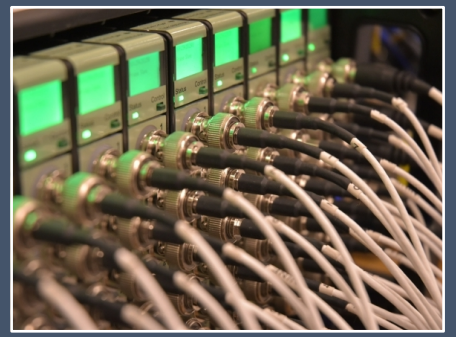
SAND2021-10931PE

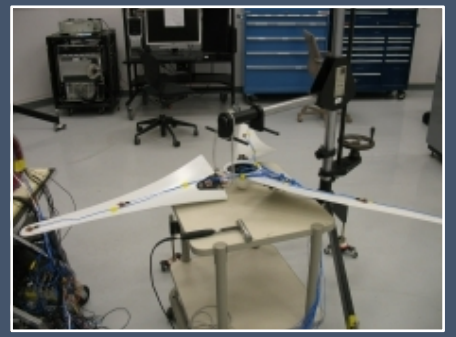
Nonlinear Structural Dynamics and Diagnostics

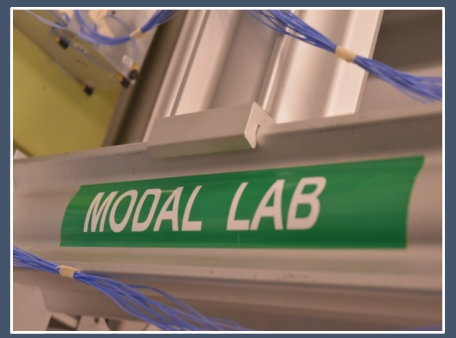
Spring 2021 Student-Sandia Summit

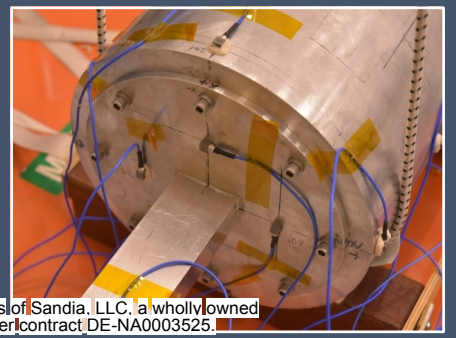
Presented By: Dan Roettgen

Date: 6/2/2021









Detect.
Inform.
Prevent.

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Agenda

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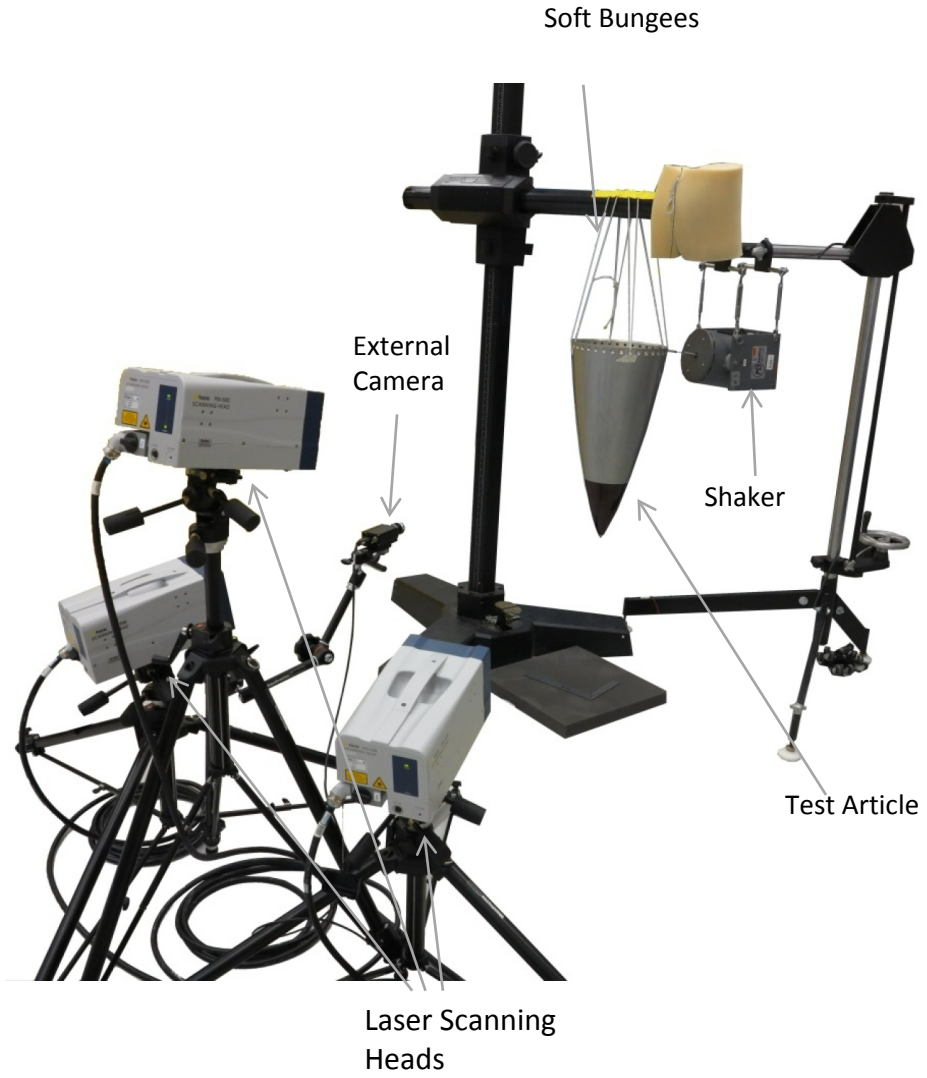
Adjourn!

Structural Dynamics at Sandia

- **Sandia National Labs (SNL) relies extensively on complex computational models for:**
  - high fidelity environment simulations
  - rapid design
  - early technology insertion
  - assessment of operational alternatives
- It is imperative that these models be validated!
  - *"Essentially, all models are wrong, but some are useful."* [1]
- **Modal properties are the fundamental science used to validate these models**
  - Experimental modal analysis (EMA)
  - Experimental Structural Dynamics Group at SNL performs these tests, plus much more

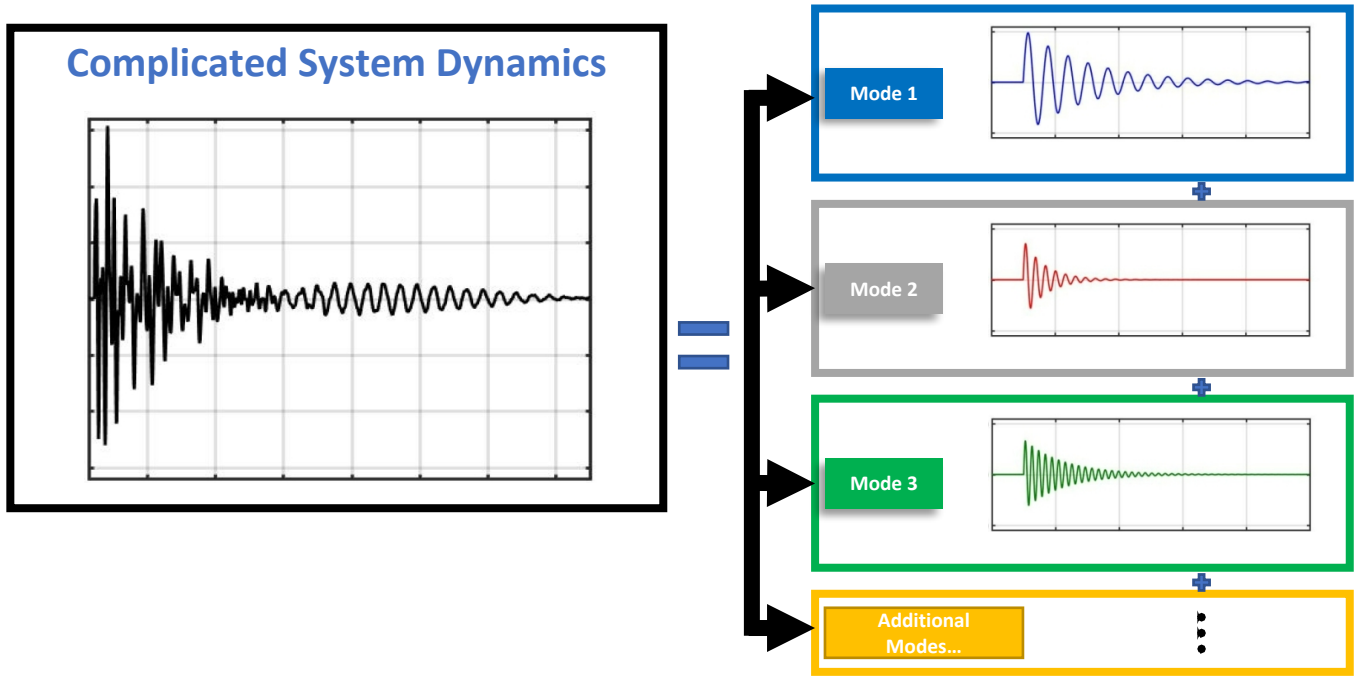


[1] G. Box, N. Draper (1987), *Empirical Model-Building and Response Surfaces*, John Wiley & Sons.

Modal Framework

- **What are modes?**
  - Modes are inherent properties of all objects
  - Describe how objects naturally respond to stimulation at different frequencies
  - **The fundamental building blocks of all complex dynamic response**
- All complex dynamic behavior is a superposition of modal responses

Natural frequency
Damping ratio
Deformation shape



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How does this work?

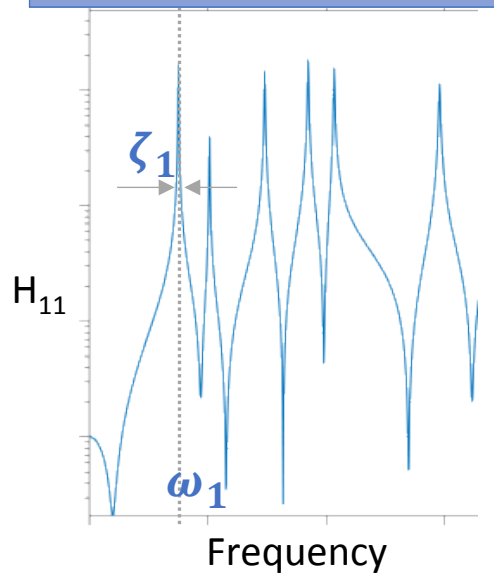
- **How do you measure modes?**
  - Excite the system and measure the input force → $F(t)$
  - Measure the system output response → $A(t)$
  - Compute Frequency Response Functions (FRF) → $H(\omega) = \frac{A(\omega)}{F(\omega)}$
  - Curve fit the FRF → $H_{ij}(\omega) = \sum_{k=1}^{m} \frac{-\omega^2 \phi_{ik}\phi_{jk}}{\omega_k^2 - \omega^2 + 2j\zeta_k\omega\omega_k}$
    - Modal parameters are extracted from the fit FRF

Modal Superposition

Mode shapes

ϕ_1

Natural Frequencies & Damping ratios



- Keys to success:
  - Measure input and output accurately
  - Excite in locations that activate the modes of interest
  - Place sensors in appropriate locations to spatially resolve modes of interest

Correlated models are used to predict dynamic behavior in complex environment simulations.

Experimental Structural Dynamics

The structural dynamics group at Sandia has a diverse function within SNL.

- Perform diagnostic pre-and-post vibration modal testing to best update finite element models
- Perform data acquisition for many field system qualification tests
- Perform research that has **direct applications in Sandia structures of interest**

For decades most engineers have known that the key to successful design progression relies on a merging of test and analysis

"A theory can be proved by experiment; but no path leads from experiment to the birth of a theory."
"No amount of experimentation can ever prove me right; a single experiment can prove me wrong."
"A theory is something nobody believes, except the person who made it. An experiment is something everybody believes, except the person who made it."
-Albert Einstein

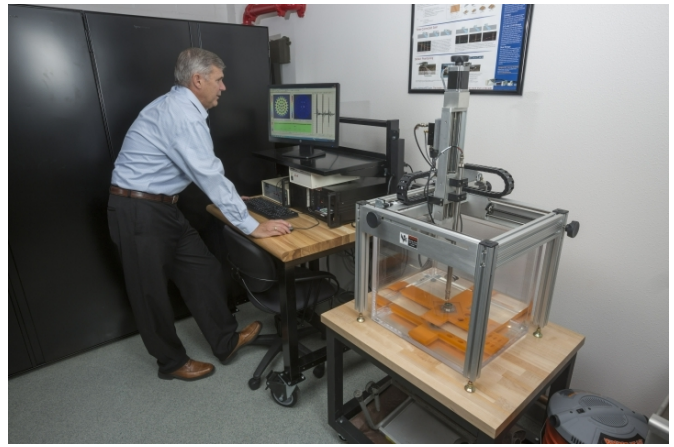
So how do we couple test and analysis?

Goal: Develop tools to aide SNL teams in prediction and qualification capabilities through combination of test and analysis

Coupled Test Analysis Methodology

1522 works hand in hand with testing and analytical methods

- Using advances in testing along with strong analytical backgrounds the team in 1522 pushes SNL structural dynamics solutions to develop a deep understanding of our products



This presentation high-lights three projects that are being worked that could have dramatic impact on qualification time reduction by bridging test and analysis:

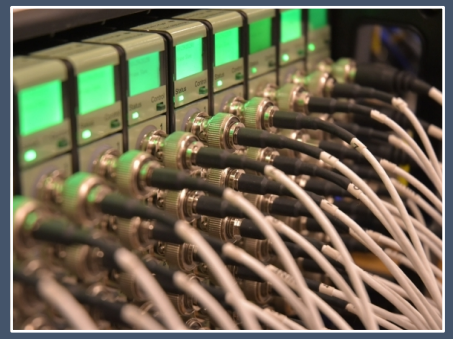
- Hybrid System Modeling - A method to connect experimental and analytical models in order to predict the response of an assembly.
- Digital Twin Technology - A new framework of testing where a model is run in parallel with a test/field environment to monitor hardware health
- Nonlinear Structural Dynamics – A field where we study the response of structures at multiple levels to best characterize hardware under large-load field conditions

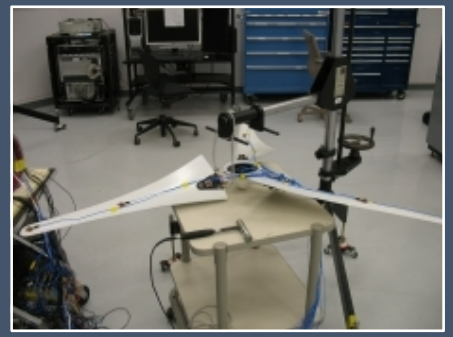
Goal: Develop tools to aide SNL teams in prediction and qualification capabilities through combination of test and analysis

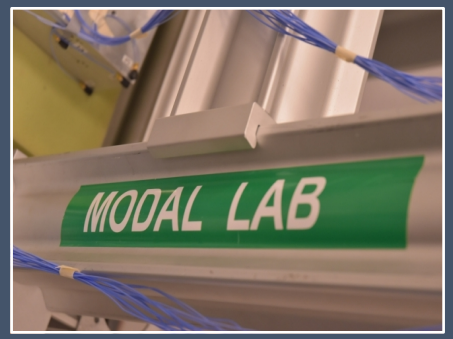
Nonlinear Structural Dynamics and Diagnostics Overview

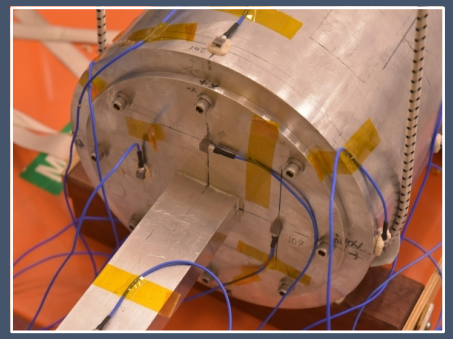
"It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."

-Sir Arthur Conan Doyle, (Sherlock Holmes)









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Diagnostics Motivation

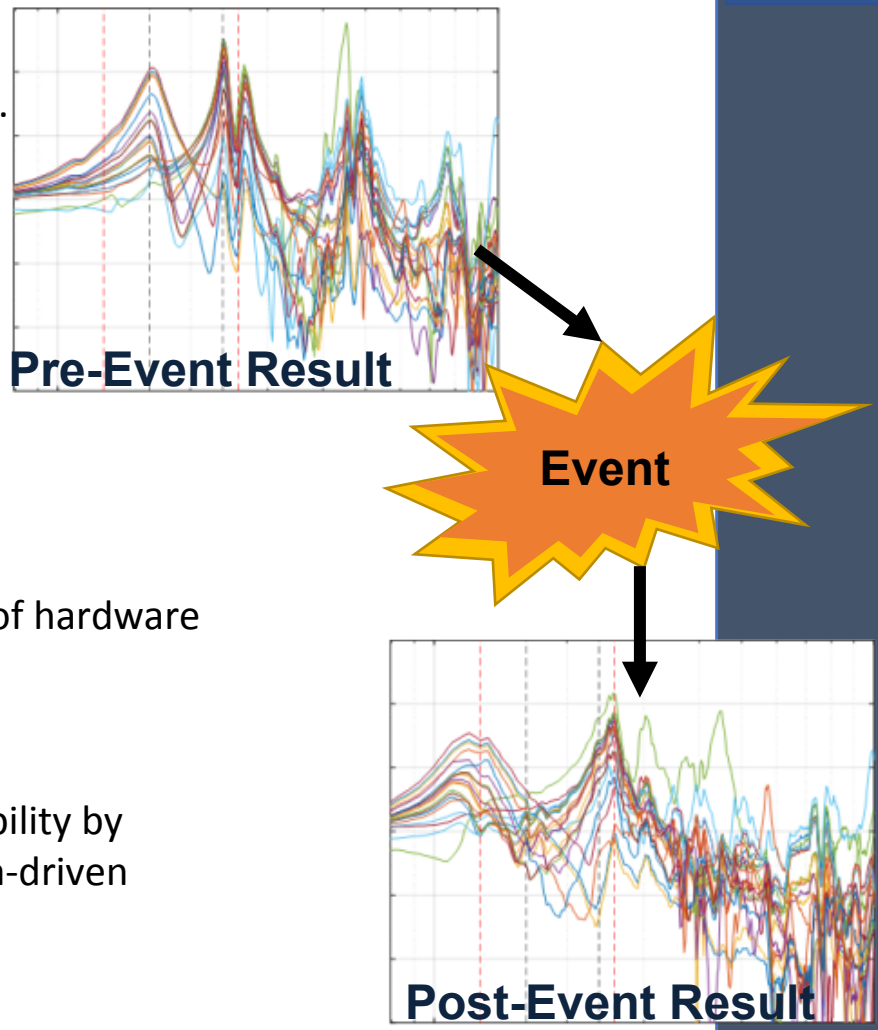
PROBLEM
The purpose of testing is to show and characterize mechanical system design robustness. Unexpected or harmful component dynamics often occur when design thresholds are reached, and must be clearly understood to inform customers and improve designs.

CHALLENGE
Current diagnostic tools are <u>unable</u> to provide key information back to designers

What happened!? When did it happen?
Where (what part)? Why (root cause)??

The “events” here can lead to long delays, unnecessary retest, and potentially rejection of hardware design!

PAYOFF
Efficient analysis and informative test results for customers. Expand future testing capability by integrating testing , diagnostics, and analysis (Digital-Twin), using physics-based and data-driven approaches to tease out information from the test data and models.

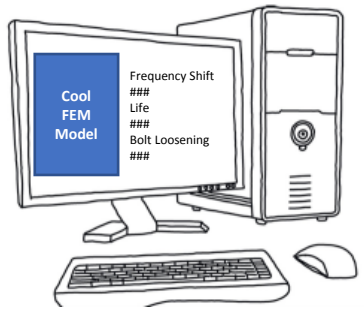


Goal: Identify and understand root causes of changes in component response in an agile timeframe

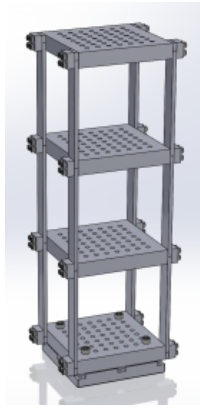
Detect.
Inform.
Prevent.

Digital Twin Concept

- Digital Twin (sometimes called As-Built-As-Deployed) is an emerging research field where some kind of model (statistical or physics-based) runs in parallel to an asset in the field. This model uses real time sensor measurements to predict failure before it occurs
- Presently we have experimental and computational projects to explore these concepts. we plan to test parts to failure and see how well models can predict these event focusing on weld failure, loosening of joints, and internal impact of components.



Digital Twin Model

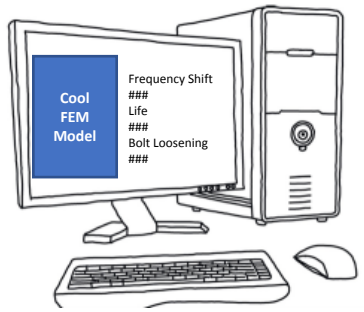


Physical Hardware Testing

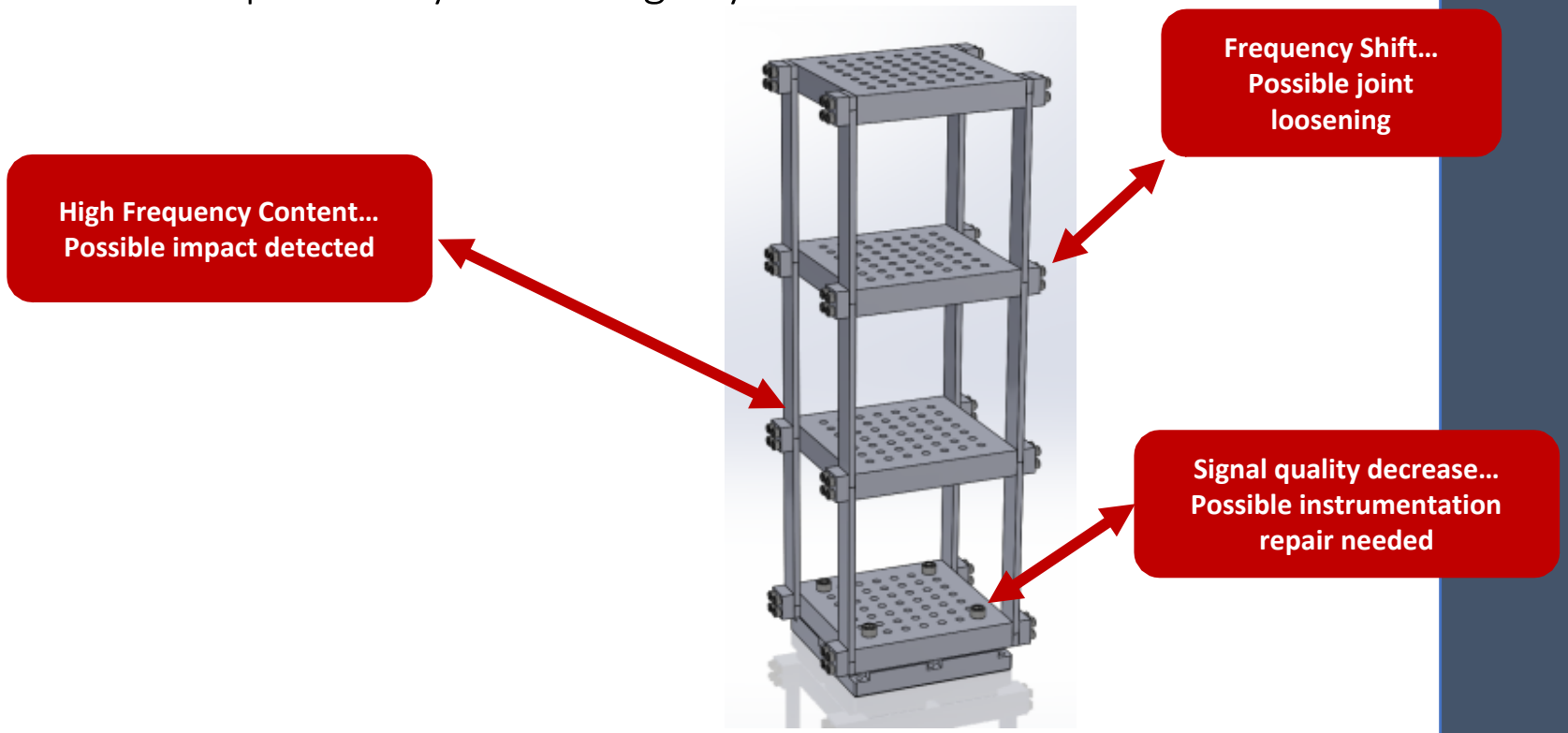
This is often thought of to track field data in aerospace structures but…
We could greatly enhance qualification testing using the same concepts!

Digital Twin Future Vision

- The long term goal is to provide heads-up alerts for test teams underdoing design qualification… alerting the team to loss of sensor quality, or potential bolt loosening could prevent significant delays on future and present system design cycles!



Heads-Up Display for improved qualification testing!



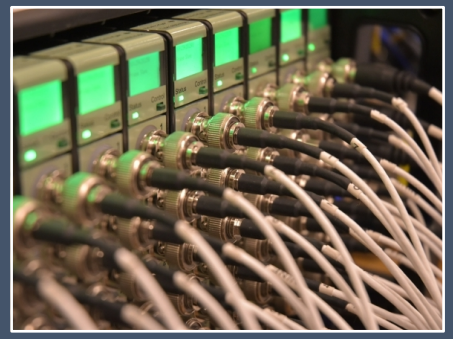
Hardware Under Test

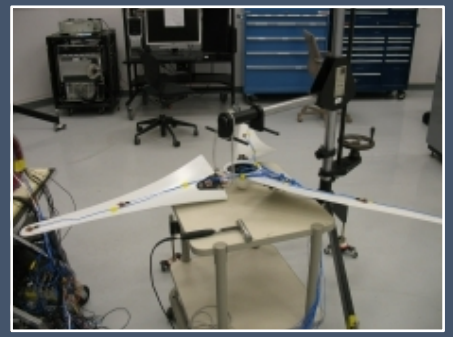
Detect.
Inform.
Prevent.

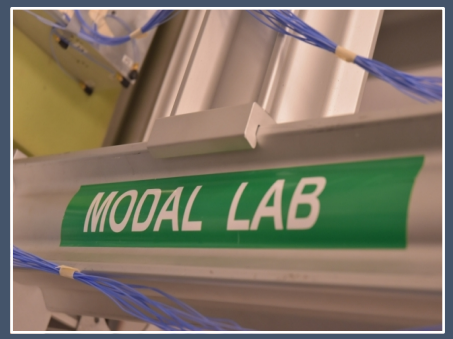
Event Detection Example

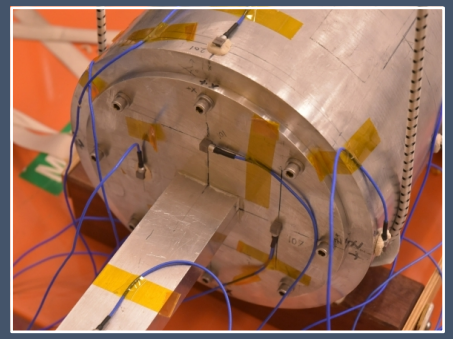
"Negative results are just what I want. They're just as valuable to me as positive results. I can never find the thing that does the job best until I find the ones that don't."

-Thomas Edison









Detect.
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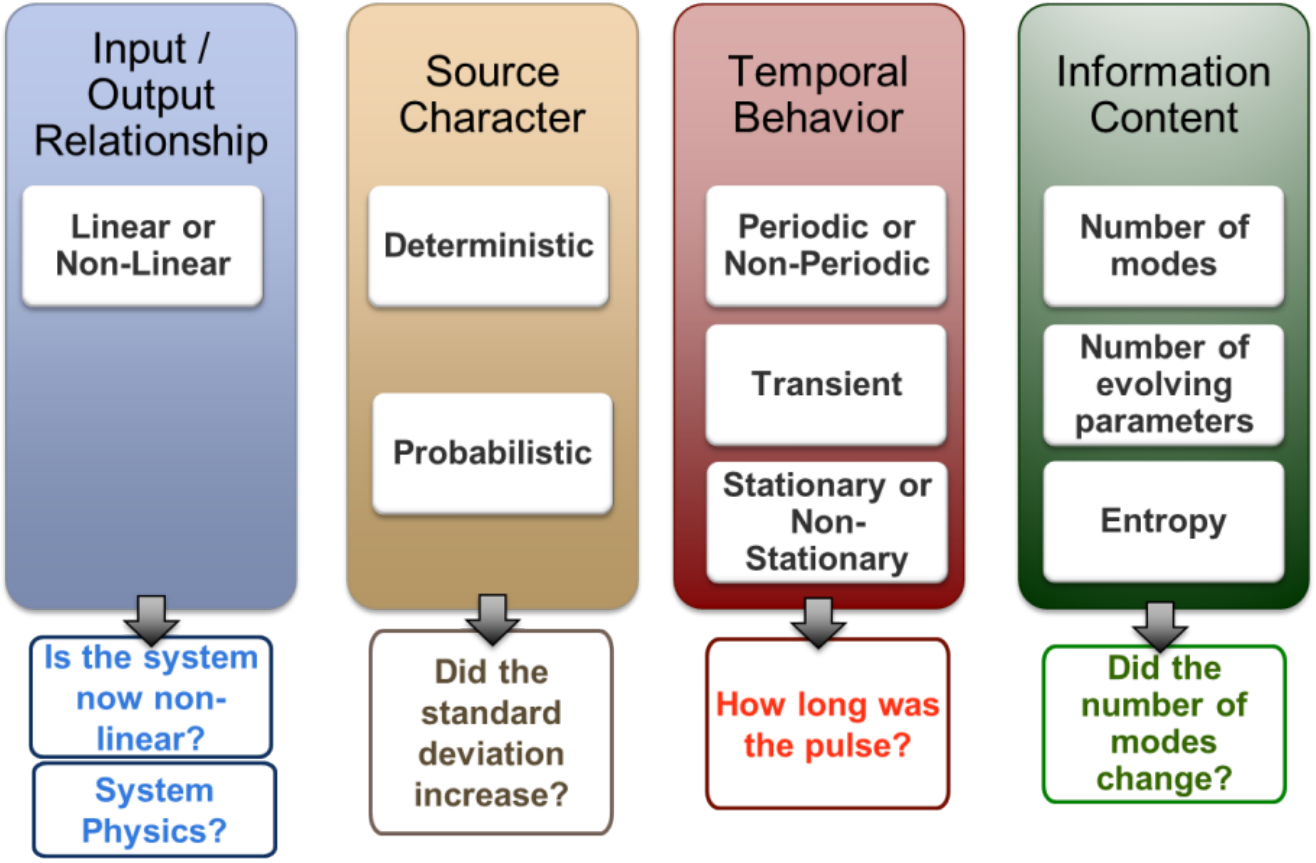
Describing Anomaly Detection

- Being developed by Angela Montoya
- Examine data across multiple dimensions
- Different tools are available for each category
- Anomaly detection involves looking for differences within these dimension across:
  - Established baseline or surrogate
  - A spatial dimension
  - Time



All of these questions give us *different* kinds of insight

Impact Detection Example

Test Case:

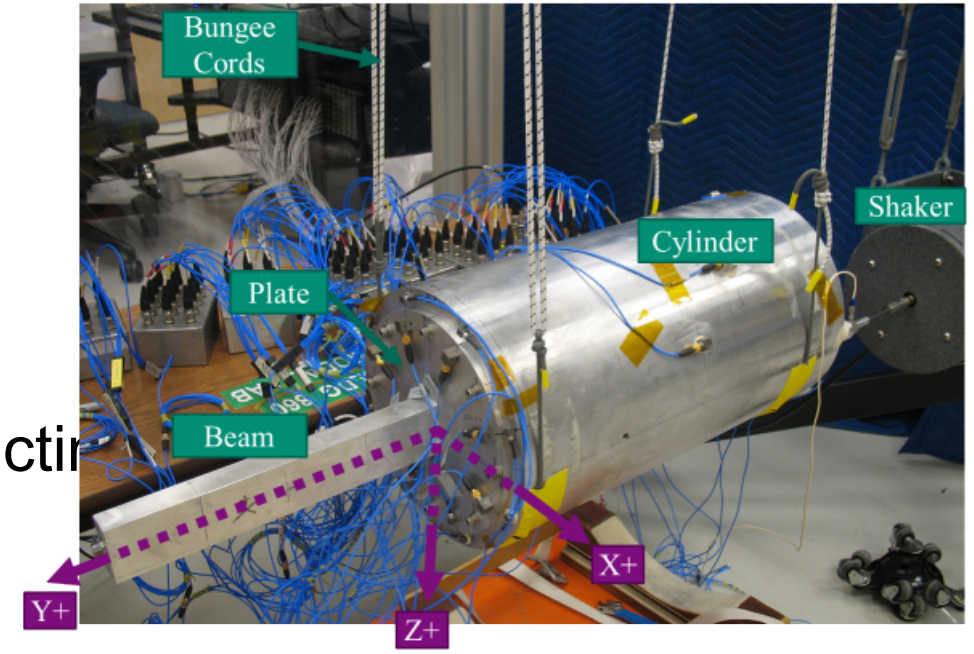
High-level random force excited into structure. Three different hammers are used to impact the structure at different locations on the part. The modal group measures the force and response data along with the location of hammer strikes (simulated component on component impacts)

Questions:

Can we detect when this impacts occur?

Can we decide where they occur?

Can we tell what type of material is impacti

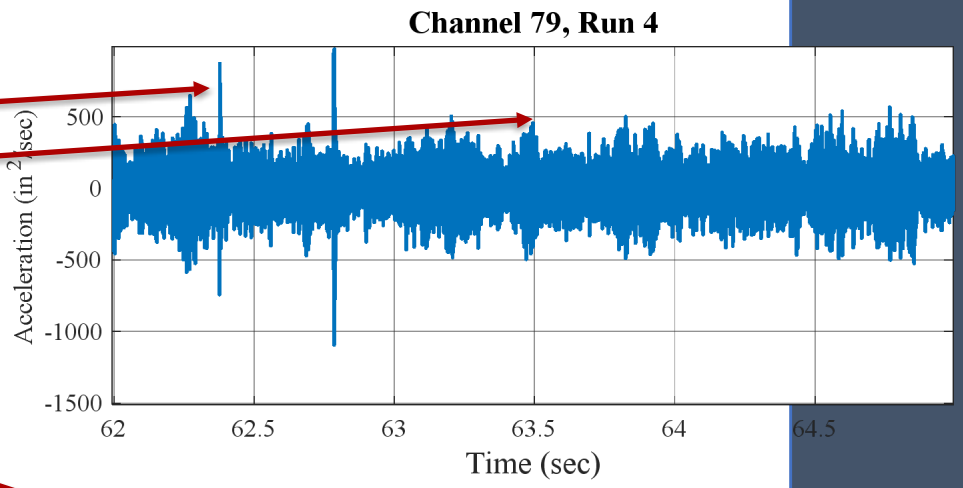


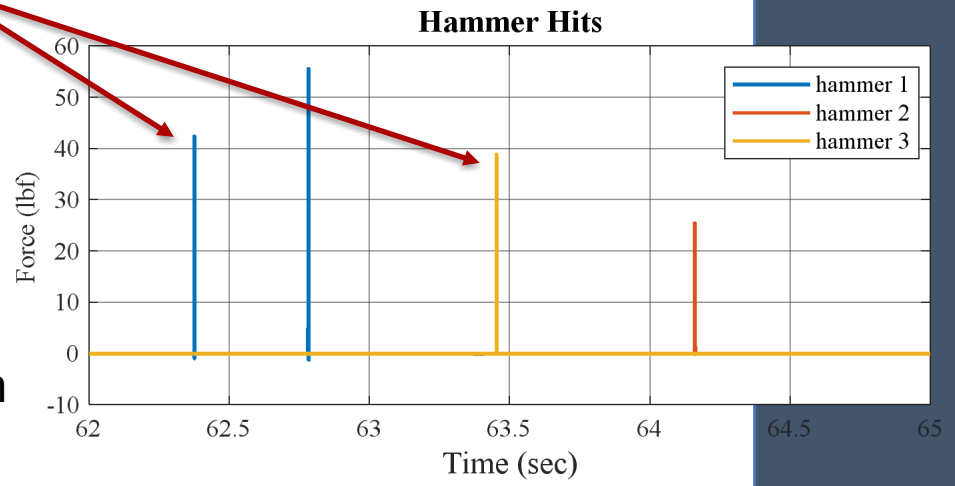
Detect.
Inform.
Prevent.

Sample Test Data

- Often test data comes in the form of raw time histories
- Sometimes impacts are easy to observe
- Others are mode hidden

- **Step 1:** Organize the Data into a Matrix
- **Step 2:** Perform a Singular Value Decomposition
- **Step 3:** Approximate by rank reduction
- **Step 4:** Calculate the Information Impulse Function **IIF**
  - *Gives the total information change due to subsequent approximation*
- **Step 5:** Changes in information content indicate impact
  - IIF can be computed in time, frequency, or channel location





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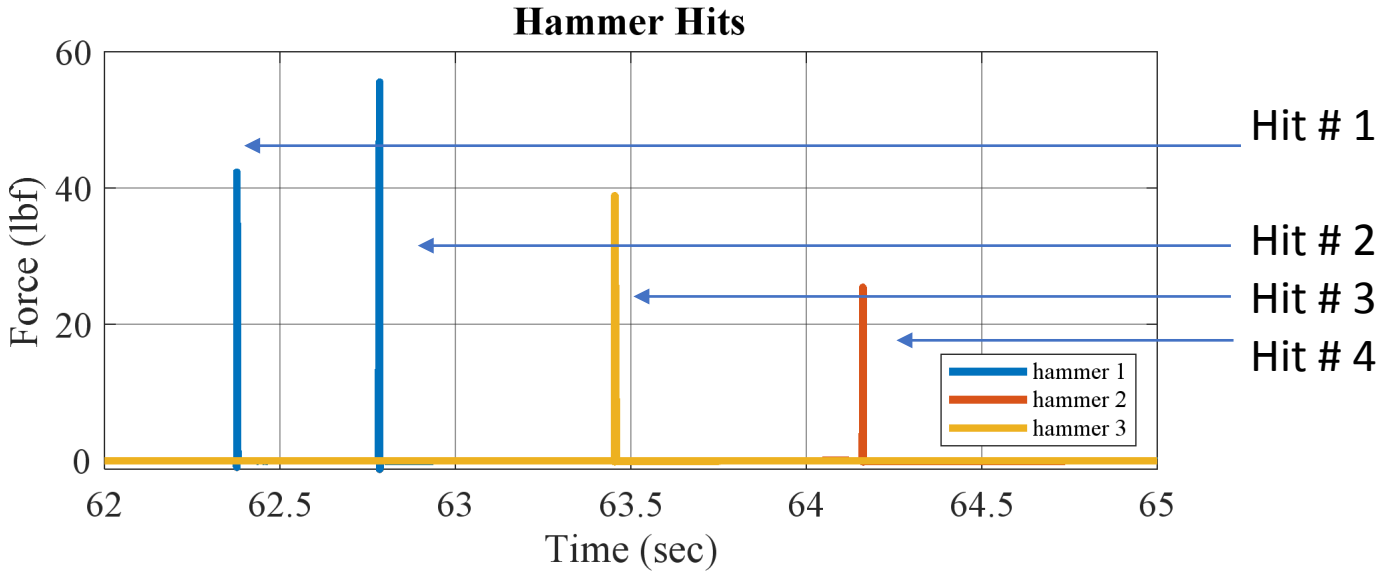
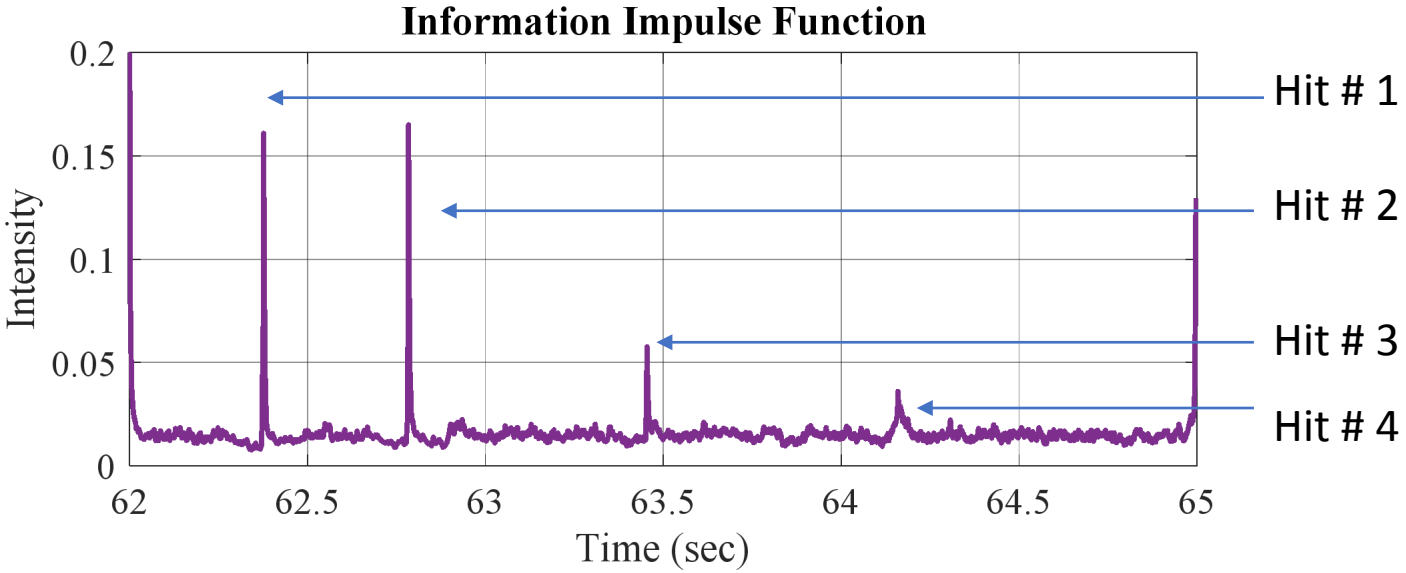
Impulse Information Function Results





- One frame of modal data shown from previous slide
- Wavelet transform was used to create the data matrix
- All four hammer inputs show a significant spike on the IIF for the right singular vectors

- **Questions:**
- Can we detect when this impacts occur?
  - **Yes**
- Can we decide where they occur?
  - **Yes, in some cases!**
- Can we tell what type of material is impacting?
  - **Given candidate information, Yes!**

Detect.
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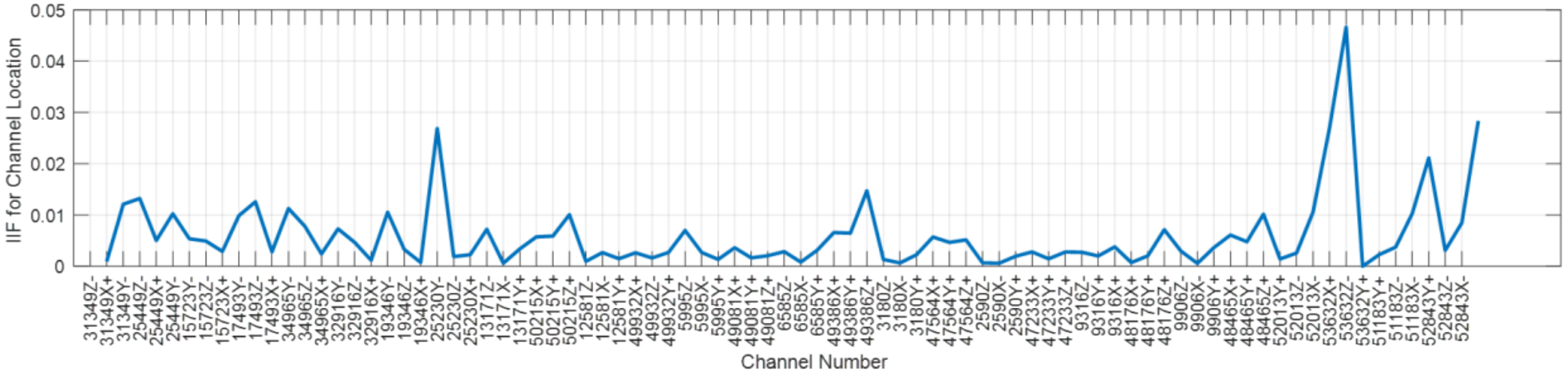
Prevent.

Favorable Proof-of-Concept



Hammer #	Number of Actual Hits	Number of Hits Identified	Mean Time-Localization Error (# of samples from actual)	Channel Identified (of ID'ed hits)	Miss-classification Rate (missed/total)
1	51	51	0.45	9316X+	0.059
2	28	28	1.5	53632X+	0.0
3	45	41	0.46	34965X+	0.05

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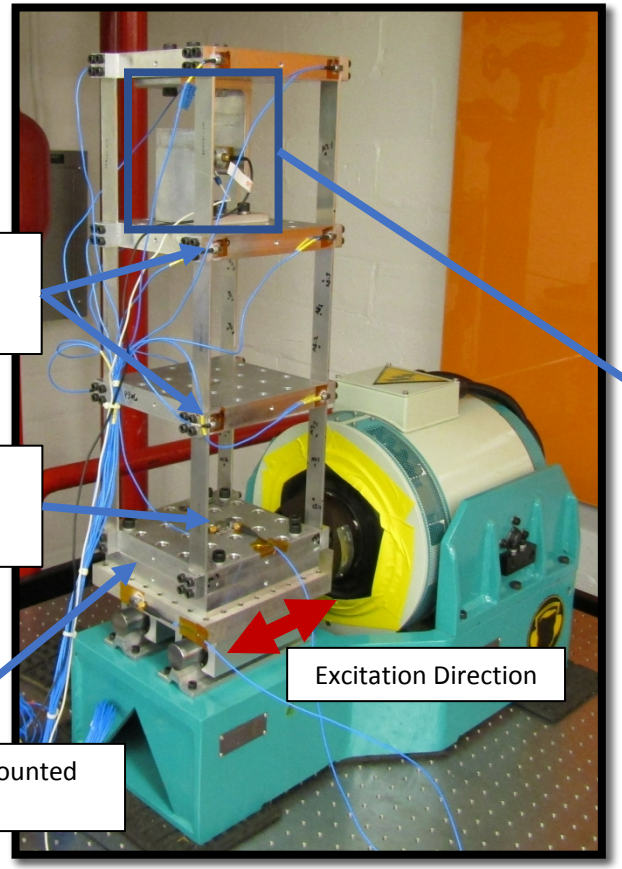
Tower Test



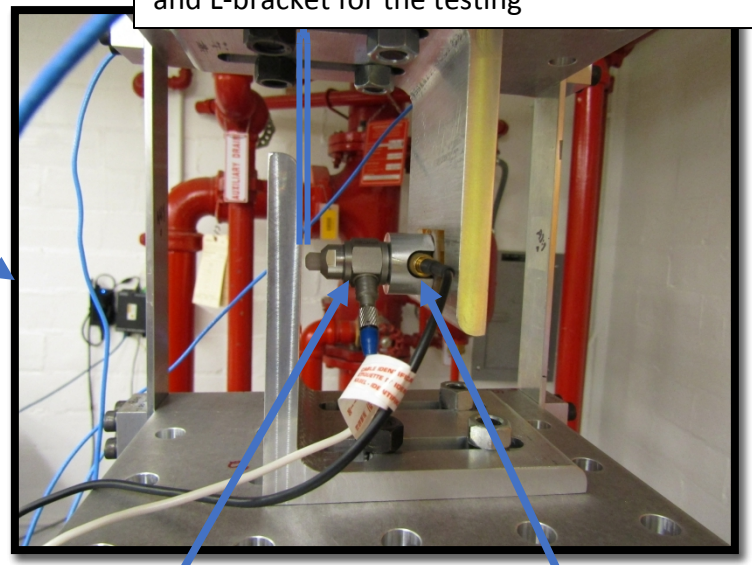
Triaxial accelerometers were mounted at the corners of platforms 2-4

A triaxial accelerometer was mounted at the center of platform 1

Excitation Direction

The tower was rigidly mounted to the shaker slip table

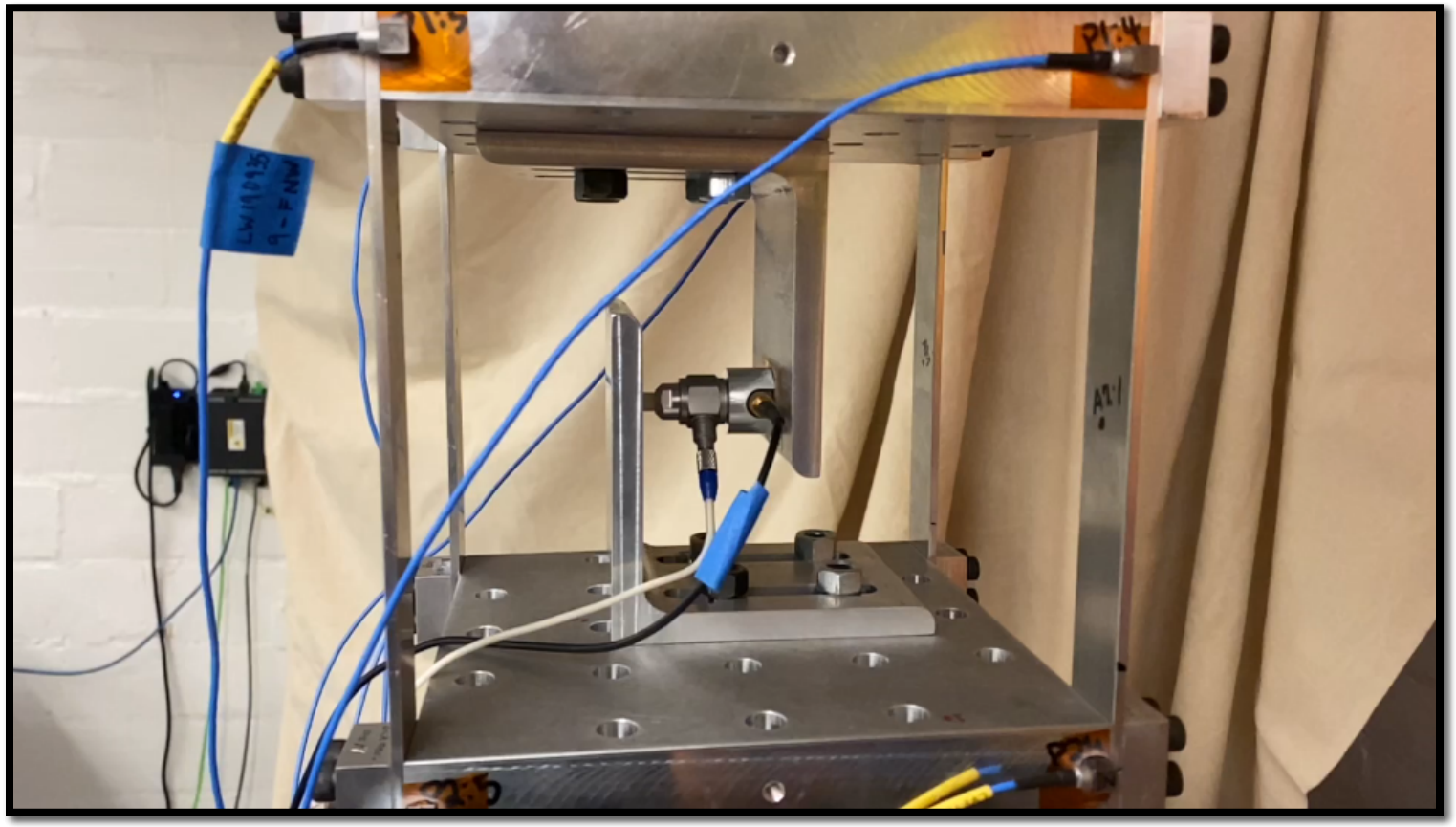
There was a 0.015” gap between the load cell tip and L-bracket for the testing



Impact Load Cell

Impact (Triaxial) Accelerometer – under aluminum cap

Internal Impact Video



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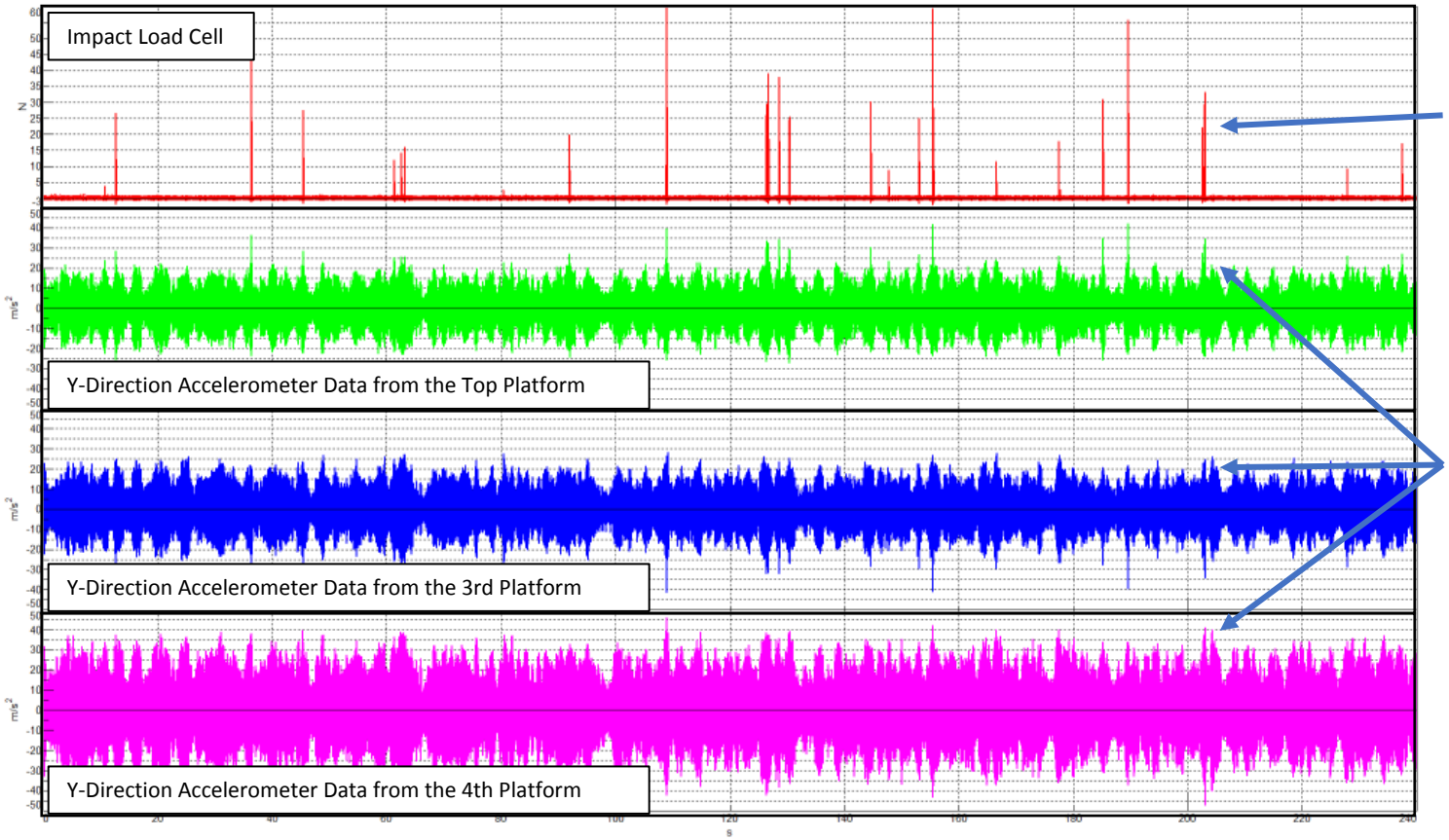
IIF Results!



The L-bracket impacts are clearly visible in the load cell data

The L-bracket impacts are somewhat visible in the top platform acceleration data, but are less obvious in the other platforms

Detect.
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Path Forward

2020	Digital Twin Project Initiation	Event Detection Proof-of-Concept	
2021	Understanding of Joint Physics	Improved Testing for Joint Loosening	Forced Response Force ID
2022-2025	HUD Development	Scope & Develop Realistic Diagnostic Tools	Develop Methods of Margin Assessment
2025	HUD Vibration Example	And beyond!	

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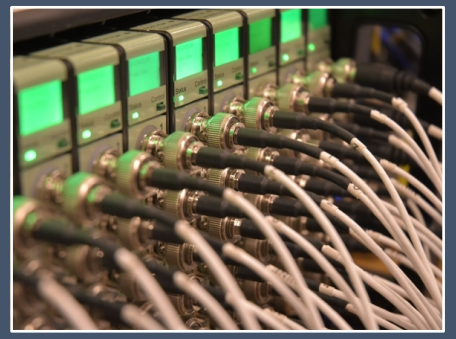
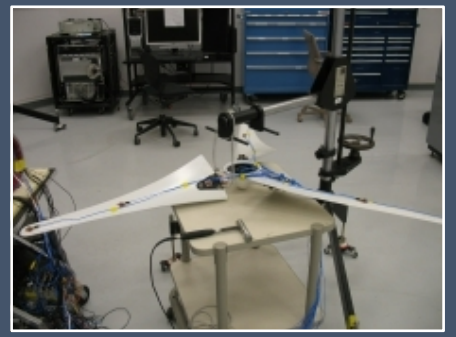
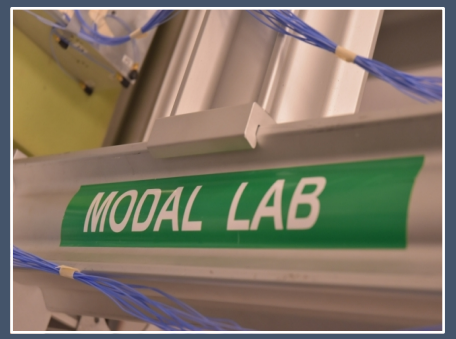
Nonlinear Structural Dynamics Example

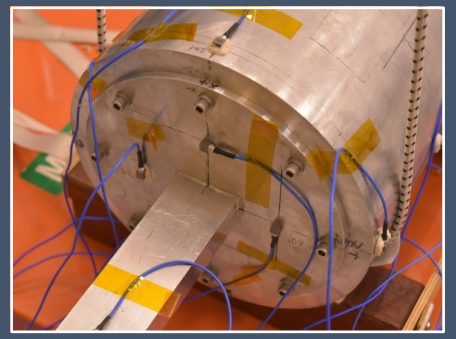
"Before I got married I had six theories about raising children; now, I have six children and no theories."

-John Wilmot









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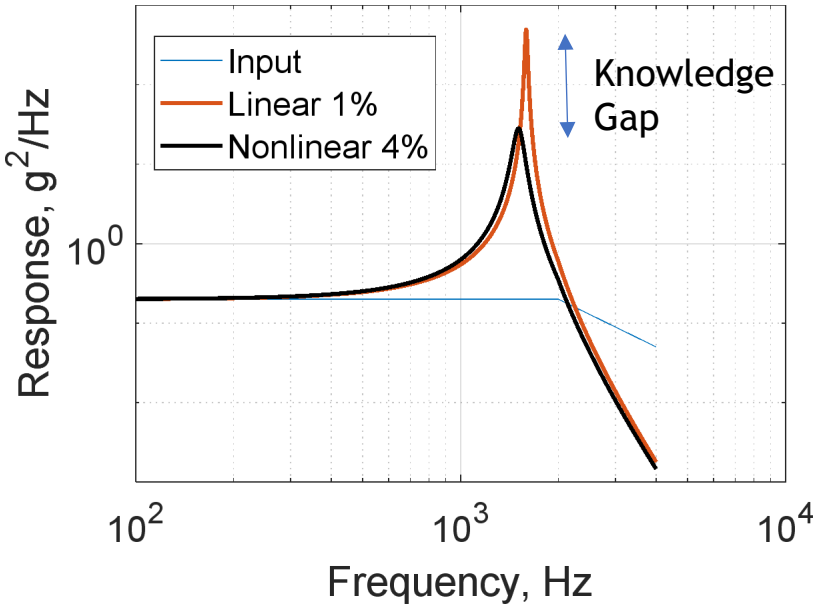
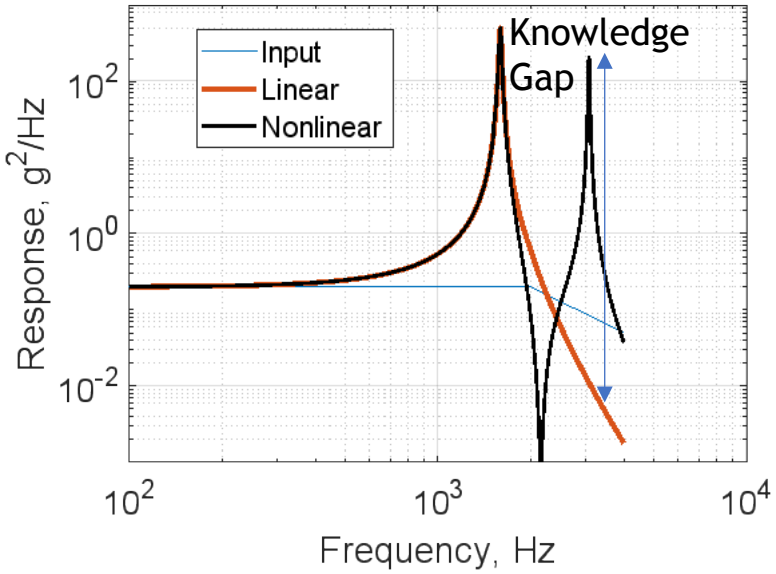
Nonlinear Response

- A **fundamental knowledge gap exists** in current structural dynamic design, test, and analysis approaches
  - Presently **nonlinear structural dynamic** response is neglected and absorbed by margin in the design process
- Because of this gap, structures are **overdesigned** and **overtested** leading to **waste** in design cycle **schedule** and **cost**
- As Sandia drives to decrease cycle time it is important to develop a framework for understanding these neglected physics so that we can continue to make world-leading products!





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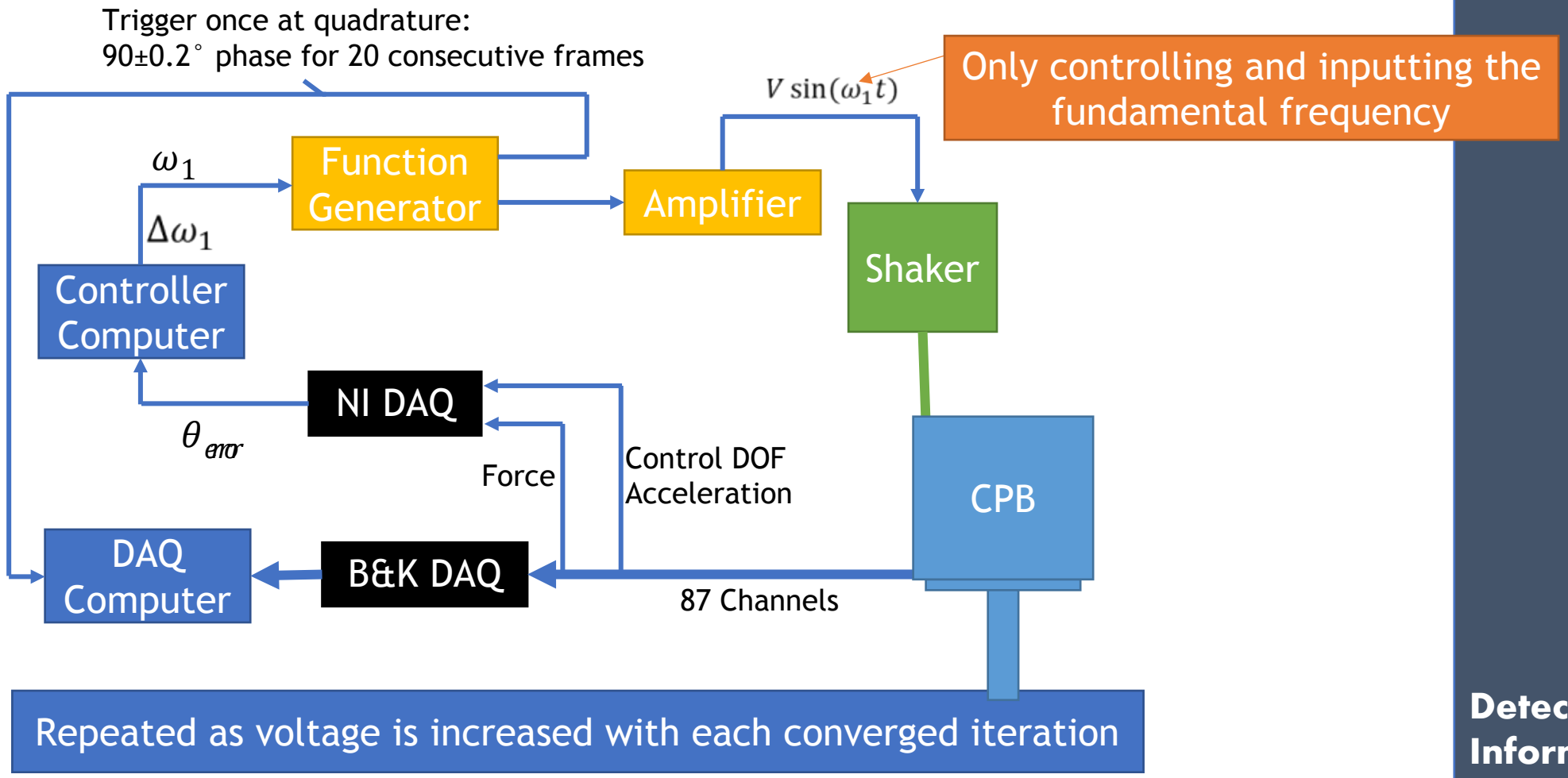
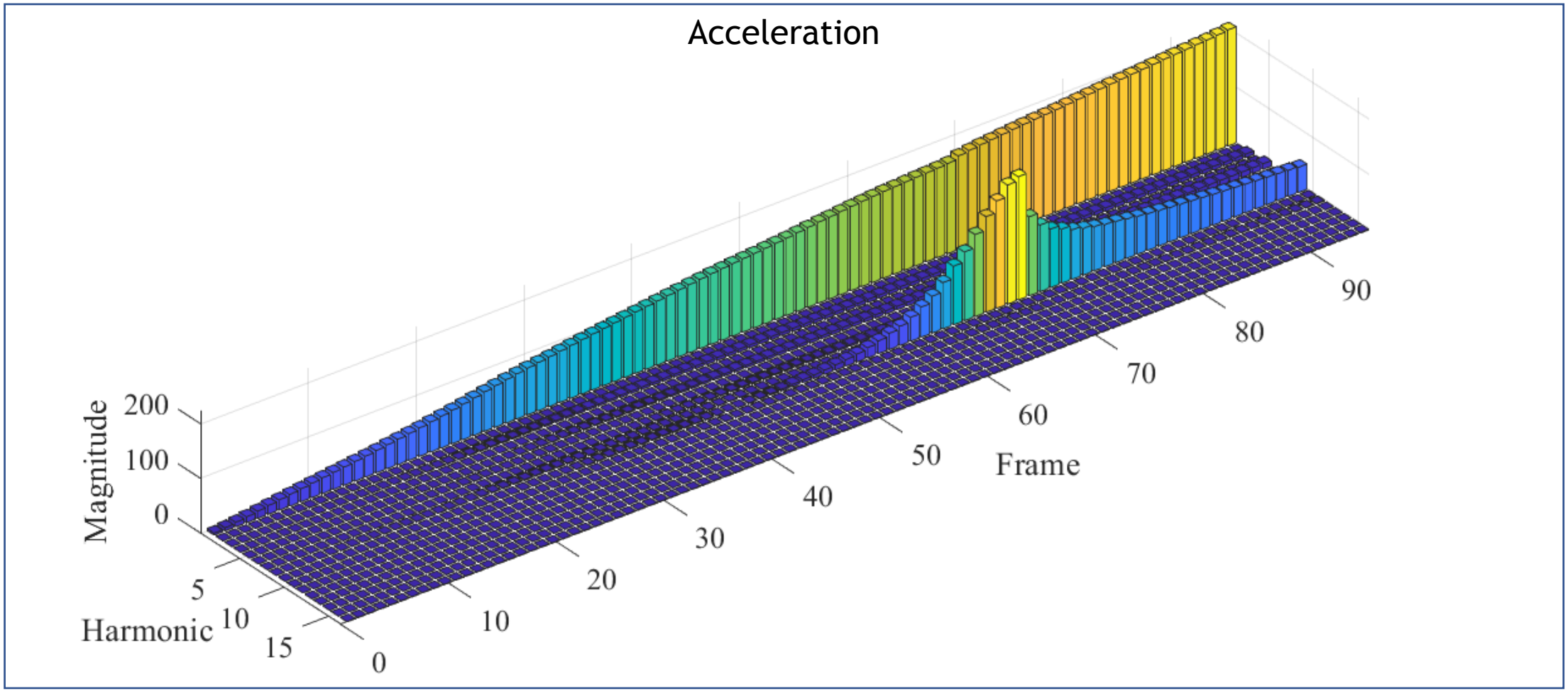
Sandia Force Appropriation Scheme

- **Can we observe these higher harmonic interactions in test?**
- University of Liege showed nonlinear modes can be approximately isolated using single input excitation and achieving phase quadrature (90° phase difference between force and response)



Higher Harmonic Nonlinear Response!



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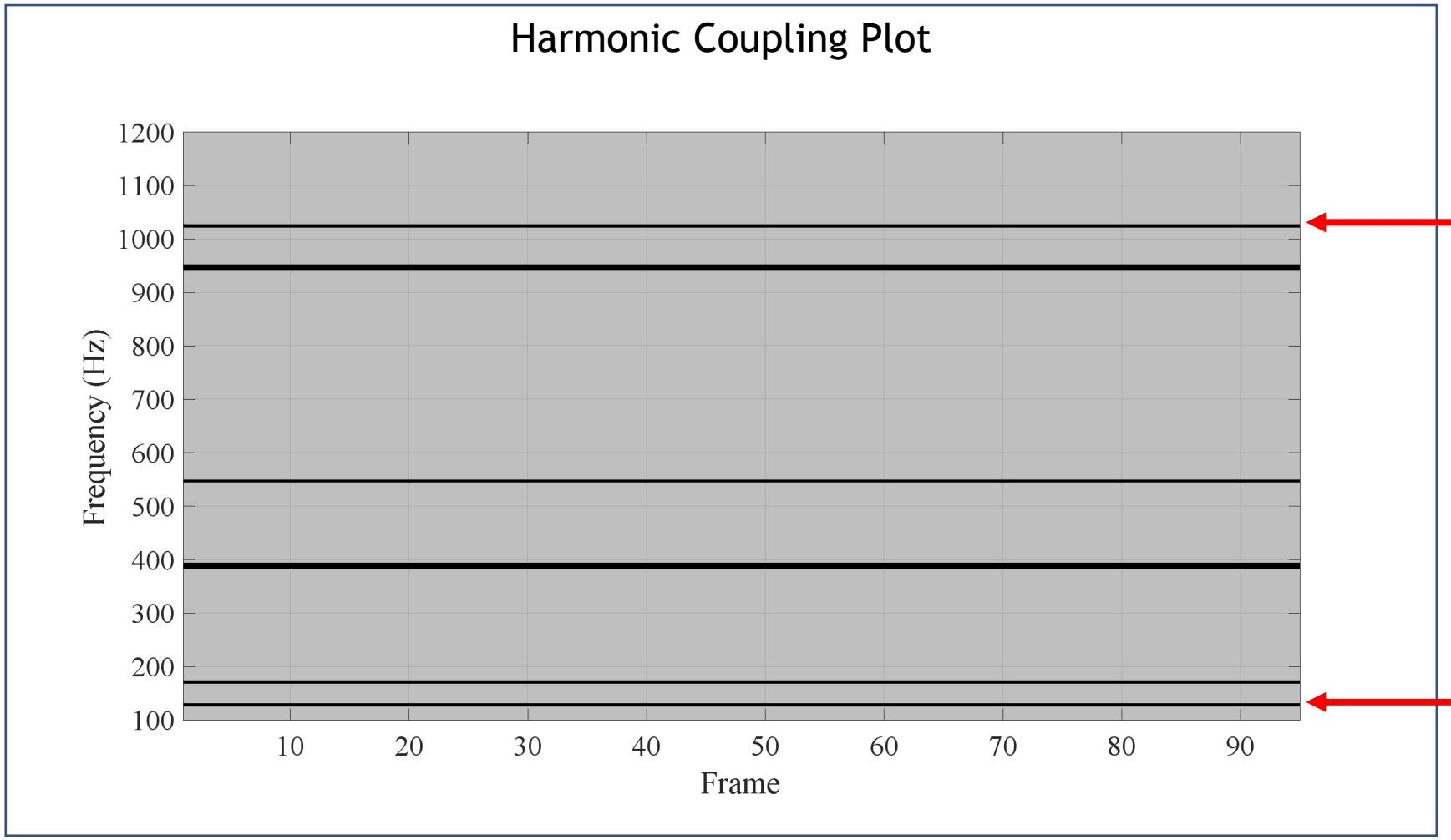
Prevent.

Harmonic Coupling Plot

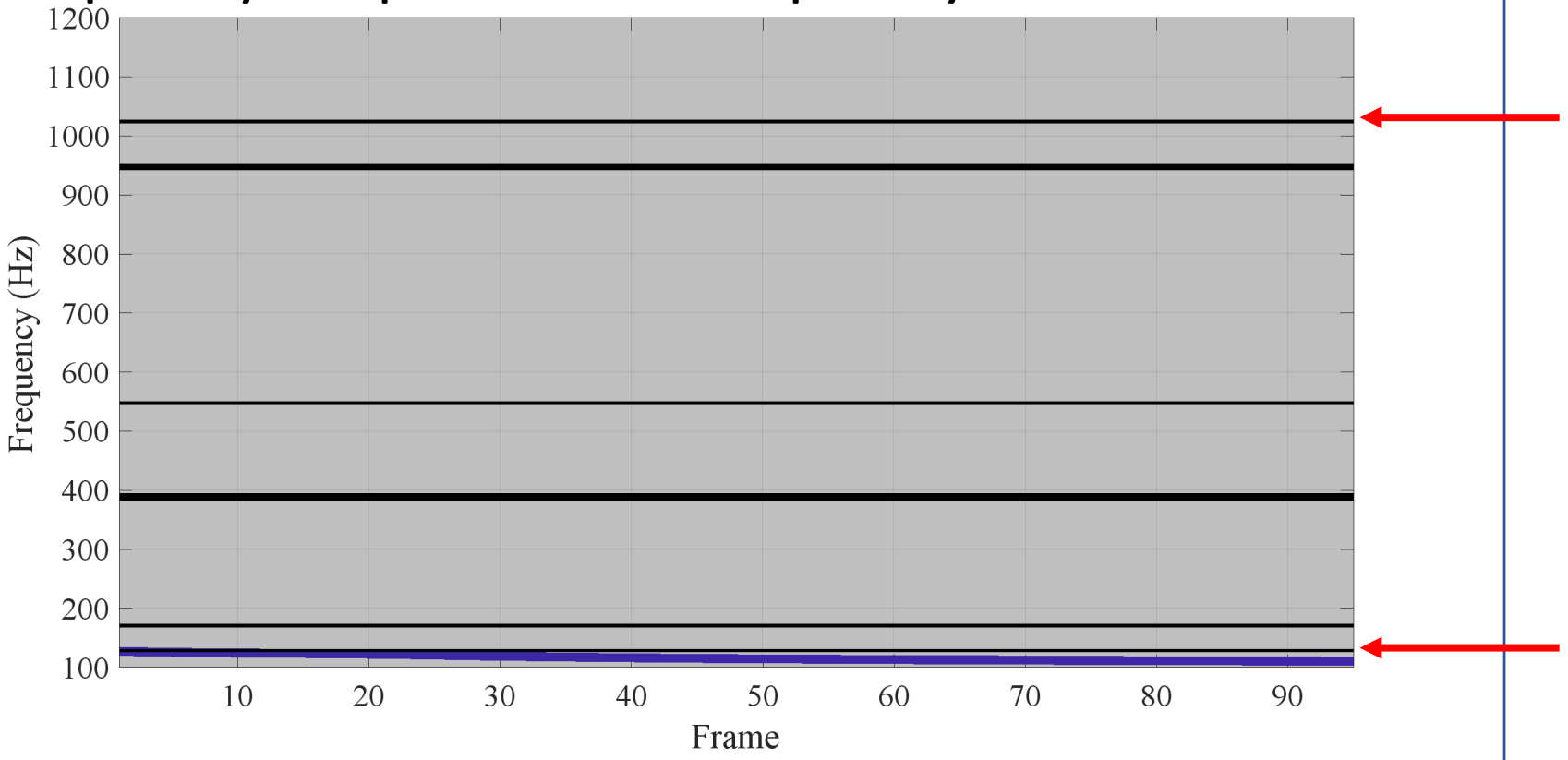


First, show the linear natural frequencies

Detect.
Inform.
Prevent.

Harmonic Coupling Plot

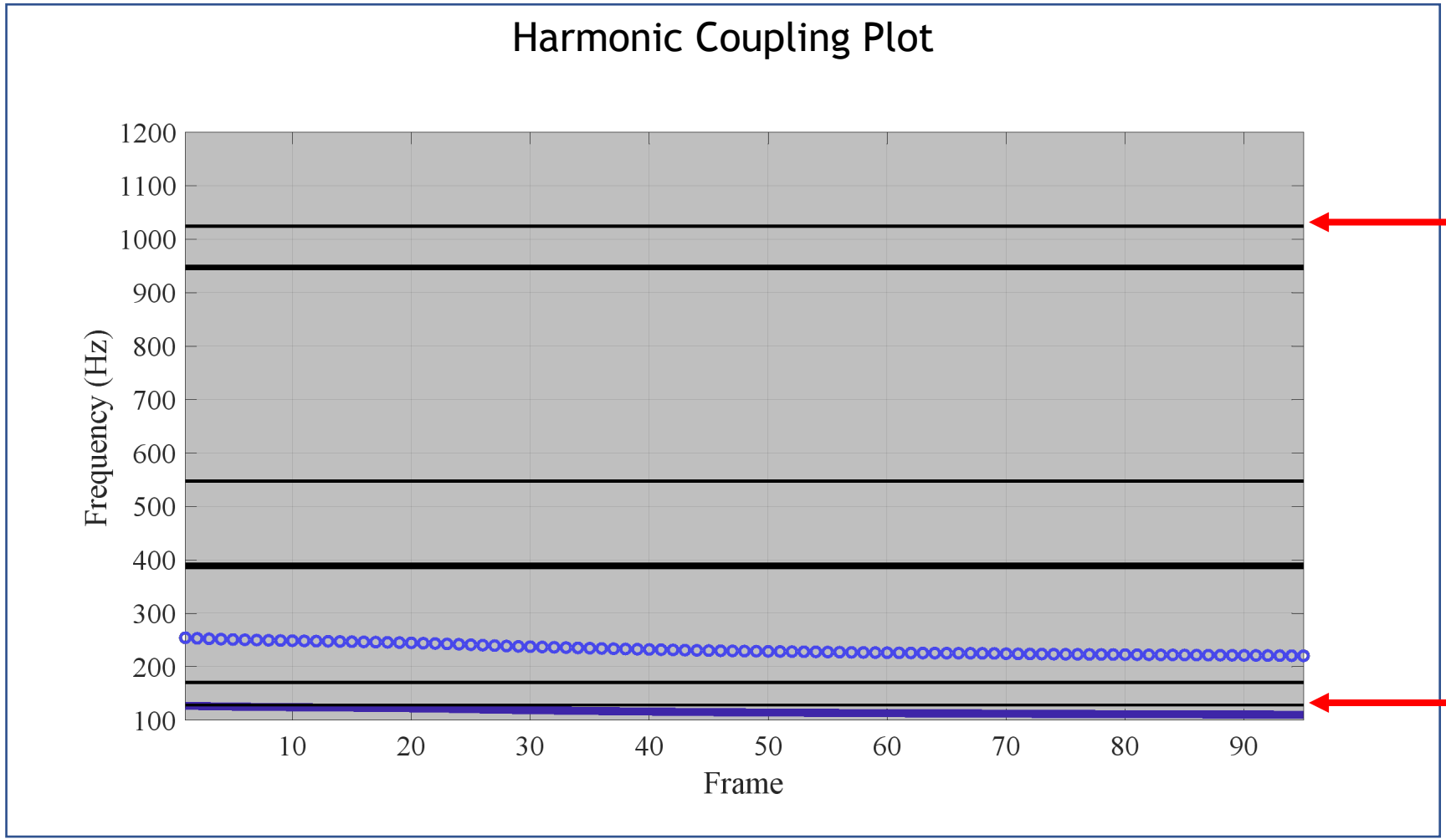
- The drive frequency or quadrature frequency is added for each frame



Next, the fundamental frequency backbone

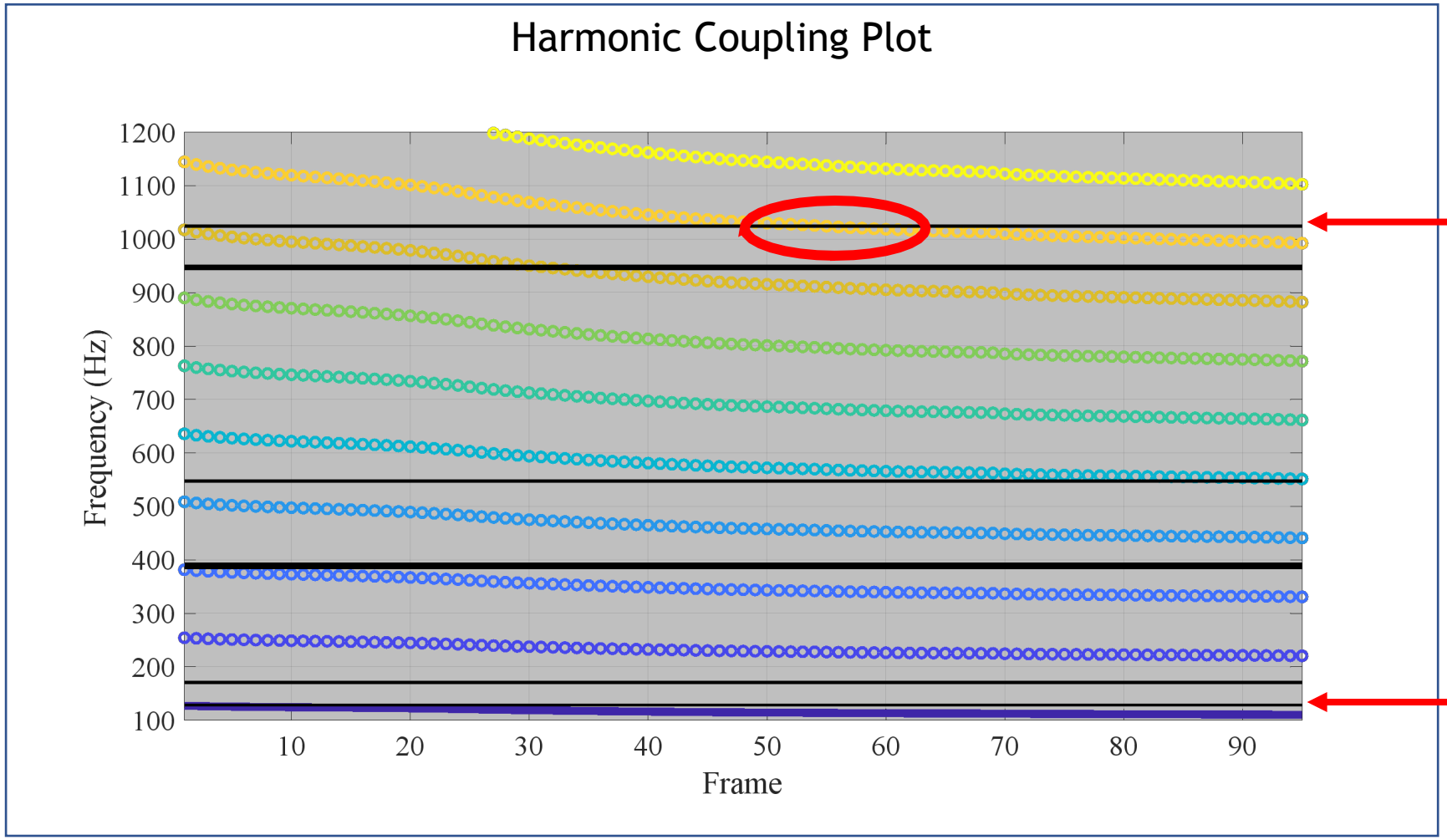
Detect.
Inform.
Prevent.

Harmonic Coupling Plot



Such as, 2ω…

Harmonic Coupling Plot

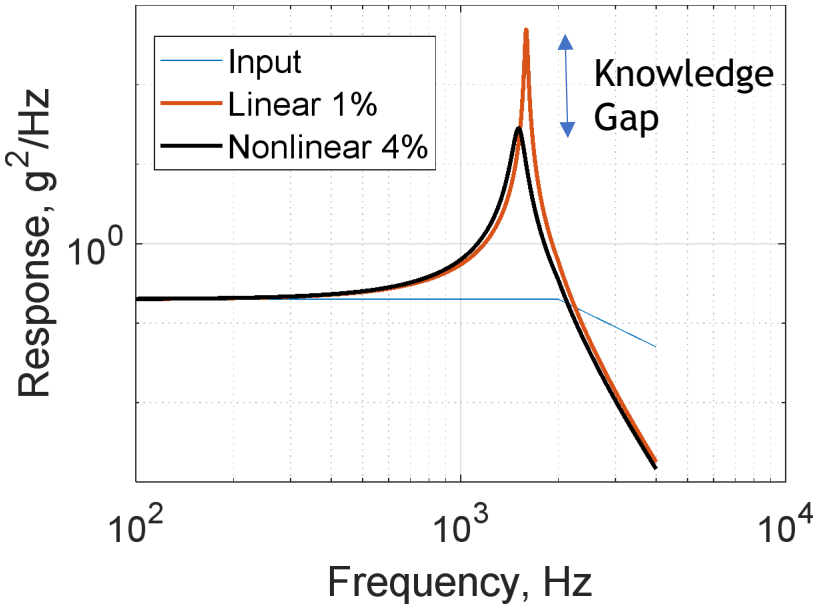


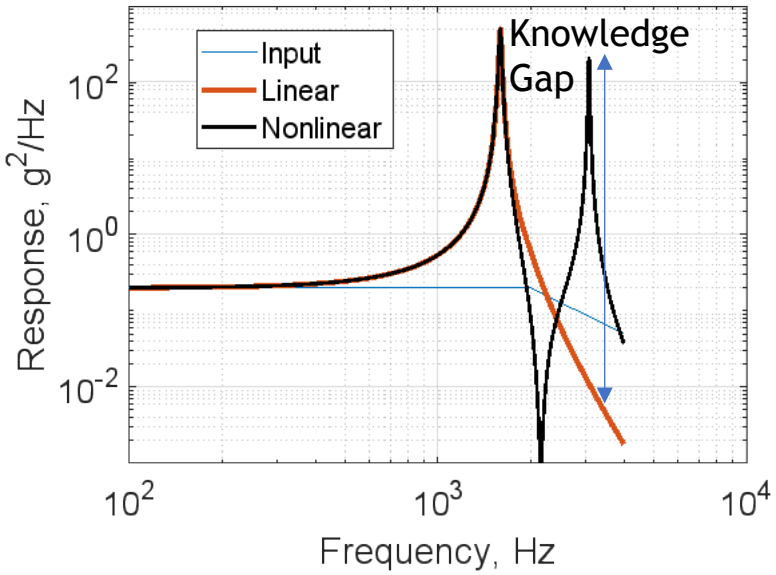
- Due to system nonlinearity we can expect energy at harmonic multiples of the fundamental frequency

Such as, 2ω, 3ω, 4ω… … 9ω

Where do we go from here?

- **We need to find ways to not only address this knowledge gap, but also explain to customers the urgent importance of quantifying it**
- Putting future efforts into not only the assessment and modeling of nonlinearity but addressing the impact of the nonlinearity is of importance
- Guiding Questions
  - How do we detect nonlinearity real-time?
  - Is certain testing ideal for detection versus identification?
  - How do we bucket nonlinear response into harmful versus helpful?
  - Can we quantify uncertainty or margin reduction due to nonlinear effects?



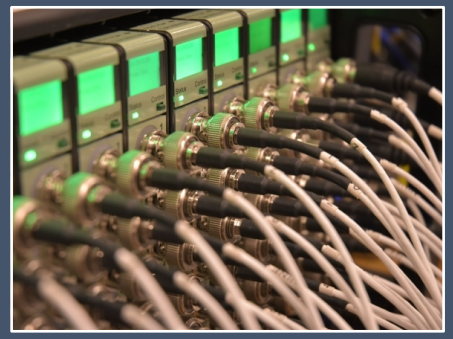


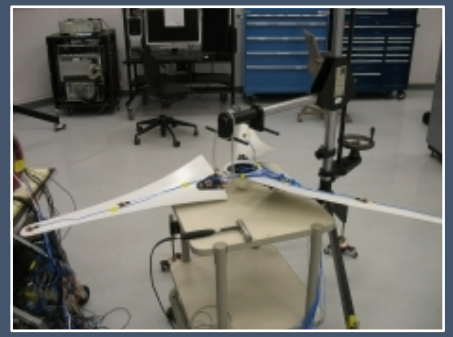
Detect.
Inform.
Prevent.

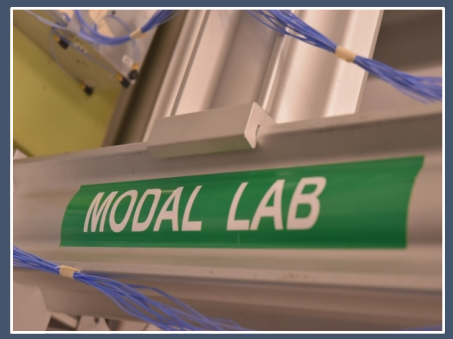
Closing Remarks

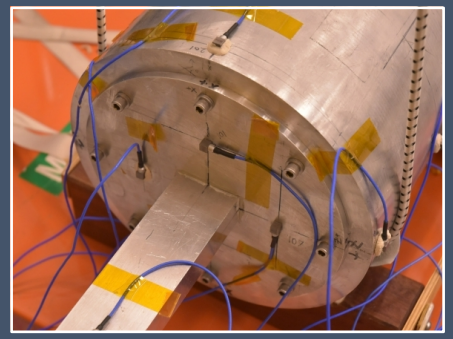
"An ounce of practice is generally worth more than a ton of theory."

-E.F. Schumacher









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Test and Analysis Coupled are the Best Solution

Both Test and Analysis are ESSENTIAL for Solving the Next-Generation of Sandia's Problems

- The correct solution is unobtainable without pieces of each discipline, in face, the best solution is found when the two disciplines integrate together!
- Today we covered three research topics from 1522 that work to bridge the divide between test and analysis
  - **Hybrid System Modeling** - Connecting test and analysis to rapidly predict solutions
  - **Digital Twin Testing** - A method to combine test and analysis to best understand failure in products
  - **Nonlinear Structural Dynamics** - Emerging capabilities that allow Sandia to look at the true (not-linearized) response!
- To be successful in the future SNL test engineers need to fully appreciate modeling techniques and vice versa

"That decision falls to scientists, engineers, and managers—with at least the tacit approval of company officers and boards of directors. All complex technology is inseparably coupled to an equally complex team of people and systems of people who should interact with one another as smoothly and with as clear a purpose as a set of well-meshed gears."

-Henry Petroski

"The key to searching for the truth is to hold passionately to your beliefs while simultaneously not feeling entrenched in your position"

-Adam Steltzner

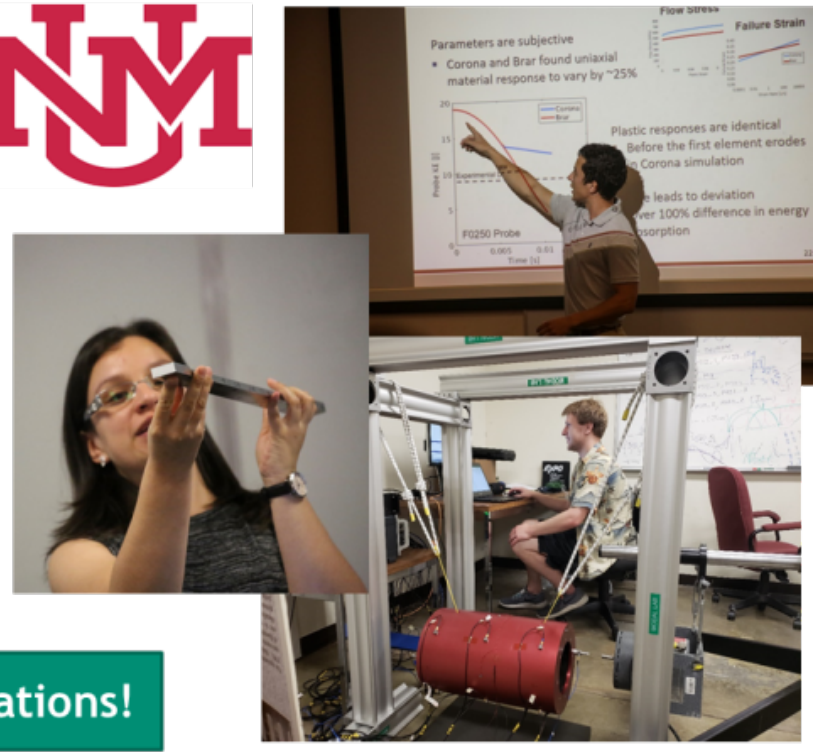
NOMAD Institute

NOMAD Overview

- Sandia sponsored Graduate student research institute held at UNM annually (June-July)
- 18-24 students work in teams of 3-4 to solve complex engineering mechanics problems of SNL interest
- All projects involve some combination of test and analysis encouraging the next generation of engineers to think beyond their discipline and learn how to best leverage neighboring fields

- Previous project include:
  - Bolt loosening phenomenon
  - Joint force reconstruction
  - FRF based Hybrid system modeling techniques
  - Interface reduction and modeling

N=O=MAD Research Institute



Always looking for new projects related to challenging SNL applications!

Detect.
Inform.
Prevent.

Thanks to all my colleagues and collaborators!

Internal to SNL:

- Andrew Steyer (1446)
- Will Larsen, Ed Habtour (1521)
- Ben Pacini, Garret Lopp, Randy Mayes, Sara Jensen and everyone else in 1522 (1522)
- Mike Ross, Brian Owens, Mo Khan (1553)
- Adam Brink (1554)
- Rob Kuether (1556)
- Angela Montoya (1557)

- **External:**
- Matt Allen, Ben Moldenhauer (Wisconsin)
- Matt Brake, Nicholas Karpov (Rice University)
- Michael Haberman, Samuel Parker (University of Texas – Austin)
- Pete Avitabile, Deborah Fowler (University of Massachusetts-Lowell)
- Dan Kammer, Joe Schoneman (ATA-Engineering)
- Jim DeClerck (Michigan Technical University)
- Simone Manzato (Siemens-LMS, Belgium)
- Julie Harvie (Vibes Technology, Netherlands)
- Andreas Linderholt (Linnæus University, Sweden)
- Steven Klaassen, Daniel Rixen (Technical University of Munich, Germany)

Hey… we know those people!

Suggested Reading

Success through Failure: the paradox of design – Henry Petroski

To Engineer is Human – Henry Petroski

Thomas Edison: Inventing the Modern World – Alexander Kennedy

Small Is Beautiful: A Study of Economics As If People Mattered – E. F. Schumacher

Surely You're Joking, Mr. Feynman!: Adventures of a Curious Character - Richard P. Feynman

I Want to Be a Mathematician: An Automathography – Paul R Halmos

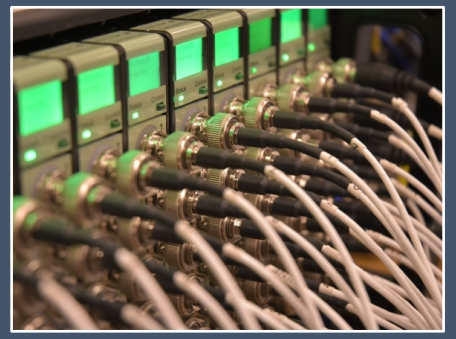
Thinking, Fast and Slow – Daniel Kahneman

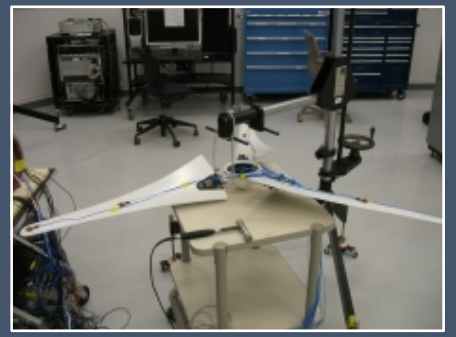
The Right Kind of Crazy – Adam Steltzner

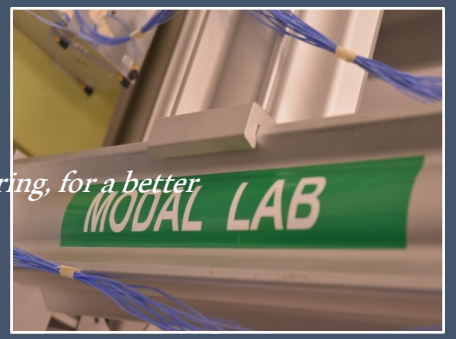
Student Profiles!

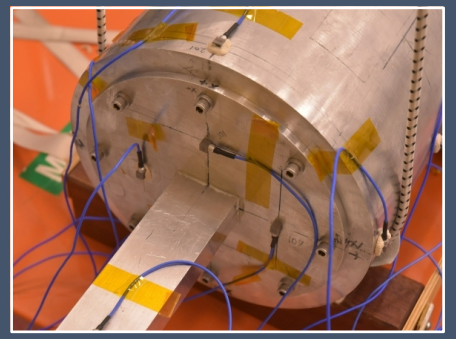
"There's nothing I believe in more strongly than getting young people interested in science and engineering, for a better tomorrow, for all humankind"

-Bill Nye









Detect.
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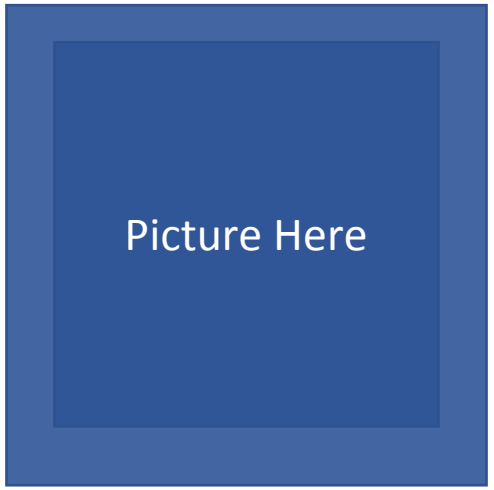
Student Profile: Dan Roettgen



Name: Dan Roettgen

Affiliation: Sandia National Labs

Education:

- Ph.D. University of Wisconsin Madison – Engineering Physics
- M.S. Ohio State University – Mechanical and Aerospace Engineering
- B.S. University of Kentucky – Mechanical Engineering and Japanese Studies

Research Interests: Substructuring, Nonlinear Experimentation, Dynamic Failure

Favorite Movie: Ant-Man

Favorite Book: The Two Towers

Hobbies: Hiking, Team Trivia, Board Games

Why are you interested in Structural Dynamics and Diagnostics? I like to understand how the dynamics of a system lead to failure and ideally how to prevent that failure.

What is an interesting fact about yourself others would not know? I used to professionally play card games and even have run podcasts about them.