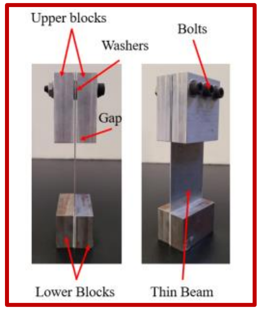
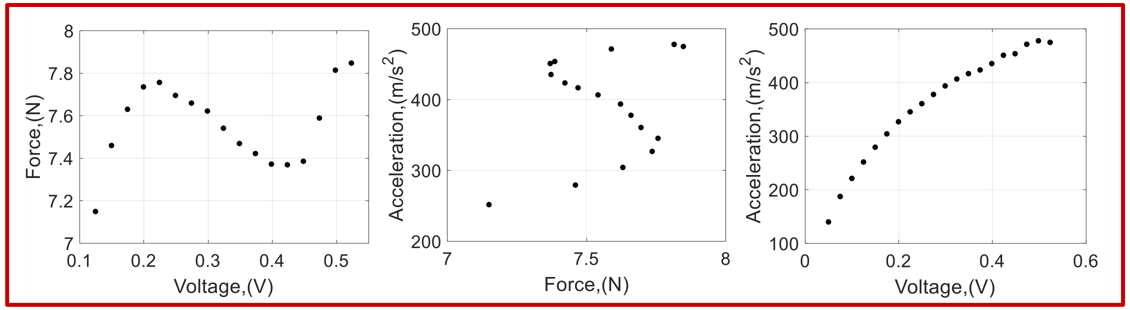
SAND2023-12027C

14423 IMAC-XLI

Stabilizing a Strongly Nonlinear Structure Through Shaker Dynamics in Fixed Frequency Voltage Control Tests





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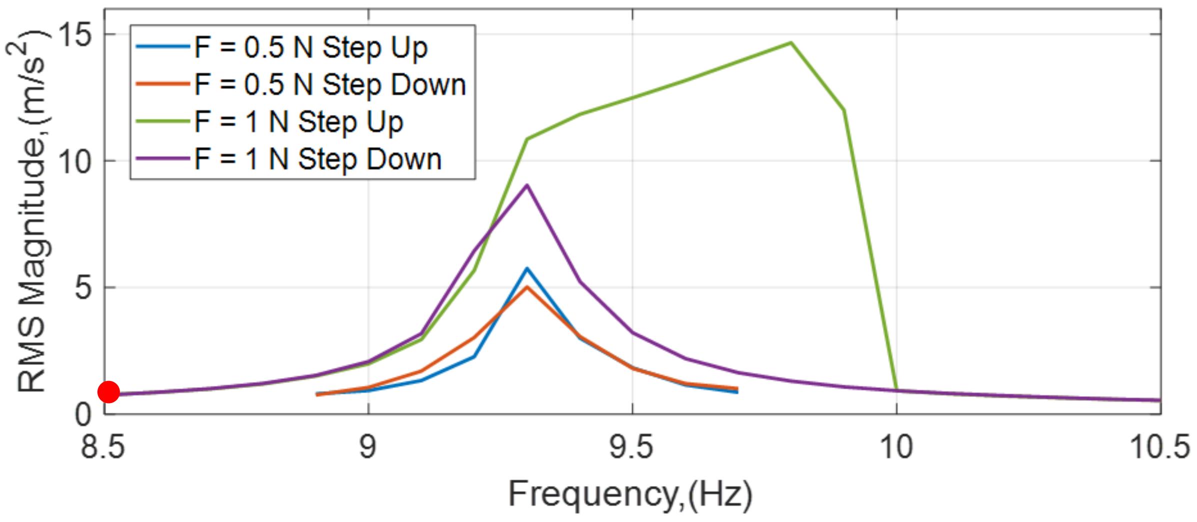
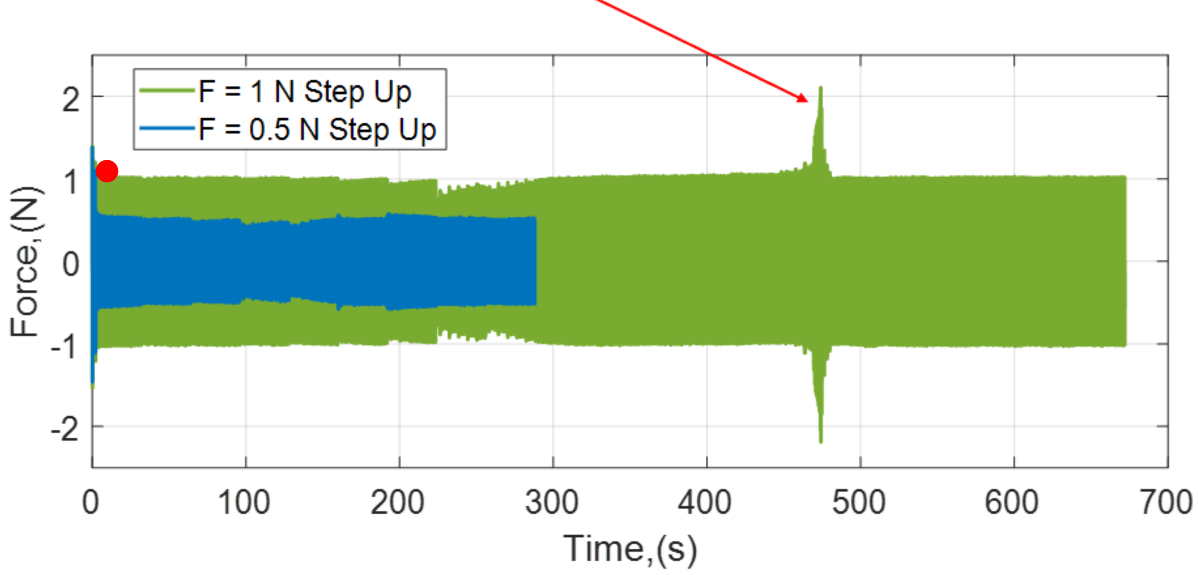
I. Introduction

Background and Motivation

- Force and amplitude control stepped sine testing generally results in:
  - Bifurcations leading to jumping behavior
  - Imperfect quality in the control parameter
- Control-based continuation [4-6] and phase-locked loop [7, 8] are used to stabilize systems through bifurcations, but they rely on specialized algorithms that are not readily available with many data acquisition software packages
- Need to explore other test strategies for system identification



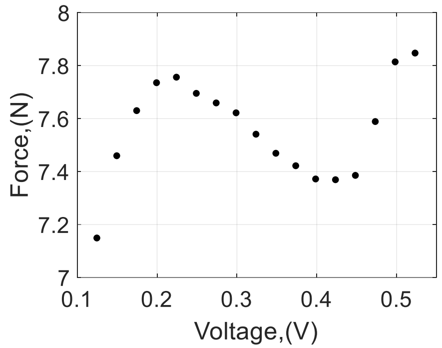
Loss of quality in the force control parameter at the jump down frequency

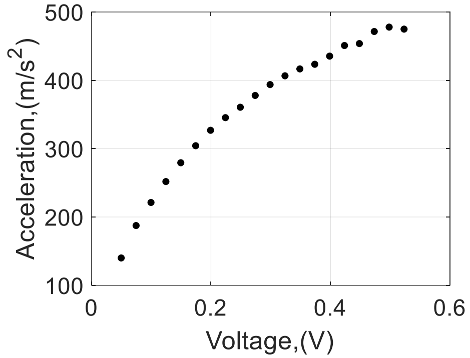


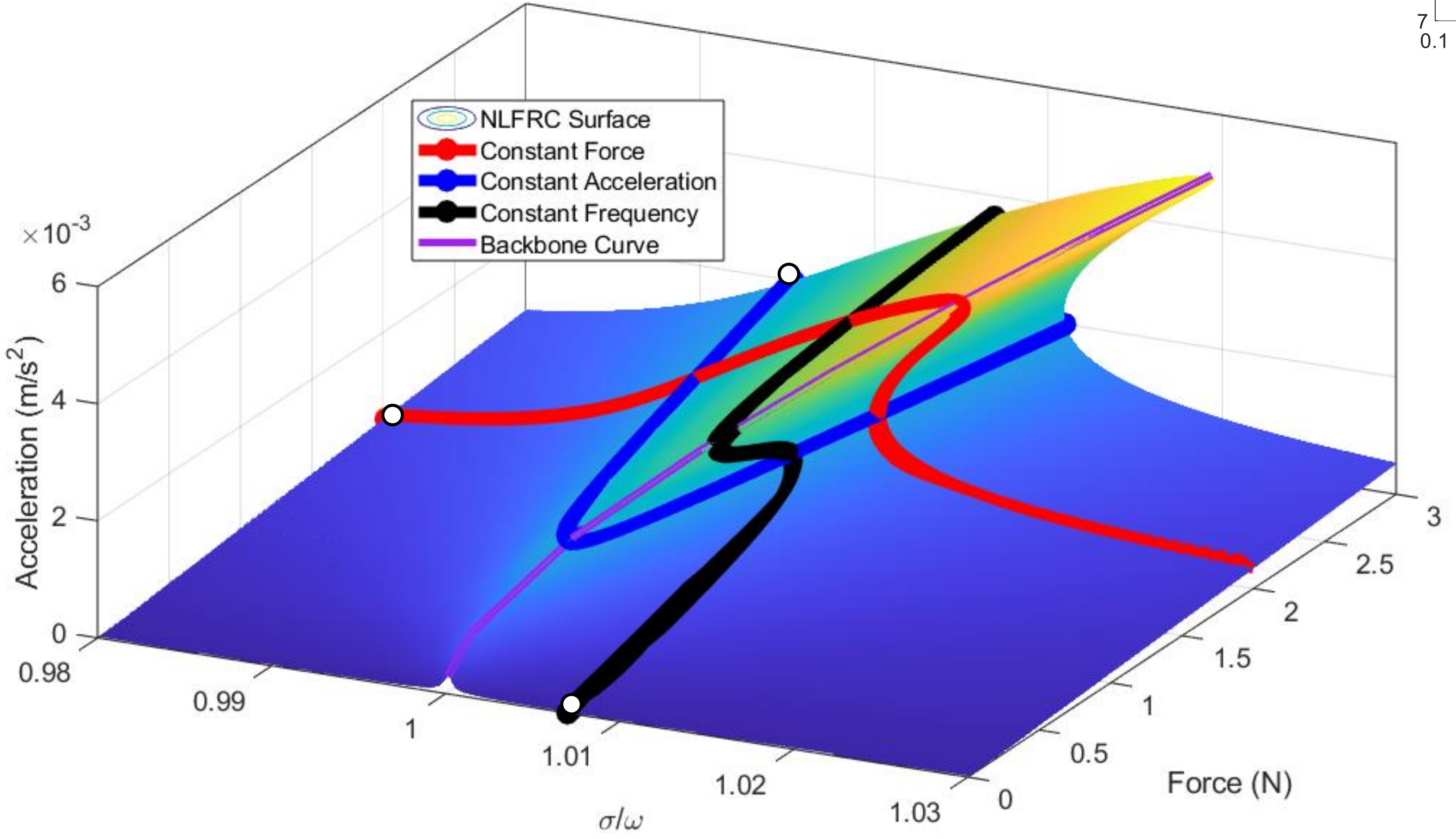
II. Theoretical Background

Fixed Frequency Voltage Control Tests

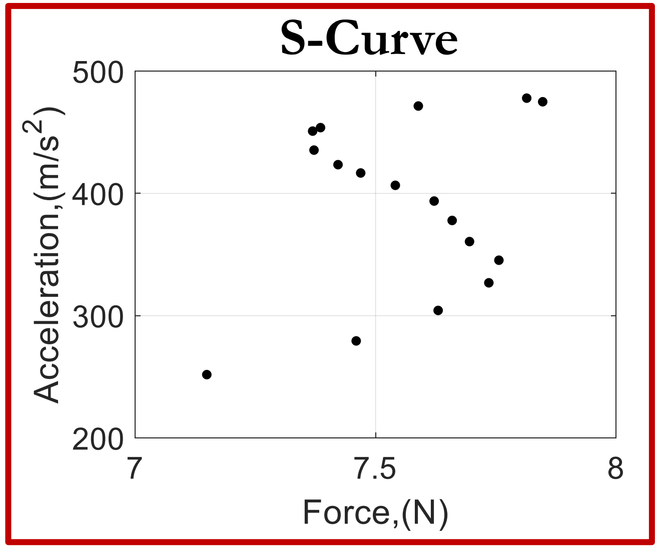
- Fixed frequency voltage control (FFVC): Open-loop control where the DAQ voltage is stepped at a fixed frequency
- The DAQ voltage serves as the continuation parameter and the force drop-out phenomena is utilized [1]





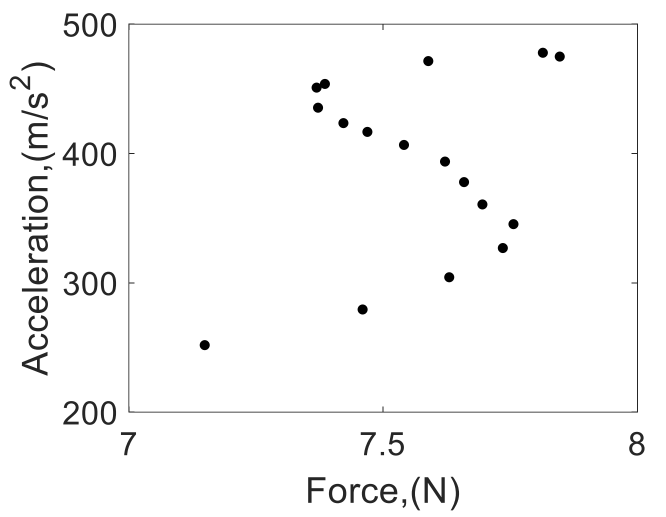


Force amplitude, F and acceleration response amplitude, R are single valued functions of the input voltage, V



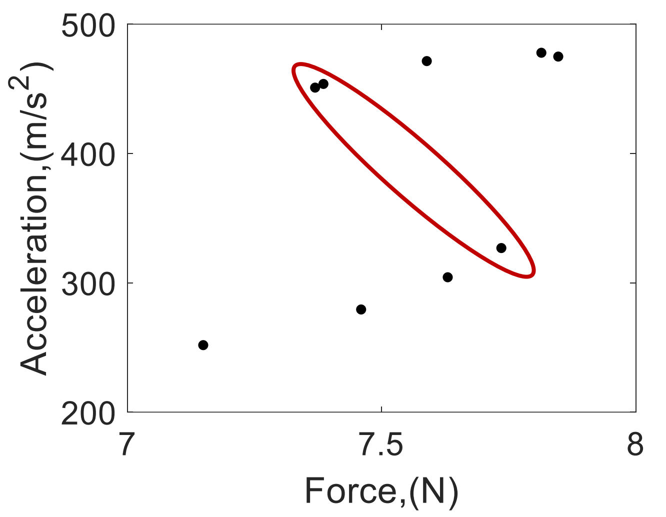
Problem Statement

Current research has demonstrated a new method to apply experimental continuation [1]



Outcome: nonlinear system effectively stabilized (S-curve measured)

New experimental continuation method applied to a nonlinear vibro-impact system



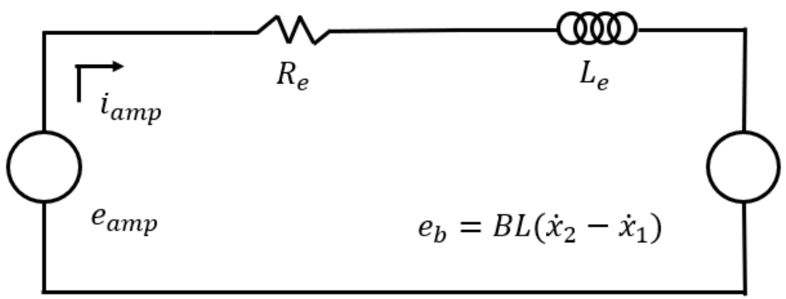
Outcome: unexpected jumping behavior has been observed

Goal: understand why this is occurring

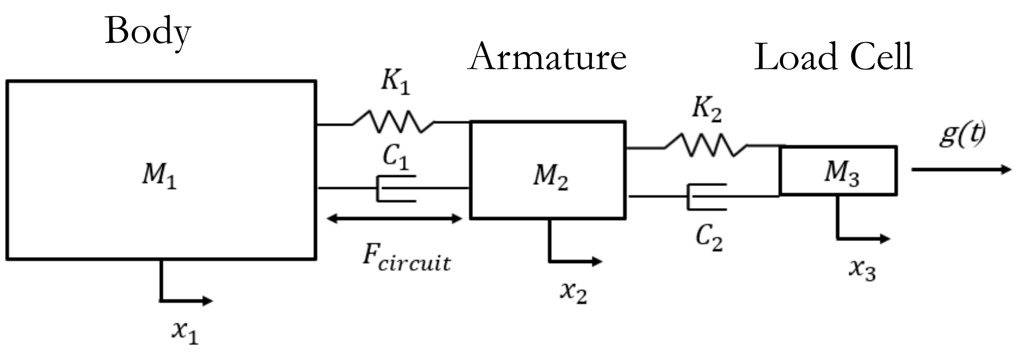
Problem Statement Continued

- It has been demonstrated in various research that the electromechanical shaker dynamics can influence the structure under test [11-15]

- It is through FFVC tests **and the electromechanical shaker dynamics** that a nonlinear system is stabilized [1,9]



Shaker Electrical Model



Shaker Mechanical Model

Approach

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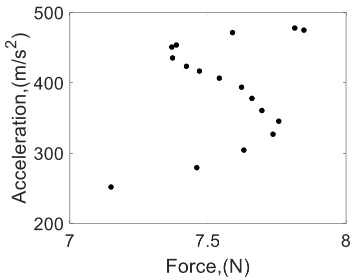
FFVC (S-curves)



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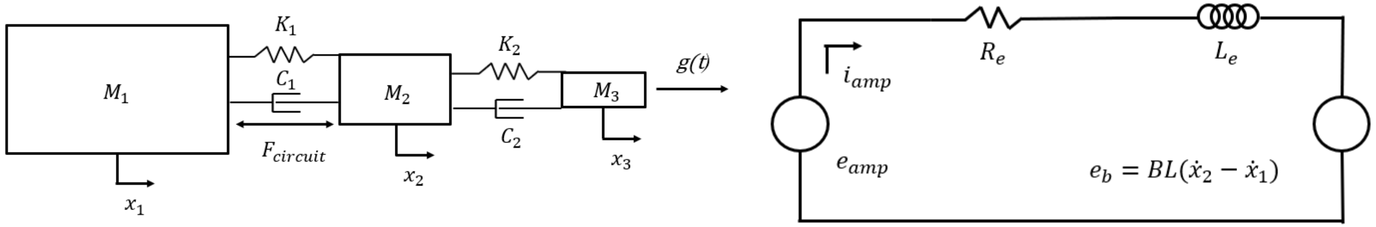
Electromechanical Shaker Dynamics

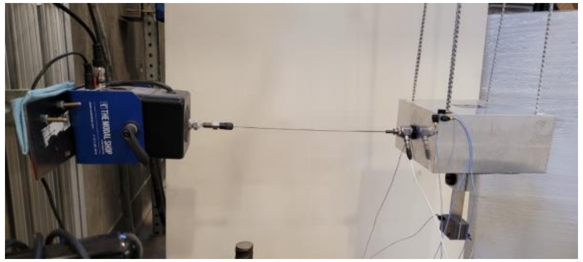


Goal: Use the various mechanical and electrical parameters in the shaker to investigate the stability of the nonlinear system

1.) Parametric Study

- M_1, M_2, M_3
- K_o, K_1, K_2
- C_o, C_1, C_2
- BL, R_e, L_e, K_a, W_b

2.) Experimental Study



III. Parametric Study through Simulations

Nonlinear Cantilever Beam Simulation

- Harmonic balance (HB) was used with an electromechanical shaker model and a 20 node Euler-Bernoulli beam with a cubic nonlinearity at the free end

- The goal was to perform FFVC tests using HB and change various shaker parameters in the model to assess the stability on the system through the reconstructed S-curves

- Insight from these simulations were later used in experimental tests for validation

Nonlinear System

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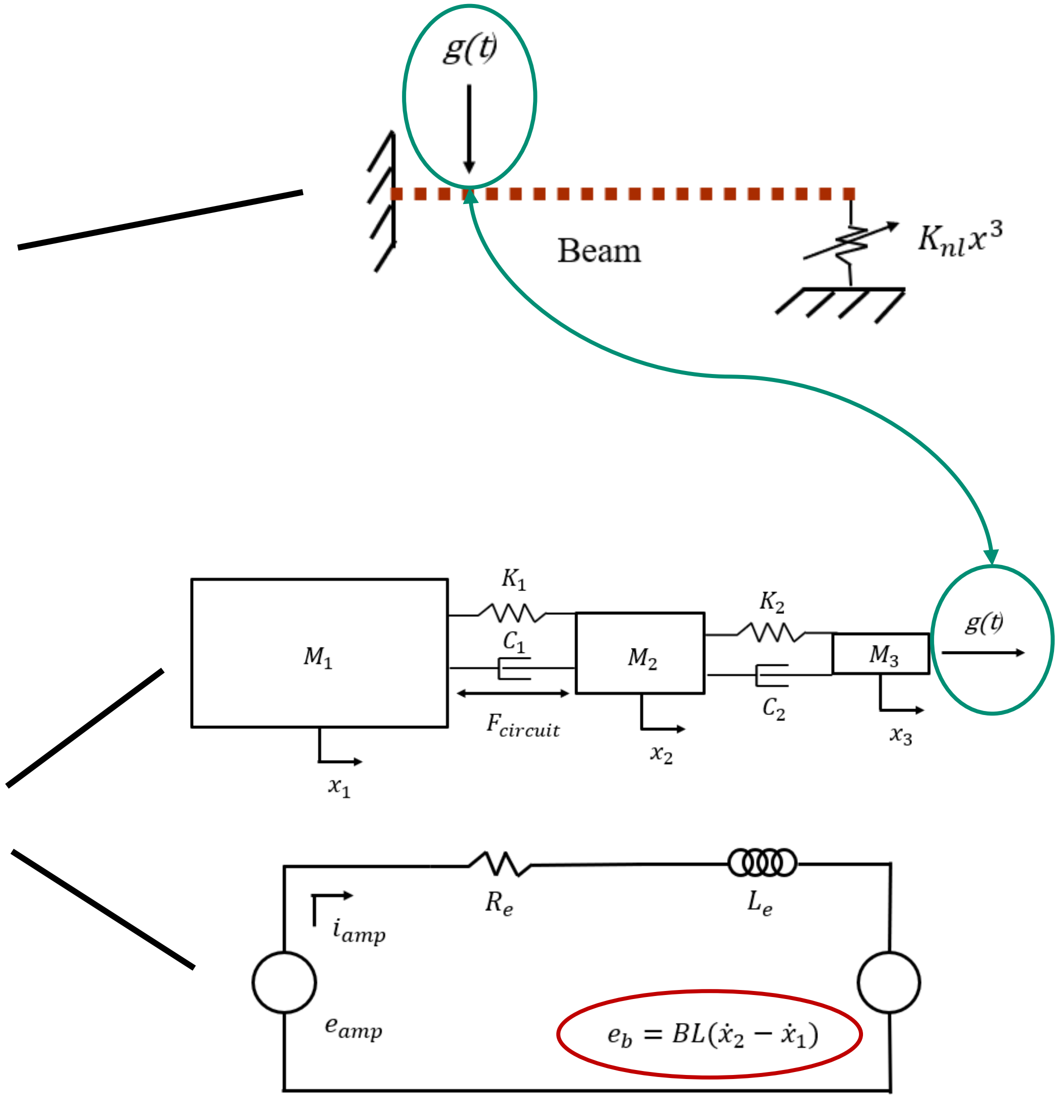
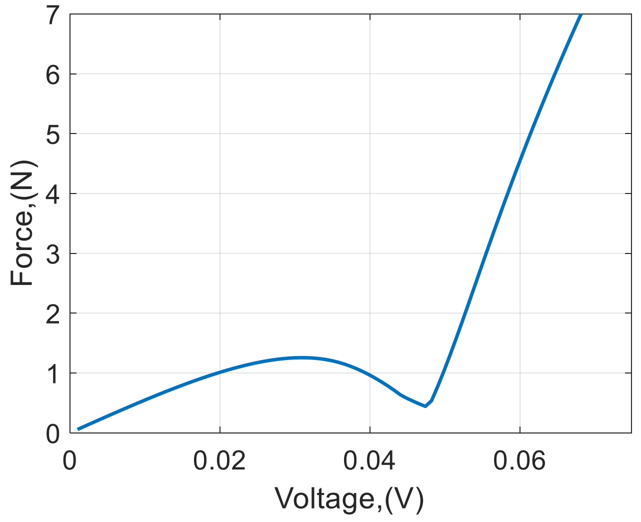
Shaker Dynamics



Stabilizing Behavior

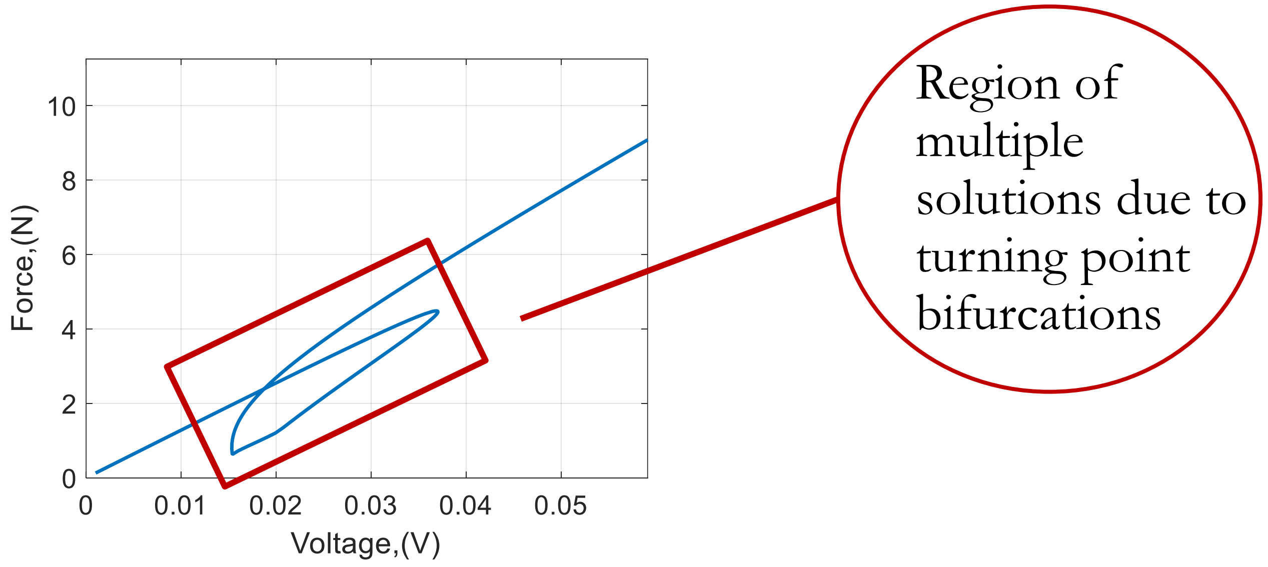
Stabilizing behavior: singular valued force drop-out curves (generally near the second local minimum)

Stable Behavior



Outcome: sequential continuation along the voltage parameter – results in fully resolved curve

Unstable Behavior



Outcome: sequential continuation not possible – results in bifurcations leading to jumping behavior

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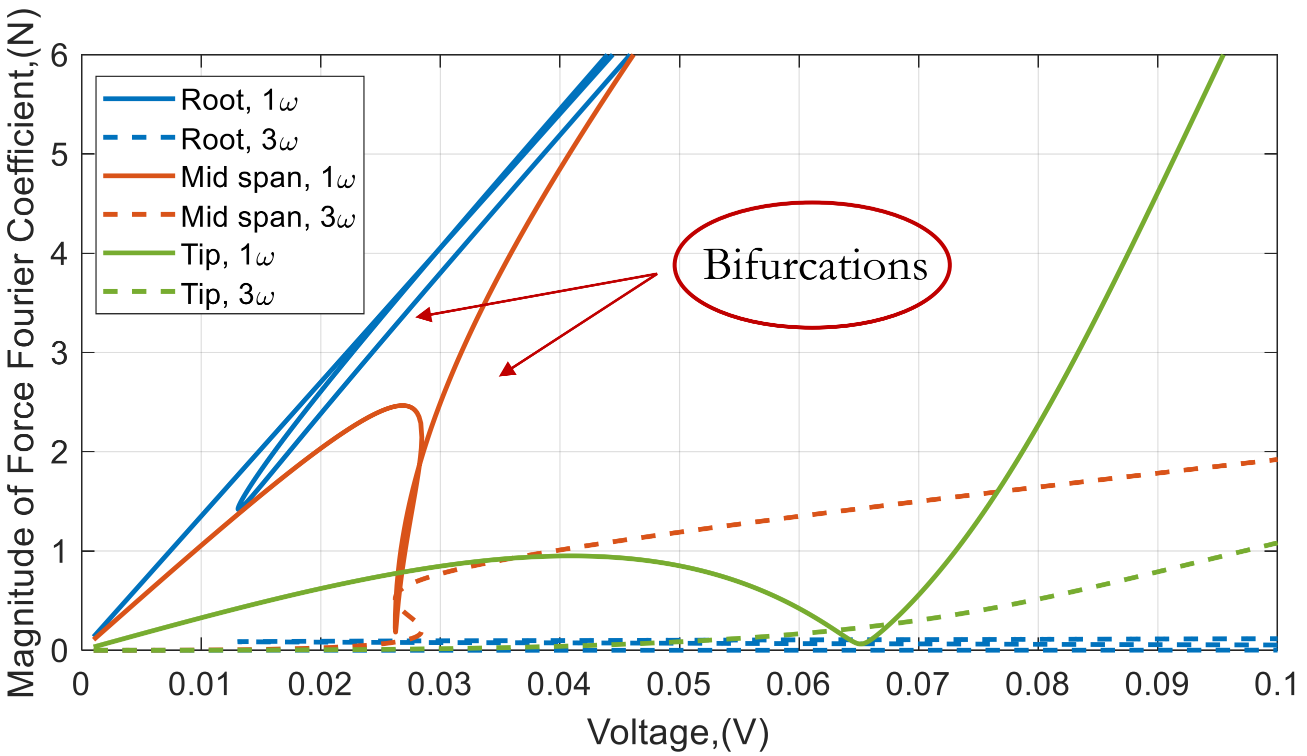
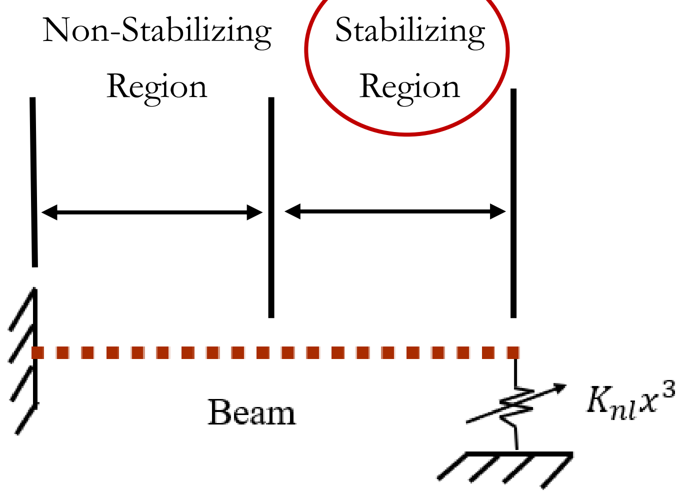
Moving Shaker Drive-Point Locations

- The stability of the shaker drive-point locations were investigated by moving the shaker node-to-node from the fixed end to the tip
- The stabilized force drop-out curves at the local minimum were dominated by the third harmonic

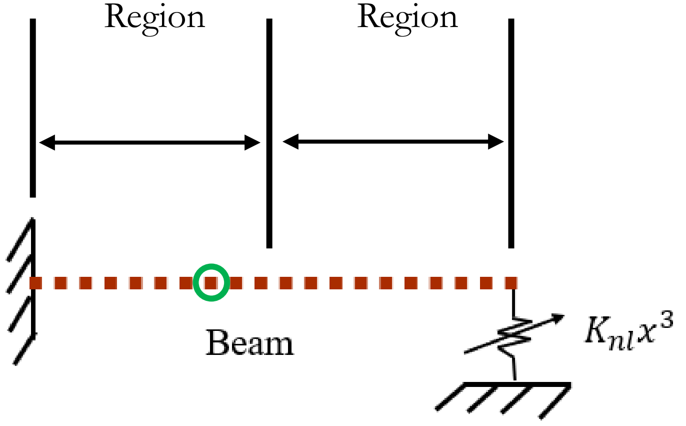


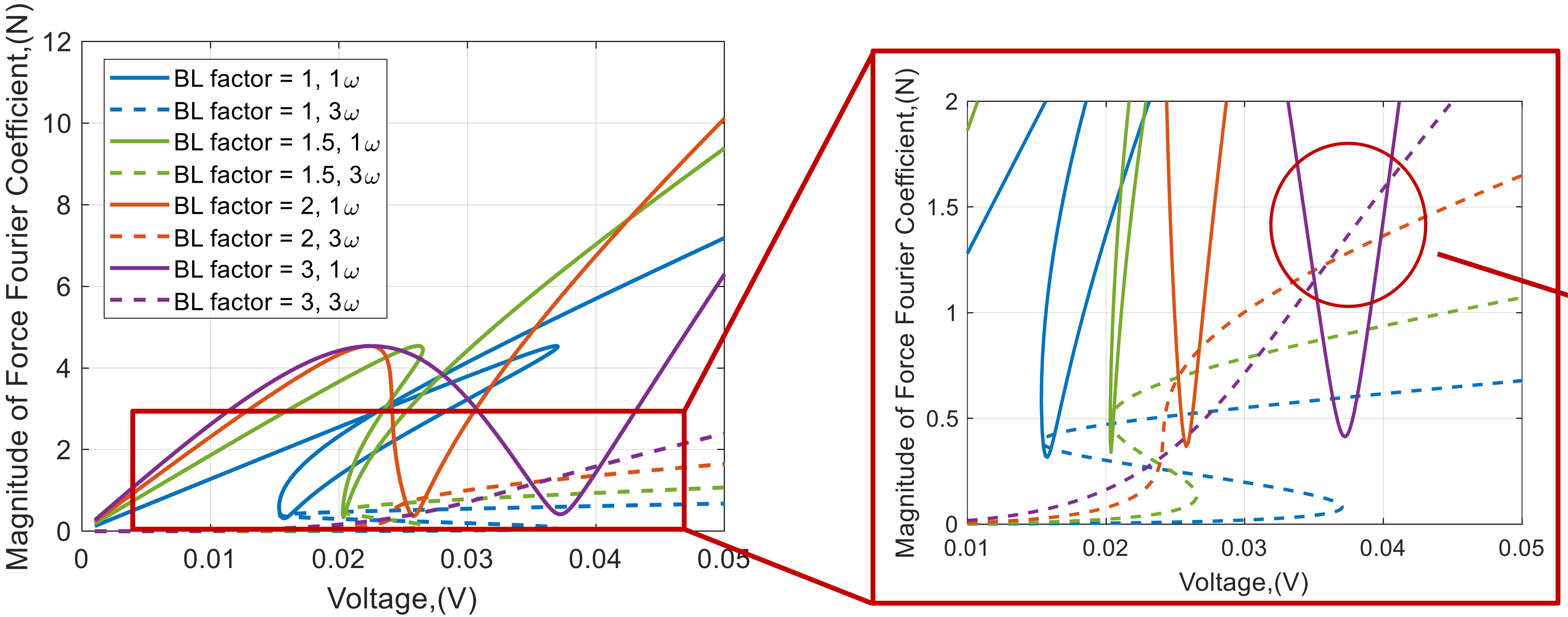
The force drop-out curves became singular valued when the shaker was attached to the beam between the mid span and tip



Fixing Shaker at Node 8 – Force Drop-out Curves

- The shaker drive-point was fixed at node 8 on the beam to investigate the BL parameter change at an inherently unstable drive-point node
    - BL = electromechanical coupling factor
- Scaling factors that increased the BL parameter resulted in singular valued force drop-out curves suggesting a stabilizing effect was occurring



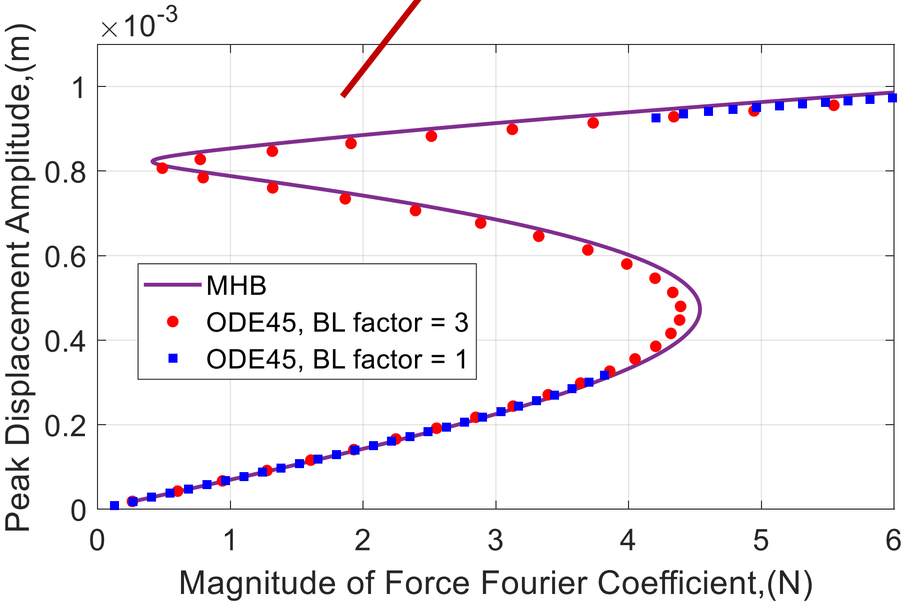


The force drop-out curves at the local minimum were dominated by the third harmonic

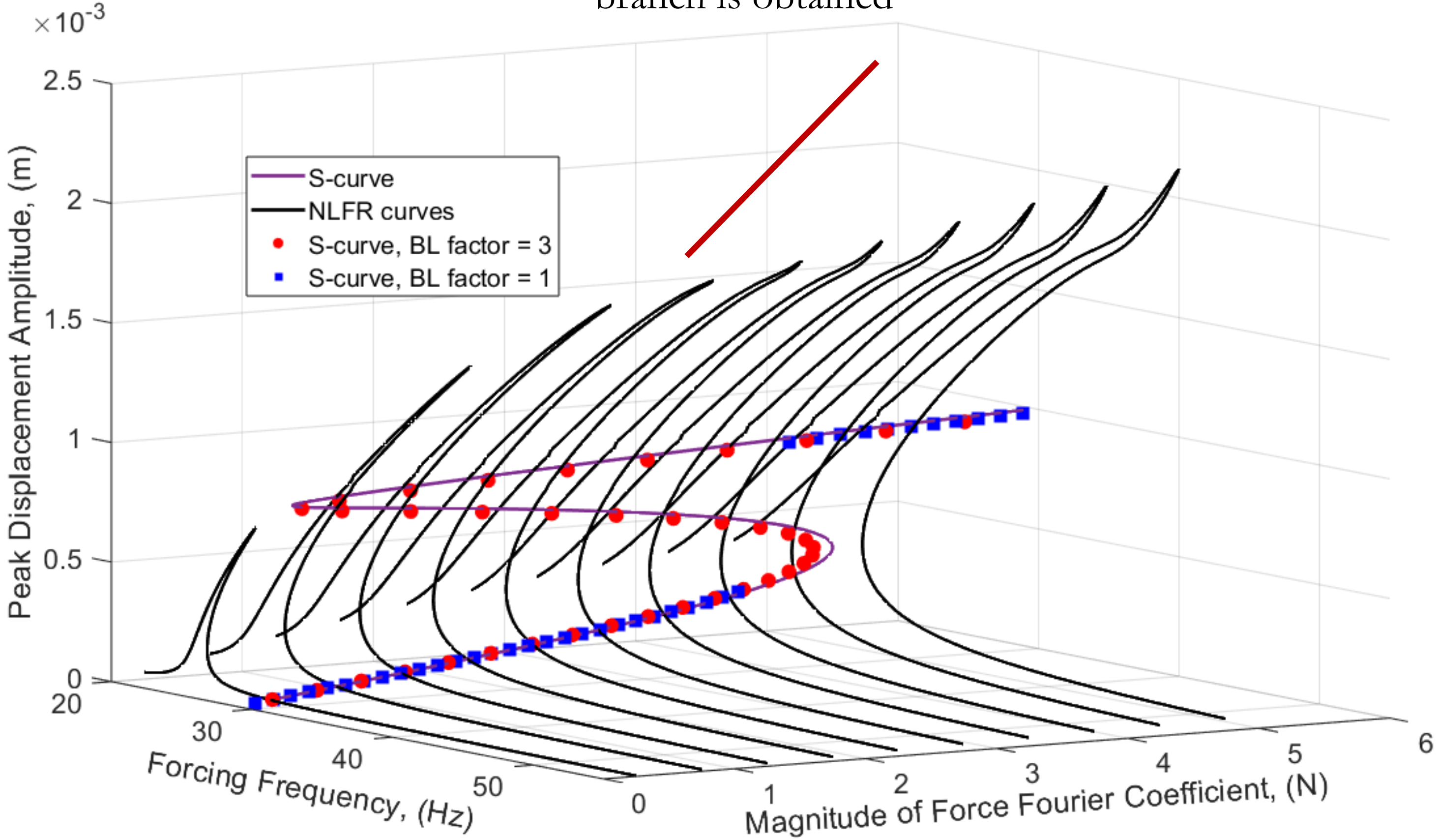
Harmonic Balance and Time Integration Comparison

- An experimental simulation using time integration was conducted with the shaker attached to node 8 on the beam - the results were compared to the MHB results

The *BL* factor was again scaled at different integers to demonstrate the stabilizing and non-stabilizing behaviors



The NLFRC was plotted to show how the S-curve intersects and how the intermediate branch is obtained



Parametric Study Outcomes Summary

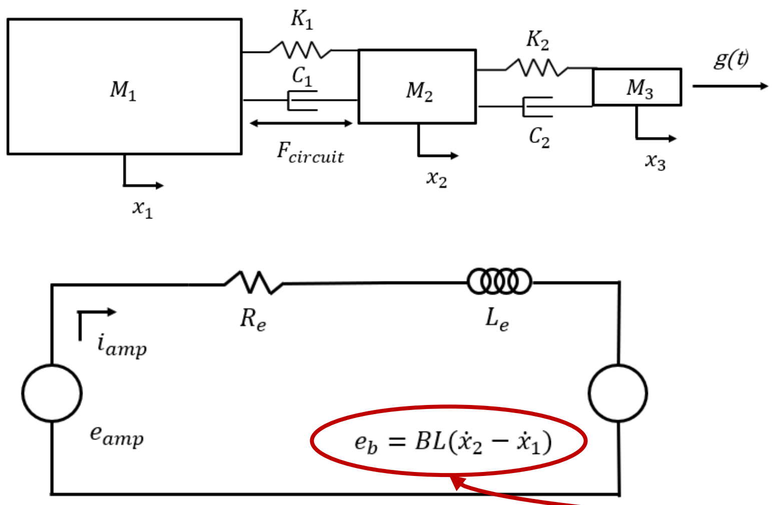
Moving Shaker Drive Points

Increasing $(\dot{x}_2 - \dot{x}_1)$

Scaling the BL Parameter

Increasing BL

Shaker Dynamics



e_b = back electromotive force (EMF) voltage that couples the mechanical motion to the electrical circuit

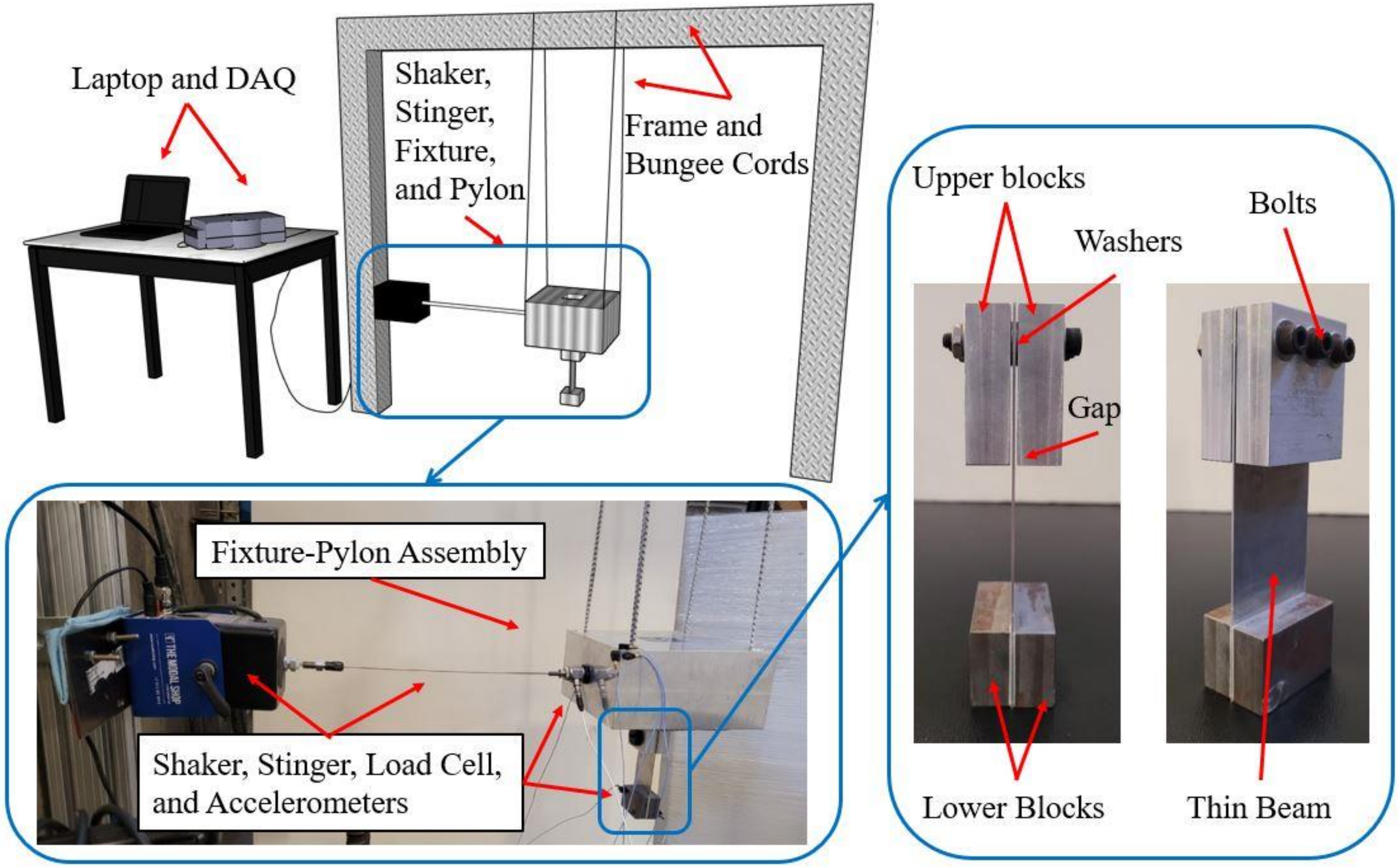
$$e_b = BL(\dot{x}_2 - \dot{x}_1)$$

For practical experimental implementation, changing the shaker drive-points on the structure to more active locations in the target mode (increasing $(\dot{x}_2 - \dot{x}_1)$) is more feasible than changing the BL parameter

IV. Experimental Setup
Fixture-Pylon Assembly

Fixture-Pylon Assembly Overview

- Linear resonance is approximately 9.1 Hz
- Through the spacing of the washers on the upper pylon blocks, a contact is created between the upper blocks and beam that creates a strong hardening vibro-impact nonlinearity [3]
- A small electromechanical shaker (integrated amplifier) was used in a fixed boundary condition with a long steel stinger



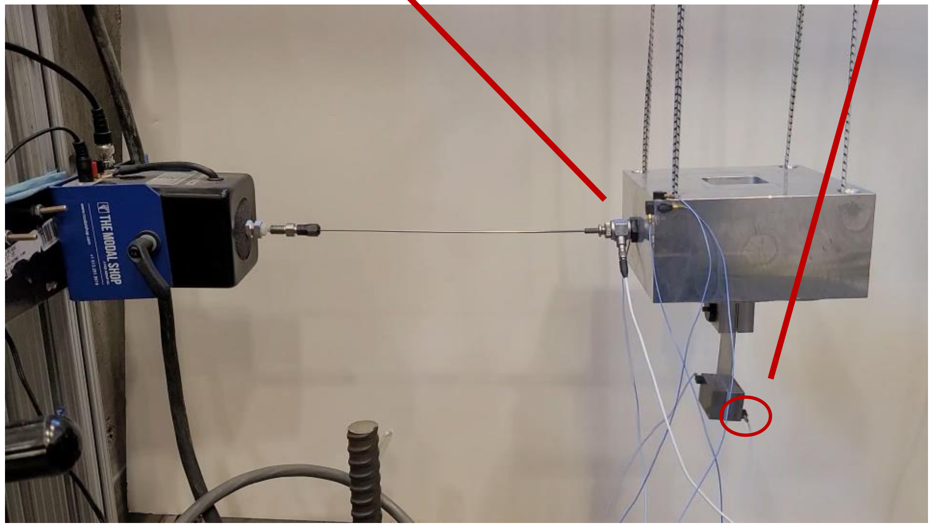
V. Experimental FFVC Tests on Assembly

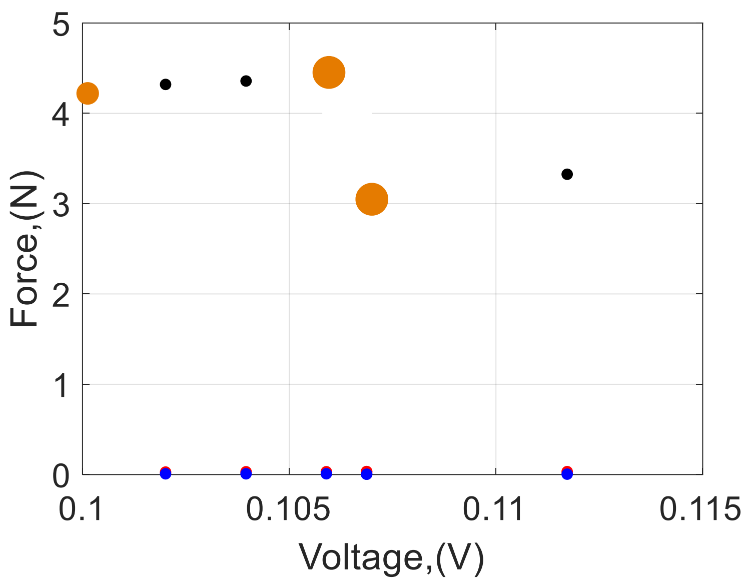
Initial Experimental FFVC Tests

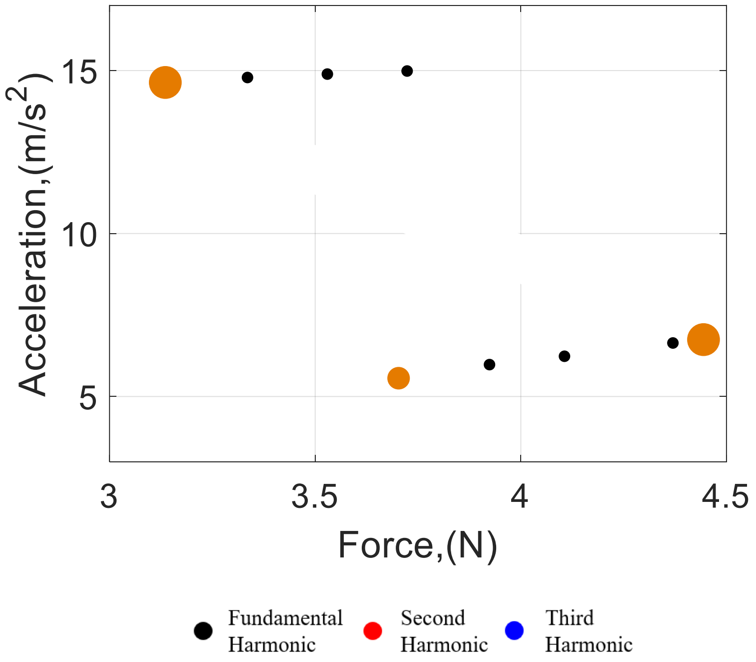
- Each point in the force drop-out and S-curve figures represents the steady state amplitude from individual sine tests at 9.7 Hz at increasing voltage steps
- Initially, jumping was occurring between the upper and lower branches such that the middle branch was unresolved [10]

Excitation drive point at middle of fixture

Output accelerometer location

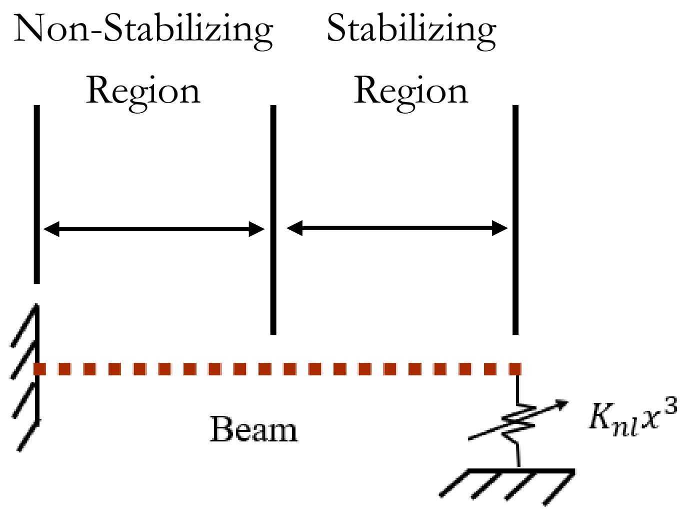




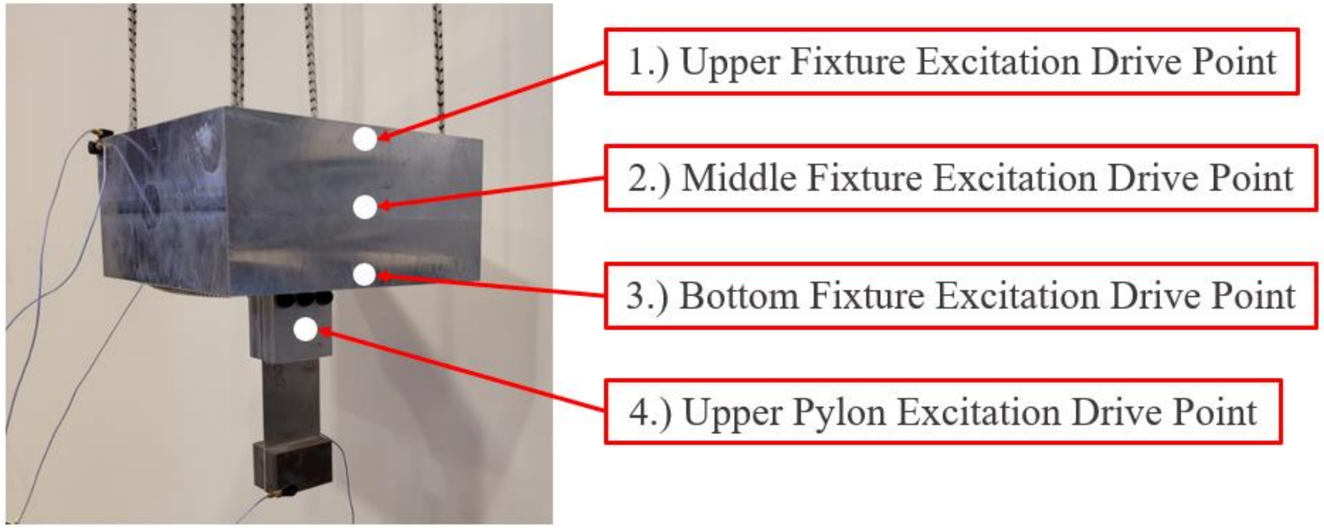


Modified FFVC Tests Based on Parametric Study Outcomes

- Based on the outcomes of the cantilever beam simulations, a set of experiments was designed to validate the previous hypothesis and see if there is any corroboration between the simulation and experiment



$$e_b = BL(\dot{x}_2 - \dot{x}_1)$$

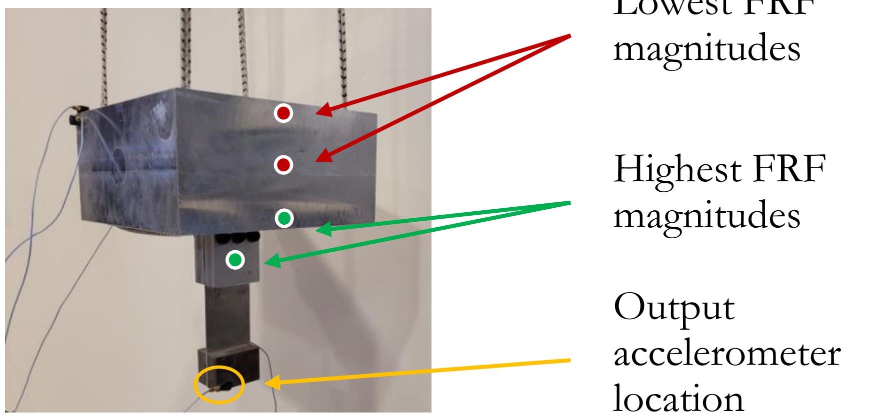


FRFs from Different Drive-Point Locations

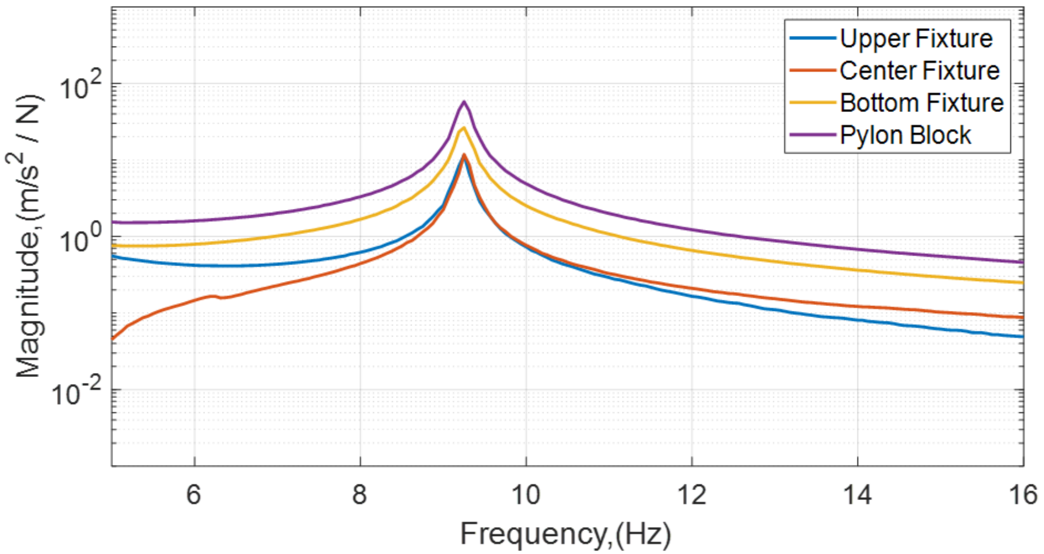
- Random vibration experimental tests at each of the four drive-points on the assembly confirmed that the two bottom drive-points resulted in more active responses in the mode

$$e_b = BL(\dot{x}_2 - \dot{x}_1)$$

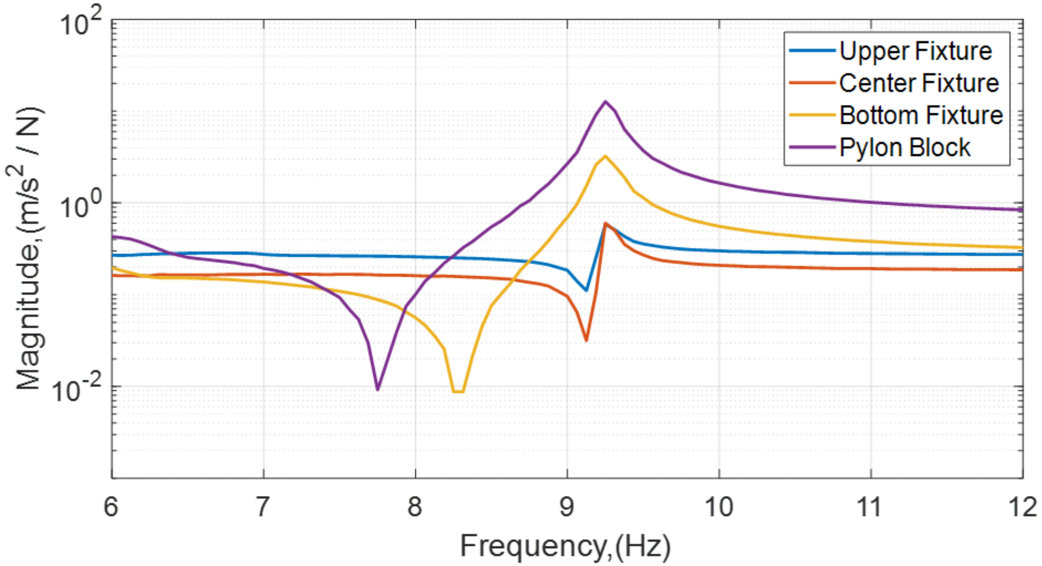
This term increases with increasing FRF magnitudes



Bottom pylon accelerometer



Shaker armature accelerometer



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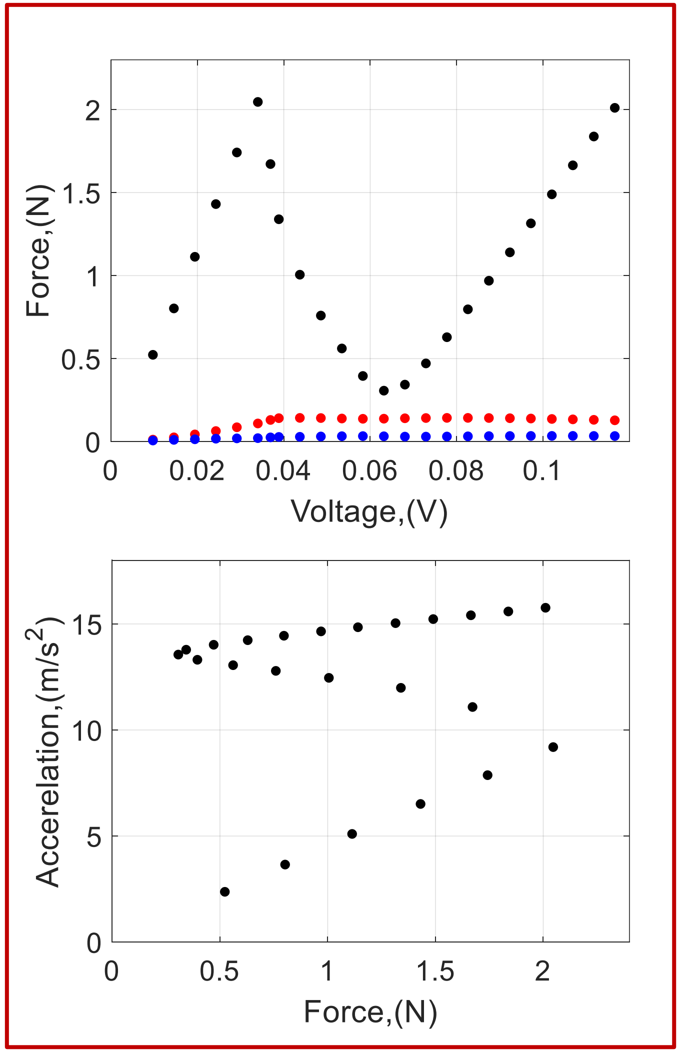
Modified FFVC Tests Based on Simulation Outcomes

- The two bottom excitation drive-point locations effectively mitigated the previous jumping behavior such that the unstable middle branch was measured – **the assembly is now experimentally stabilized!**

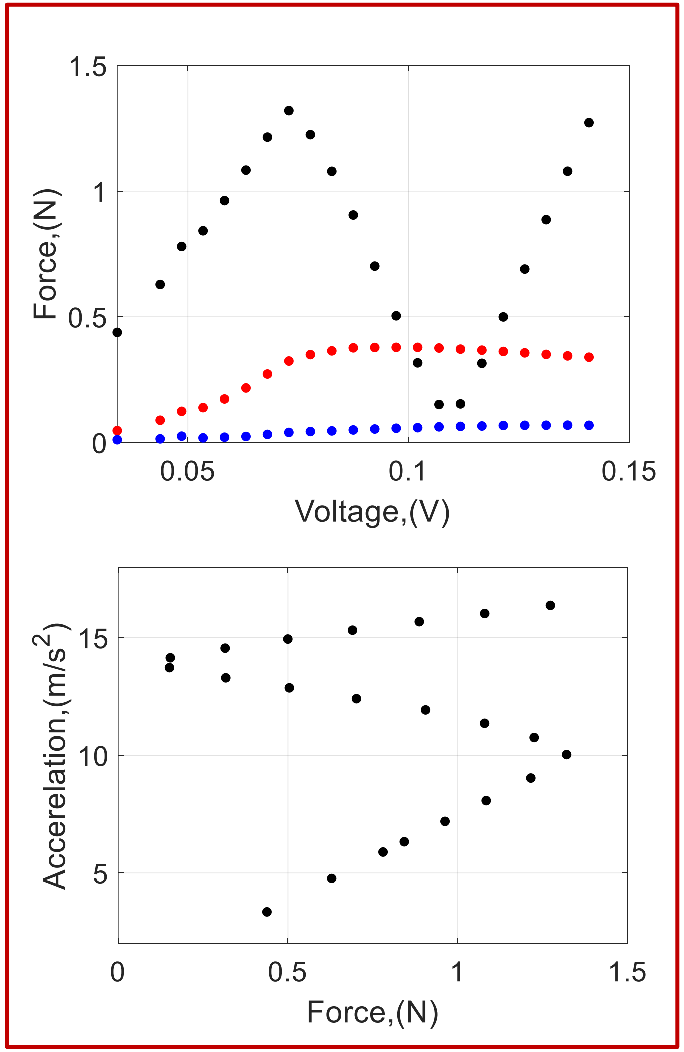
- Unlike the upper pylon block drive-point location, there was actually no distortion from the second harmonic at the bottom fixture drive-point location at the local minimum

Fundamental Harmonic | Second Harmonic | Third Harmonic

Bottom Fixture



Upper Pylon Block



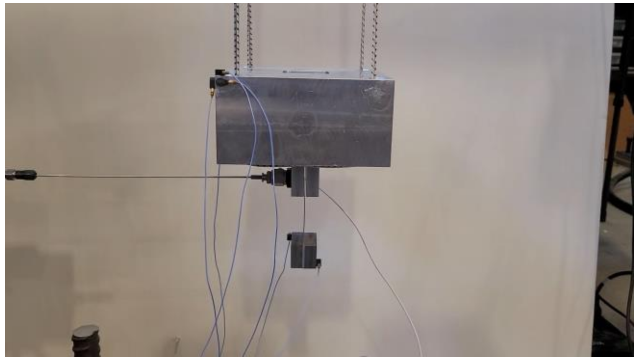
VI. Conclusions

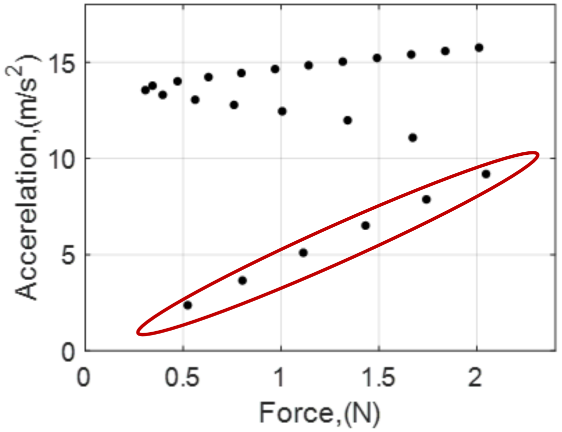
Conclusions

- Increasing (decreasing) the BL parameter at inherently unstable (stable) drive points resulted in stabilizing (non-stabilizing) behavior in the system
- **One of the most significant stabilizing parameters in terms of practical experimental implementation was moving the shaker to active locations in the mode (increasing $(\dot{x}_2 - \dot{x}_1)$)**
  - There was strong corroboration between the simulated and experimental results based on this finding
- Future research including a stability analysis based on a model of the shaker and assembly will help validate the results demonstrated by this research

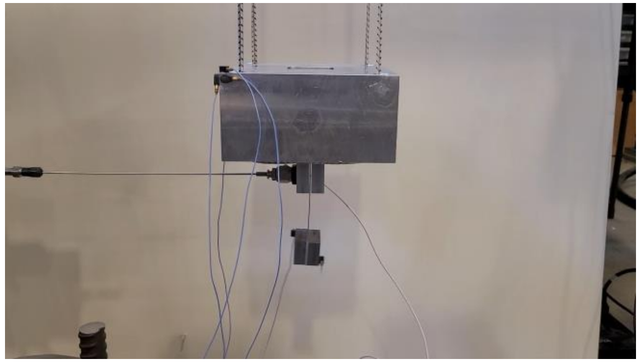
Thank You! Questions?

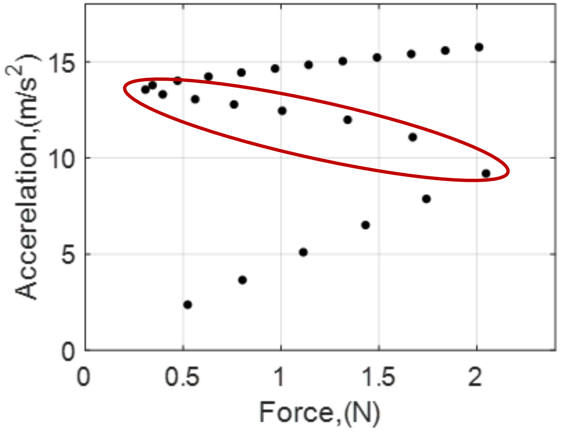
Lower Branch Vibration



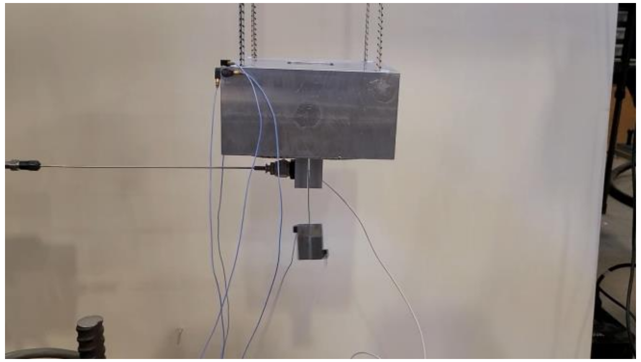


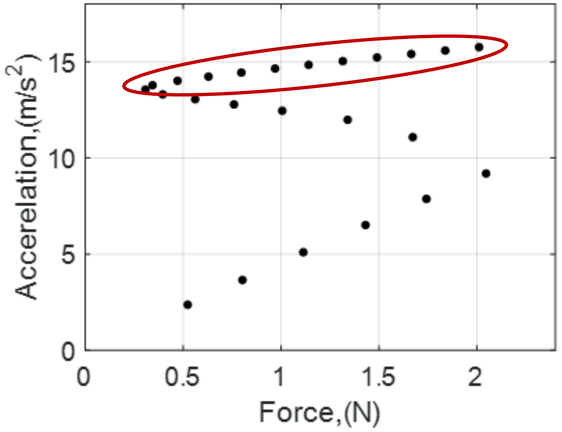
Middle Branch Vibration





Upper Branch Vibration





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Acknowledgements

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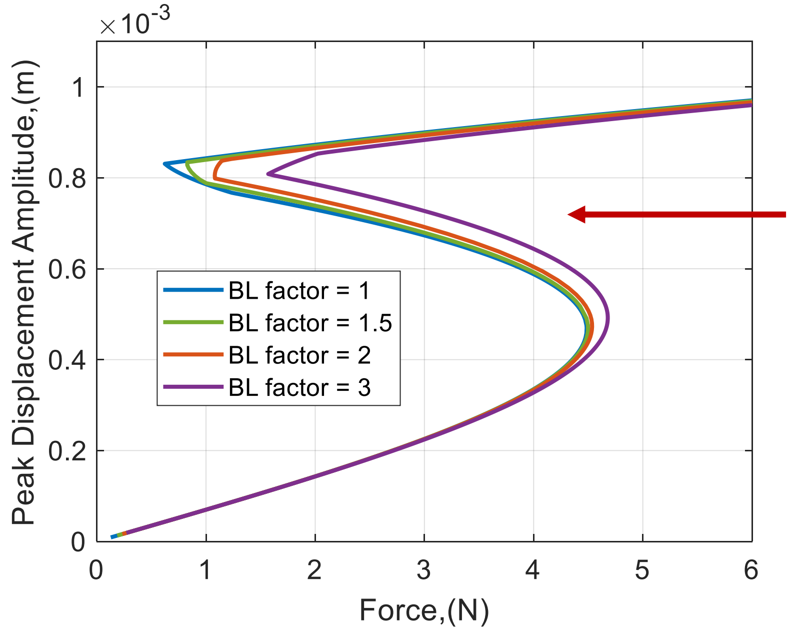
Backup Slides

Fixing Shaker at Node 8 – Reconstructed S-Curves

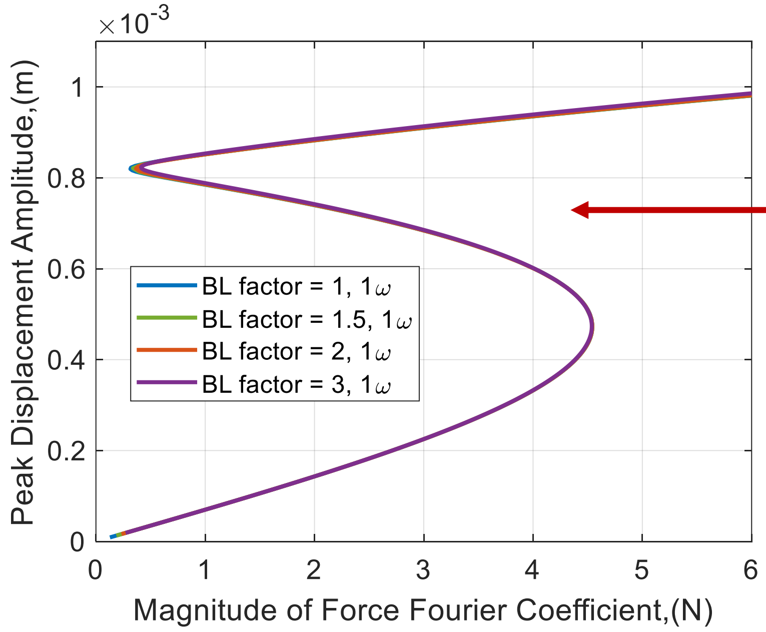
- Reconstructing the force drop-out curves to S-curves and viewing the different harmonic interactions resulted in different agreement between the two turning points and middle branches

Maximum absolute value of load cell force



Poor agreement at the middle branch between the upper and lower turning points due to the higher harmonics

Fundamental harmonic of load cell force

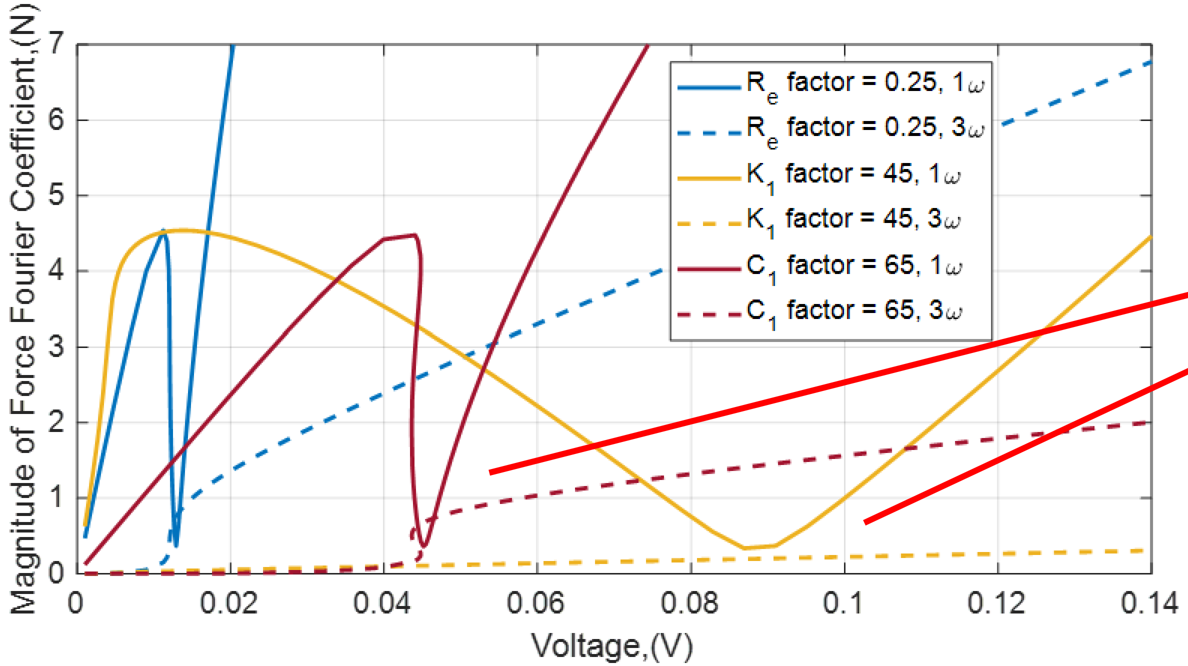


Good agreement between the first harmonic in the force drop-out curves

Fixing Shaker at Node 7 – Force Drop-out Curves

- Factoring the K_1 and C_1 parameters demonstrated similar results to those shown before but required more extreme scaling factors
- Changing the R_e parameter also resulted in the desired stabilizing behavior but only required a minimal decrease

- K_1 = armature stiffness
- C_1 = armature damping
- R_e = shaker resistance



Observe the different behaviors of each curve:

- Different local minimum voltages
- Wide or narrow voltage ranges
- Different harmonic interactions

The underlying dynamics of the system is likely changing

Fixing Shaker at Node 17 – Force Drop-out Curves

- When starting at an inherently stable drive-point node the reverse effect was observed – decreasing the BL factor destabilized the system such that the force drop-out curves were no longer singular valued

- Higher harmonic distortion was still present at the local minimums