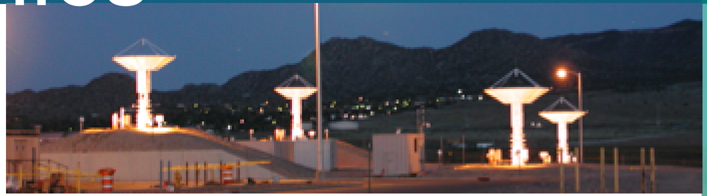
Failing to Fail: Lessons Learned from Attempting to Fatigue a Bolt Using Structural Dynamics



PRESENTED BY

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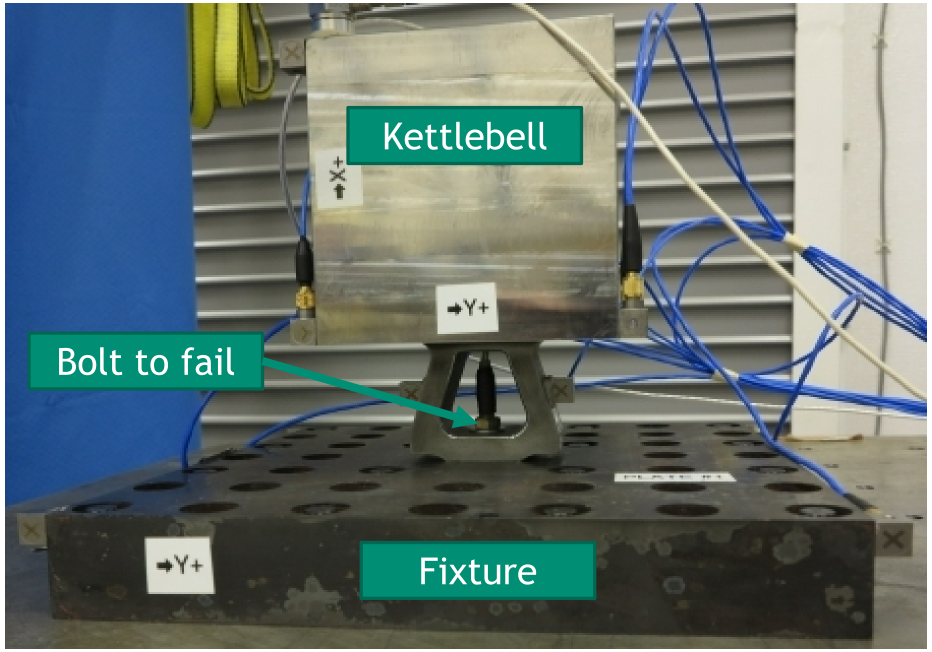
Motivation

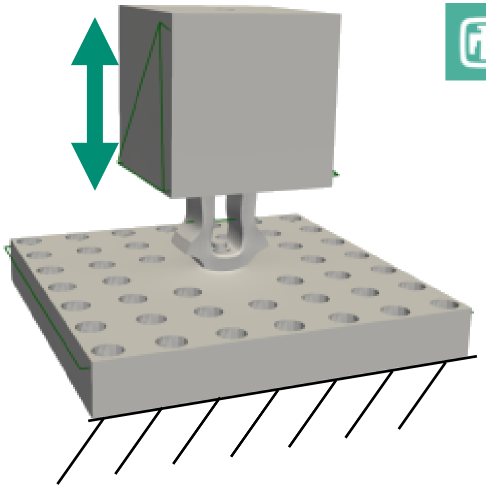
- Understanding fatigue failure of bolts within joints in various dynamic environments is an important aspect in the design of jointed structures
  - Fatigue life data of isolated bolts does exist
  - Predicting fatigue failure in the context of a joint under extreme dynamic loading present additional challenges
- This work is part of a larger project which evaluates how well a linear finite element model (FEM) is able to predict fatigue failure within a joint
  - Preliminary testing and modelling are presented in [1] and [2]



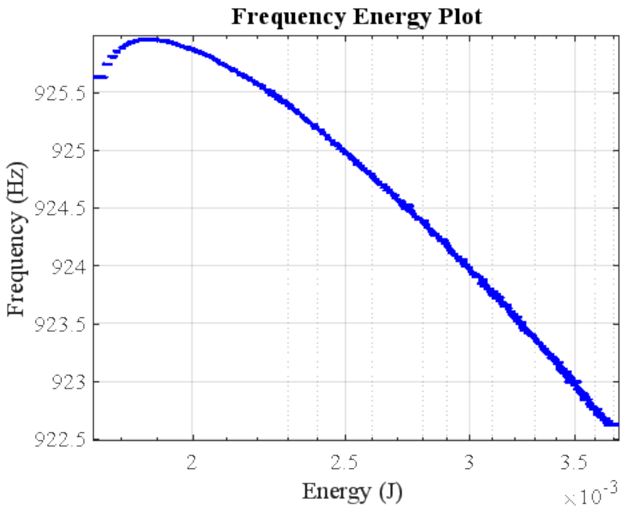
- **This presentation is focused on the development of the fatigue test and corresponding results**

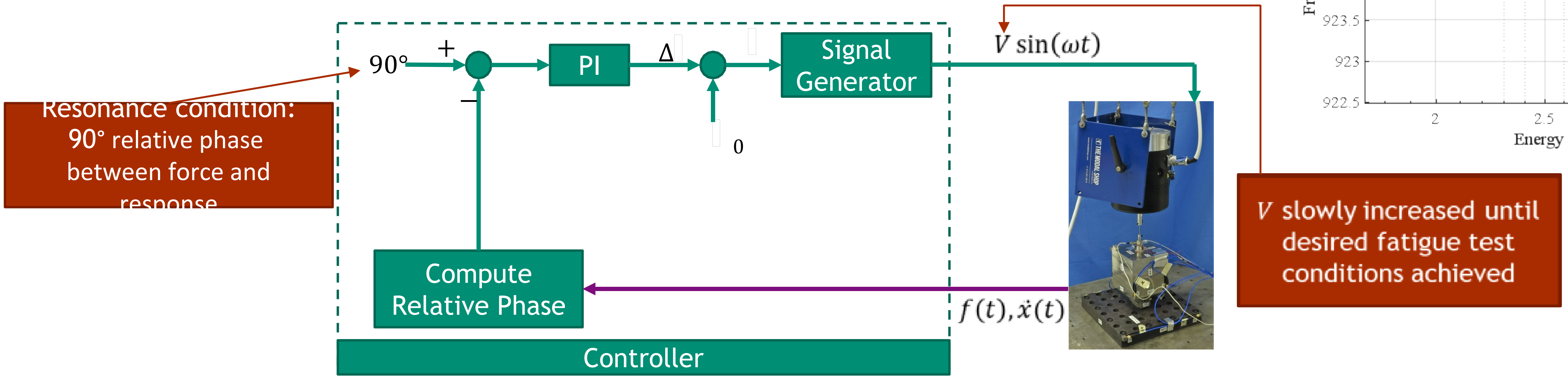
[1] Khan, M. et al "Evaluation of Joint Modeling Techniques Using Calibration and Fatigue Assessment of a Bolted Structure," *Proceedings of the 39th International Modal Analysis Conference*, virtual, 2020
[2] Submission 12411 "Nonlinear Characterization of Joint Exhibiting a Reduction in Damping at Higher Energy", Session 54 Jointed Structures II

Initial Test Approach

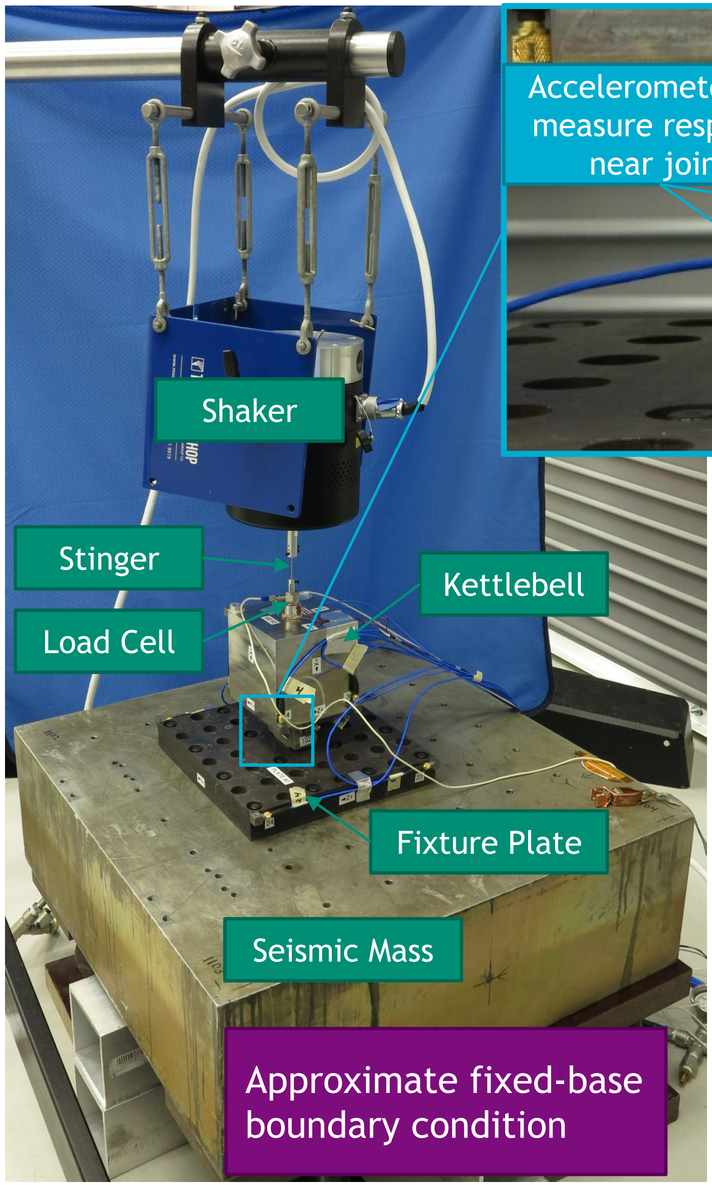


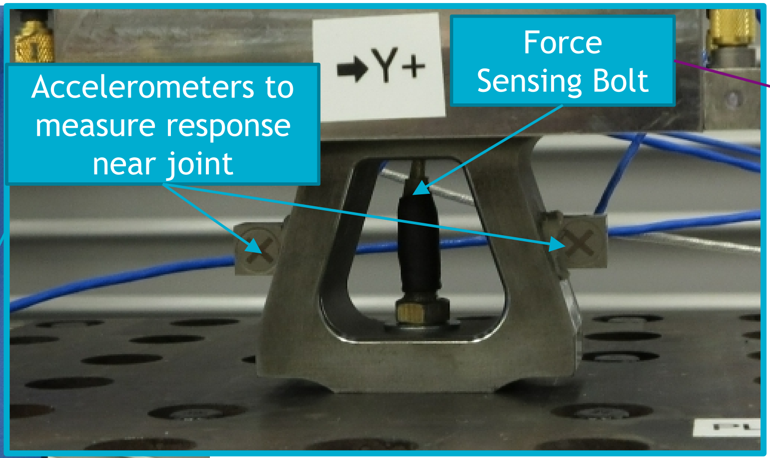
- **Objective**: design and conduct an in-situ fatigue test to fail a bolt within a joint using a dynamic environment
- **Approach:** dwell at the axial mode of the structure until the bolt fails
  - The response of the Kettlebell loads the bolt axially
    - Literature review indicated this would be the easier failure mode
- Since the structure is nonlinear, a closed loop controller is used to maintain resonance throughout testing
- **This test method is called nonlinear force appropriation (NFA)**





Test Set Up and Predicted Failure Conditions



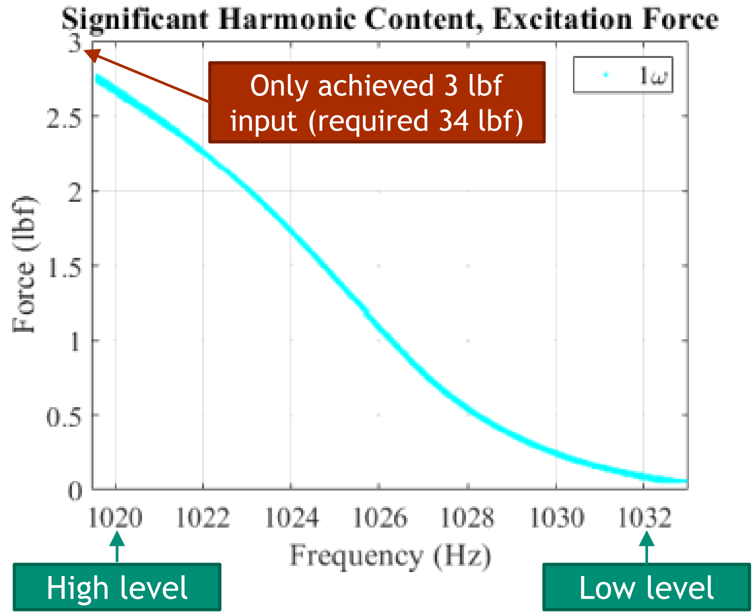


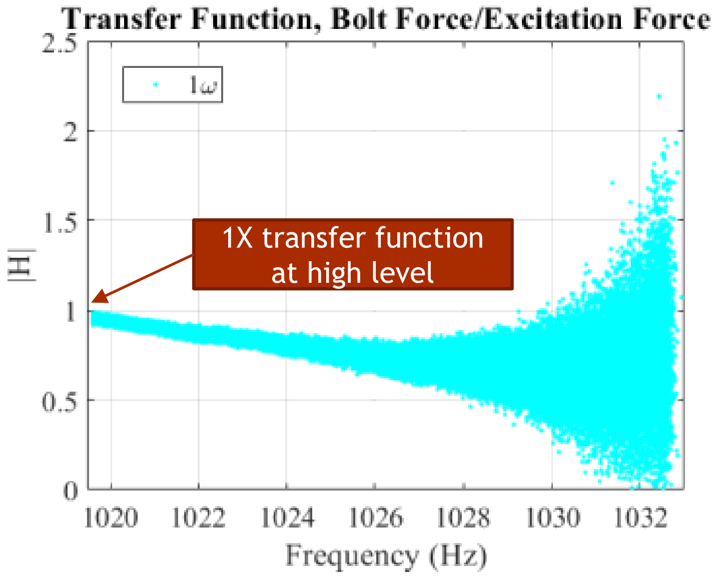
Monitor the force in the bolt during assembly and testing

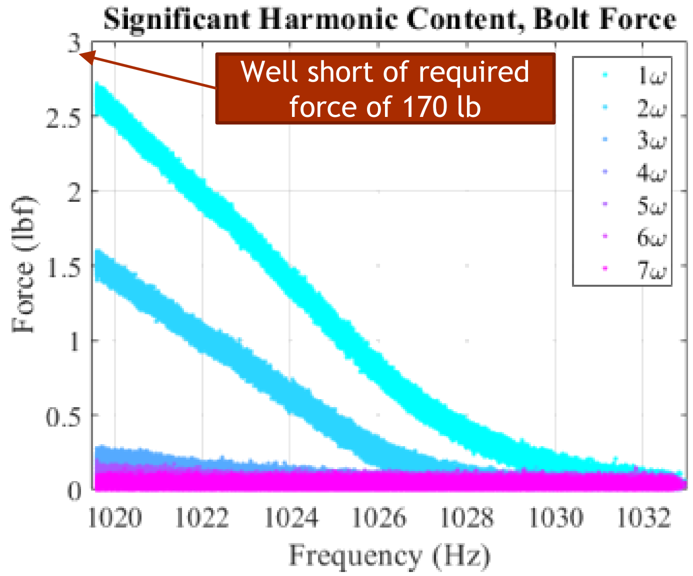
- **Predicted bolt force for fatigue failure = 170 lbf**
- Guiding metrics:
  - Excite only the axial mode
  - 5X amplification from excitation force to bolt force
  - 34 lbf excitation force to top of Kettlebell
- This proved to be a challenging set of requirements, as four different attempts were performed

Attempt #1—Fully Torqued Bolt

- NFA was conducted on the structure where the bolt had a preload of 2,100 lbf.
- During testing, the electrical limit of the shaker amplifier was reached prior to providing sufficient load to fail the bolt in fatigue



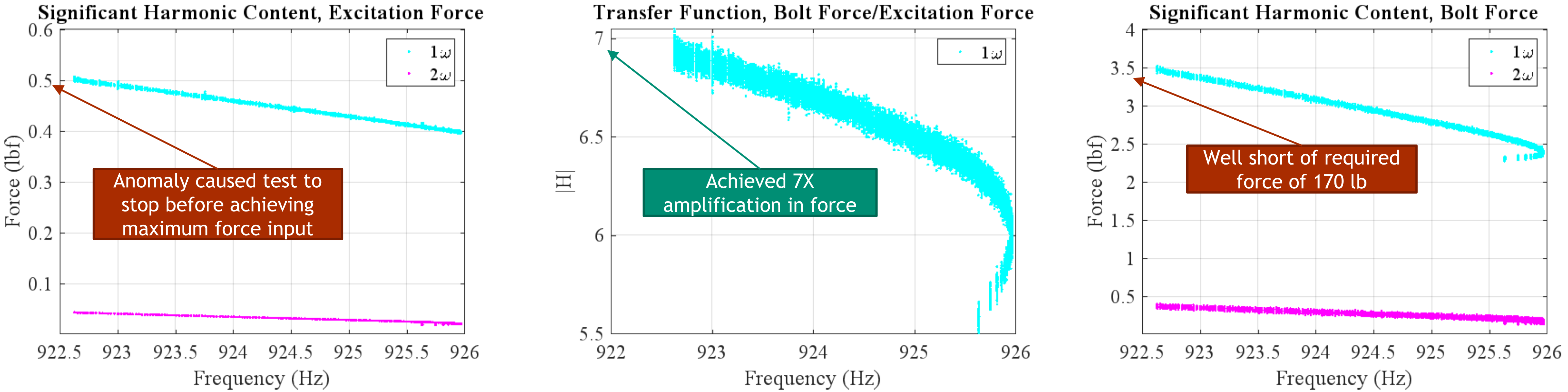




Too much of the joint force was carried by the Kettlebell and Fixture material at the interface. Therefore, **the torque was greatly reduced so that the bolt would take more of the load.**

Attempt #2—Reduced Torque

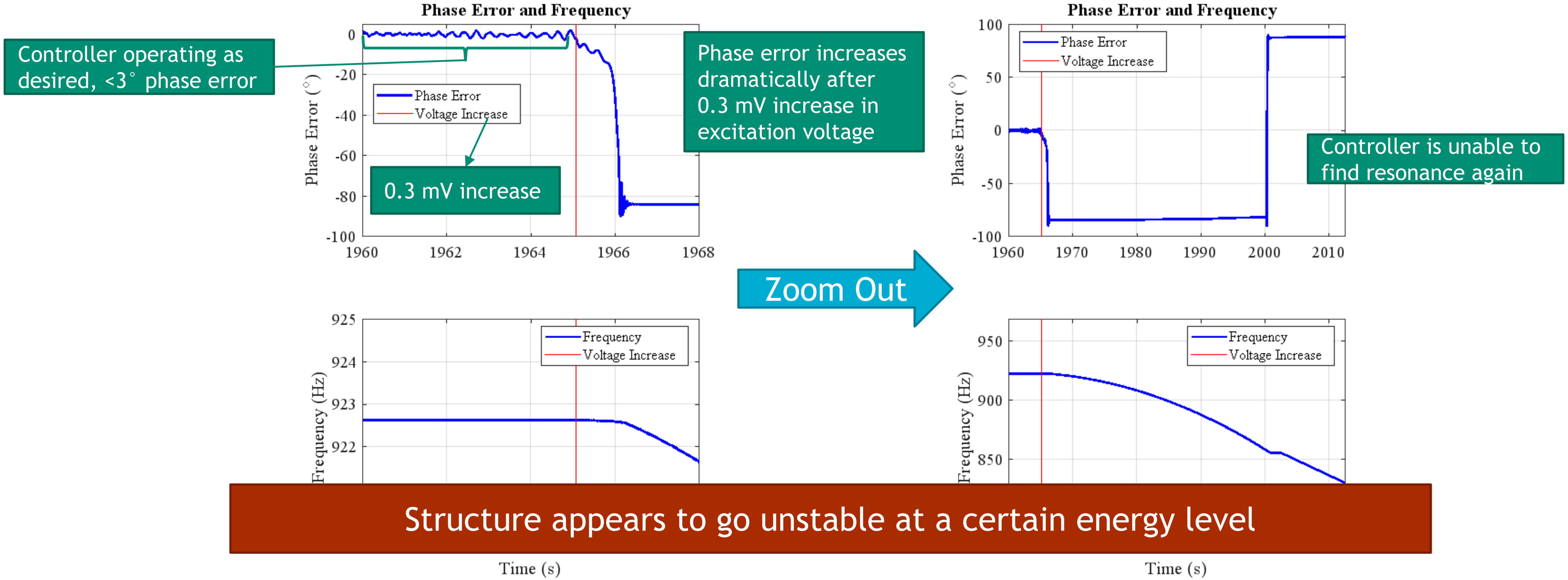
- The Kettlebell bolt force at assembly was reduced from 2,100 lbf to about 250 lbf
  - This reduced force should quicken the onset of the preload loss of the joint, resulting in larger bolt forces



These results were promising, but an anomaly stopped the test before the desired fatigue conditions could be met. WHAT HAPPENED?!

Attempt #2—Reduced Torque, NFA Results

- During the NFA, a threshold was reached where:
  - There was a noticeable change in the dynamics
  - The controller could no longer maintain the structure at resonance
- Many additional NFAs were conducted and a similar event happened every time

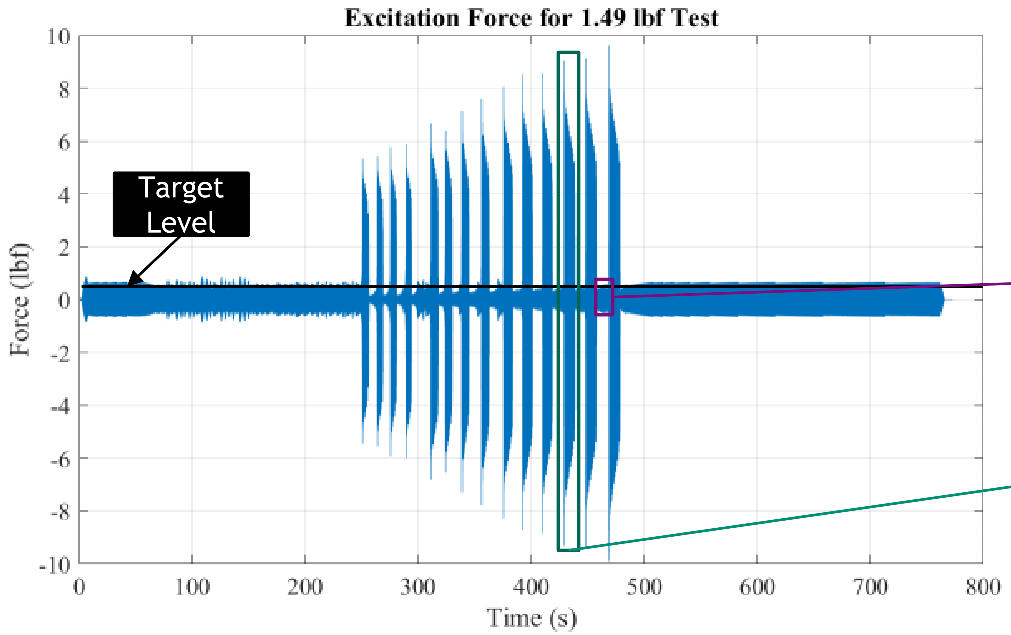


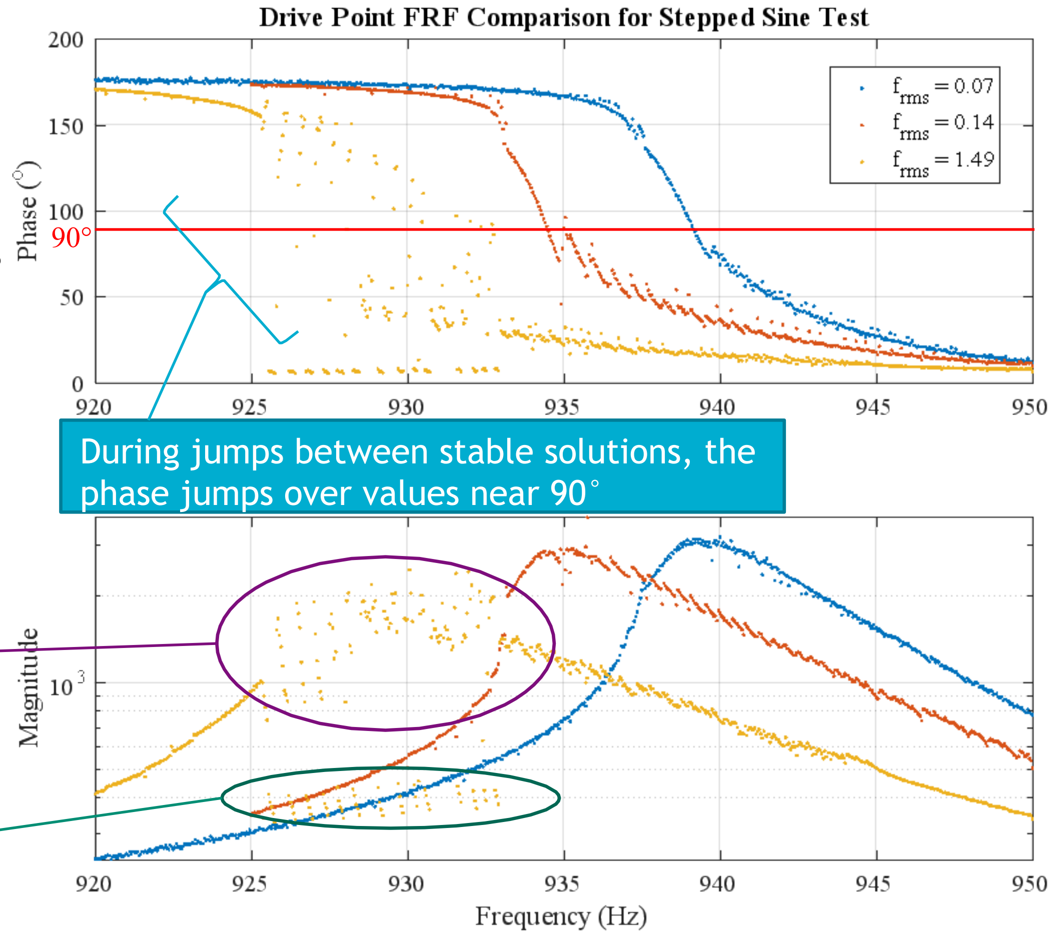
Structure appears to go unstable at a certain energy level

Attempt #2—Reduced Torque, Stepped Sine Results

- To help diagnose the NFA test results, force controlled stepped sine tests were conducted at different force levels

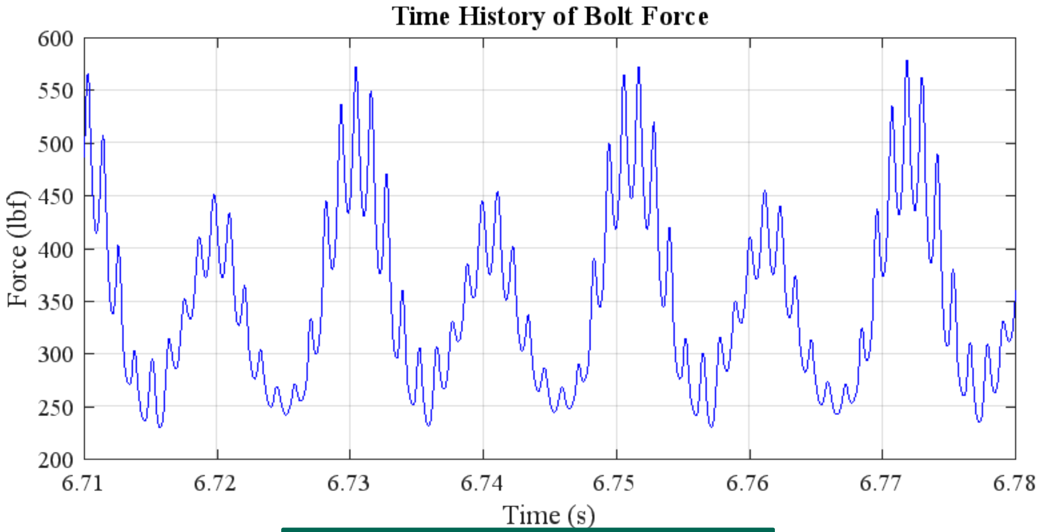
- At high forcing, there appeared to be stability issues as the system vacillated between two different states



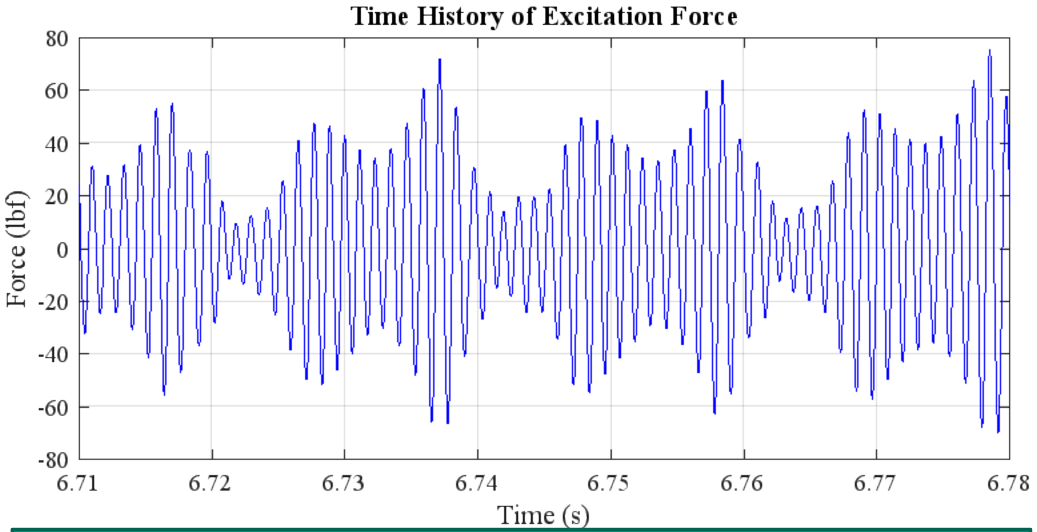


Attempt #3—Ad Hoc Method

- The Attempt #2 results demonstrated that **the current implementation of NFA was not a viable option** to conduct the fatigue test and **was thus abandoned**
- There was a hope that the instability was only present for a limited voltage range
- **Through a series ad hoc sinusoidal testing** at different voltage levels and frequencies near 900 Hz, **the desired conditions were met**



Cyclic bolt force ≈ 300 lbf

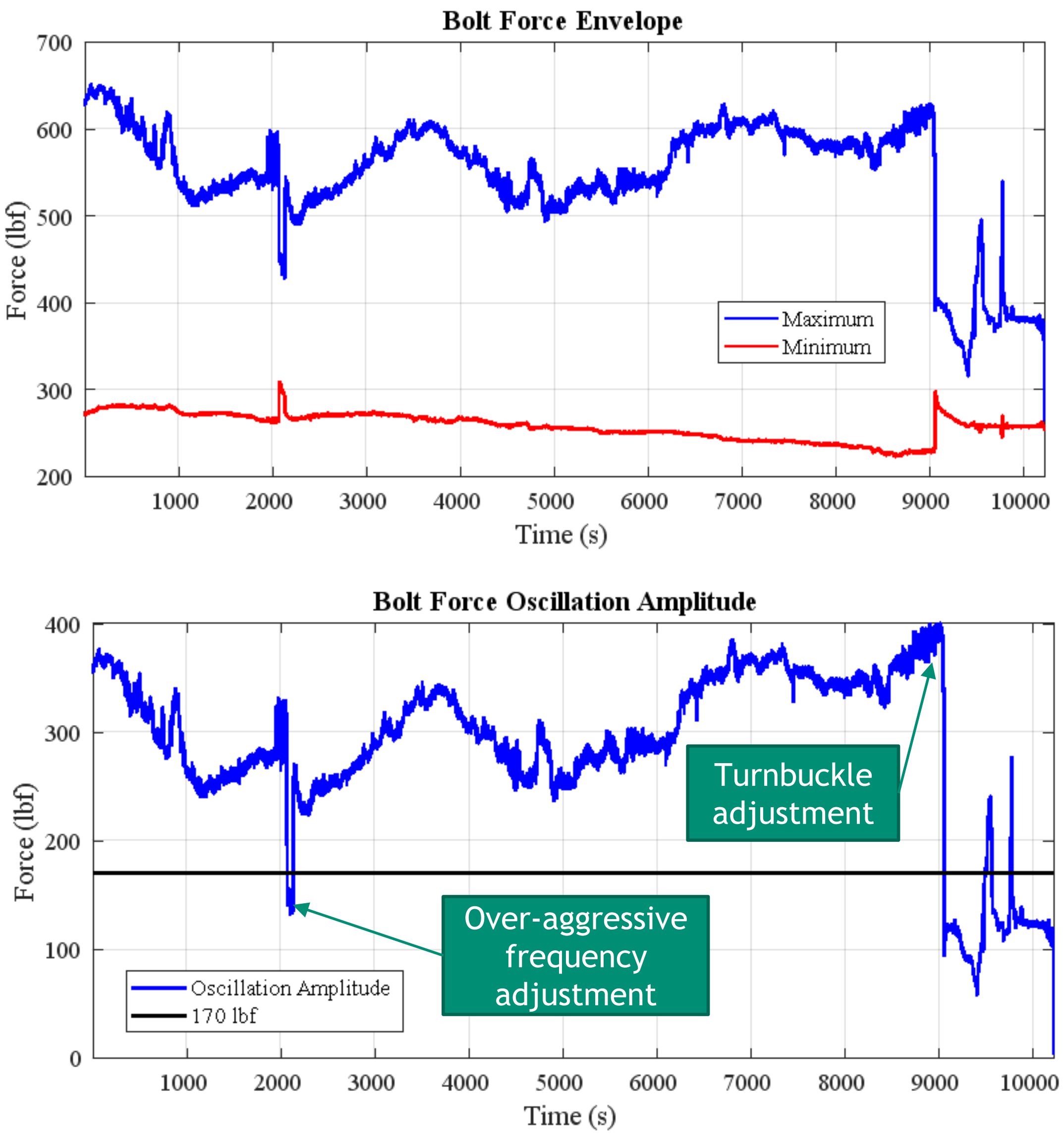


Shaker force remains below 100 lbf (manufacturer's limit)

- **Attempt #3 employed this ad-hoc test method**
  - Target cycle count = 10 million cycles of the excitation frequency

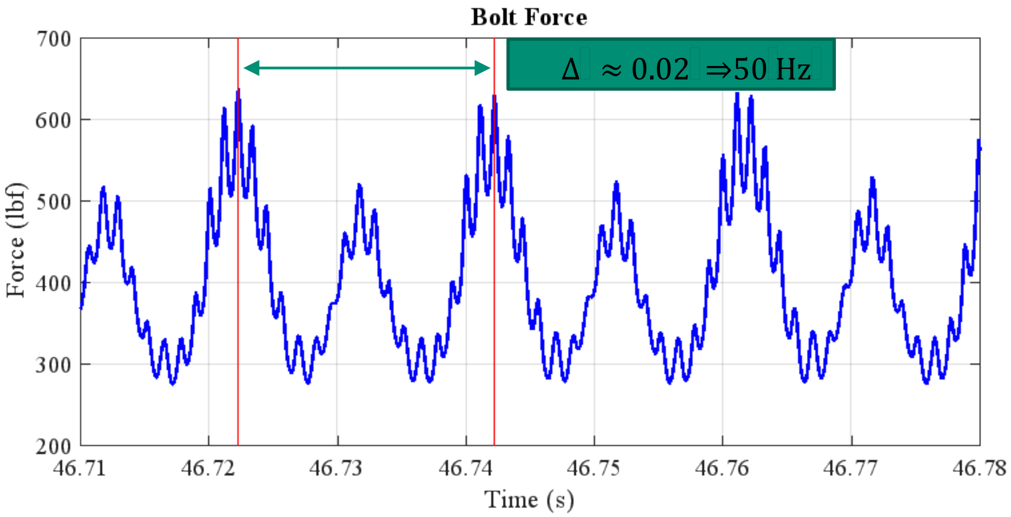
Attempt #3—Ad Hoc Method, Fatigue Test Results

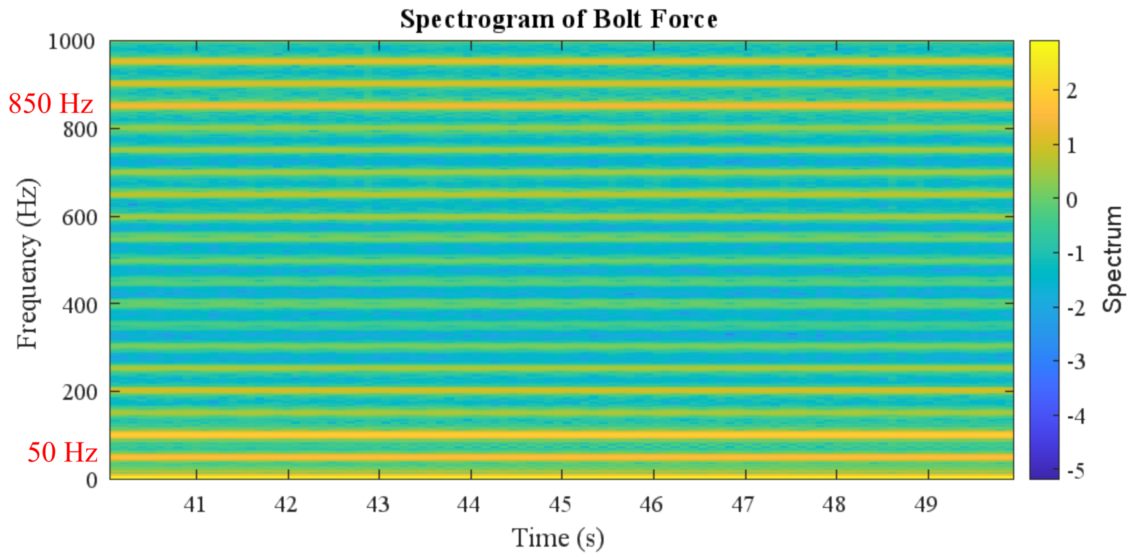
- **The bolt did <u>not</u> fail during this test**
- Peak-to-peak bolt force > 170 lbf
  - Dip near 2000 s = over-aggressive frequency adjustment to maximize bolt force
- Just after 9000 s, a slight adjustment of the shaker suspension resulted in an unrecoverable change in the dynamics
  - One of the turnbuckles supporting the shaker was vibrating/rattling so it was slightly adjusted with unfortunate consequences



Attempt #3—Ad Hoc Method, Why Did the Bolt Not Fail?

- **Potential Reason #1: insufficient loading cycles**
  - Peak-to-peak bolt force amplitude occurred at 50 Hz, not at the excitation frequency of 850 Hz
  - Cycle count for 9000 s
    - 850 Hz × 9000s = 7.65 million cycles
    - 50 Hz × 9000s = 0.45 million cycles

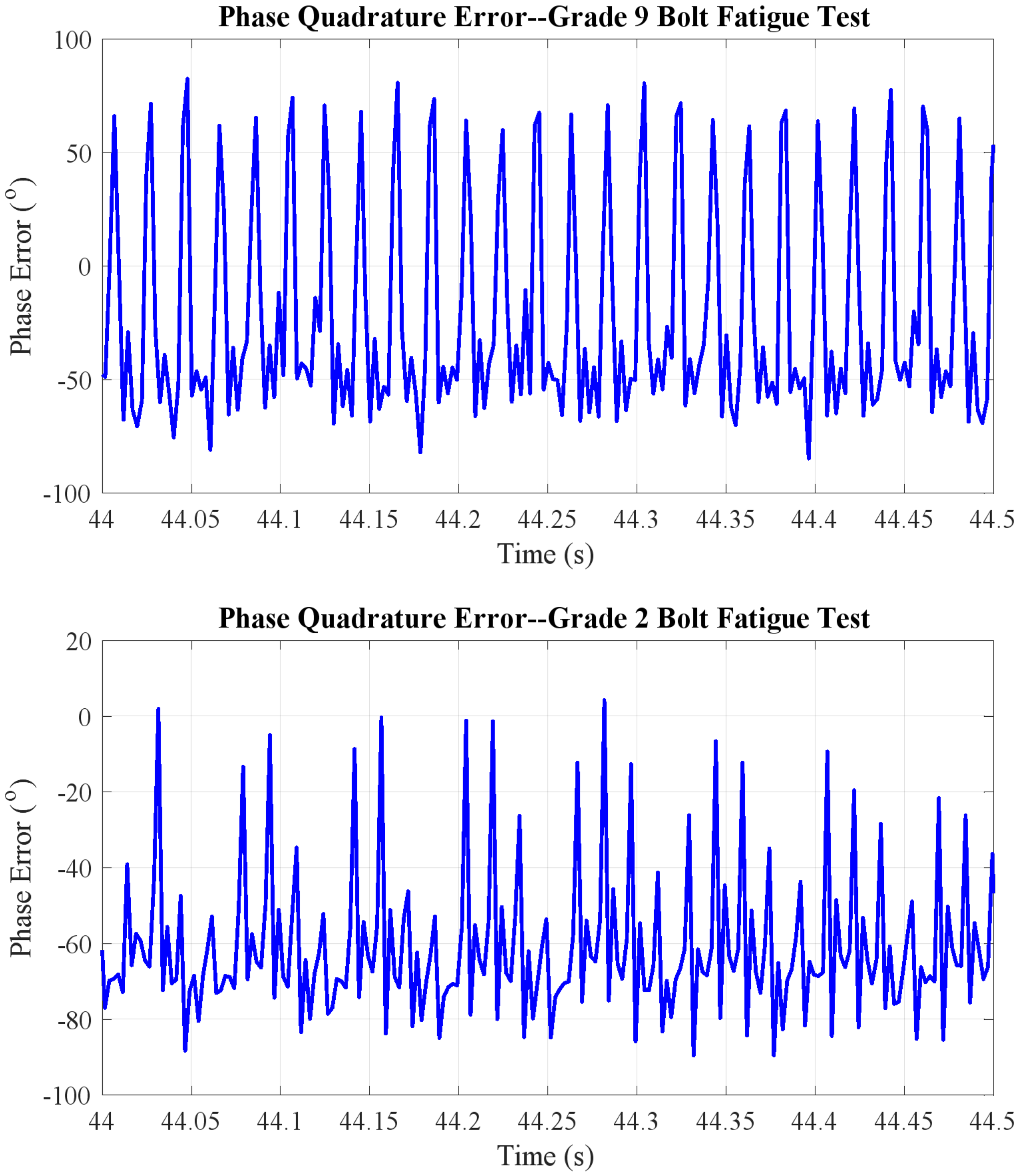




- **Potential Reason #2: tested bolt too tough**
  - The fatigue failure conditions were derived for a Grade 2 bolt, but the force sensing bolt is considered Grade 9

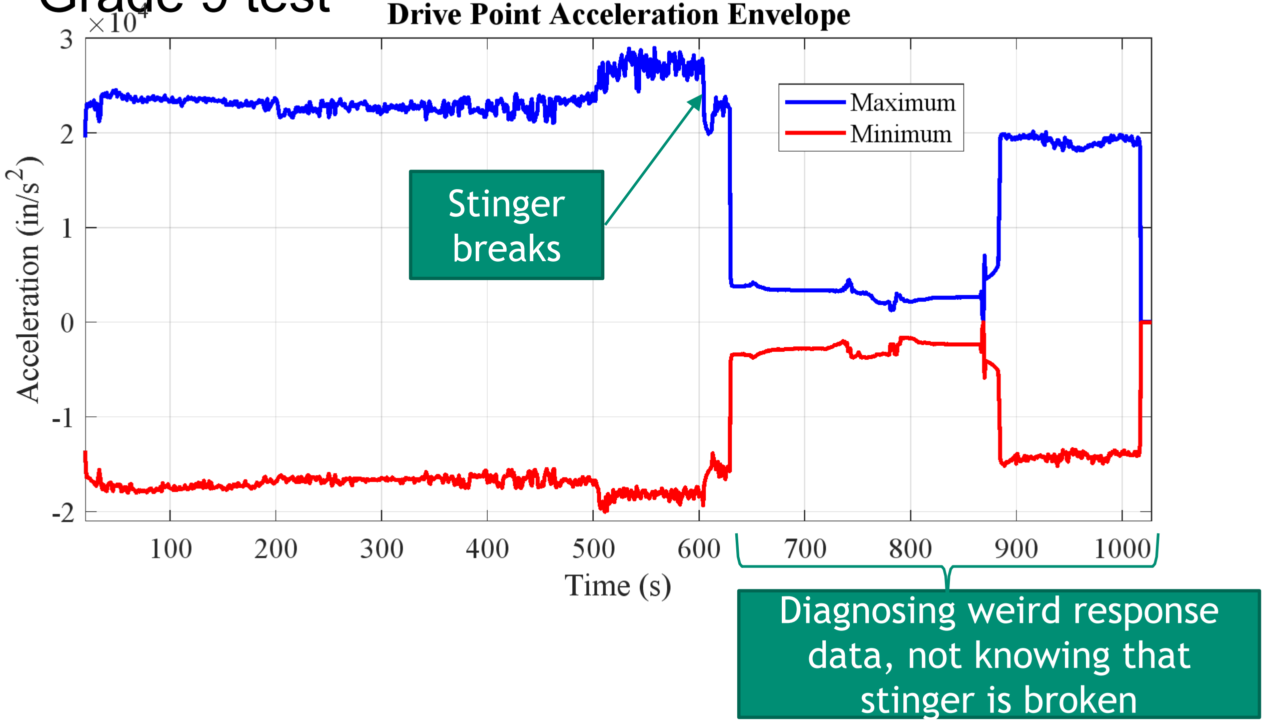
Attempt #4—Ad Hoc Method with Grade 2 Bolt

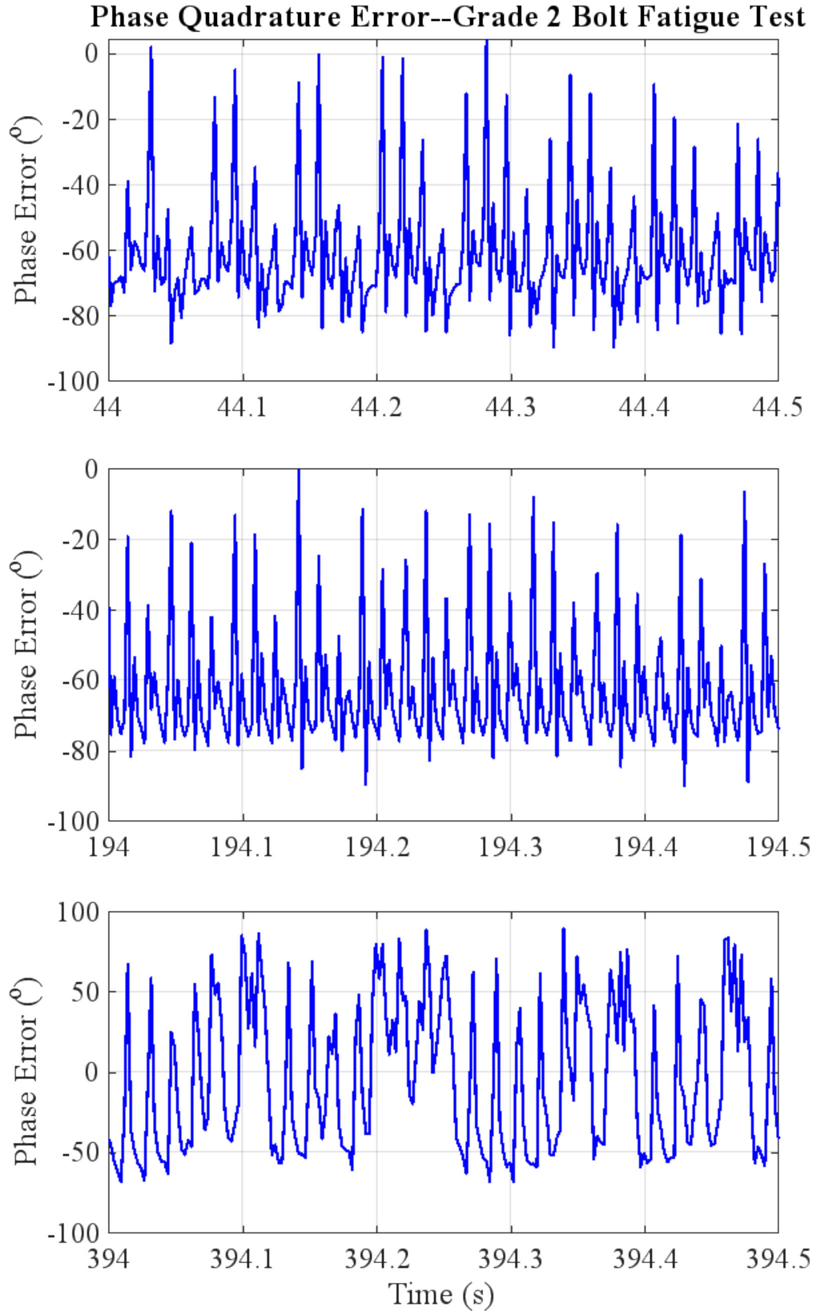
- The fatigue test was repeated with a Grade 2 bolt
- However, this bolt was not instrumented to measure force
  - Could not measure clamping force during assembly
  - Could not monitor bolt force during fatigue test
- Other measurements had to be used to **estimate** if the desired fatigue test conditions were met
  - **Selected metric:** Pattern of the relative phase between excitation force and drive point response
  - This appeared to be the most accurate indicator of the state of the system
- **The test proceeded with a large uncertainty in bolt force**
- **Target cycle count = 1 million cycles of excitation frequency**



Attempt #4—Ad Hoc Method with Grade 2 Bolt, Fatigue Test Results

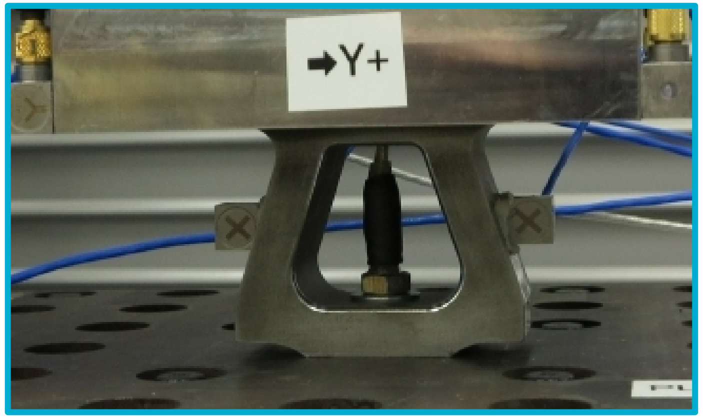
- **The bolt did not fail**
- The stinger failed in fatigue mid-way through the test
  - Stinger was replaced and testing restarted
- Phase quadrature pattern changed throughout testing, some portions not matching that from Grade 9 test

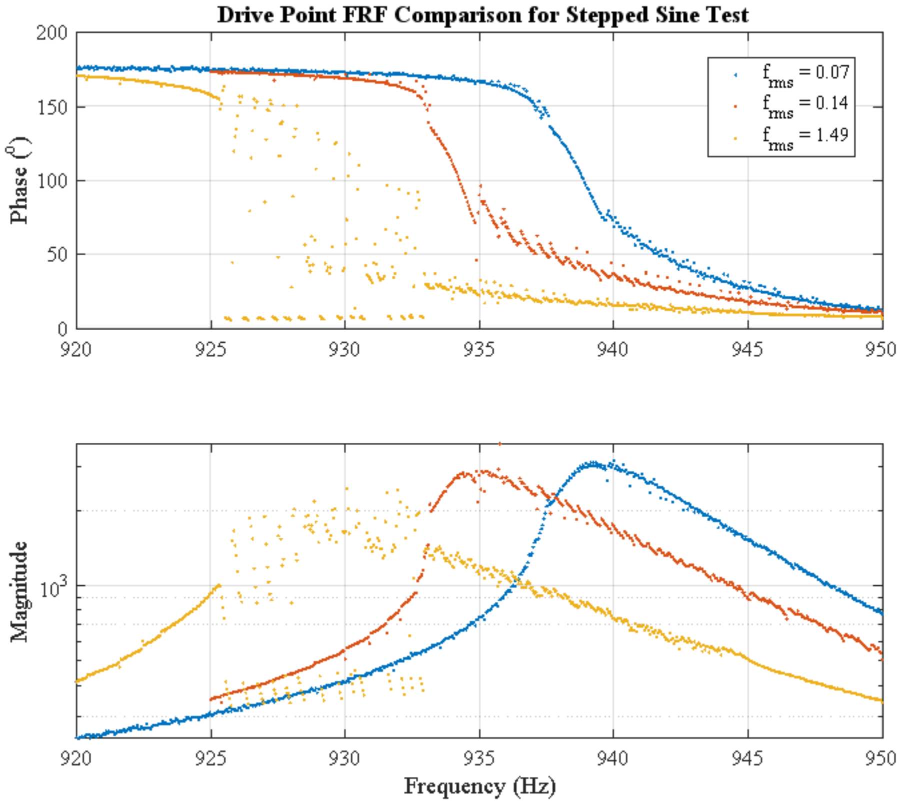


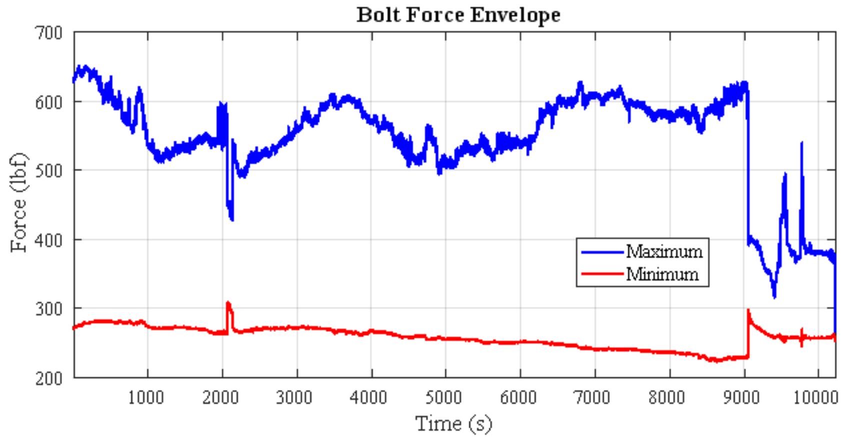


Summary

Attempt	Outcome	Reason
1	Did not fail bolt	Test equipment limitations
2	Did not fail bolt	NFA controller/structure instability
3	Did not fail bolt	Insufficient cycle count or incorrect bolt type
4	Did not fail bolt	Uncertainty in bolt loading







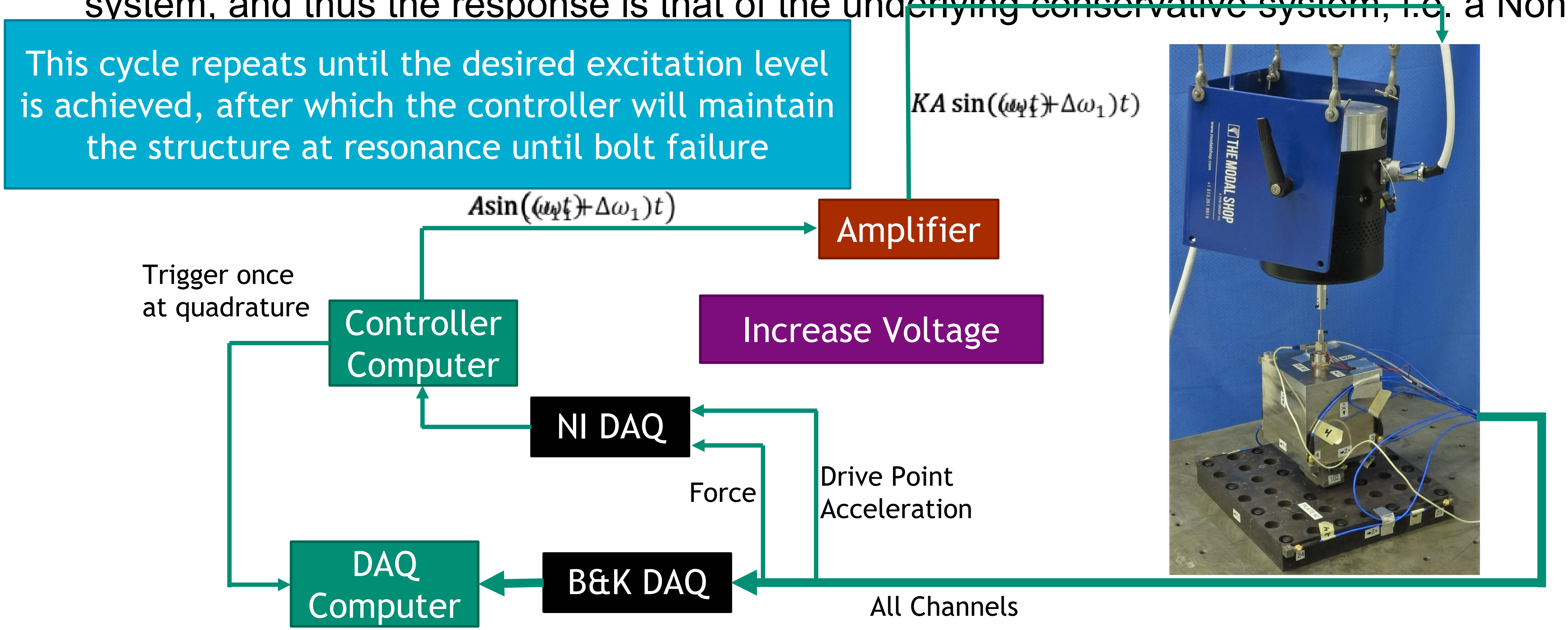
Lessons Learned

- **Lower assembly torque quickened the onset of higher bolt forces**
  - Attempt #1 (fully torqued) vs Attempts #2-4 (reduced torque)
- **An NFA control scheme which is able to stabilize structure is the recommended test method**
  - Conceptually, a stabilizing NFA maintains the structure at resonance, providing large bolt force for less input than ad hoc method
  - Potential Paths Forward
    - Incorporate incommensurate frequencies to the NFA controller
    - Different NFA control scheme (Phase-Locked-Loop or Control Based Continuation)
- **A force-measuring bolt is essential for this type of testing**
  - Attempt 4: large uncertainty in bolt force cast doubt on whether desired test conditions were met
- **A nonlinear model of the joint (even if un-tuned) would have aided in diagnosing testing issues**
  - Example benefits: determine cause of instability during NFA, interpretation of dynamics during fatigue testing

Back Ups

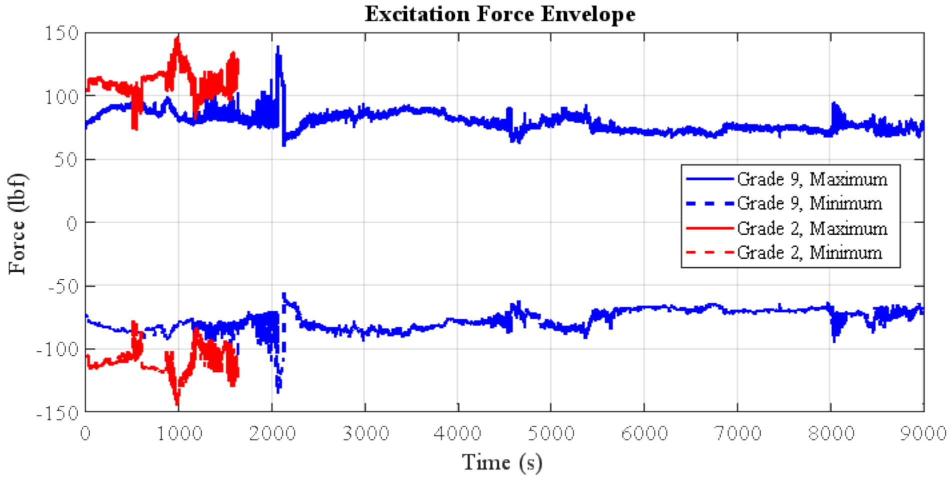
Test Method—Nonlinear Force Appropriation

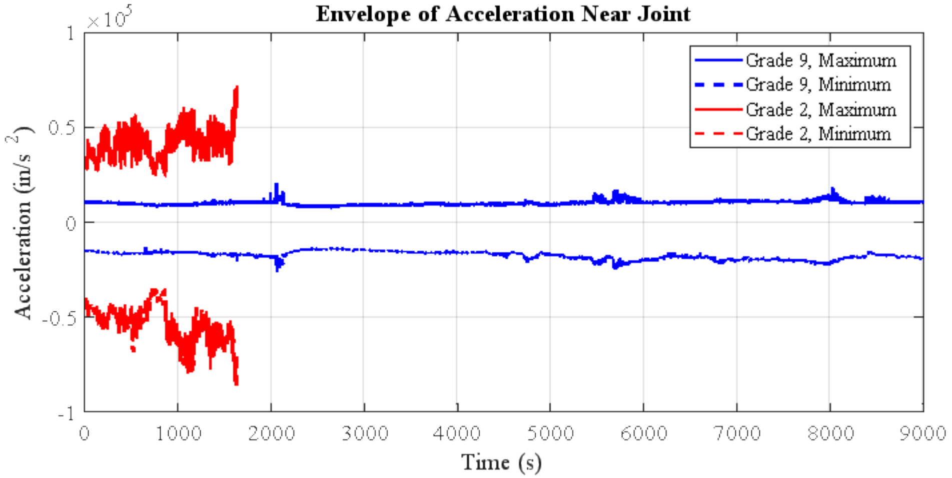
- Nonlinear force appropriation is a method used in nonlinear structural dynamics testing where the excitation is maintained 90° out of phase (i.e. in phase quadrature) with the acceleration response
- Under this phase condition, the excitation is assumed to balance the energy dissipated by the system, and thus the response is that of the underlying conservative system, i.e. a Nonlinear

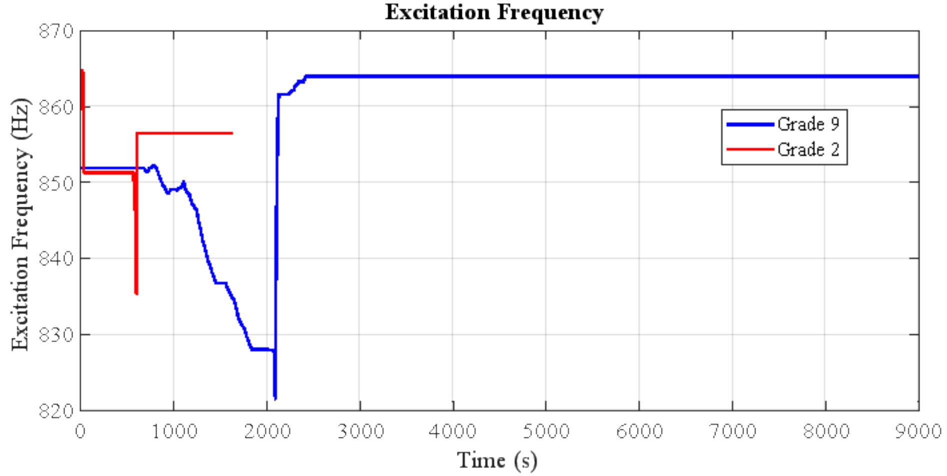


Grade 9 vs Grade 2 Fatigue Test Comparison

- It was unclear whether the desired bolt force was achieved during the Grade 2 fatigue test
- Select data from the two fatigue tests are compared as an additional method of evaluation of the Grade 2 test results



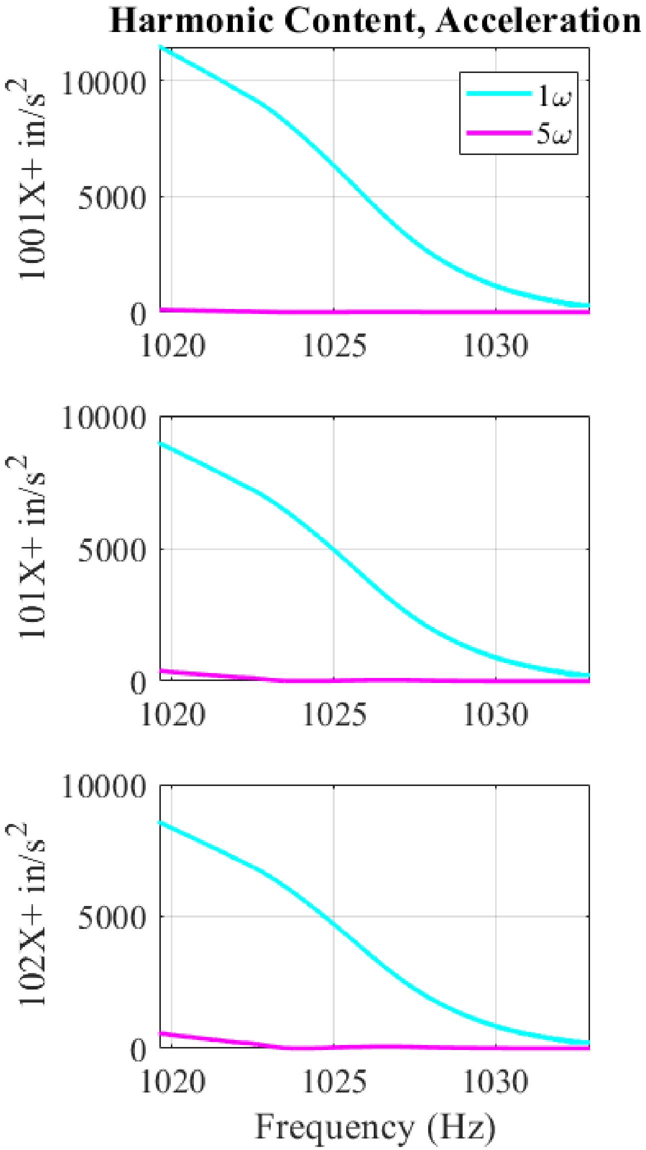


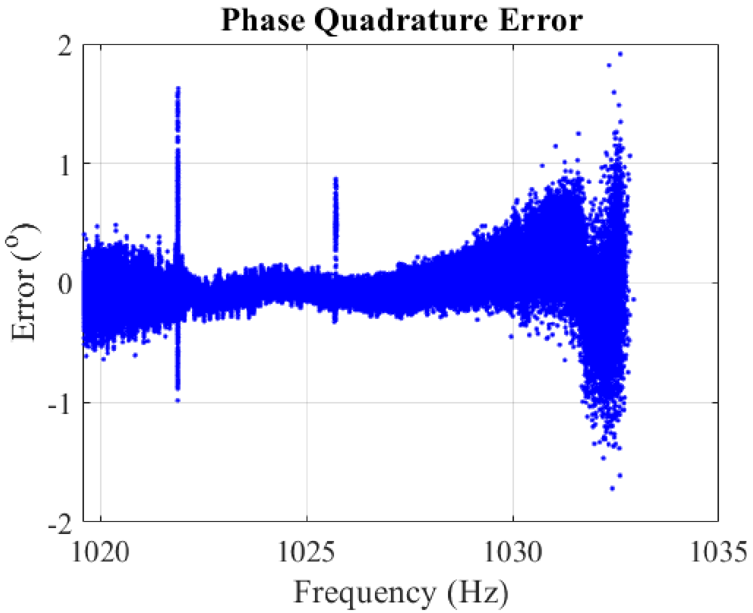


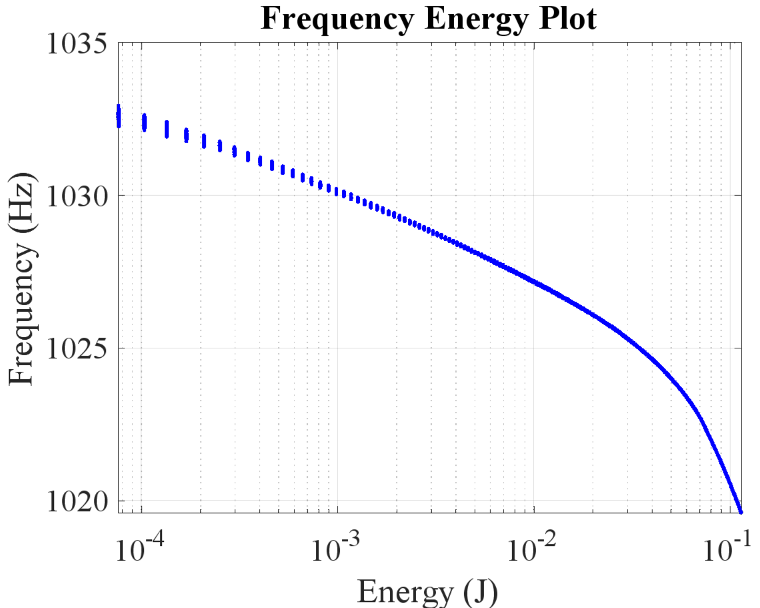
Interpretation 1
Larger acceleration near joint ⇒ **larger bolt forces in Grade 2**

Interpretation 2
Larger acceleration near joint for similar forces ⇒ lower damping ⇒ joint material taking more of the load ⇒ **smaller bolt forces in Grade 2**

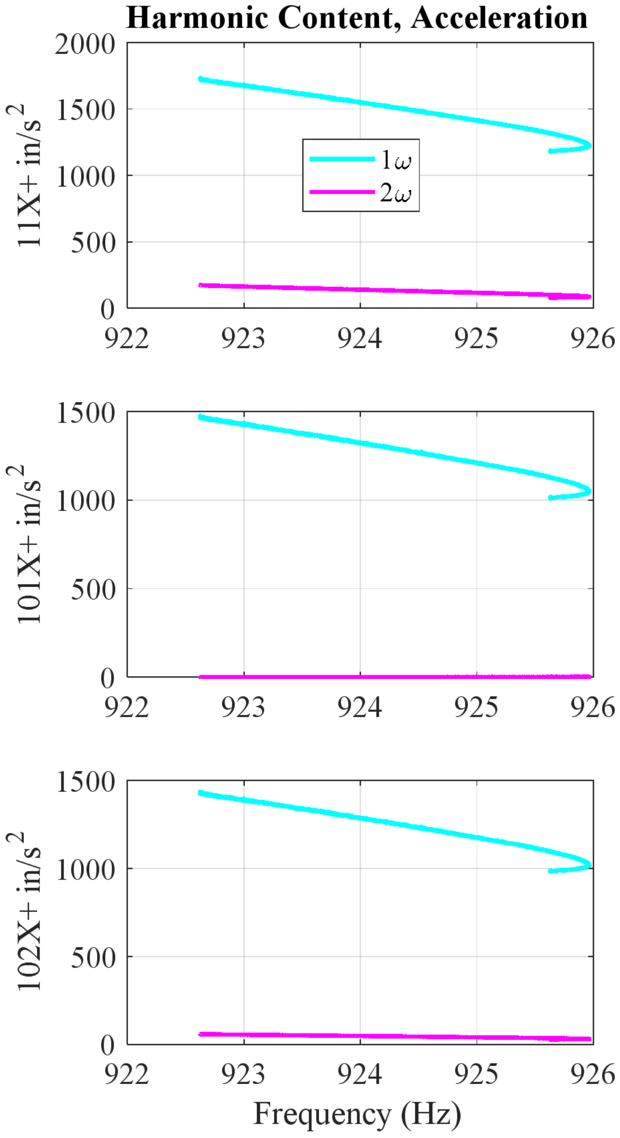
Attempt #1—More NFA Results

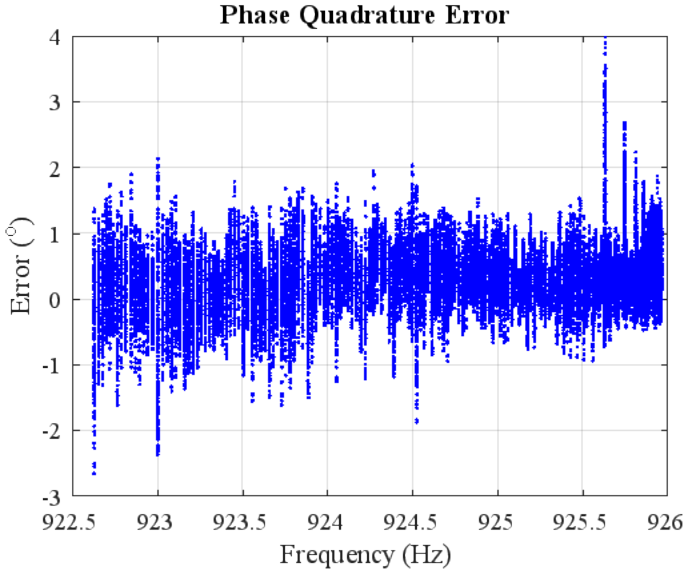


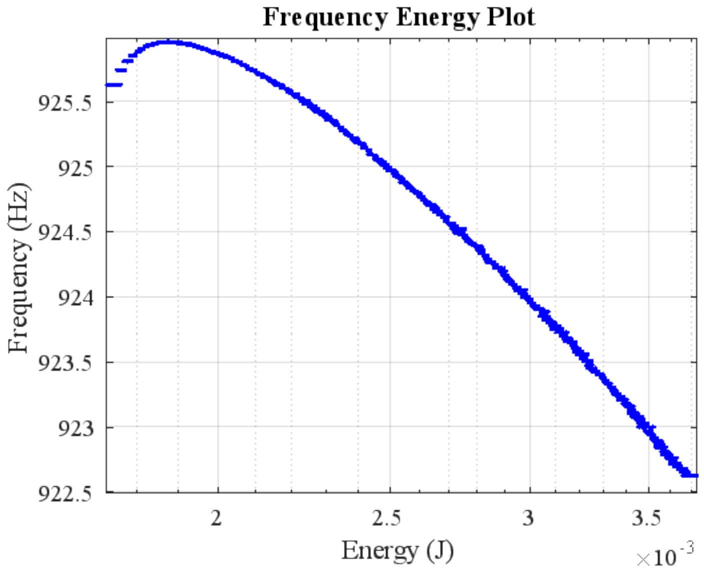




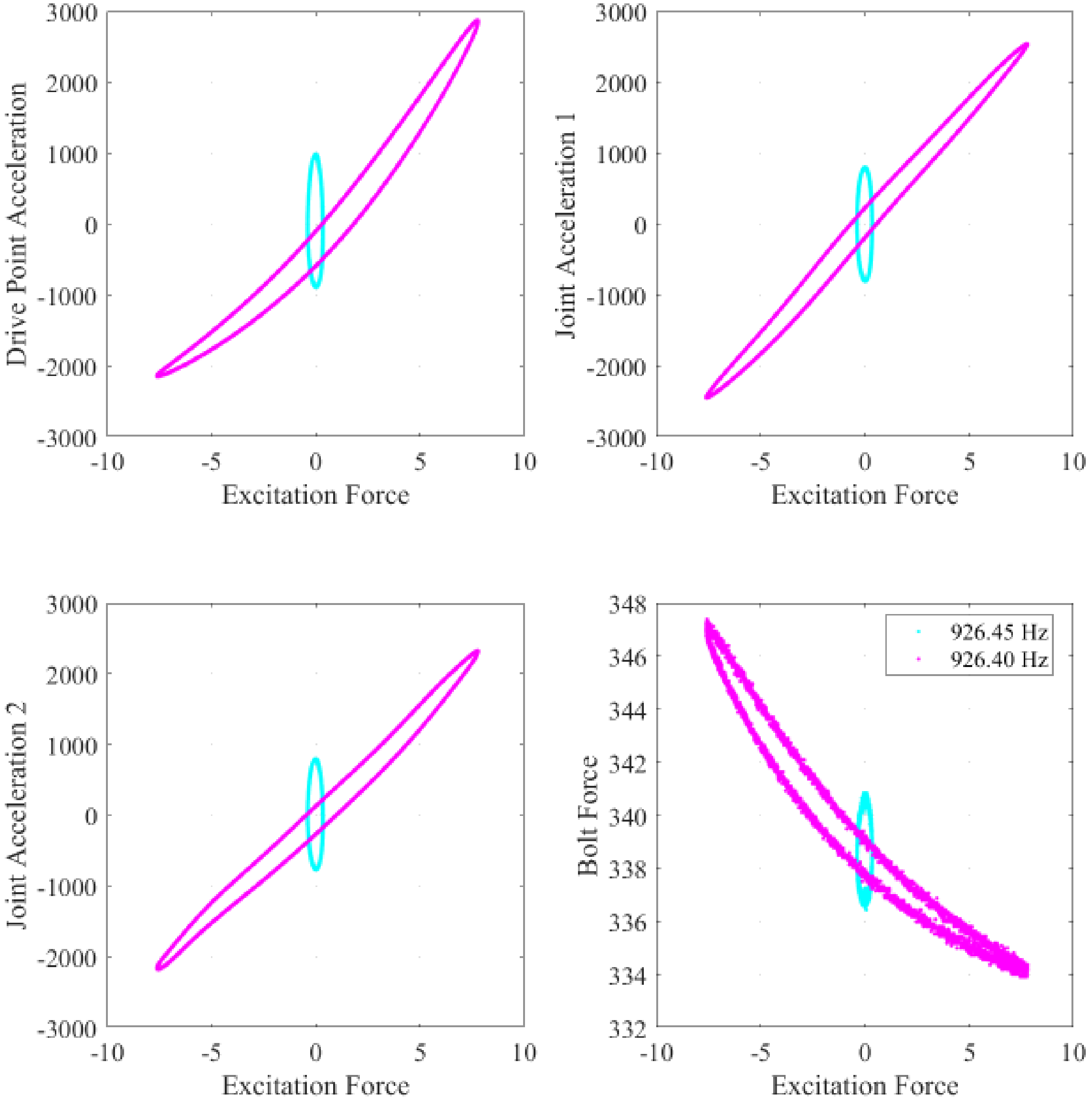
Attempt #2—More NFA Results



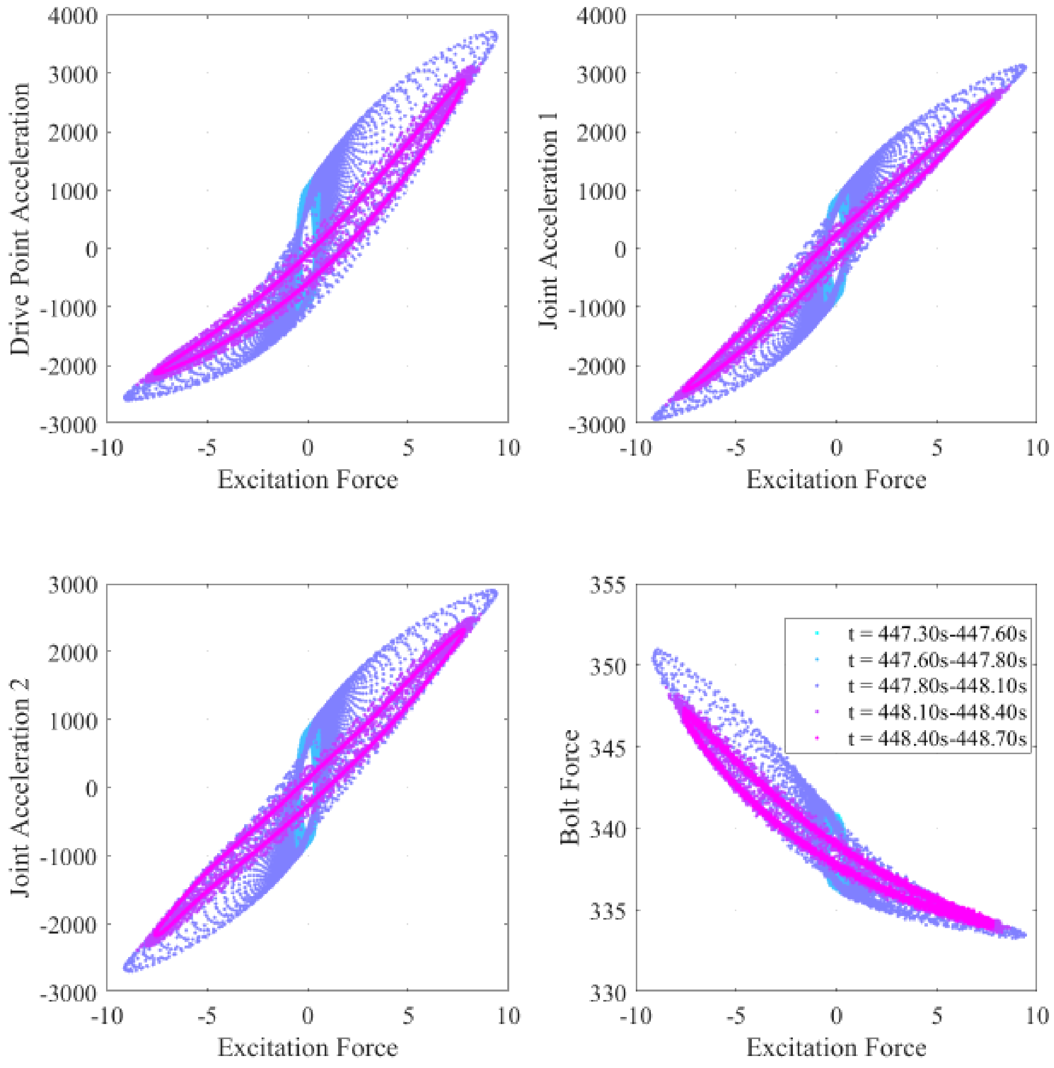


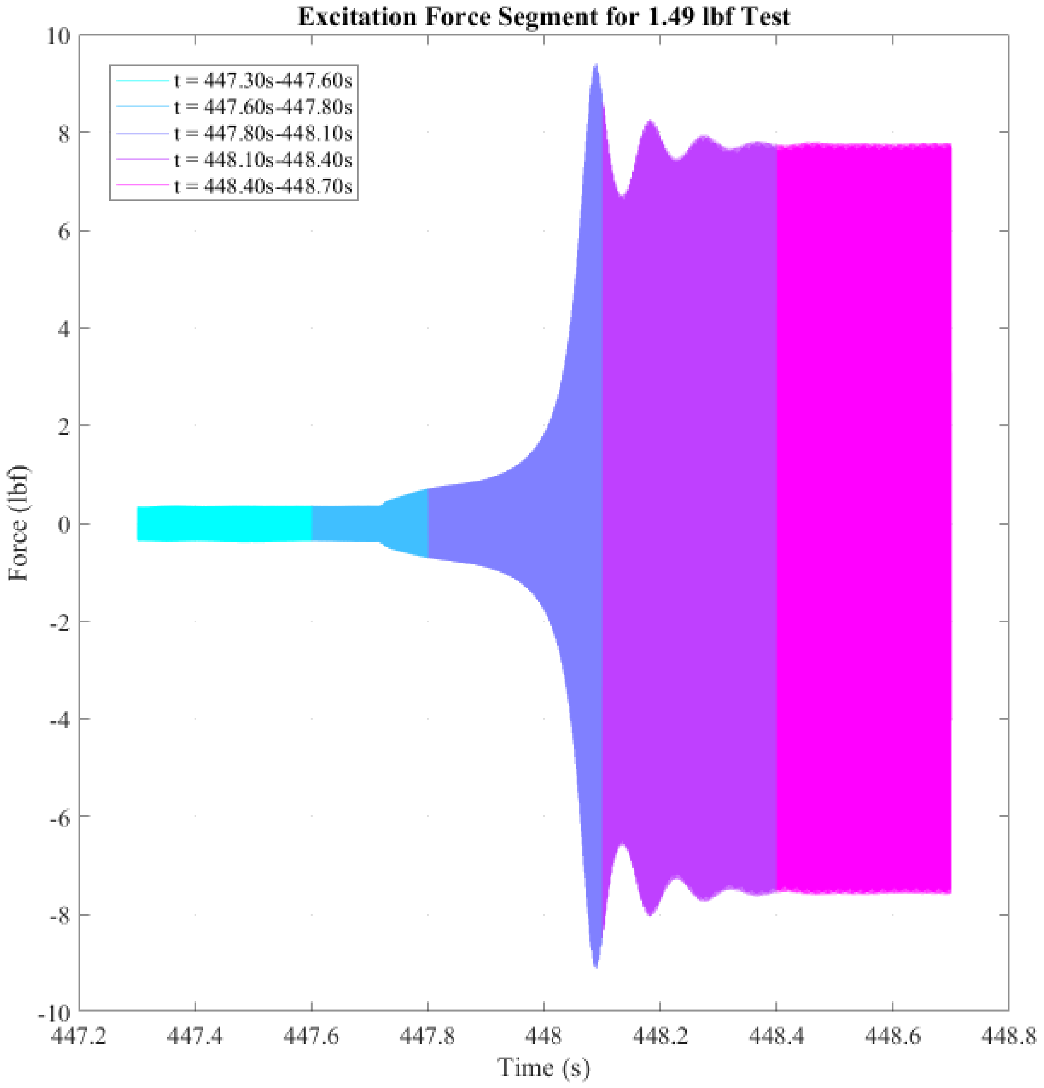


Attempt #2—Reduced Torque, Stepped Sine Results, State Changes



Exploring System Transitions During Attempt #2 Testing





Grade 9 vs Grade 2 Linear Modal Test Results

Mode	Frequency (Hz)		Damping (%)	
	Grade 9	Grade 2	Grade 9	Grade 2
1st Bending	101	101	0.79	0.23
1st Bending	127	137	0.42	0.30
Torsion	339	---	0.28	---
Axial	**944**	**959**	**0.21**	**0.13**
2nd Bending	1124	1139	0.05	0.05
2nd Bending	1452	1491	0.13	0.08