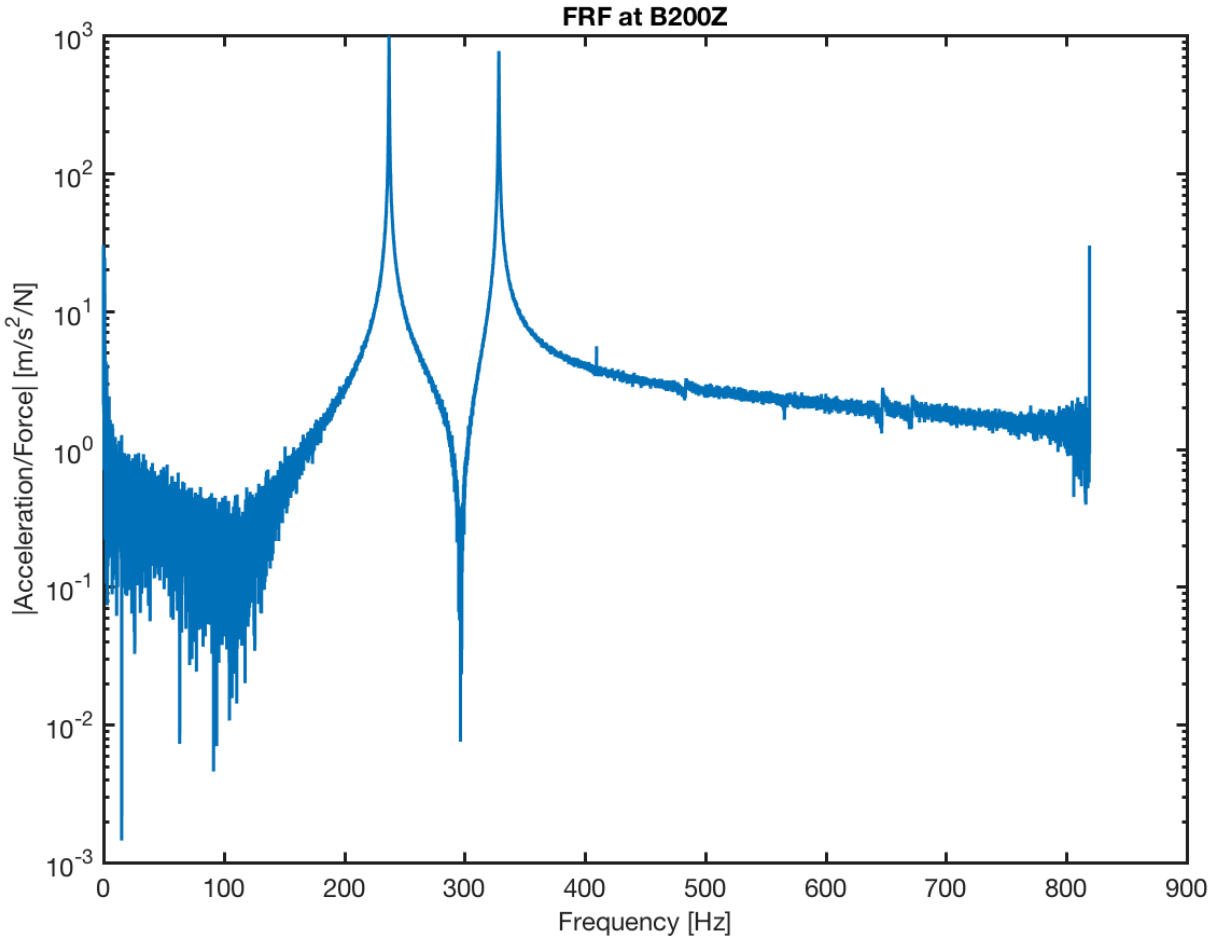
- B1B2 & B1B6 [685 - 695] Hz
- B1B2W & B5B6 [815 - 850] Hz

# Numerical Analysis

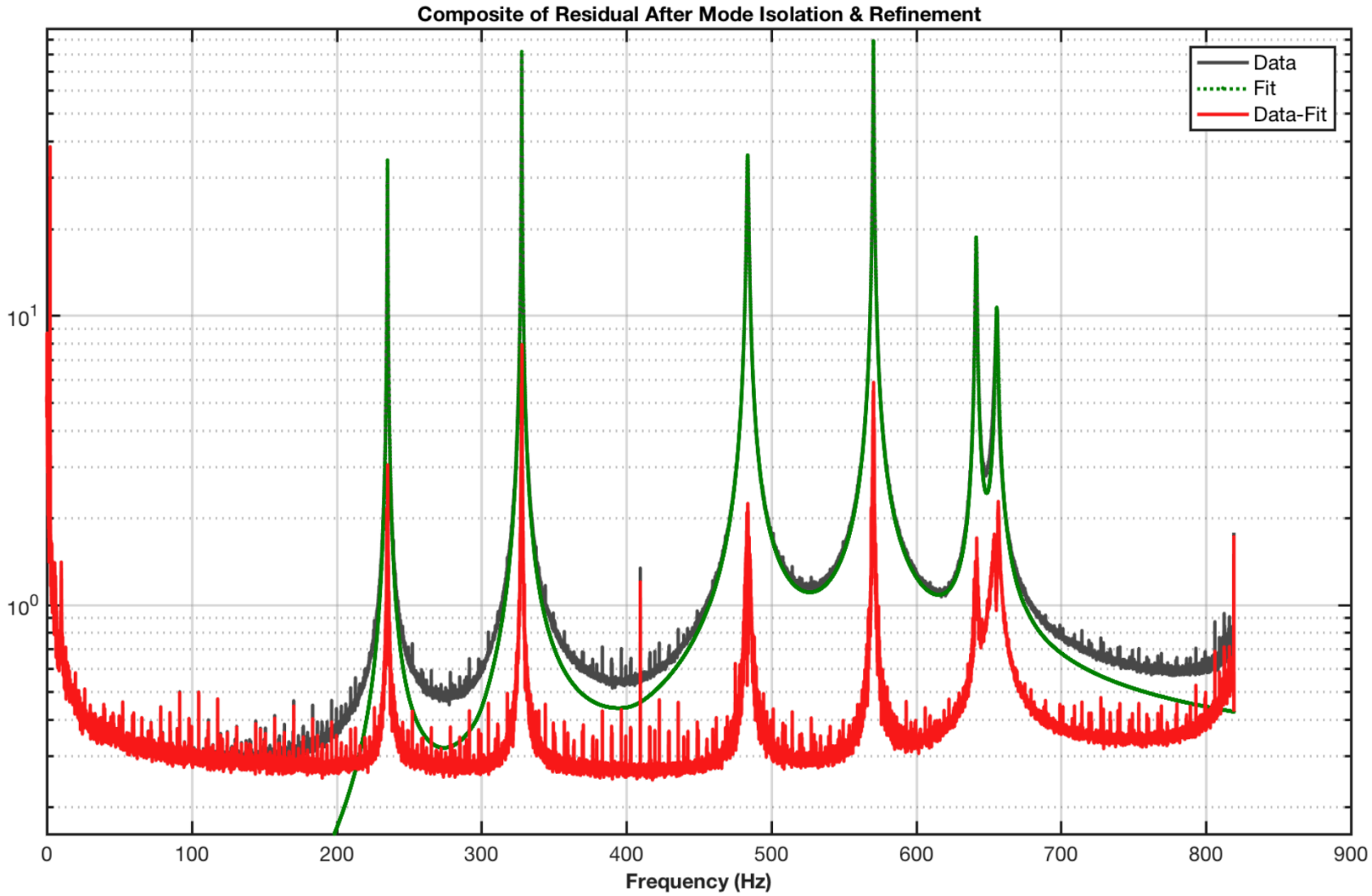


# Data Acquisition

- Coupled motion of modes
  - Difficult to numerically model
  - Not ideal

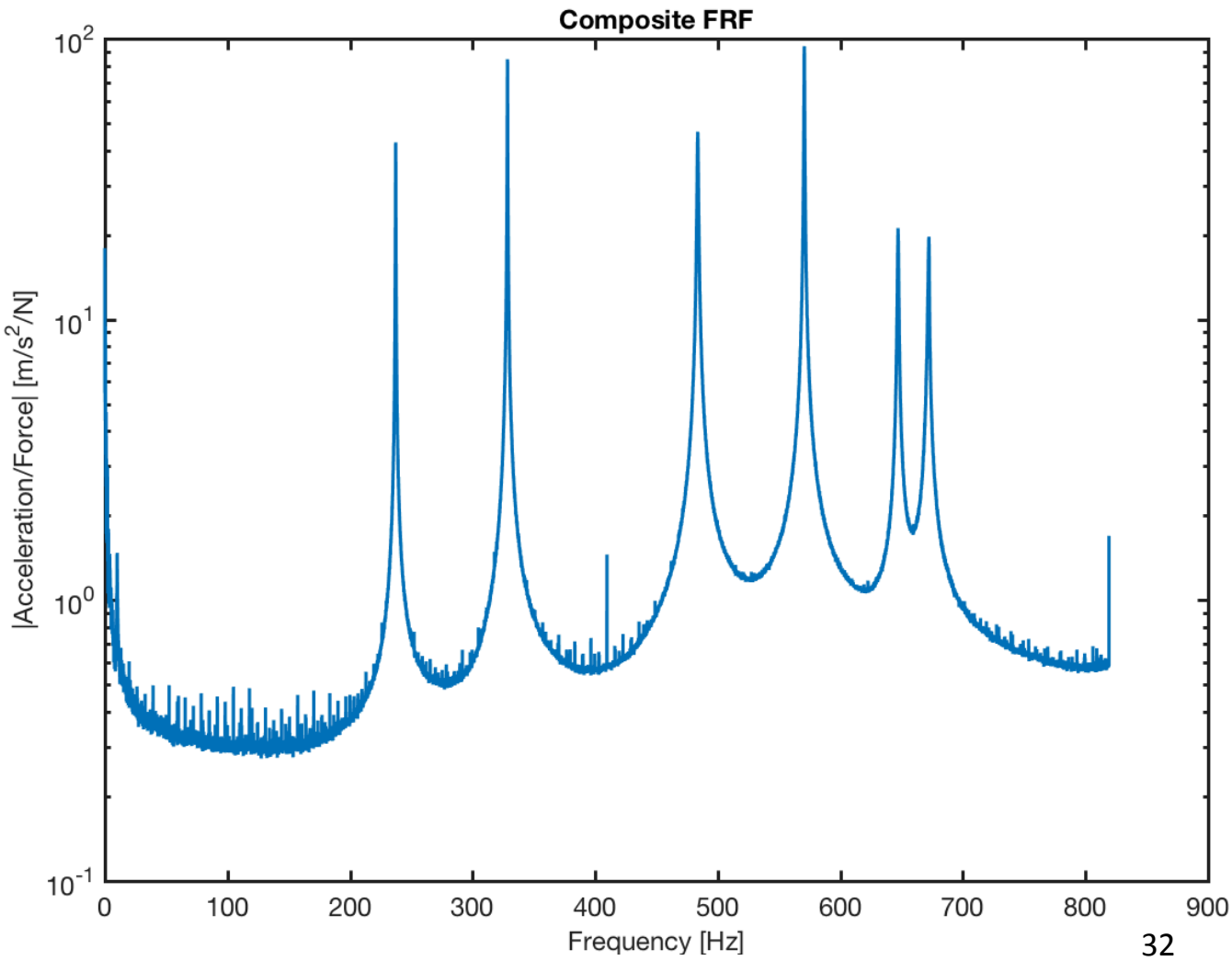


# Obtain Mode Shapes



# Decouple motion

- Convert to modal coordinates using $\ddot{x} = [\Phi]\ddot{\eta}$




Physical Domain (x)

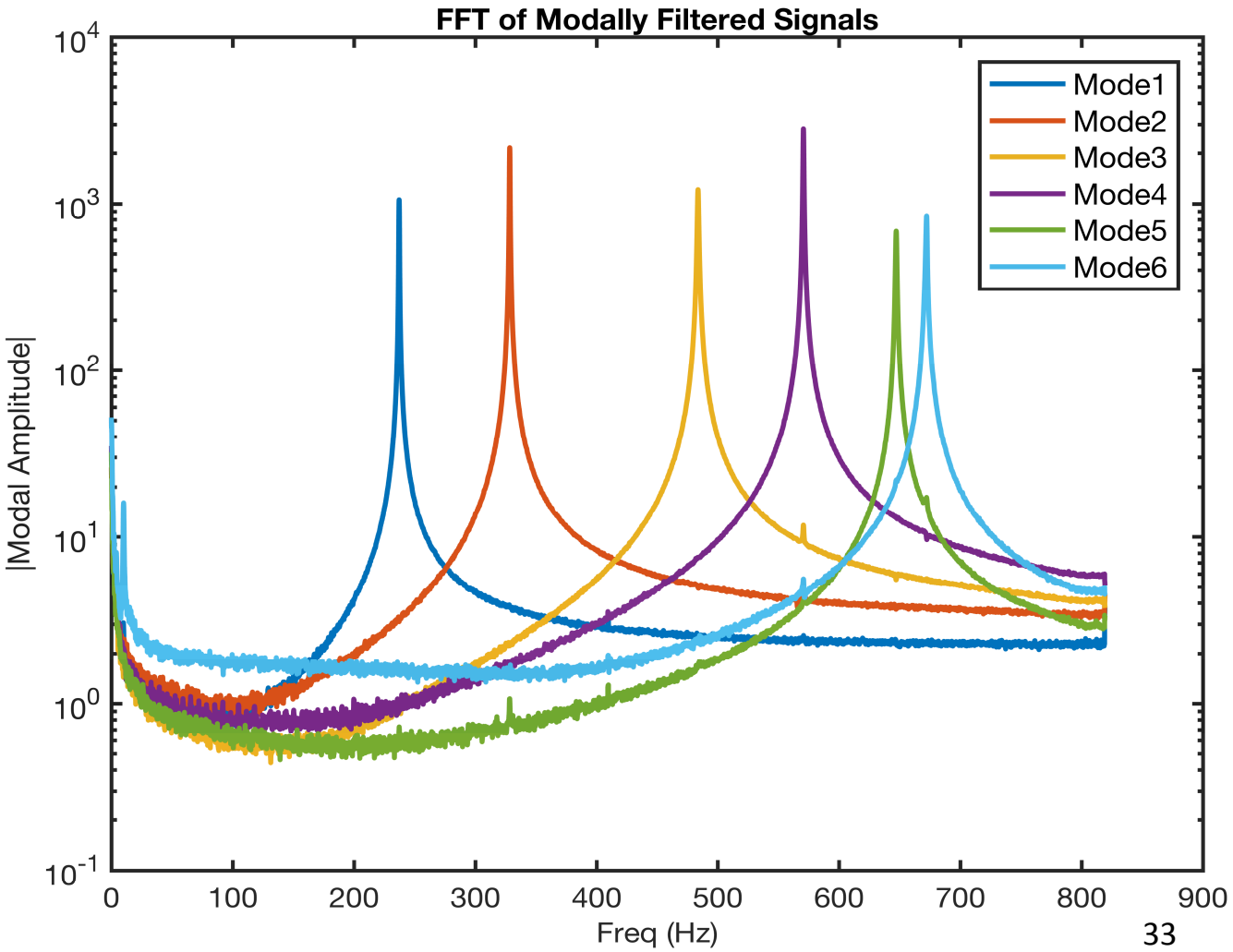
- 28 accelerometer measurements
- 7 input points
- Coupled motion

# Decouple motion

- Convert to modal coordinates using $\ddot{\mathrm{x}} = [\Phi]\ddot{\eta}$

Modal Domain ($\eta$)

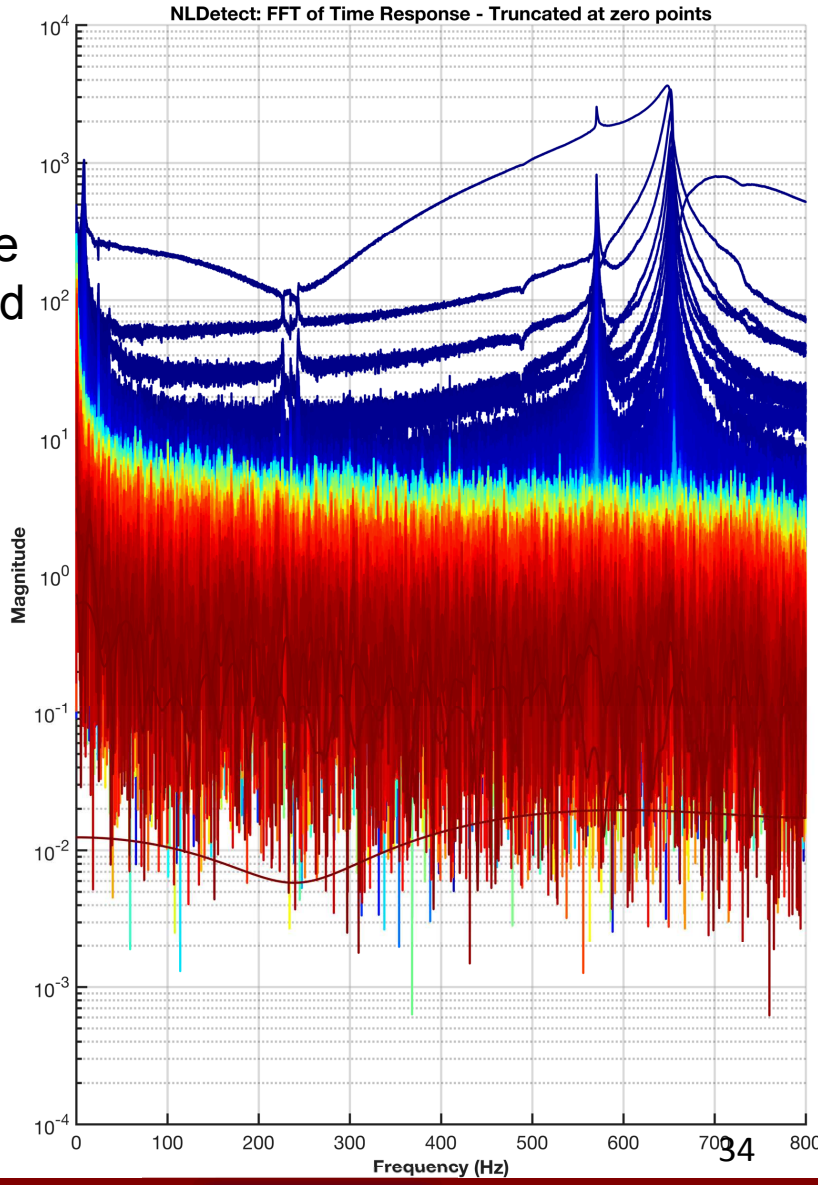
- 6 modes
- 7 input points
- decoupled motion



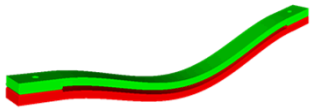
# Zeroed Time NL Detection

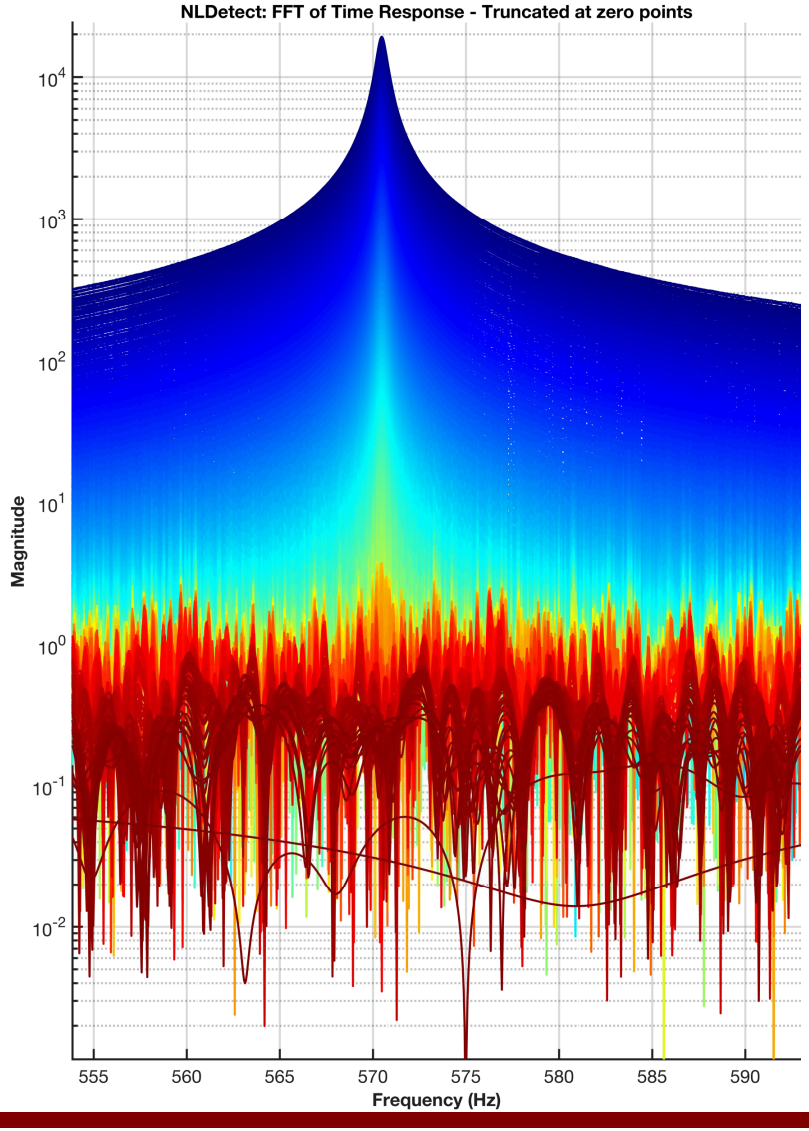
- Method to verify degree of nonlinearity of the modal peak
- Methodology based on Allen and Mayes
  - Zeroes the initial time response at varying intervals
  - Computes the FFT at these varied zeroed time histories

Increase in zeroed time



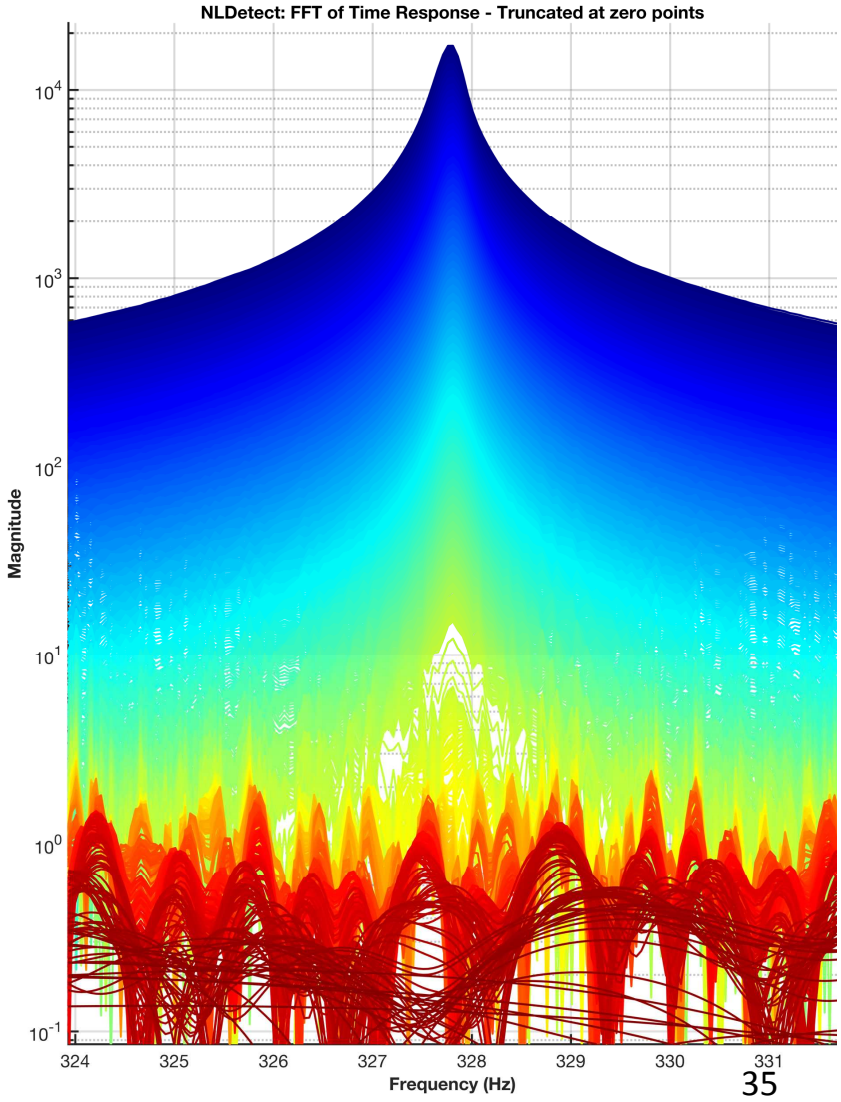
# B1B2 – 10.2 Nm – 15N
# Mode 1 and 2

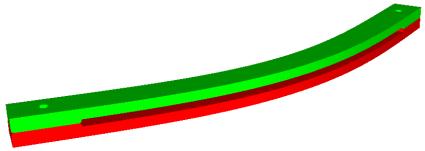




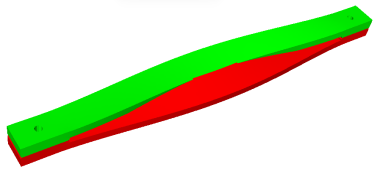

Mode 1

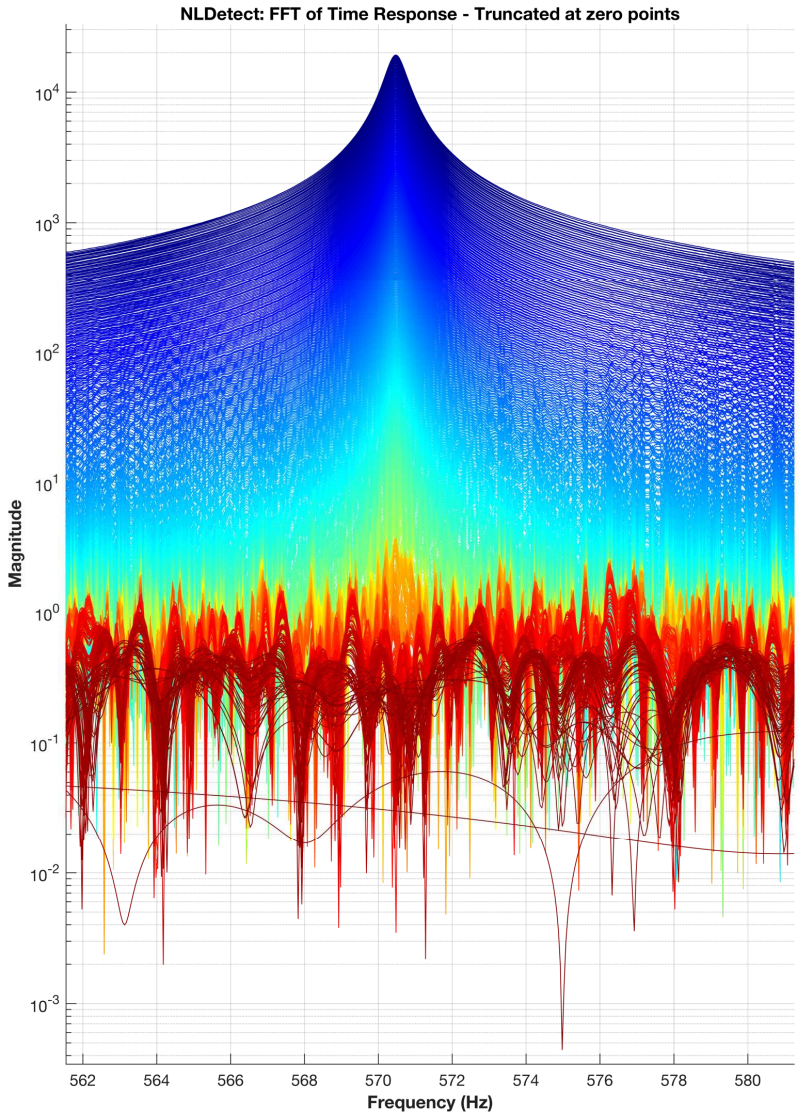
Mode 2





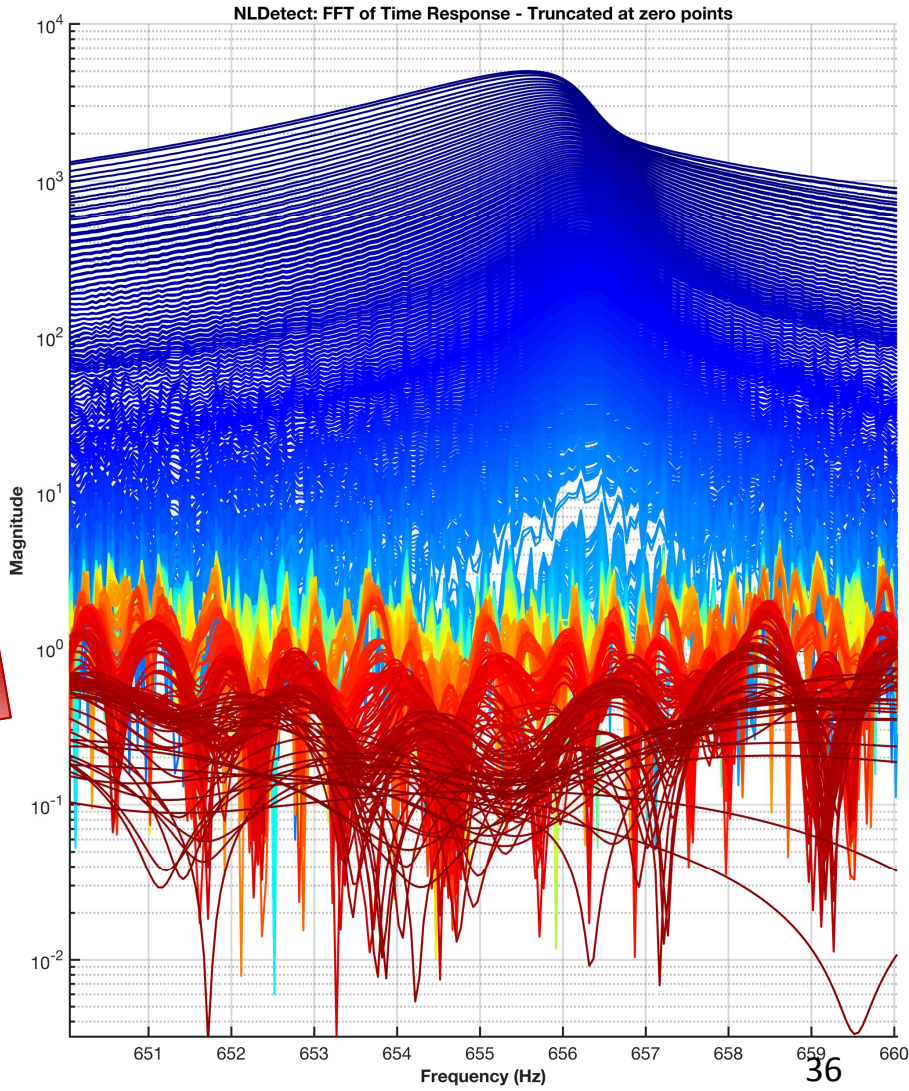
# B1B2 – 10.2 Nm – 15N
# Mode 4 and 6






Mode 4

Mode 6

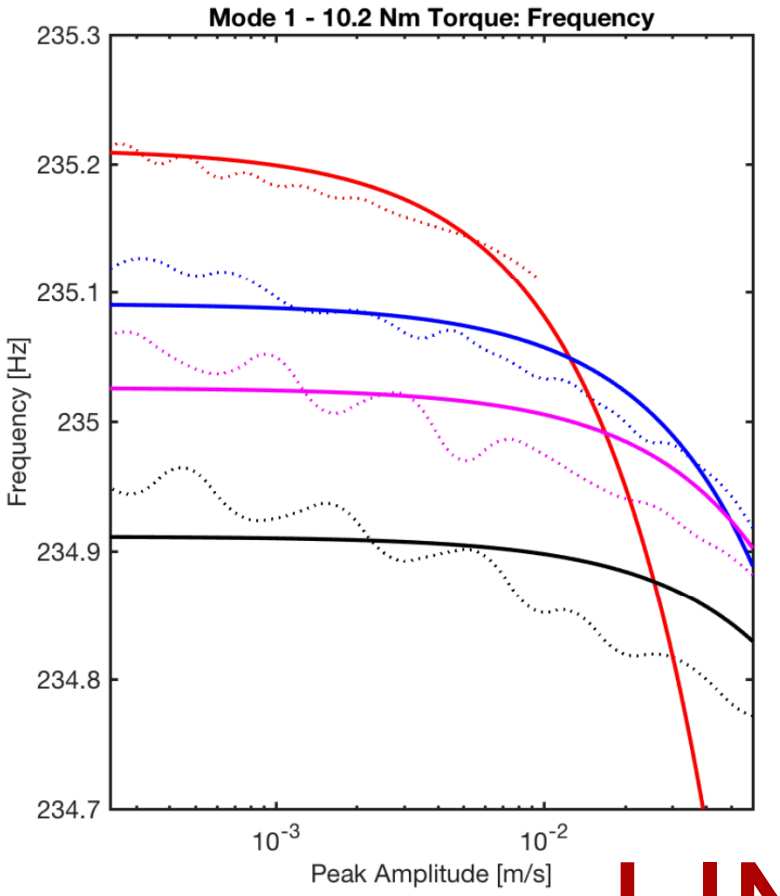


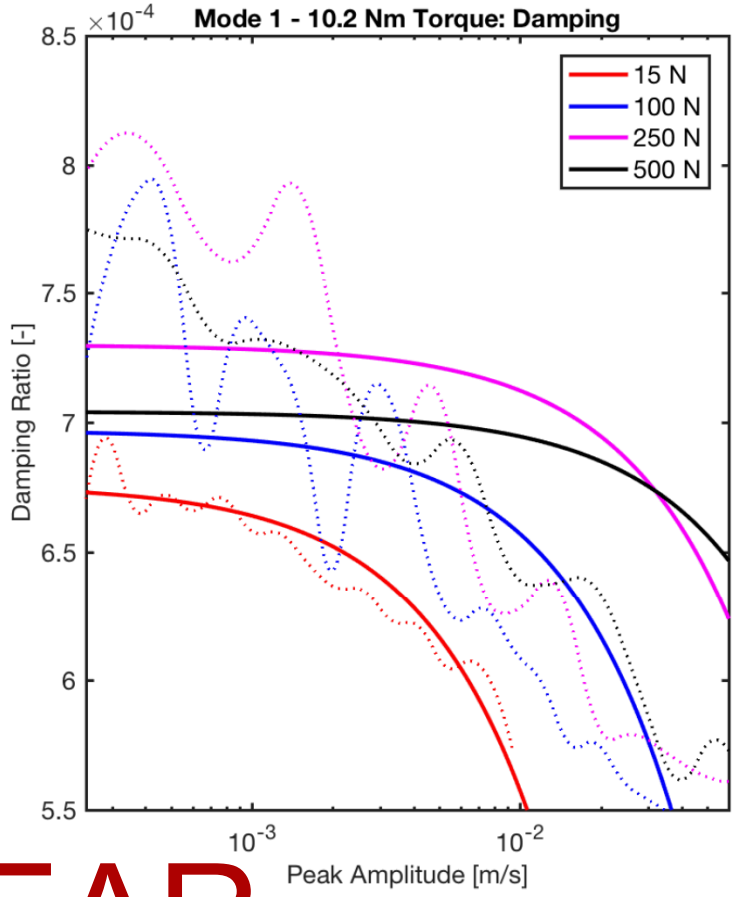
# Hilbert Analysis

- Requires that each response be uncoupled such that it can be represented by a SDOF system
  - Signal can be represented by a decaying harmonic
  - $\ddot{\eta} = Re\left[\exp\left(\psi_1(t) + i\,\psi_2(t)\right)\right]$

- Compute Hilbert Transformation ($\mathcal{H}(t)$) for an amplitude dependent representation of damping and frequency
- $\omega_{d,r} = \frac{d\psi_2}{dt}$
- $\zeta_r \triangleq \frac{d\psi_1}{dt} \Big/ \omega_r$

# B1B2 – Mode 1 – Force Variation



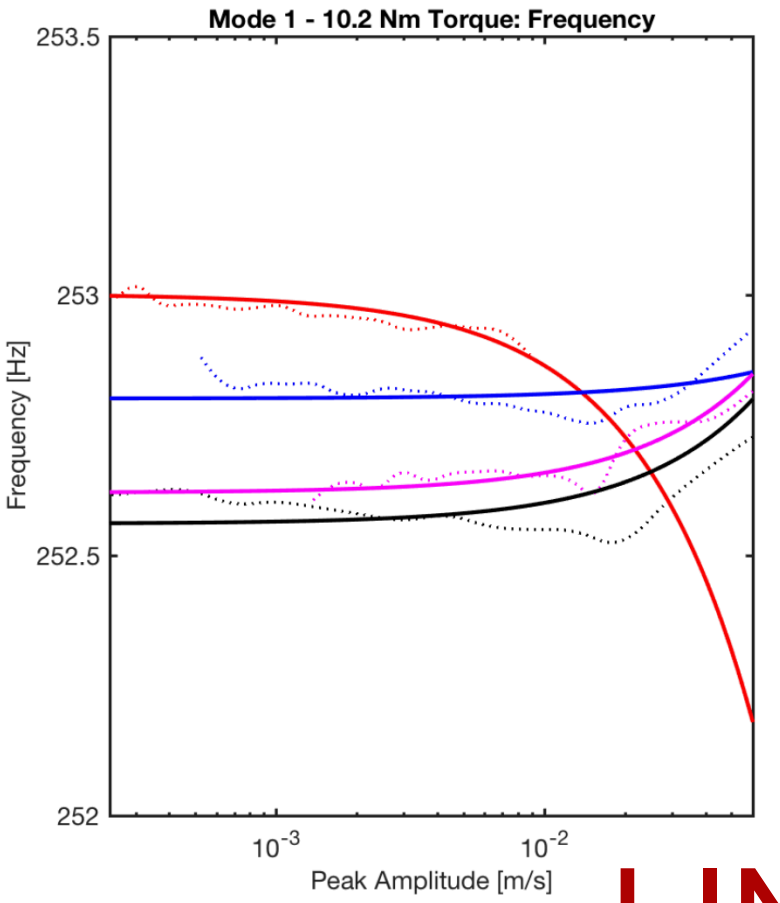



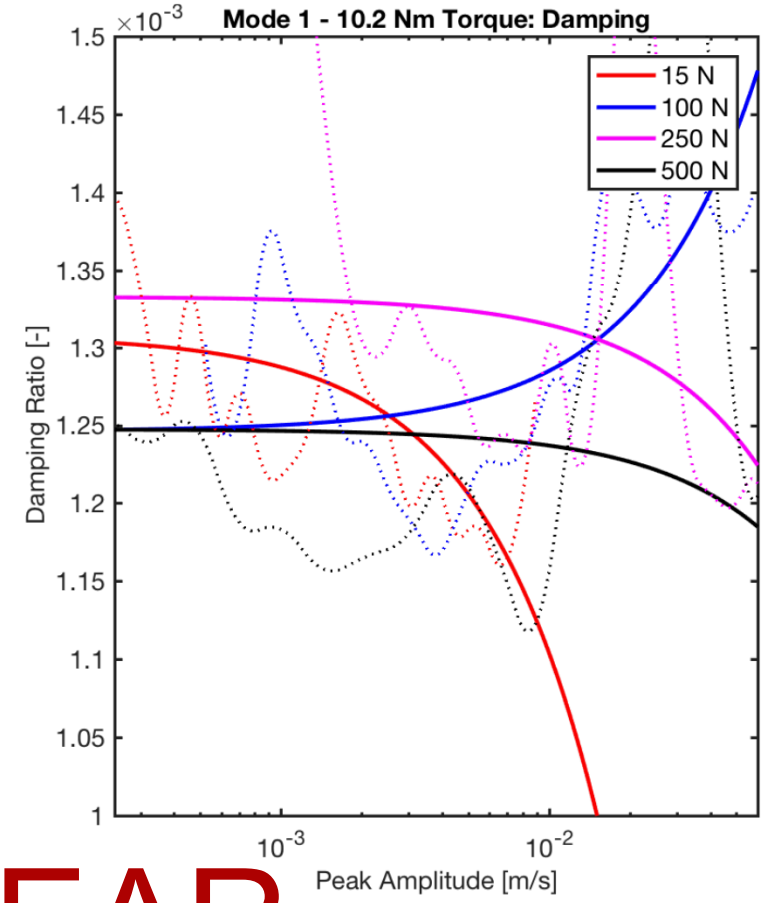

LINEAR

$\omega_{avg} = 235\ Hz$

$\zeta_{avg} = 0.0007$

# B5B6 – Mode 1 – Force Variation



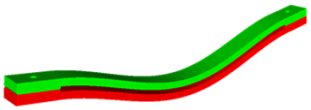



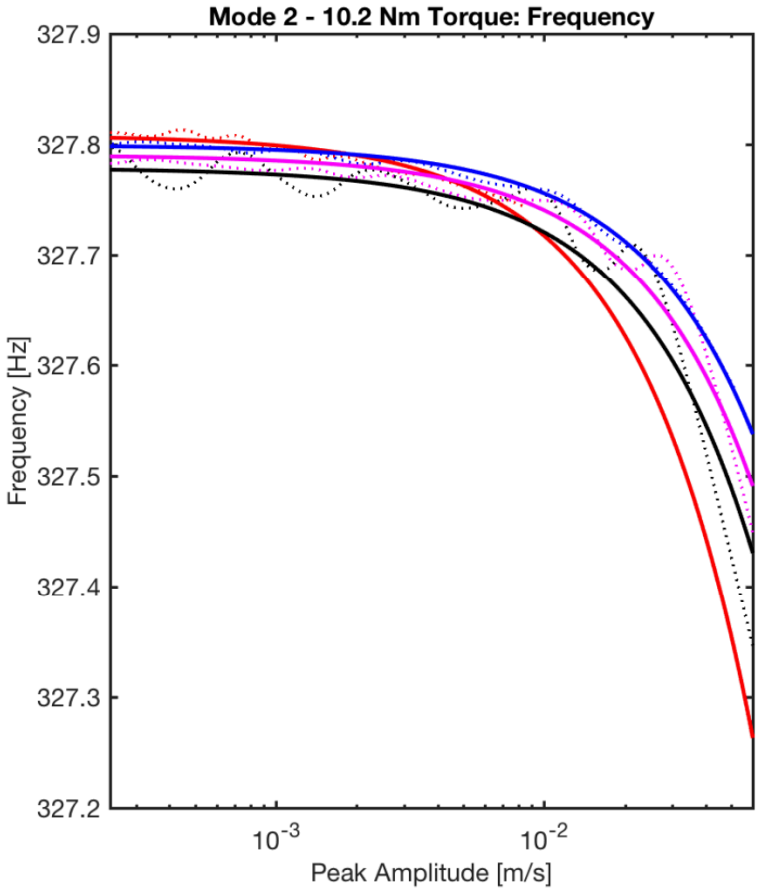

LINEAR

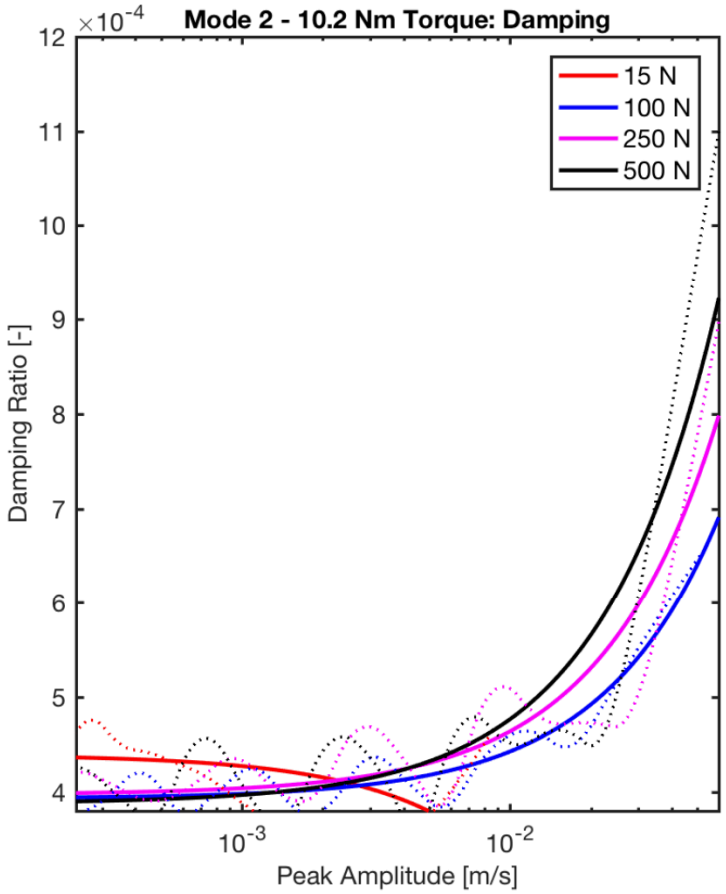
$\omega_{avg} = 253\ Hz$

$\zeta_{avg} = 0.0012$

# B1B2 – Mode 2 – Force Variation



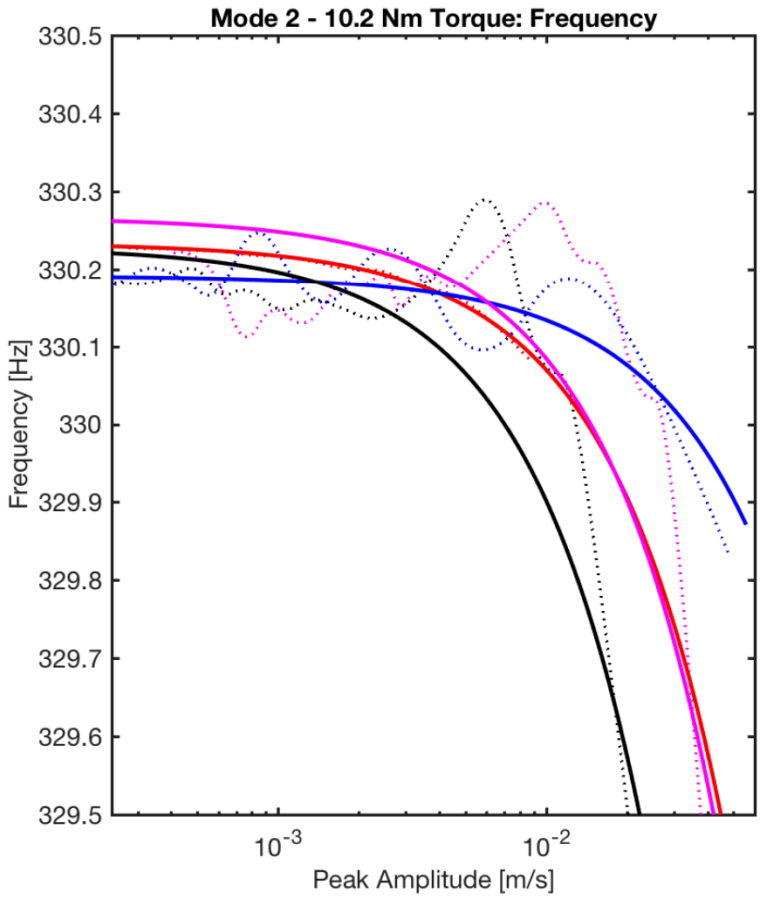


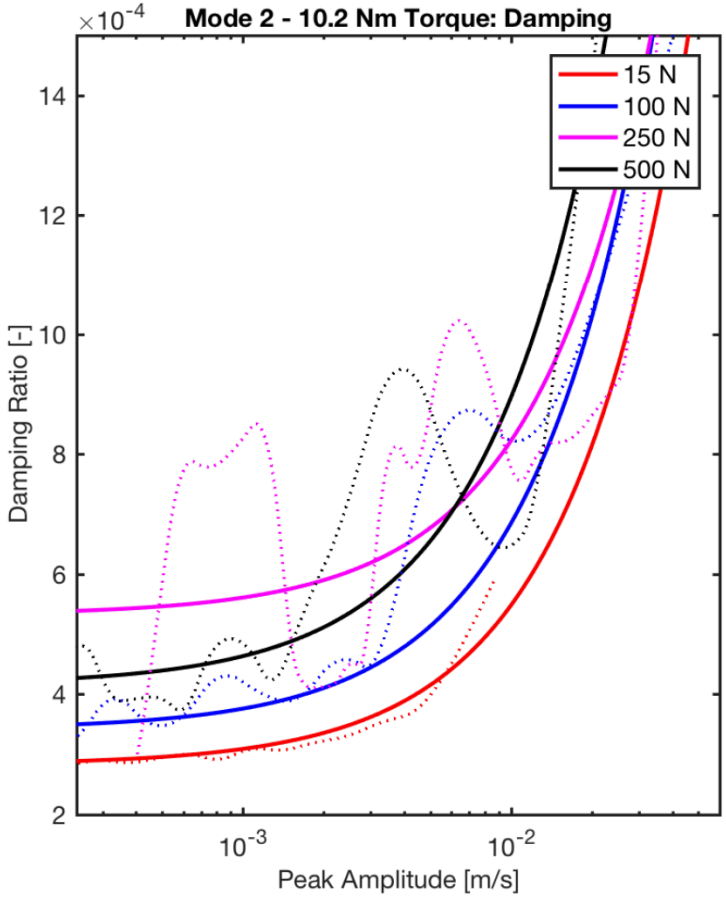




$\omega_{avg} = 328\ Hz$

$\zeta_{avg} = 0.0004$

# B5B6 – Mode 2 – Force Variation

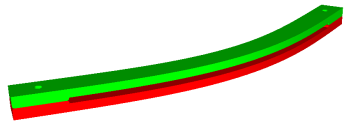


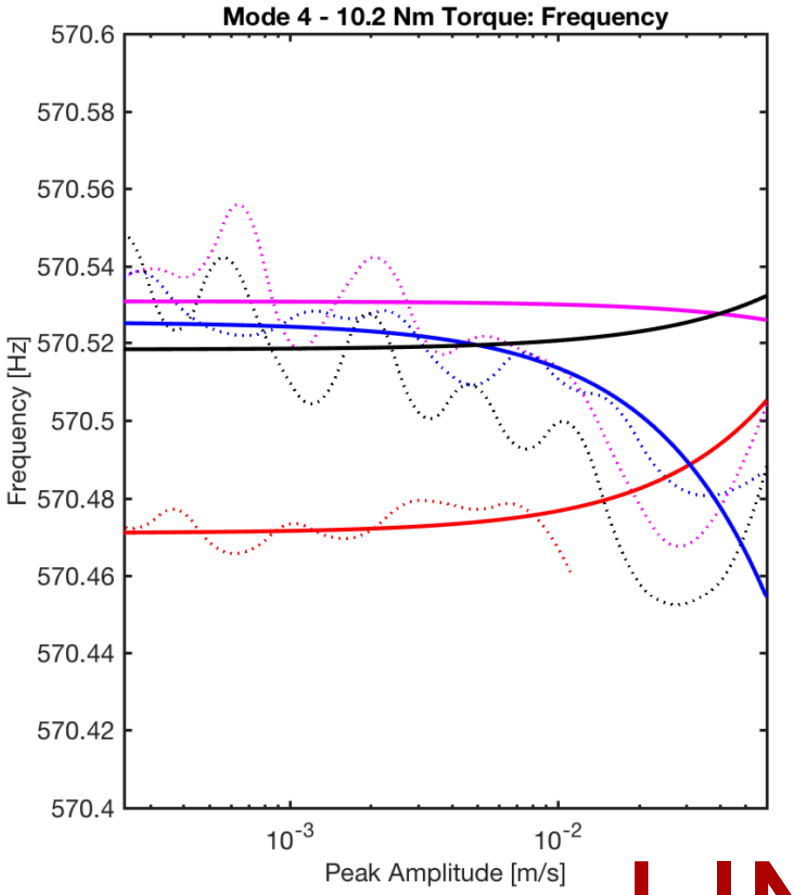



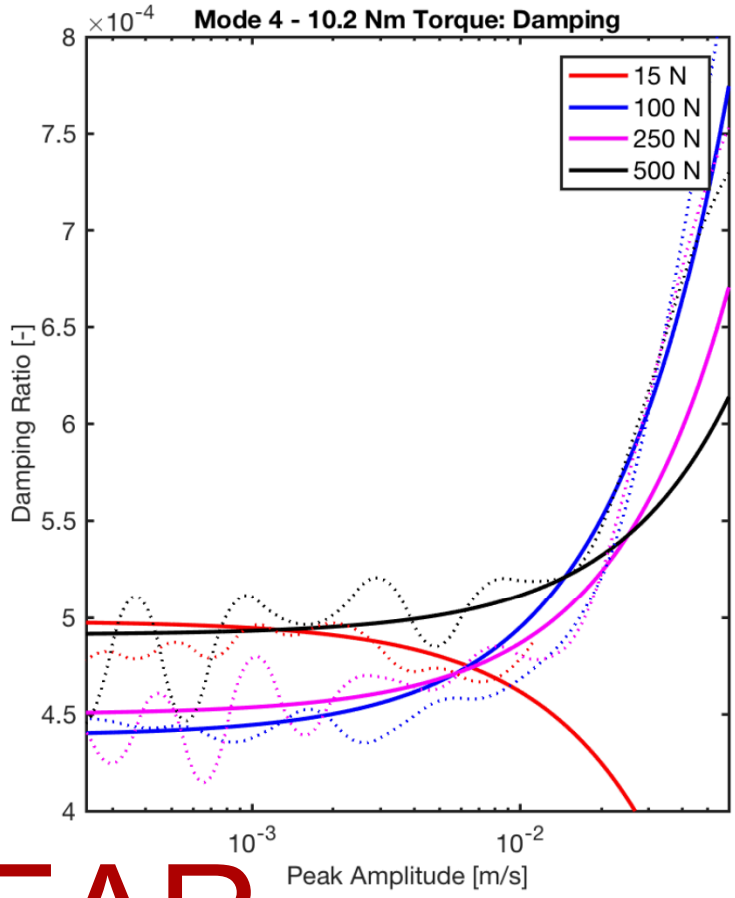

$\omega_{avg} = 330\ Hz$

$\zeta_{avg} = 0.0005$

# B1B2 – Mode 4 – Force Variation





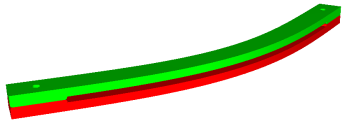



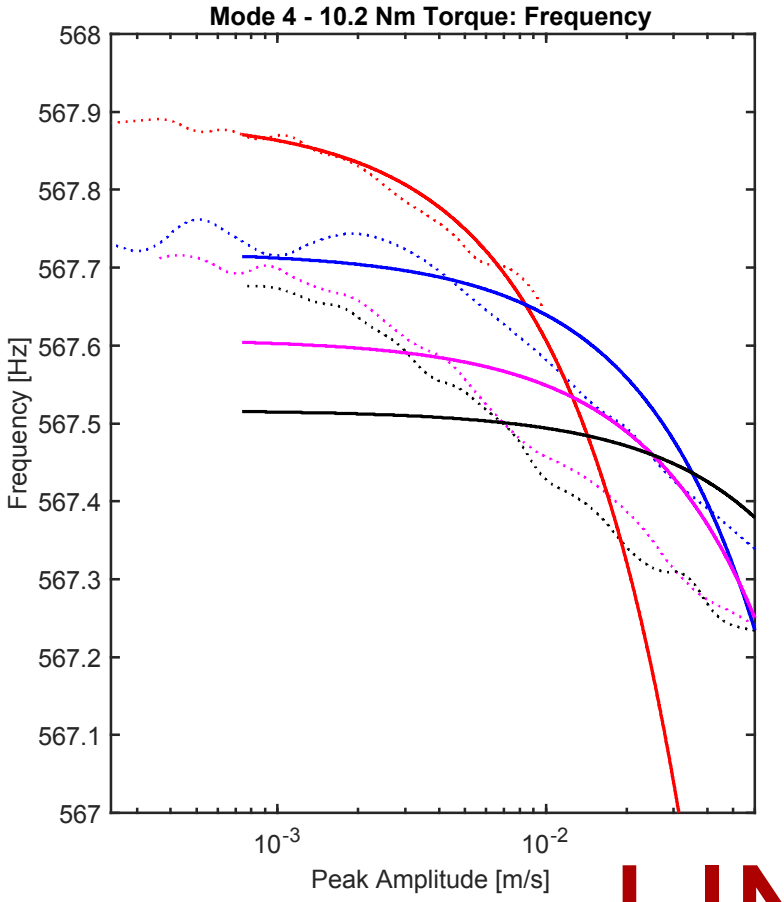

LINEAR

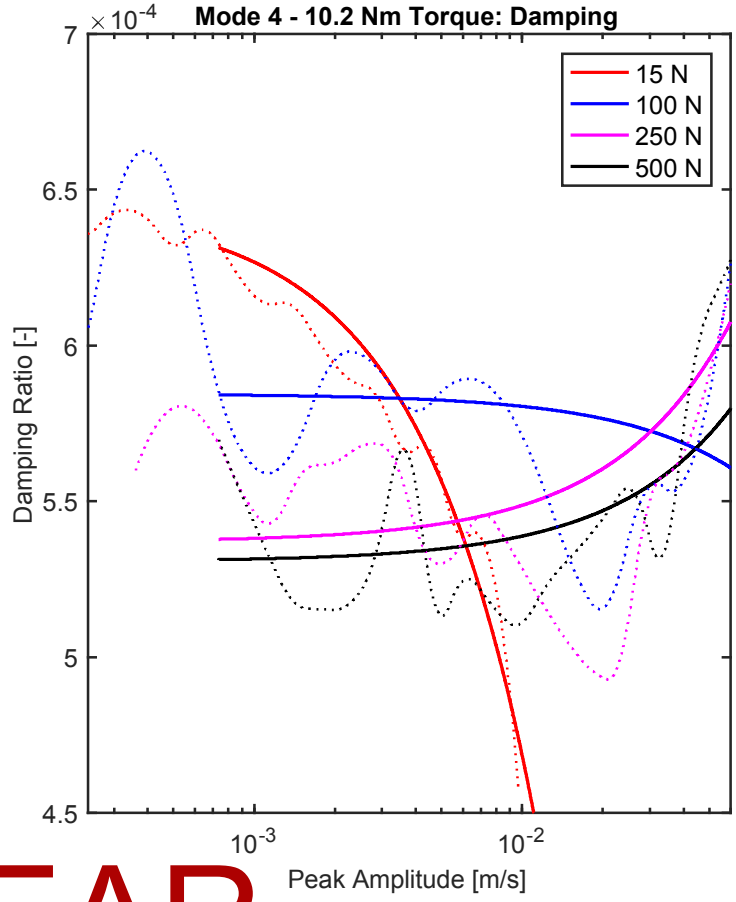
$\omega_{avg} = 571\ Hz$

$\zeta_{avg} = 0.0005$

# B5B6 – Mode 4 – Force Variation





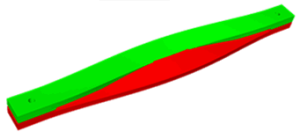



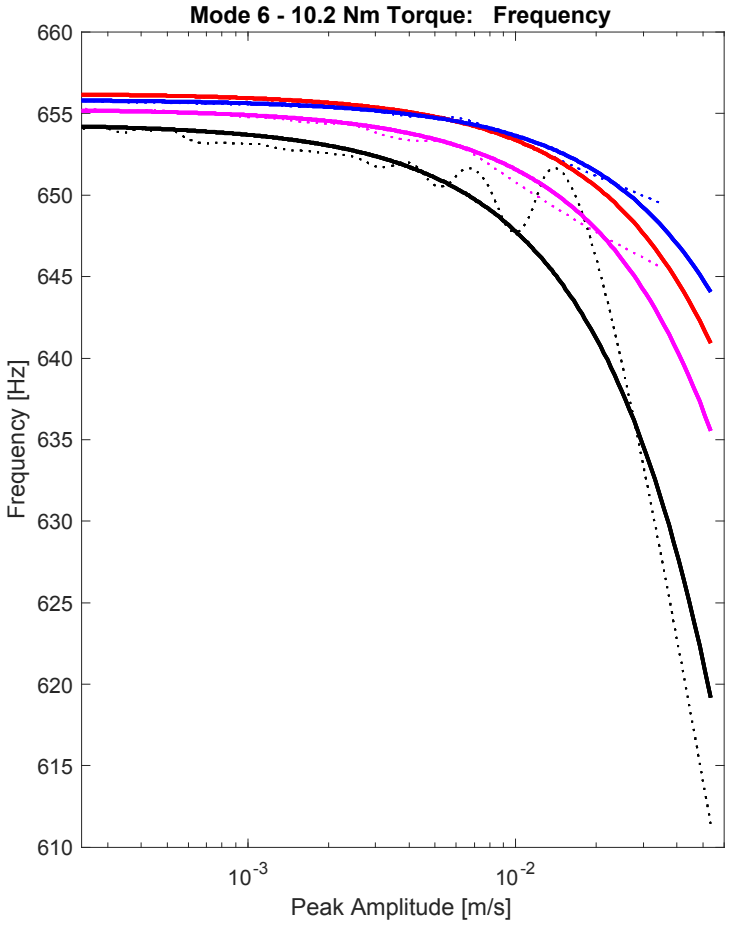

LINEAR

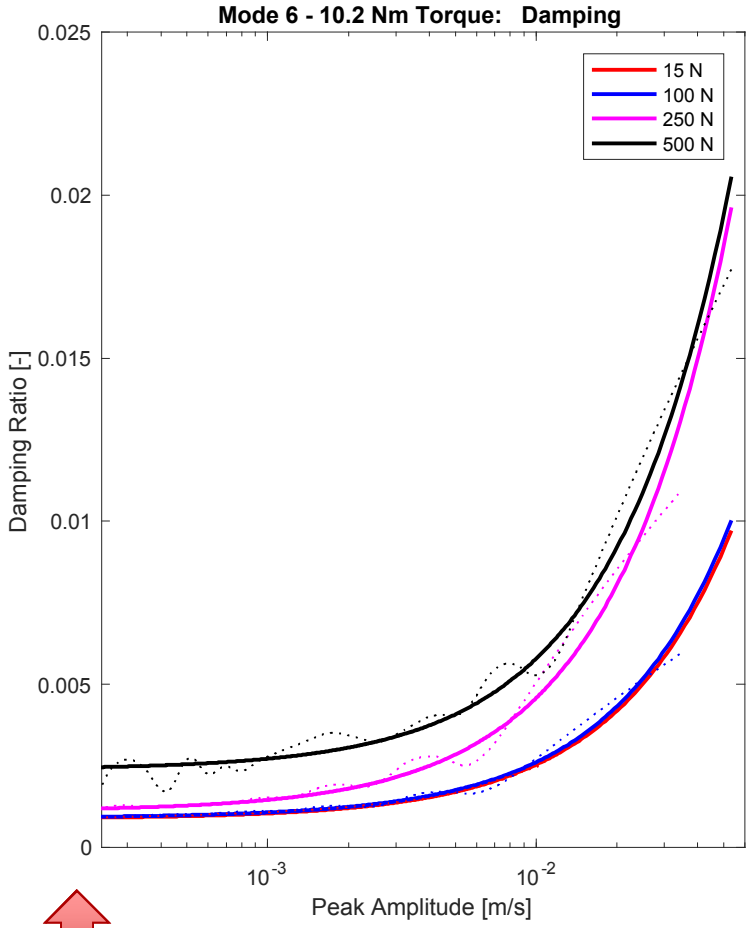
$\omega_{avg} = 568\ Hz$

$\zeta_{avg} = 0.0005$

# B1B2 – Mode 6 – Force Variation



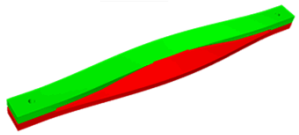


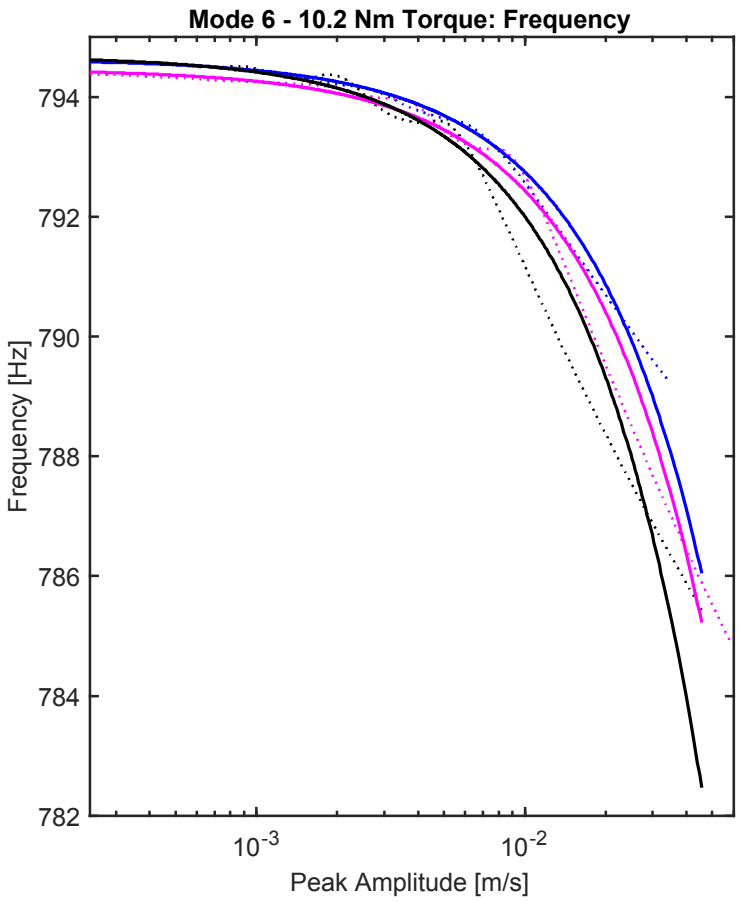



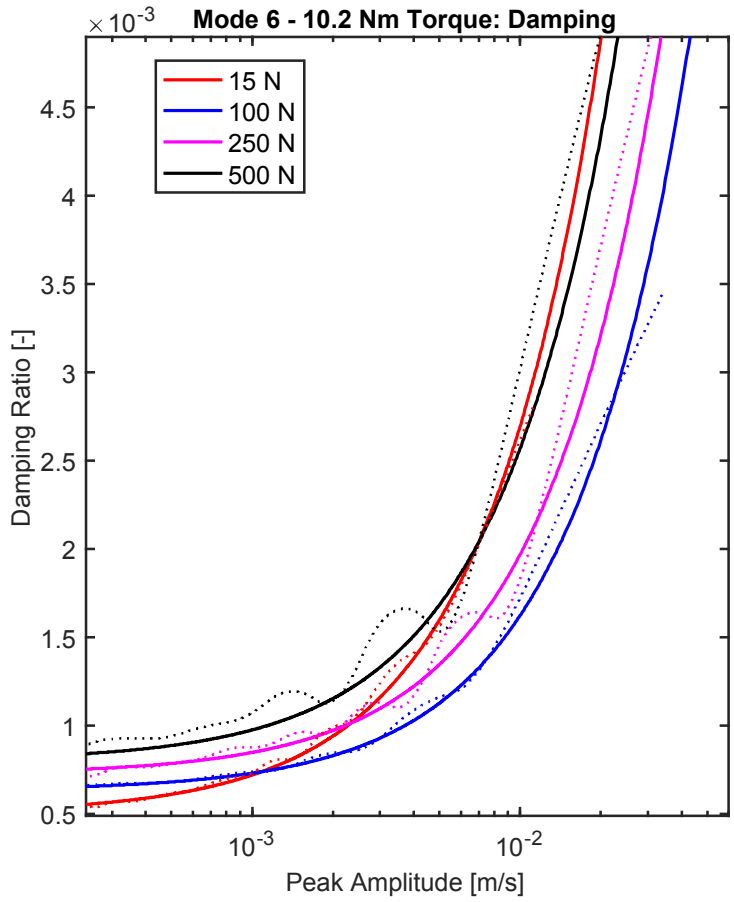

$\omega_{avg} = 654\ Hz$

$\zeta_{avg} = 0.0019$

# B5B6 – Mode 6 – Force Variation



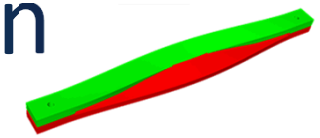


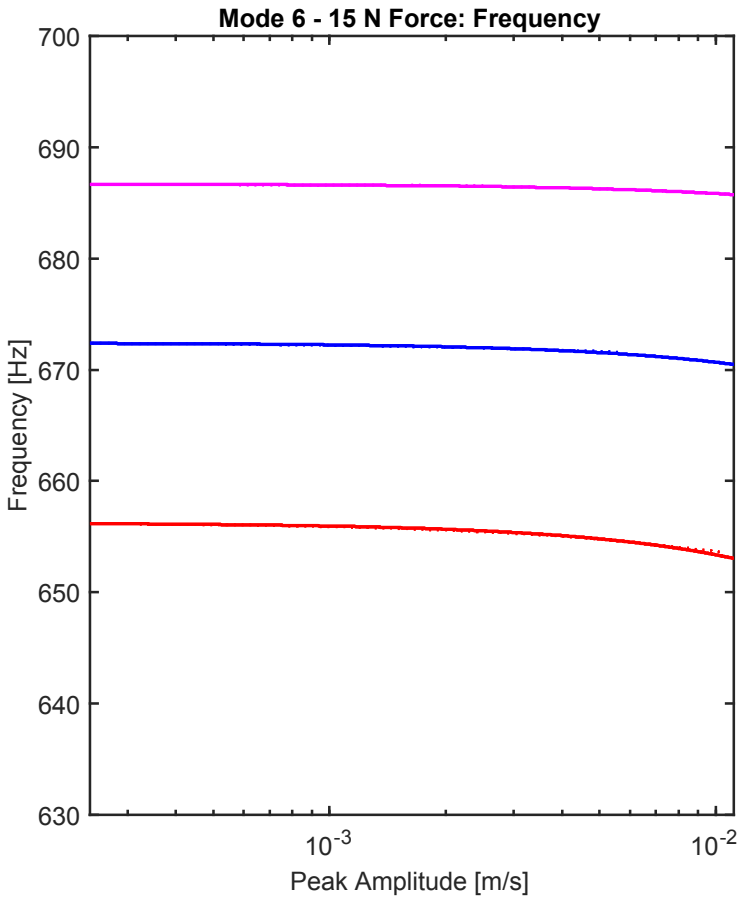



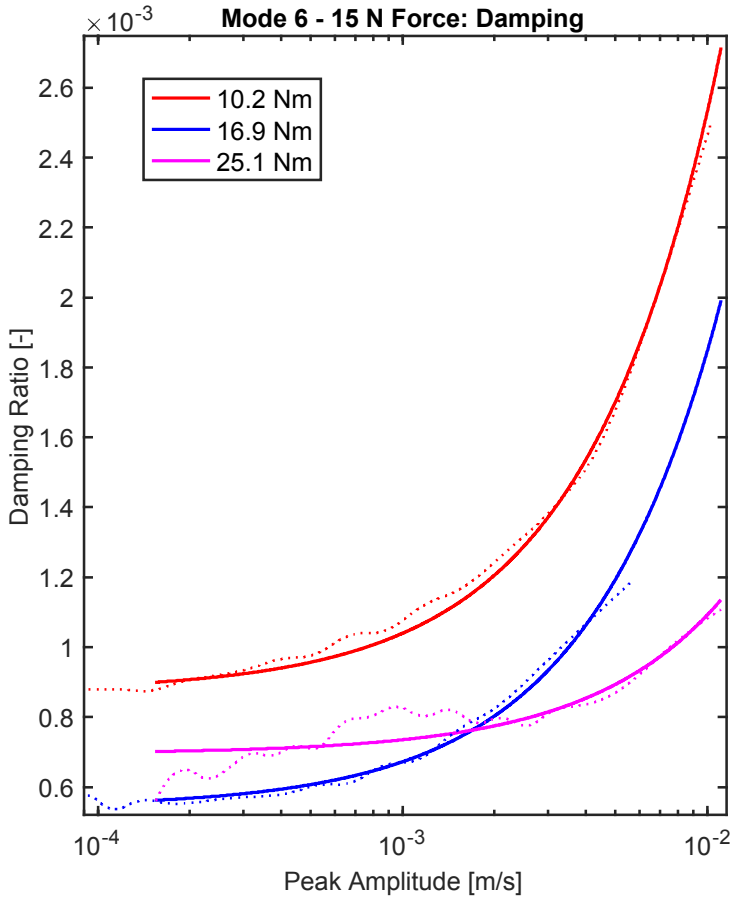

$\omega_{avg} = 794\ Hz$

$\zeta_{avg} = 0.0009$

# B1B2— Mode 6 – Torque Variation



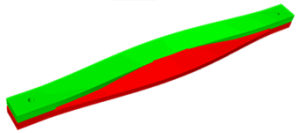


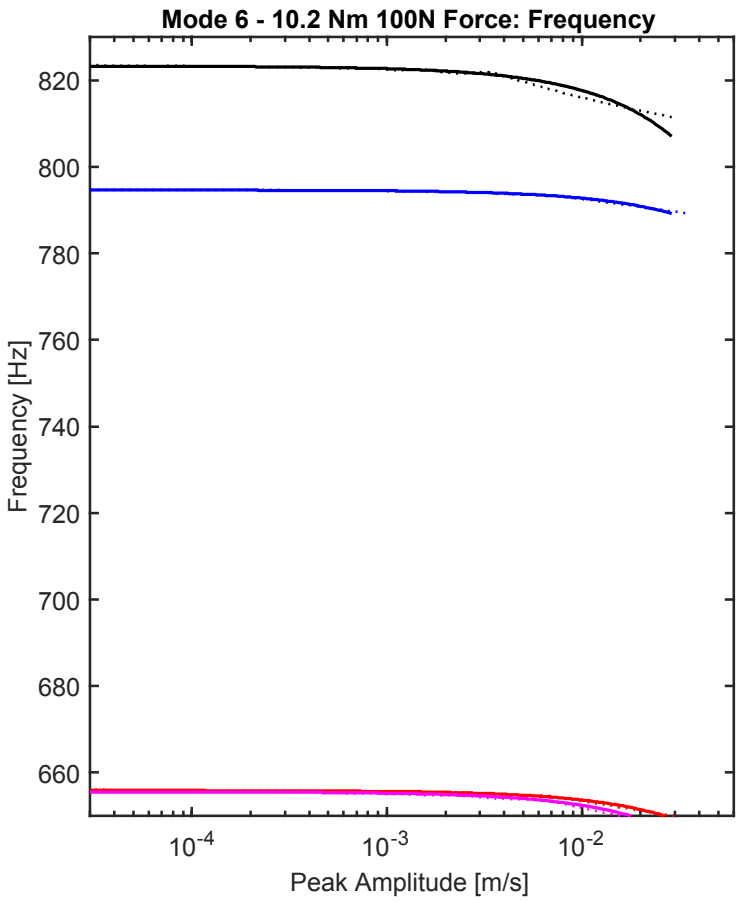



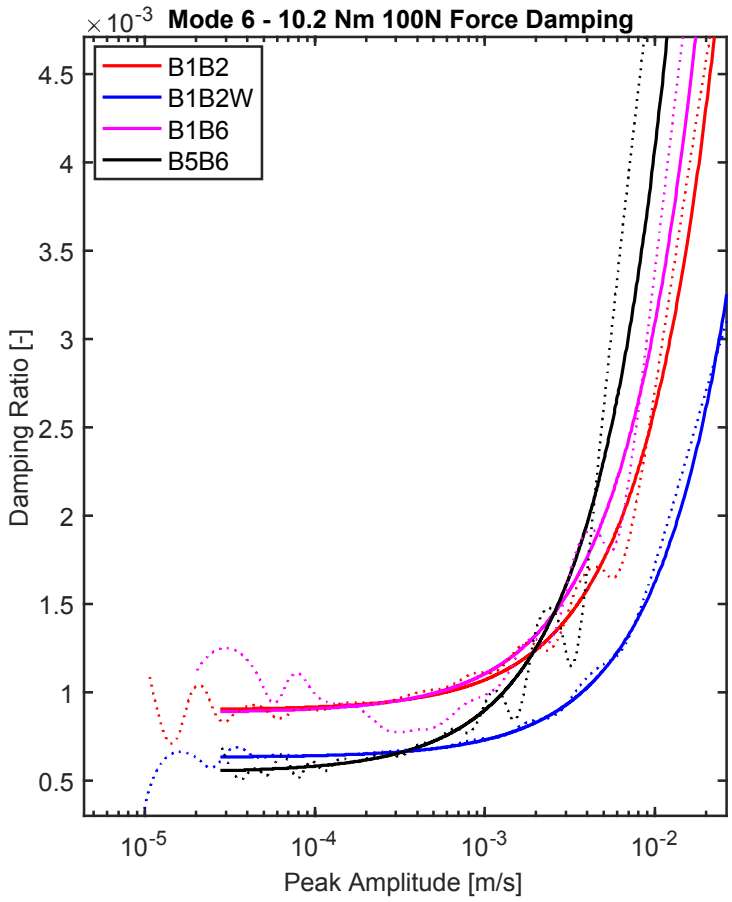

$\omega_{avg} = 672\ Hz$

$\zeta_{avg} = 0.0008$

# Mode 6 – Beam Comparison






$\omega_{avg} = 732\ Hz$

$\zeta_{avg} = 0.0011$

# Restoring Force Surface (RFS)

- Estimate degree of nonlinearity as a function of polynomials
- Inverse least squares problem
- Equation of Motion:
  - $\ddot{x} + C_1\dot{x} + \cdots + C_N\dot{x}^N + K_1\dot{x} + \cdots + K_N\dot{x}^N = F$
- Methodology:
  - $[Force\ -Acceleration] = [A] * \{coefficients\}$

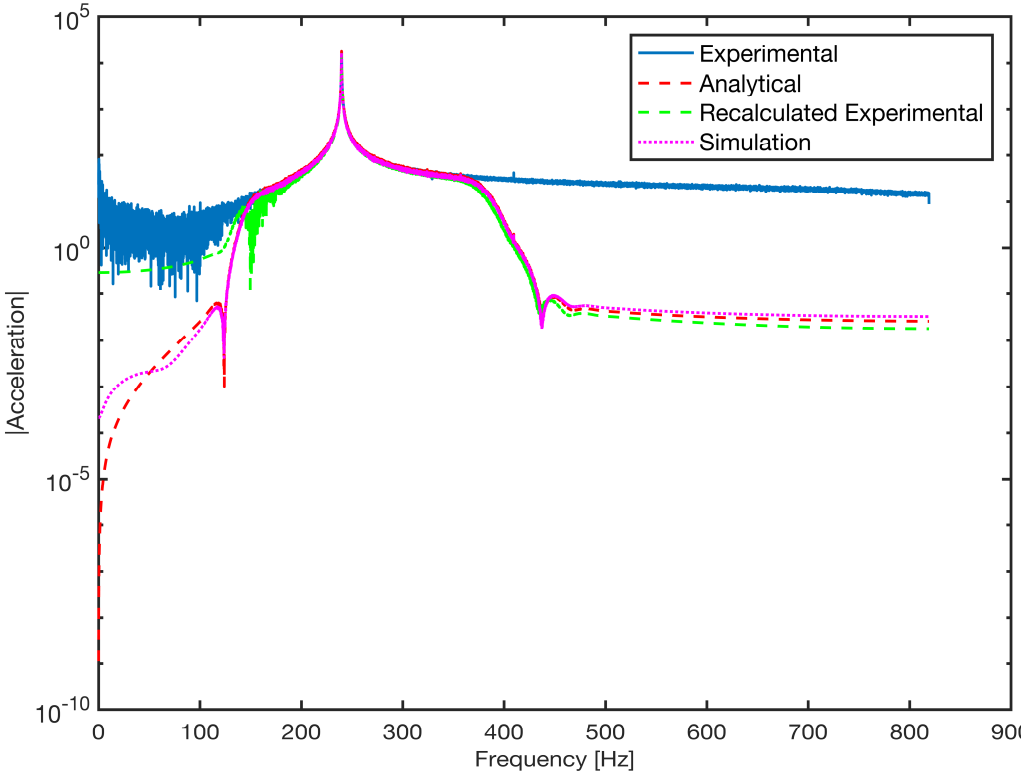
$$[A] = [X(\omega) \ldots X^N(\omega), \mathrm{V}(\omega) \ldots V^N(\omega)]$$

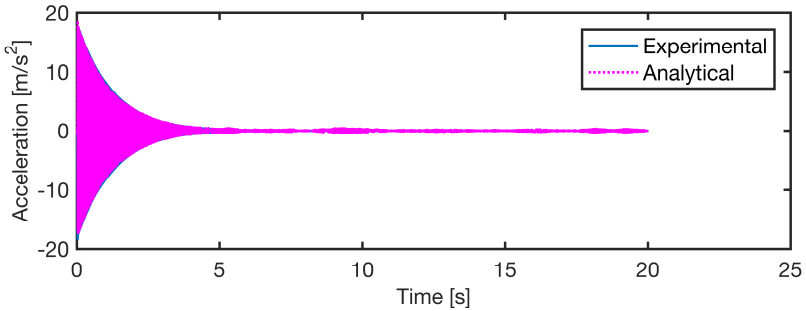
- Problem: Difficulty in capturing degree of damping nonlinearity

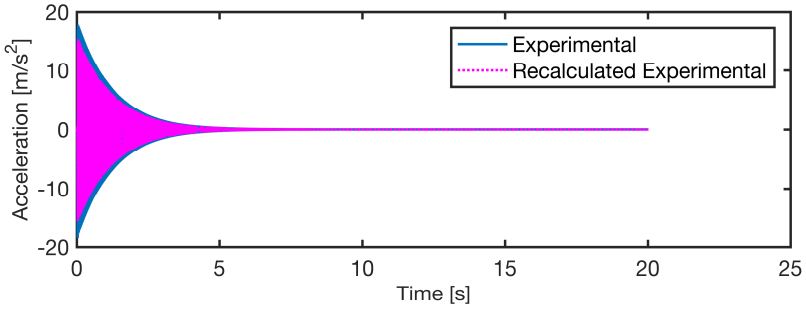
# B1B2 Mode 1 – RFS

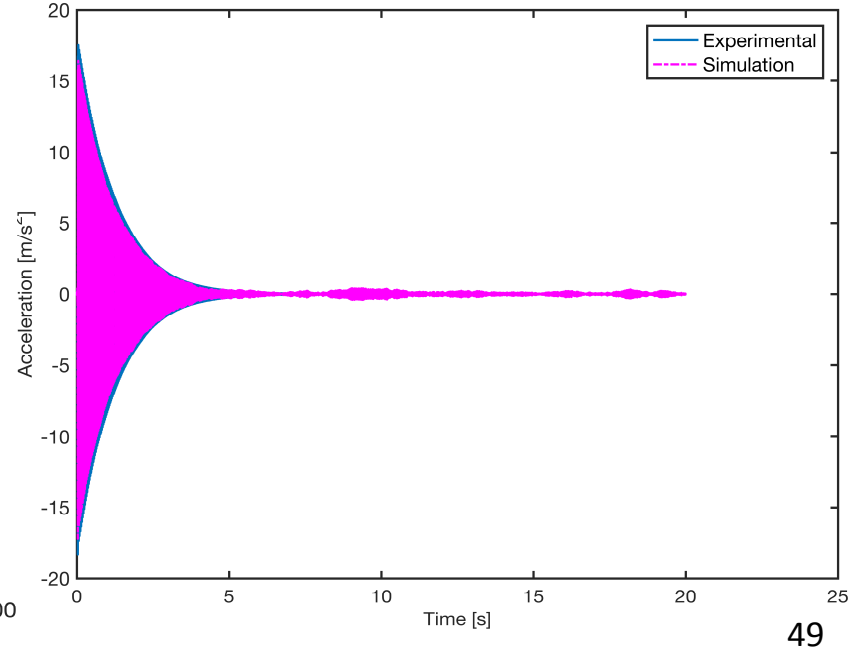
- Cubic damping and stiffness nonlinearities
- Compare against linear solution

$$a_{linear} = -\frac{\omega^2 F}{-\omega^2 + i2\zeta\omega_n + \omega_n^2}$$



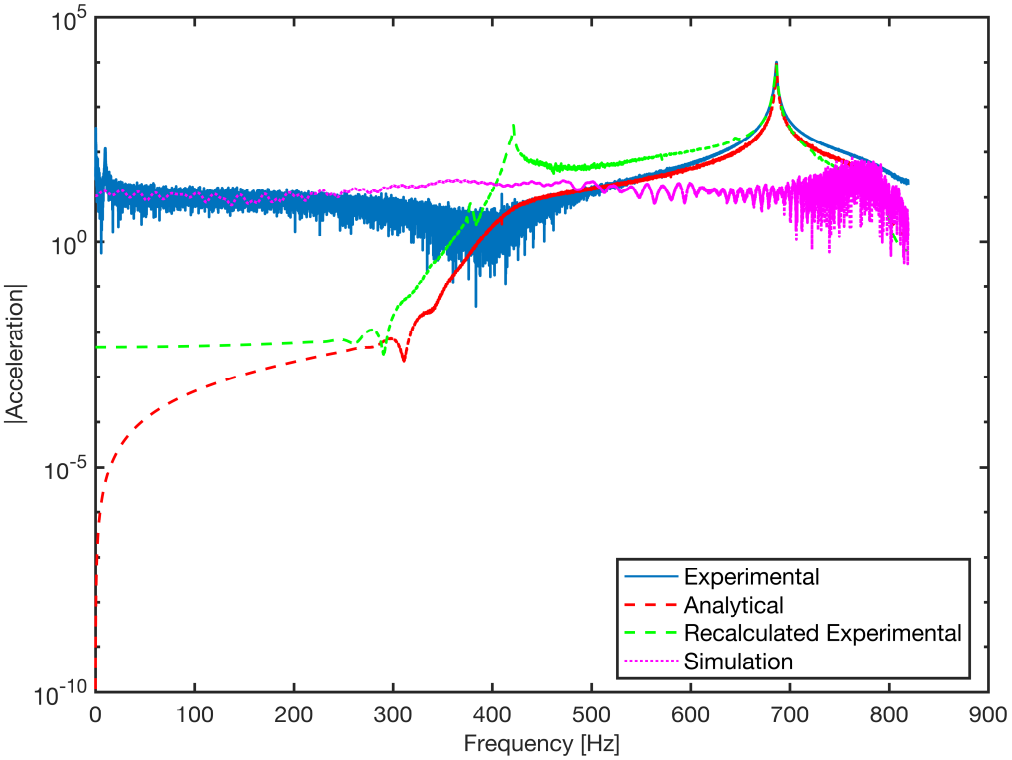



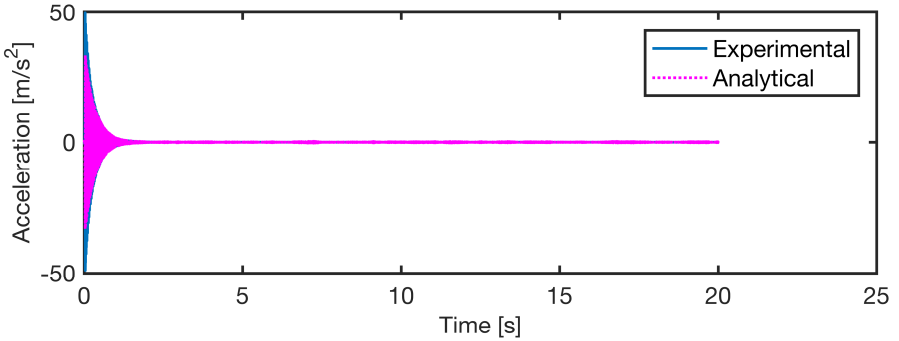



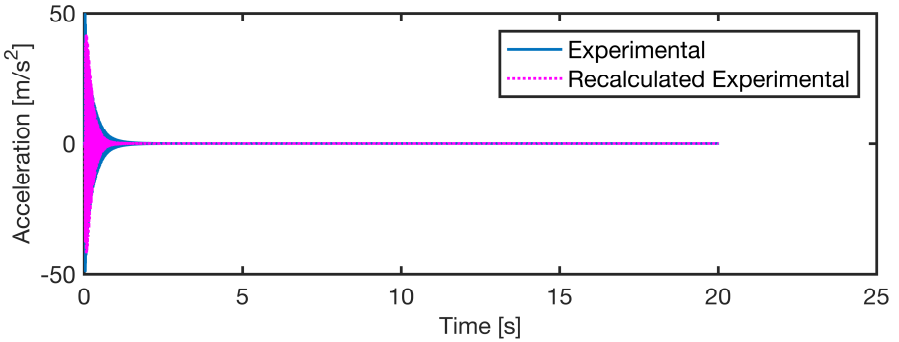



# B1B2 Mode 6 – RFS

- Simulation fails due to sensitive parameters
  - Clearly visible in frequency domain




| | | |
|---|---|---|
| $K_1$ | 1.8607e7 | N/m |
| $K_2$ | 1.7623e15 | N/m$^2$ |
| $K_3$ | -4.82e21 | N/m$^3$ |
| $C_1$ | 6.029 | N-s/m |
| $C_2$ | 1.42e5 | N-s$^2$/m$^2$ |
| $C_3$ | -4.906e7 | N-s$^3$/m$^3$ |

# Conclusion

- The structural response (FRF) results correspond well with the joint characteristics
- Different beams interfaces and torque levels
  - Affect the contact area
  - Lead to differently frequency spacing for the modes
- Increasing force amplitudes lead to increasingly nonlinear responses
- We believe the simplicity of the bolted beam design and the sufficient amount of data collected by our team makes the S4 beam a good benchmark for future research in joint characterization and design

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