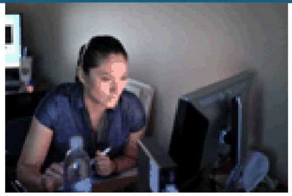
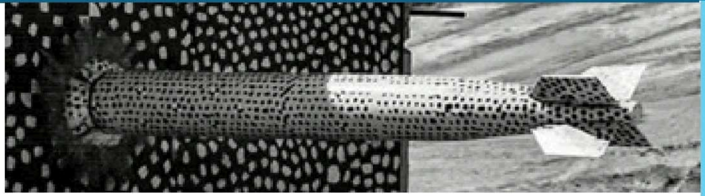
SAND2020-1050C

Launching DIC as an Experimental Modal Analysis Capability





IMAC XXXVIII

Bryan Witt, Dan Rohe

Sandia National Laboratories
Experimental Structural Dynamics

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Overview

- What's the problem?
- Test planning
- Test Setup
- Test Execution
- Post-Processing
  - DIC Output
  - Noise Mitigation
- Conclusions & Future Work

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- Collection of practical aspects
- 1st hand experience, issues, observations
- Current practices, developing as we learn

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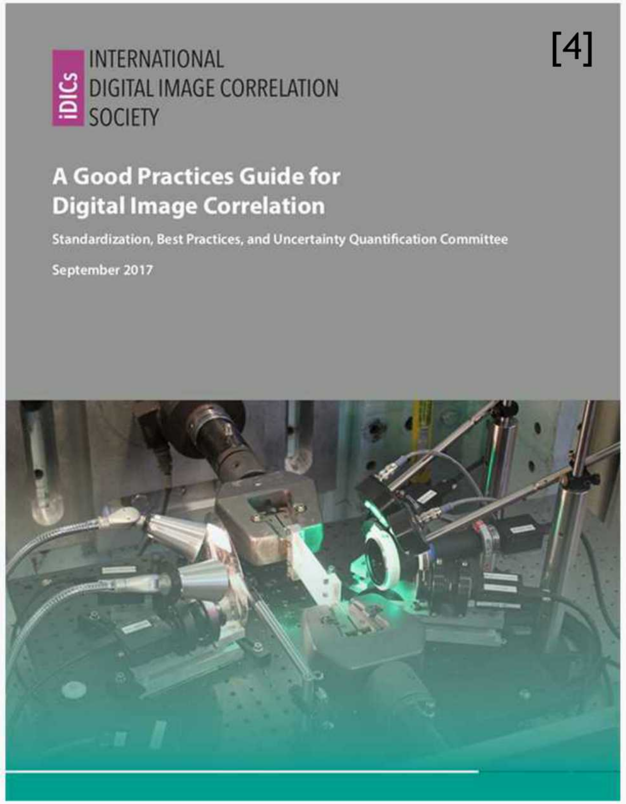
This talk is not:

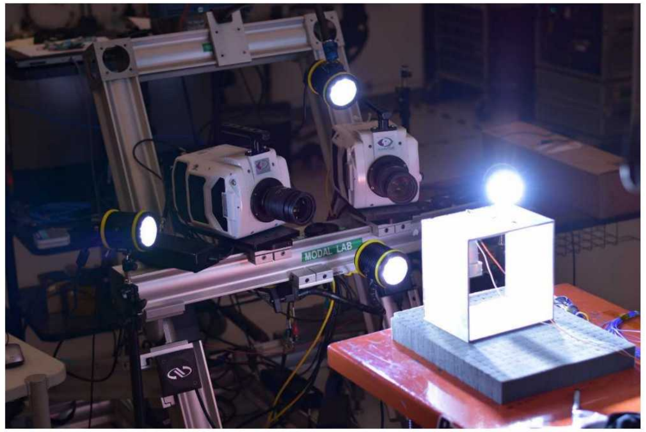
- How-to guide
- Gospel truth

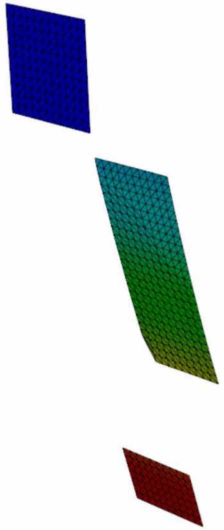


www.idics.org/guide

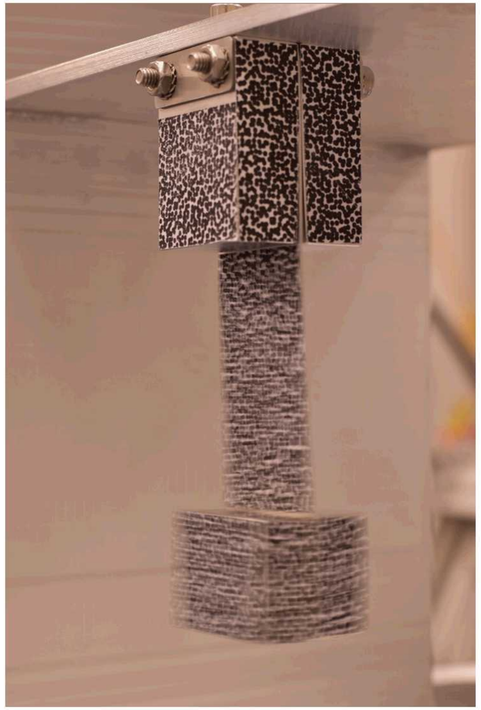
What's the problem?

- Digital Image Correlation (DIC) is well established…
  - True for **large amplitude** motion, **low frequency** response
  - Operational Deflection Shapes (ODS) are often assumed to be representative of mode shapes
- **Goal: DIC as a general modal test capability**
  - Displacements can range from very small (sub-pixel) to very large (laser measurements not valid)
  - Frequencies can range from low (DC) to high (~2000 Hz)
  - Extracted modes can be used for model validation (vs. ODS and frequency peak picking)
- Main difficulties:
  - Noise Floor
  - Determining appropriate test-setup
  - No commercially available hardware/software solutions for end-end DIC modal testing





1st Mode (ODS): ~7 Hz



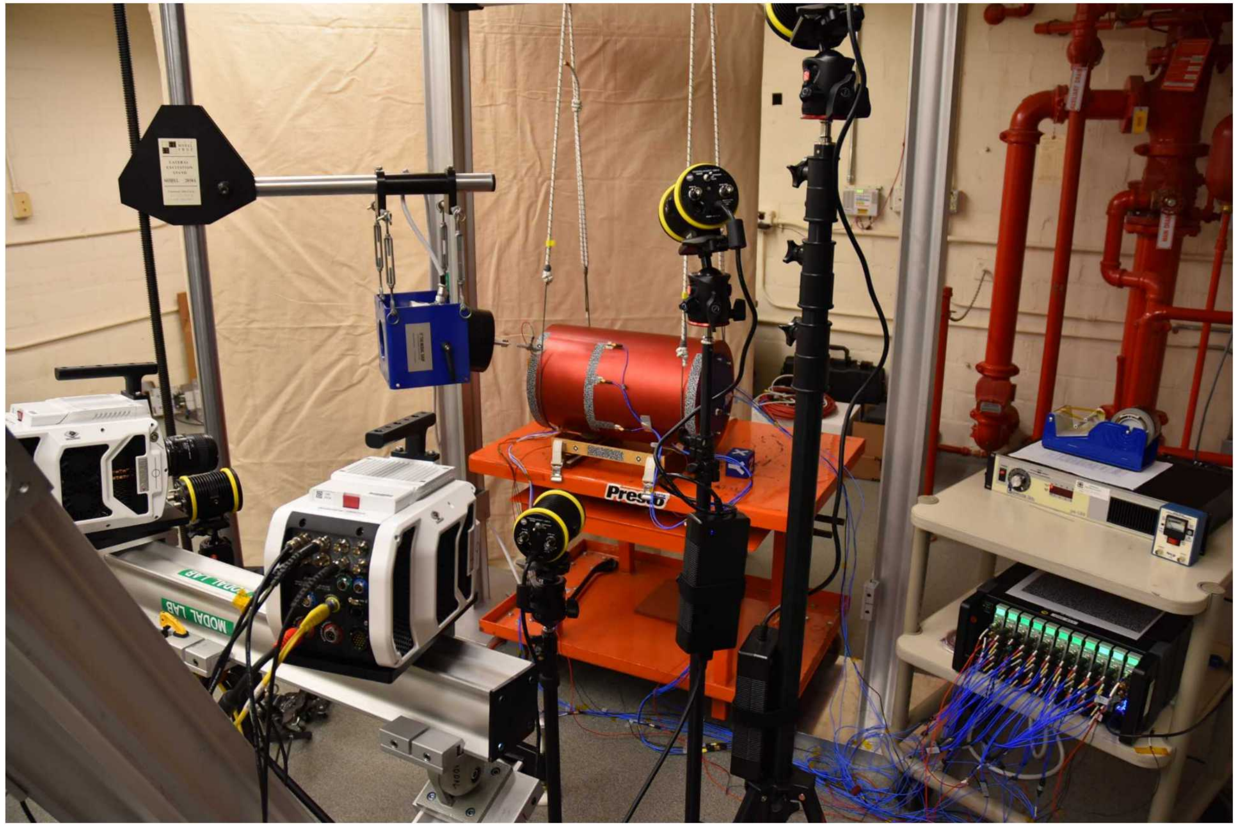
Test Planning

You've got to be very careful if you don't know where you are going, or you might not get there. -Yogi Berra

Test Planning

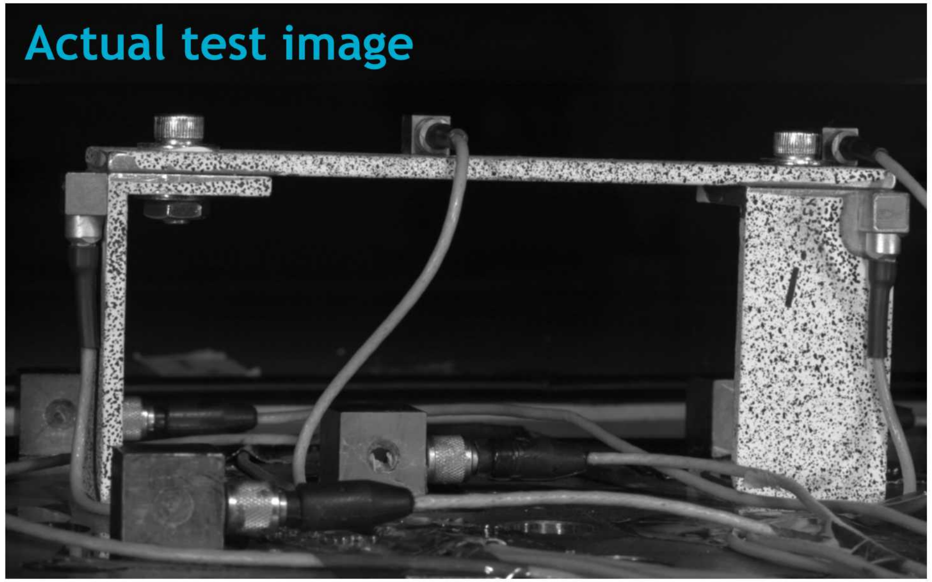
- **You probably want to combine DIC with a traditional Data Acquisition System (DAS)**
  - **Input forces**
    - Transfer function derivations
  - **Drive point accelerometers**
    - Mode shape scaling
    - Data checks
  - **Additional accelerometers**
    - Help determine DAS settings like frame length, etc!
    - Places not visible to cameras
      - Especially locations necessary for modal extraction or expansion!
    - Higher signal-to-noise ratio makes it possible to identify frequencies of interest below camera noise floor [5]

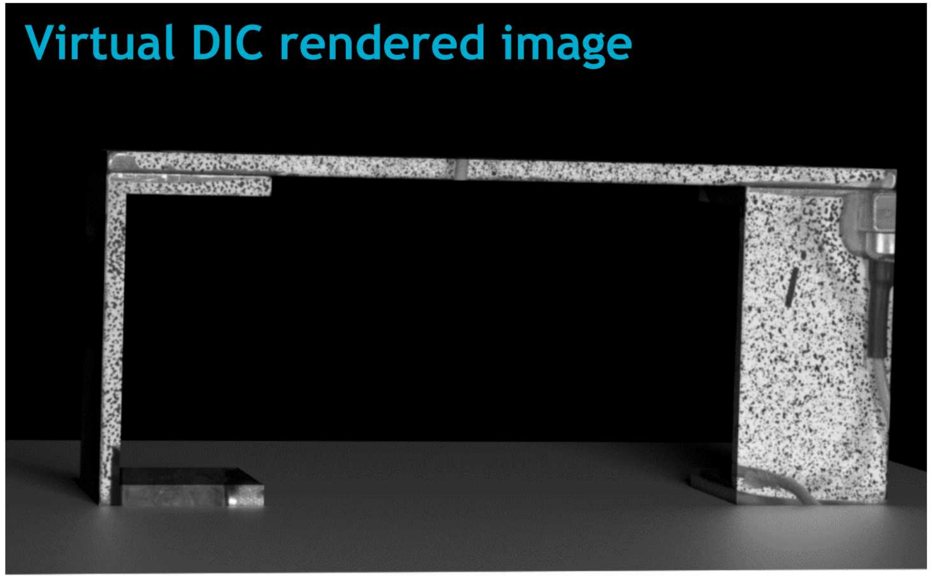
  - Causes synchronization issues that we will deal with in post-processing.
  - Extra planning & setup, but makes your test capabilities more flexible.



Test Planning

- **How much displacement is enough?**
  - **Displacement drops with frequency squared.**
    - Easy to set up a test and get nothing but noise…
  - **Pixels of displacement is key metric.**
    - Can use "Virtual DIC" to estimate [6]:
      - Uses finite element model (FEM) and rendering software (e.g. Blender)
      - Takes a lot of user skill
    - Working on Geometry + FEM based estimation tool:
      - Use geometric properties to help determine camera setup, estimate camera matrices
      - Use FEM to determine physical displacements due to excitation
      - Convert physical to pixel displacement using projection equations
    - Both methods dependent on input signal and model response accuracy
  - Heuristic: minimum of 0.1 px peak displacement
  - Fast, accurate pretest pixel-displacement estimation is an area for improvement!





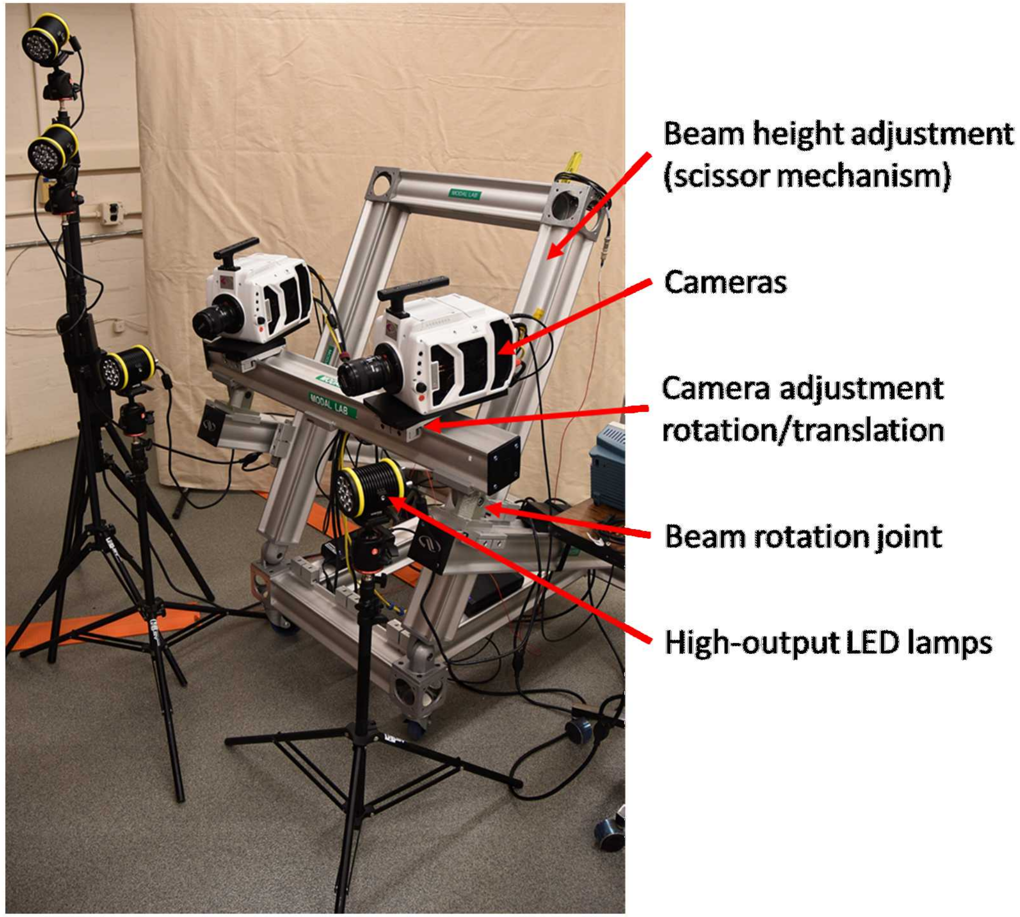
Test Setup

We're almost finished…we just need to get started.

Test Setup

- **Camera choices**
  - **No substitution for pixels.**
    - Improve signal-to-noise ratio (SNR) by increasing image resolution (px/mm)
  - **Extreme frame rates are not necessarily required.**
    - For general modal, you can go with Nyquist criterion for frequency domain analysis
    - Caveat: aliasing of responses above your imaging frame rate (glad we had those additional accelerometers sync'd up!)
  - **Onboard non-volatile memory is worth it for modal.**
    - Reduces time between test runs, minimizes risk of test object changes
    - Larger memory sizes means more tests before time-consuming data transfers
    - Can turn the cameras off and not lose all your data (after transfer from RAM to disks)

- **Spend some time designing your camera stands**
  - **Rigid, maneuverable, leveling**
  - **Easy adjustment of translation, rotation, and height**
    - Makes it easier to maximize Field of View (FOV) = better SNR
    - Reduces setup time



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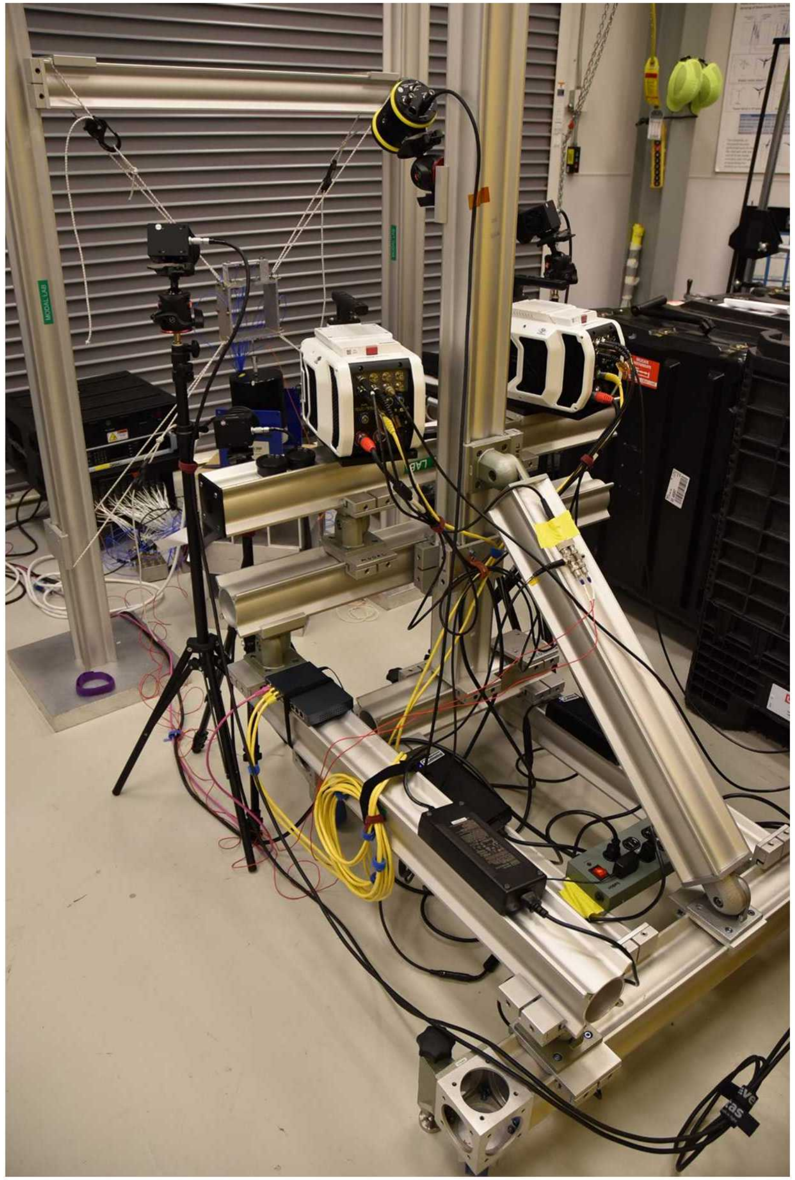
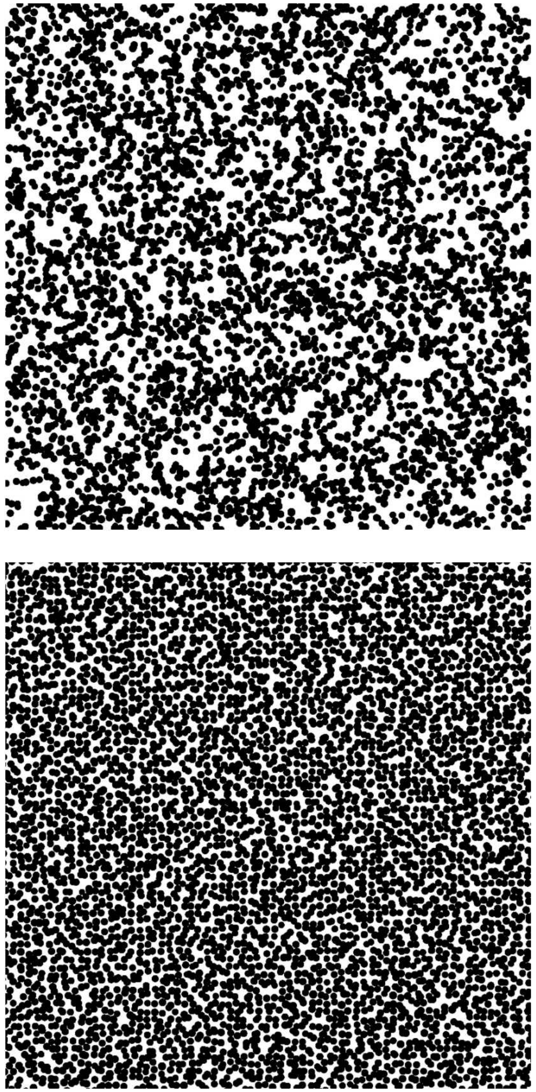


Test Setup

- **Contrast Patterns**
  - **For modal, don’t count stickers out.**
    - Small, continuous displacements
  - **Easy to numerically generate custom patterns.**
    - Can be optimized (pick a metric)
    - Create custom shapes using FEM geometry for easy application
  - **Arts and crafts day in the lab.**
    - Repeatable
    - Faster, cleaner, less permanent that painting
    - Fits nicely into work flow for Virtual DIC in planning stages

Numerically generated patterns



True Random

“Jitter” Random

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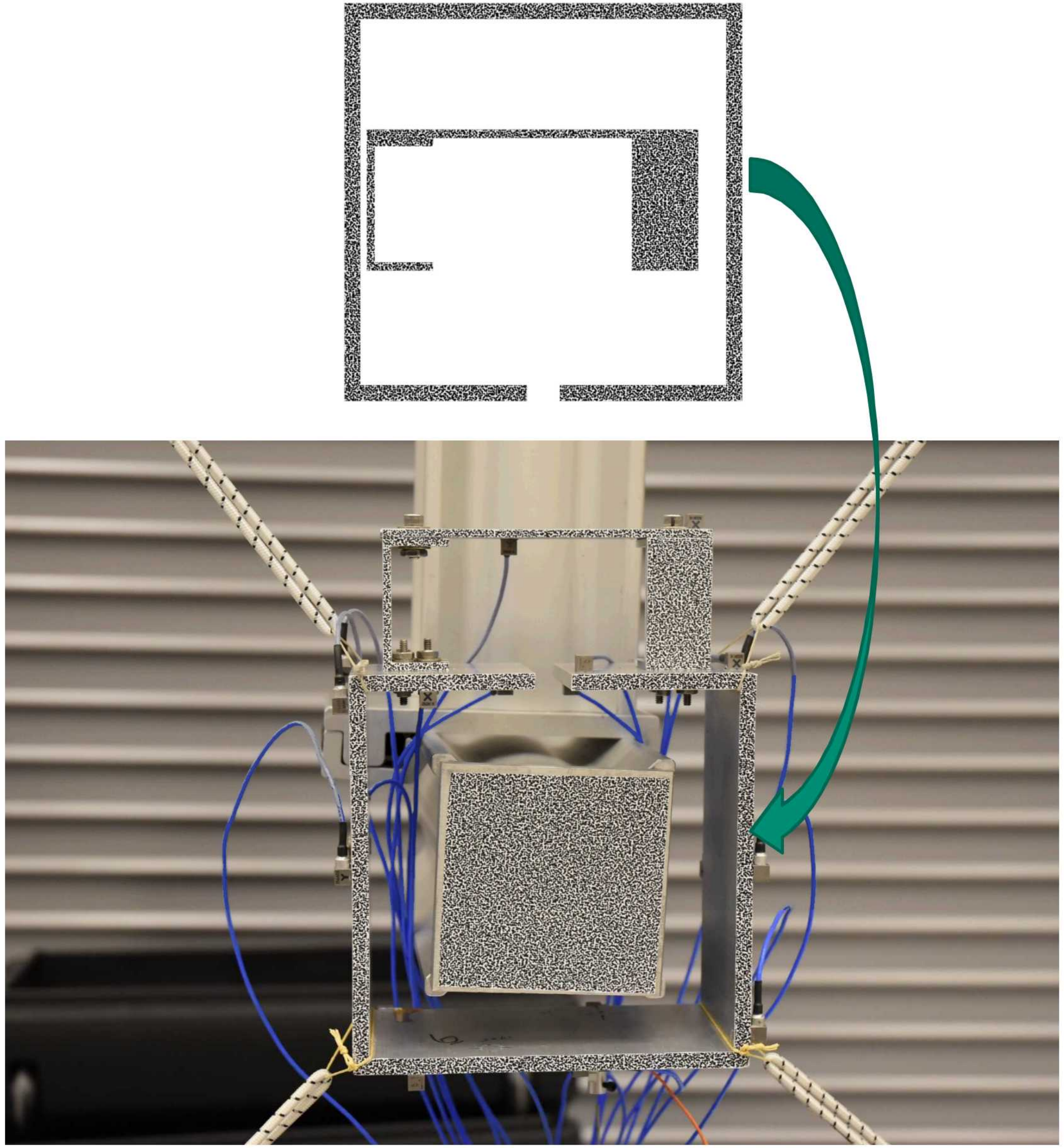
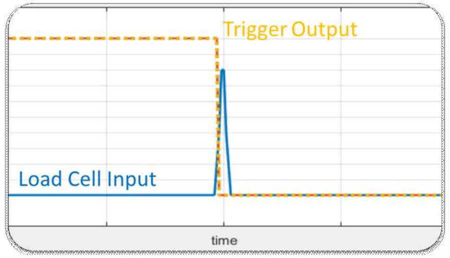
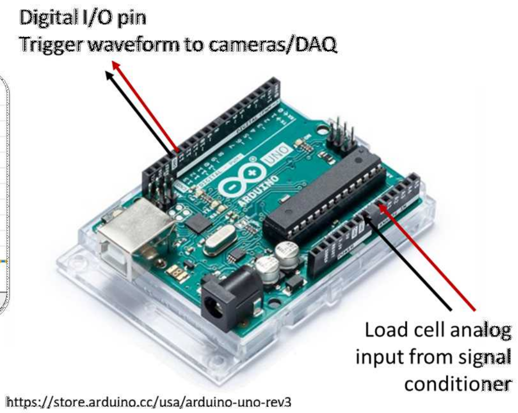
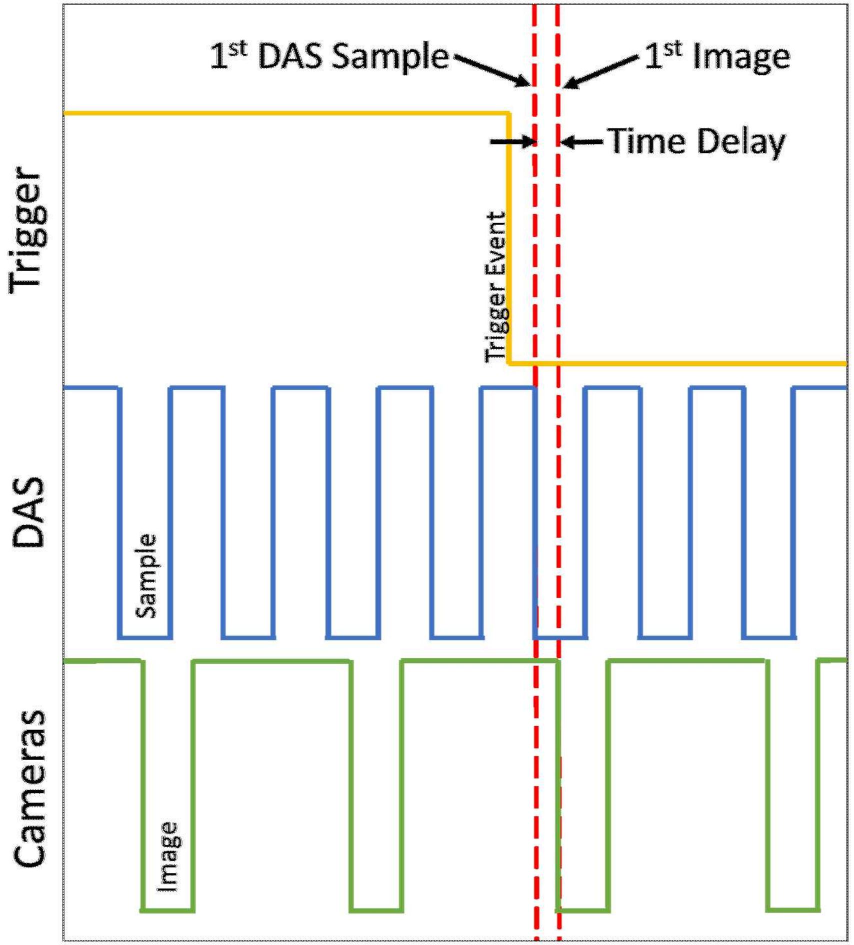


Test Setup

- **Triggering the DAS and Cameras**
  - **I want to use my own DAS…not a supported 3rd party board.**
    - Low channel count, just another system to maintain
  - **Get the cameras synchronized first.**
    - Time Code Out → Time Code In, Frame sync → Frame sync
    - Use oscilloscope and set delay of one camera (can get < 25 ns time difference)
  - **Trigger both systems with same TTL signal.**
    - Shaker: plunger switch
    - Hammer: need additional equipment (Arduino, Digital Delay Generator, etc.)
  - **Triggering ≠ Synchronized!**
    - Constant, non-integer time delay between both systems
    - We will fix this issue in post-processing!

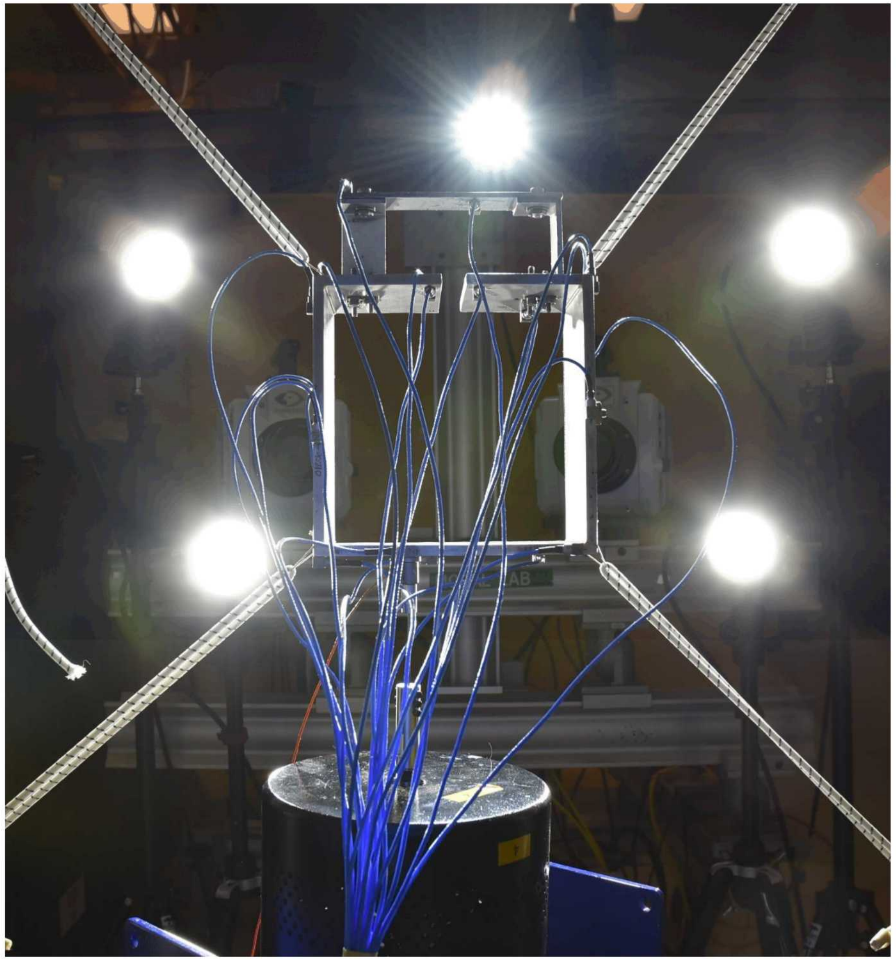






Test Setup

- **Other Thoughts on Test Setup:**
  - **Dang, those lights get hot!**
    - Heatwaves from lamps can cause bias errors as high as 100 Hz [1]
    - Try to keep lamps behind cameras, minimize on-time
    - High-pass filter data as a last resort (where are your modes?)
  - **Make sure your test article suspension is stable.**
    - Bungees sag, foam compresses, air bags leak, life happens…
    - Remember you are playing a sub-pixel game
  - **Oversample the DAS relative to the camera frame rate.**
    - DAS probably has fixed sample rates at $\mathbf{n^2}$,
      might not line up with best camera frame rate…
    - Check for aliasing in camera data
    - Keep camera frame rate as low as reasonable to keep file size down
    - Use proper resampling to prevent aliasing (e.g. Matlab's *resample* function)
  - **Collect time histories with the DAS!**
    - Not just FRF output
    - Need to process the DIC and DAS time histories together using same tools
  - **Take static reference images with the shaker powered on.**
    - Armature jumps to fixed position when shaker is powered on
    - Do as soon as possible before testing

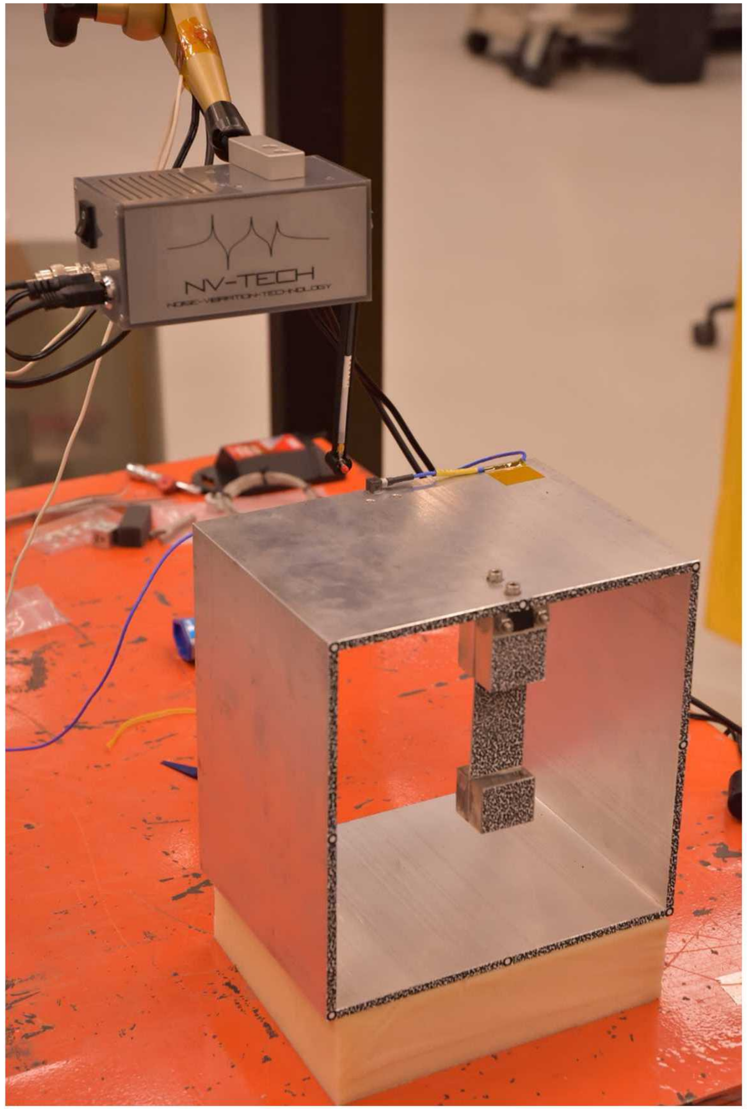


Test Execution

40,960 stereo images are worth 8.1920e+10 words.

Test Execution

- **Hammers or Shakers?**
  - **Shakers please. Hammers add complexity:**
    - Require more equipment for triggering
    - New undeformed reference image(s) after each impact?
    - Need more averages for clean Frequency Response Functions (FRF) [7]
    - Large rigid body motion (lose focus, leave FOV)
    - Harder to control frequency range (aliasing is the boogey-man)
- **What kind of shaker excitation?**
  - **Depends how much data you're willing to deal with.**
    - True random: need several averages for clean FRF [7] = lots of images
    - Burst random: have to process entirety of each frame
    - Sine sweep/dwell = OMG image quantities (but should be high SNR)
  - **Pseudorandom has a few nice features.**
    - Fewer averages for cleaner FRF [7]
    - You can average images across data frames,
      collapsing the number of images going into DIC
    - Easily shaped: ramp higher frequency amplitudes to get better SNR



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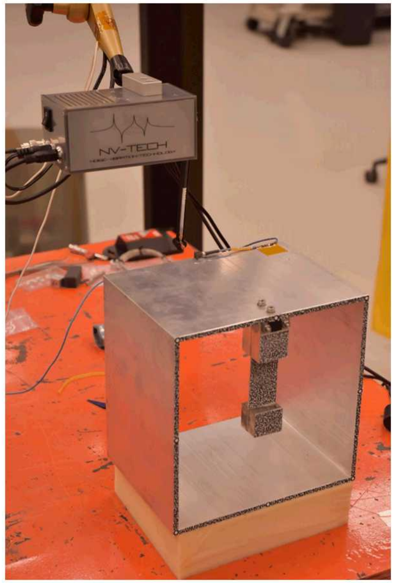
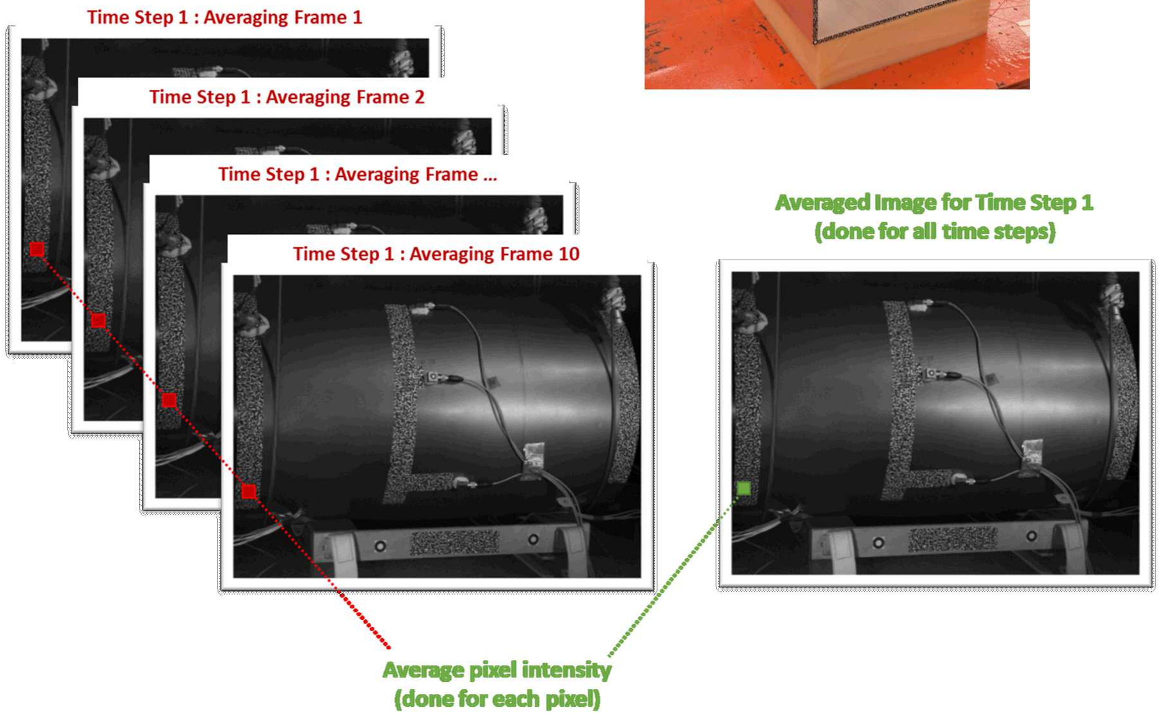
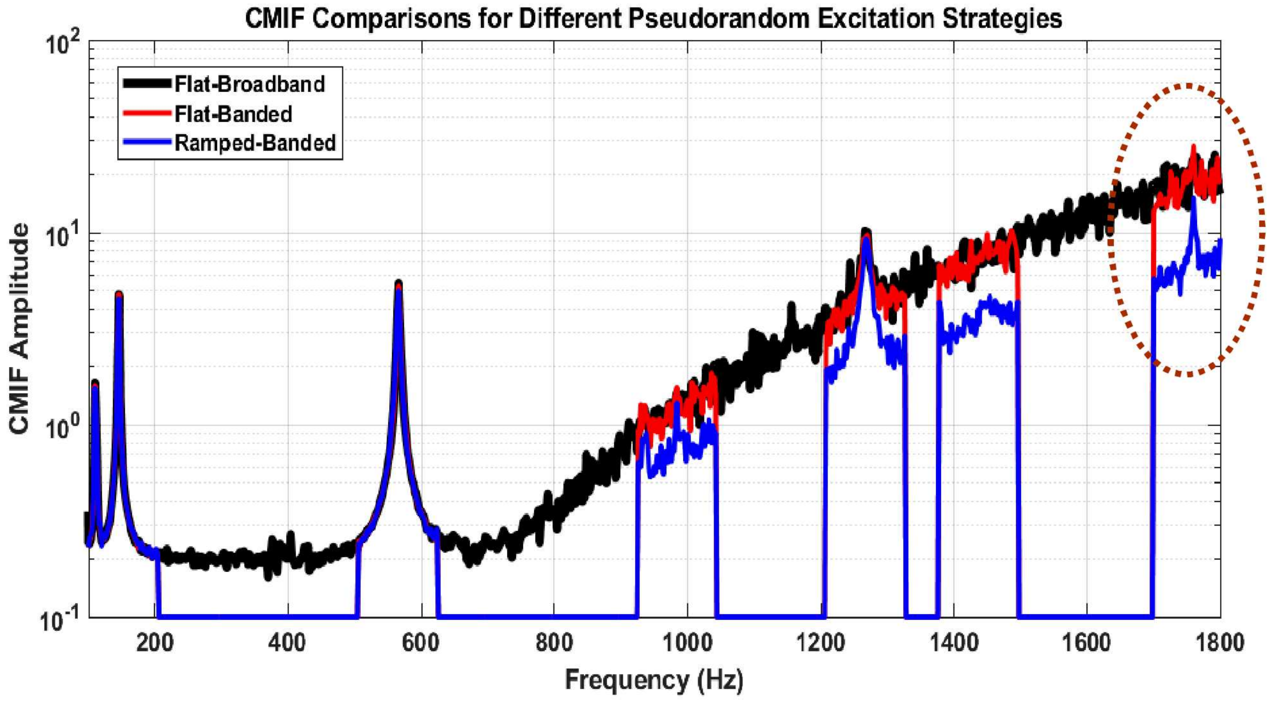




Test Execution

- **Shaping your pseudorandom can help with SNR**
  - **Typical flat-voltage excitation**
    - Suffers at high frequency where displacements are small
  - **Does banding the flat-voltage signal help?**
    - More efficient use of the shaker energy?
    - Our experience has been that it doesn't buy you anything except weird looking FRF
  - **Ramp excitation amplitude with frequency?**
    - Put more energy in where the SNR naturally suffers
    - Example here is linear ramp, in hind-sight an $\mathbf{n^2}$ ramp is more logical…
    - This has been found to help!
  - **Flat-force excitation?**
    - Shaker works harder to force excitation at resonances
    - Better excitation at frequencies of interest
    - BUT…you run out of shaker capability quickly, and it takes a little more effort to derive your input signals
    - This has been found to help!

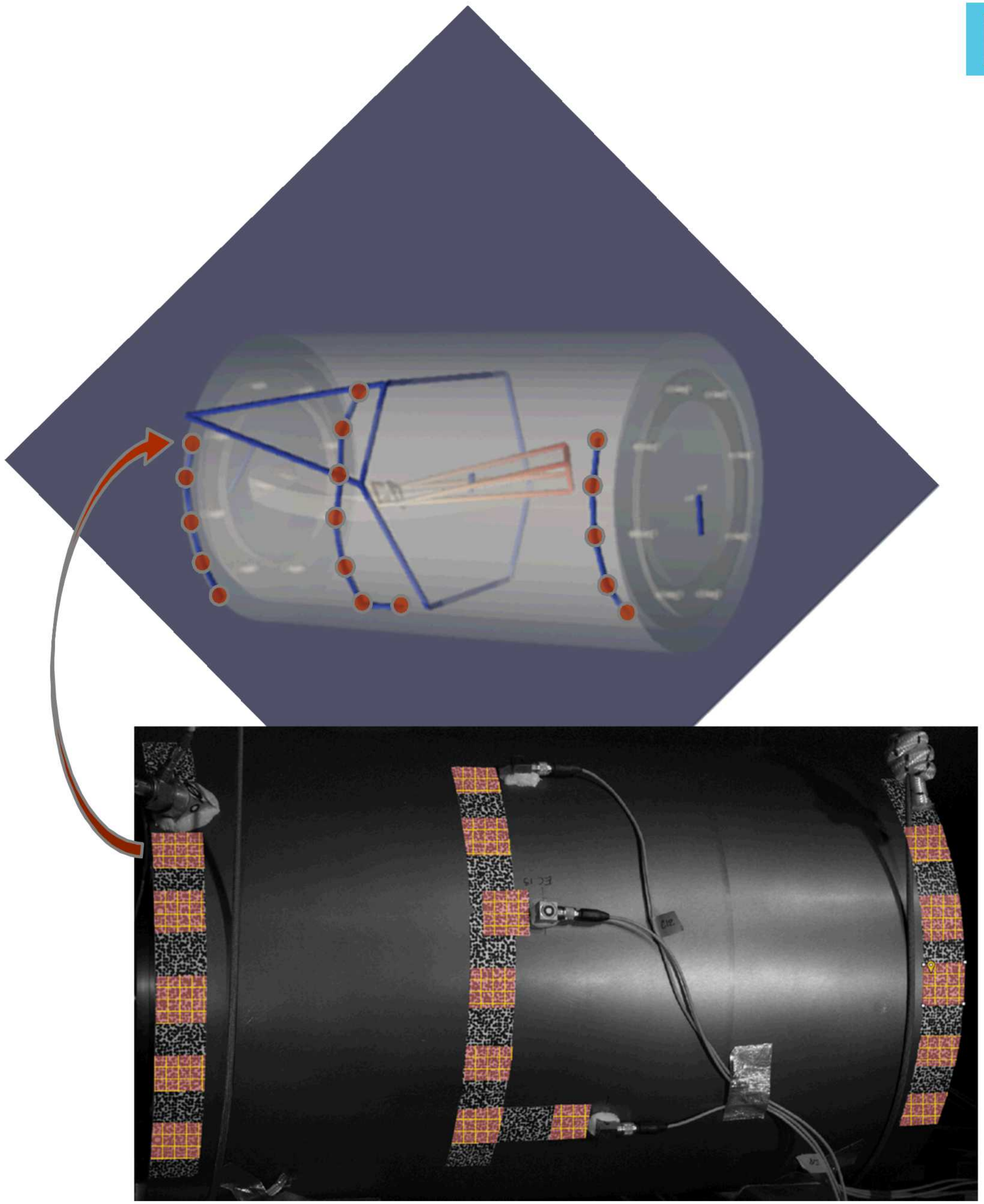


Post-Processing

The details got him…I'm afraid it was a slow and painful death.

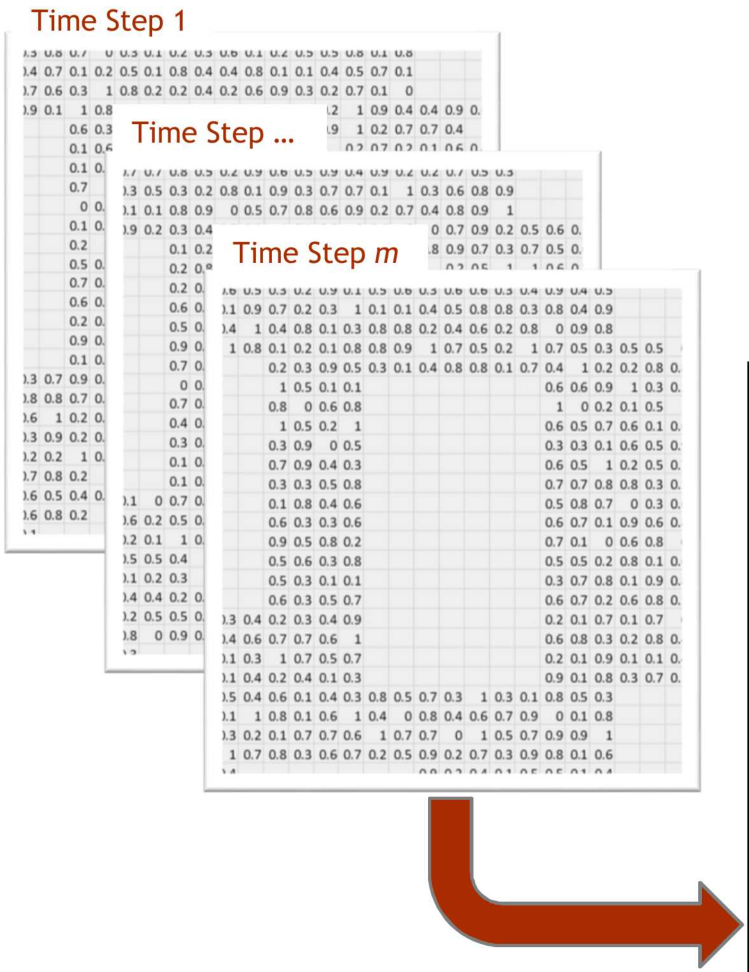
Post-Processing

- **You're on your own.**
  - **Currently, no end-to-end DIC Modal software.**
    - ODS/frequency peak-picking modules don't count (great preliminary quick-look though)
    - Especially if you are combining other DAS data
    - Up to us to manipulate the DIC data to get it ready for modal analysis
- **You have a bunch of images, now what?**
  - **Make your reference image.**
  - **Average images over all data frames (if applicable).**
  - **Run DIC analysis:**
    - "Large" subsets may not be the worst thing in the world
    - Do you really need full field for modal?
      - Consider averaging subsets around areas where you would have put accelerometers (make AOI's "sensor patches")
      - Sparse data, but more averaging to reduce noise



Post-Processing: DIC Output

- **Reformat the output data.**
  - **Specific to your DIC program and EMA needs.**
    - Flatten matrix formats consistently over all time steps
    - Combine multiple areas of interest (AOI)
    - Watch out for subsets that didn't solve in all time steps
    - End result needs to be a time history vector for each subset
  - **This is a good time to check your units!**
    - Example: DIC data are Metric and your DAS data are Imperial, convert one to match the other now.



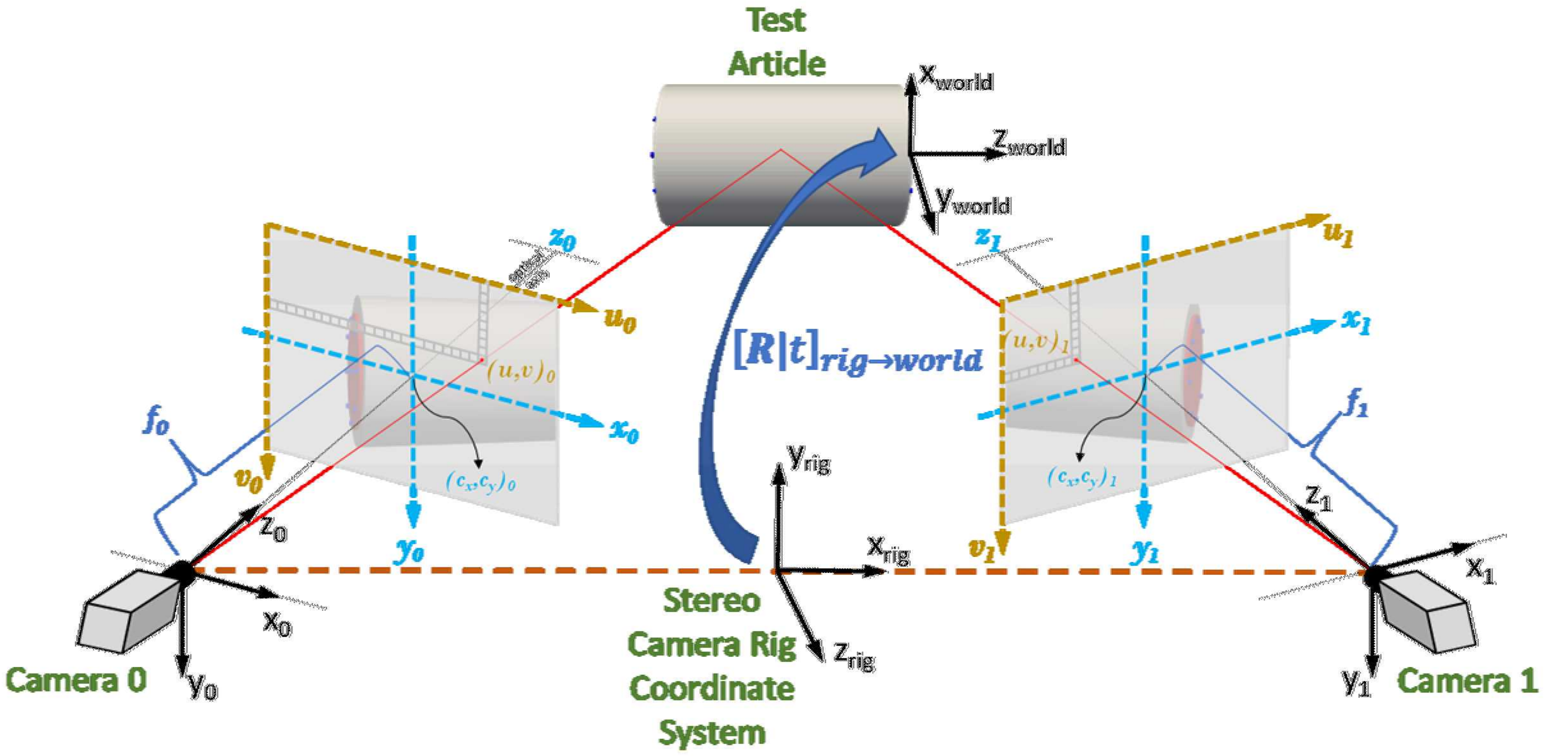
Time History Column Vectors

Subset 1	Subset 2	...	Subset n
0.2	0.8		0.3
0.6	0.5		0.2
0.4	0.5		0.5
0.6	0.0		0.6
0.9	0.0		0.0
0.0	0.8		0.3
0.5	0.7		0.2
0.7	0.2		0.8
0.1	0.5		0.5
0.5	0.1		0.8
0.4	0.4		0.0
0.1	0.2		0.2
0.6	0.9		0.2
0.2	0.1		0.4
0.3	0.9		0.4
0.7	0.6		0.0
1.0	0.2		1.0
0.7	0.7		0.2
0.5	0.2		0.2
0.2	0.8		0.3

Post-Processing: DIC Output

- **What coordinate system am I in?**
  - **Stereo-DIC analysis will give you results in the camera rig coordinate system.**
    - Not consistent with your other DAS data! Or anything else!
    - Need to convert data to your test article's global coordinate system
  - **Transform DIC data from Rig t**
    - Least-squares Rigid Motion Transformati singular value decomposition [10]
    - Faster than doing transformation in DIC
    - More flexible if you want to change later

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{world} = \boldsymbol{R} \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{rig} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$$



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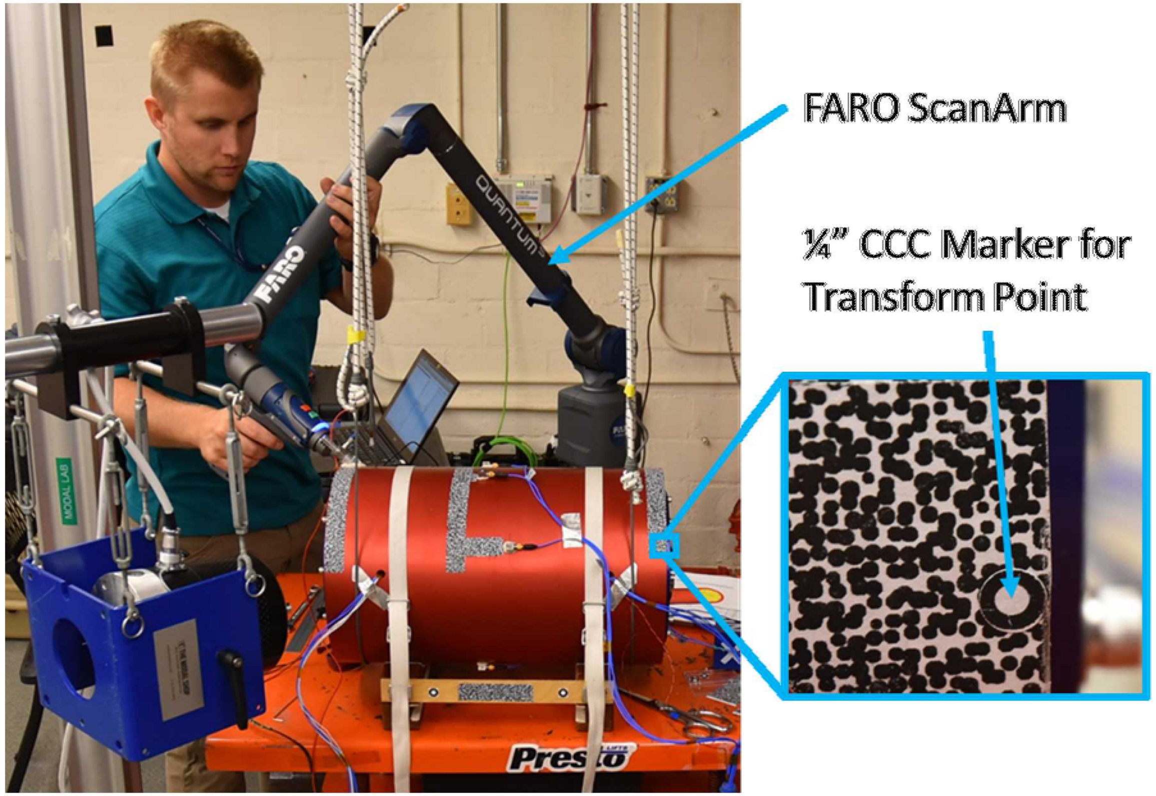
    - **Have to know 3D coordinates of at least 3 points in both coordinate systems.**
      - Can use known locations (FEM)
      - Fiducial markers are handy here:
        -Extract automatically in rig coordinates during DIC
        -Easy to measure on part



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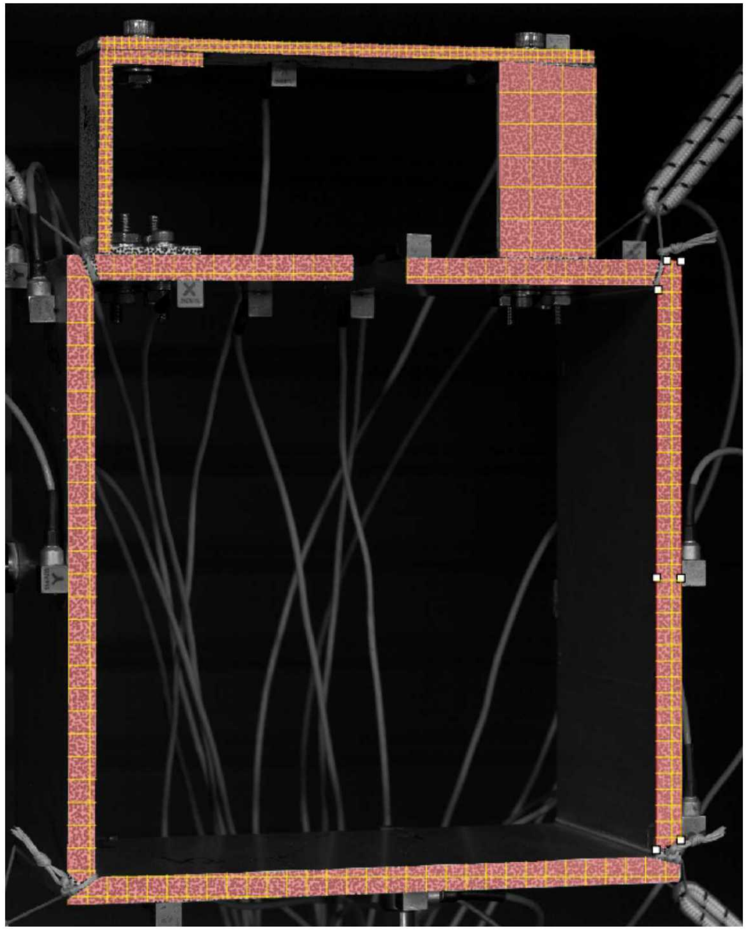
    - **Subset test geometry can be automatically generated from reference image! And combined with DAS geometry!**
    - **Now you can easily stitch together multiple camera views!**



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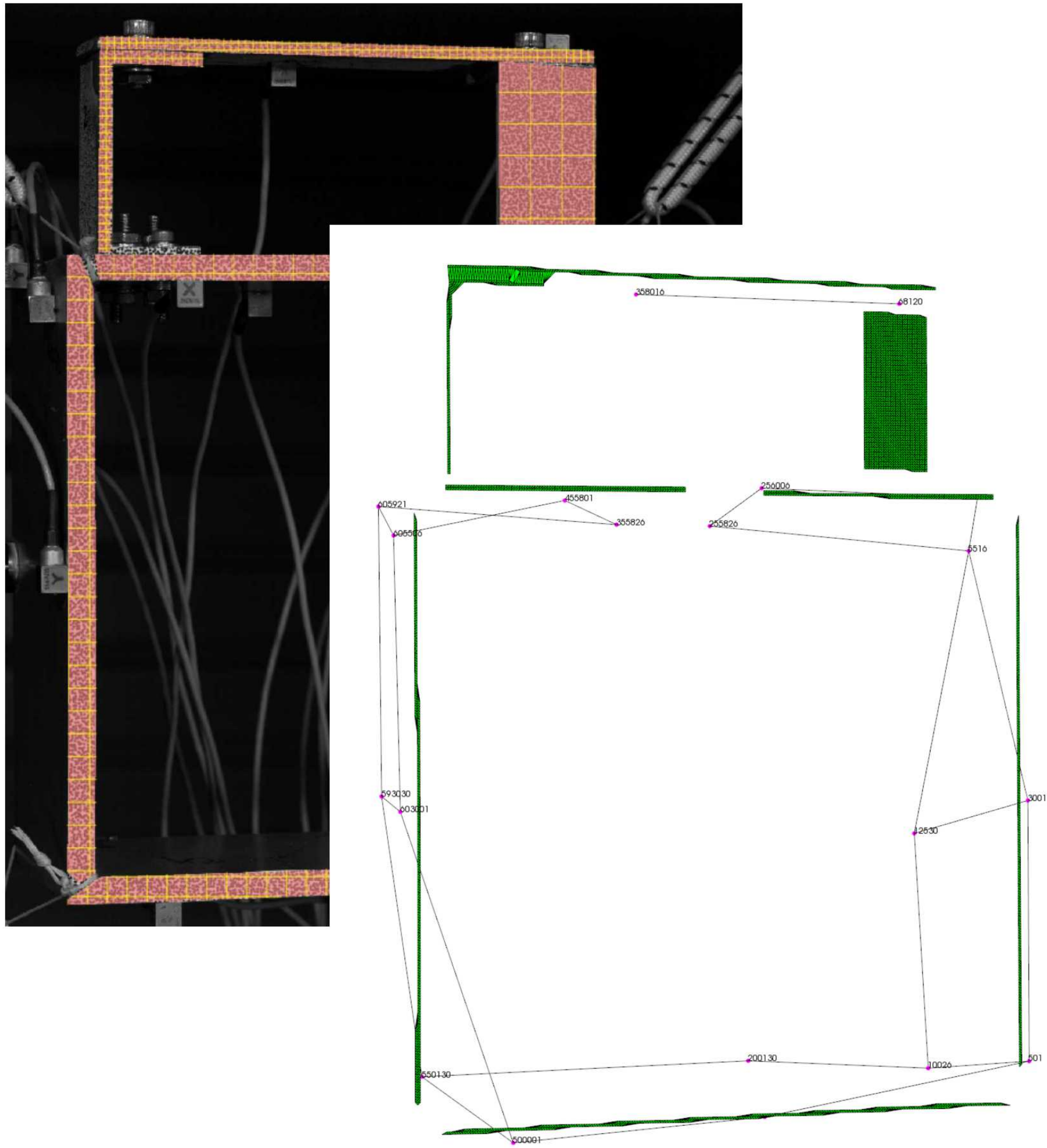
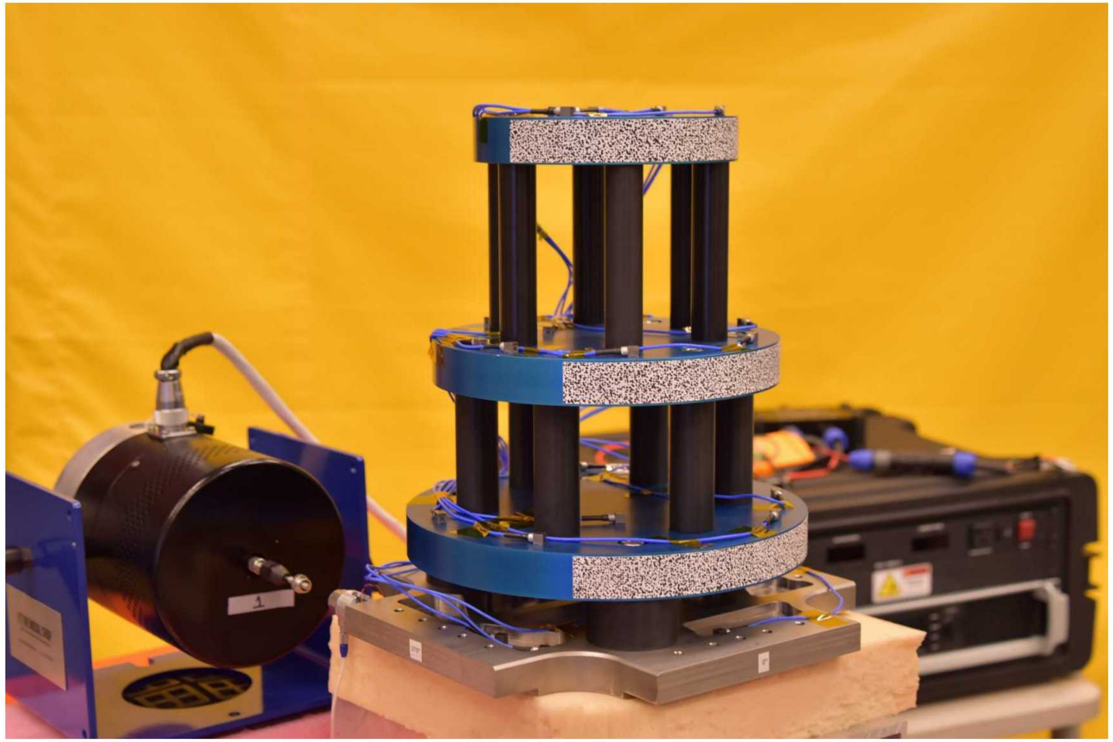


Post-Processing: DIC Output

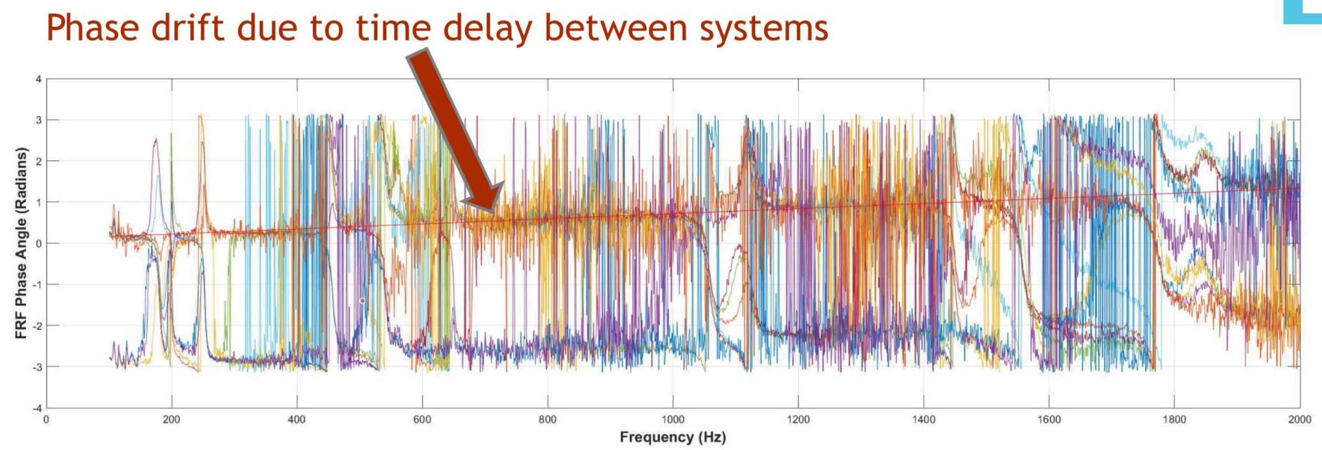
- **More data processing and manipulation.**
  - **Displacement to Acceleration.**
    - Different ways to accomplish
    - Differentiation in the frequency domain is usually a good approach (DFT requirements have to be met)
  - **Resample the DAS to match camera sample rate.**
    - Avoid aliasing issues by making sure you resample correctly
    - Matlab's *resample* function works well.
  - **Re-index subset node numbers.**
    - Subset numbers have been used as node ID's
    - Possible conflicts with DAS node ID's for accelerometers/load cells

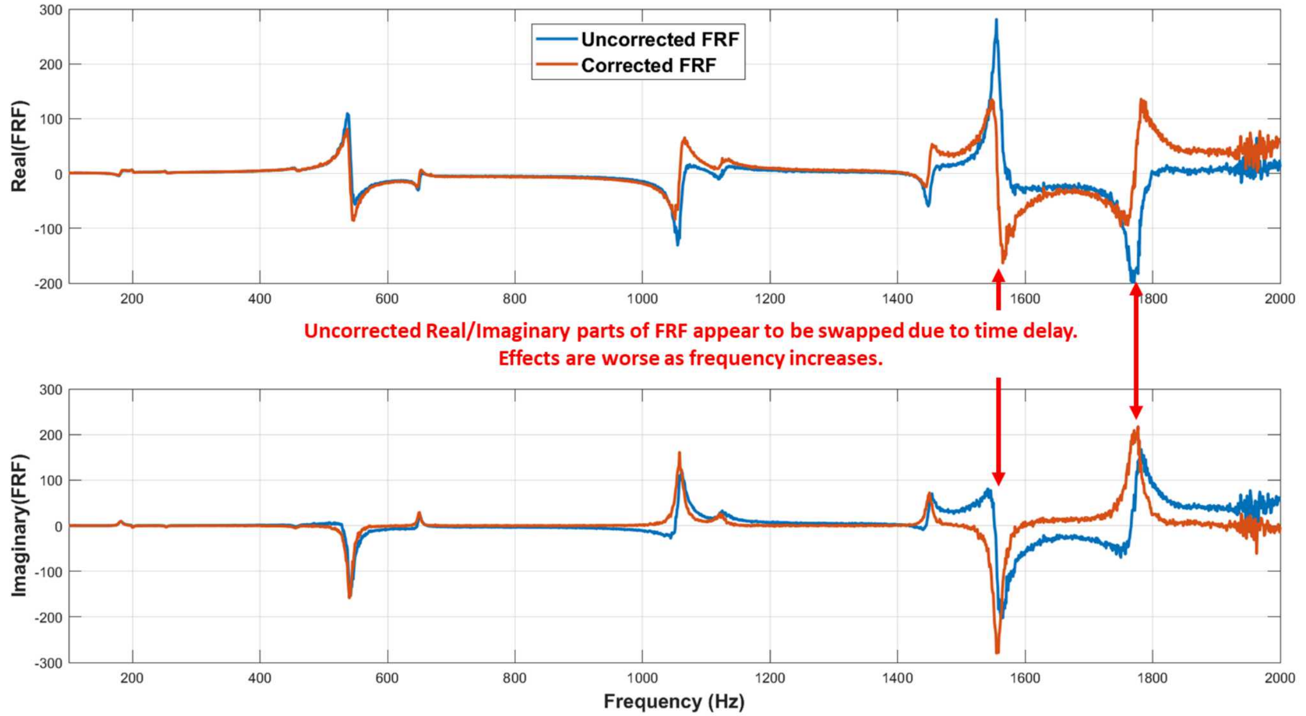


- **Putting it all together.**
  - **Combine DIC and DAS data into one file.**
    - Compatible with your modal analysis extraction software of choice
  - **Compute FRF per normal practice for modal.**
    - H1 estimator is a good choice (be honest, your DIC response data are going to be noisy)

Post-Processing: DIC Output

- **Remember that synchronization issue between the cameras and DAS?**
  - **Aligning data samples isn't good enough.**
    - Delay is most likely sub-timestep
    - Constant over all samples
    - **Manifests as a linear phase angle drift in the FRFs**
      - Gets worse as frequency increases
    - **Will start to make the Real/Imaginary parts of FRFs look like they are swapped**





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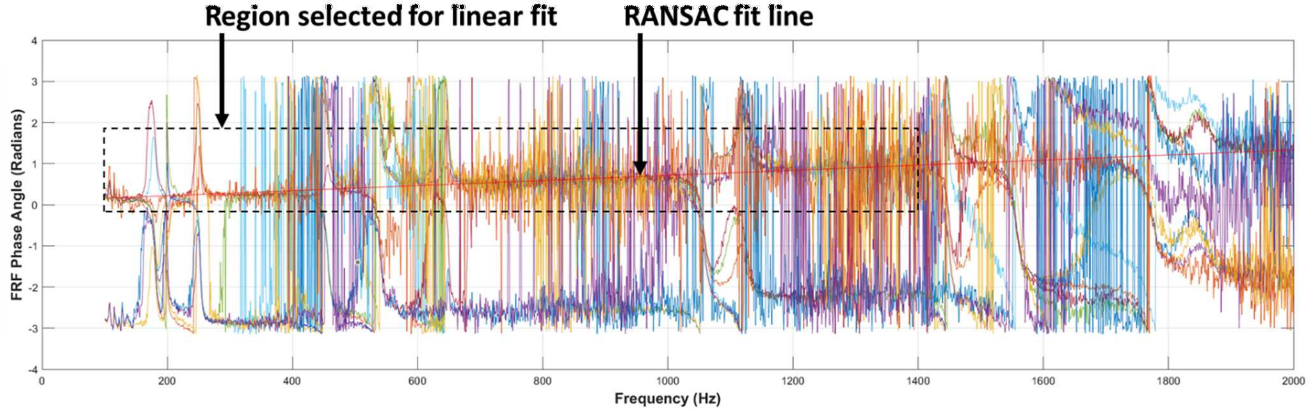
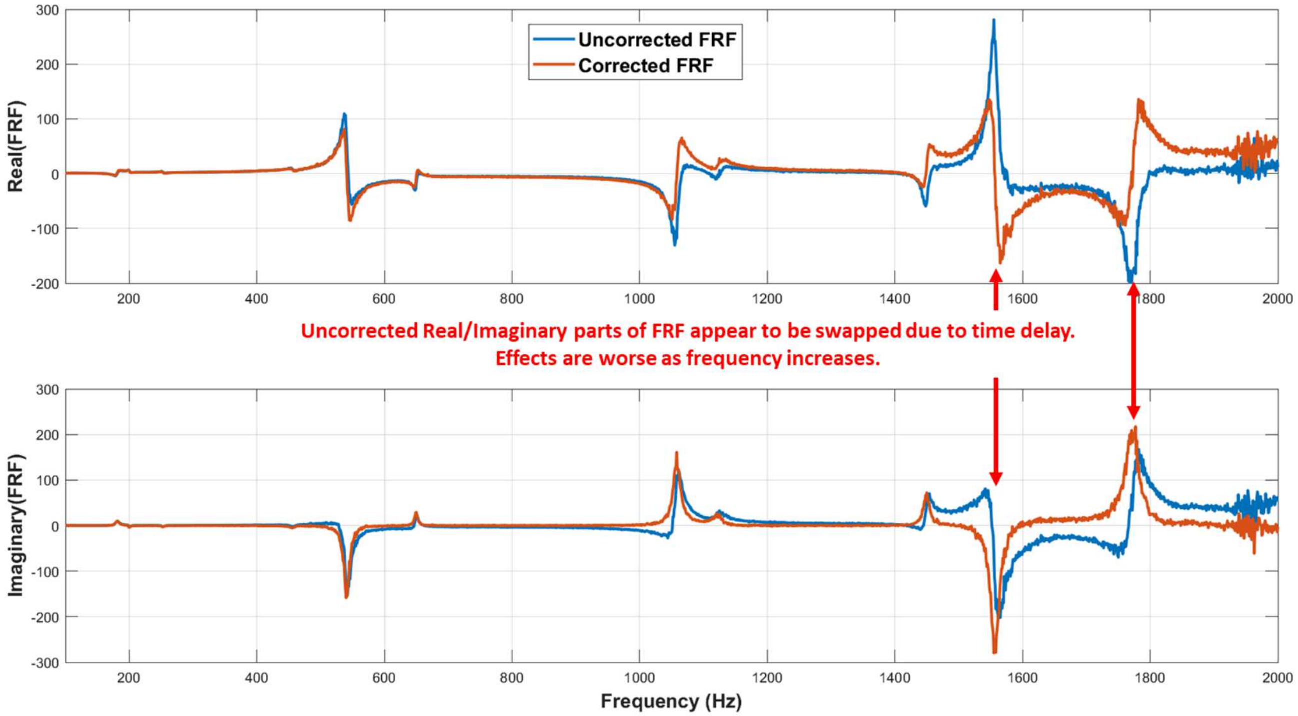
  - **Remove time delay by fitting a line to the phase drift and subtracting it out.**
    - Method has to be robust to outliers/noise: Selected RANSAC [12]
    - Remove linear trend from phase at each frequency line
    - Recombine with amplitude to correct FRFs





Post-Processing: DIC Output

- **Remember that synchronization issue between the cameras and DAS?**
  - **Aligning data samples isn't good enough.**
    - Delay is probably sub-timestep
    - Constant over all samples
    - **Manifests as a linear phase angle drift in the FRFs**
      - Gets worse as frequency increases
    - **Will start to make the Real/Imaginary parts of FRFs look like they are swapped**
  - **Remove time delay by fitting a line to the phase drift and subtracting it out.**
    - Method has to be robust to outliers/noise: Selected RANSAC [12]
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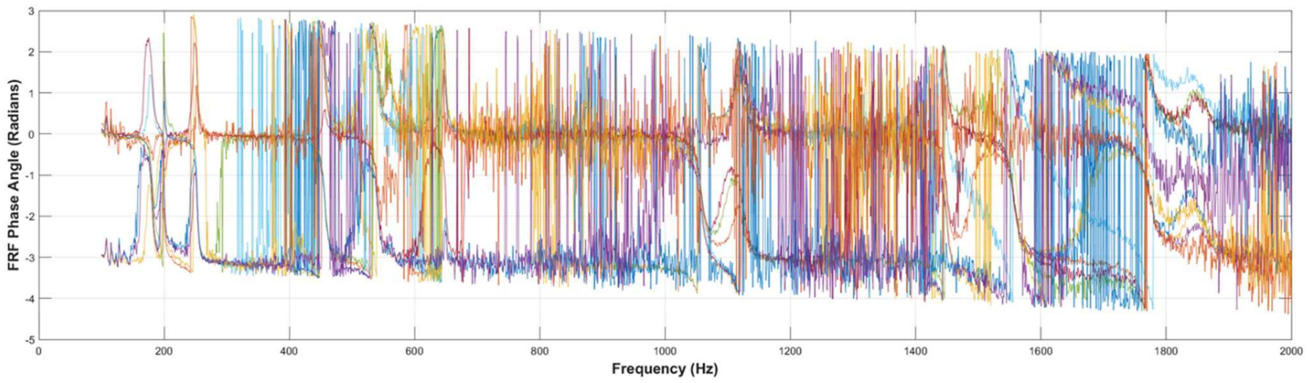
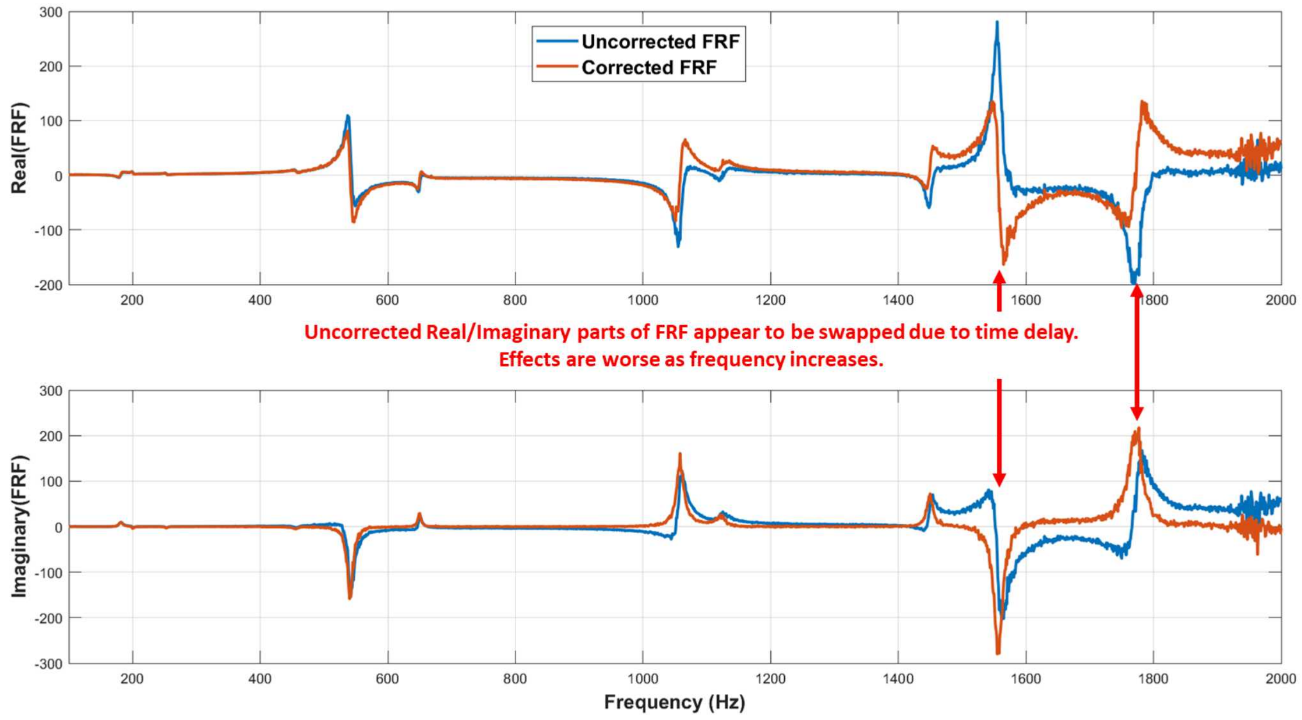
Now we can extract modes!

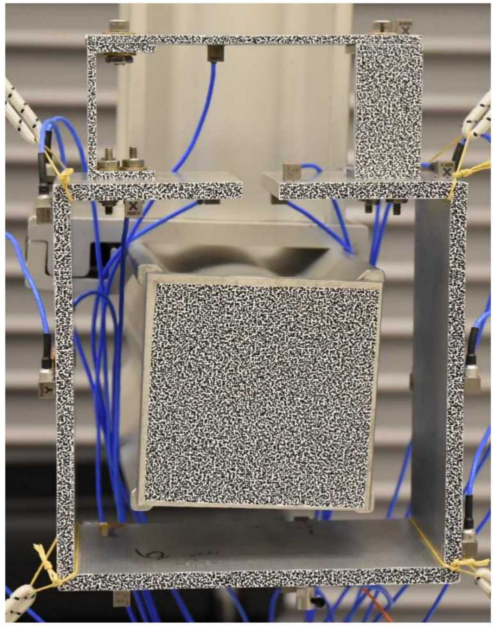
Corrected phase



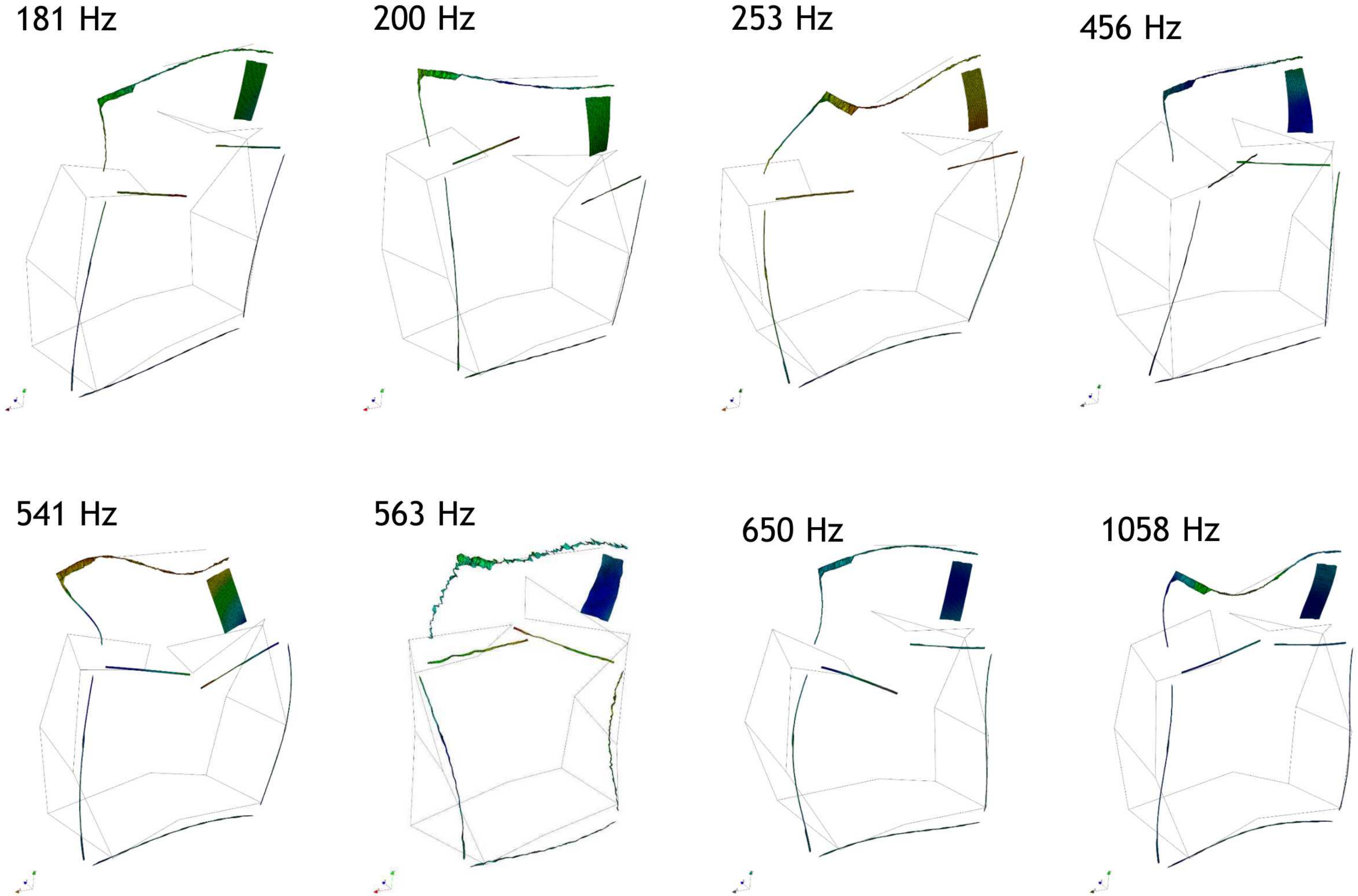


Post-Processing: Noise Mitigation

- **Examples of extracted modes over a bandwidth of 0-2000 Hz:**



~0.3 px peak displacement



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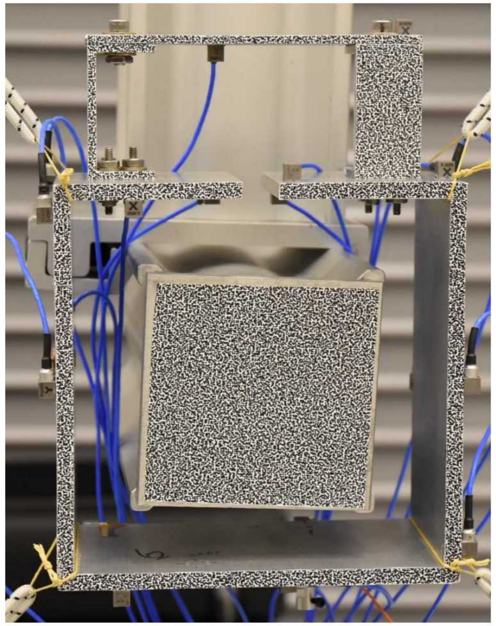
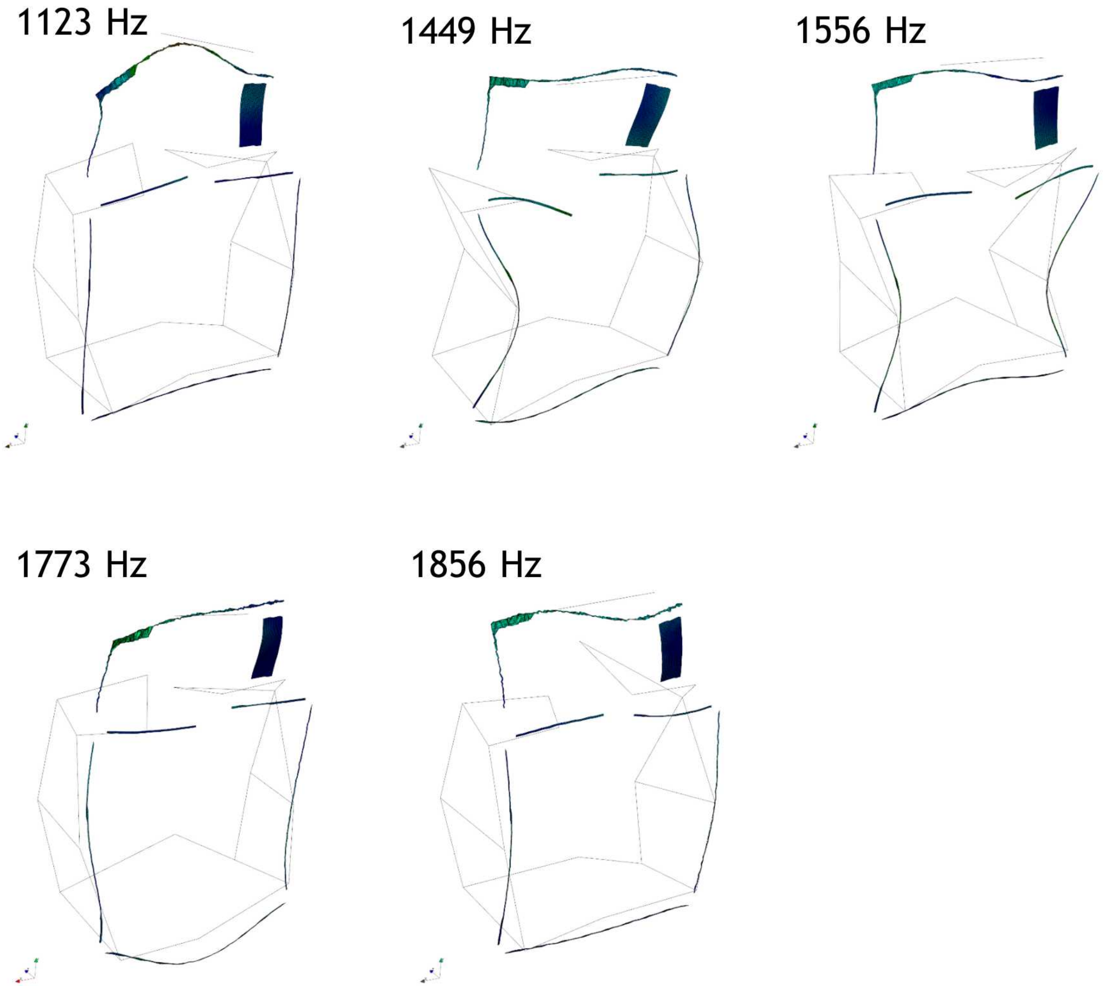
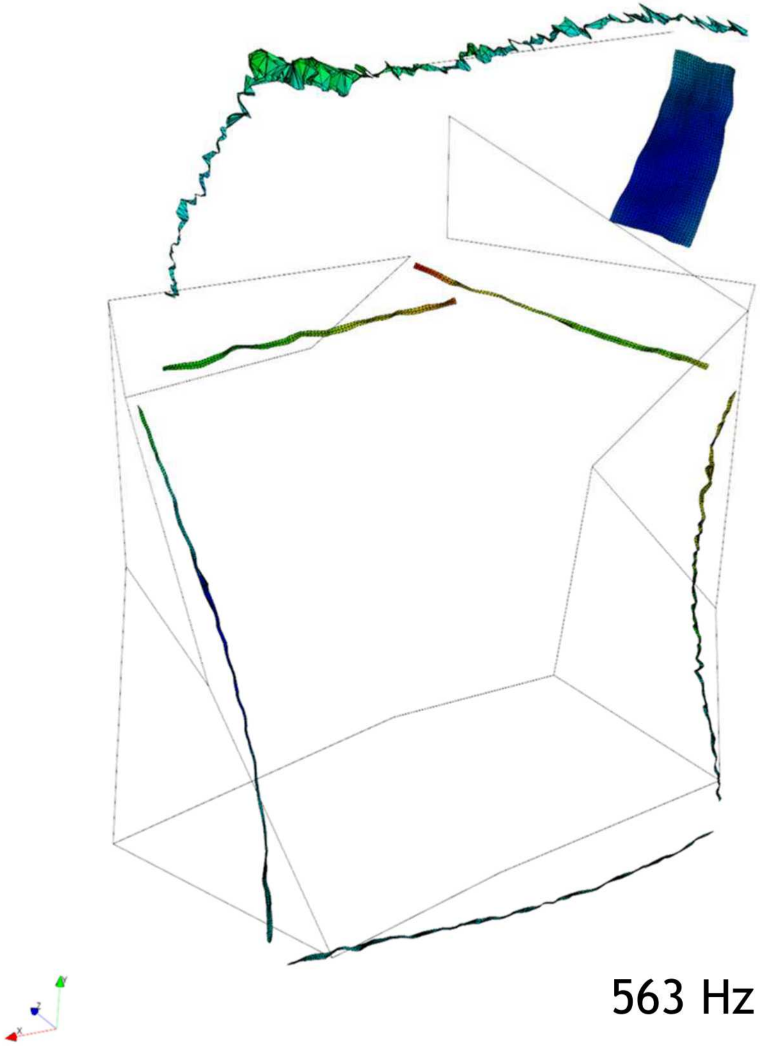


~0.3 px peak displacement



Post-Processing: Noise Mitigation

- **Do some of your mode shapes look like they have fuzzy mold growing on them?**
  - **Things to go back and check:**
    - Do you have good contrast in your images?
    - Did you maximize the number of pixels across your AOI?
    - Did you do some kind of averaging (image, FRF, subset)?
    - Can you better excite the higher frequency modes?
    - Can you use larger subsets?



563 Hz

Post-Processing: Noise Mitigation

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- **I did all the above…my shapes still look pretty rough.**
  - **Try System Equivalent Reduction Expansion (SEREP) [13].**
    - Provides a least-squares smoothing of the noisy shapes
    - Can be done in measurement space (no expansion)
    - Can expand noisy shapes to obtain clean shapes in full FEM space!
    - **Extremely effective for DIC obtained shapes!**

$$\boldsymbol{\Psi}_a' = \boldsymbol{\Phi}_a \boldsymbol{\Phi}_a^{\dagger} \boldsymbol{\Psi}_a$$

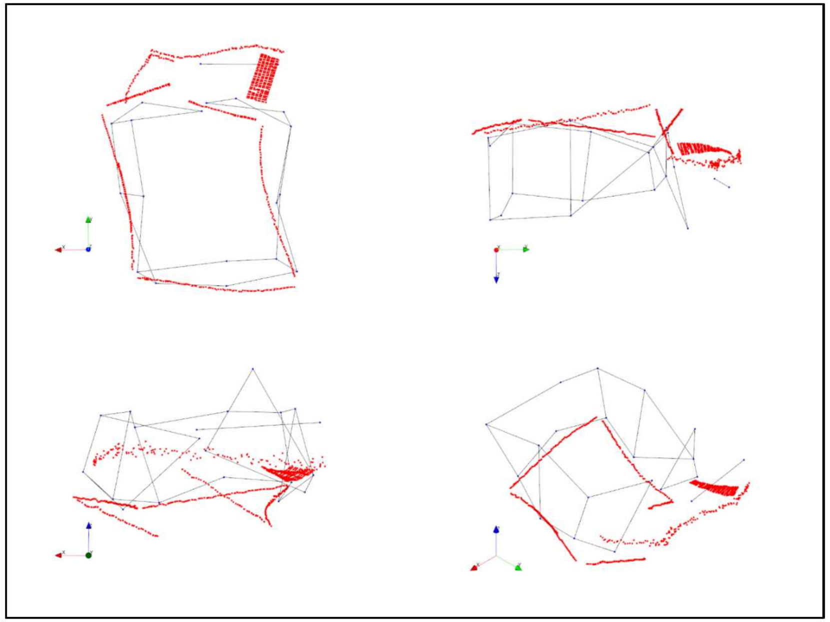
Smoothing, no expansion

Smoothed experimental shapes

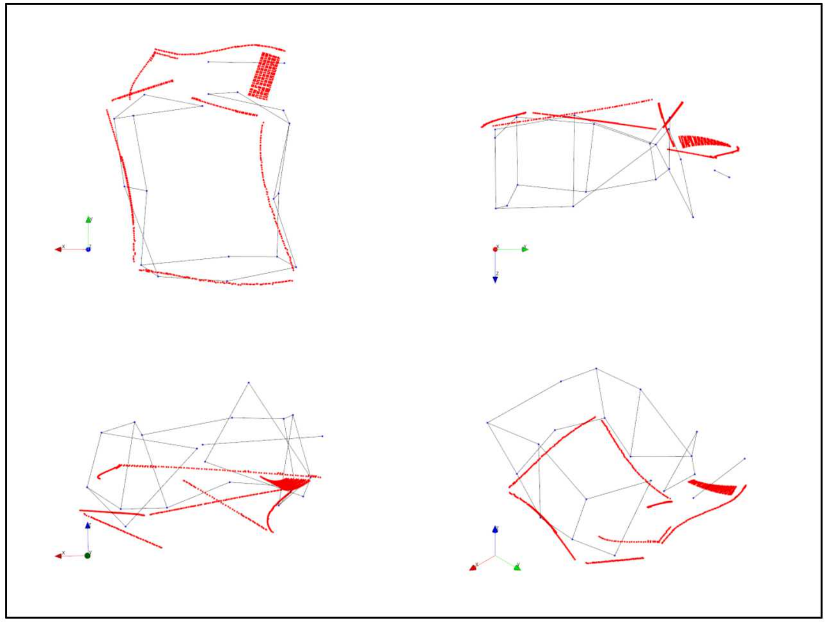
FEM shapes (at measured DOF)

Experimental shapes

Noisy shape direct from DIC



SEREP Smoothing



Post-Processing: Noise Mitigation

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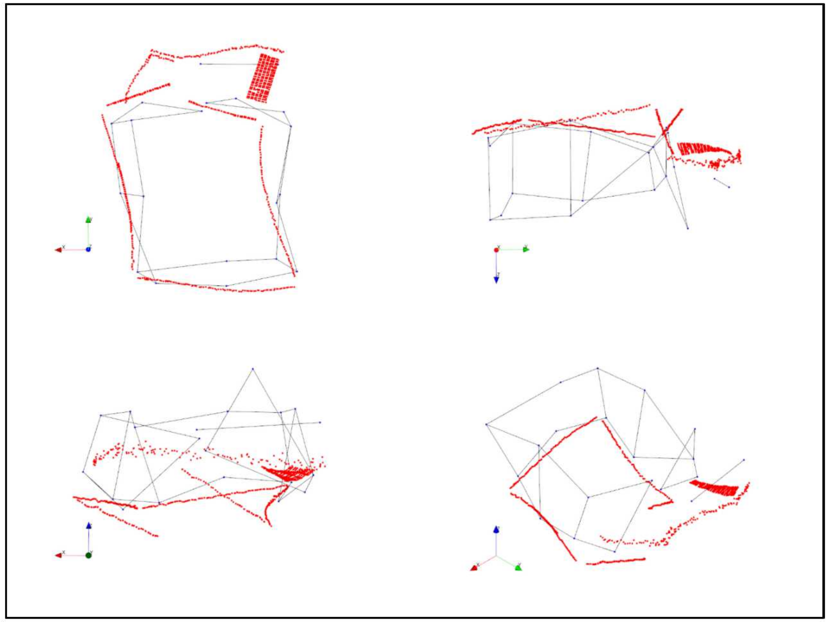
$$\mathbf{\Psi}_a' = \mathbf{\Phi}_a \mathbf{\Phi}_a^{\dagger} \mathbf{\Psi}_a$$ Smoothing, no expansion

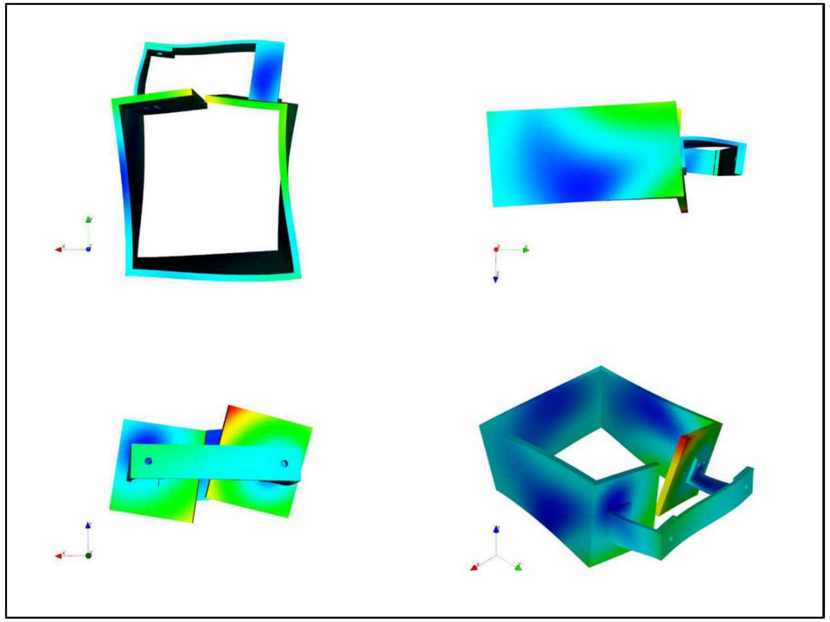
$$\mathbf{\Psi}_n = \mathbf{\Phi}_n \mathbf{\Phi}_a^{\dagger} \mathbf{\Psi}_a$$ Smoothing, with expansion

FEM shapes (all DOF)

Noisy shape direct from DIC



SEREP Expansion



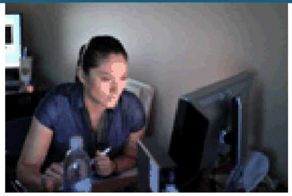
Conclusions & Future Work

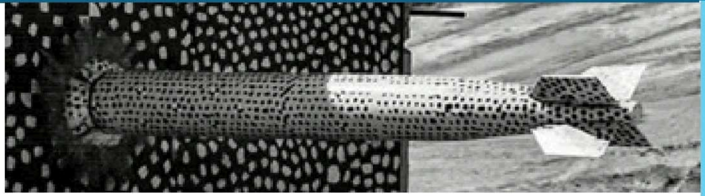
The future ain't what it used to be. –Yogi Berra

Conclusions & Future Work

- **In Conclusion:**
  - **DIC is a viable measurement capability for experimental modal analysis.**
    - Attention to detail in planning and setup are crucial
    - You have to have enough pixels of displacement to get usable answers
    - Be prepared to create a lot of your own post-processing tools
- **What are we working on for the future?**
  - **Noise reduction is 1st priority.**
    - By far the largest limiting factor in making DIC modal testing mainstream
    - Approaching variance noise (random pixel intensity) by looking at **phase-based motion extraction**
    - Approaching bias noise (heat waves, camera vibration, etc.) by looking at **Weiner filters, machine learning, and other signal processing methods**
  - **We want to reduce test setup time/uncertainty.**
    - Developing tools to help select optimized camera equipment and positioning
    - Looking at better speckling patterns, materials, and methods
    - Generating tools that help estimate pixels-displacement for a given excitation
  - **Putting the wagon way in front of the horses.**
    - Investigating the use of photogrammetry to extract 3D motions from radiographic images

Launching DIC as an Experimental Modal Analysis Capability





Questions?

IMAC XXXVIII

Bryan Witt, Dan Rohe

Sandia National Laboratories
Experimental Structural Dynamics