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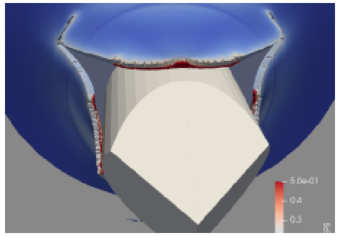
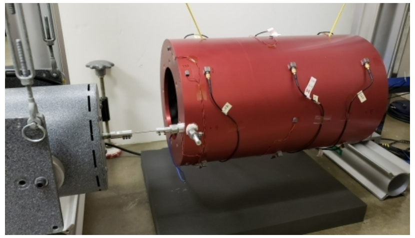
Sandia National Laboratories

Nonlinear System Identification of a Fixture-Pylon Assembly using Stepped Sine Testing





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I. Introduction

Background and Motivation

- Nonlinear system identification is constantly developing as new computational and test strategies continually emerge in research
- Key developments in nonlinear system identification leads to better characterization of complicated nonlinear behavior experimentally which is useful for model updating and computational modeling [2, 3]
- This research addresses experimental system-shaker limitations and explores the application of recently developed control test strategies

Goal: Conduct nonlinear system identification of fixture-pylon assembly

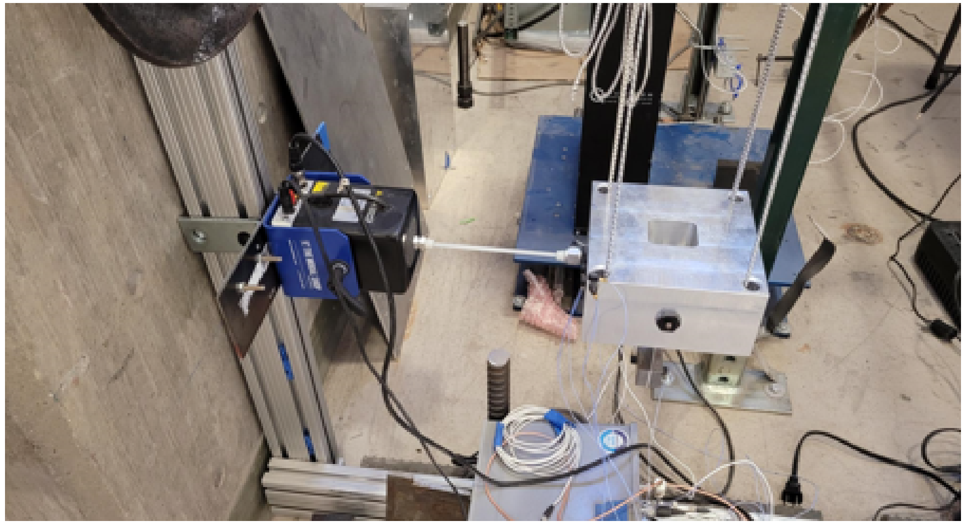

Fig. 1: Suspended Fixture-Pylon System

Overview of Research

- Use commercial software to apply new test strategies to a fixture-pylon assembly with a strong nonlinearity to obtain the unstable solutions of the system without any jumps

1. **Force control:** Commonly applied test strategy where force is held constant, and frequency is stepped – generally results in jump down during tests
2. **Acceleration amplitude control:** A test strategy where acceleration amplitude is held constant, and frequency is stepped – results in force dropout and acts as experimental turning point where unstable solutions are resolved [6]
3. **Voltage control:** Another test strategy where voltage is held constant, and force/amplitude are uncontrolled – also results in force dropout and acts as experimental continuation parameter and resolves unstable solutions [7]

Apply amplitude and voltage control tests to fixture-pylon assembly

Presentation Content

1. Fixture-pylon assembly overview
2. System-shaker interactions and linear/nonlinear testing
3. Application of control strategies
4. C-beam system overview
5. Application of control strategies
6. Conclusions

First step: Introduce the fixture-pylon assembly

II. Fixture-Pylon Assembly

Fixture-Pylon Assembly Overview

- The pylon is bolted to a rigid suspended fixture in order to isolate the system from dynamic excitation
- Through the spacing of the washers on the upper blocks, a contact is created between the upper blocks and beam [1]
- The gap in the pylon creates a strong hardening gap-spring nonlinearity [1]

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(\boldsymbol{t}) + \boldsymbol{C}\dot{\boldsymbol{x}}(\boldsymbol{t}) + \boldsymbol{K}\boldsymbol{x}(\boldsymbol{t}) + \boxed{\boldsymbol{f}_{\boldsymbol{nl}}\{\boldsymbol{x}(\boldsymbol{t})\}} = \boldsymbol{u}$$

First Step: Characterize linear modes of fixture-pylon assembly

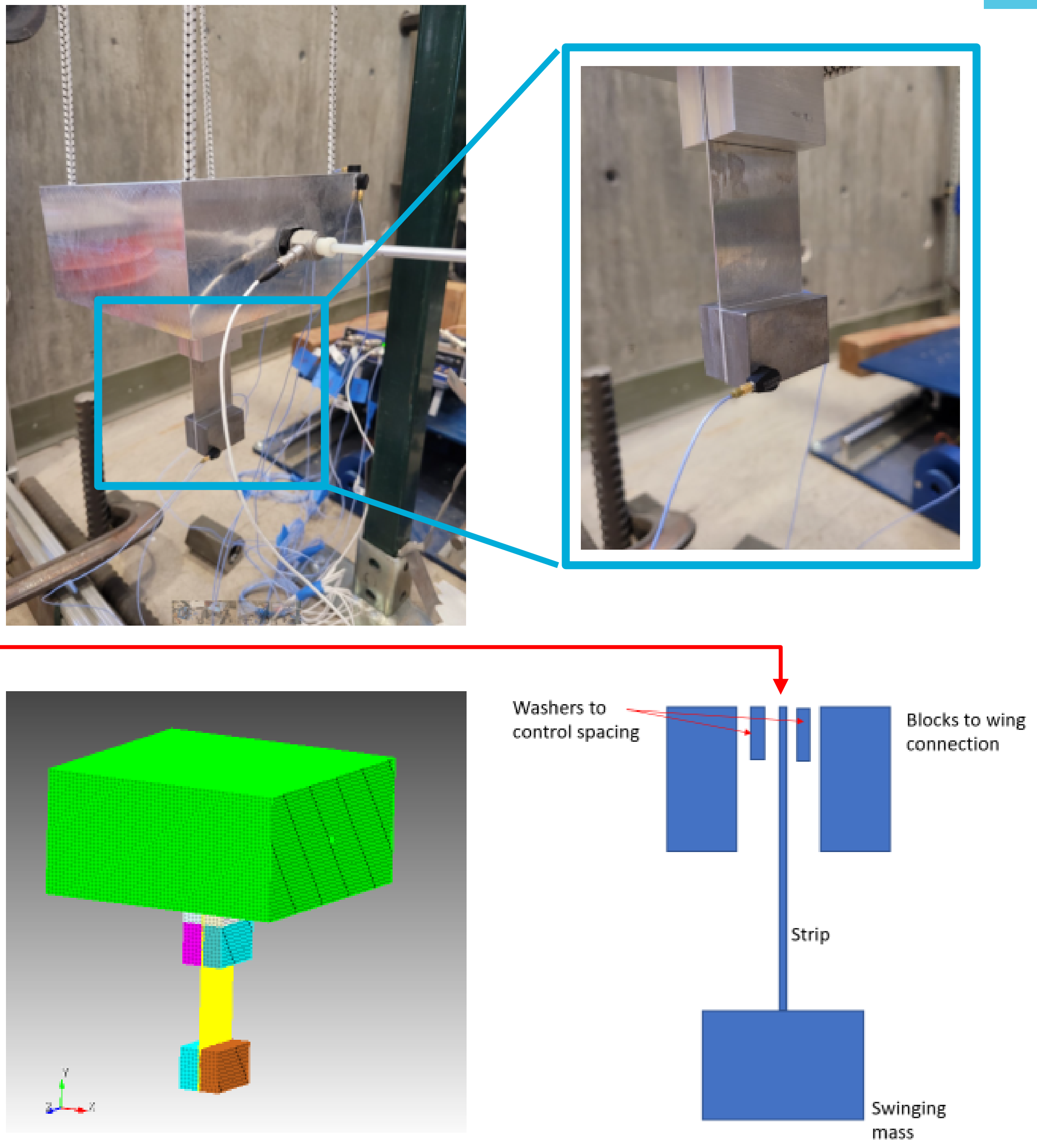

Fig. 2: Fixture-pylon assembly detailed view

Linear Testing Overview

- Before nonlinear tests could be conducted on the assembly it was first important to understand the underlying linear system
- The mode of interest on the pylon was the first bending mode which occurred at approximately 9 Hz (FEM model)
- It was of interest to characterize the rigid body and system modes between FEM model, impact hammer, and the shaker FRFs so there was mutual agreement before nonlinear testing

Conduct impact hammer and shaker tests at drive point and obtain FRF's from accelerometer location

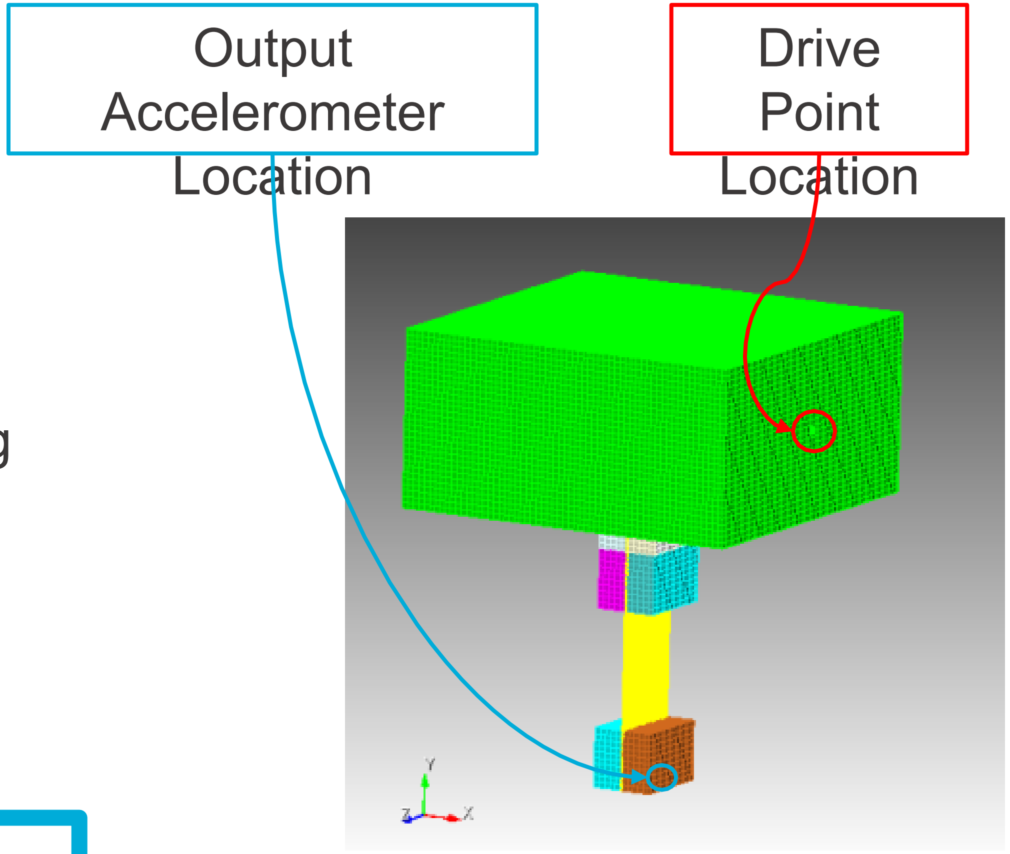

Fig. 3: Fixture-pylon CAD assembly

Impact Hammer and Shaker Tests

- Impact hammer and random vibration shaker tests were first conducted on the assembly - poor agreement between the tests FRFs was revealed
- Generally, poor agreement between the hammer impact and shaker tests were found for a few reasons:
  - There were various system-shaker modes near the frequency of interest and added significant damping [4, 5]
  - The stingers length and materials generally affected the feedback loop during testing

The impact hammer and shaker FRFs had poor agreement

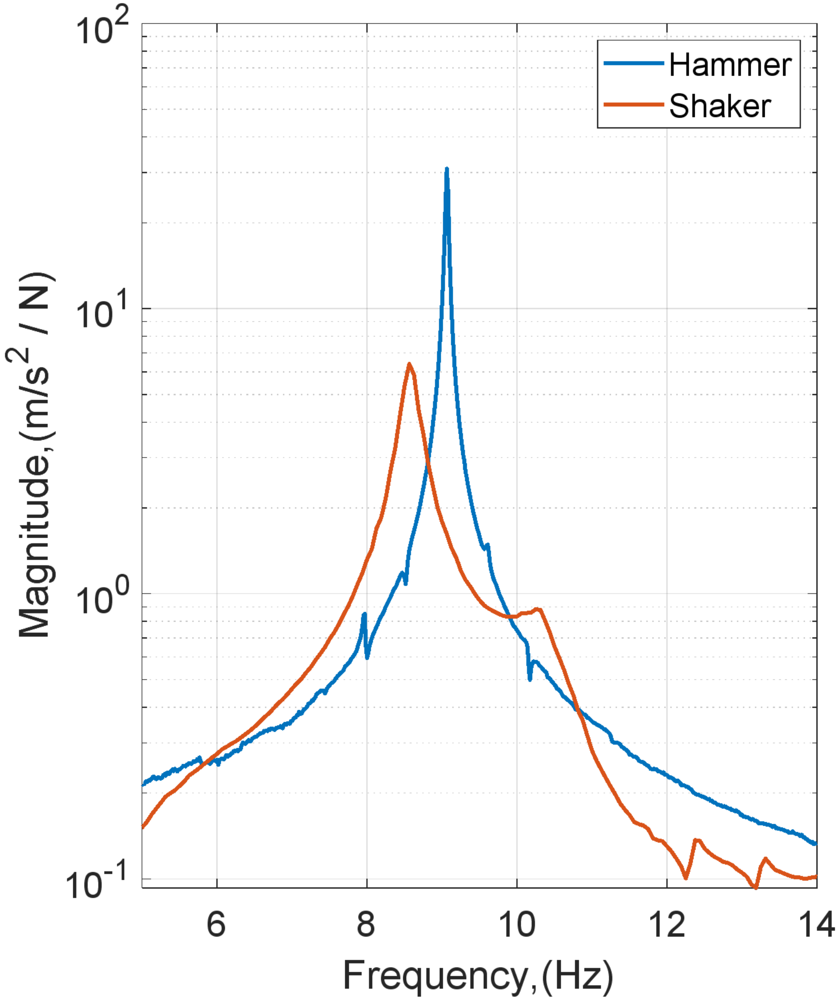

Fig. 4: Hammer and Shaker FRF Comparison

Shaker System Interaction

- Generally, the first system-shaker mode occurred too close to the mode of interest
- In order to achieve good agreement between the hammer and shaker modes, various linear random vibration shaker tests were run on the fixture-pylon assembly with:
  - Short/long nylon stingers
  - Short/long steel stingers
  - Free (bungee cord) shaker boundary conditions
  - Fixed (bolted) shaker boundary conditions

The shaker in a fixed boundary condition with a short steel stinger produced the most accurate results

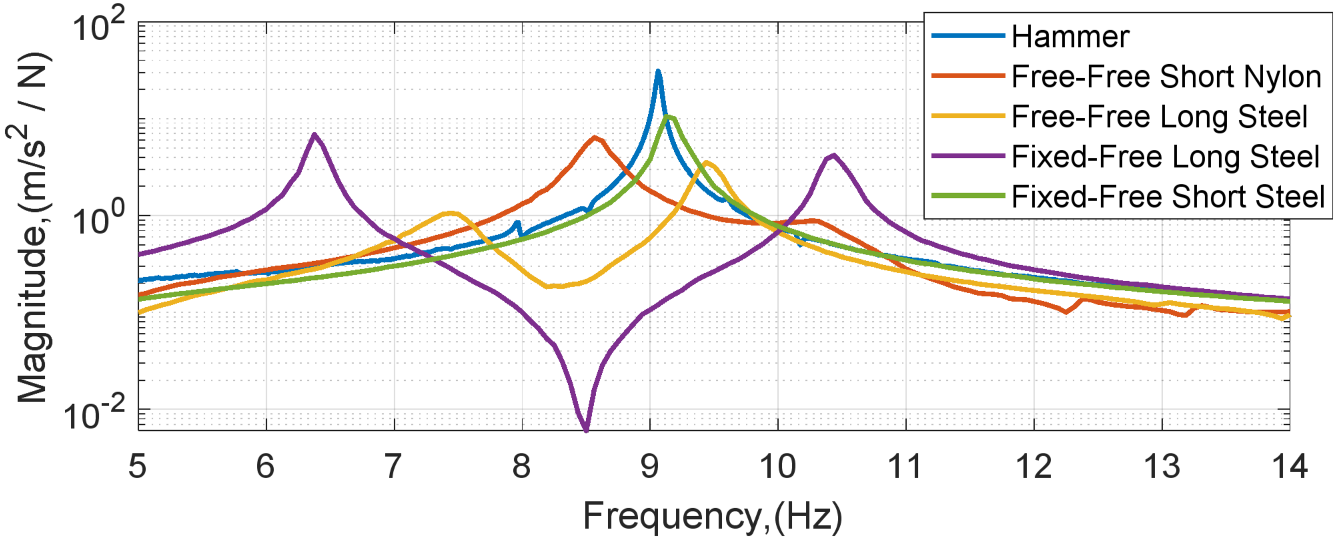

Fig. 5: FRF comparisons of hammer and shaker with various b.c.'s and stingers

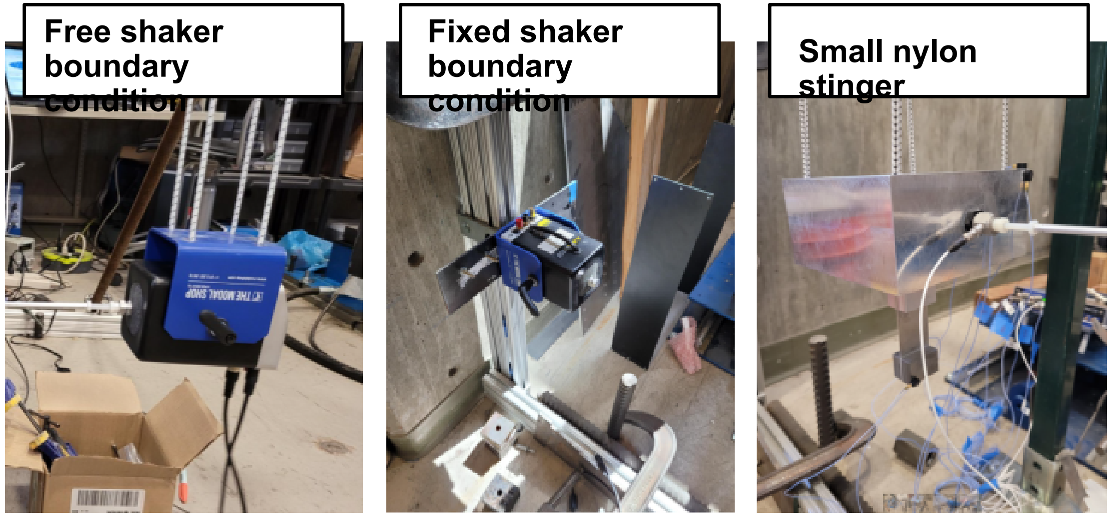

Fig. 6: Different shaker configurations

Effects of Shaker-System Interaction on Quality of Force Control

- Generally, the boundary condition of the shaker and different lengths/materials of the stingers influenced the quality of the force control during linear/nonlinear stepped sine testing

- Most boundary condition and stinger type combinations would result in random drop-offs during testing

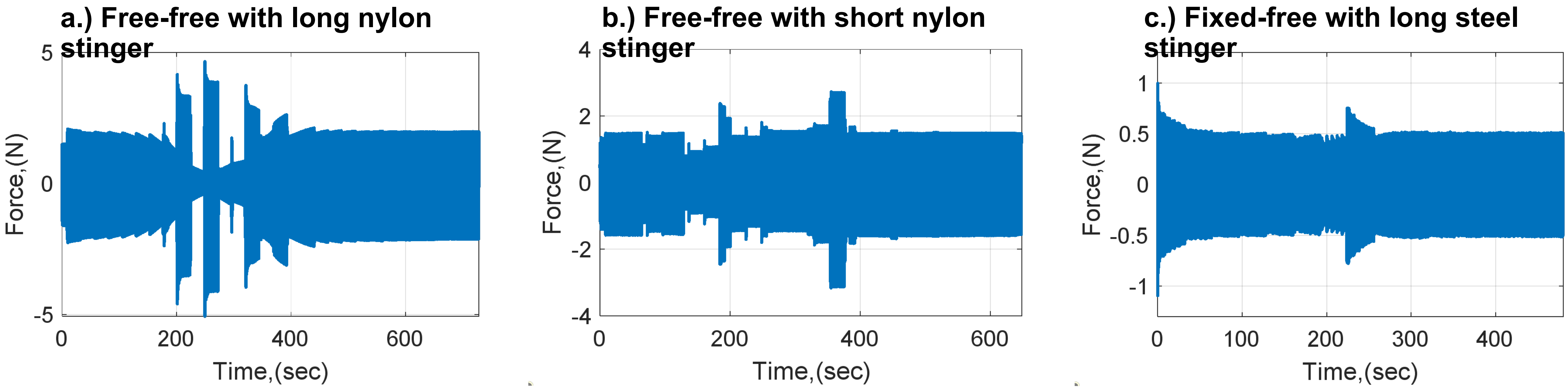

Fig. 7: Effects of shaker boundary conditions and stinger type on quality of force control a.) Free-free b.c. with 6.5” nylon stinger, b.) Free-free b.c. with 3.25” nylon stinger, and c.) Fixed-free b.c. with 12” steel stinger

The fixed shaker with a short steel stinger resulted in the highest quality force control for stepped sine testing

III. Nonlinear Testing

Nonlinear Testing on Fixture-Pylon Assembly – Force Control

- A series of stepped sine tests at varying force levels were conducted on the assembly
- At approximately 0.6-0.65 N the gap started to close on the pylon such that a strong nonlinear hardening started to occur and spanned up to 0.8 Hz at 0.75 N
- Jump downs occurred near the resonant peaks at higher excitation levels

Linear responses at lower force levels

Approximately 0.8 Hz of hardening at highest force level

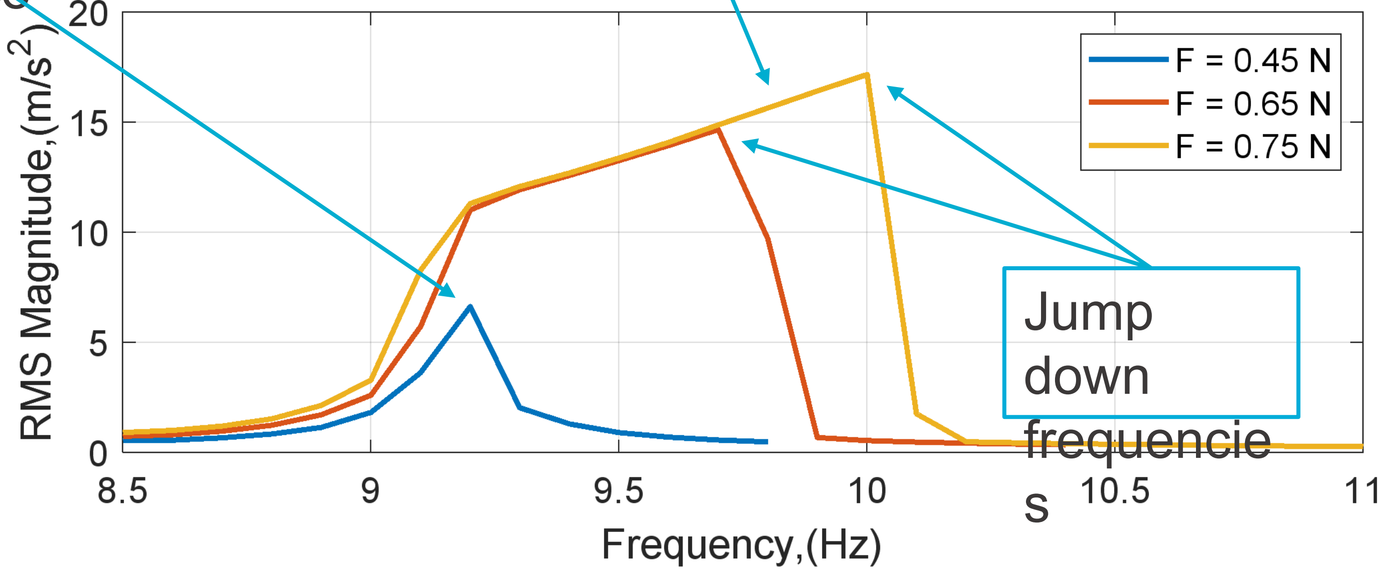

Fig. 8: Linear and nonlinear stepped sine test response spectra

At the highest force level, a strong hardening effect occurred which spanned about 0.8 Hz then jumped down around 10 Hz

Nonlinear Testing on Fixture-Pylon Assembly – Amplitude Control

- An acceleration amplitude control test strategy was applied to the assembly to generate the multivalued responses (low/high stable and unstable solutions) by:
  - Performing stepped sine tests with an accelerometer (at midspan of beam) as the constant, control parameter

- Based on the results of the tests, the pylon would continue to jump between the low and high stable solutions, like that of the force control stepped sine tests

The gap-spring nonlinearity was perhaps too strong for the amplitude control tests as jumping still occurred

Similar jumps as seen in force-controlled tests

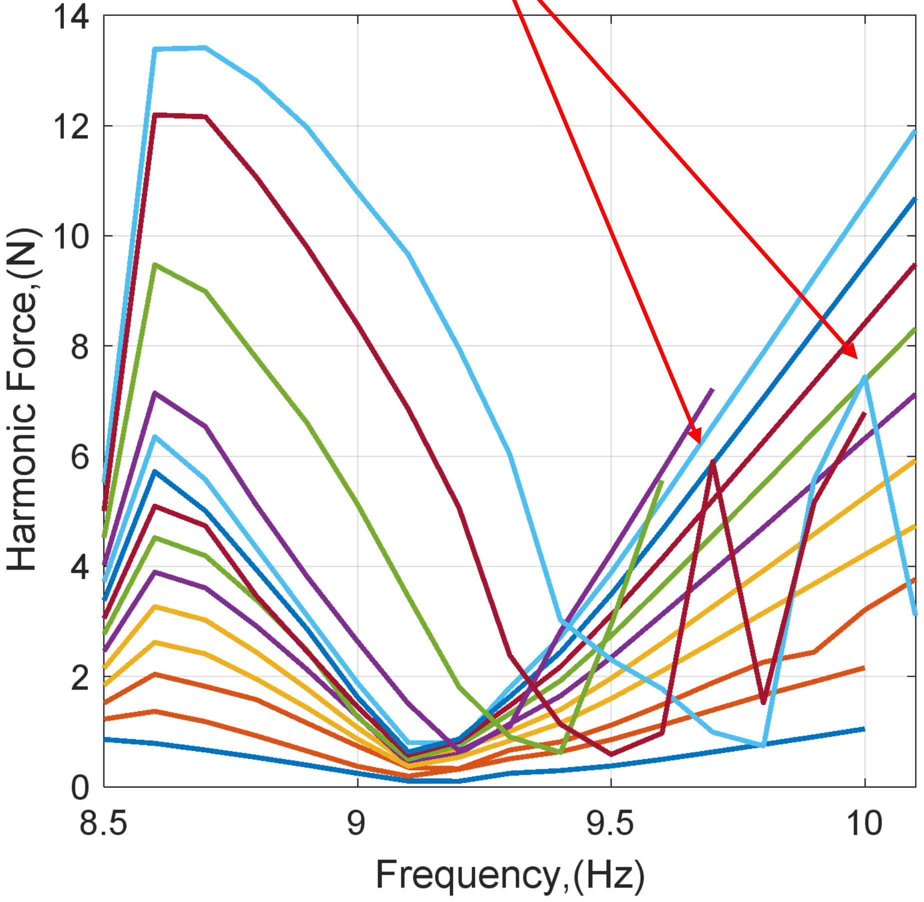

Fig. 9: Amplitude control response curves

Nonlinear Testing on Fixture-Pylon Assembly – Voltage Control

- In addition to the amplitude control test strategy, a similar method was applied to the assembly to generate the multivalued responses by:
  - Performing a series of individual sine tests on the assembly by keeping the voltage constant and leaving the amplitude and force uncontrolled
  - Note: the voltage was increased for each individual test

- Based on the results of the tests, the pylon would again continue to jump, similar to that of the force and amplitude control stepped sine tests

Jumping still occurred during the voltage control tests – apply test strategies to a new system with a weaker nonlinearity

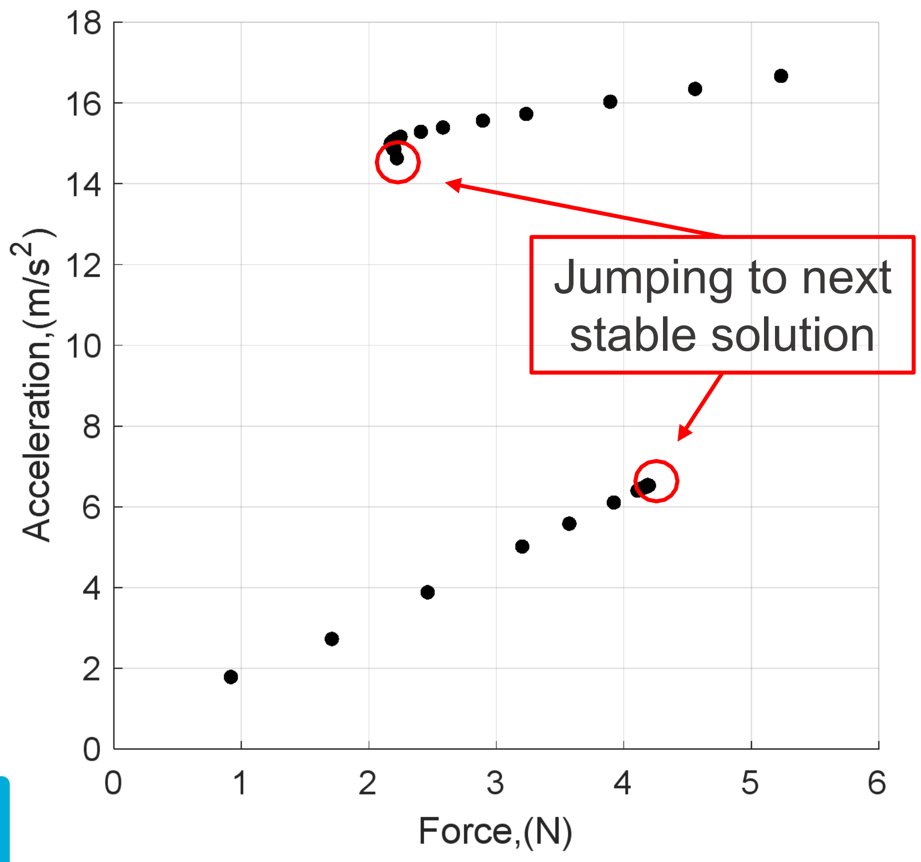

Fig. 10: Voltage control response curve

IV. C-Beam Assembly

C-beam Overview

- A C-beam was freely suspended from a rigid frame by bungee cords and a shaker was attached and excited the far end of the beam
- The second mode (out-of-plane and in-phase bending mode) was of interest with a natural frequency of 352.4 Hz

Output accelerometer location

Two C-beams bolted together

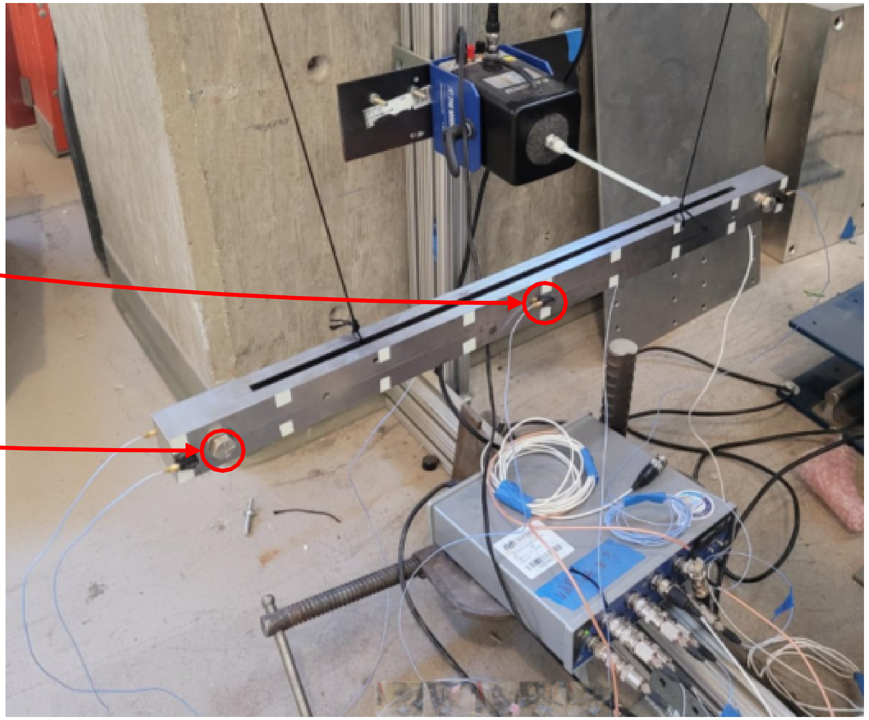

Fig. 11: C-beam shaker test setup

The C-beam was used as the new system to test the voltage and amplitude control strategies with – it has a weak nonlinearity due to frictional damping

Linear and Nonlinear Tests

- Linear tests were first carried out on the C-beam where the hammer FRF demonstrated a resonant peak at the out-of-plane, in phase bending mode at 352.4 Hz
- Linear and nonlinear stepped sine tests (stepped down) were conducted - the C-beam demonstrated a weak softening nonlinearity as the resonant peak shifted to the left at increasing excitation levels

Mode of interest

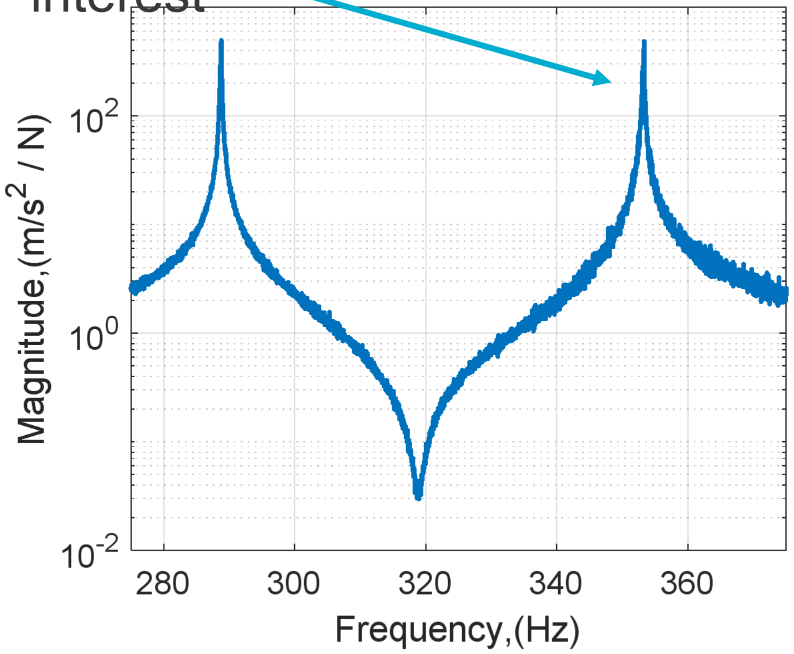

Fig. 12: Impact hammer test FRFs of the 1st and 2nd modes

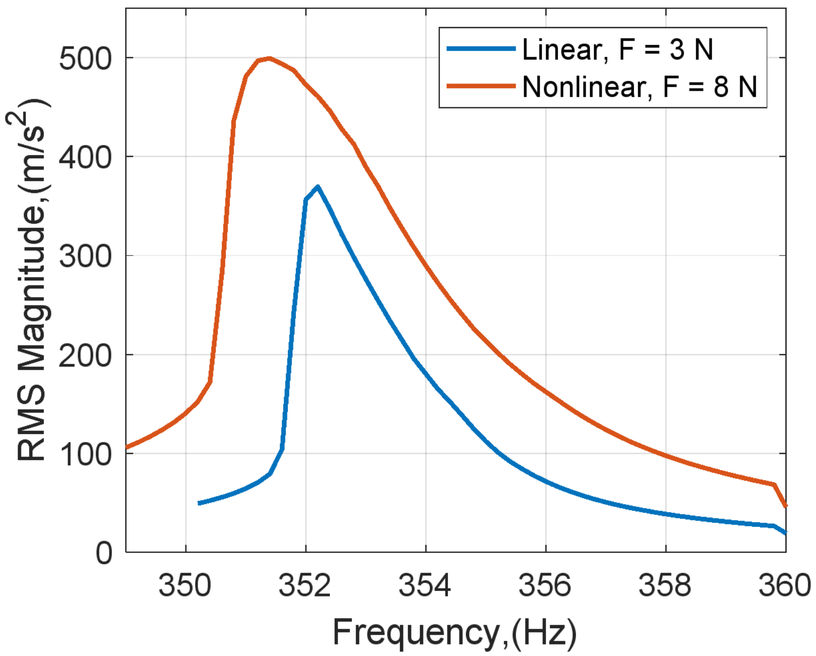

Fig. 13: Softening effect of the nonlinear stepped sine test on the C-beam

The force, amplitude, and frequency range of the softening nonlinearity was established so the amplitude and voltage control test strategies can be applied

Voltage and Amplitude Control Tests

- Unlike the voltage and amplitude control tests on the fixture-pylon assembly, the two test strategies were able to continue through the turning points, avoiding jumps, and thus obtaining the unstable solutions of the system
- The weak friction type nonlinearity behaved as expected, similar to the applications found in literature [6, 7]

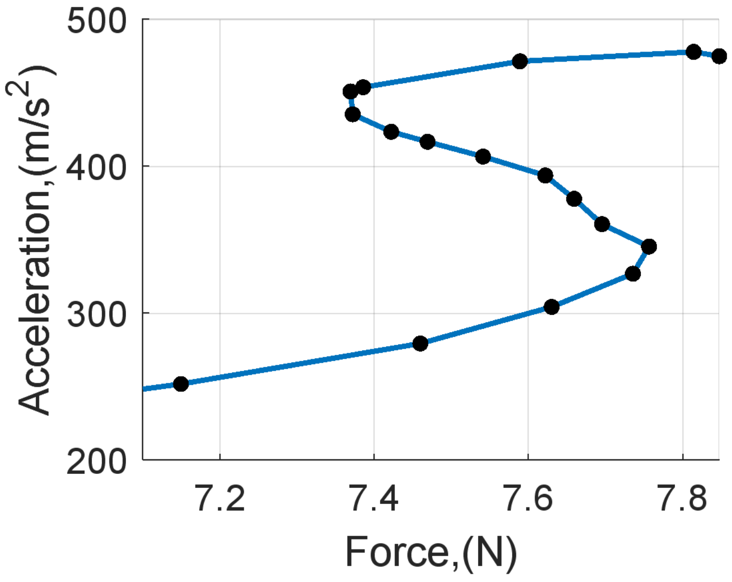

Fig. 14: Multivalued response curve at 351 Hz from voltage control test

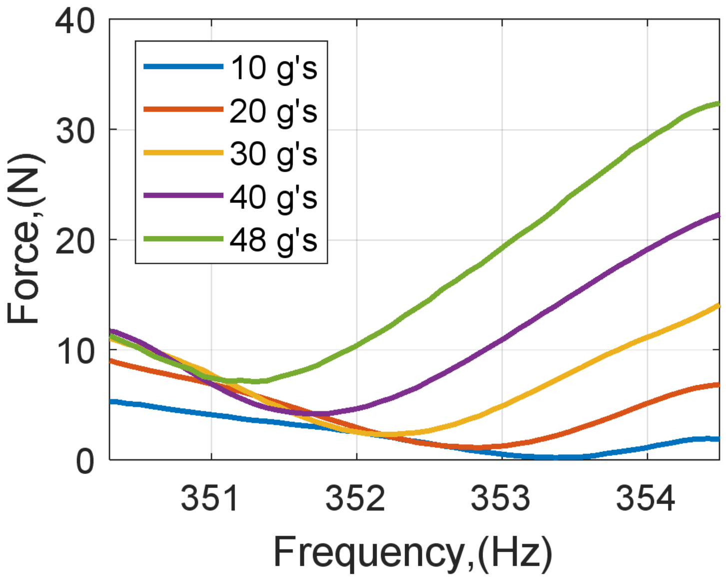

Fig. 15: Force dropout response curves from amplitude control tests

The voltage and amplitude control tests were effective on the C-beam as the unstable solutions were realized

V. Conclusions

Conclusions

Conclusions

- Stingers of different lengths and material had a significant affect on the system-shaker modes, damping, and quality of force and amplitude control during shaker tests
- Force control stepped sine testing on the fixture-pylon assembly revealed a strong hardening response resulting in jump downs
- Voltage and amplitude control tests on the fixture-pylon assembly resulted in jump downs suggesting the nonlinearity may have been too strong for the applied test-strategies
- The voltage and amplitude control test on the C-beam demonstrated multivalued responses consistent with literature
- More research needs to be conducted on the fixture and pylon assembly to obtain the multivalued response curves

THANK YOU

References

[1] E. Robbins, et al., “Pre-test Predictions of Next-Level Assembly using Calibrated Nonlinear Subcomponent Model”, presented at the 39th International Modal Analysis Conference (IMAC), February 2021.

[2] Gaëtan Kerschen, Keith Worden, Alexander F. Vakakis, Jean-Claude Golinval,"Past, present and future of nonlinear system identification in structural dynamics", Mechanical Systems and Signal Processing, Volume 20, Issue 3, 2006, Pages 505-592, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2005.04.008.

[3] J.P. Noël, G. Kerschen, “Nonlinear system identification in structural dynamics: 10 more years of progress”, Mechanical Systems and Signal Processing, Volume 83, 2017, Pages 2-35, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2016.07.020.

[4] Thomas G. Carne, D. Todd Griffith, Miguel E. Casias,“Support conditions for experimental modal analysis”, Sound and Vibration, 2007, 41. 10-16

[5] Wolf, J., “The influence of mounting stiffness on frequencies measured in a vibration test”, SAE Technical Paper 840480, 1984, https://doi.org/10.4271/840480

[6] Taylan Karaağaçlı, H. Nevzat Özgüven, "Experimental modal analysis of nonlinear systems by using response-controlled stepped-sine testing", Mechanical Systems and Signal Processing, Volume 146, 2021, 107023, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2020.107023.

[7] Genbei Zhang, Chaoping Zang, Michael I. Friswell, "Measurement of multivalued response curves of a strongly nonlinear system by exploiting exciter dynamics", Mechanical Systems and Signal Processing, Volume 140,2020, 106474, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2019.106474.

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