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Optical Modal Methods

PRESENTED BY

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Engineering Sciences Center

NM Tech Collaboration Meeting

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Outline

- Motivation
- Overview of Experimental Modal Analysis
- Need for Agility in Modal Testing
- Optical Modal Methods: Technical details
- Demonstrating Agility
- Future Work for Optical Methods

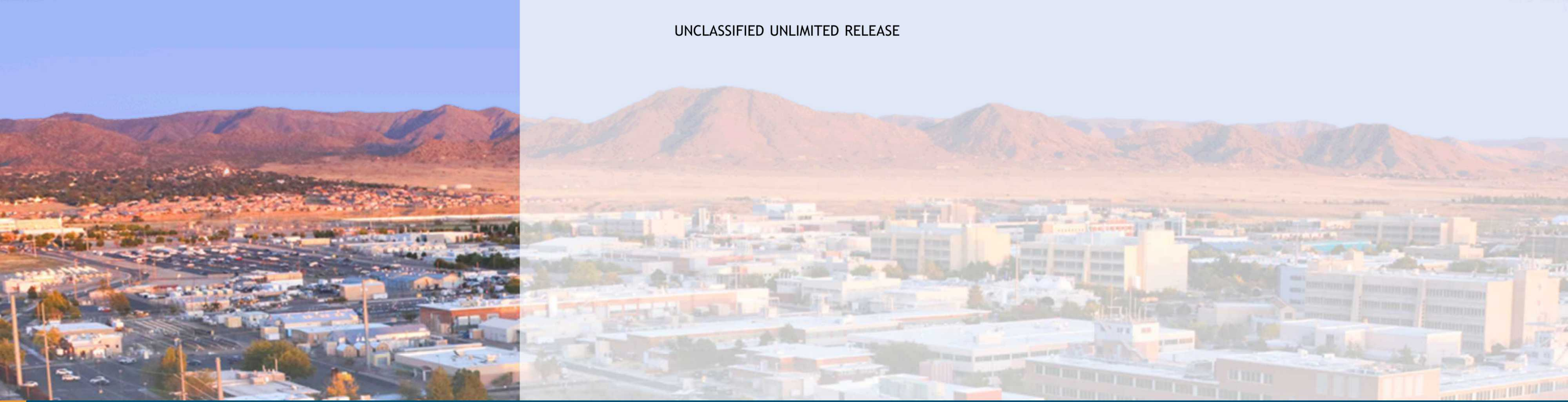
Motivation

"What would you say you do here?"

Motivation

- **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.



Overview of Experimental Modal Analysis

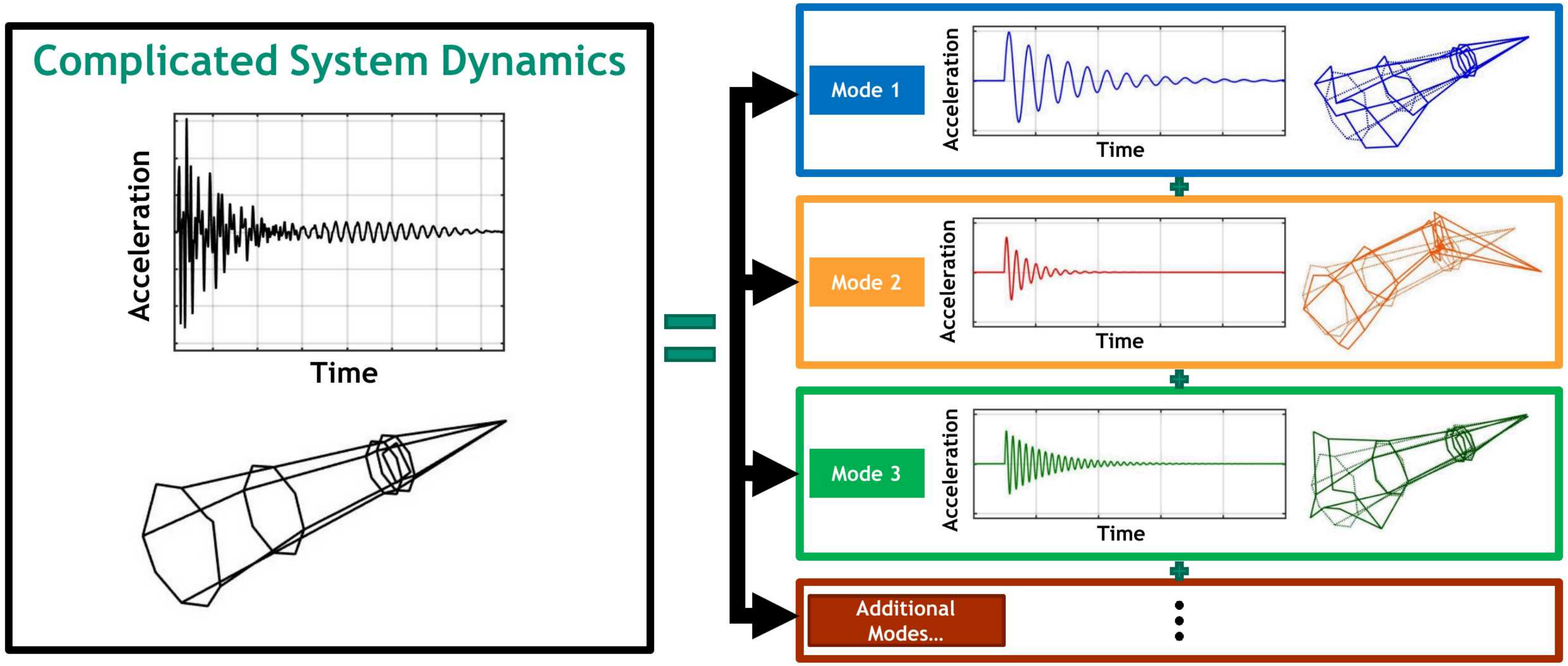
"Did you mean *model* ?"

Overview of Experimental Modal Analysis (EMA)

- **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**

Natural frequency
Damping ratio
Deformation shape

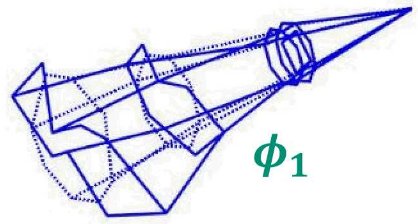
- All complex dynamic behavior is a superposition of modal responses



Overview of Experimental Modal Analysis (EMA)

- **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

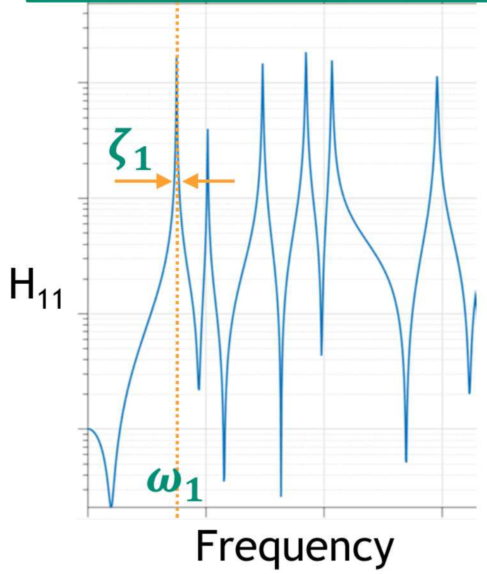
Mode shapes



Natural Frequencies & Damping ratios

Modal Superposition

- 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.

Need for Agility in Modal Testing

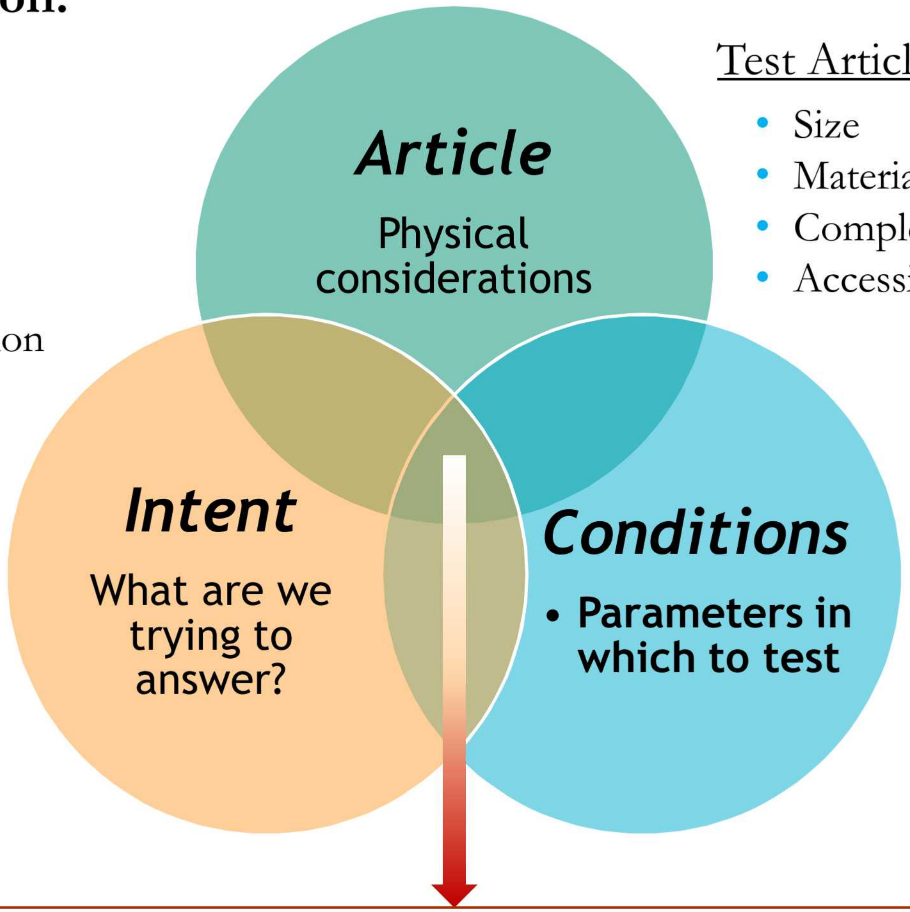
"You want me to test *what* ?"

Need for Agility in Modal Testing

- **Every test is different based on:**

<u>Test Intent</u>

- Modal data:
  - Model calibration and validation
  - Digital twin development
  - Support system requirements
- Experimental modal model
- Aging effects
- Part-to-part variability
- Damage detection
- Material properties



<u>Test Article</u>

- Size
- Materials
- Complexity
- Accessibility

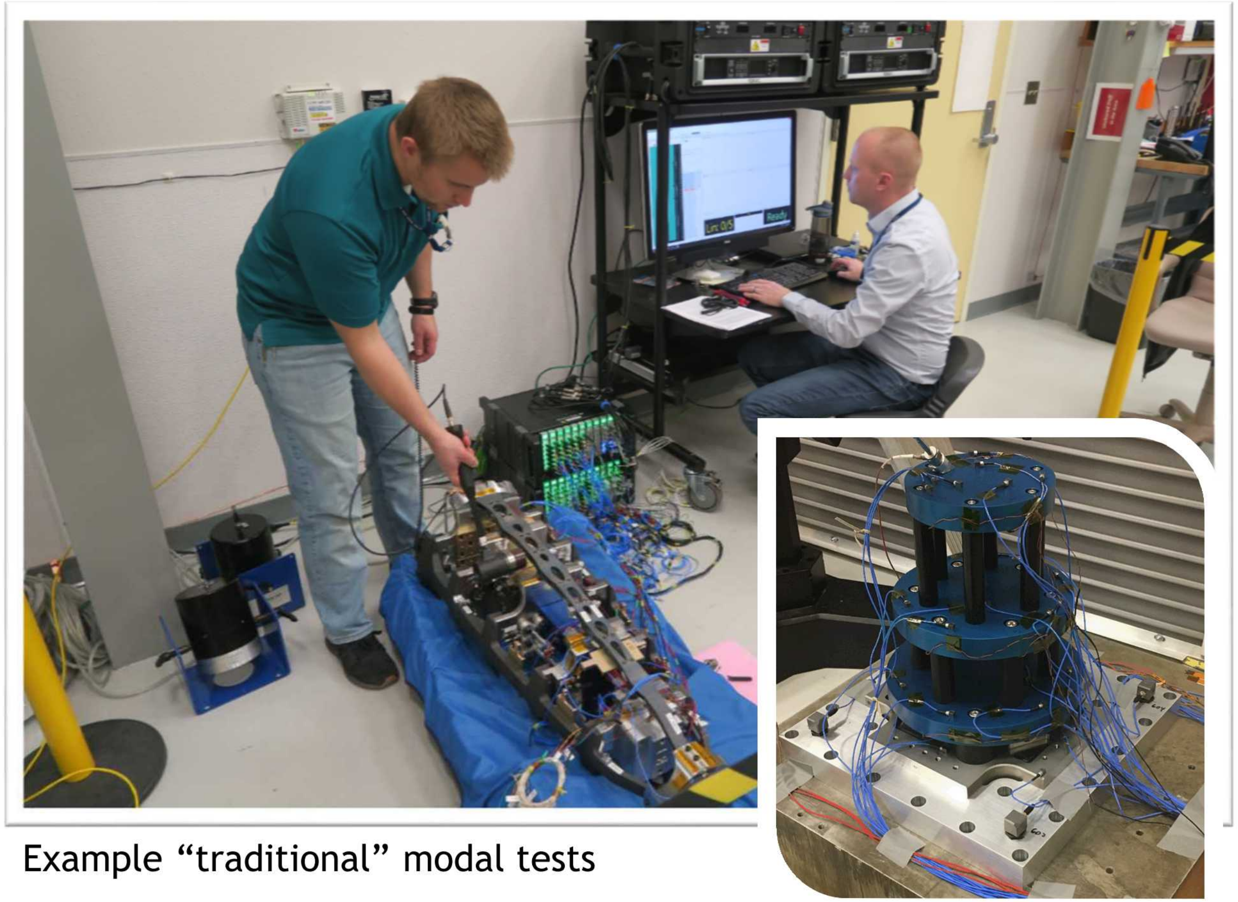
<u>Test Conditions</u>

- Boundary conditions
- Excitation type/level
- Temperature
- Time varying dynamics

Unique Test Space
Requires Collaboration with Customers (especially Analysts)

Need for Agility in Modal Testing

- **Pushing our capabilities outside the "traditional" experimental modal realm**



Example "traditional" modal tests

- Non-contact measurements
- Full-field data needed
- Part too small to attach accelerometers
- Extreme temperatures
- No time to perform normal test setup
- Dynamic or frequency response ranges
- Test object standoff distance
- No access to measurement locations
- Accelerometer cable effects/routing
- Combinations of the above…
- Future needs?

Need for Agility in Modal Testing

- **What does that mean for Experimental Structural Dynamics?**
  - New customers with new parts
  - New conditions for data collected
  - Different questions to be answered
  - Less physical instrumentation space, but need more data
  - Harder to convey meaningful modal results to customer
- **What are we doing about it?**
  - **Make our data acquisition modular: add Optical Modal Methods to our capabilities**
  - Better integration between test and analysis – leverage our models: **utilize modal expansion**
  - Improve how we interface with the analysts: **find advanced data visualization and delivery methods**

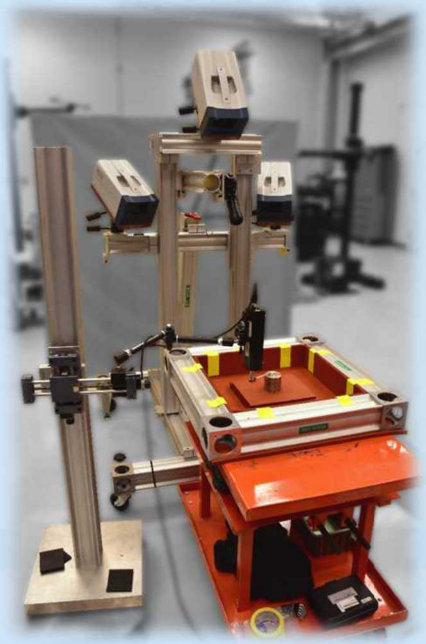
Optical Modal Methods Technical Overview

"Finally…laser beams and fancy cameras."

Optical Modal Methods: Technical Overview

- **Optical Modal Methods (OMM) studies at SNL currently encompasses two major technologies:**

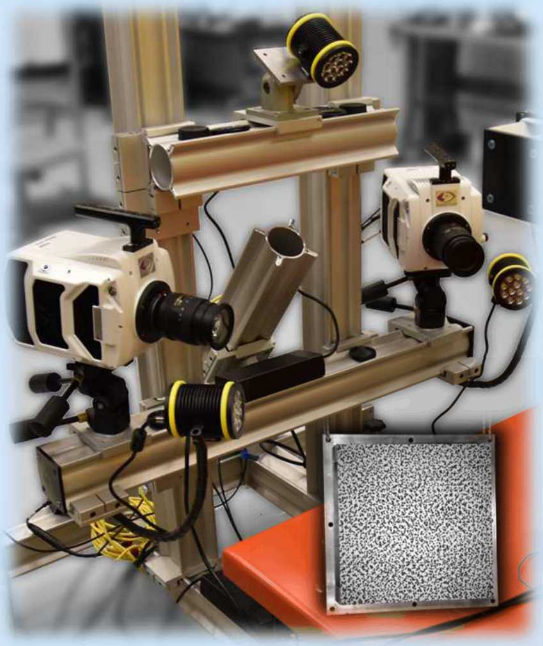
3D Laser Doppler Vibrometry



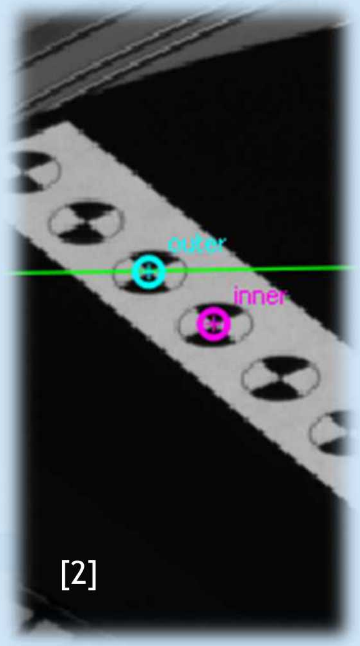
Scanning (SLDV)

Multi-Point (MPV)

3D High-Speed Imaging



Digital Image Correlation (DIC)

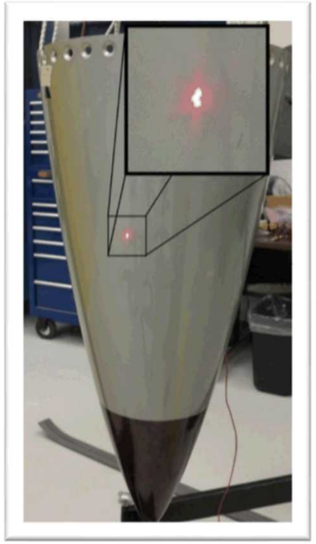


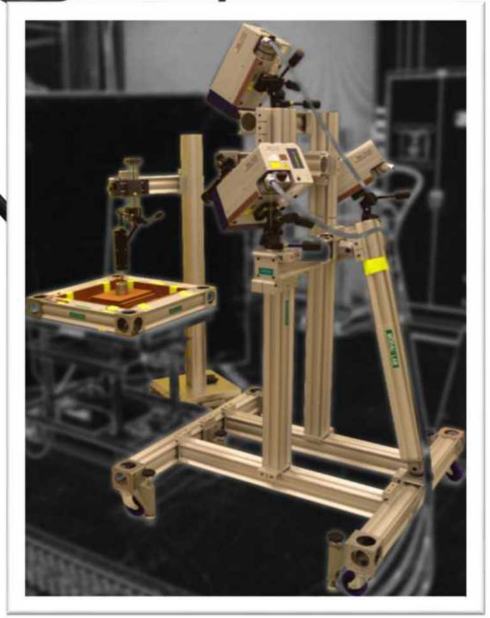
Discrete Point Marker Tracking (MT)

[2] Correlated Solutions VIC-3D (from https://www.correlatedsolutions.com/products/marker-tracking/

Optical Modal Methods: 3D Scanning Laser Doppler Vibrometry

- Uses Doppler shift principle to measure velocity
- Three lasers aimed at same spot for triaxial measurement
  - Calibration procedure for head positions relative to each other
  - Mirrors in each head control spot location
  - Measure one point at a time
- HeNe or Infrared (IR) heads





Benefits

- Non-contact
- Very small sensor footprint
- “Full-field” measurements, including strain
- Precision pointing
- 3D test geometry automatically generated
- Fast fielding time
- Measure response frequencies in the kHz and MHz

Drawbacks

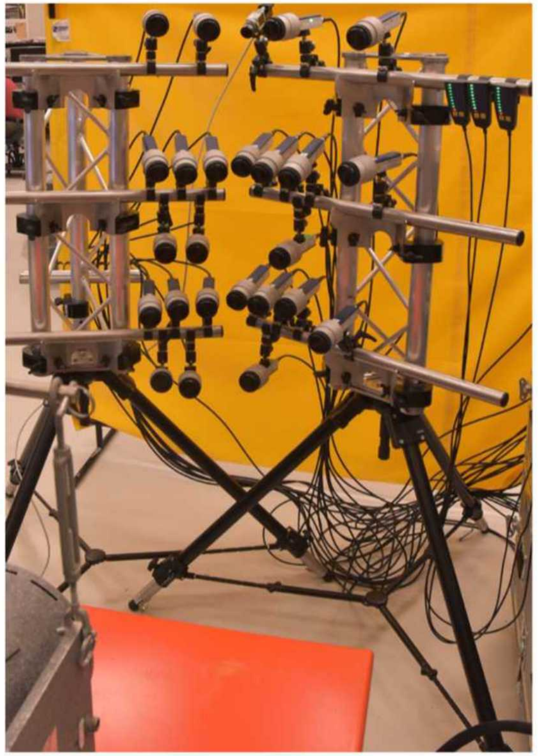
- Line-of-sight only
- Input must be repeatable, system can’t change
- Small motions only
- LDV noisier than accelerometers

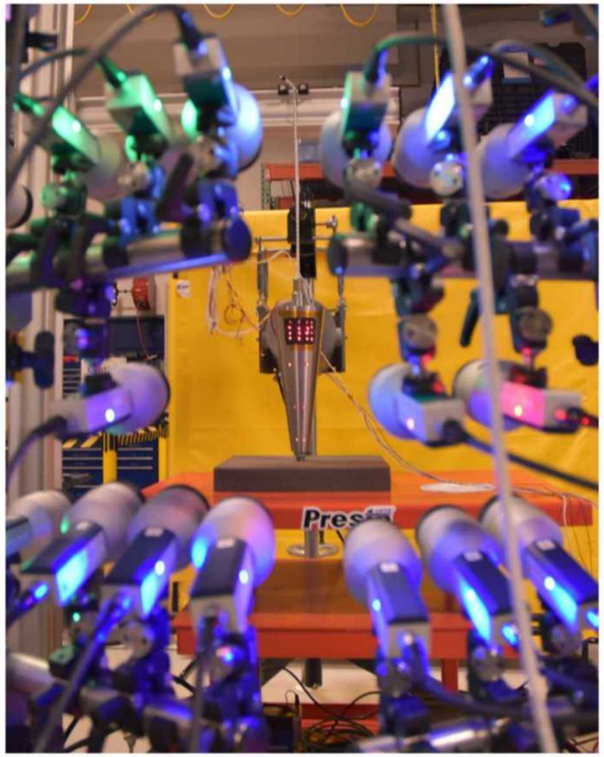
Optical Modal Methods: Multi-Point Vibrometry

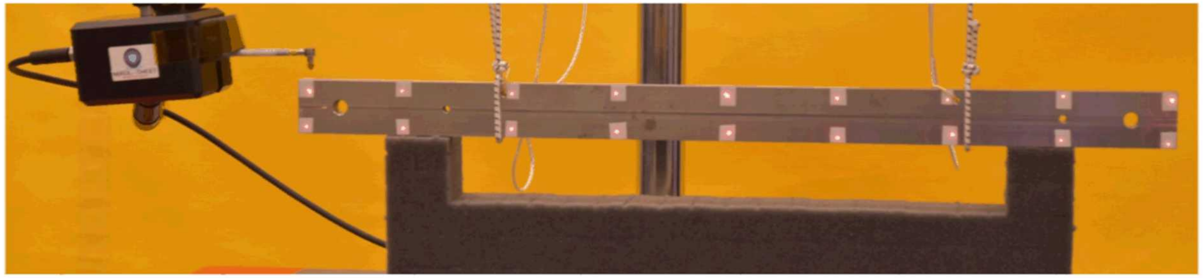
- System loaned by Polytec for evaluation
- Uses Doppler shift principle to measure velocity
- 24-48 independent infrared (IR) fiber optic lasers
- Combine three to make a triaxial measurement
- Measure all points at one time

Benefits
- Non-contact
- Concurrent measurements
  - Transient input/system changes
- Flexibility in number of points measured
- Positioning of laser heads around object
- Infrared

Drawbacks
- Time consuming to set up
- Manually aimed, no automatic geometry
- Estimate Euler angles and surface normal
- Line-of-sight only
- Small motions only
- Not full-field







Optical Modal Methods: 3D Digital Image Correlation (DIC)

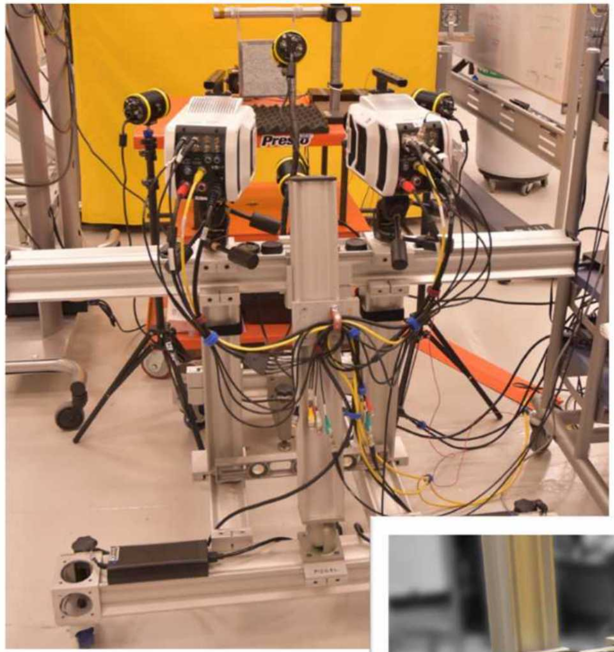
- High-speed stereo camera setup
  - 12,000 frames/second (fps) at 1280x800 pixels
  - Calibration to determine camera parameters
- DIC tracks speckle pattern subsets
  - Sub-pixel accuracy
  - Use photogrammetry to triangulate positions in 3D

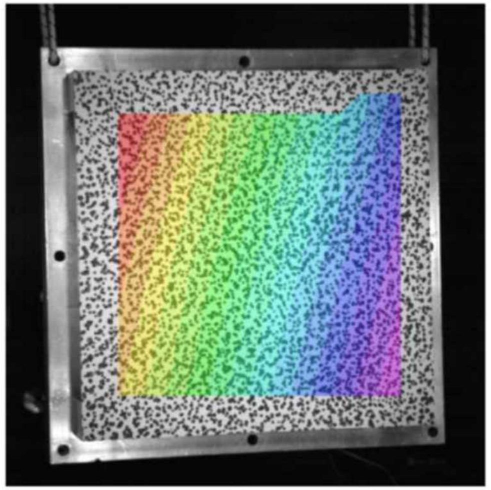
Benefits

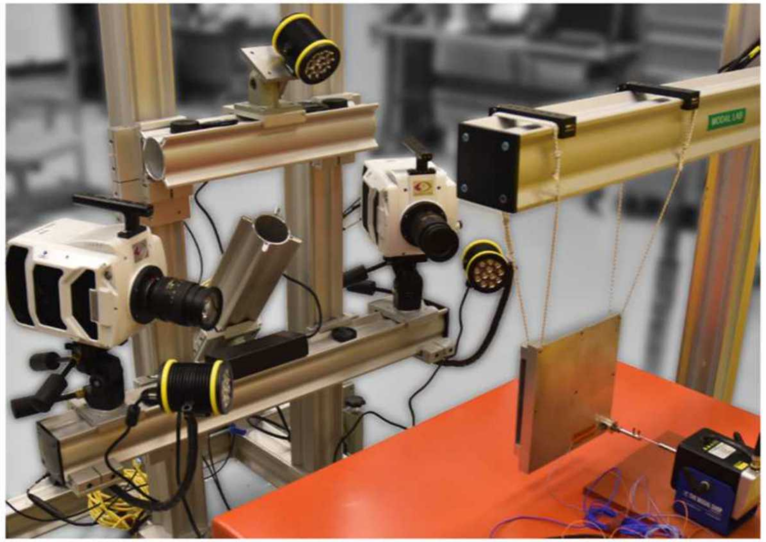
- Non-contact
- Full-field concurrent measurements
- Large deformations are permissible
- Extremely fast setup and data collection
- Flexibility in camera setup

Drawbacks

- Extensive data processing times and data storage
- Measurement resolution dependent of field of view
- Line-of-sight only
- Noisy measurements relative to other methods





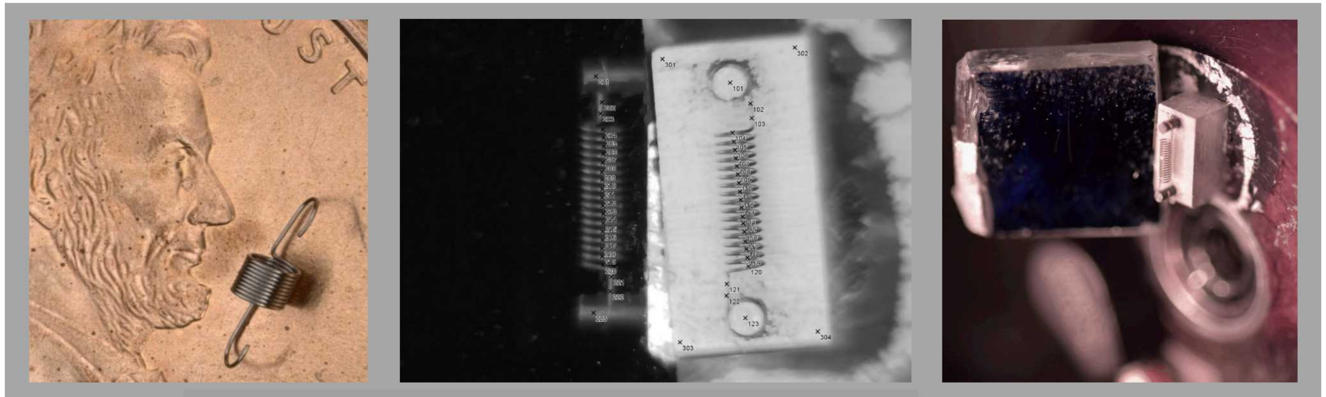


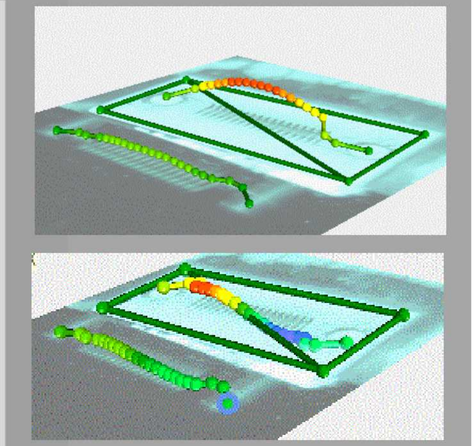
Demonstrating Agility

"Does it actually work?"

Agility: Physical Size

- **Test a range of different sized objects**
  - Spring – much too small for accelerometers
  - Full NW system – difficult to get dense measurements without mass loading, cable effects, long test times

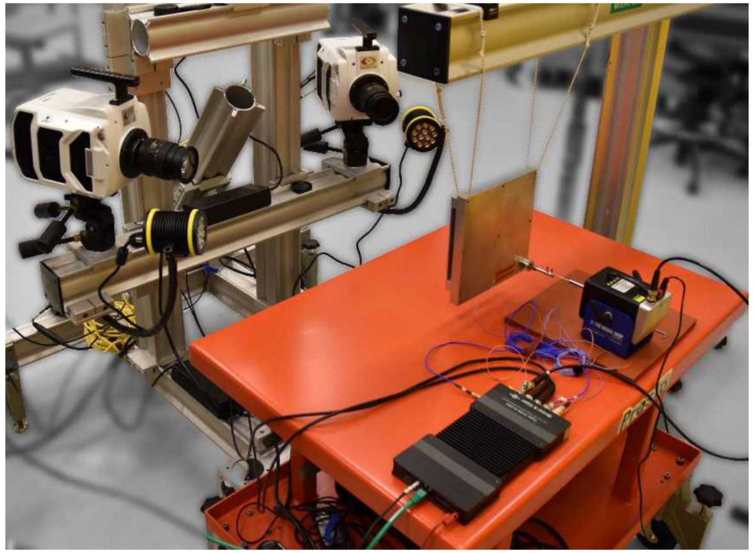


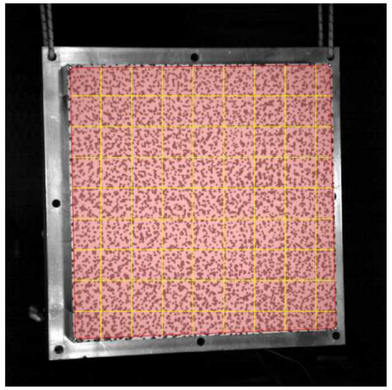


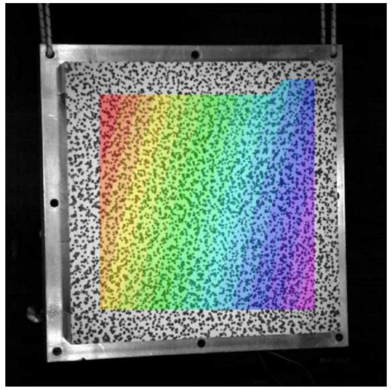
Impact (Immediate-Long Term):
Capability to test small parts we previously could not. Large tests can be conducted with high spatial density.

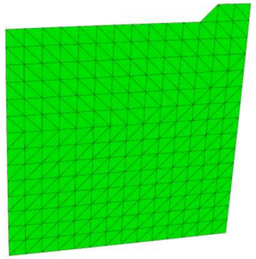
Agility: New Capability

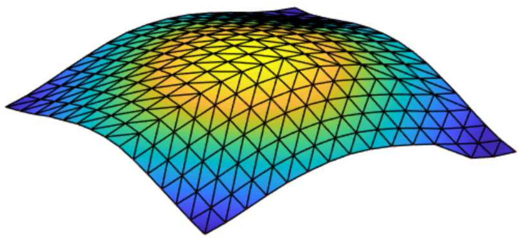
- **Assess DIC for modal applications**
  - Is it a viable tool?
  - Combine with standard modal data acquisition
  - New data processing needs
- Academic plate structure
  - Used in previous studies, well characterized
  - Collected synchronized time history data (DAQ + Cameras)
  - Data processing
    - Correlated Solutions VIC-3D → Python → Matlab

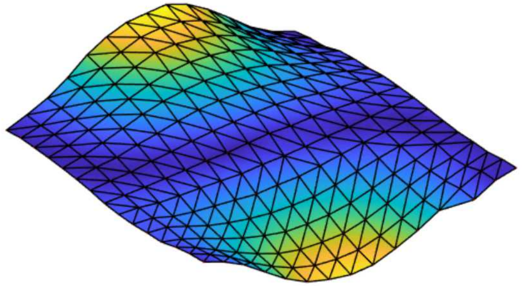








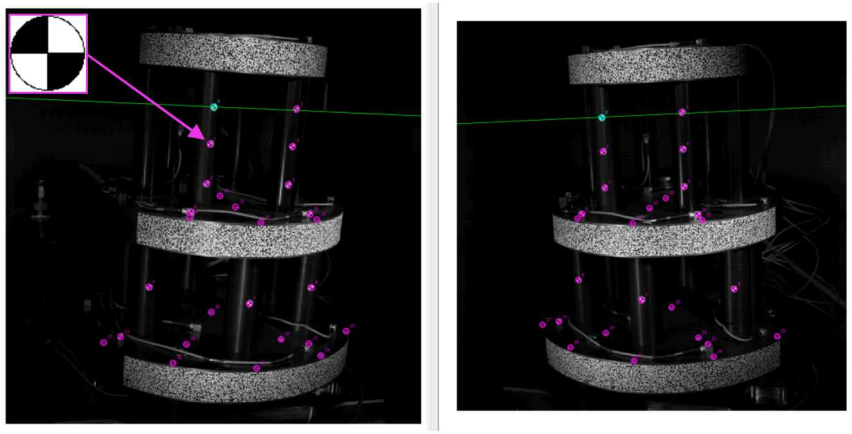


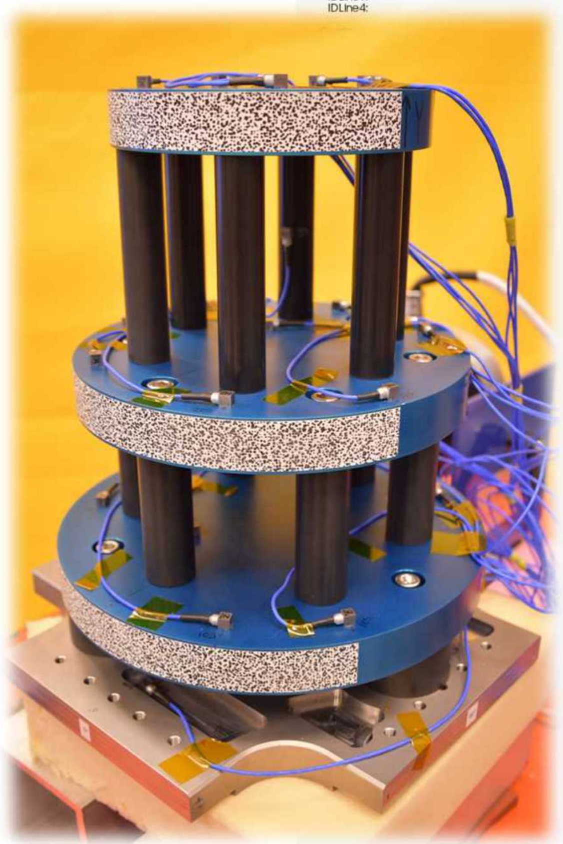


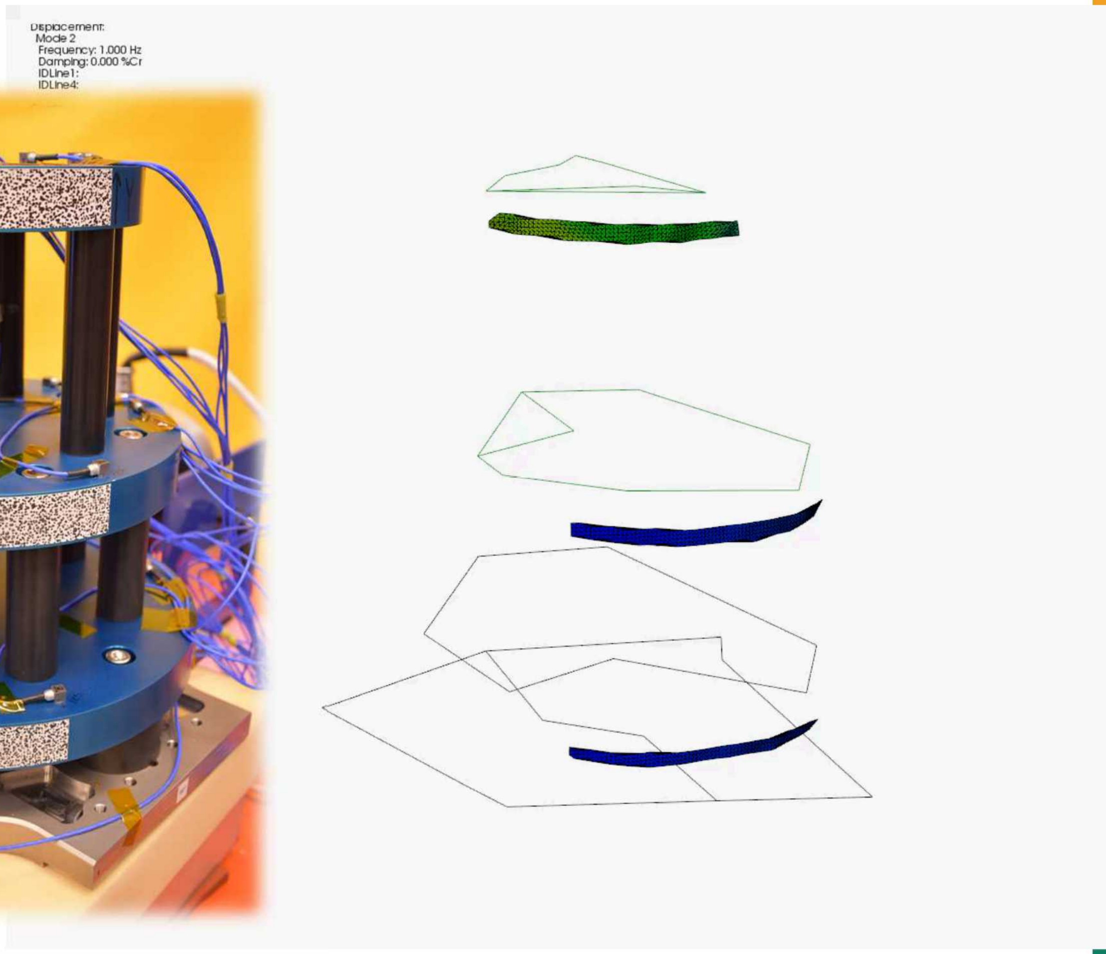
Impact (Near Term):
Demonstration of new lab capability – combining traditional DAQ and optical data, using our standard tools.

Agility: New Capability

- **Assess DIC for modal applications**
  - Is it a viable tool?
  - Combine with standard modal data acquisition
  - New data processing needs
- "Wedding Cake" test structure
  - Combined accelerometers with camera data
  - Worked with marker tracking also
  - Printed markers and speckles on label stickers



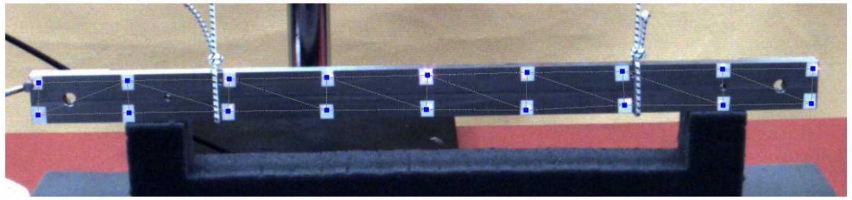


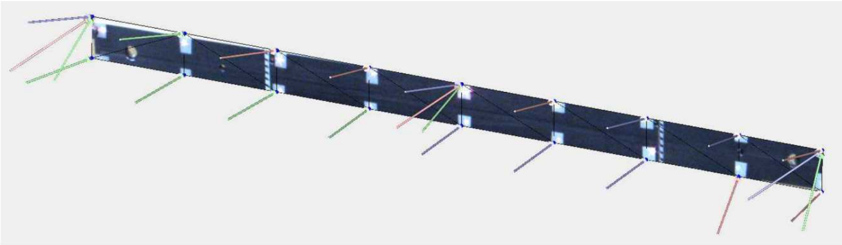


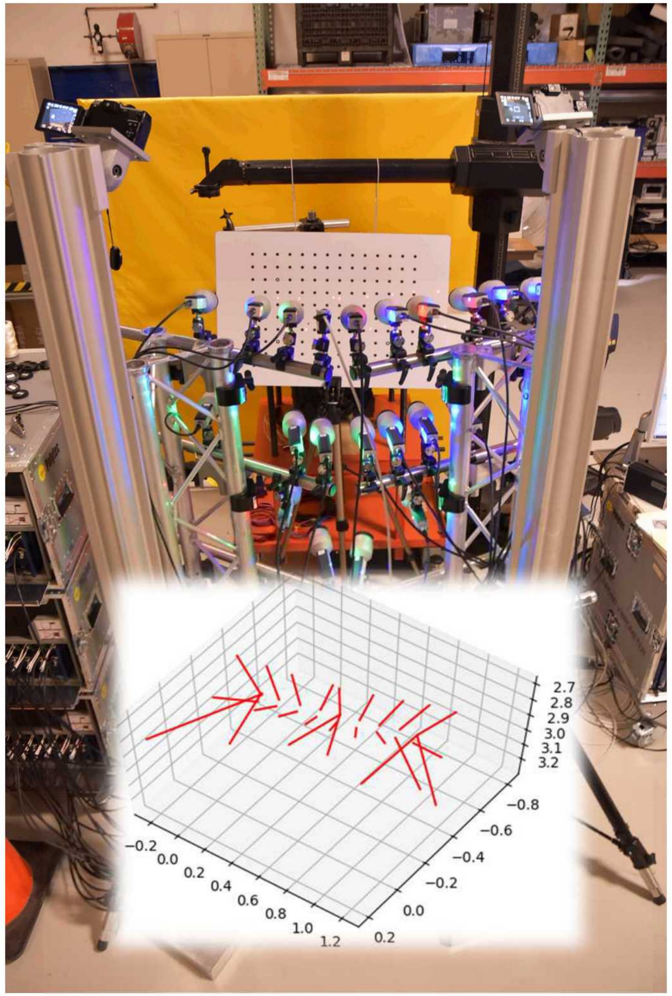
Impact (Near Term):
Demonstration of new lab capability – combining traditional DAQ and optical data, using our standard tools.

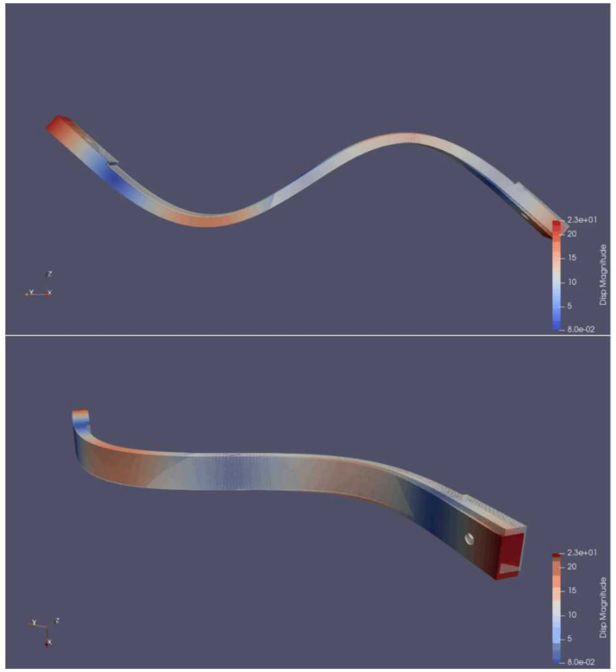
Agility: Non-Contact Measurements

- **Beam with sensitive contact pads for Advanced Simulation and Computing (ASC) project**
  - Require non-contact measurements
  - Euler angles had to be estimated manually
    - Used stereo-camera 3D triangulation to measure angles
  - Modal expansion of results for model comparison





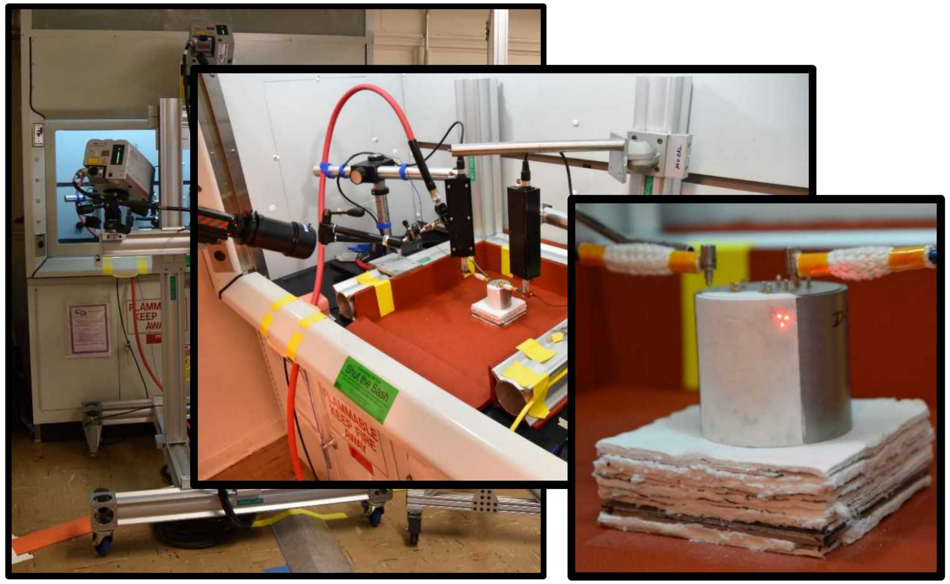


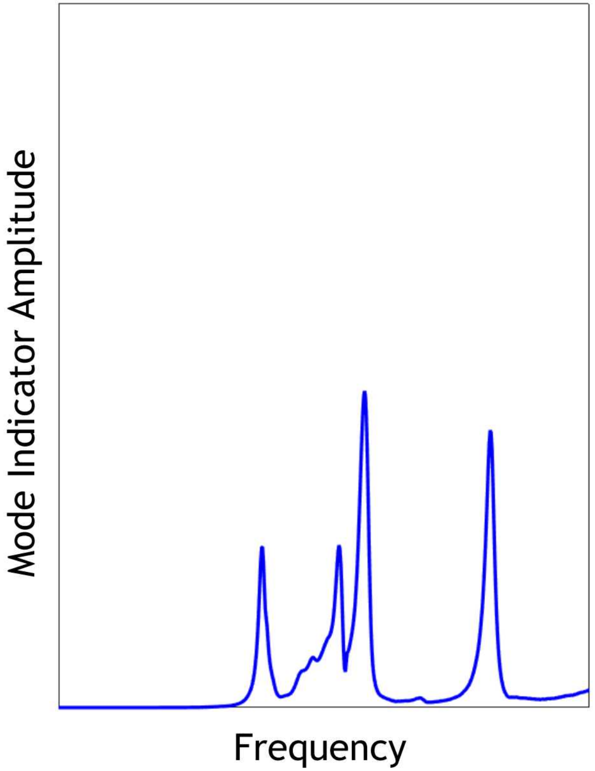


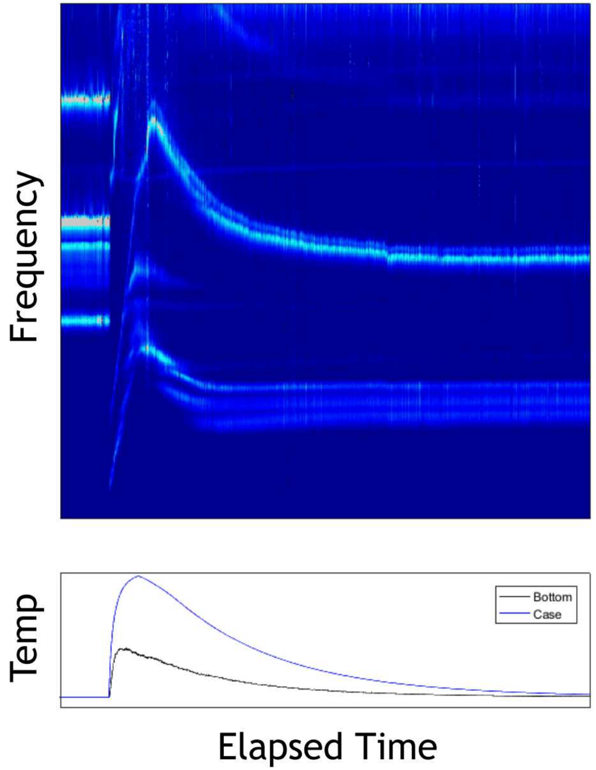
Impact (Near):
Protected customer test hardware. Made MPV practical to use with a cross-field optical solution.

Agility: Extreme Temperature + Time Varying Dynamics + Inaccessibility

- **Activated thermal battery test**
  - How do the dynamics change during life cycle?
  - Difficult test:
    - Extreme temperature
    - Time varying dynamics
    - Inaccessible internals
    - Standoff distance + glass barrier







Impact (Immediate – Long Term):
Provided important, never before observed, dynamic characterization data for model updating.

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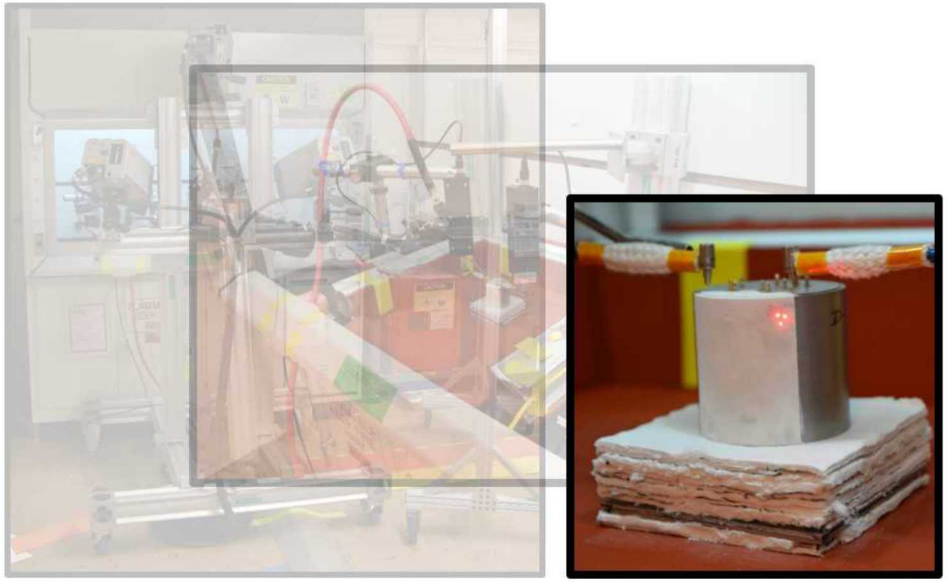

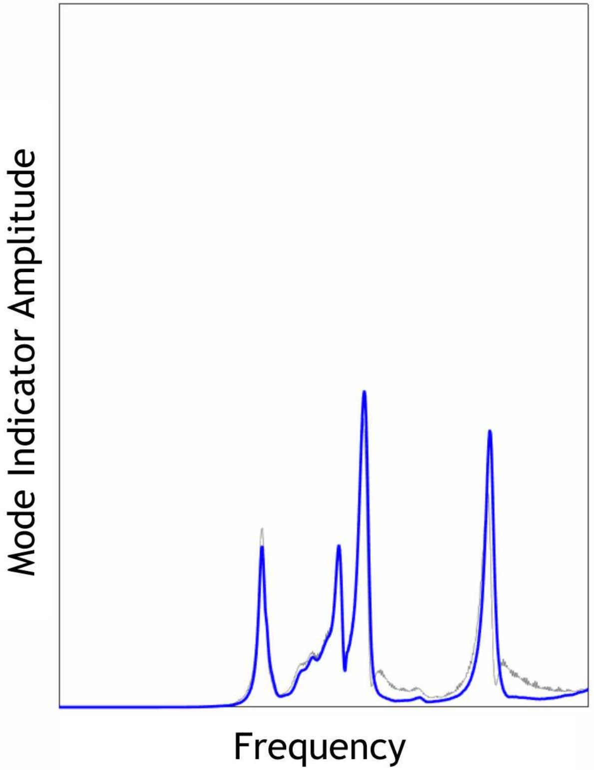

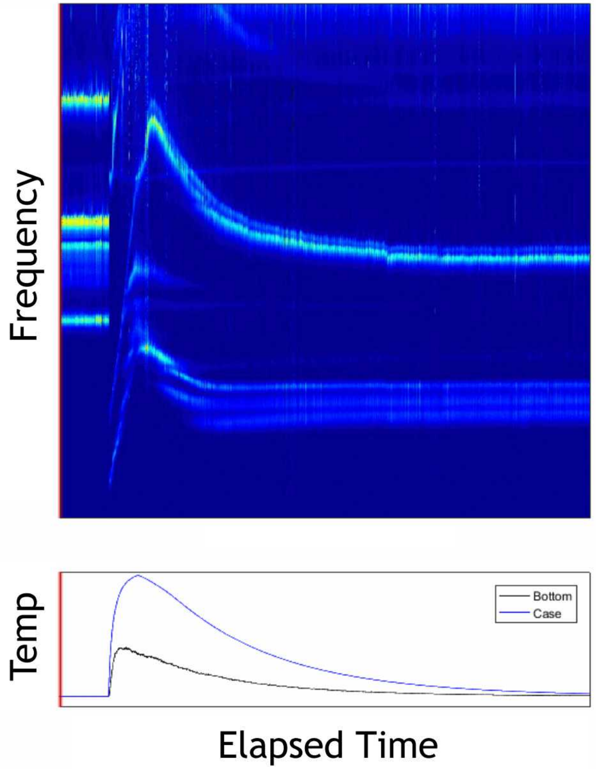

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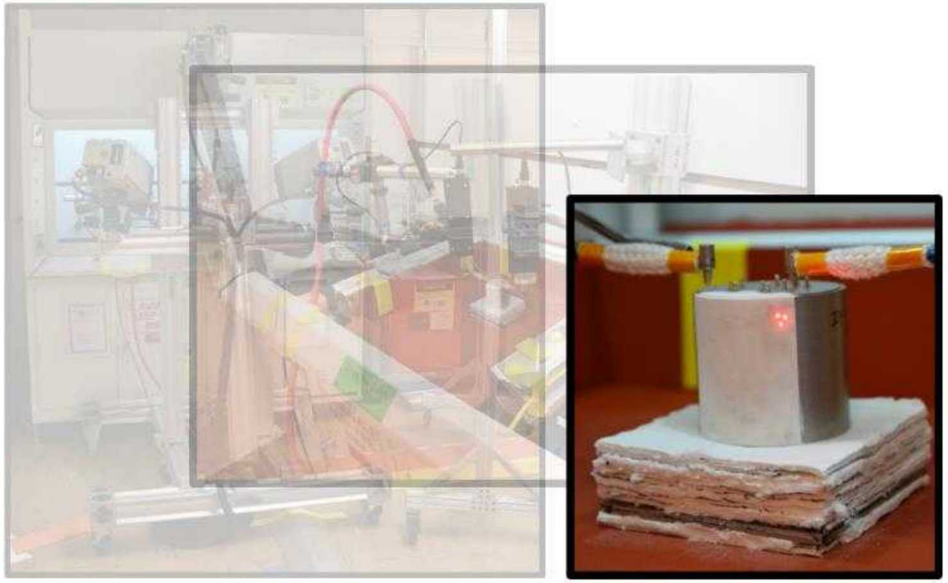

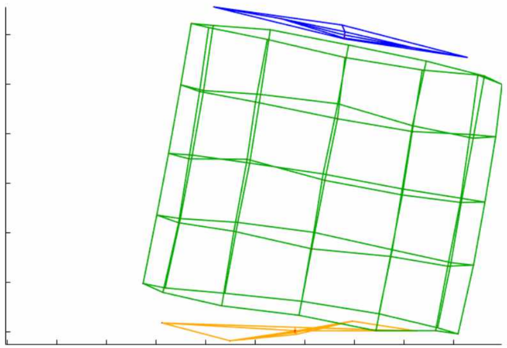

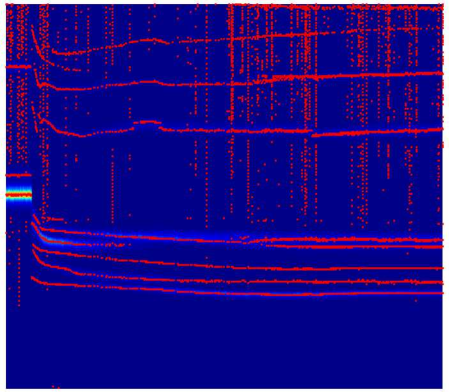

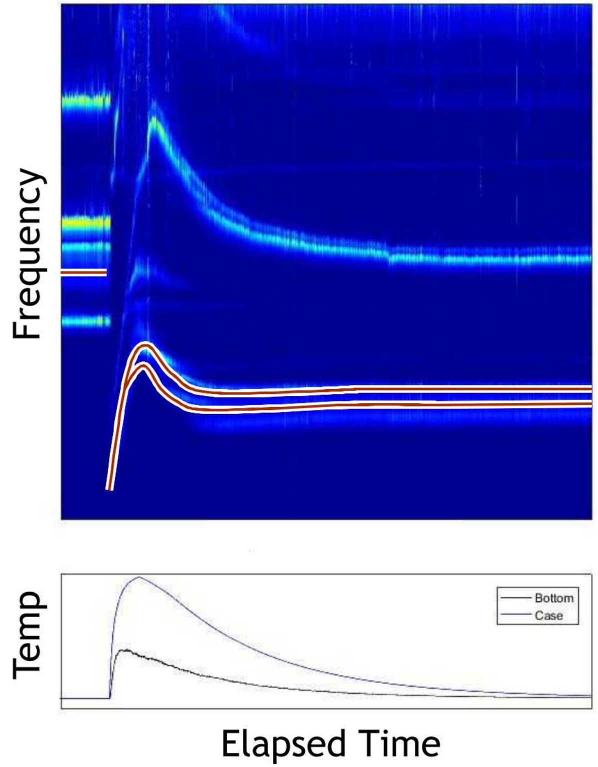

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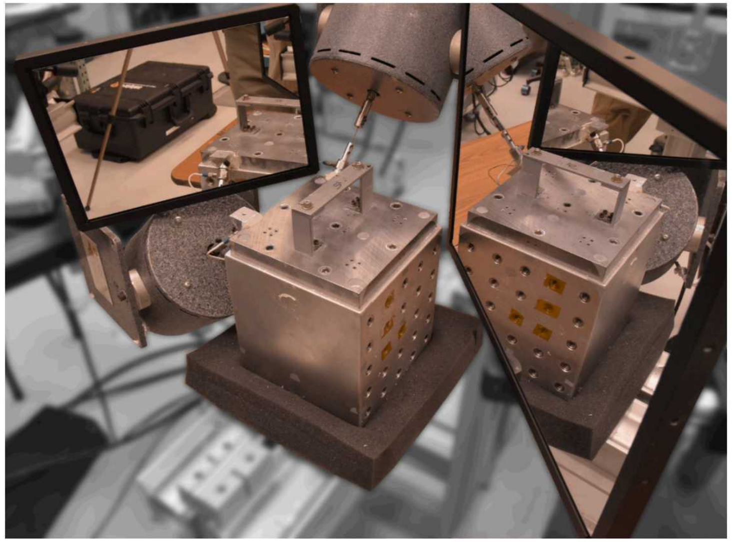
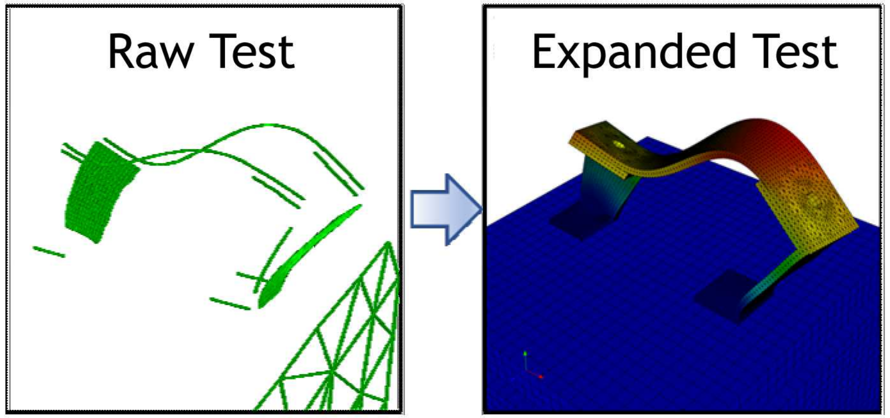
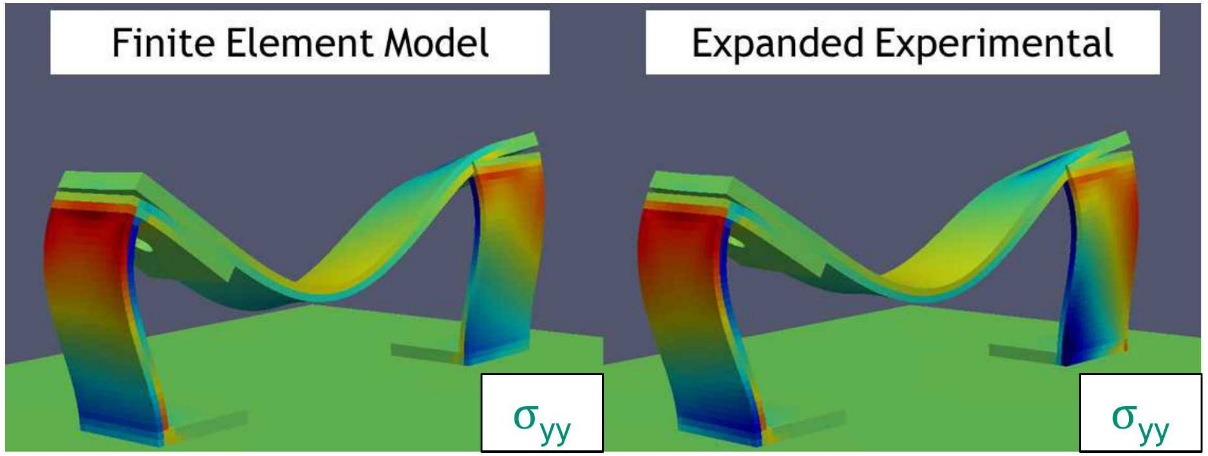
Agility: Full-Field Data

- **Full-Field Strain from 3D SLDV**
  - LDV strain measurements are difficult due to noise
  - Dense scan times can be long (hours)
  - Developed method for full-field strain from LDV
    - Uses modal expansion
    - No filters, smoothing happens in expansion
    - Fast scan times







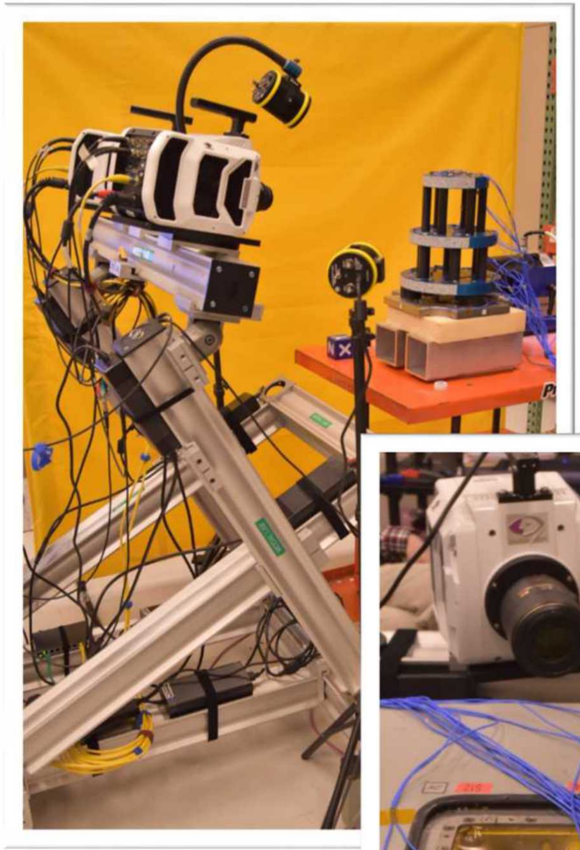
Impact (Near):
New method for full-field strain measurements with LDV that is robust to noise and free of filter effects.

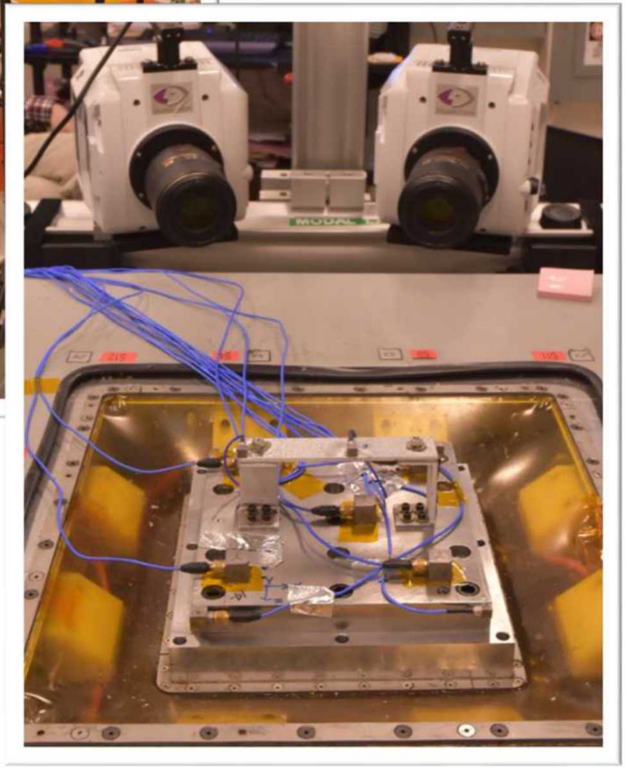
Closing Thoughts

"Almost there."

Future Work for Optical Methods

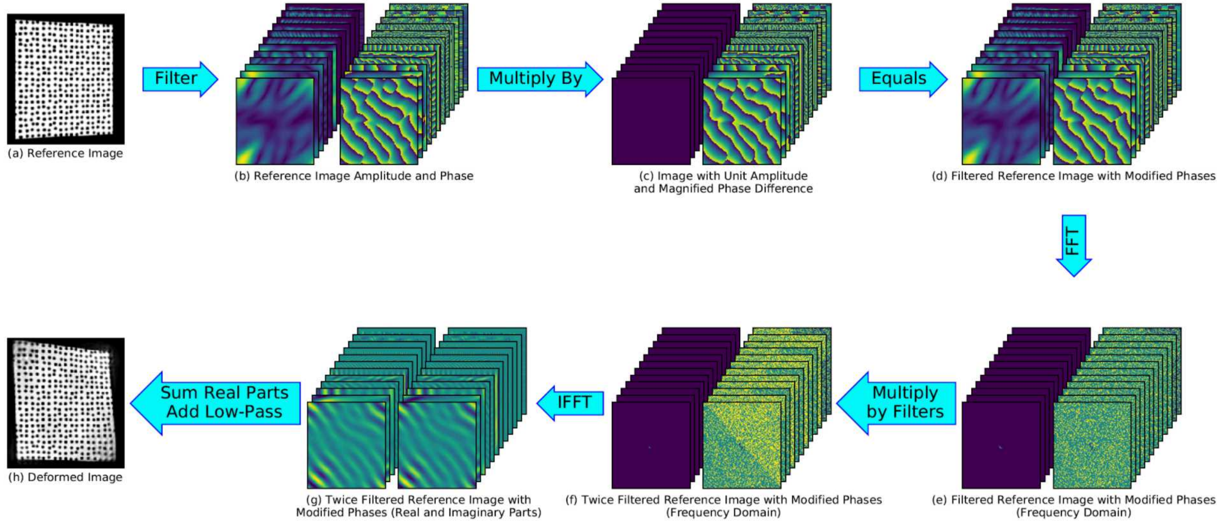
- Push SLDV into mainstream for large scale modal tests
  - Well established tool at this point
- Continue investigating high-speed imaging for dynamics
  - Establish best-practices, current limitations
  - Explore noise floor
  - Uncertainty quantification?
  - Move from Research & Development to established tool
  - Extended applications space for optical structural dynamics?
- Expand to nonlinear experimental work
  - Nonlinear models becoming more prevalent
  - Need methods for test/model validation
  - Imaging offers full-field, concurrent measurements for large deformations

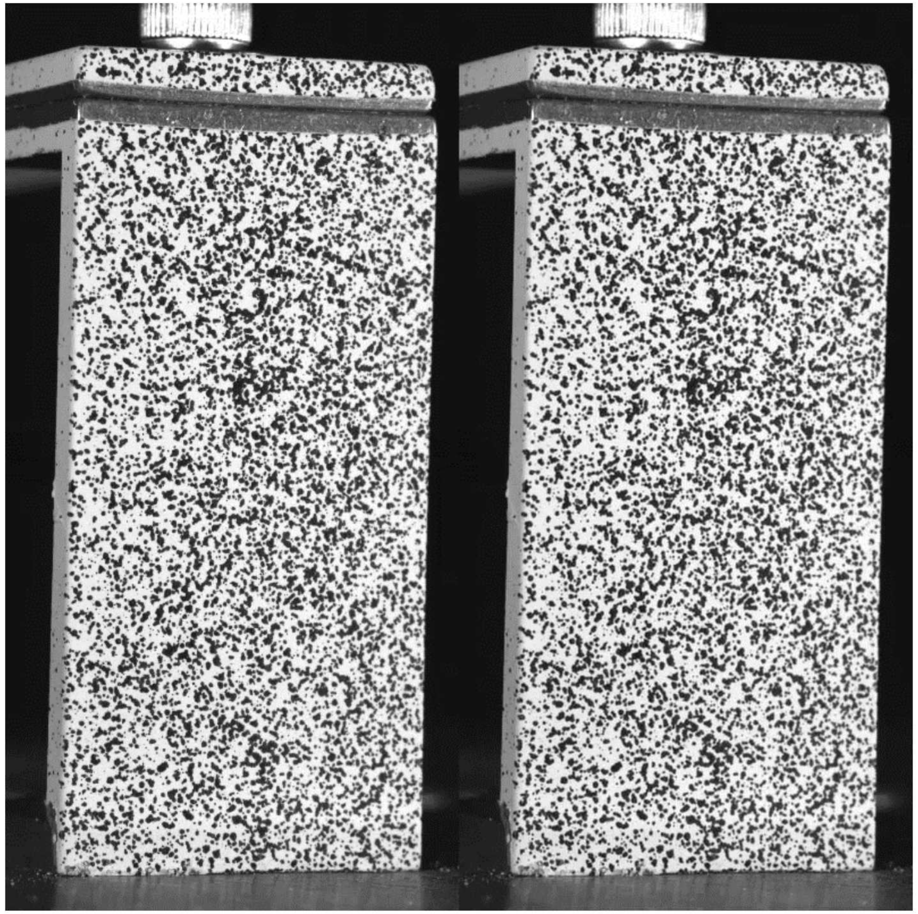




Future Work for Optical Methods

- Other image processing techniques
  - Phase-based motion extraction/magnification
  - Optical flow
- High-speed X-ray
- Increased collaboration with academia
  - Contract with University of Massachusetts Lowell





Motion magnification

Relevant Publications

1. Rohe D.P. (2019) ***Using High-Resolution Measurements to Update Finite Element Substructure Models***, In: Di Maio D. (eds) Rotating Machinery, Vibro-Acoustics & Laser Vibrometry, Volume 7. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham

2. Witt B., Rohe D., Schoenherr T. (2019) ***Full-Field Strain Shape Estimation from 3D SLDV***, Proceedings of the 37th International Modal Analysis Conference, Orlando, Florida, 2019

3. Rohe, D.P. (2019) ***Dynamic Measurements on Miniature Springs for Flaw and Damage Detection***, In: Di Maio D. (eds) Rotating Machinery, Vibro-Acoustics & Laser Vibrometry, Volume 7. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham

4. Witt B., Zwink B. (2018) ***Pushing 3D Scanning Laser Doppler Vibrometry to Capture Time Varying Dynamic Characteristics***, In: Rotating Machinery, Hybrid Test Methods, Vibro-Acoustics & Laser Vibrometry, Volume 8, Conference Proceedings of the Society for Experimental Mechanics Series, Springer

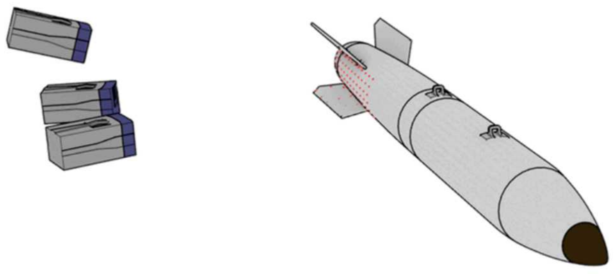
5. Rohe, D.P. (2017) ***Strategies for Testing Large Aerospace Structures with 3D SLDV***, In: Di Maio D., Castellini P. (eds) Rotating Machinery, Hybrid Test Methods, Vibro-Acoustics & Laser Vibrometry, Volume 8. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham

6. Witt B., Zwink B., Hopkins R. (2017) ***Applications of 3D Scanning Laser Doppler Vibrometry to an Article with Internal Features***, In: Rotating Machinery, Hybrid Test Methods, Vibro-Acoustics & Laser Vibrometry, Volume 7, Conference Proceedings of the Society for Experimental Mechanics Series, Springer

7. Reu, P.L., Rohe, D.P., Jacobs, L.D. (2016). ***Comparison of DIC and LDV for practical vibration and modal measurements***, Mechanical Systems and Signal Processing. 86. 10.1016/j.ymssp.2016.02.006.

8. Rohe, D.P. (2016) ***Modal Testing of a Nose Cone Using Three-Dimensional Scanning Laser Doppler Vibrometry***,. In: De Clerck J., Epp D. (eds) Rotating Machinery, Hybrid Test Methods, Vibro-Acoustics & Laser Vibrometry, Volume 8. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham

Questions?



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