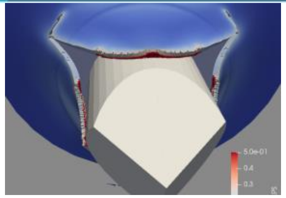
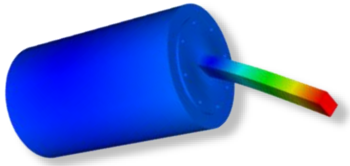
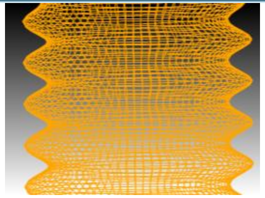
Sensor Placement Optimization for Expansion of Mixed-Domain Dynamic Response



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08.06.2024

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

SAND2024-10179PE

Agenda

1

- Motivation

2

- Methods & Results
  - Experimental Setup
  - Finite Element Model
  - Neuromorphic Data Collection
  - Mixed Domain Expansion

3

- Conclusions & Future Work

Vibration response data is desired to characterize structural responses.

[Honeywell Aerospace]

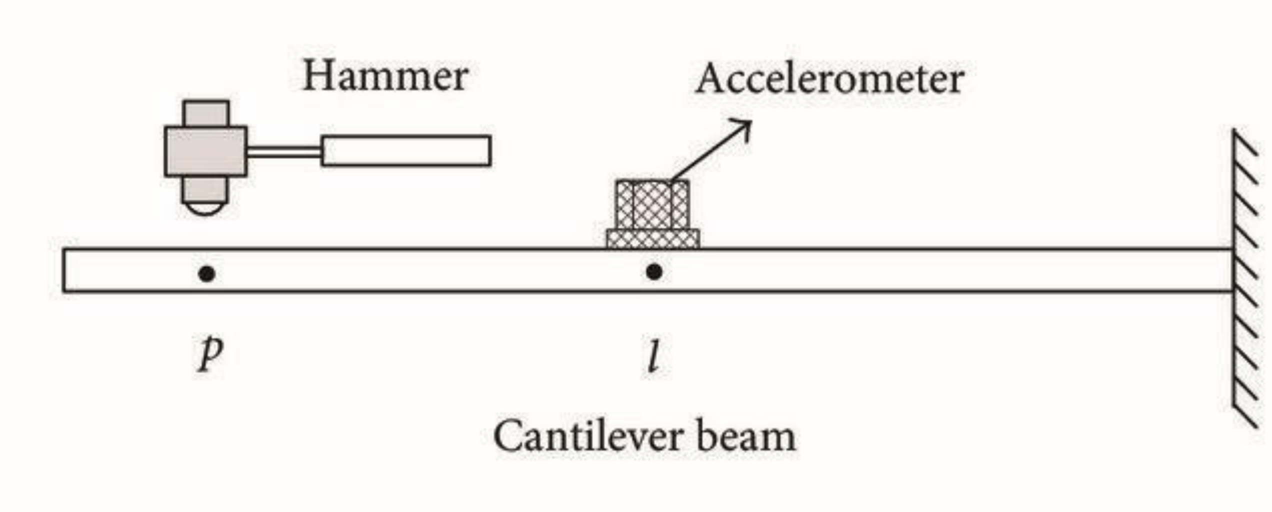
Vibration Environments

[Lifttow]

Shock Environments

Spatial resolution can be limited by the use of physical sensors such as accelerometers.

[Siemens]



[J. Ren et al, 2017]

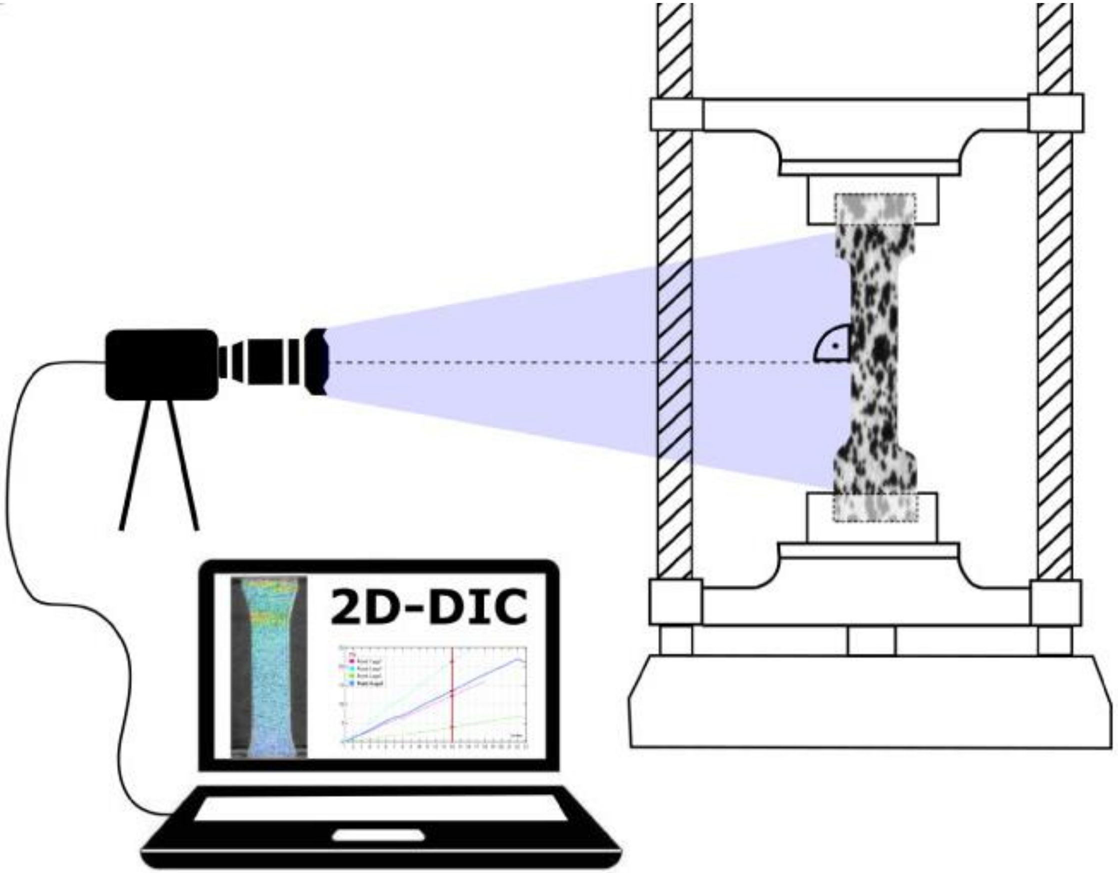
Channel Count Limits

Mass Loading Effects

Full-field measurements can be achieved using a variety of technologies.

[Polytec]

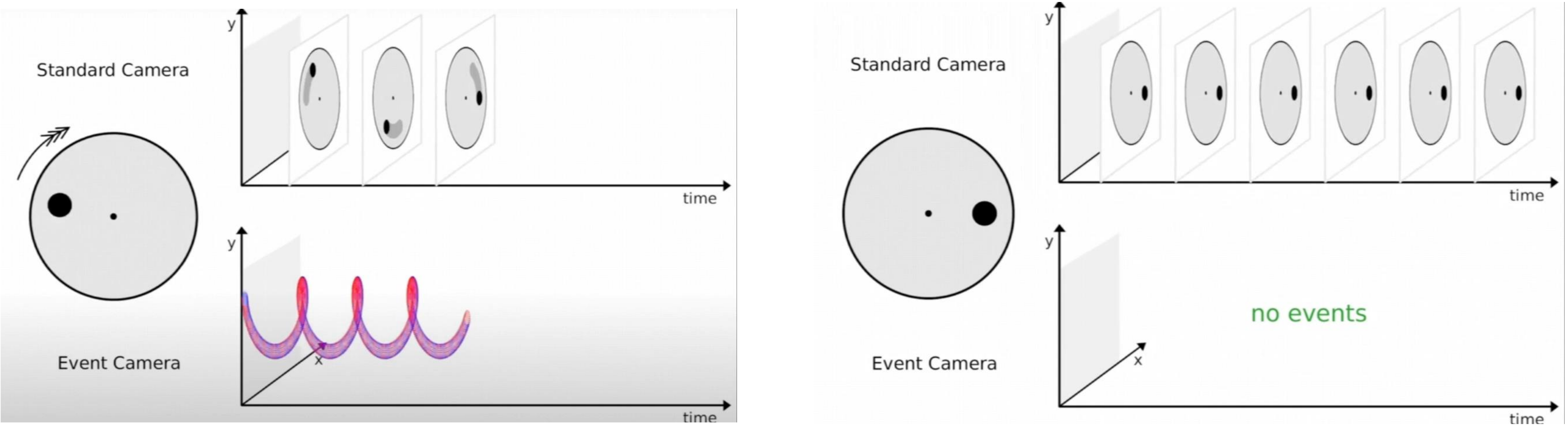
Laser Doppler Vibrometer (LDV)



[M. Mylo and S. Poppinga, 2024]

Digital Image Correlation (DIC)

Neuromorphic imaging is an emerging technique in acquiring full-field vibration measurements.



[H.Kimm, 2016]

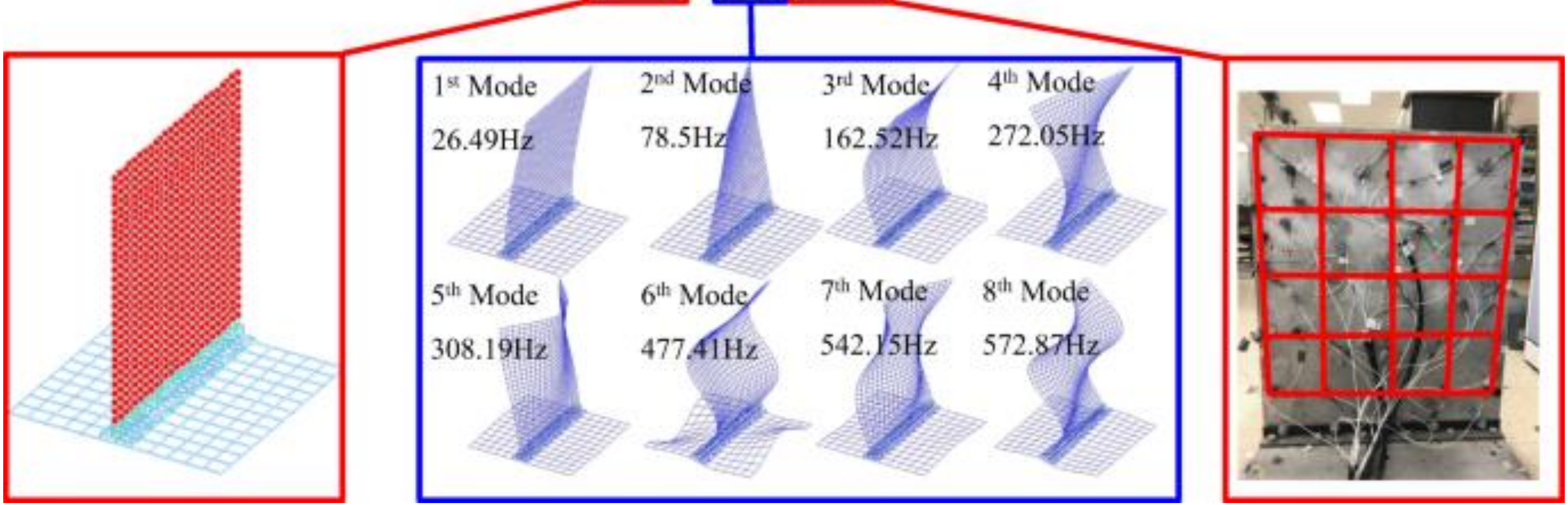
Events are triggered when changes in brightness exceed a set threshold per pixel, at a given location and time.

Event stream ***e = (x, y, p, t)*** p = Polarity: brightness change (+1,-1)
t = time of event

Benefits: less expensive (the camera cost and less data to process), low-latency

A low-latency alternative to full-field data acquisition is to expand vibration responses from accelerometer data at limited measurement points.

$$\{X_n\} = [T]\{X_a\}$$



[Y. Chen et al, 2019]

Neuromorphic imaging and expansion procedures are both low-latency techniques to achieve full-field response information with different requirements.

[PCB Piezotronics]

[iniVation]

Expansion Methods

- Relies on pre-test analysis to select optimal DOF sets
- Requires a FEM to generate mode shapes

Neuromorphic Imaging

- Emerging field
- Varying levels of fidelity and confidence in the results
- High displacement = more coherent data

Neuromorphic imaging and expansion procedures are both low-latency techniques to achieve full-field response information with different requirements.

[PCB Piezotronics]

+

[iniVation]

Expansion Methods

Neuromorphic Imaging

Could combining neuromorphic imaging and model-based expansion lead to improved low-latency estimation of full-field responses?

The goal of this research was to investigate how to integrate neuromorphic imaging data with responses from accelerometers in a single expansion procedure.

1) Exploring DOF selection methods to combine accelerometer and neuromorphic imaging data locations
2) Implementing the resulting mixed-domain expansion (acceleration + displacement)

Broader Impacts

Contribute to active areas of research

Develop a foundation for an improved approach to acquire low-latency full-field response data

Big Picture

Develop methods to provide real-time response information for vibration control

Mixed domain expansion was achieved through the following steps.

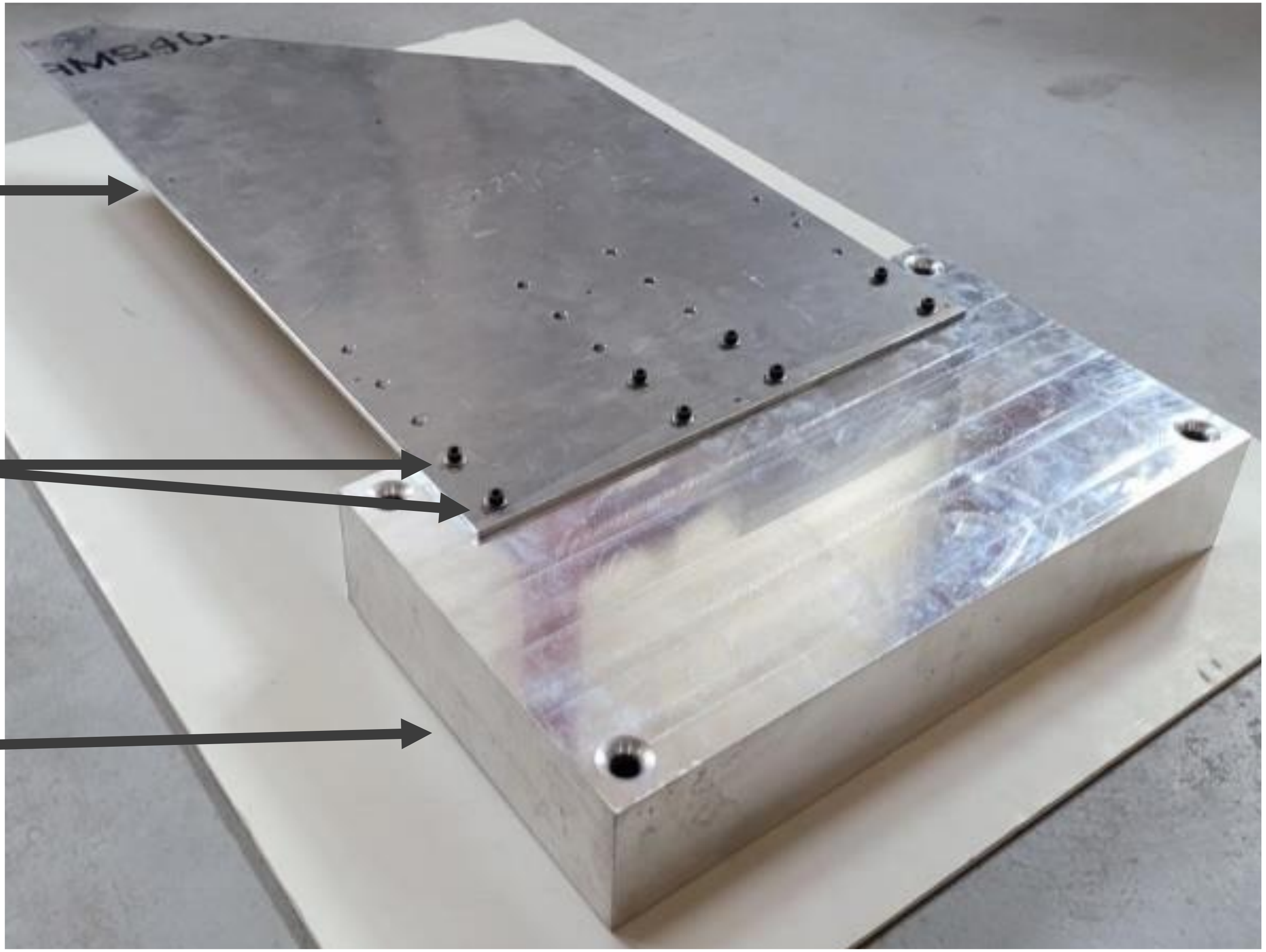
1. Conduct Modal Tests
2. Refine the Finite Element Model
3. Collect and Process Neuromorphic Imaging Data
4. Conduct DOF Selection
5. Compute and Compare Single and Mixed Domain Expansion

This investigation was performed using a wing-shaped aluminum plate bolted to an aluminum block.

AL6061 Wing, 13″x26″x$\frac{3}{16}$″

SS316 Washers between the wing and block.
Bolts torqued to 25 lbs/in

AL6061 Block, 16″x9″x3″



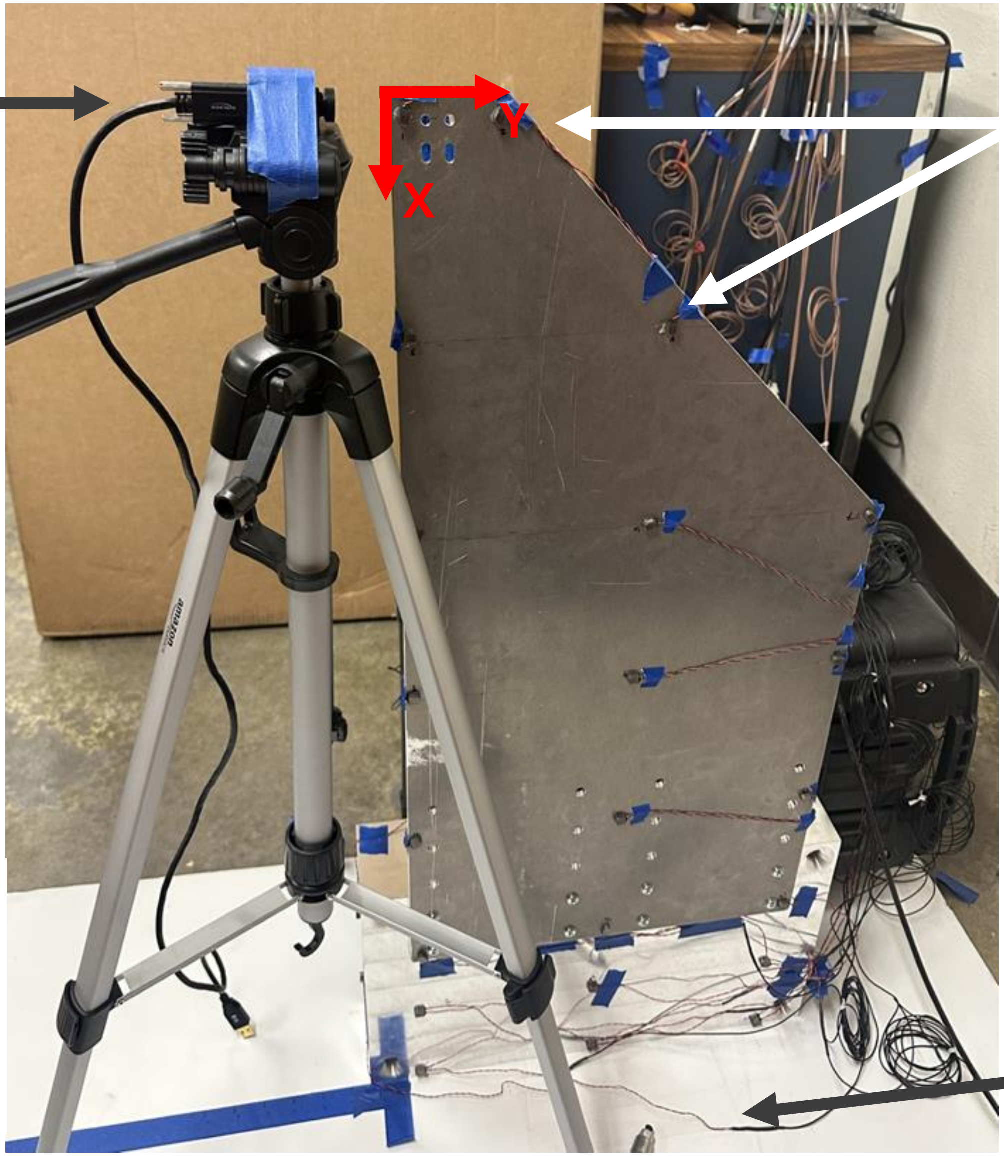
Experimental Test Setup

Neuromorphic Camera

[iniVation]

Impact Hammer
soft plastic tip
(10mV/lbf sensitivity)

[PCB Piezotronics]



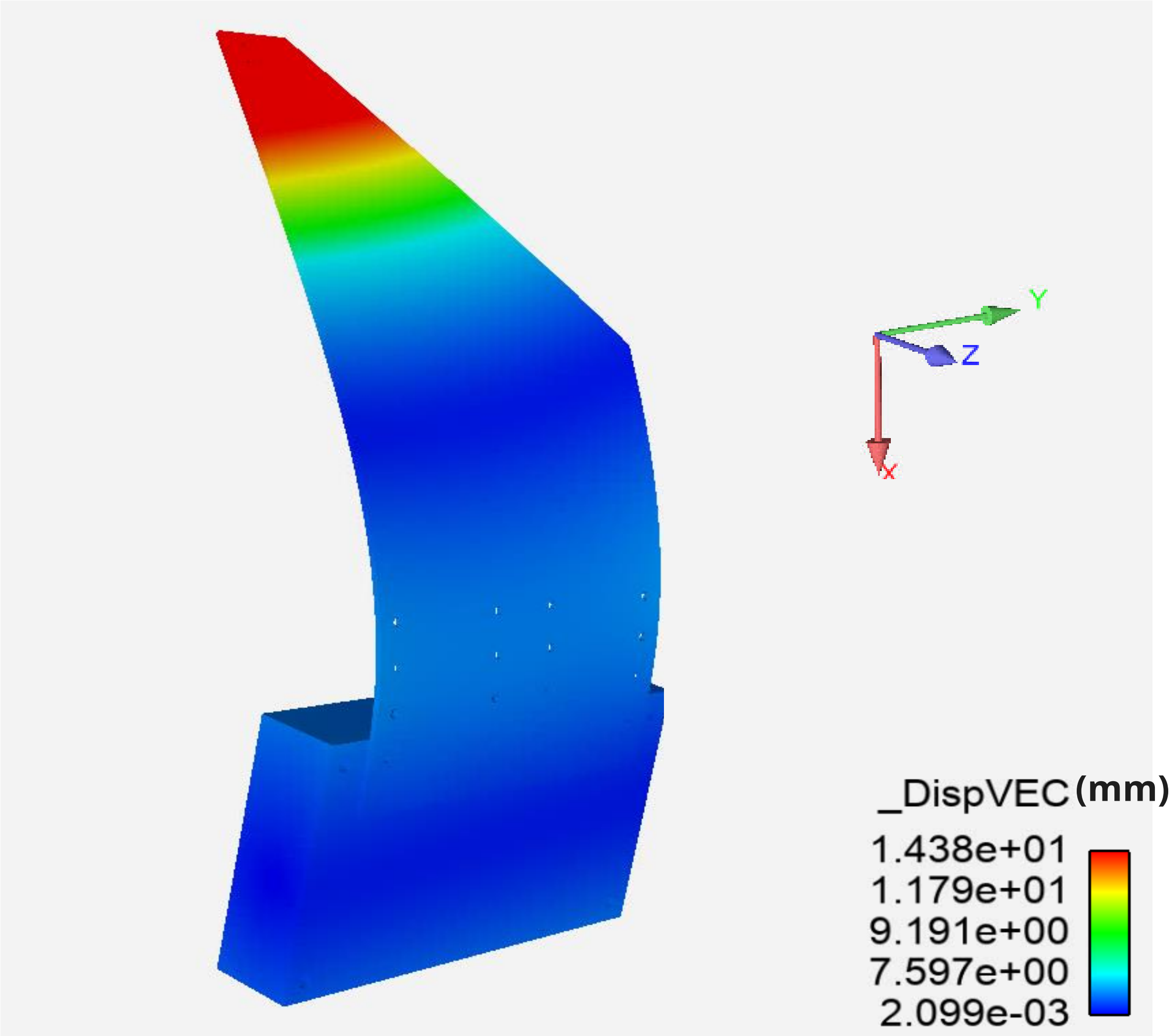
24 Uniaxial Accelerometers
(10mV/g sensitivity)

[PCB Piezotronics]

29 Node mesh
24 DOFs

Foam Poster Board

A finite element model was refined to represent the experimental setup.

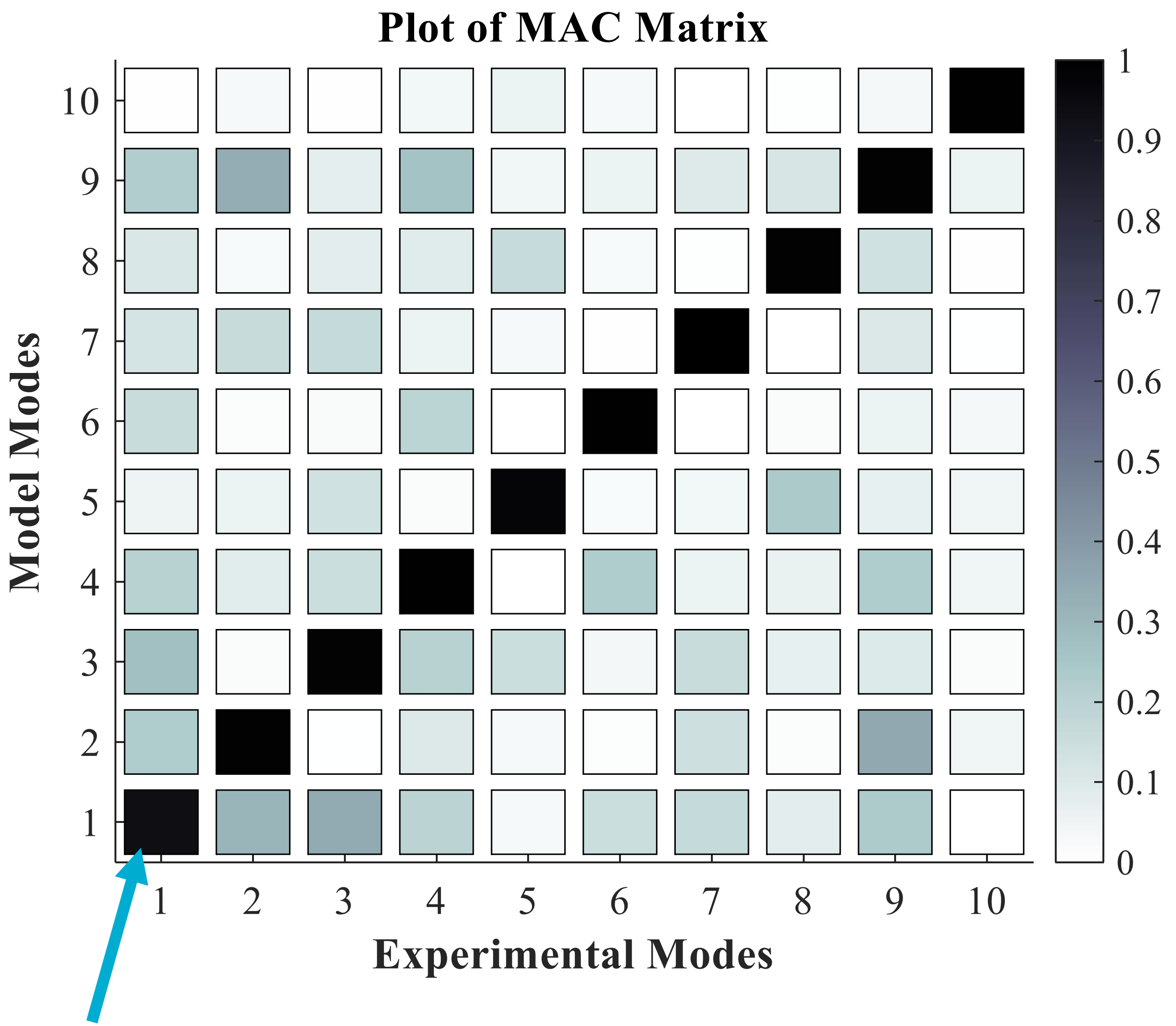


Added point masses for accelerometers

Free-Free
Boundary Conditions

Hexahedral Mesh
About 770,000 elements

A Modal Assurance Criteria (MAC) was created to compare the experimental mode shapes with the model mode shapes.



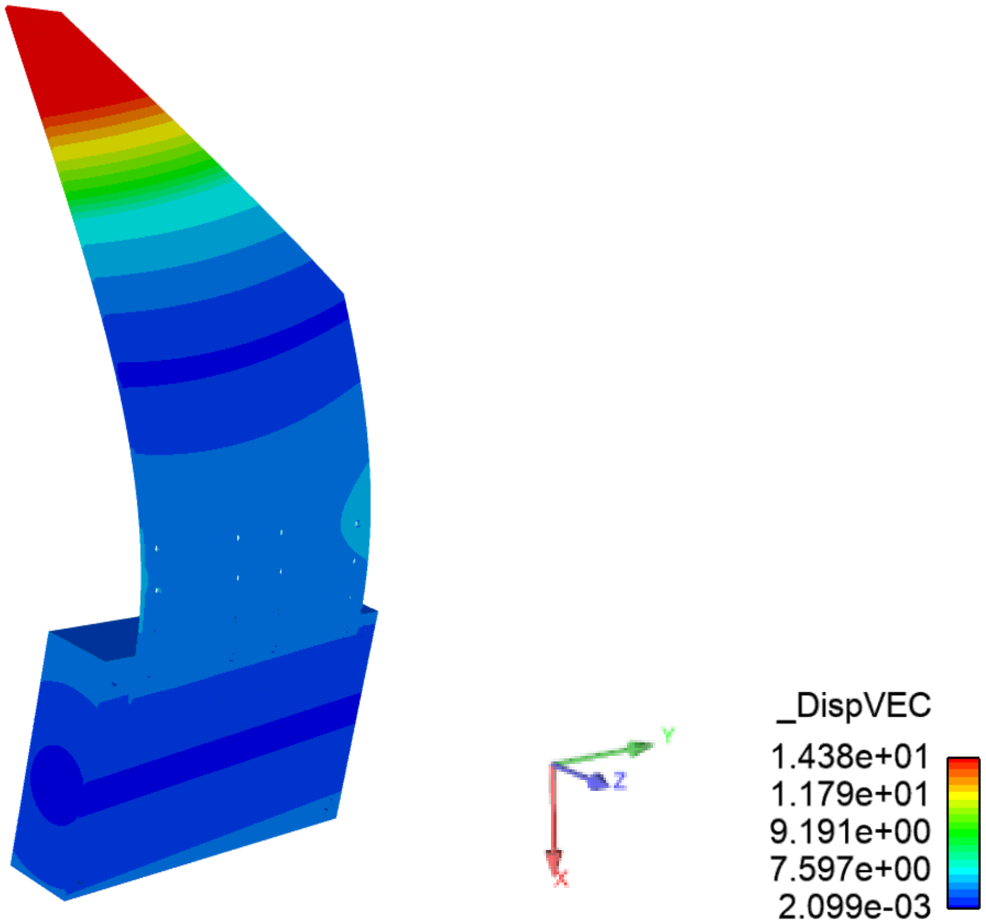
Mode 1: 0.94

All other modes 0.99 or higher

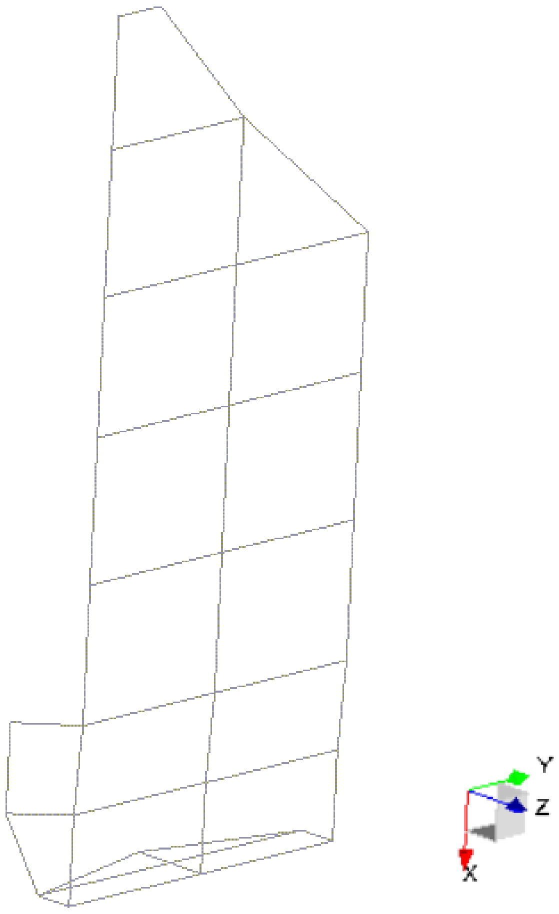
Natural Frequencies (Hz)			
Mode #	Model	Experimental	% Error
1	25.5	20.8	22.5%
2	59.2	55.7	6.3%
3	89.0	83.9	6.1%
4	167.8	162.2	3.5%
5	223.9	217.2	2.7%
6	288.9	283.1	2.0%
7	341.4	338.4	0.9%
8	406.7	397.3	2.4%
9	496.3	488.7	1.6%
10	549.8	542.5	1.3%

This model is acceptable for the expansion due to the highly correlated mode shapes.

Model Mode 1



Experimental Mode 1

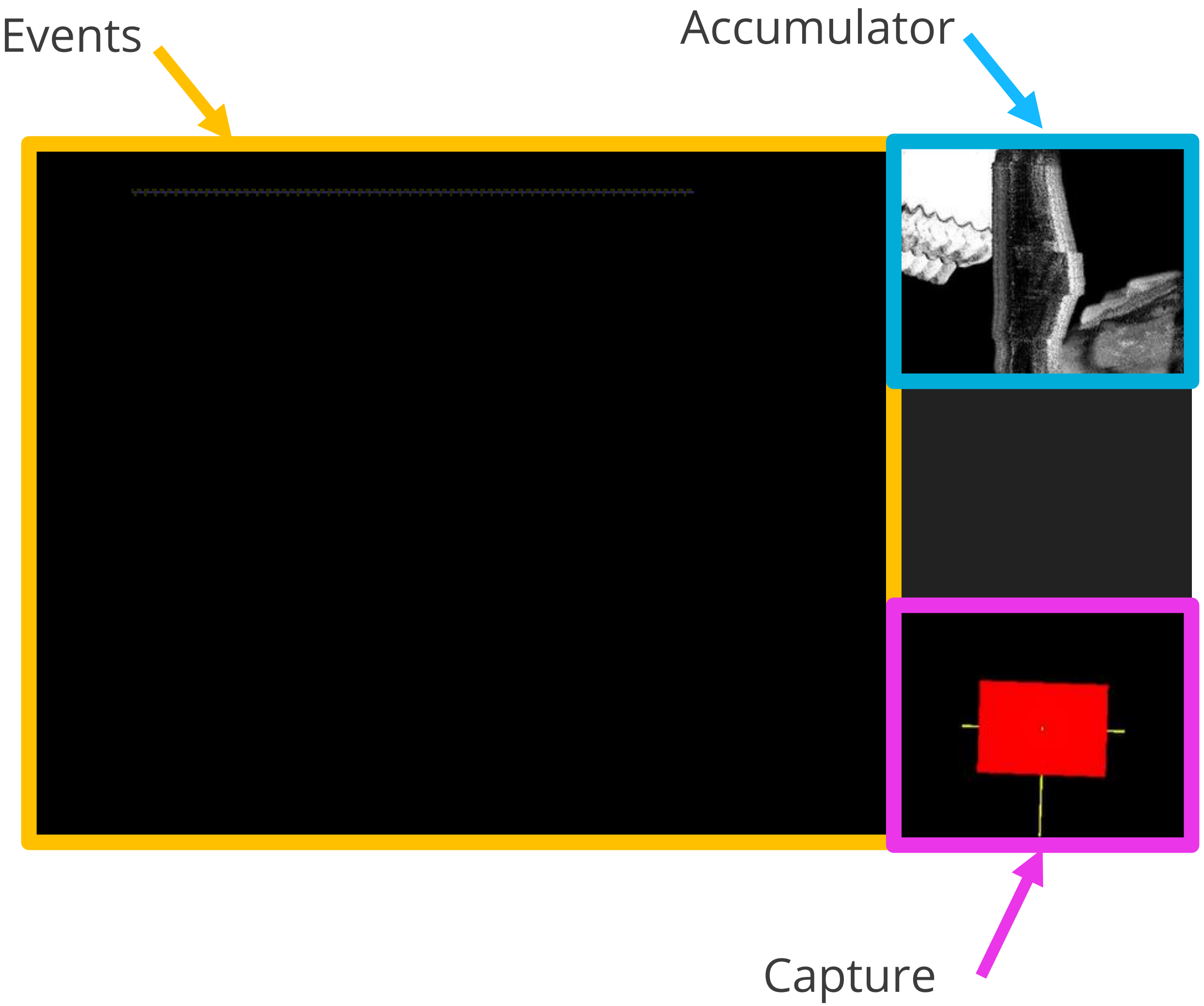


Neuromorphic imaging data was collected using a DVXplorer mini camera.

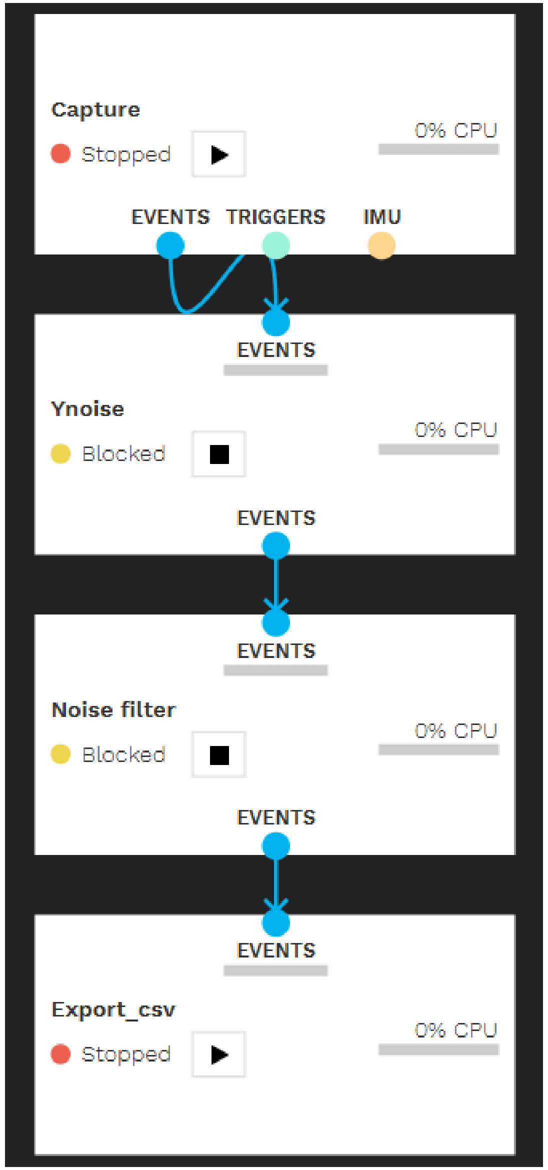
DVXplorer Mini

Spatial Resolution: 640 x 480 pixels

Event rate: 450 million events per second throughput



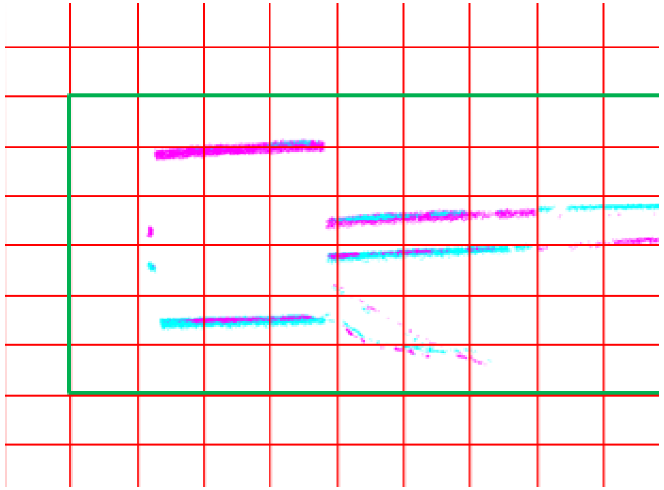
CSV File

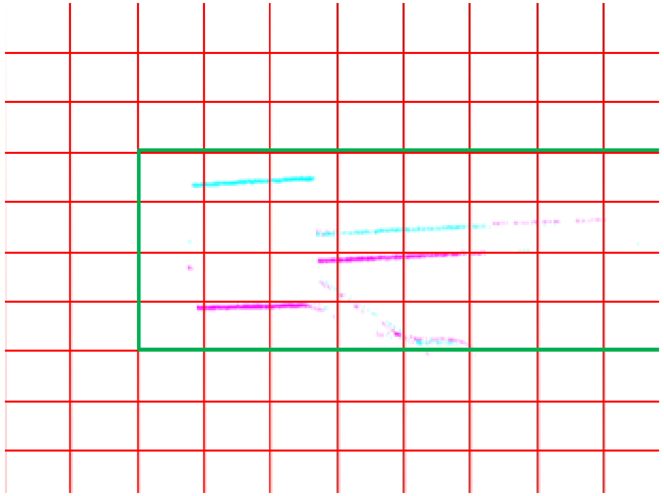


The neuromorphic camera was calibrated by first finding the pixel to mm conversion factor.

2 inch distance

3 inch distance



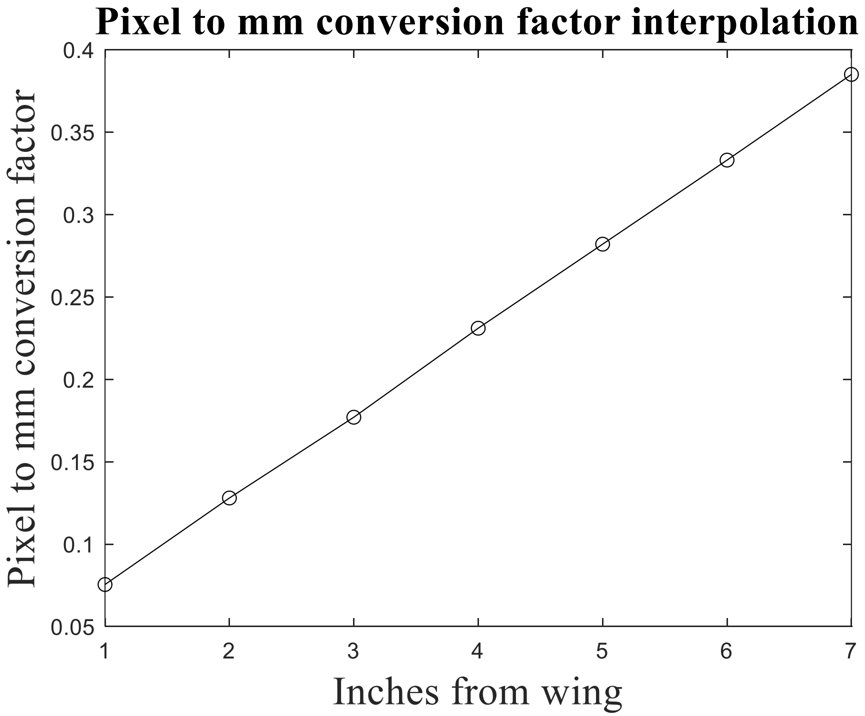


Calibration square: 21mm X 21mm

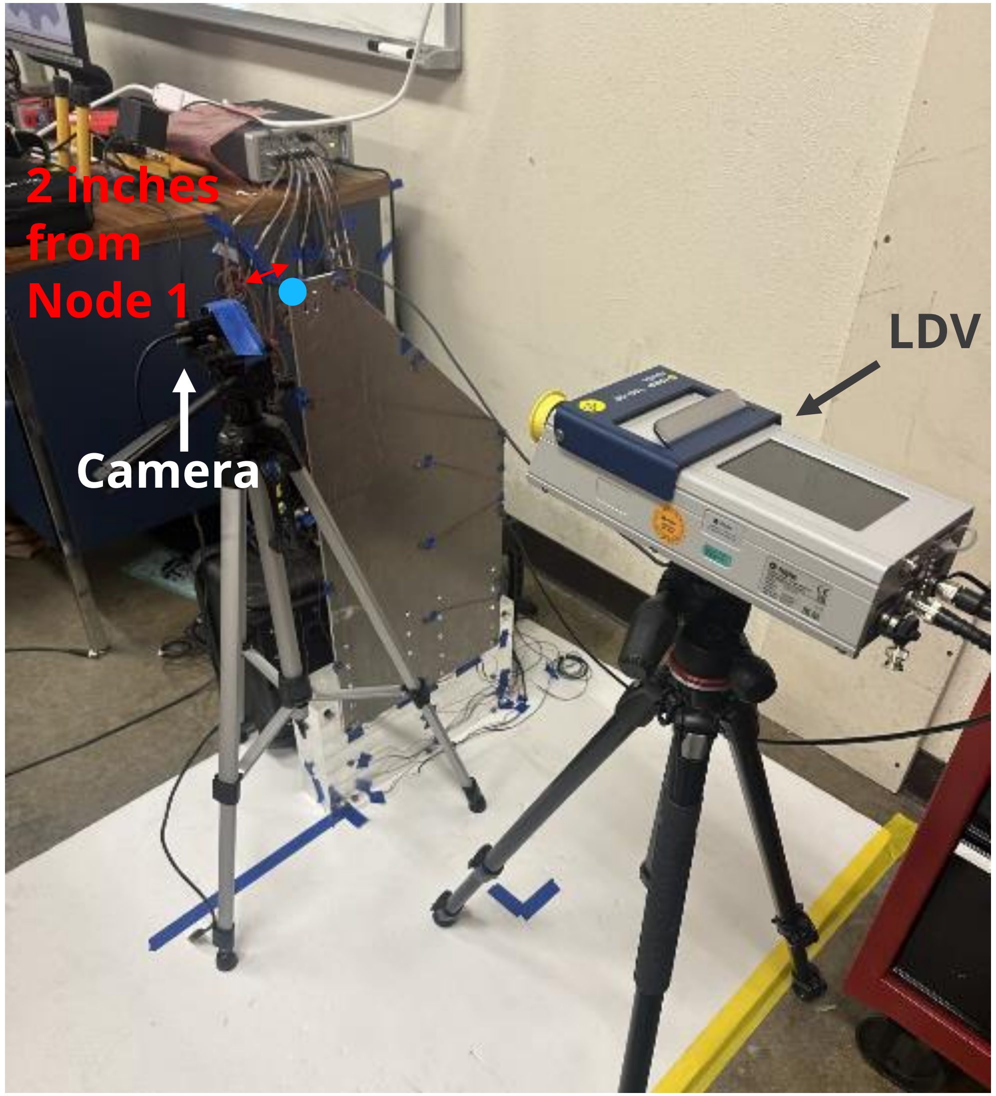
Frame of Camera: 640 X 480 pixels

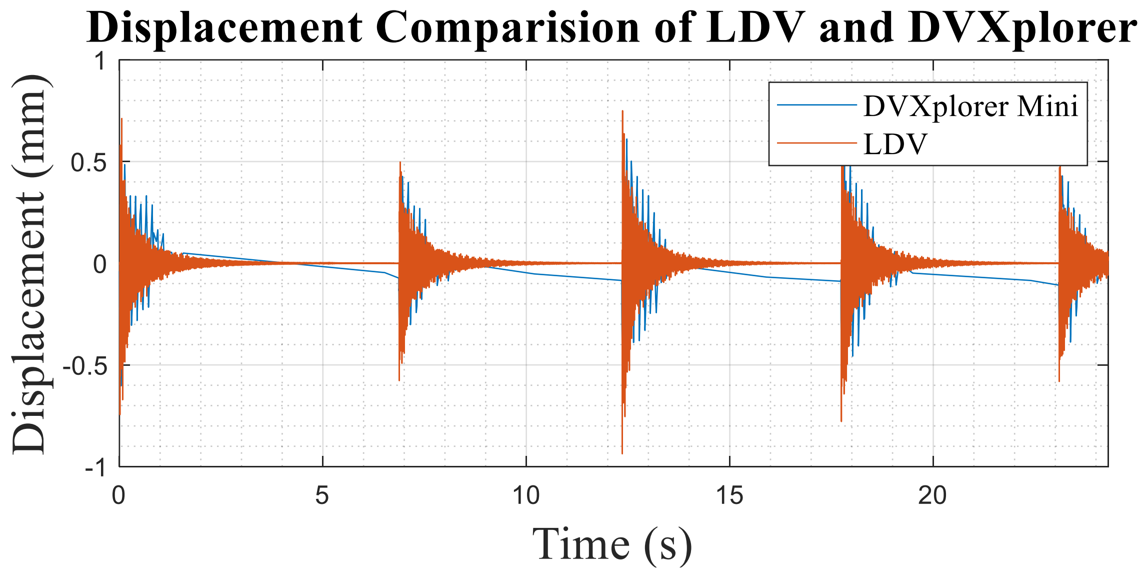
Boxes are 10 by 10

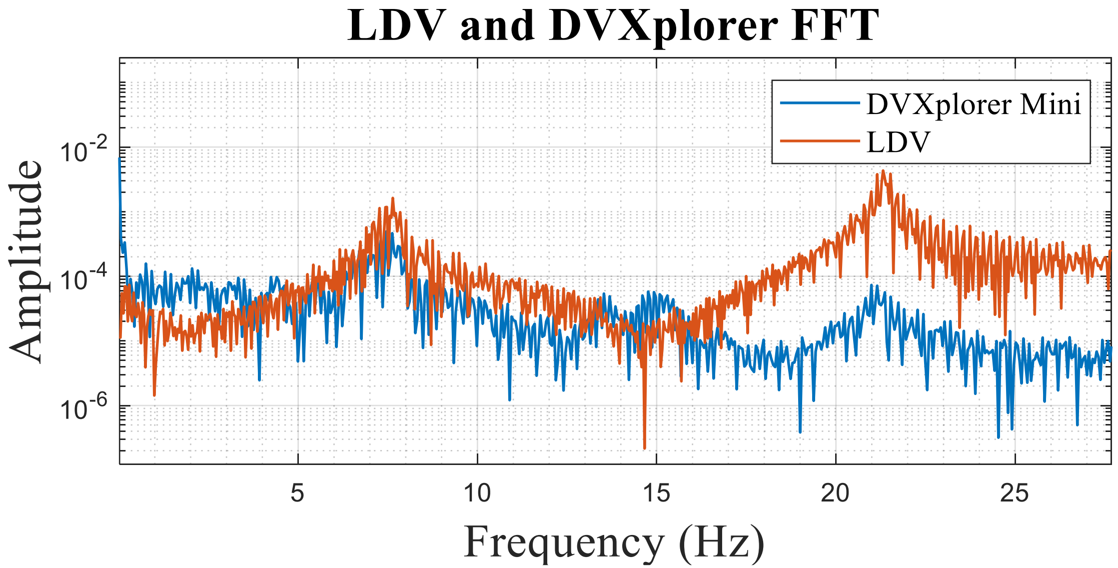
1 box is 64 by 48 pixels



Displacement was calculated using the conversion factor, and the results were fine tuned using LDV data



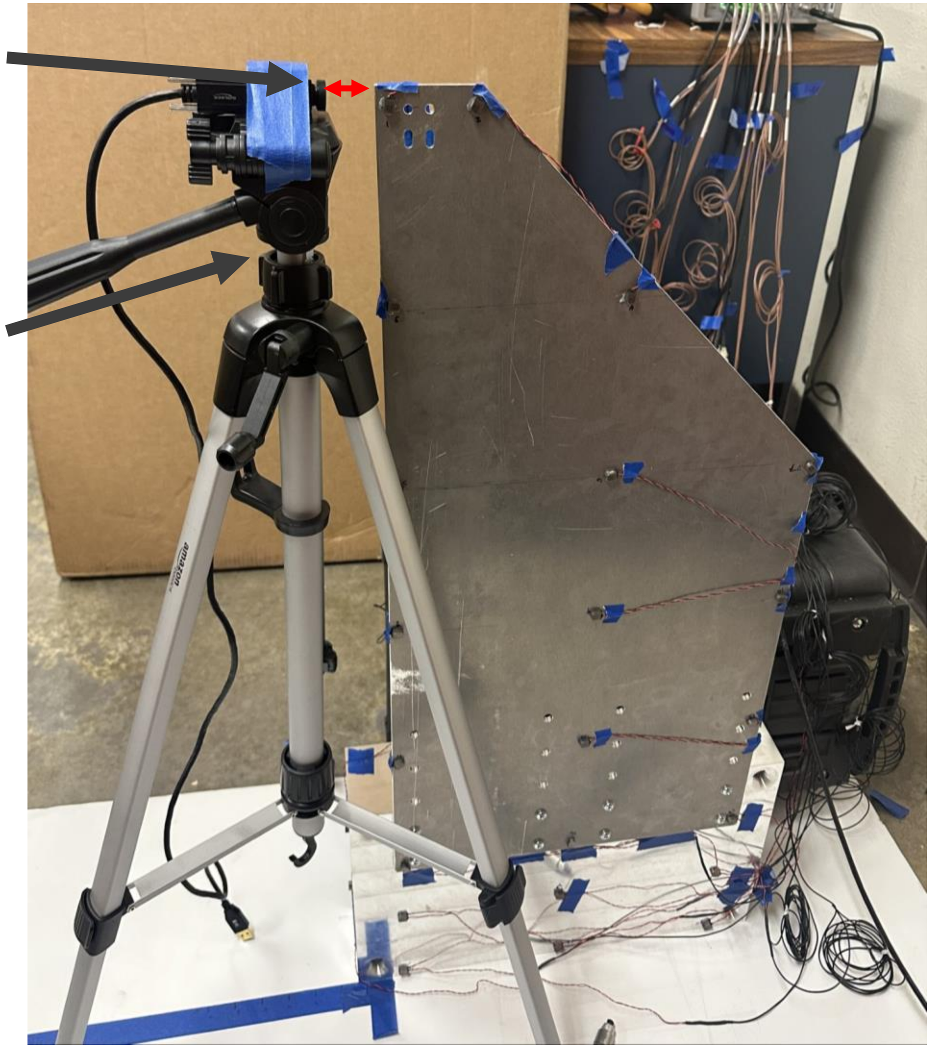


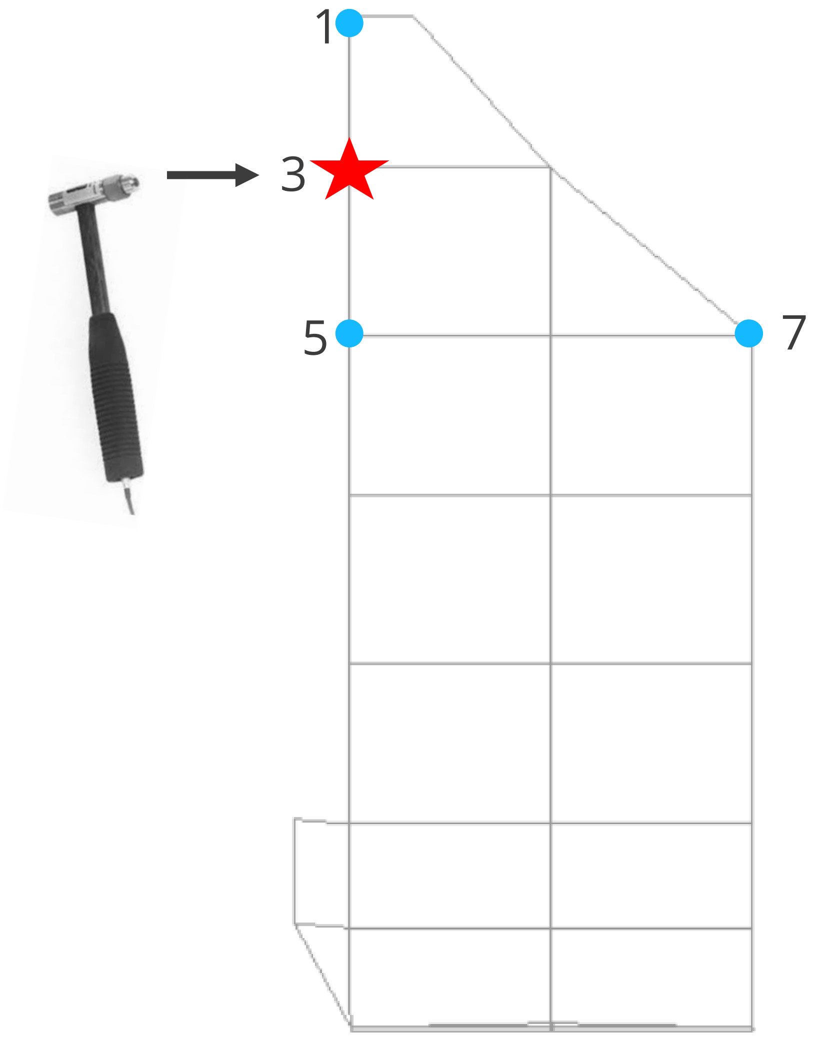


Neuromorphic imaging data was collected from three nodes for this experiment.

1 inch distance

Camera on Tripod

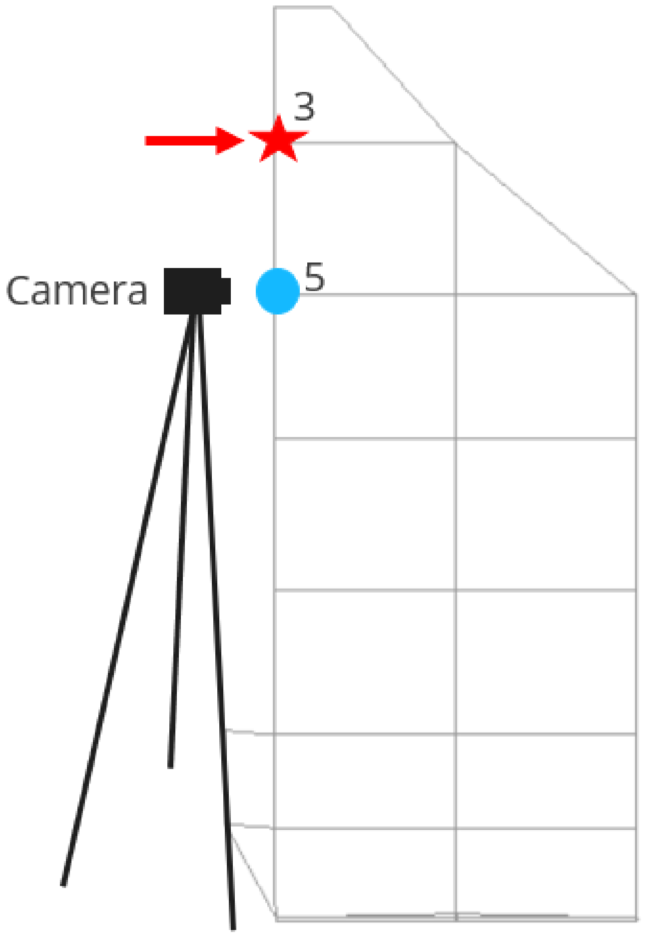


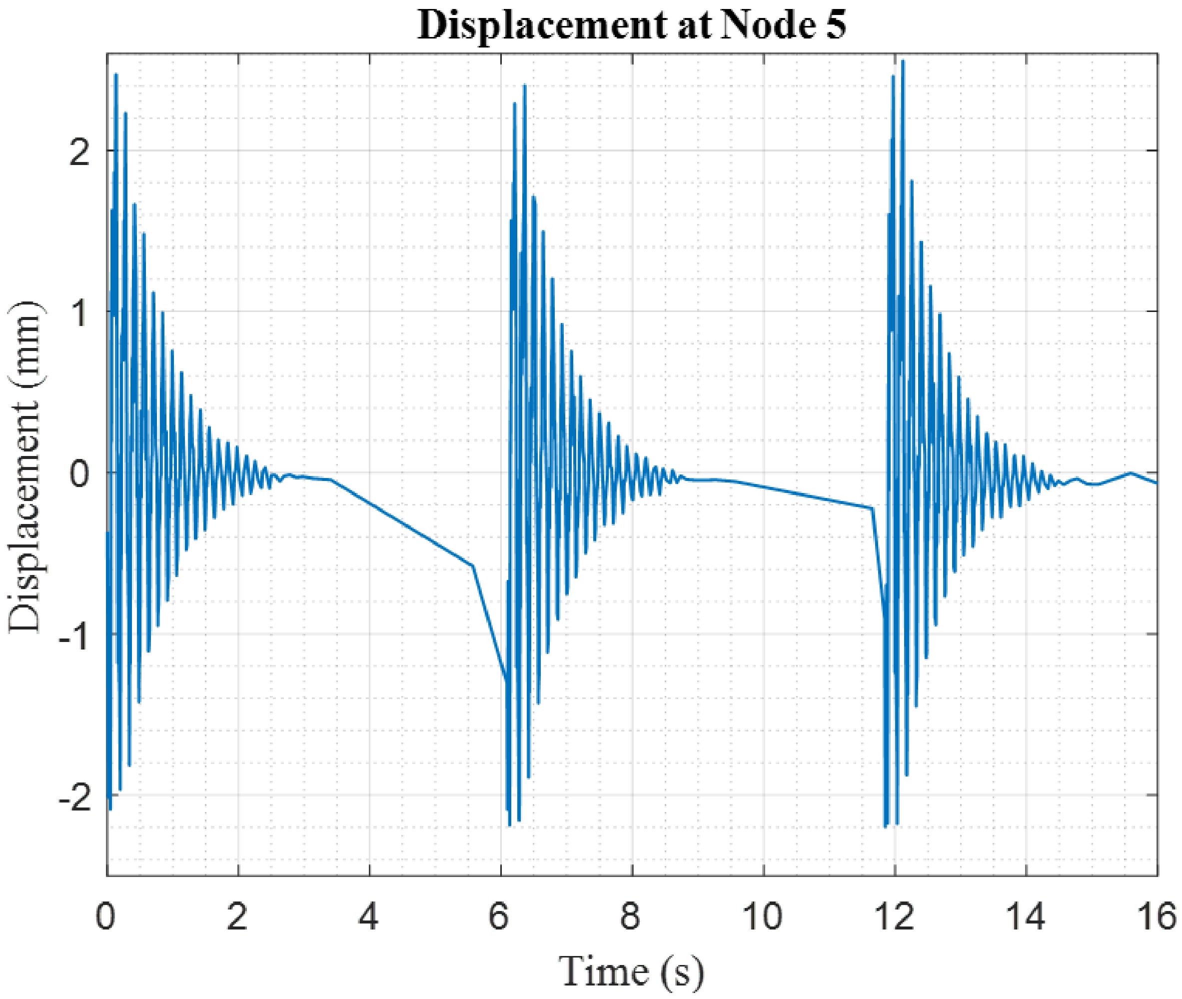


★ Impact Node: 3

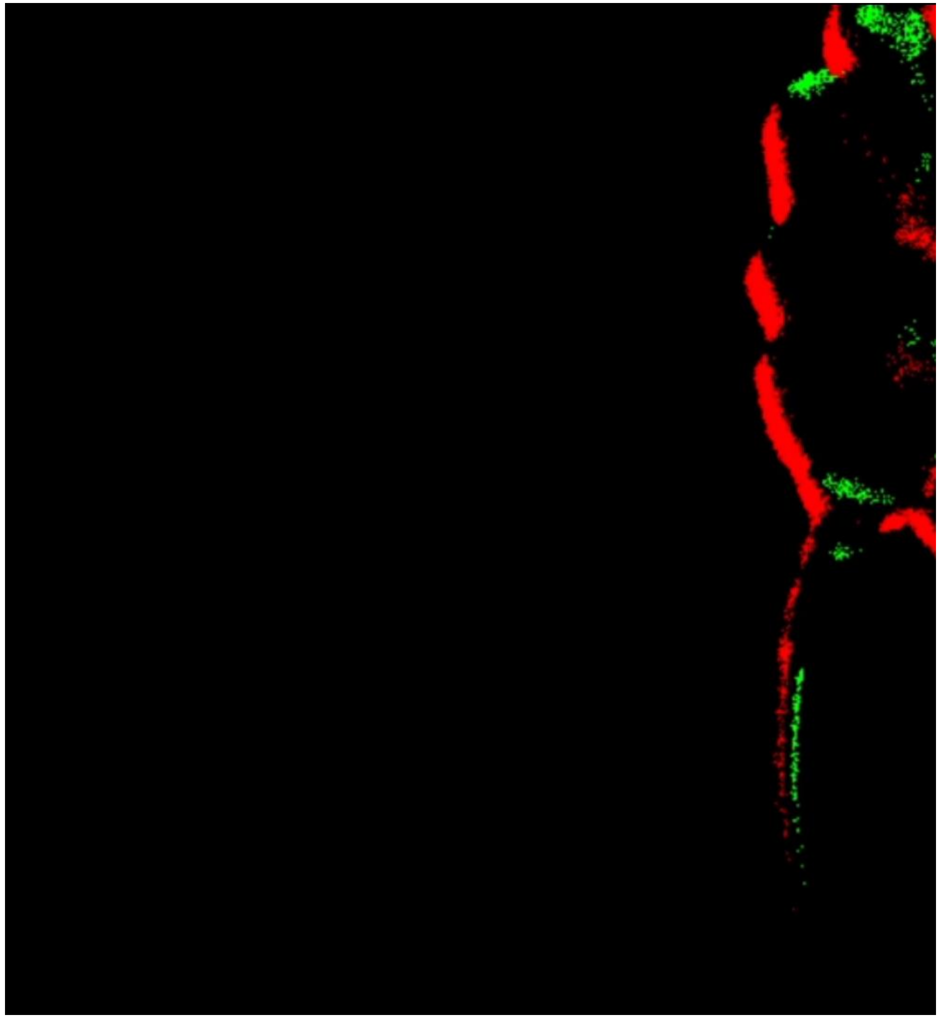
● Measured Node: 1, 5, 7

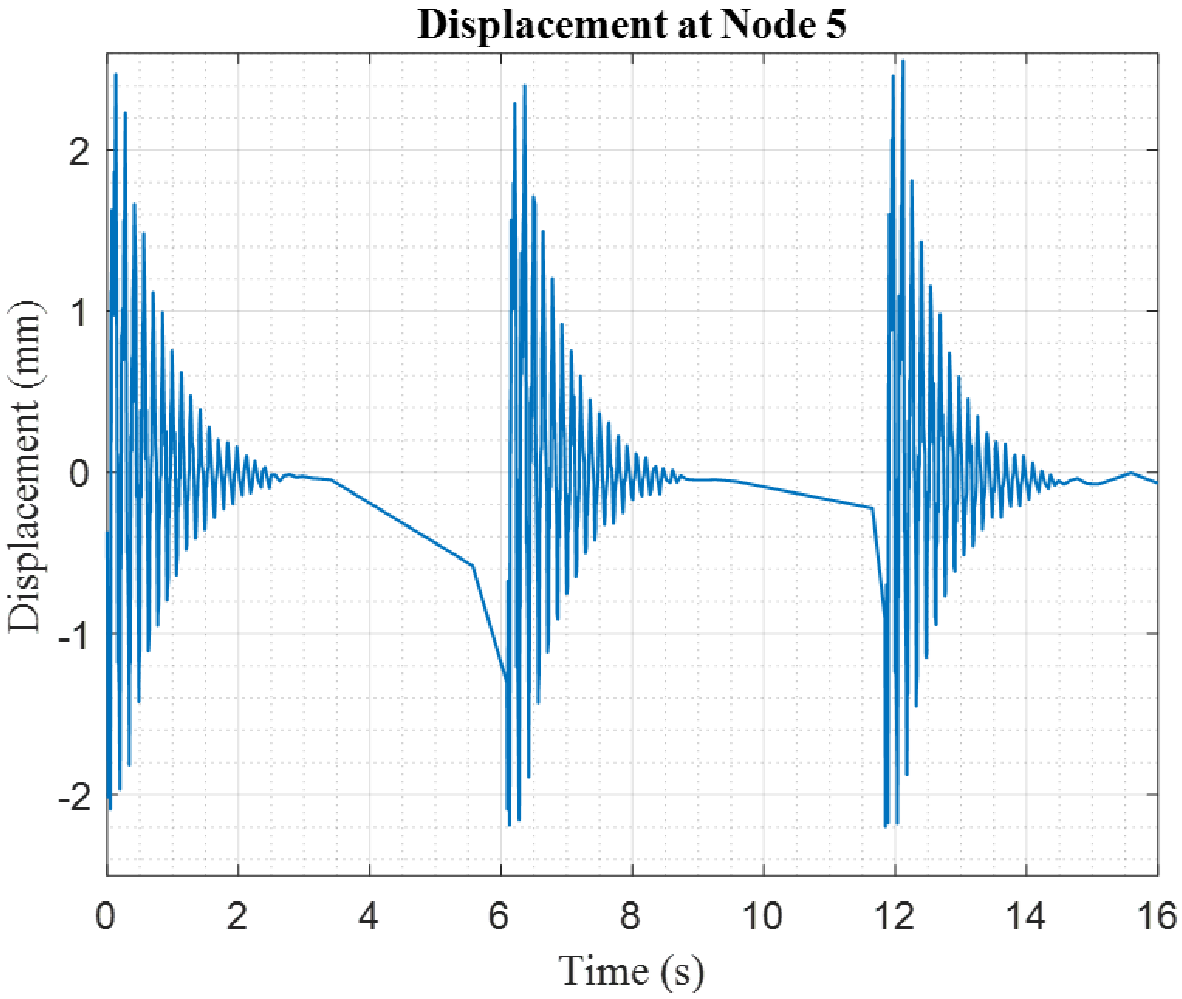
Displacement data was refined using the previous post-processing methods.



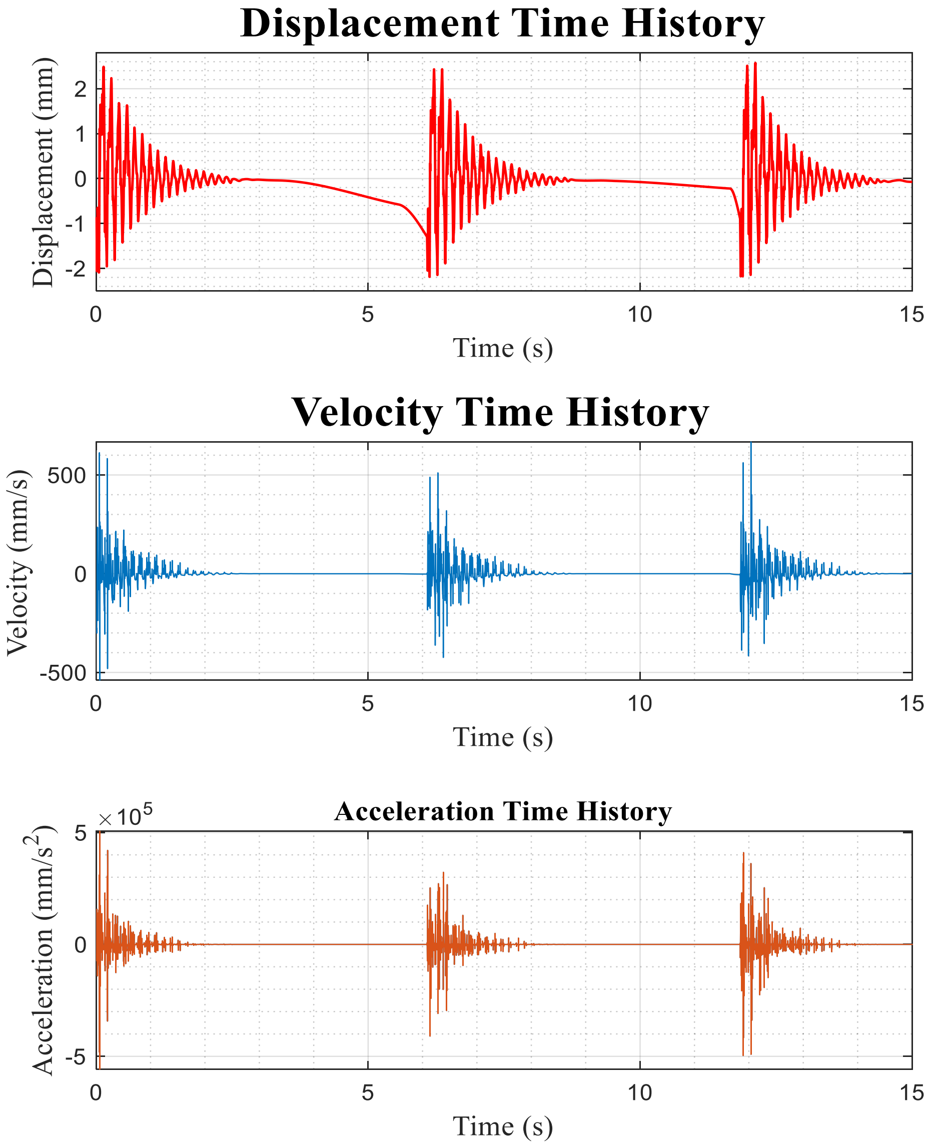


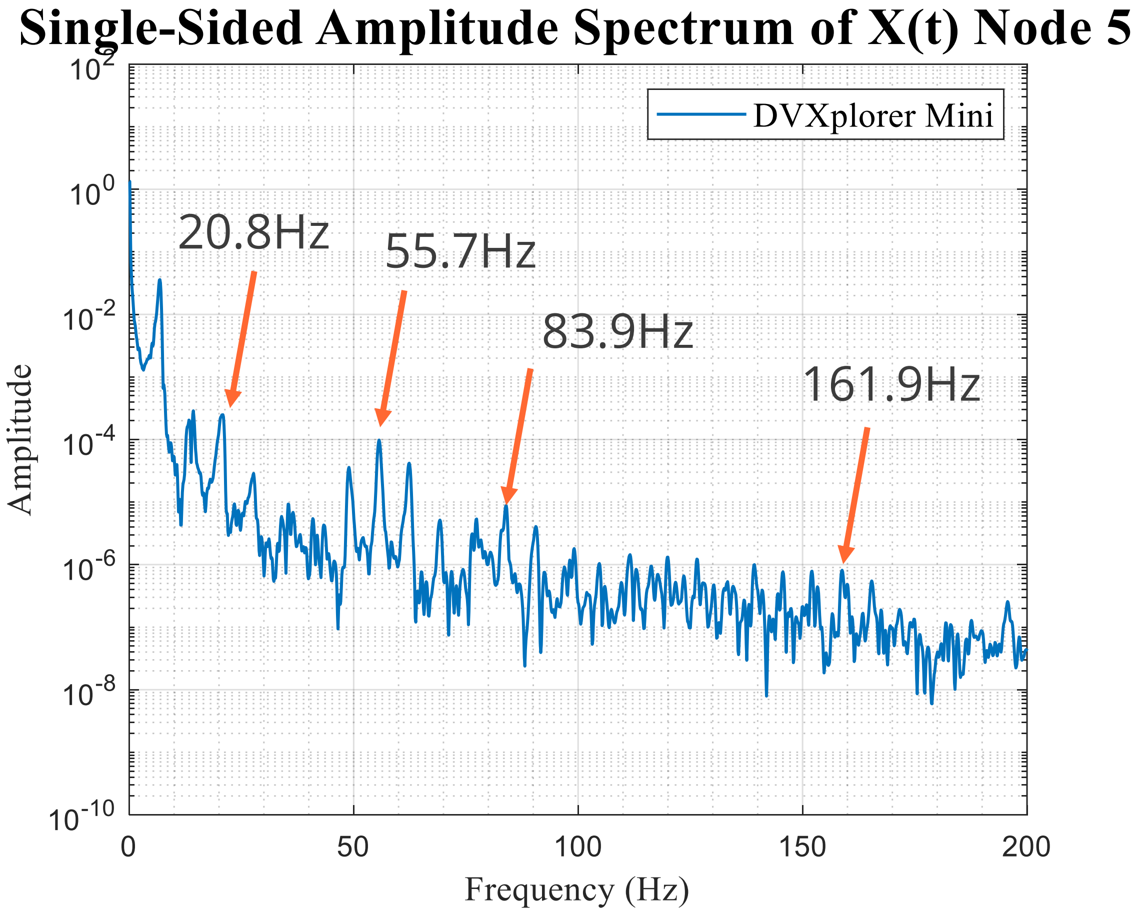
Displacement data was refined using the previous post-processing methods.





Acceleration response data was computed in the time and frequency domain.





Bandwidth of interest: 10 to 200Hz

Two DOF selection methods were explored to pick the best DOF set to use in the expansion.

Effective Independence

[D.C. Kammer, 1991]

Uses a computation of the fractional contribution of each sensor location to the linear independence of the mode shapes

$$E = U_a \left[{U_a}^T U_a \right]^{-1} {U_a}^T$$

U_a is the matrix of mode shapes U partitioned to the reduced set of a DOF.

The minimum values of $E_{diagonal}$ are found and the associated DOF are removed from the candidate set.

Condition Number Optimization

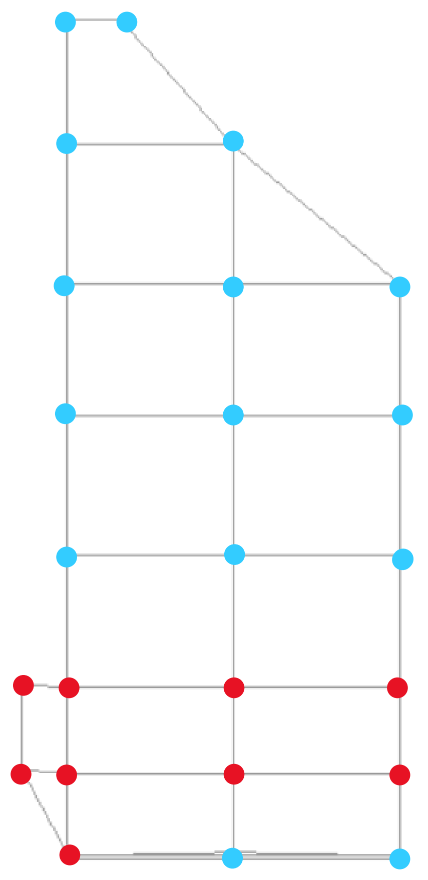
[B.C. Owens et al, 2020]

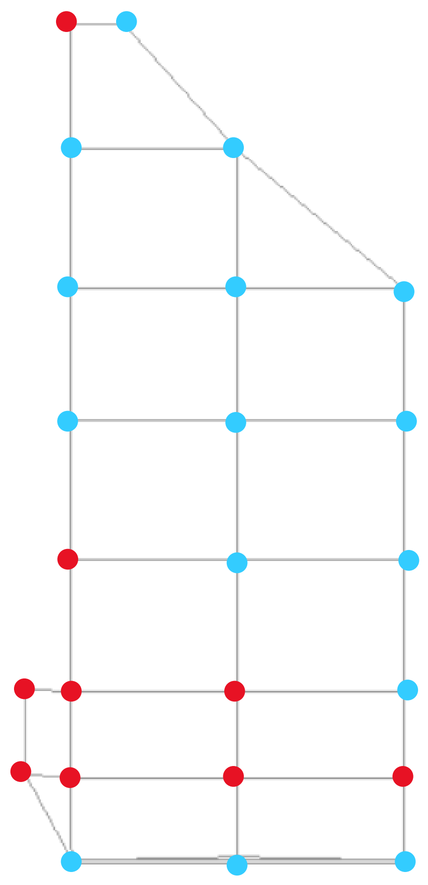
1. Each DOF is removed one at a time
2. The condition number of the remaining set is computed
3. The set with the best (lowest) condition number is selected
4. Process repeated until desired number of DOF is reached

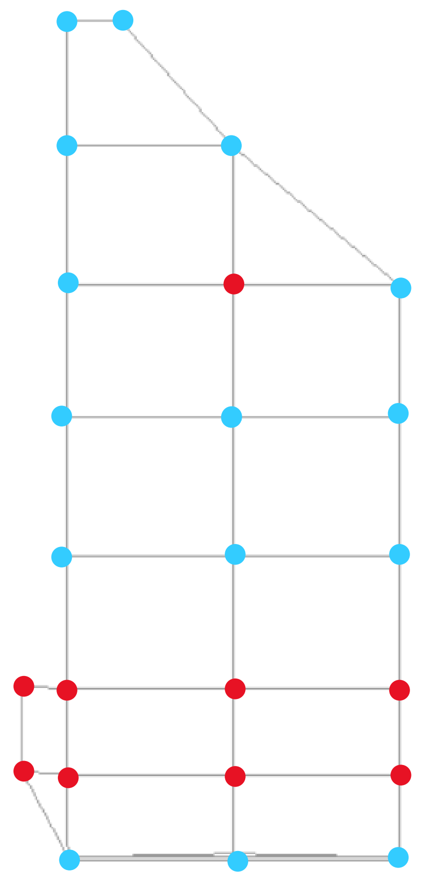
Fifteen DOFs were selected to use 10 modes within the expansion.

Selected DOFs
Removed DOFs

Effective Independence	Condition Number Optimization	Manual Selection







System Equivalent Reduction Expansion Process (SEREP) was the modal expansion method utilized.

Step 1: Modal Filter

$$x_{new} = \Phi_{new}\Phi^{+}_{measured}x_{measured}$$

Step 2: Expansion

Where:

- $\boldsymbol{\Phi_{new}}$ is mode shape matrix of all DOFs from the model ***(24 DOFs x 10 Modes)***
- $\boldsymbol{\Phi^{+}_{measured}}$ is mode shape matrix of the selected DOF set from the model ***(15 DOFs x 10 Modes)***
- $\boldsymbol{x_{measured}}$ is experimental acceleration response data of the selected DOFs ***(15 DOF x n frequency steps)***
- $\boldsymbol{x_{new}}$ is estimated acceleration response data of all DOFs ***(24 DOF x n frequency steps)***

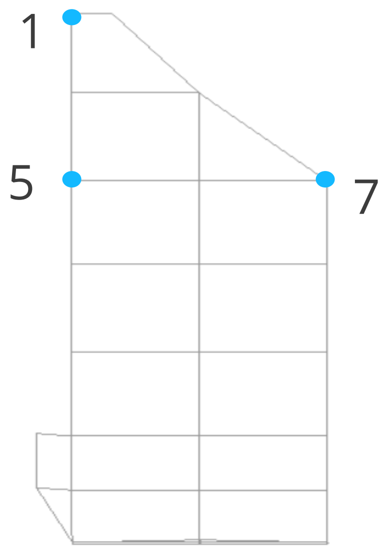
[J. O'Callahan et al, 1989]

Mixed Domain Expansion was achieved by incorporating neuromorphic acceleration data into $x_{measured}$.

Step 1: Modal Filter

$$x_{new} = \Phi_{new}\Phi^{+}_{measured}x_{measured}$$

Step 2: Expansion



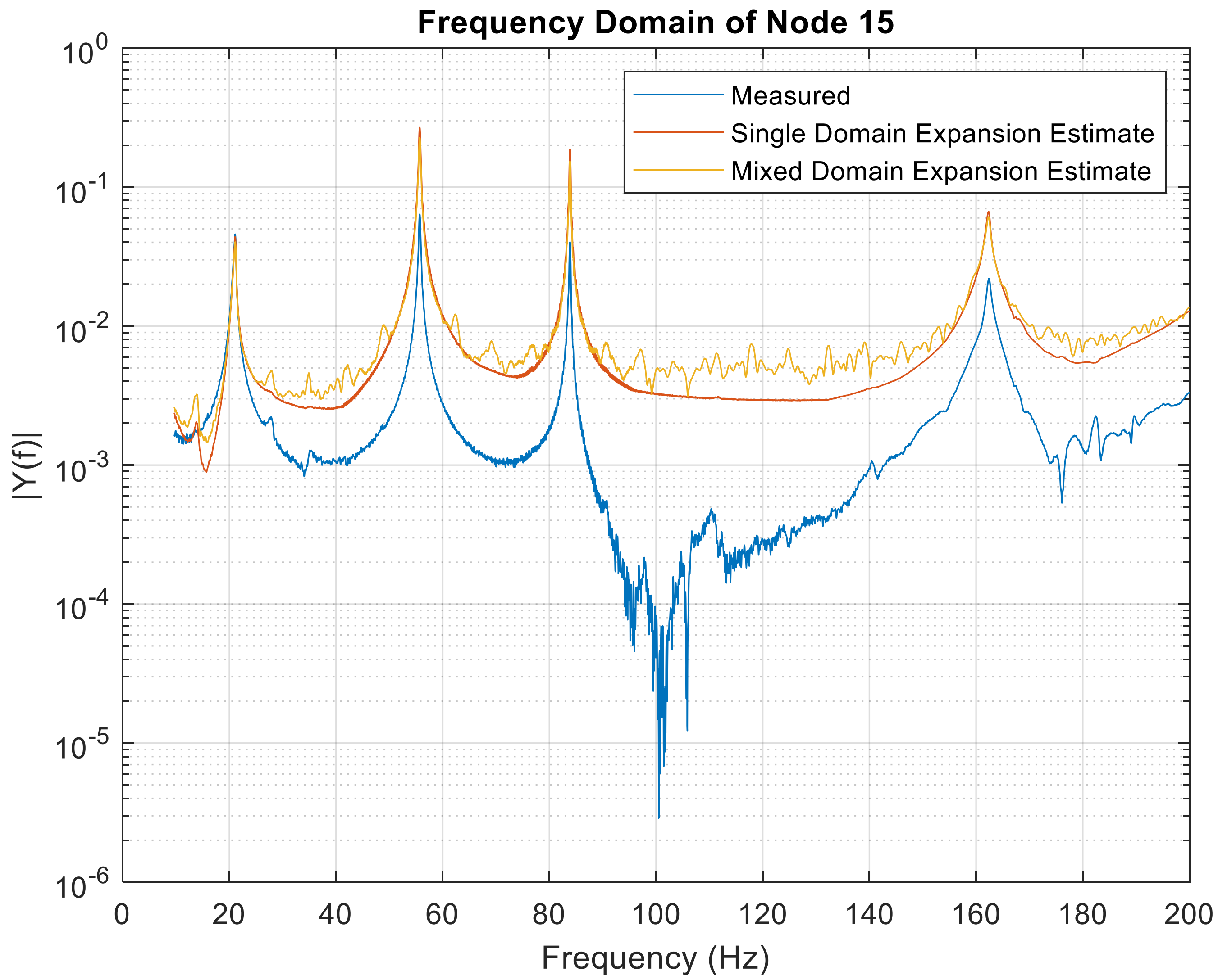
Single Domain:

$$\boldsymbol{x_{measured}} = \begin{bmatrix} Accelerometer\ DOF\ 1 \\ Accelerometer\ DOF\ 2 \\ Accelerometer\ DOF\ 3 \\ Accelerometer\ DOF\ 4 \\ Accelerometer\ DOF\ 5 \\ \vdots \\ Accelerometer\ DOF\ 15 \end{bmatrix}$$

Mixed Domain:

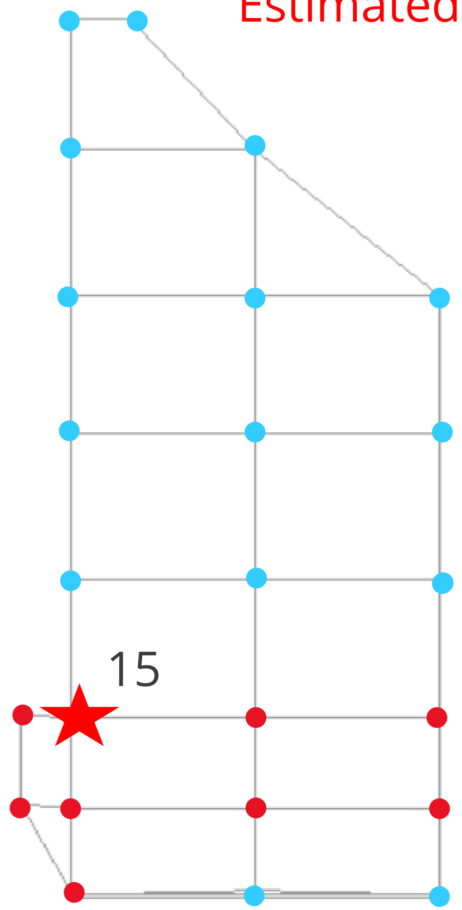
$$\boldsymbol{x_{measured}} = \begin{bmatrix} \boldsymbol{Neuromorphic}\ DOF\ 1 \\ Accelerometer\ DOF\ 2 \\ Accelerometer\ DOF\ 3 \\ Accelerometer\ DOF\ 4 \\ \boldsymbol{Neuromorphic}\ DOF\ 5 \\ \vdots \\ Accelerometer\ DOF\ 15 \end{bmatrix}$$

Mixed domain expansion estimates to the block represent the measured response data relatively well.



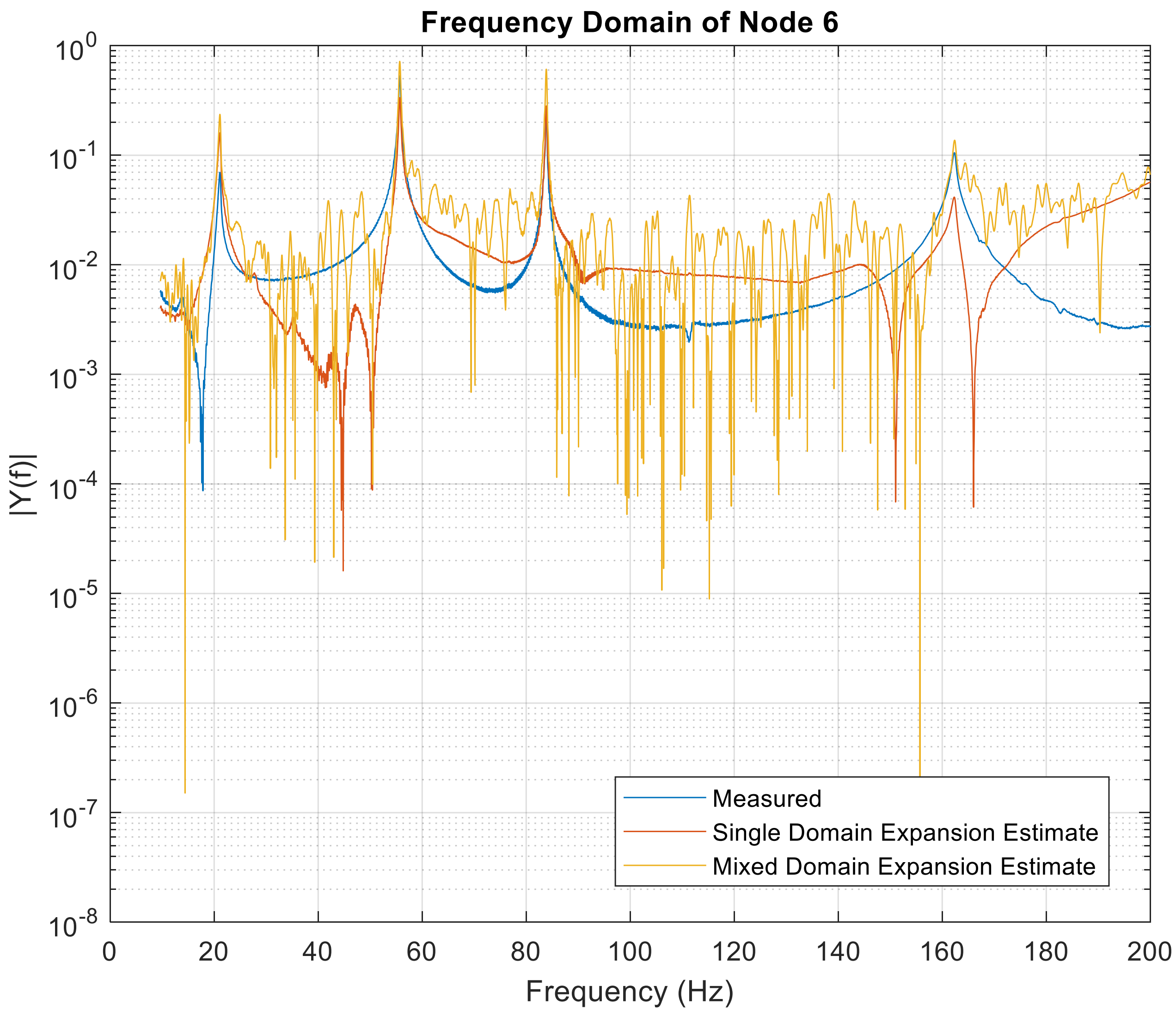
Single Domain
RMSE: 0.024

Mixed Domain
RMSE: 0.022



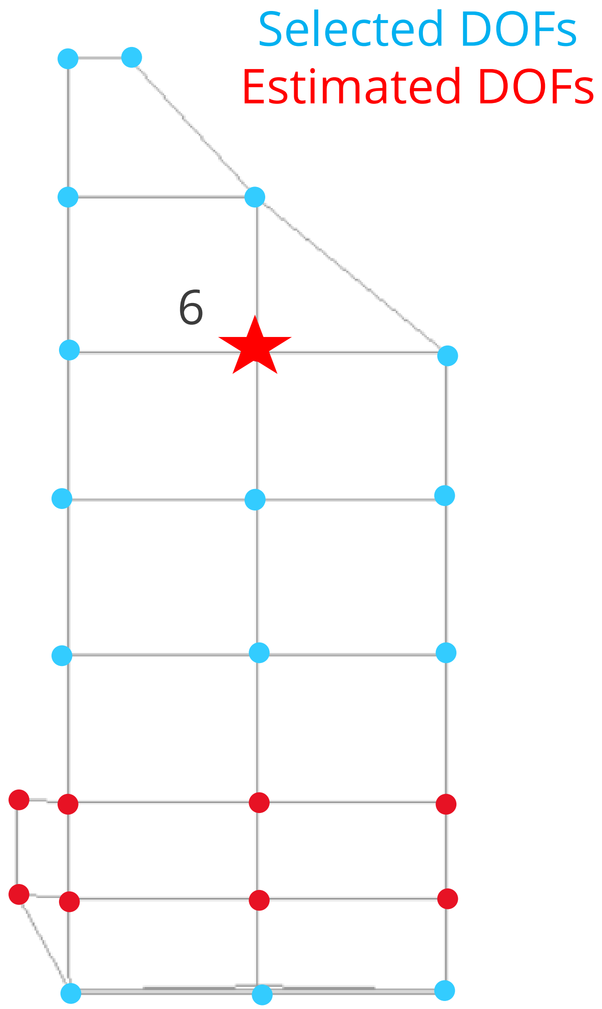
Effective Independence Method

Mixed domain expansion estimates to the wing are more noisy than estimates to the block



Single Domain
RMSE: 0.13

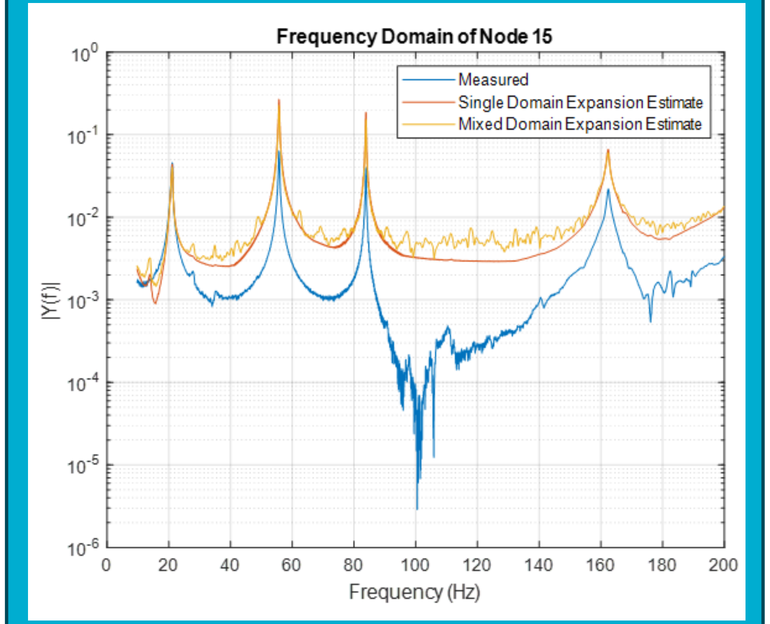
Mixed Domain
RMSE: 0.10



Manual Selection Method

Three key conclusions can be drawn from this work.

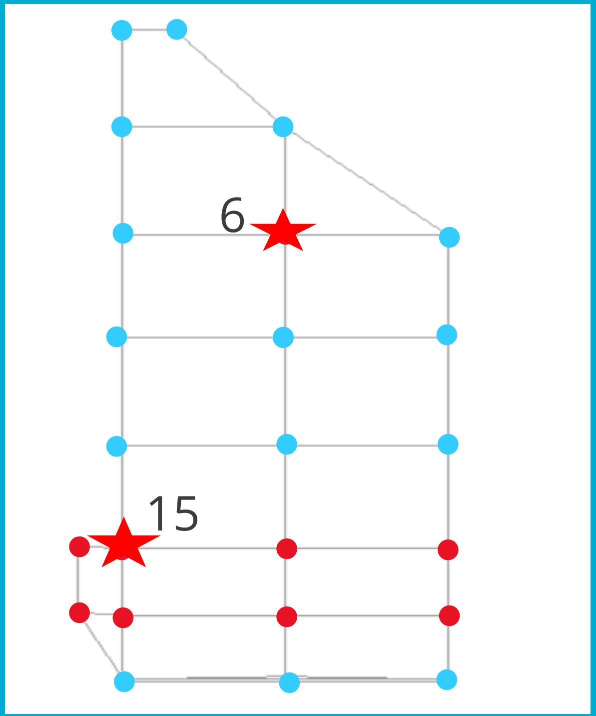
Mixed domain expansion with neuromorphic data and accelerometers **can** be done



Developed a **foundation** for this mixed domain expansion process

- Collected displacement from a neuromorphic camera
- Explored two DOF selection methods
- Converted displacement to acceleration to compute a mixed domain SEREP expansion

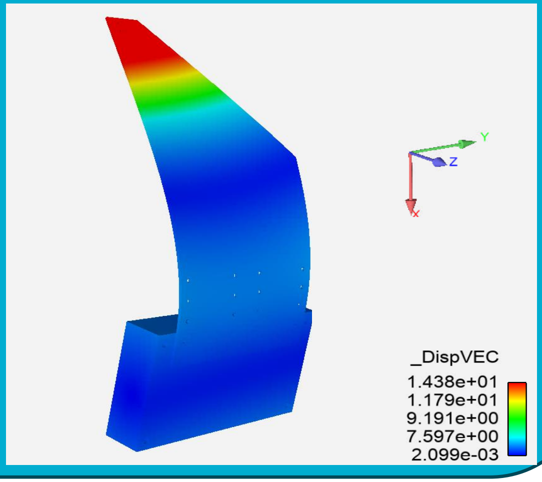
Expanding to the **smaller displacements** of the block has **less noisy** estimates than the higher displacement point of the wing



Four areas could be further improved in future work.

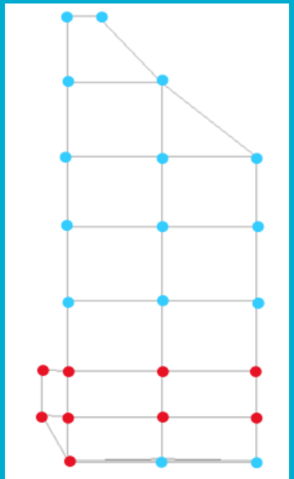
Refine the model

- Better replicate boundary conditions
- Increase number of nodes to expand to



Explore DOF selection methods

- Sensor Elimination using Auto-Modal Assurance Criterion (SEAMAC)
- Modal Projection Error (MPE)



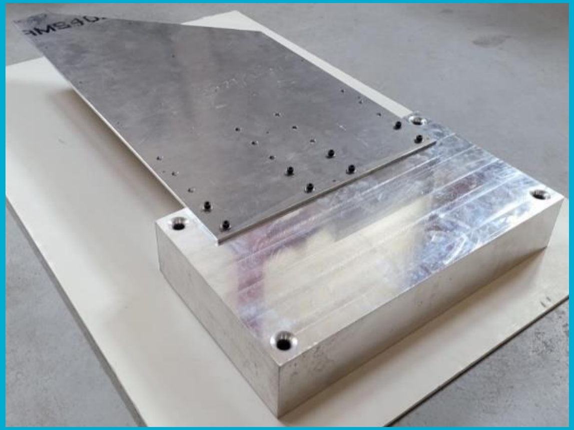
Improve neuromorphic camera data

- Refine calibration methods
- Improve post processing methods

DVXplorer Mini

Test on a different structure

- More flexible structure with higher displacement
- More modes at lower frequencies



Acknowledgements

This research was conducted at the 2024 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.

We would like to acknowledge and thank Bill Flynn and Charles Rice from Siemens for their support and for donating Testlab licenses throughout the summer.

Additionally, we would like to thank Rob Warmbold from Polytec for donating the lasers used for data collection during our experiments.

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Questions?

Conduct Modal Tests

Refine the Finite Element Model

Collect and Process Neuromorphic Imaging Data

Conduct DOF Selection

Compute Single and Mixed Domain Expansion