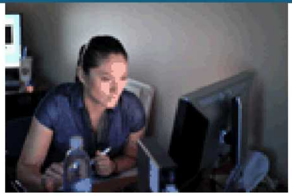
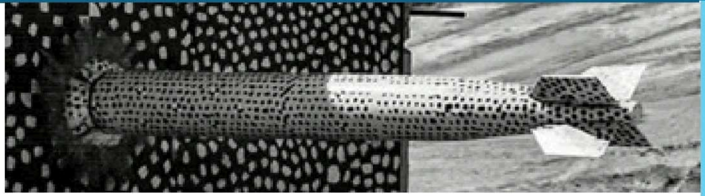
SAND2019-5428PE

Recent Developments in Optical Modal Methods





PRESENTED BY

Bryan Witt, SNL Experimental Structural Dynamics

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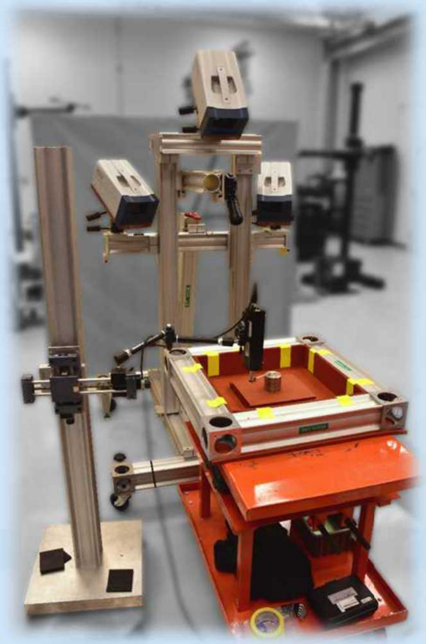
Outline

- Optical Modal Methods
- Multi-Point Vibrometer Assessment
- Photogrammetry for Structural Dynamics
  - Overview
  - Challenges
  - Setup
  - Current studies
- Future Work

Optical Modal Methods

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

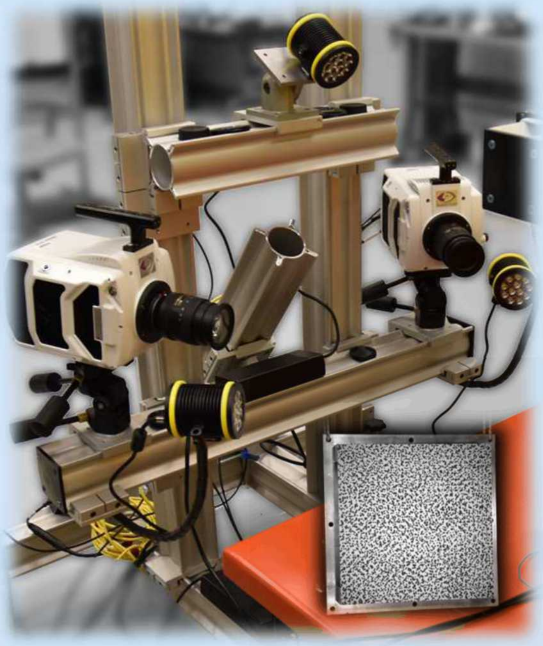
3D Laser Doppler Vibrometry



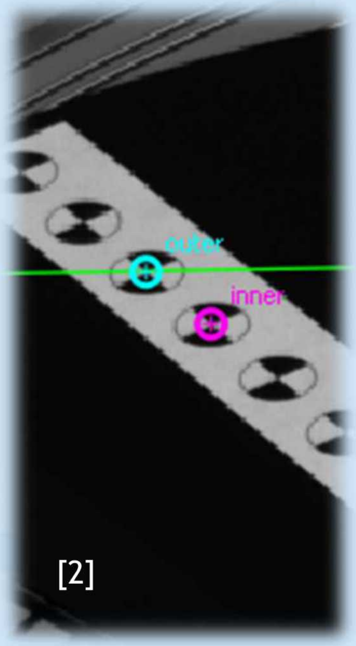
Scanning (SLDV)

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/

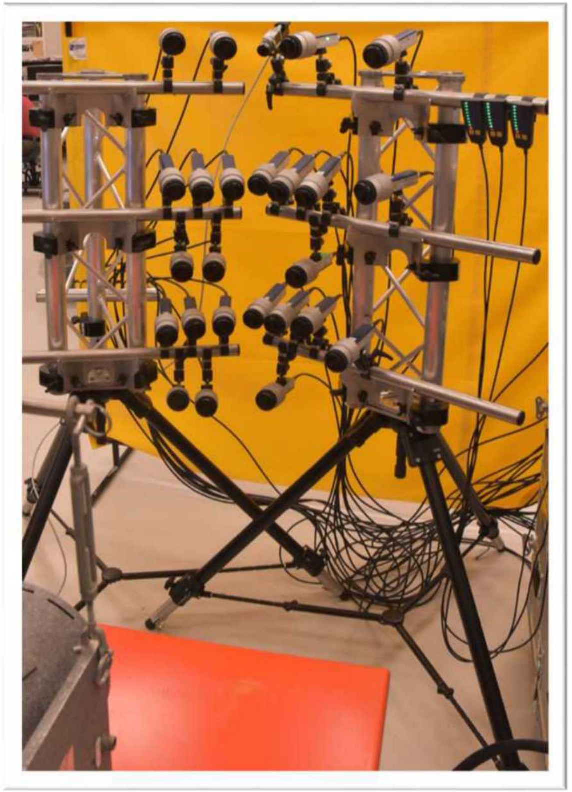
Multi-Point Vibrometer Assessment

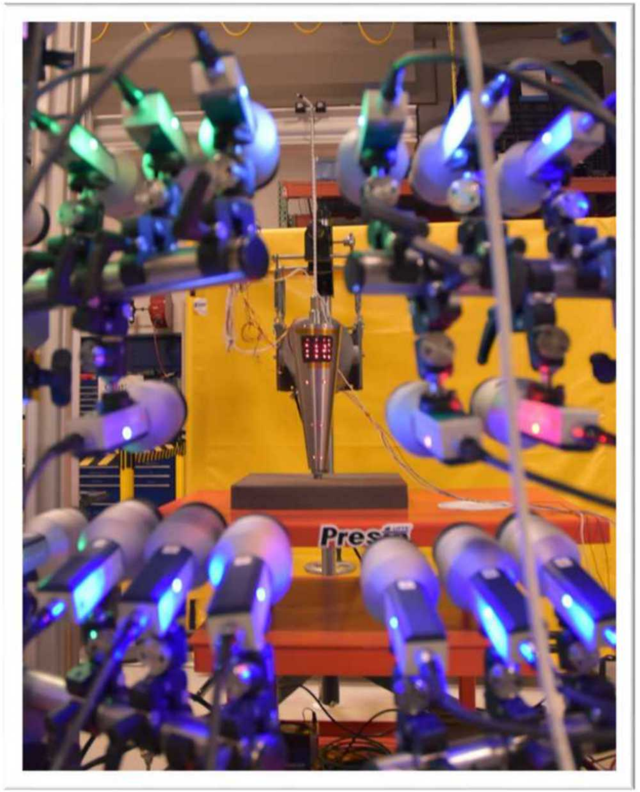
Multi-Point Vibrometry Overview

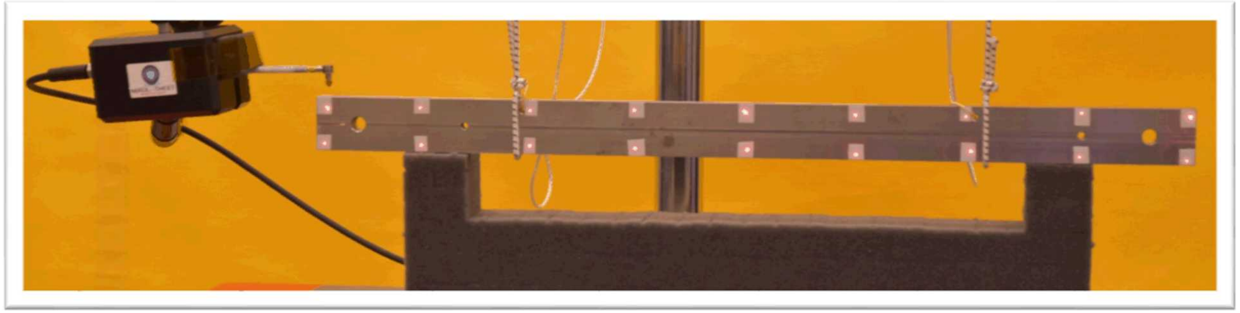
- System loaned by Polytec for evaluation
- Uses Doppler shift principle to measure velocity
- 24-48 independent infrared (IR) fiber optic lasers
- Combine three to make a triaxial measurement
- Measure all points at one time

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

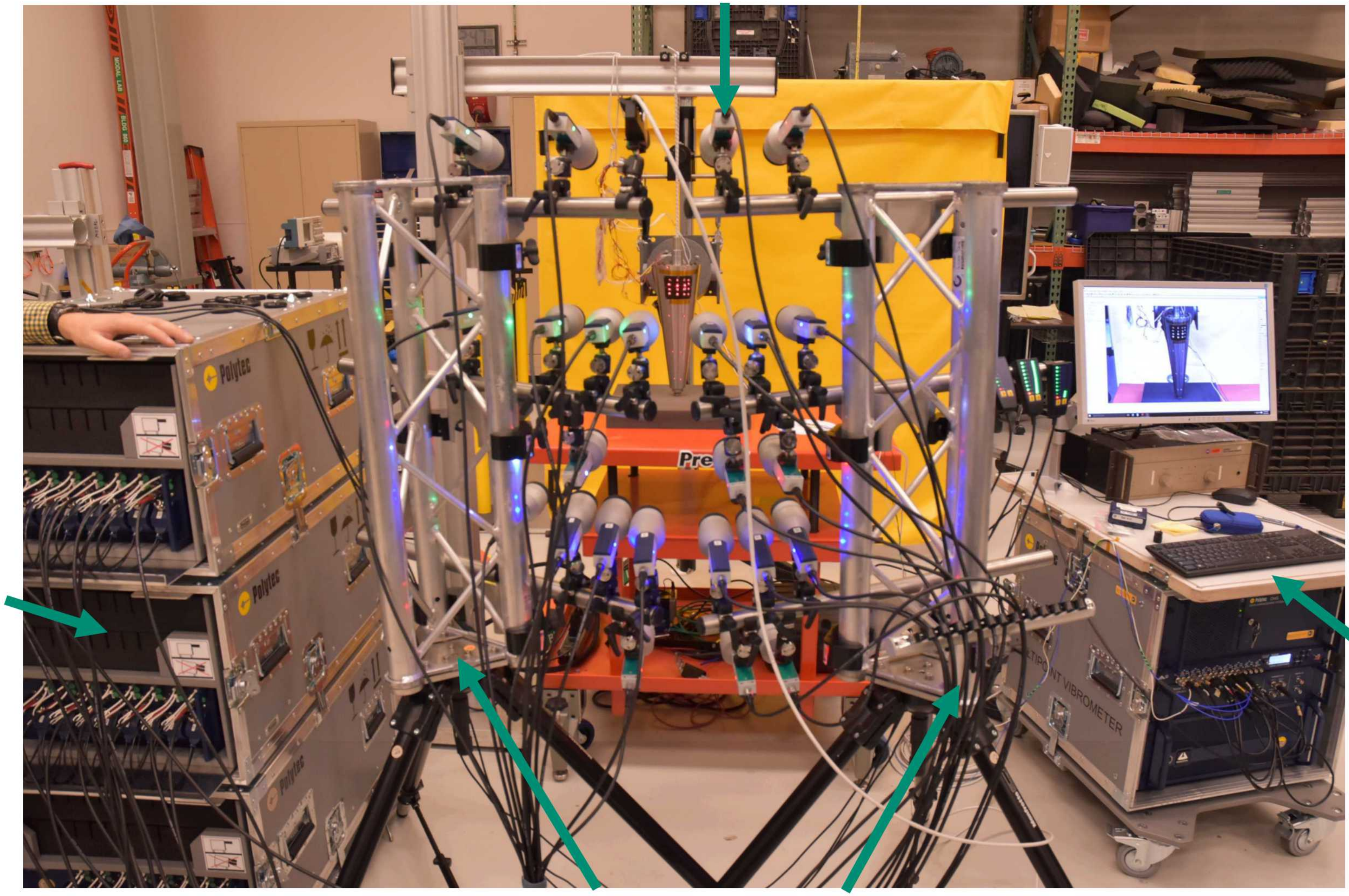






Multi-Point Vibrometry Assessment

24-48 Independent Laser Heads

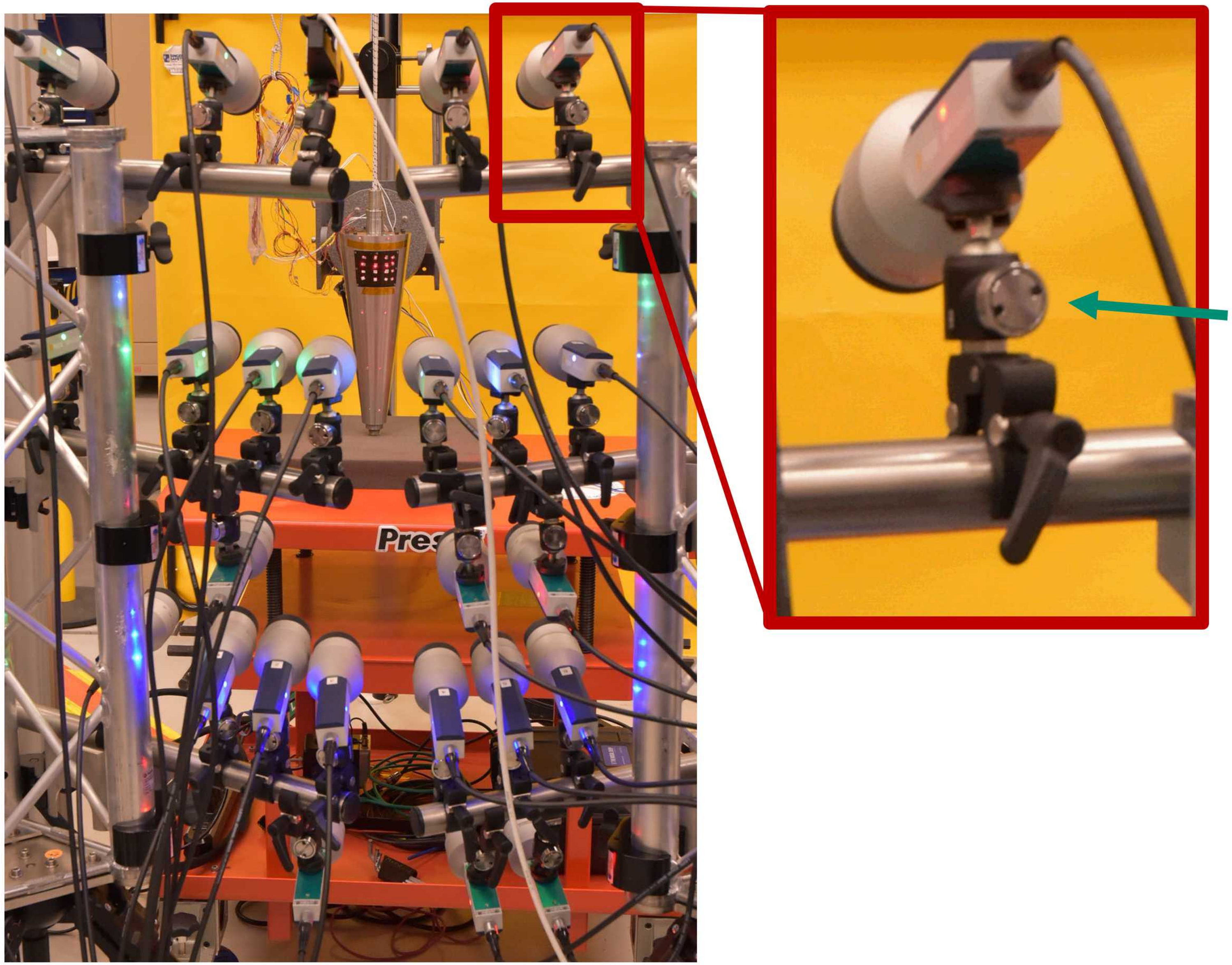


Fiber optics cabinet

Data Acquisition Station

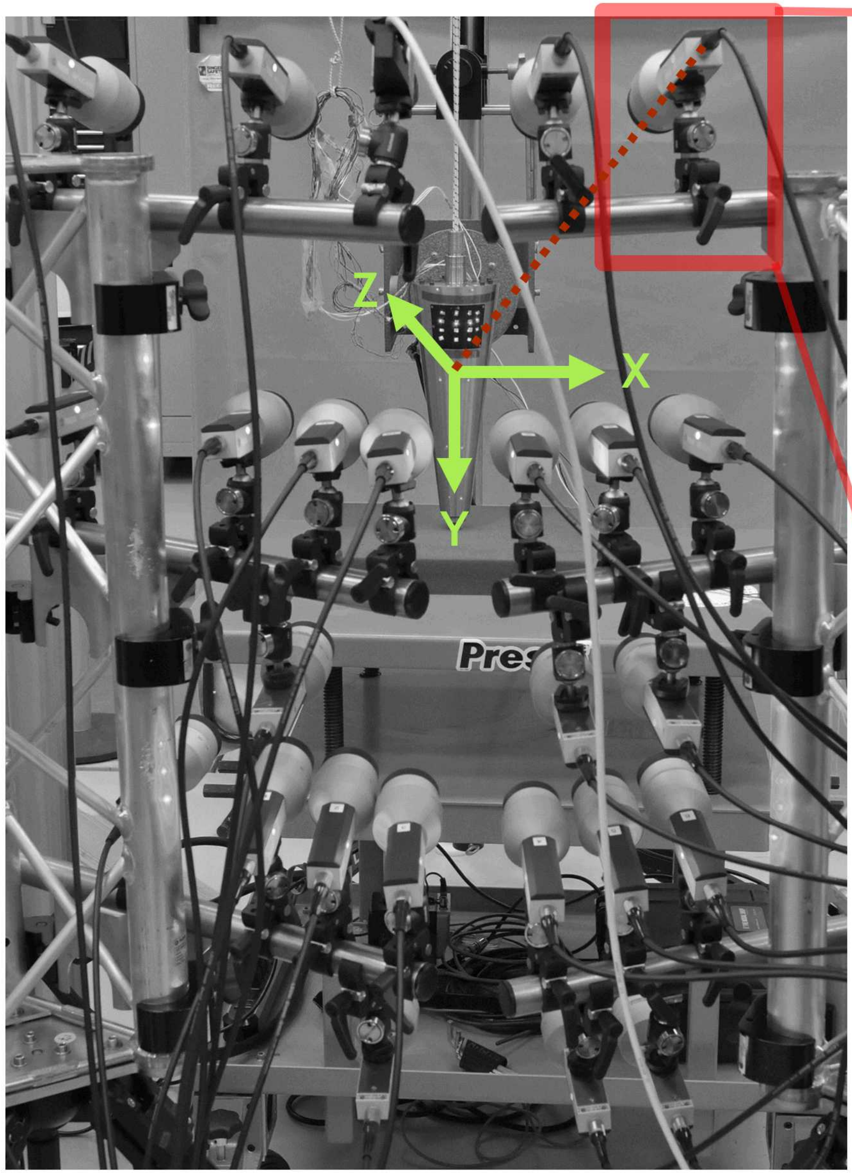
Mounting "trees"

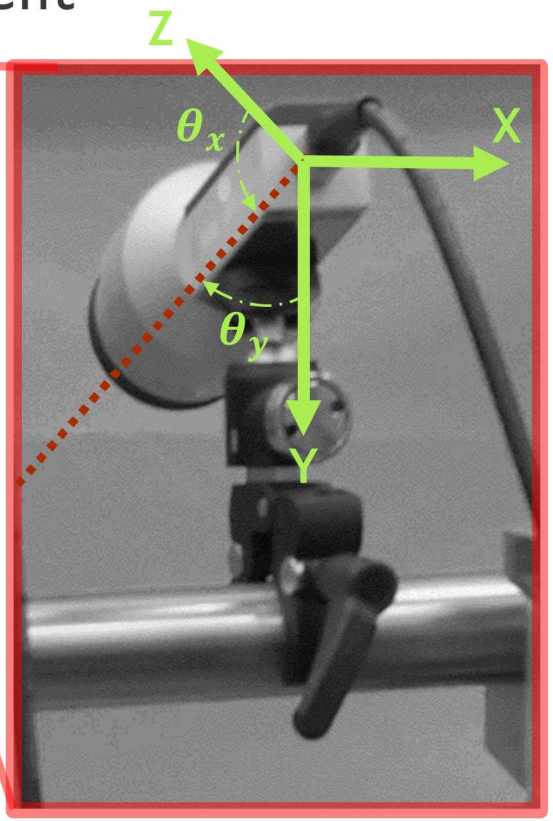
Multi-Point Vibrometry Assessment



Ball socket clamp for positioning, hand tighten with specialty tool

Multi-Point Vibrometry Assessment





Manual estimation of Euler Angles relative to part coordinate system

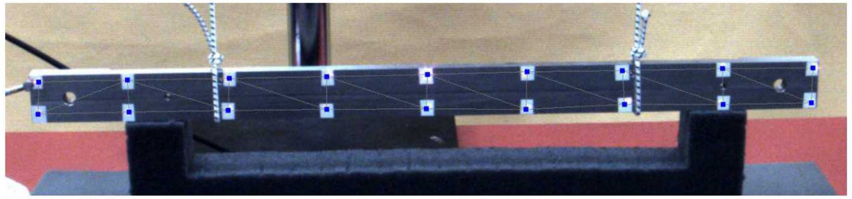
- Done for each laser head
- Time consuming
- Inaccurate
- Mildly infuriating

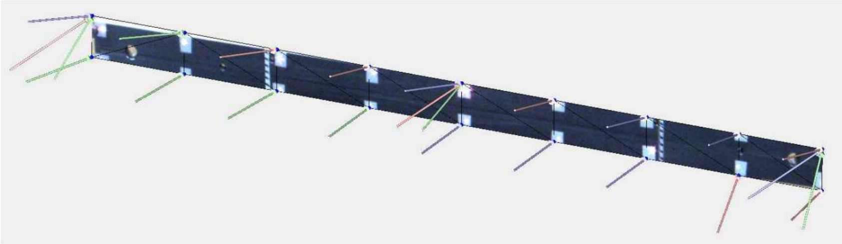
User has the ability to define test geometry coordinate system…
But defining Euler Angles become impossible

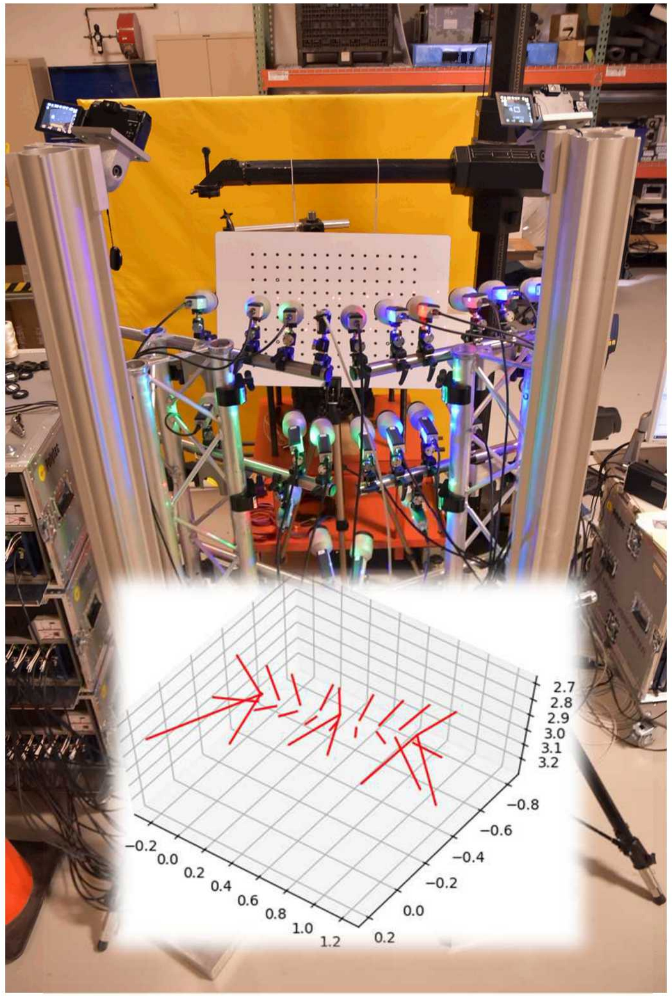
- Best bet is to use the default CS
- Transform your data in post processing

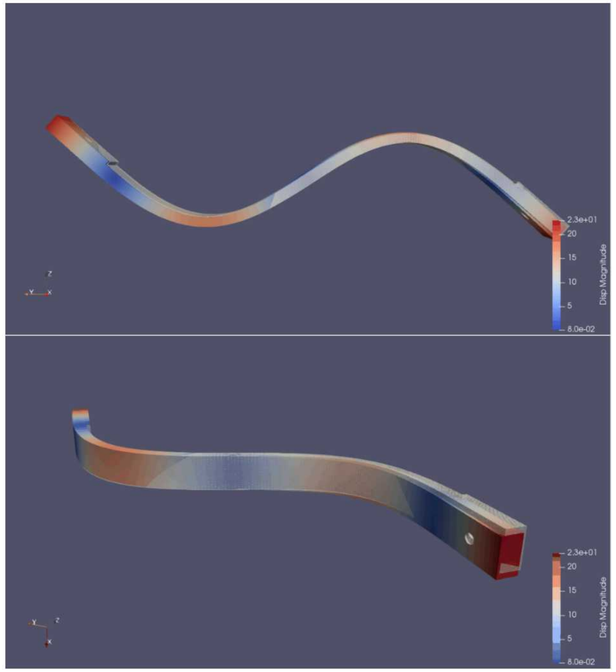
Multi-Point Vibrometer Assessment

- **Beam with sensitive contact pads for Advanced Simulation and Computing (ASC) project**
  - Require non-contact measurements
  - Used stereo-camera 3D triangulation to measure Euler angles
    - Two points in 3D space forms vector
  - Modal expansion of results for model comparison









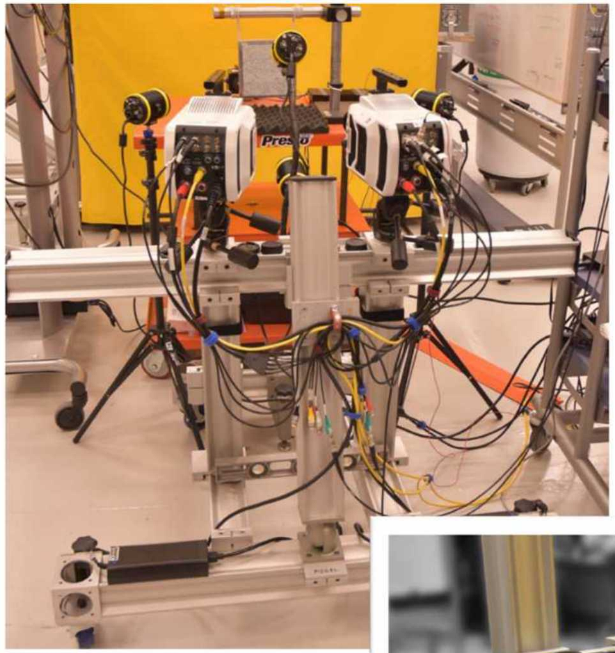
Photogrammetry for Structural Dynamics

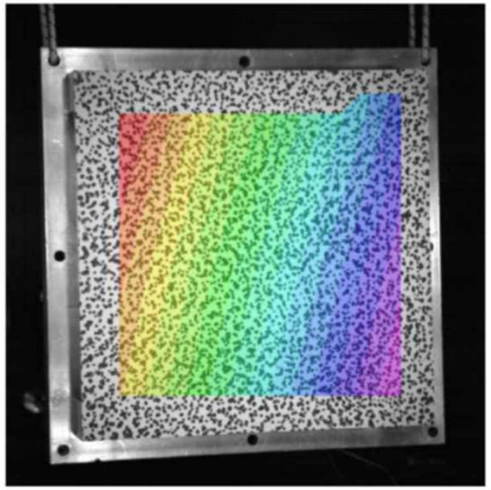
Photogrammetry (DIC) Overview

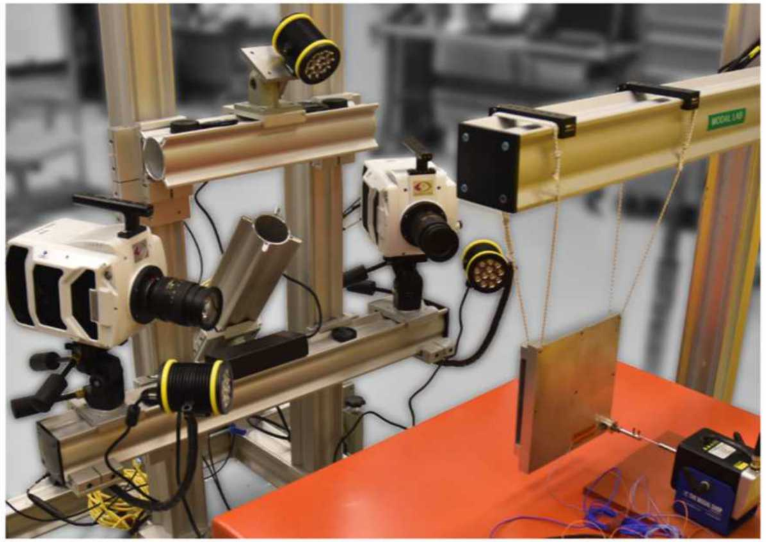
- **High-speed stereo camera setup**
  - Vision Research Phantom v1212 cameras
  - 12,600 frames/second (fps) at 1280x800 pixels
  - 1 μs minimum exposure time
  - 288 GB high speed internal RAM
- **DIC tracks speckle pattern subsets/markers**
  - Photogrammetry to triangulate positions in 3D
  - Sub-pixel accuracy

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

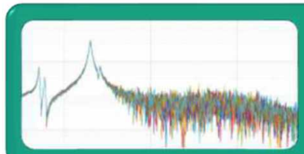






Photogrammetry for SD: Challenges

- "Typical" DIC performed entirely in commercial software (VIC-3D)
- For Structural Dynamic applications there are additional complications
- Ultimately, desire to process camera data with existing Modal tools (Matlab)



Modal displacements are bloody small…

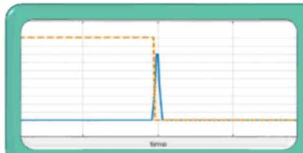
- High frequency is a challenge
- Starting off in the noise floor

Synchronize DAQ & Cameras

- Triggering
- Sample rates

Data volume

- Multiple runs for data averaging



Transient triggering

- Example, hammer impact tests
- Requires additional hardware

correlated SOLUTIONS

python

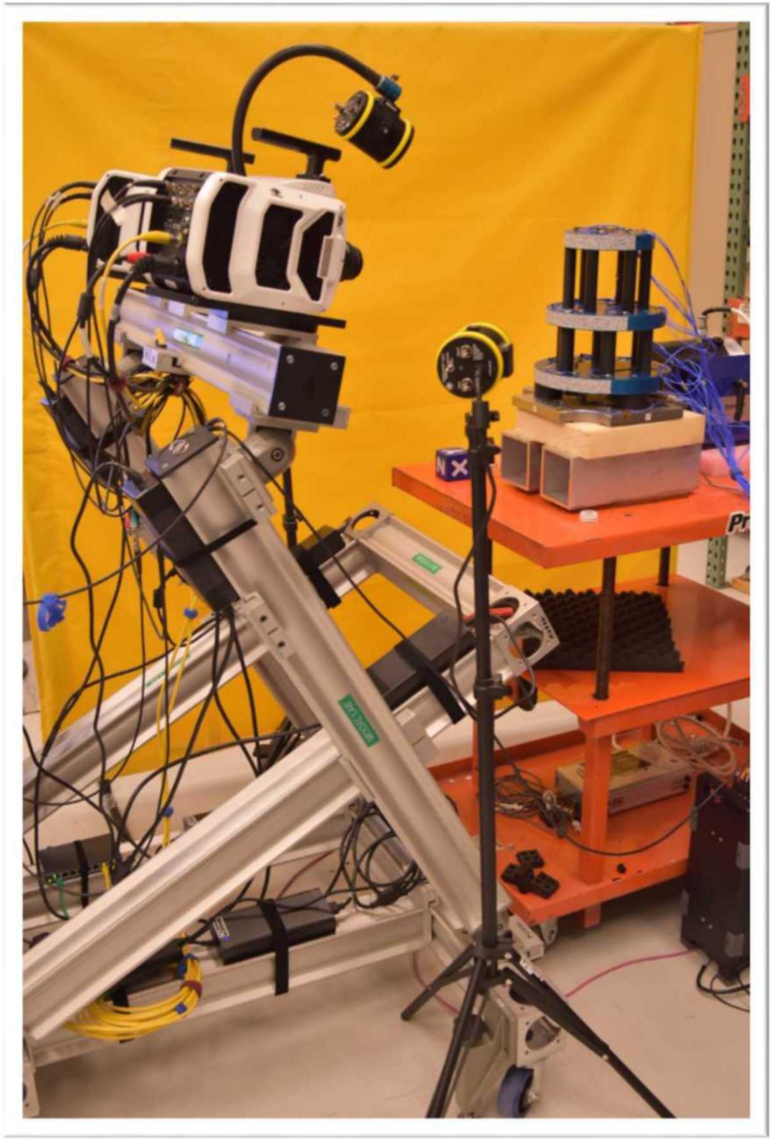
MathWorks

Custom Data Processing

- Reorder and reshape DIC data files
- Mask partially solved subsets
- Coordinate transformations between point sets (LS rigid body motion SVD)
- Extract test geometry from reference
- Package DIC results into MAT files
- Displacements ←→ accelerations
- Camera/DAQ consistency: units, node ID conflicts, etc.
- Merge Camera/DAQ data files, create IMAT files (geometry, AFU)

Photogrammetry (DIC)

- **Physical Setup**
  - Rigid stand, mobile and adjustable
  - Connections
- **Field of View (FOV)**
  - Lens selection (24-105mm, Macro)
  - Camera angles and baseline separation
  - Resolution (1024x800)
- **Lighting**
  - 4 high power continuous LED lamps
- **Camera triggering**
  - TTL pulse (5V to DC)
  - Soft trigger in GUI
- **Calibration**



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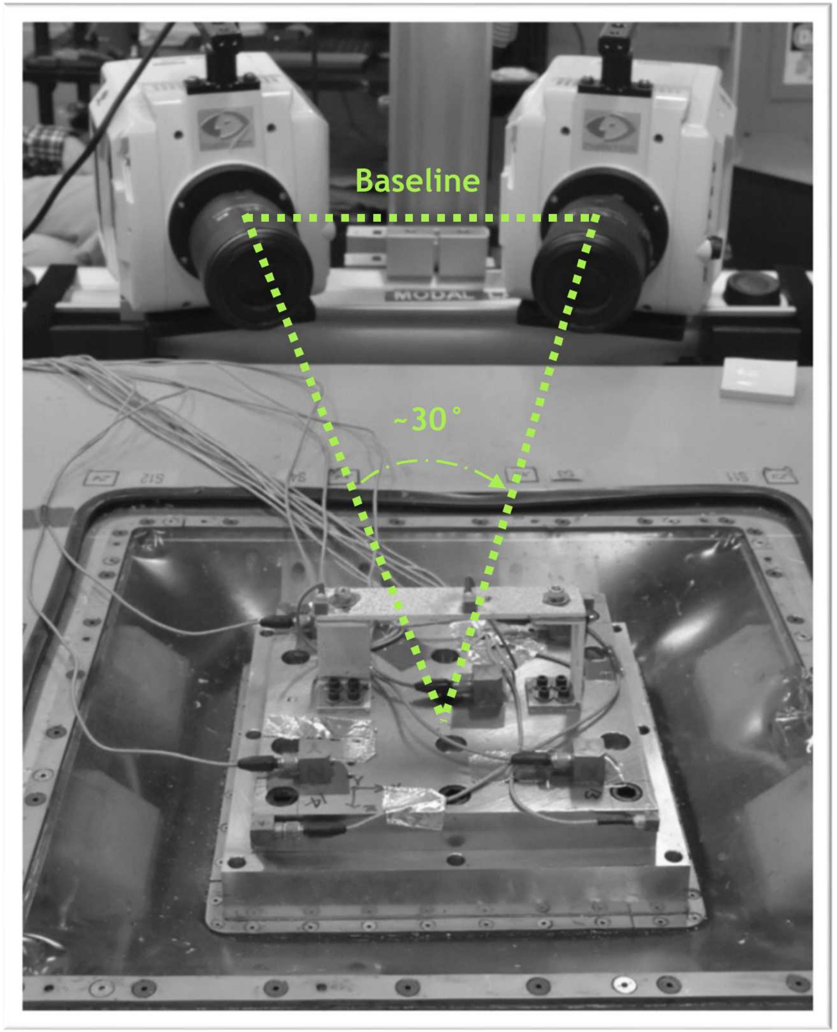
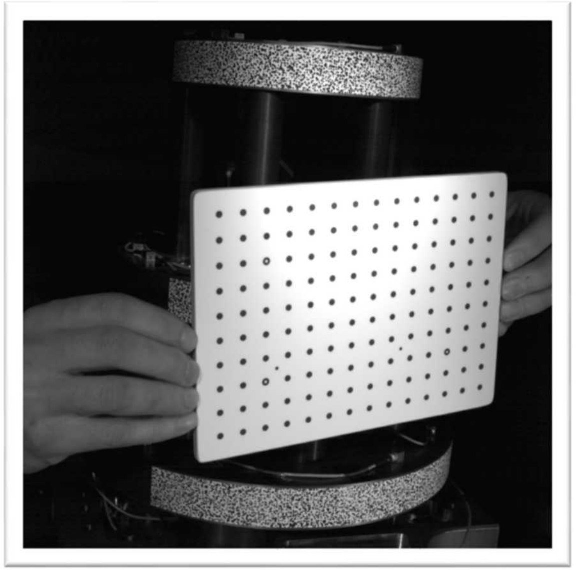
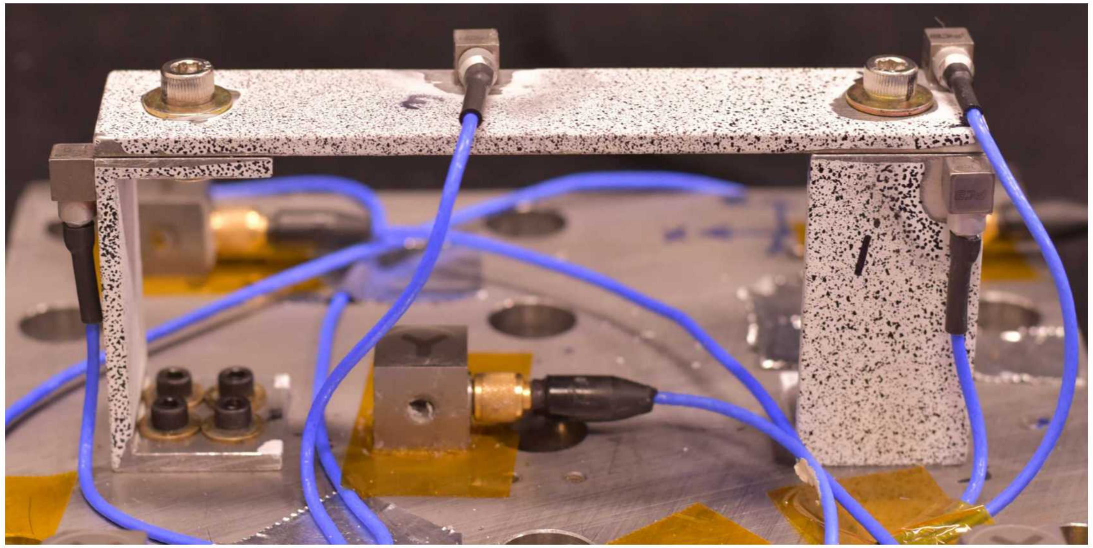
- **Camera Calibration Images**

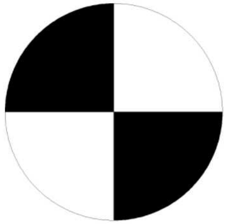


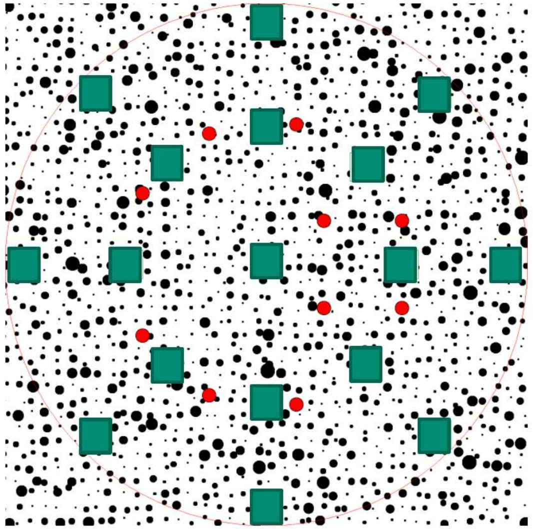


Photogrammetry (DIC)

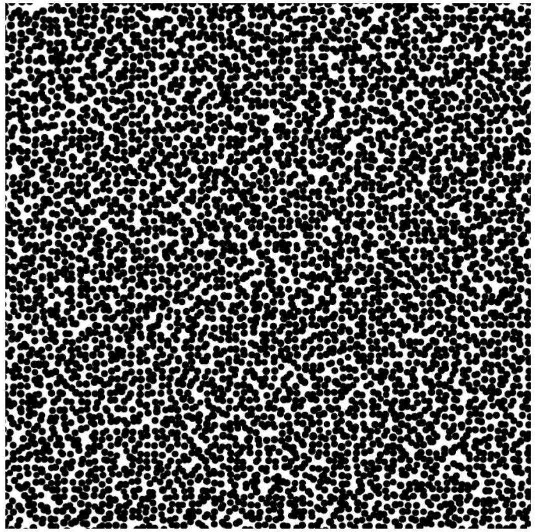
- **Test article preparation**
  - Speckles or Fiducial Markers
  - Paint, permanent marker
  - Stickers for small continuous displacements
    - Use Python to generate patterns, print on label paper
    - Specify random patterns
    - Adjust dpi, density, size variations, positional variations
    - Specify size (e.g. 1” x 6” strip)
    - Create markers: quarters, concentric ellipse styles



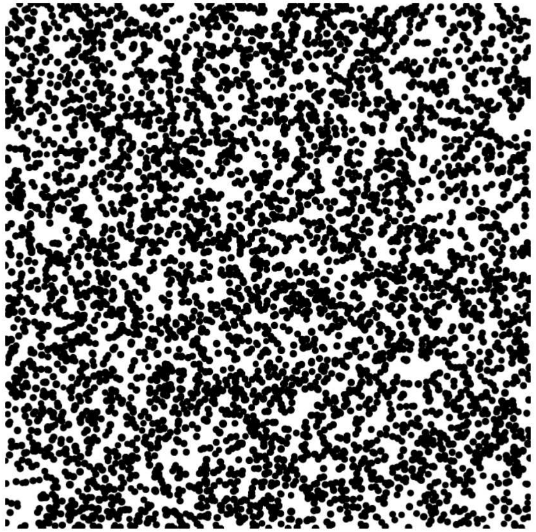


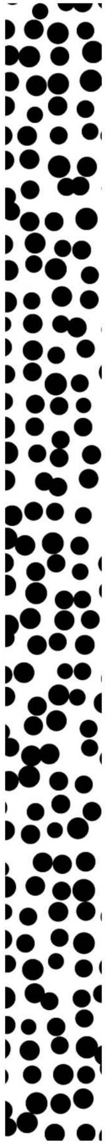


Jitter Random



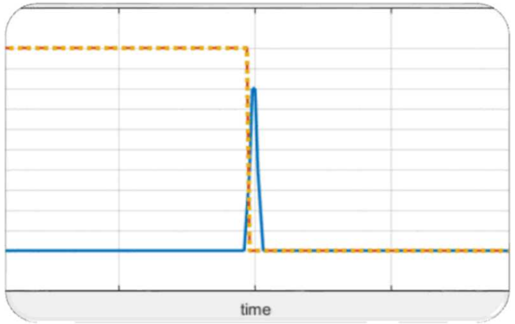
Pure Random

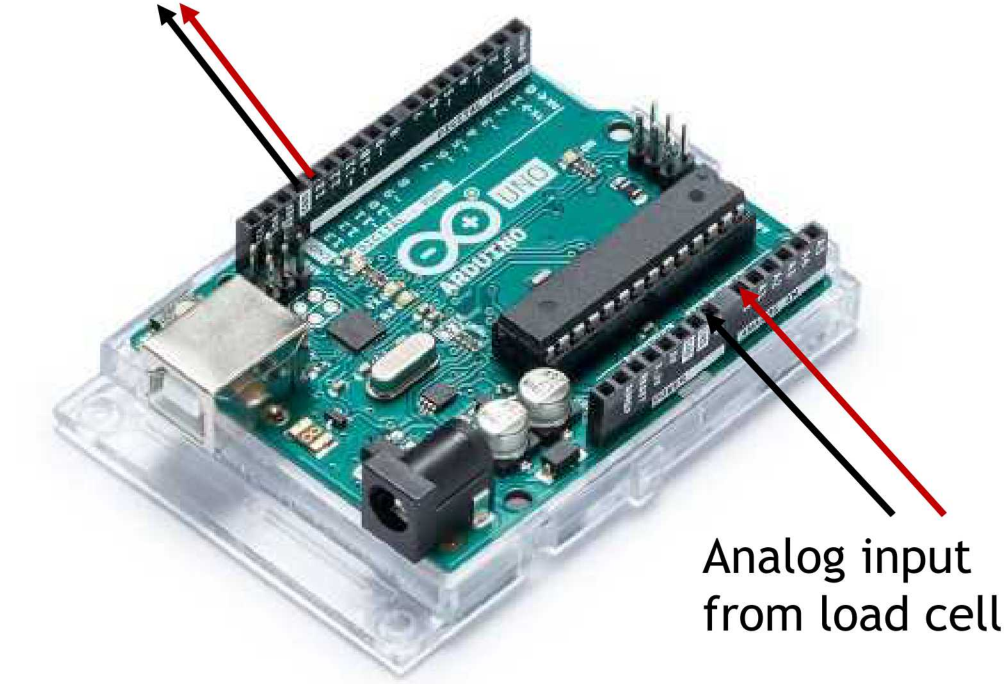




Photogrammetry (DIC)

- **Excitation & DAQ Synchronization**
  - **Shakers**
    - Trigger Cameras and DAQ with contact switch
    - Non-deterministic: Random
    - Deterministic: Sine dwell/sweep, pseudo-random
      - Allows for image averaging
  - **Modal Hammer Impacts**
    - Trickier to trigger, using Arduino microcontroller
    - Partition camera memory for subsequent frames
      - Up to 64 frames

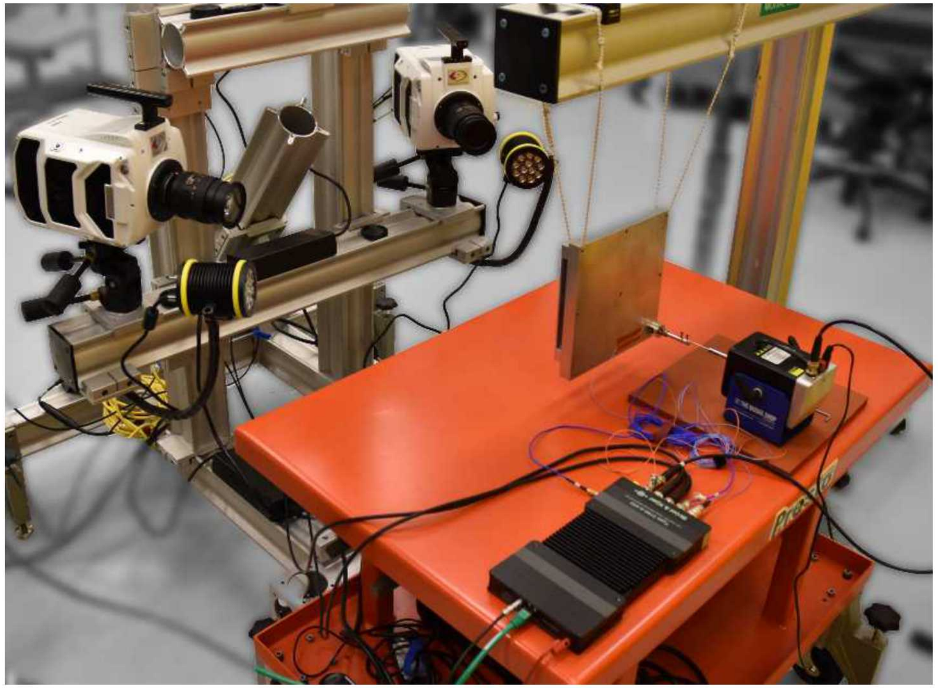


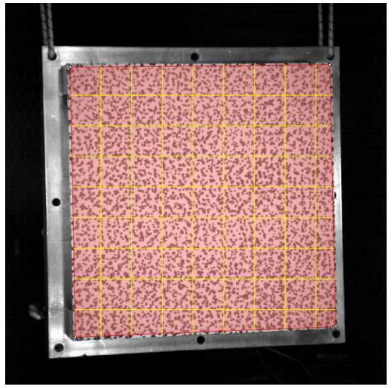


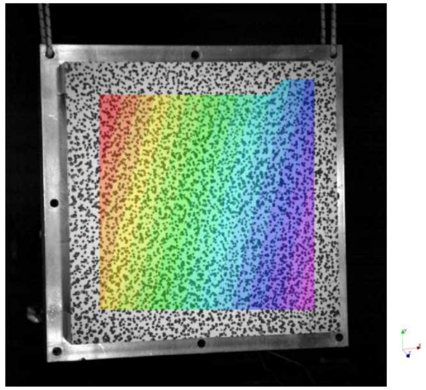
https://store.arduino.cc/usa/arduino-uno-rev3

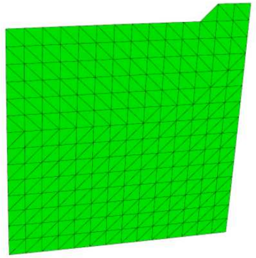
SD DIC Proof of Concept

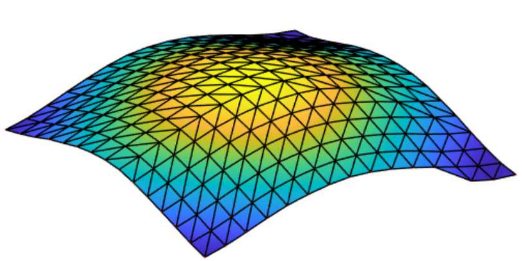
- Assess DIC for modal applications
  - Is it a viable tool?
  - Combine with standard modal data acquisition
  - New data processing needs
- Academic plate structure
  - Used in previous studies, well characterized
  - Synchronized Cameras and DAQ
  - Post-processing pipeline
    - Correlated Solutions VIC-3D → Python → Matlab

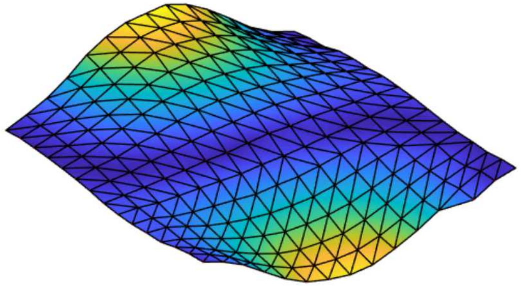






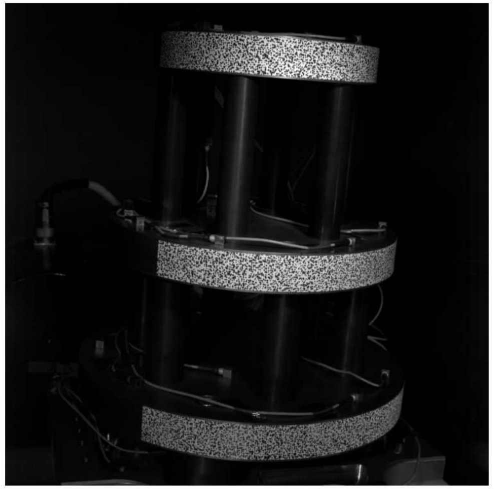


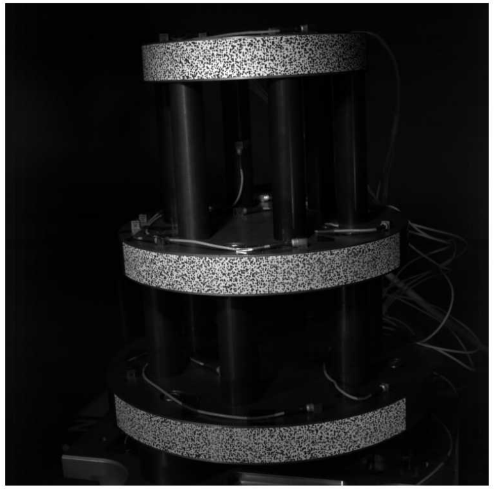


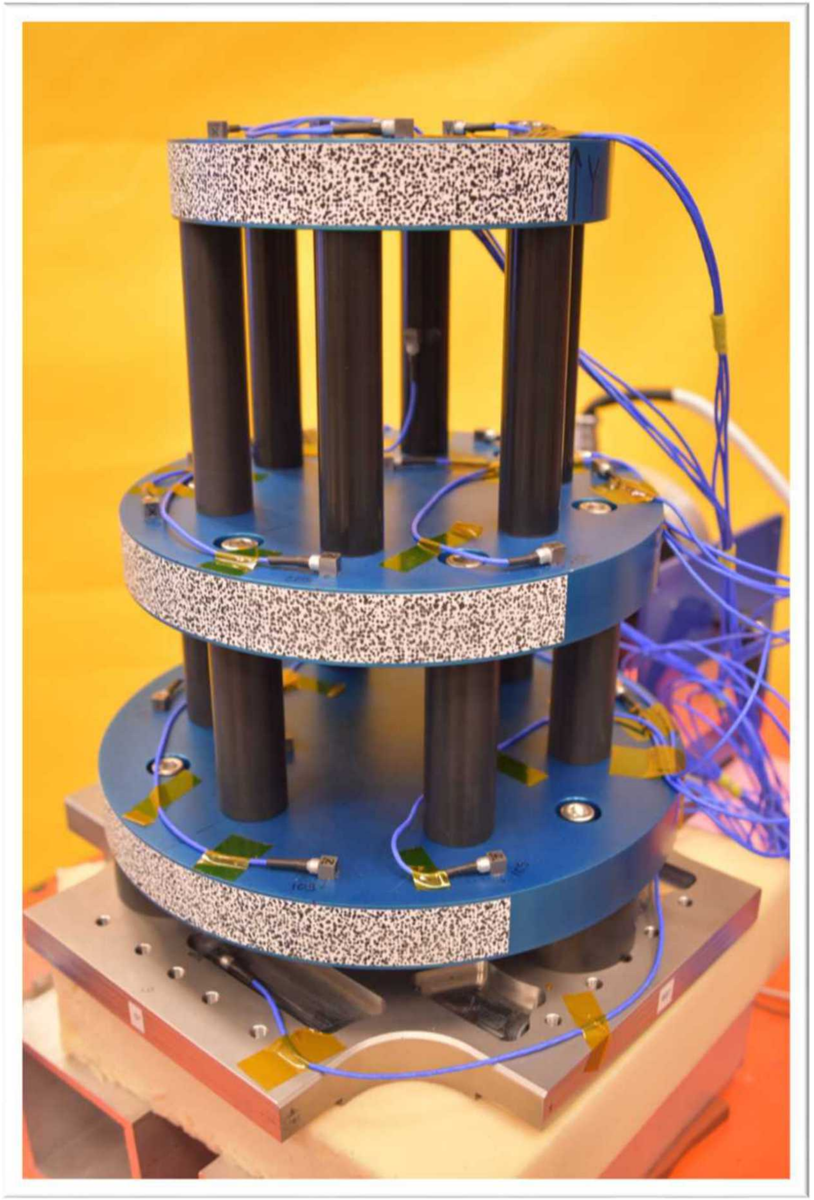


SD DIC Early Exploration

- **Added Complexity "Wedding Cake"**
  - Dynamically & geometrically
  - Merge multiple accelerometer and camera AOIs
  - Depth of Field (DoF) considerations
- **Topics of Interest:**
  - Excitation level/noise floor
  - Practical aspects of subset and step sizes
  - Marker tracking
  - Image averaging (vs. FRF averaging)

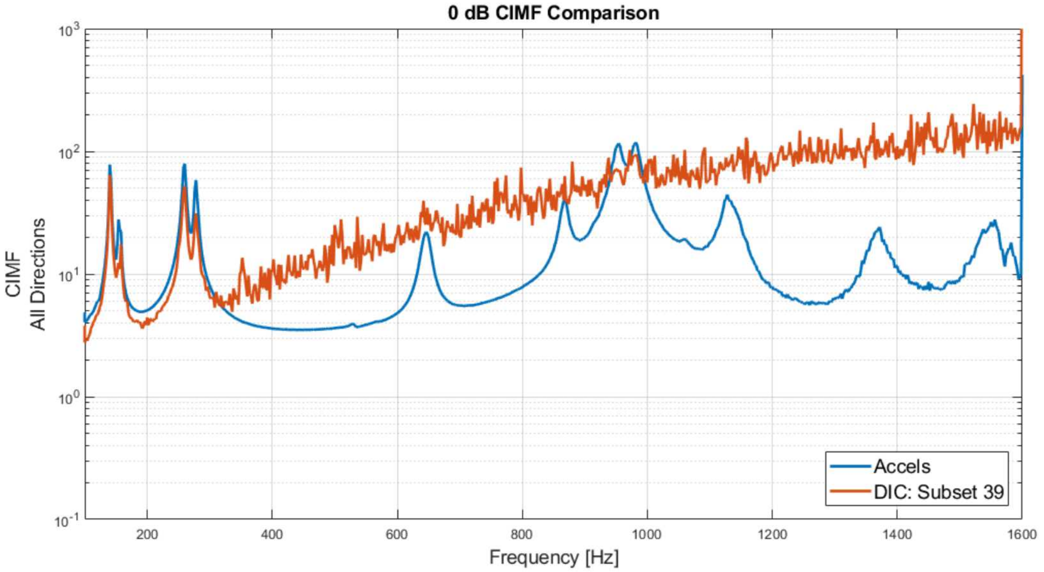


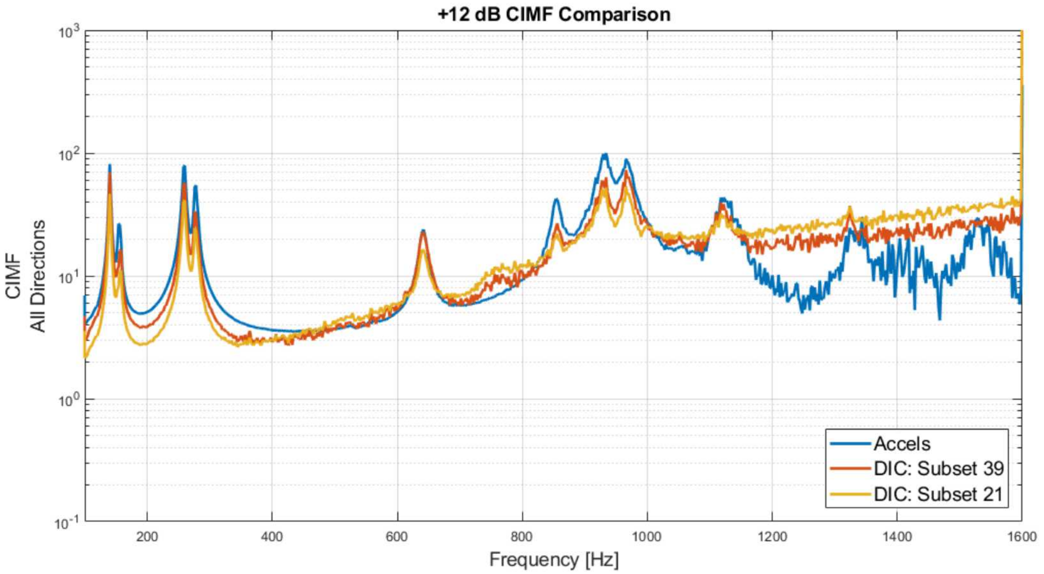




SD DIC Early Exploration

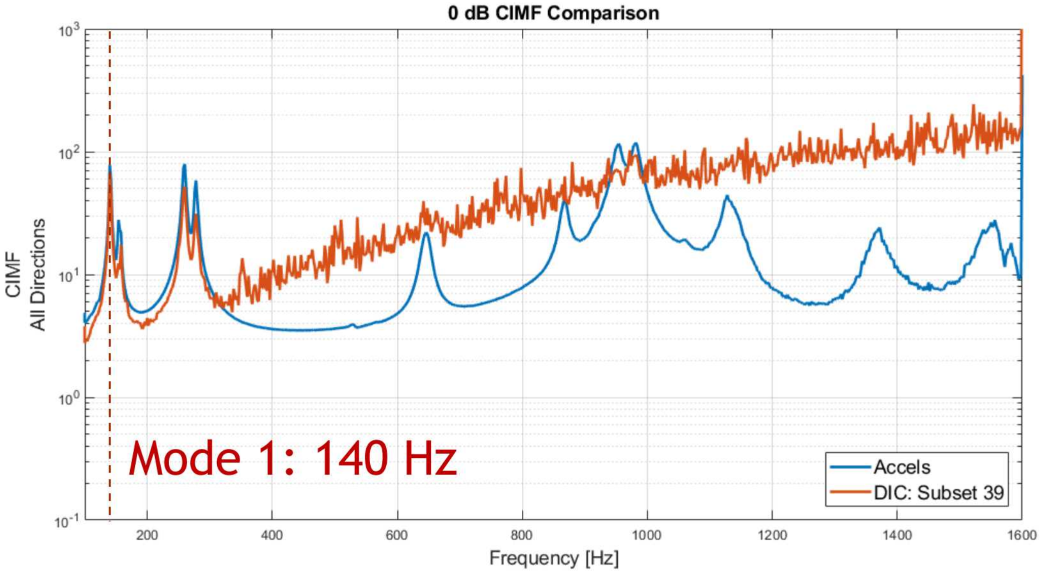
- **Excitation Level / Noise Floor**
  - Performed same test at two forcing levels
    - 0dB (~2lb RMS)
    - +12dB (~9lb RMS)
  - Pseudo-random excitation 100-1600 Hz
  - Sample Rate: 4096 fps
  - 0.5sec frame, 10 averages = 20480 images
- CMIF comparisons
  - On surface, not overly encouraging…
  - Only first few modes above camera noise floor
  - +12dB better, still noisy
- Pixels Displacement
  - **0dB: 0.108 pixels**
  - **+12dB: 0.781 pixels**
  - **Current heuristic: >0.03 px bare min**
    >0.10 px realistic min

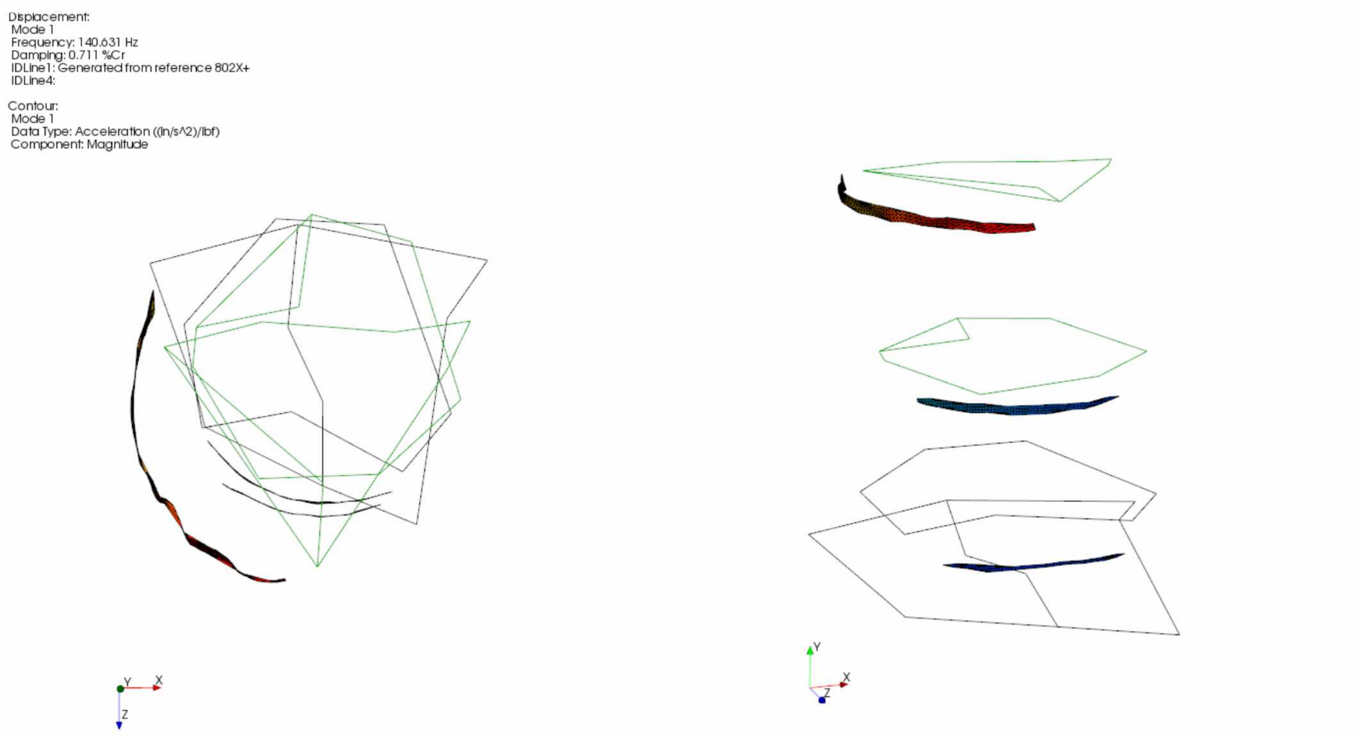




SD DIC Early Exploration

- **Excitation Level / Noise Floor**
  - **0dB low level**
    - Subset size = 39 px
    - Step size = 5 px
    - 535 Subsets





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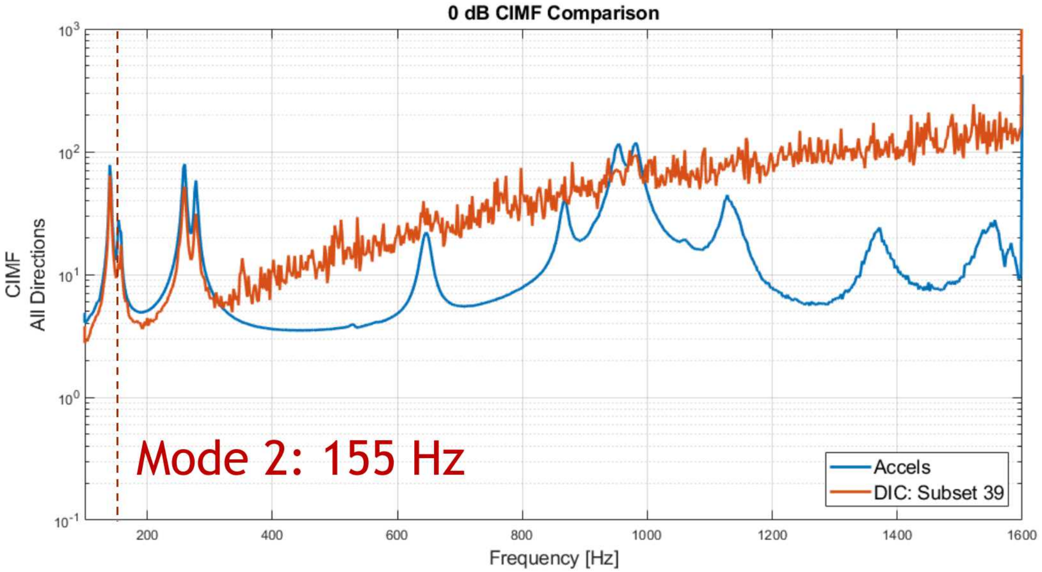

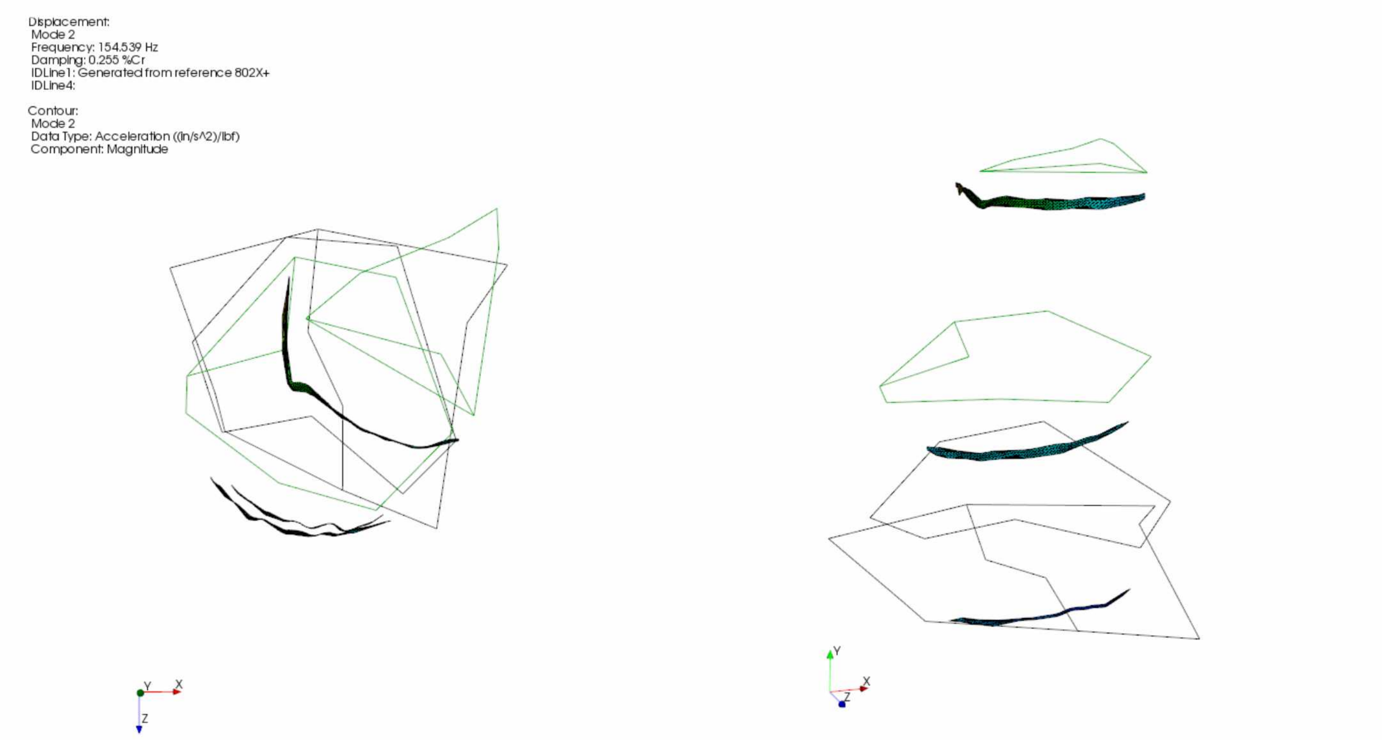

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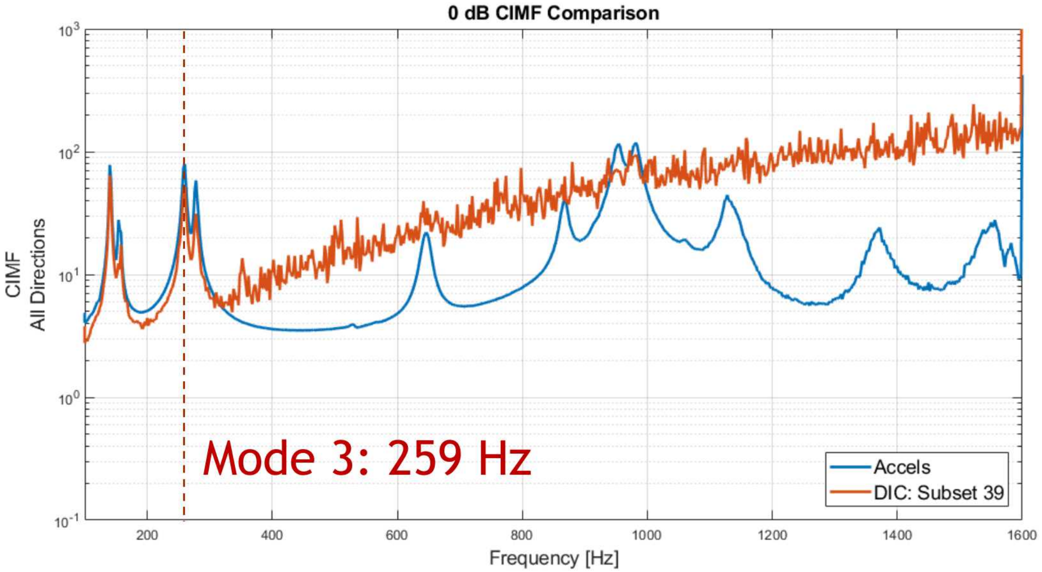

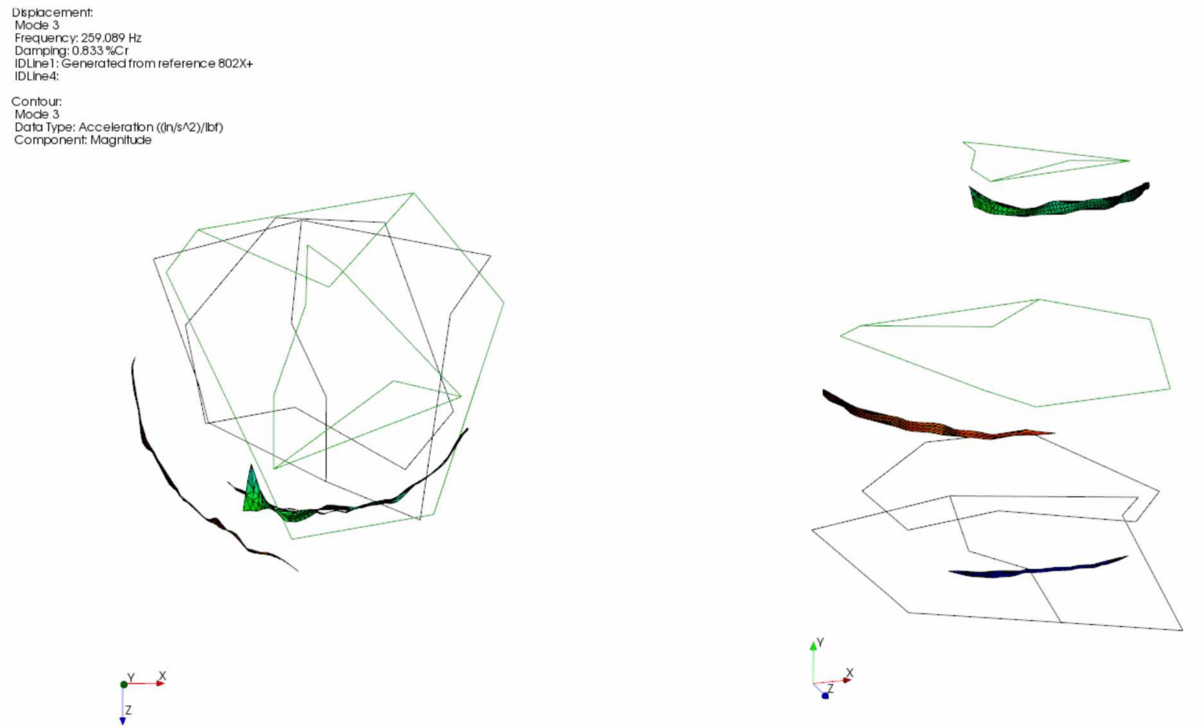

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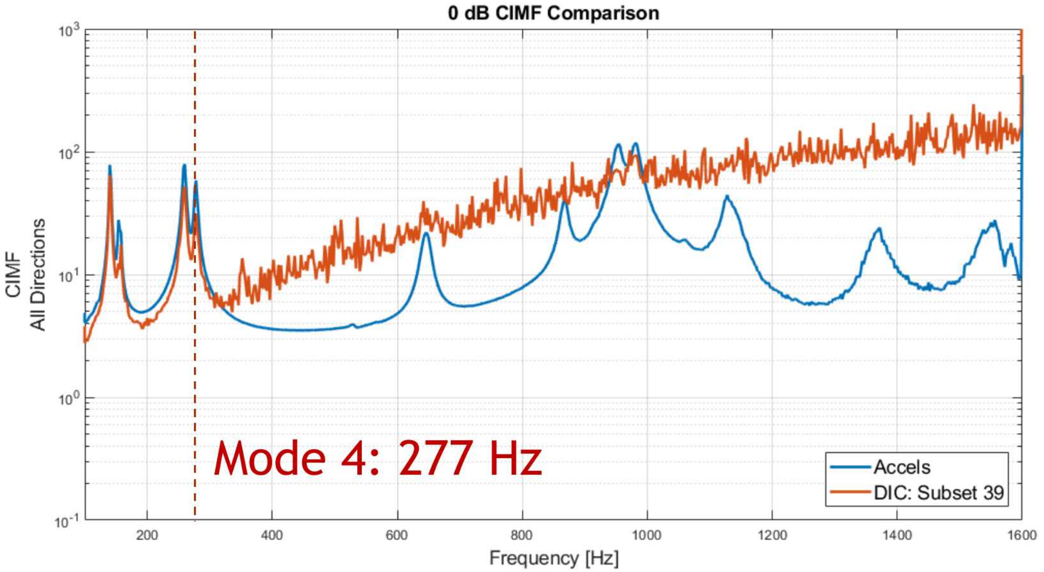

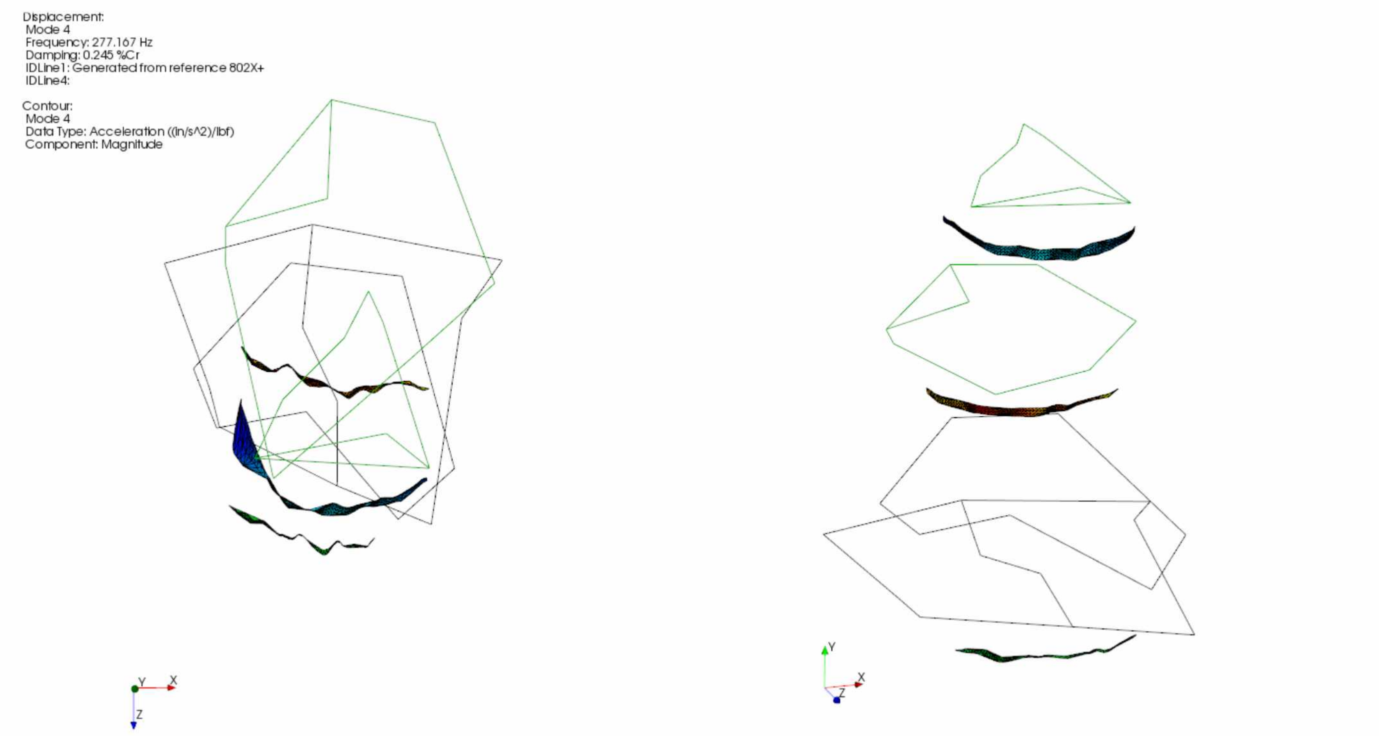

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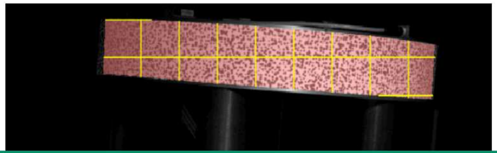
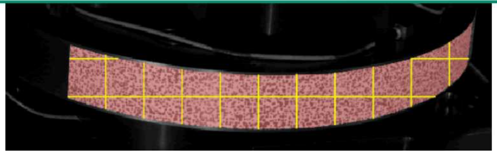
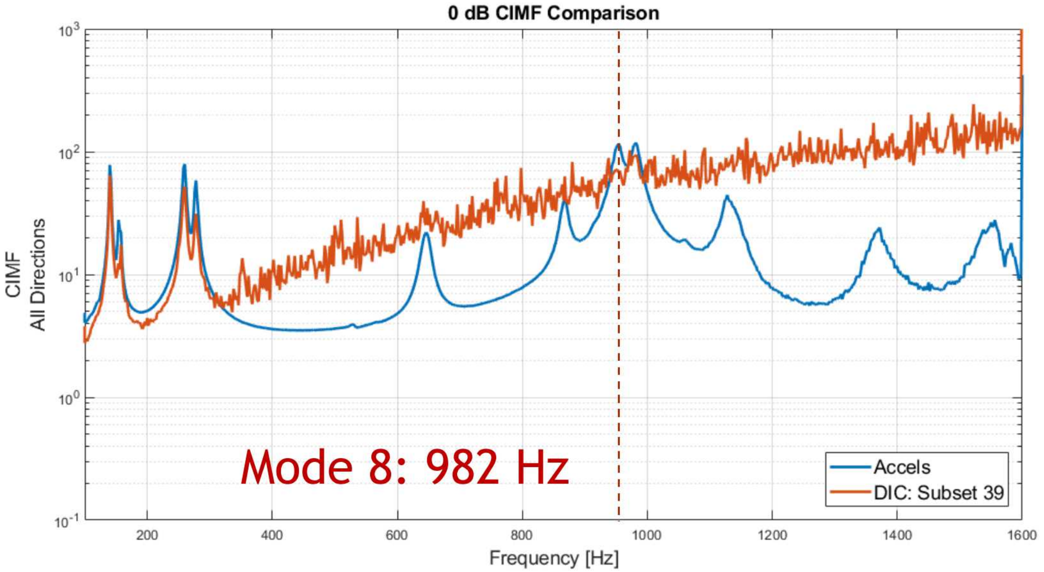


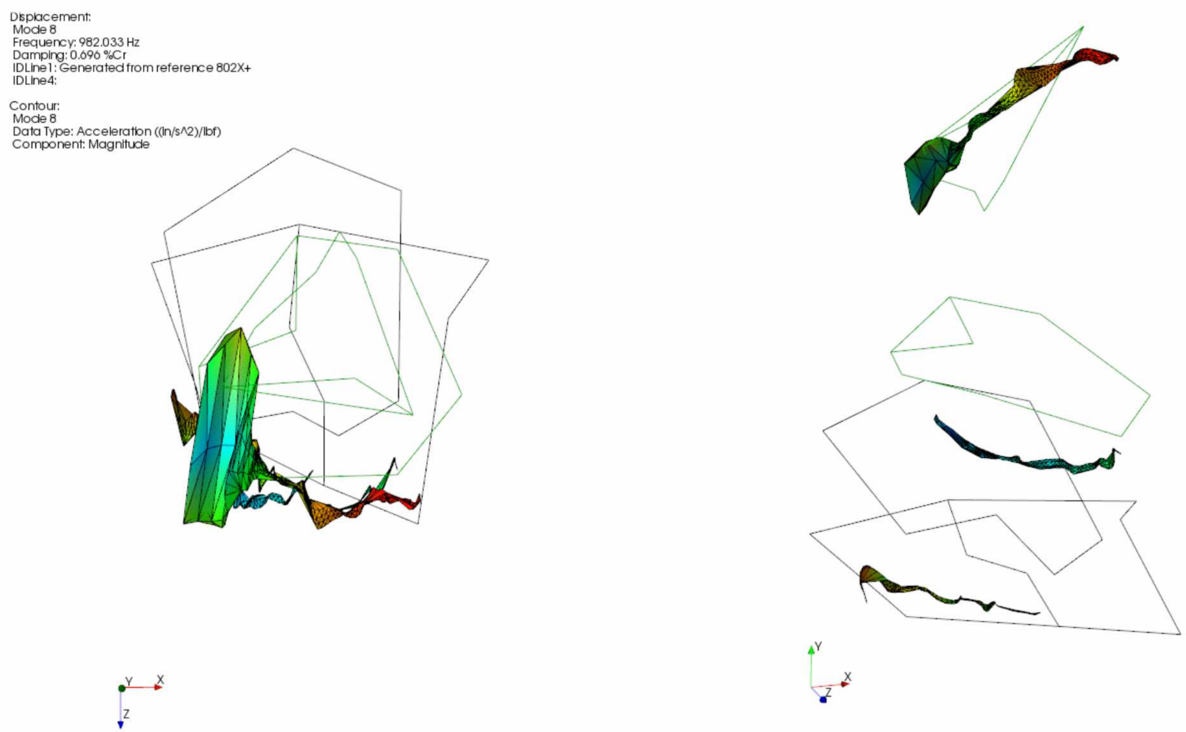


Noisy, but bulk motion is there!

Accelerometers inform where to look. Other works observed similar.[1]

Can we employ data de-noising methods to clean and extract information?

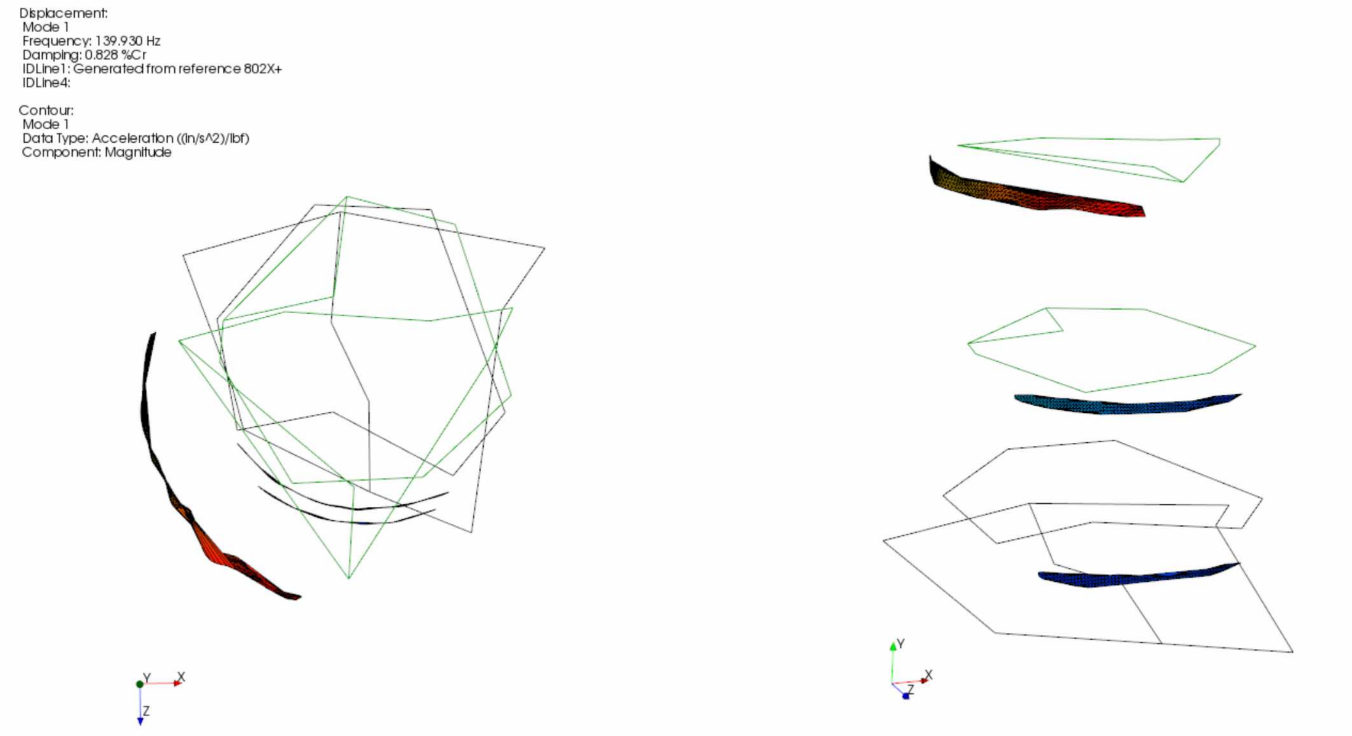


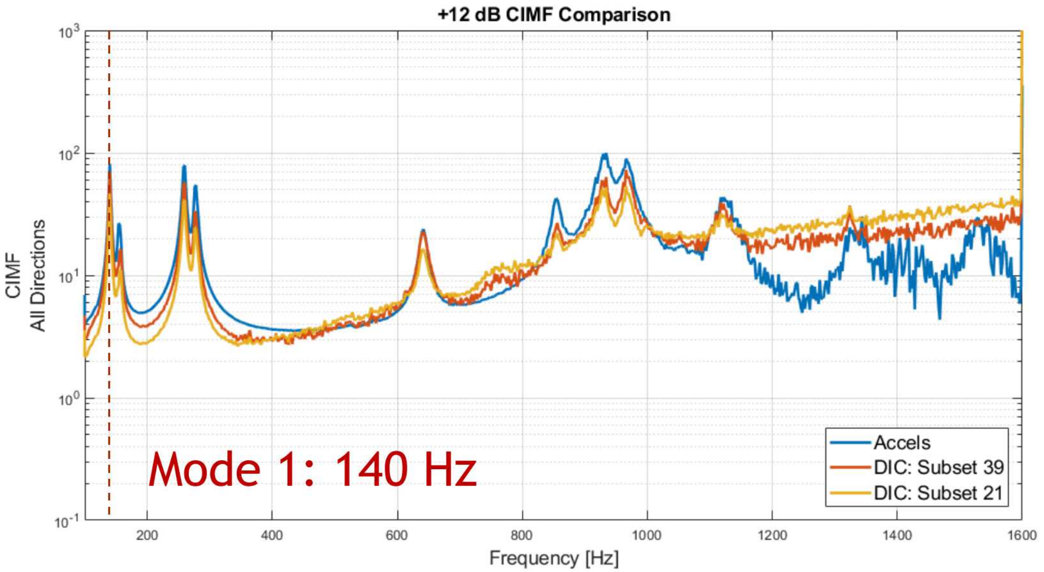


[1] J. Javh, J. Slavic, M. Boltezar, (2018) "High Frequency Modal Identification on Noisy High-Speed Camera Data," Mechanical Systems and Signal Processing, Vol 98, pp. 344-351, Elsiver

SD DIC Early Exploration

- **Excitation Level / Noise Floor**
  - **+12dB level test**
    - Subset size = 39 px
    - Step size = 5 px
    - 656 Subsets





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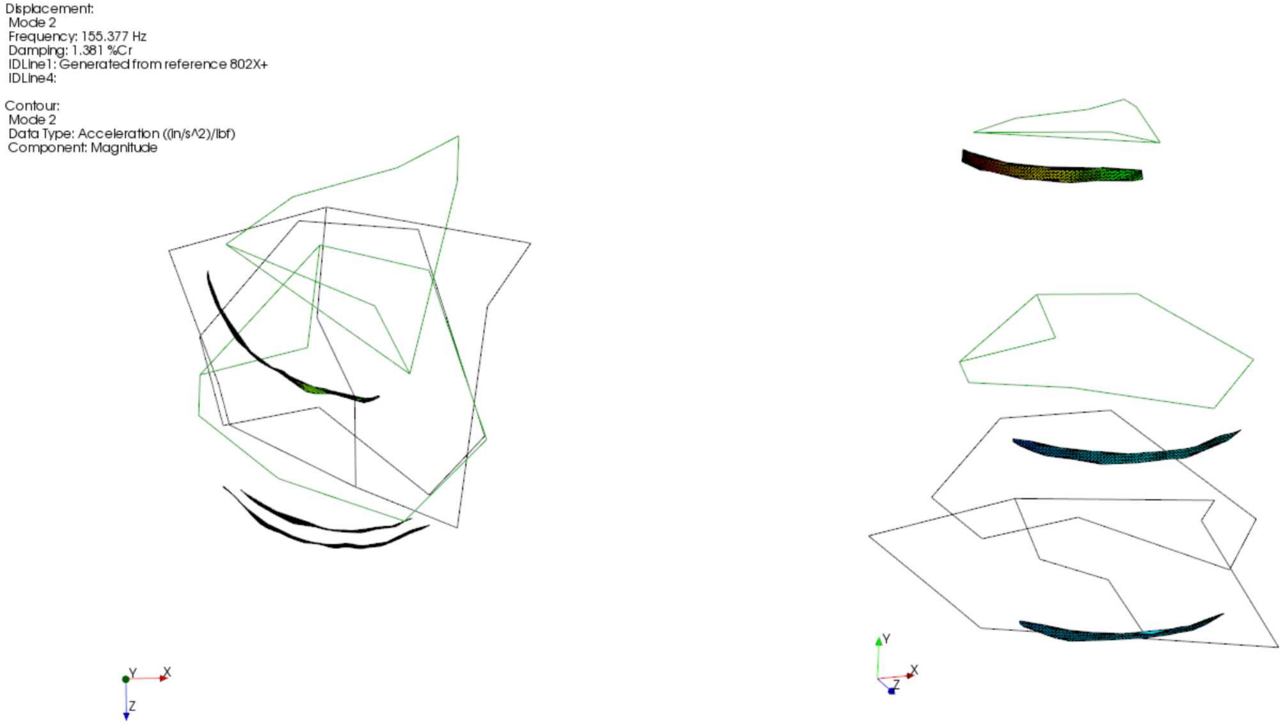

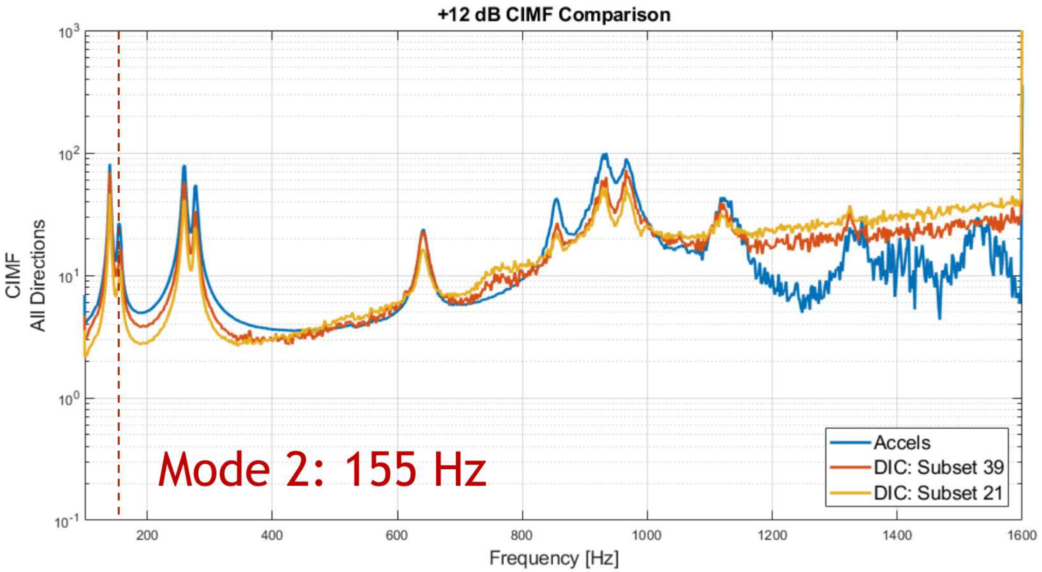

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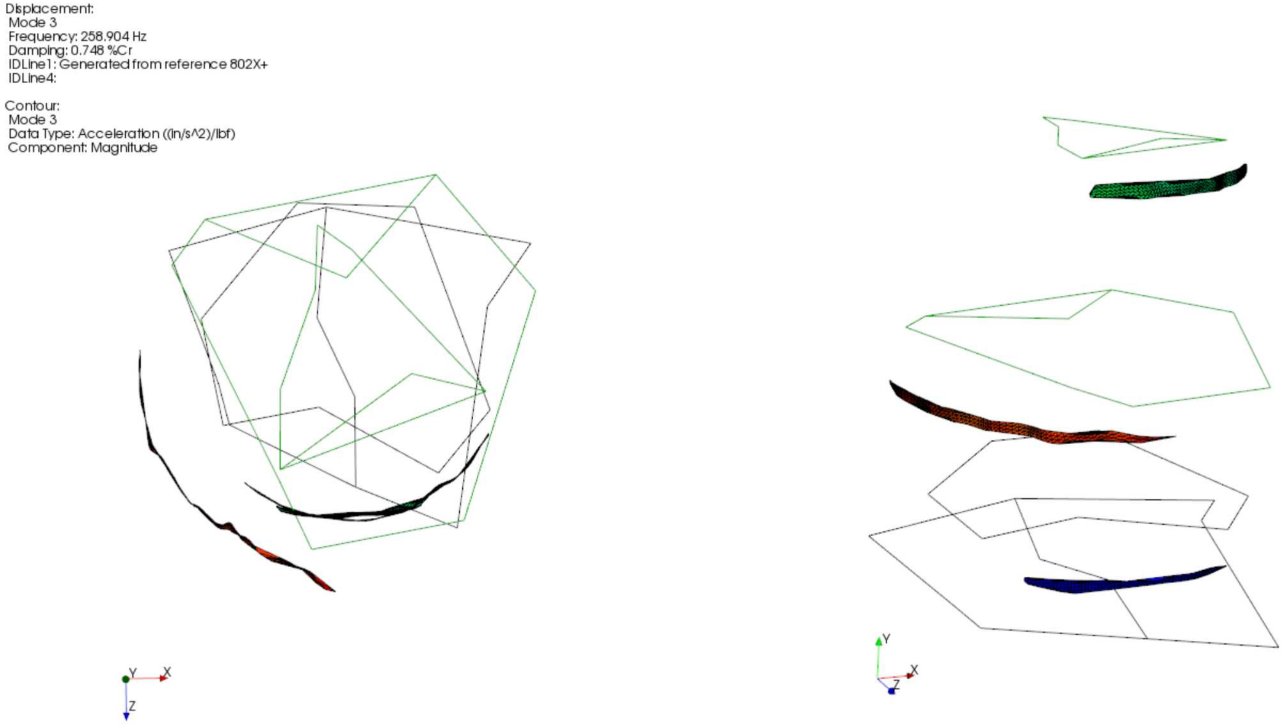

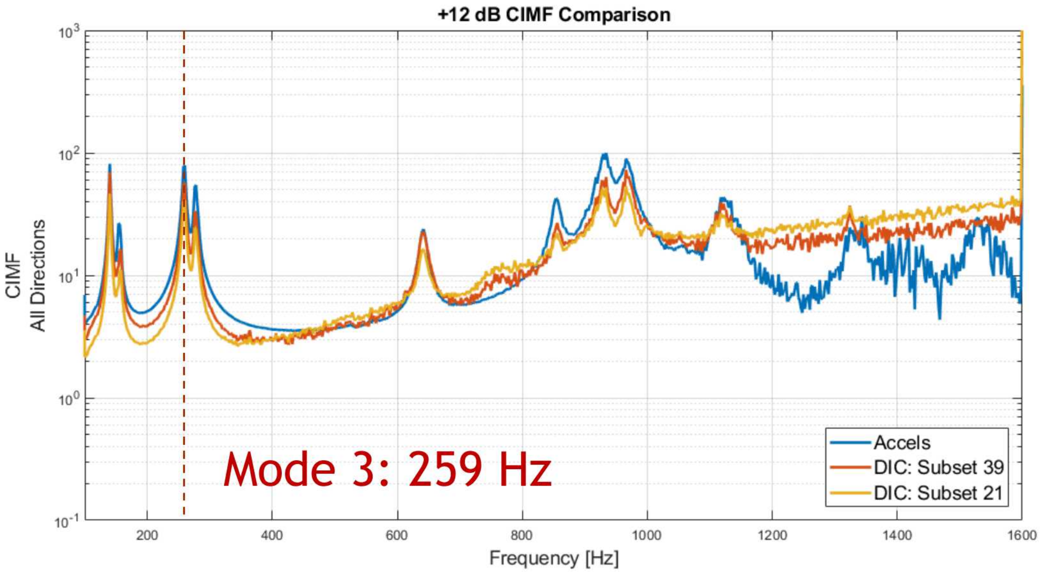

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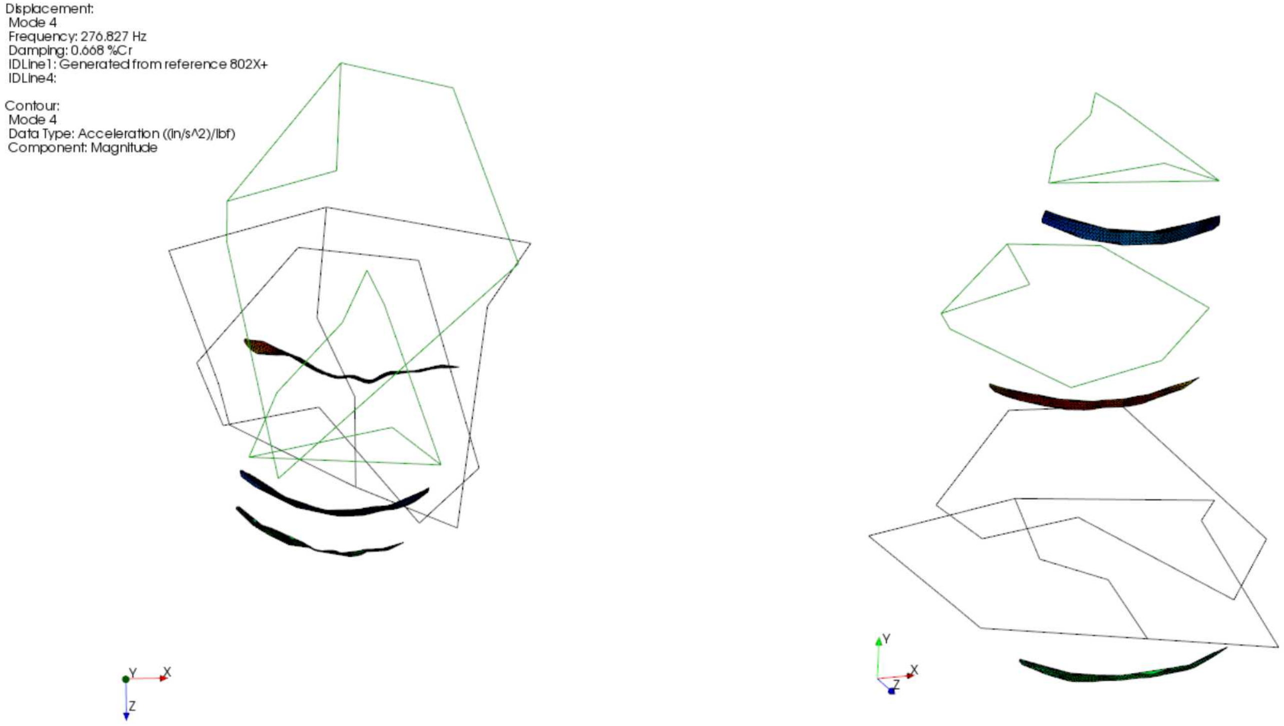

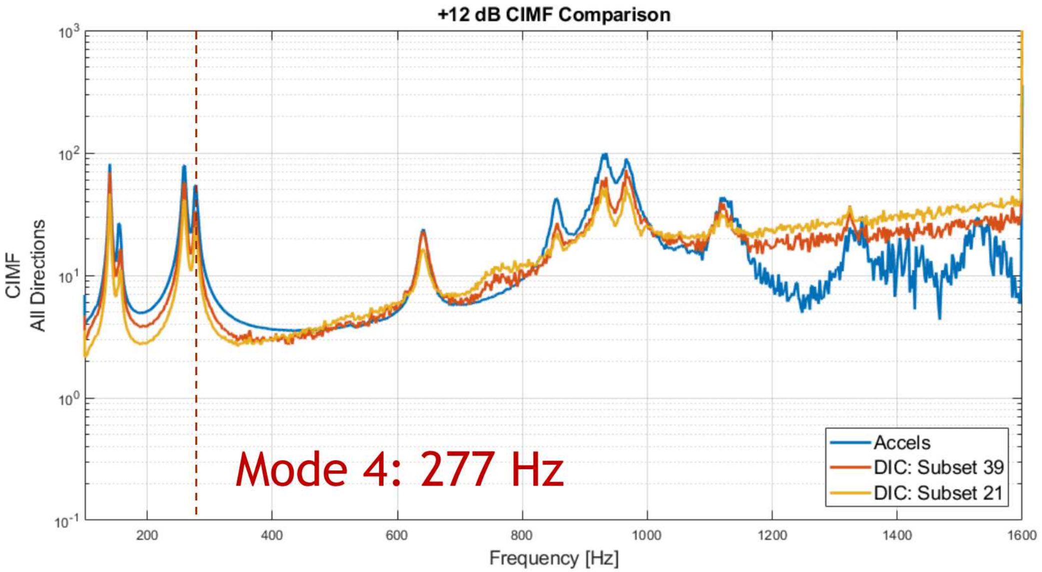

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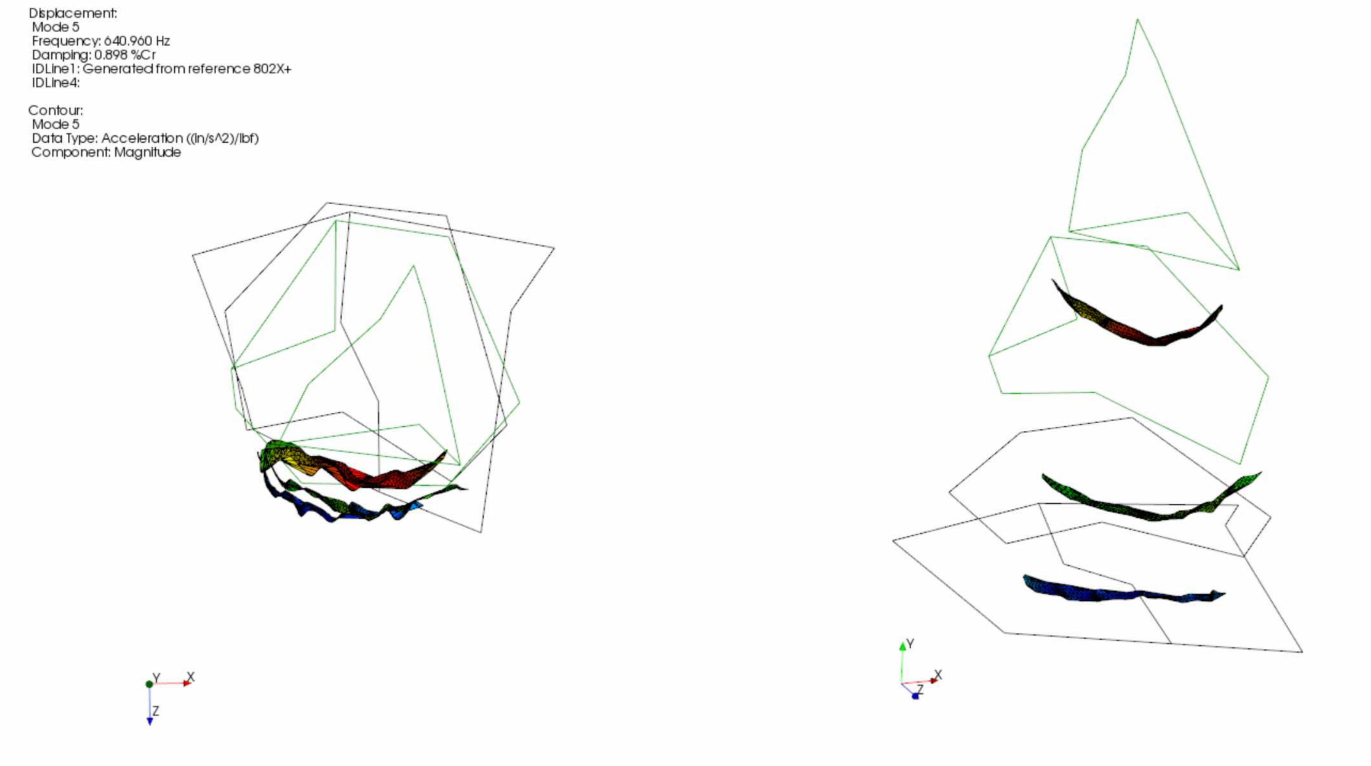

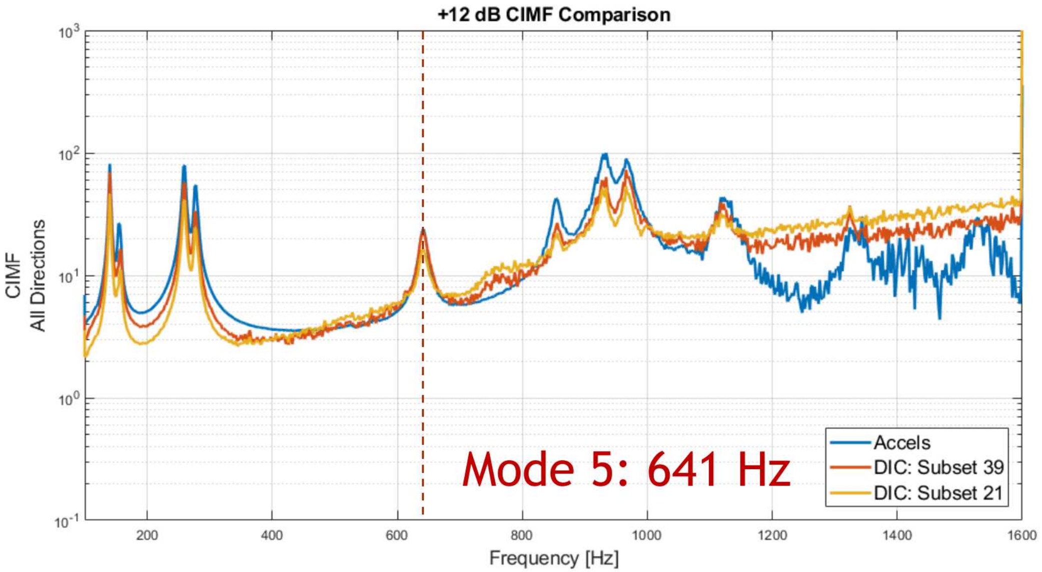

SD DIC Early Exploration

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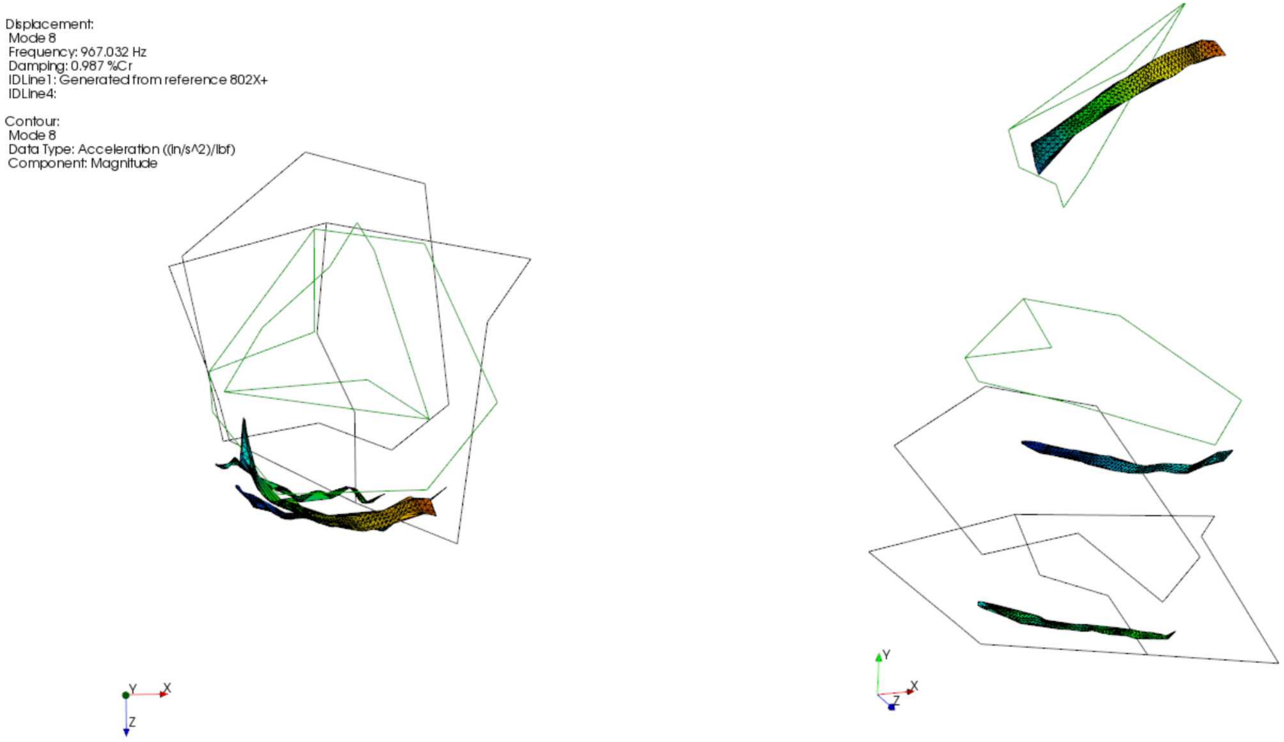
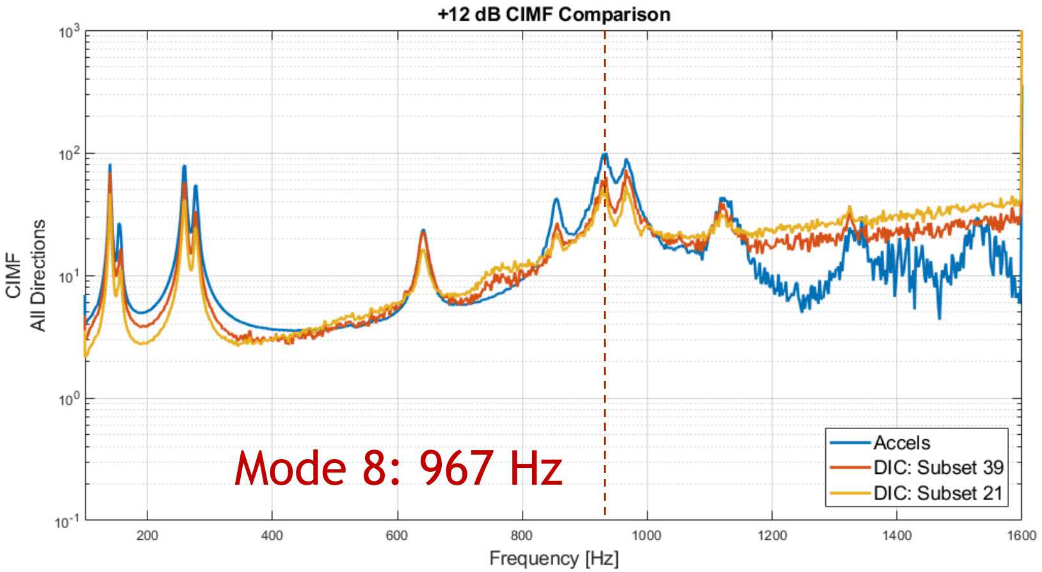
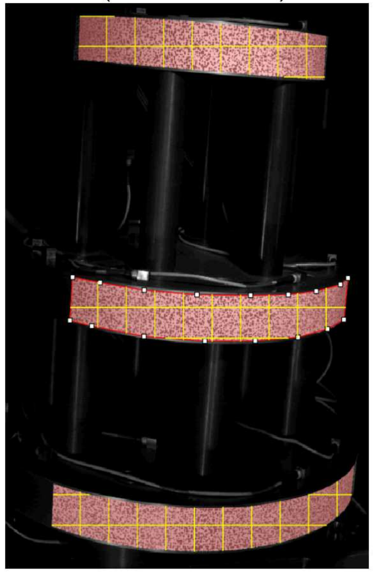




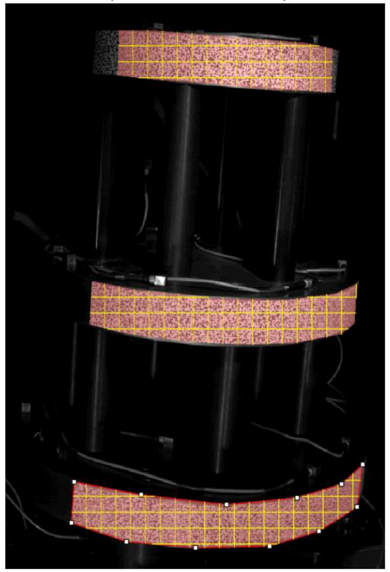
SD DIC Early Exploration

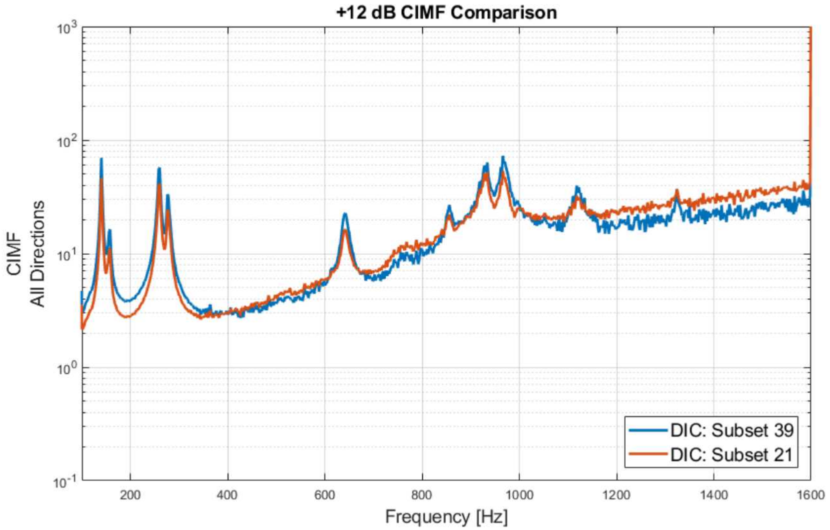
- **Practical aspects of Subset/Step Sizes**
  - +12dB data processed with two subset sizes
  - CMIF shows higher noise for smaller subset
    - Averaging over smaller area
    - Modal applications don't need incredible spatial density
    - Opposite of "normal" DIC users
  - Differences in shapes are pronounced

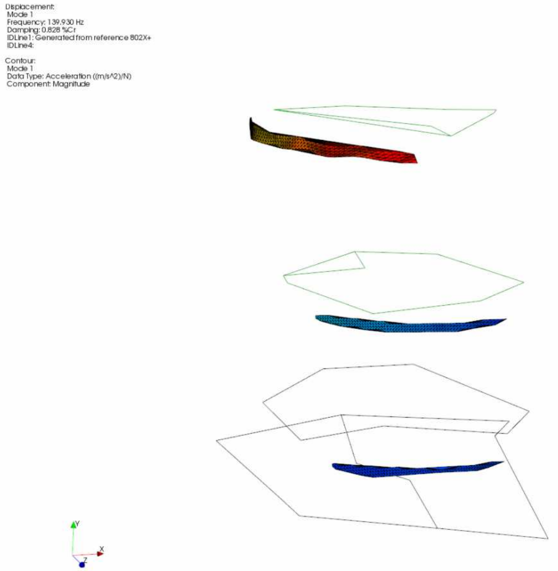
Subset 39 px, Step 5 px
(656 Subsets)



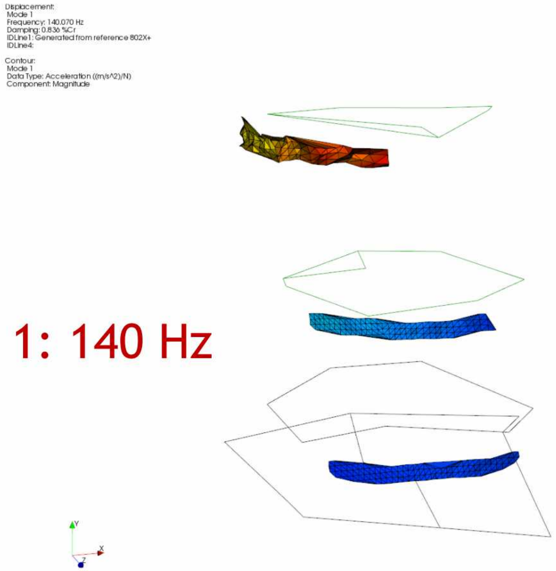
Subset 21 px, Step 10 px
(352 Subsets)







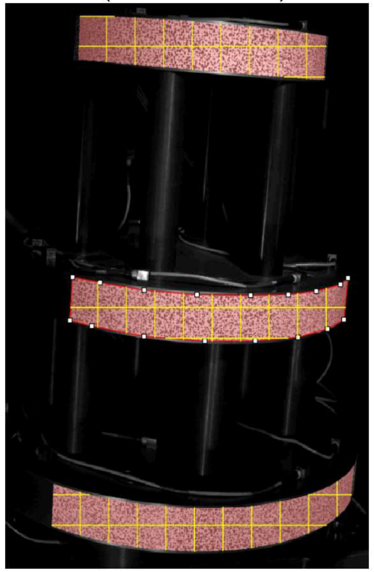
Mode 1: 140 Hz



SD DIC Early Exploration

- **Practical aspects of Subset/Step Sizes**
  - +12dB data processed with two subset sizes
  - CMIF shows higher noise for smaller subset
    - Averaging over smaller area
    - Modal applications don't need incredible spatial density
    - Opposite of "normal" DIC users
  - Differences in shapes are pronounced
  - **Recommend using larger subsets, reduce step size to increase spatial density**

Subset 39 px, Step 5 px
(656 Subsets)



Subset 21 px, Step 10 px
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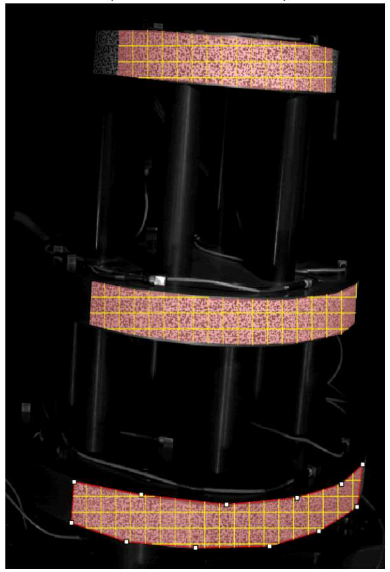
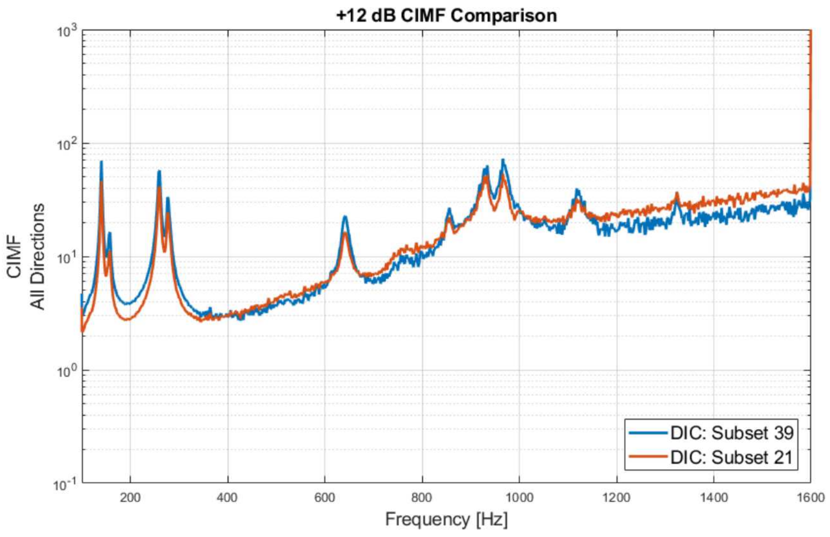
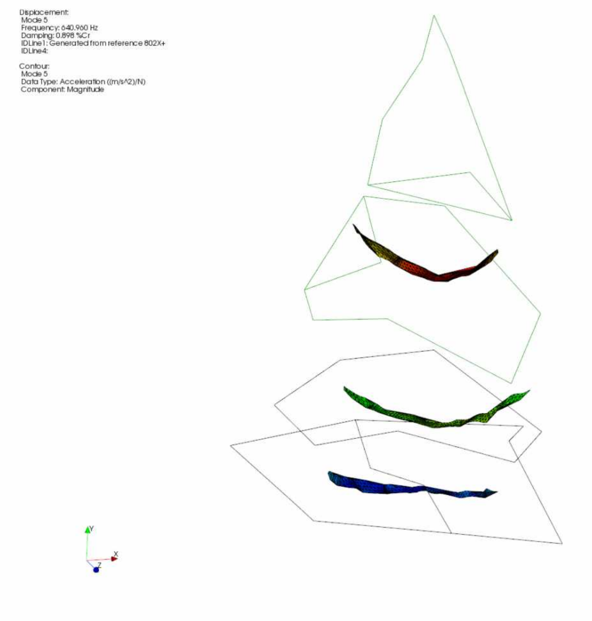
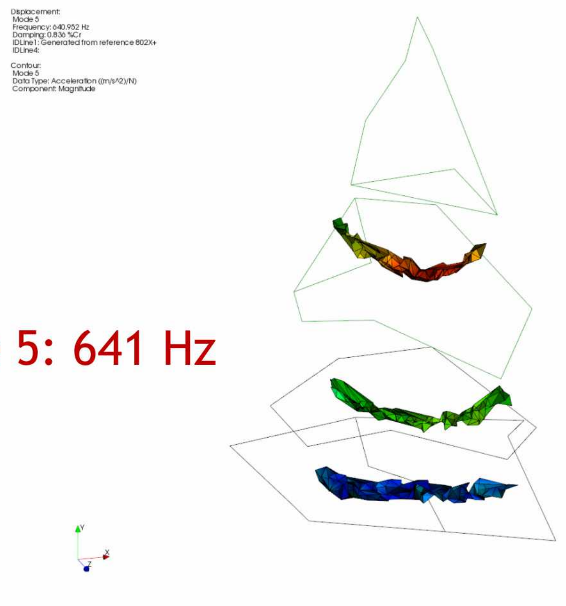




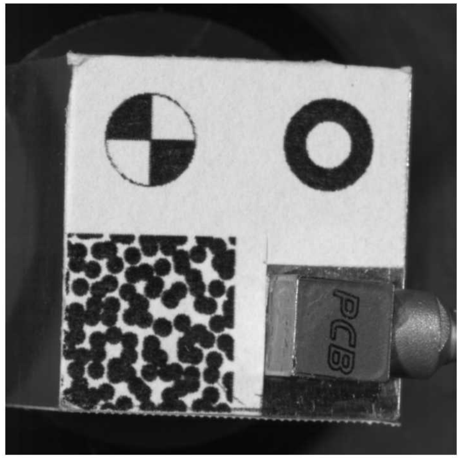


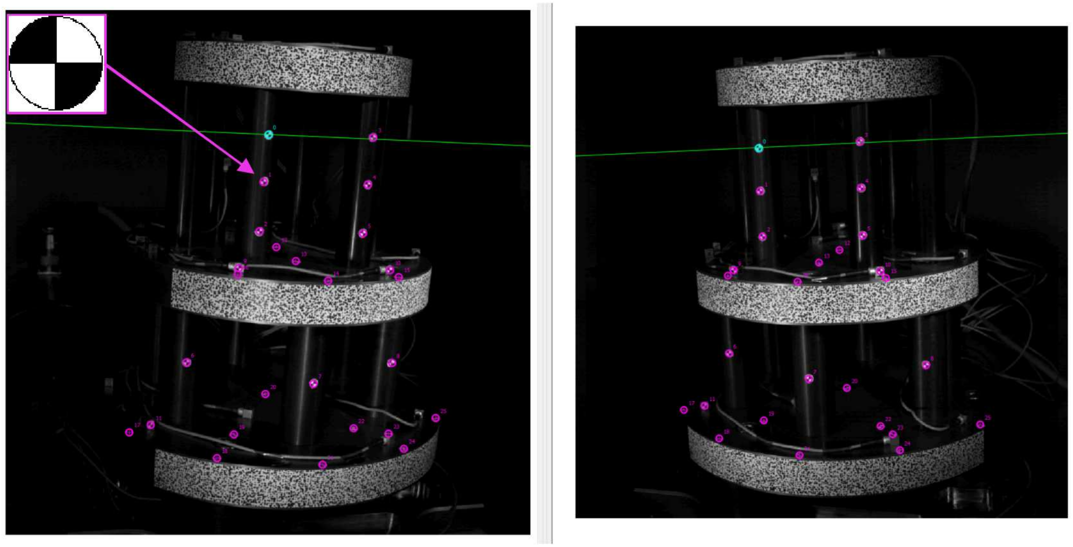
Mode 5: 641 Hz

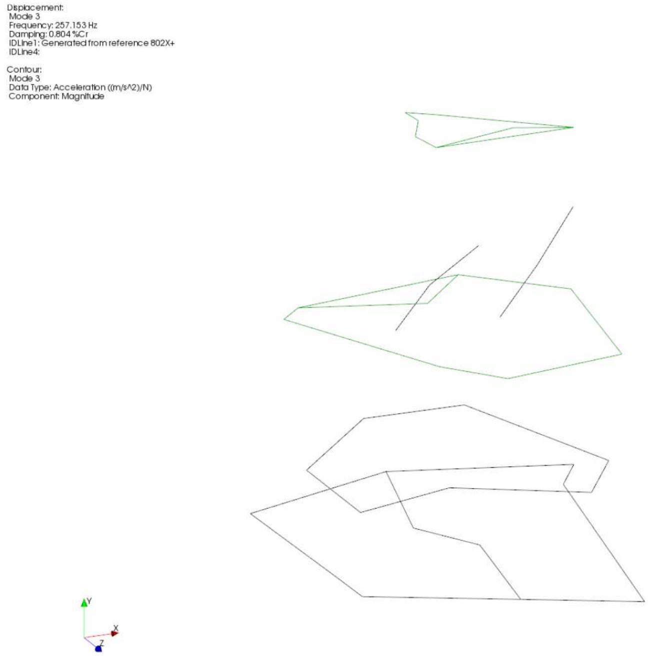


SD DIC Early Exploration

- **Marker Tracking**
  - Fiducial markers printed on label paper
  - Two styles supported in VIC-3D
  - Not impressed with quarter-circle style so far…
    - Doesn't handle oblique angles very well
    - If too many pixels at center, it gets confused
  - Concentric ellipses seems to be more stable in tracking
- Appears to work based on shape extraction…
  - Have only looked at data export formats, one proof-of-concept data set so far
  - More rigorous comparison of accelerometer to marker types is underway.

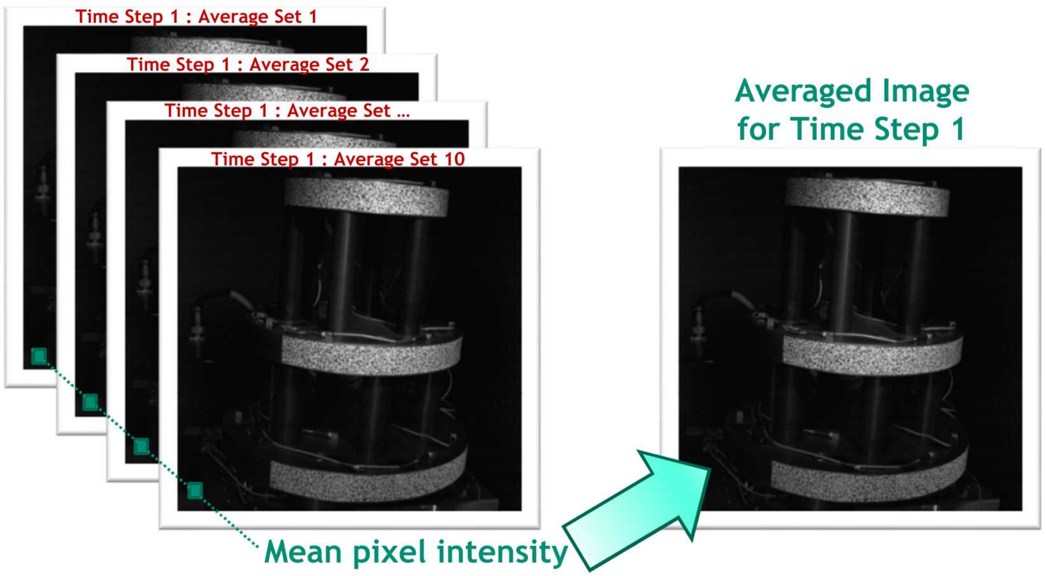


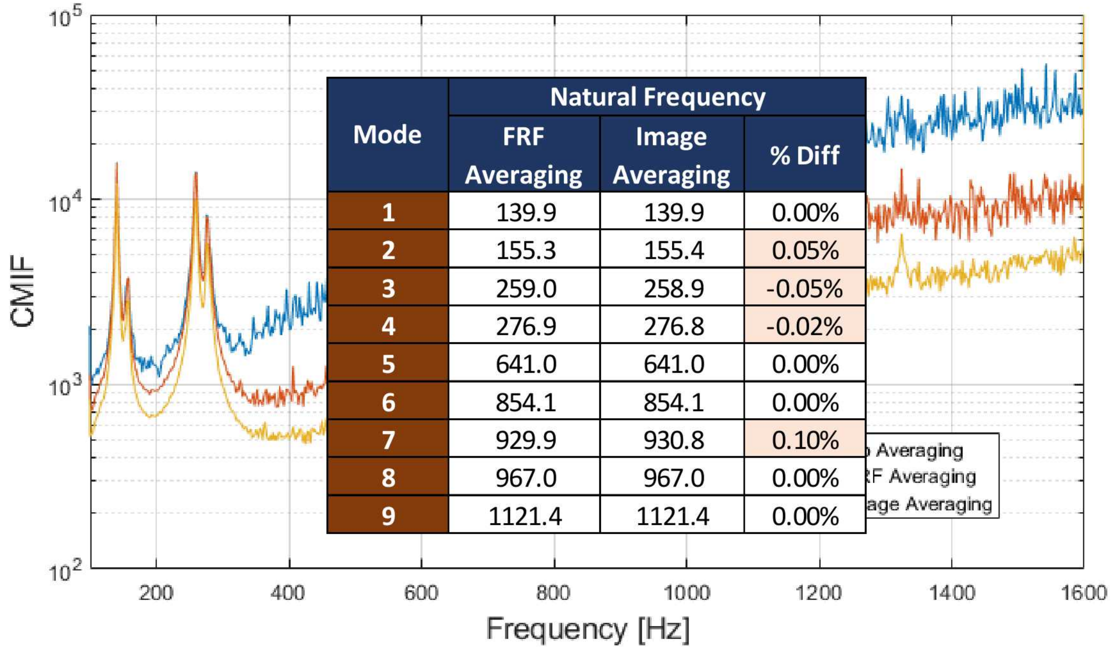




SD DIC Early Exploration

- **Image Averaging**
  - Deterministic inputs are same at each time step
    - Sine Dwell/Sweep
    - Pseudo-Random
  - Large time savings in DIC processing times
  - Easily implemented in Python or Matlab
  - Benefits over standard FRF averaging





Mode	Natural Frequency		
	FRF Averaging	Image Averaging	% Diff
1	139.9	139.9	0.00%
2	155.3	155.4	0.05%
3	259.0	258.9	-0.05%
4	276.9	276.8	-0.02%
5	641.0	641.0	0.00%
6	854.1	854.1	0.00%
7	929.9	930.8	0.10%
8	967.0	967.0	0.00%
9	1121.4	1121.4	0.00%

10 Averages
- 2048 images per data frame
- Per camera

20,480 Images
- Per Camera
- DIC processing time ~1.25 hours

Image Averaging

2048 Averaged Images
- Per Camera
- DIC processing time ~2 minutes

SD DIC Early Exploration

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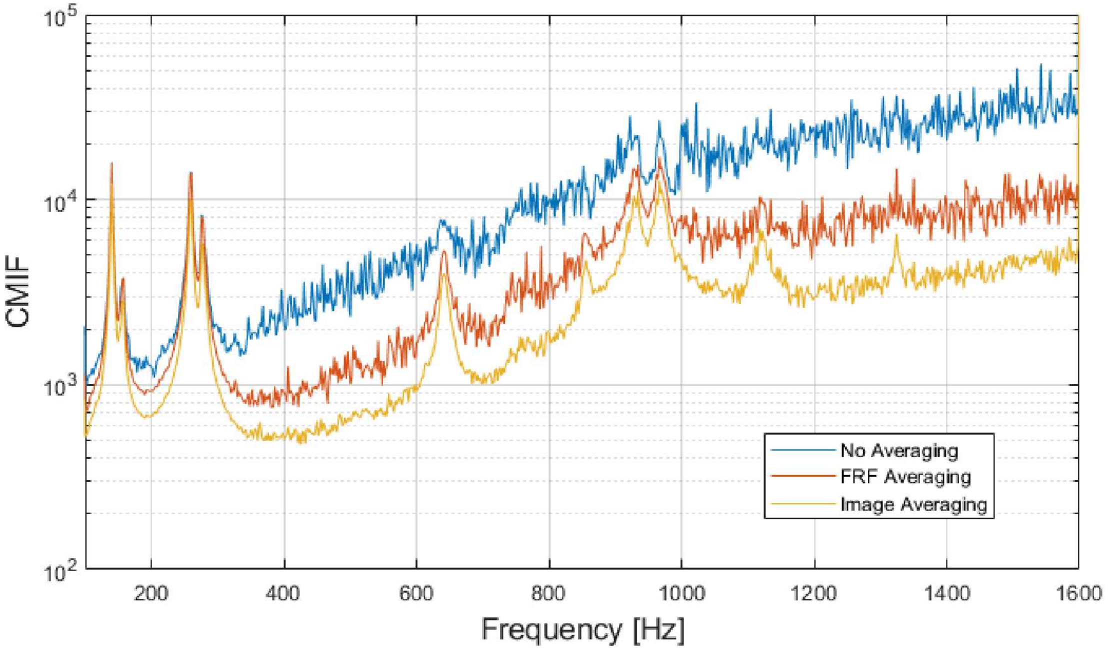
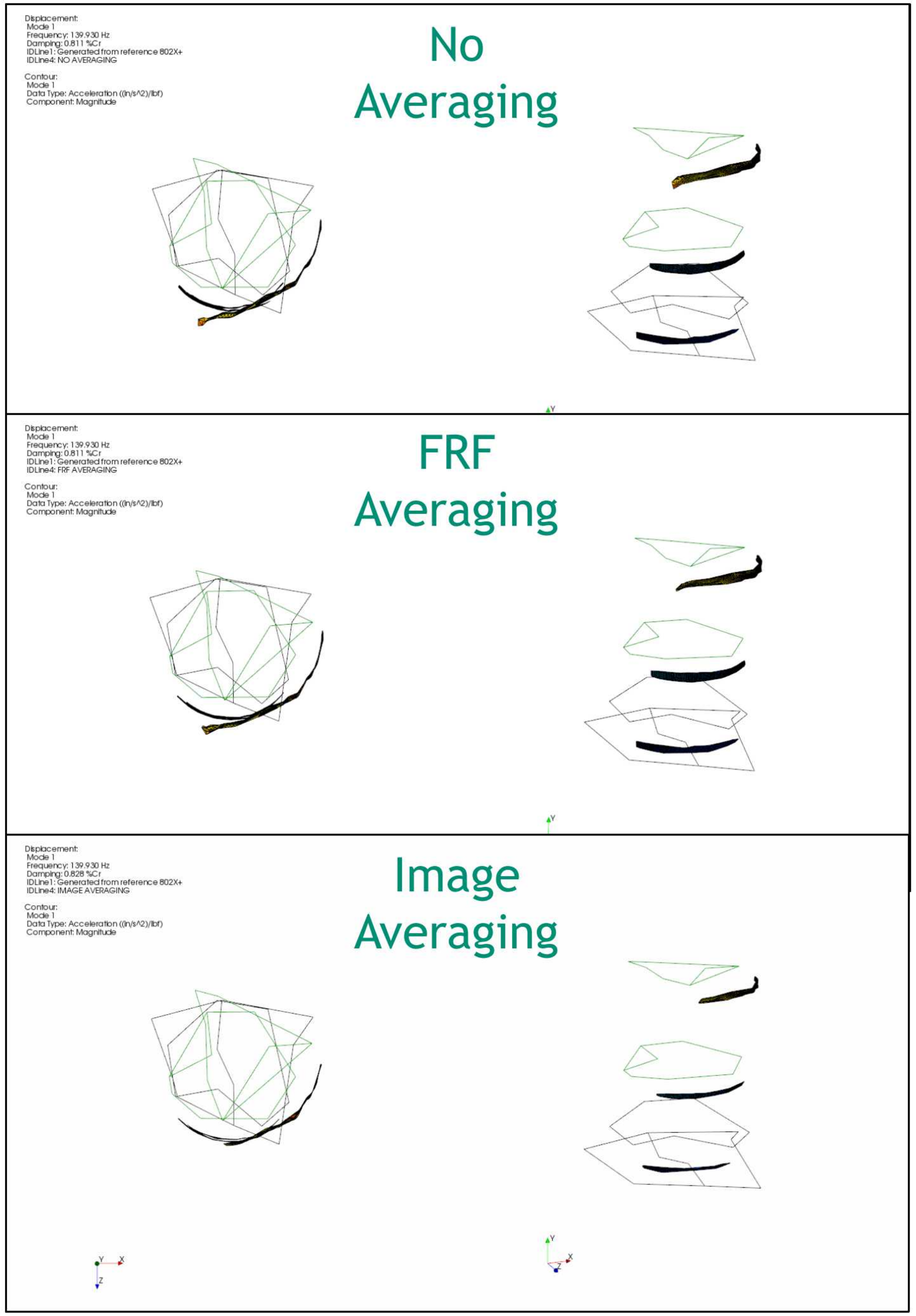


Mode 1:
140 Hz



SD DIC Early Exploration

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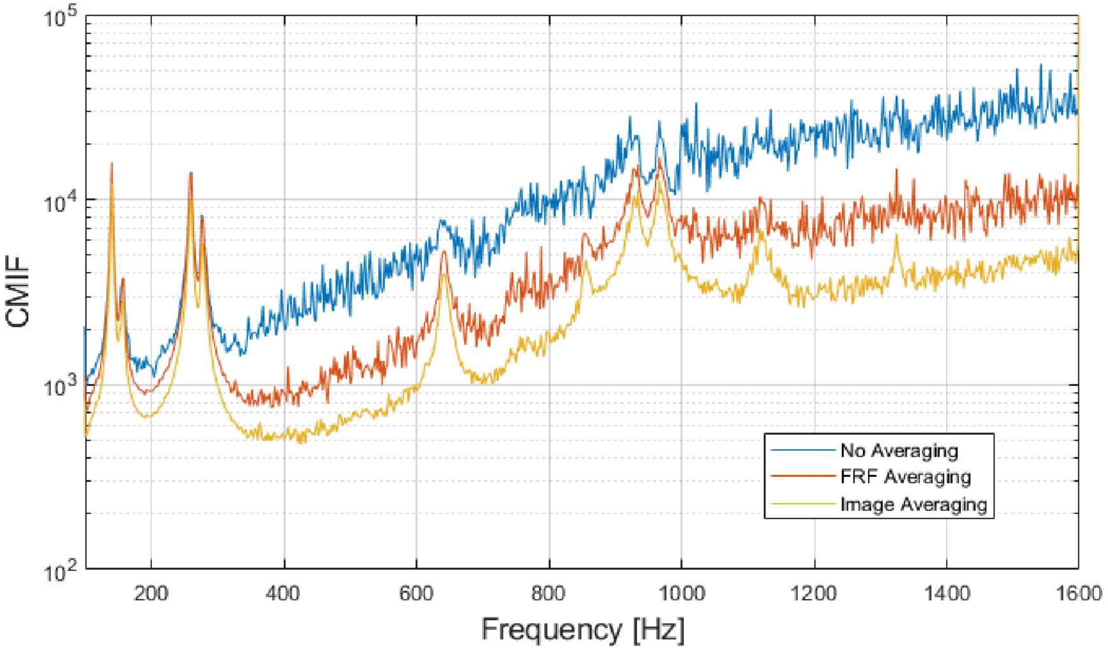
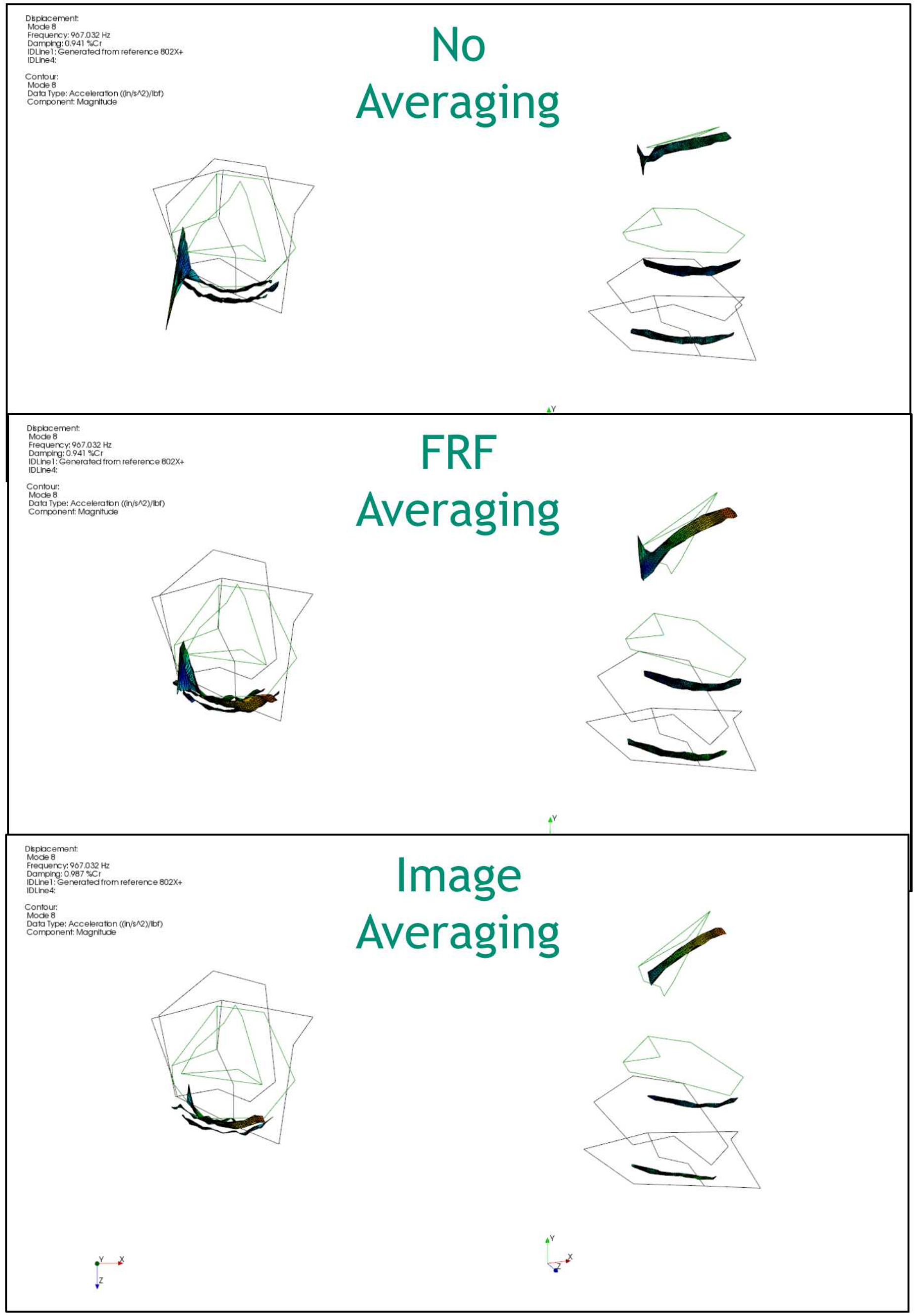


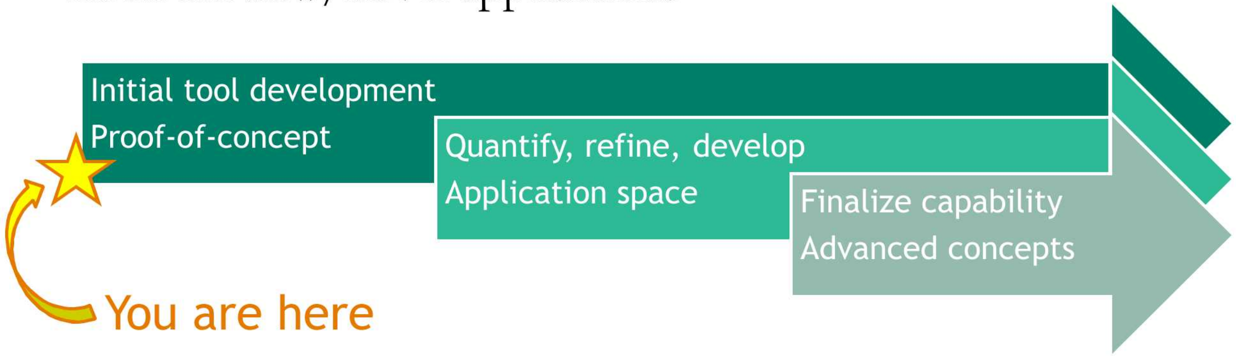
Mode 8:
967 Hz

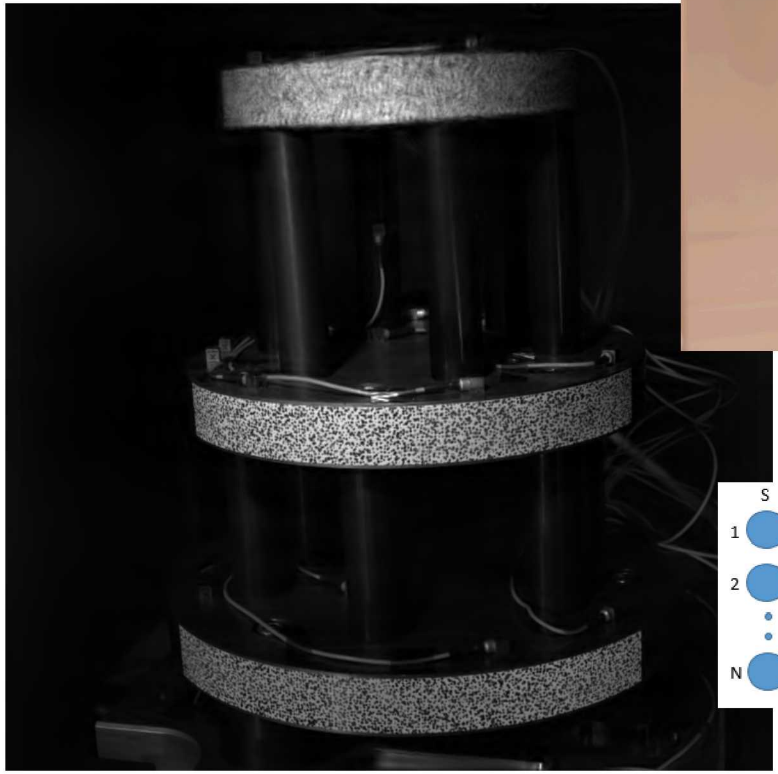


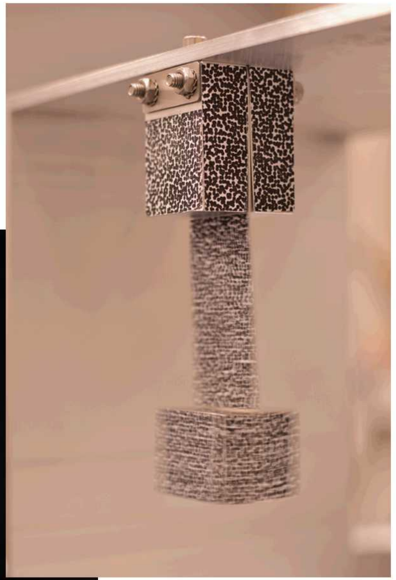
Future Work

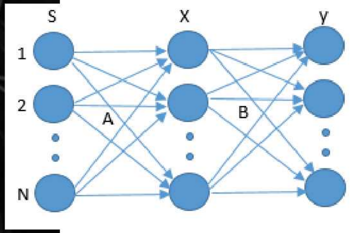
Future Work

- MPV
  - Limited applications at SNL (currently)
  - Have capability to potentially use system in future in on-off cases
  - 3D-SLDV and Photogrammetry span the space of most areas where MPV would be useful
- Photogrammetry
  - Develop enhanced OMM tools (code/hardware)
  - Explore methods for data de-noising
  - Advanced optical methods
  - Increase collaboration work
  - Uncertainty quantification and model verification/validation
  - Look for new/novel applications







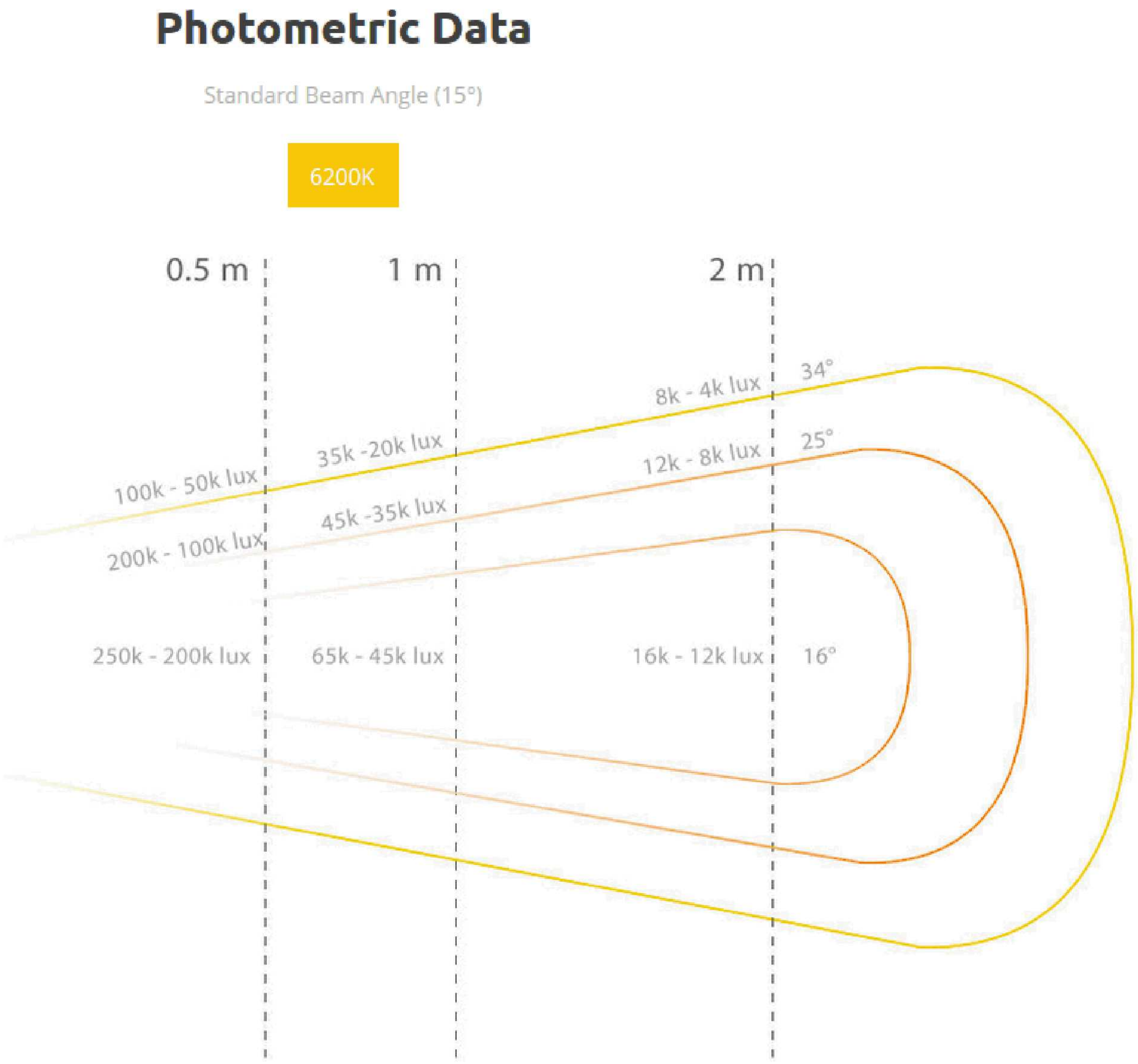


https://en.wikipedia.org/wiki/Blind_signal_separation

Backup Slides

Veritas LED Lights

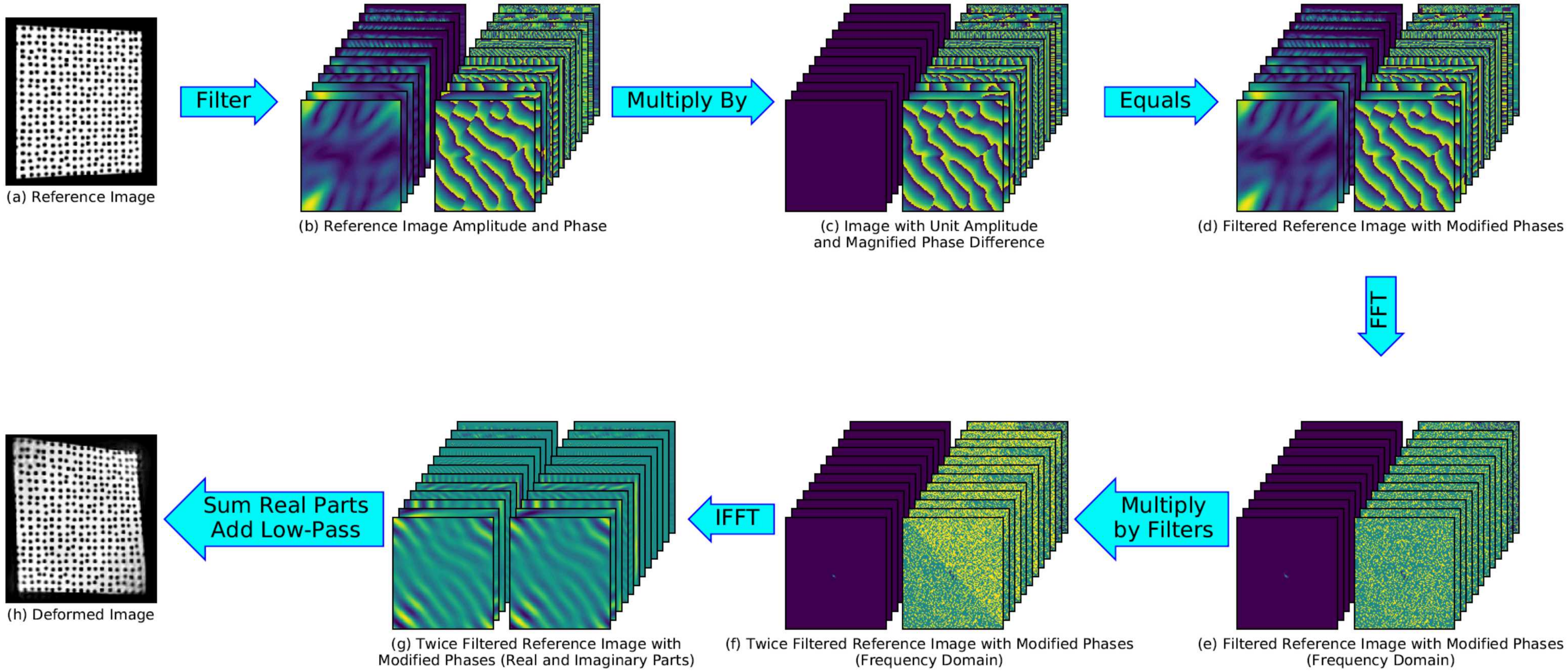
- 6200K
- Standard 15 deg beam angle



https://veritaslight.com/constellation-120e/

SD DIC Future Work

- **Motion Magnification**
  - This could (will) be a talk in itself…
  - Phase-based image processing method – proportional to displacement



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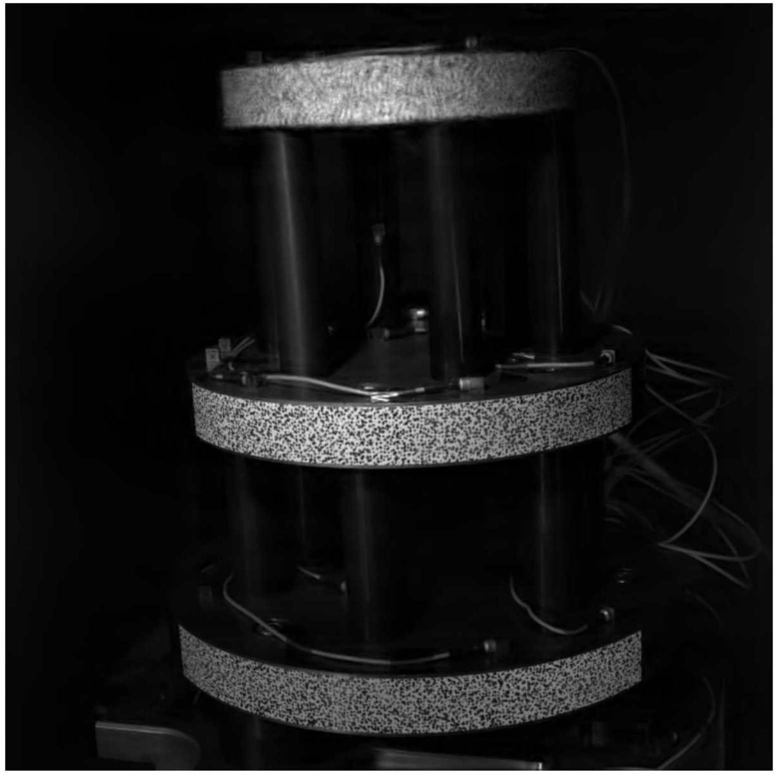
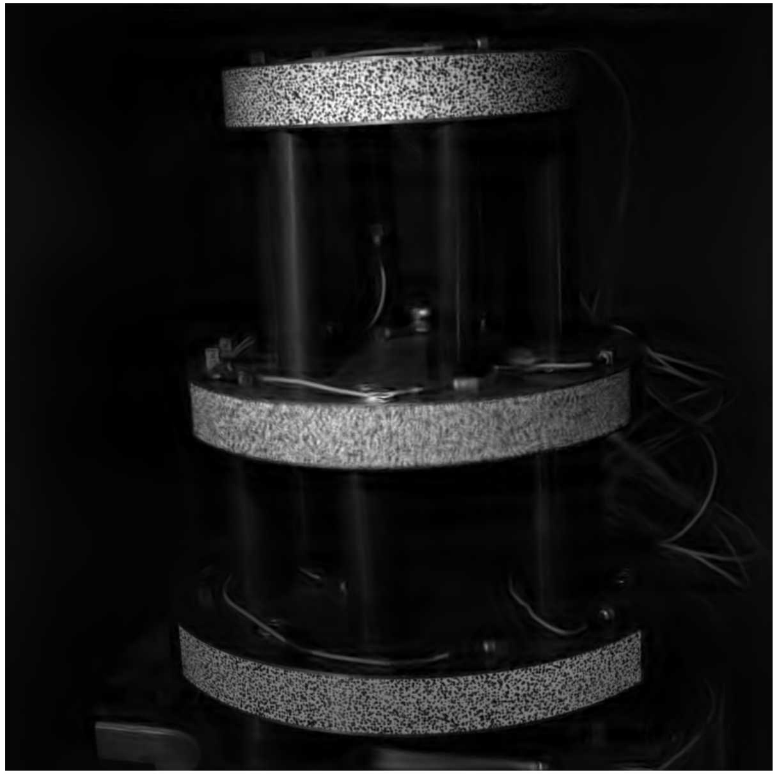
Mode 1: 140 Hz



Mode 2: 155 Hz



Mode 8: 967 Hz