

Preliminary Results for Simulation Assisted Guided Wave Structural Health Monitoring of Aerospace Structures

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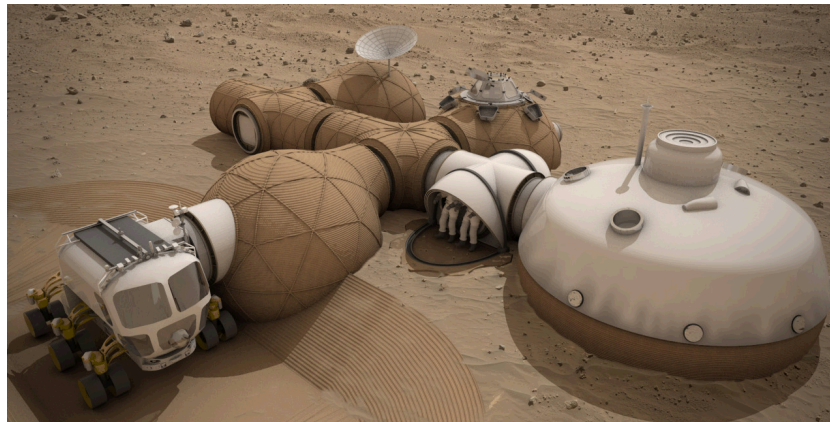
FAA Technical Center

- Structural Health Monitoring (SHM) for NASA missions
- Model Assisted SHM
- Elastodynamic Finite Integration Technique
- FAA Panel Simulation
- Conclusions and Future Work

- Automated in-situ NDE monitoring of component state
 - During flight or at set increments on ground
 - Often requires integrated instrumentation
- Potential to reduce inspection time/cost
- Condition based maintenance
- Challenges:
 - False negatives, false positives
 - System validation/certification
 - Confidence in detectability
 - Assessment of limitations
 - Assessment of lifetime

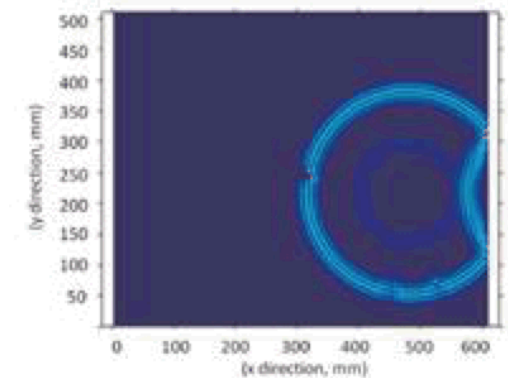
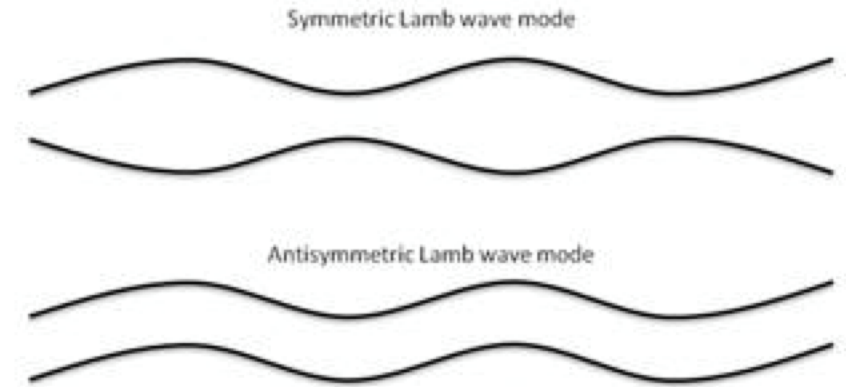


- Aeronautics
 - Enable advanced materials and designs
- Spaceflight
 - On-orbit
 - On-planet habitation



- Federal Aviation Administration = US civil aviation regulatory institution
- Answer questions on SHM validation and POD to guide how to set regulations
- FAA goal for MAPOD is to develop ‘missing’ data for validation studies
 - Ability to create data to help foster POD studies

- Based on guided wave (GW) propagation, interaction, scattering from defects
- Physics of GW = long propagation
 - But affected by environmental changes (temperature, loading, etc)
- Highly studied area (many new publications yearly)
- Multiple commercial companies worldwide sell GW SHM hardware/software

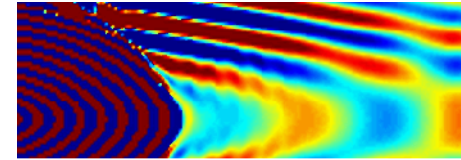


Model Assisted SHM System Assessment

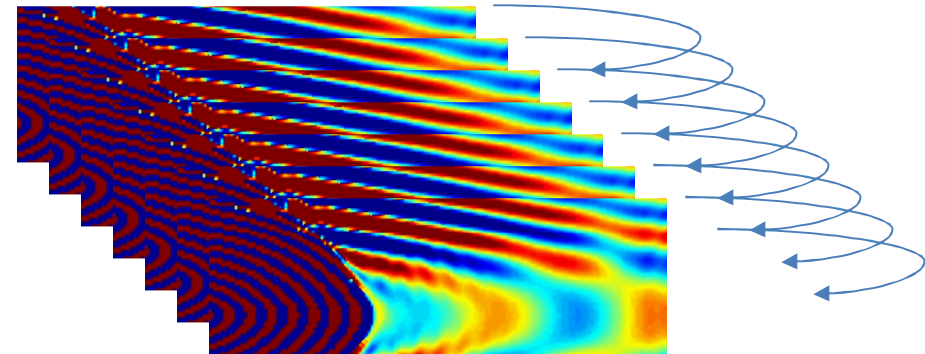


- Aim to aid in addressing SHM Challenges:
 - Confidence in detectability
 - Assessment of limitations
- Requirements on models
 - Validated for relevant physics
 - Resulting data represents key features of experimental system (e.g., speed of wave modes, amplitude)
 - Necessary features will be based on the detection/quantification algorithm being used

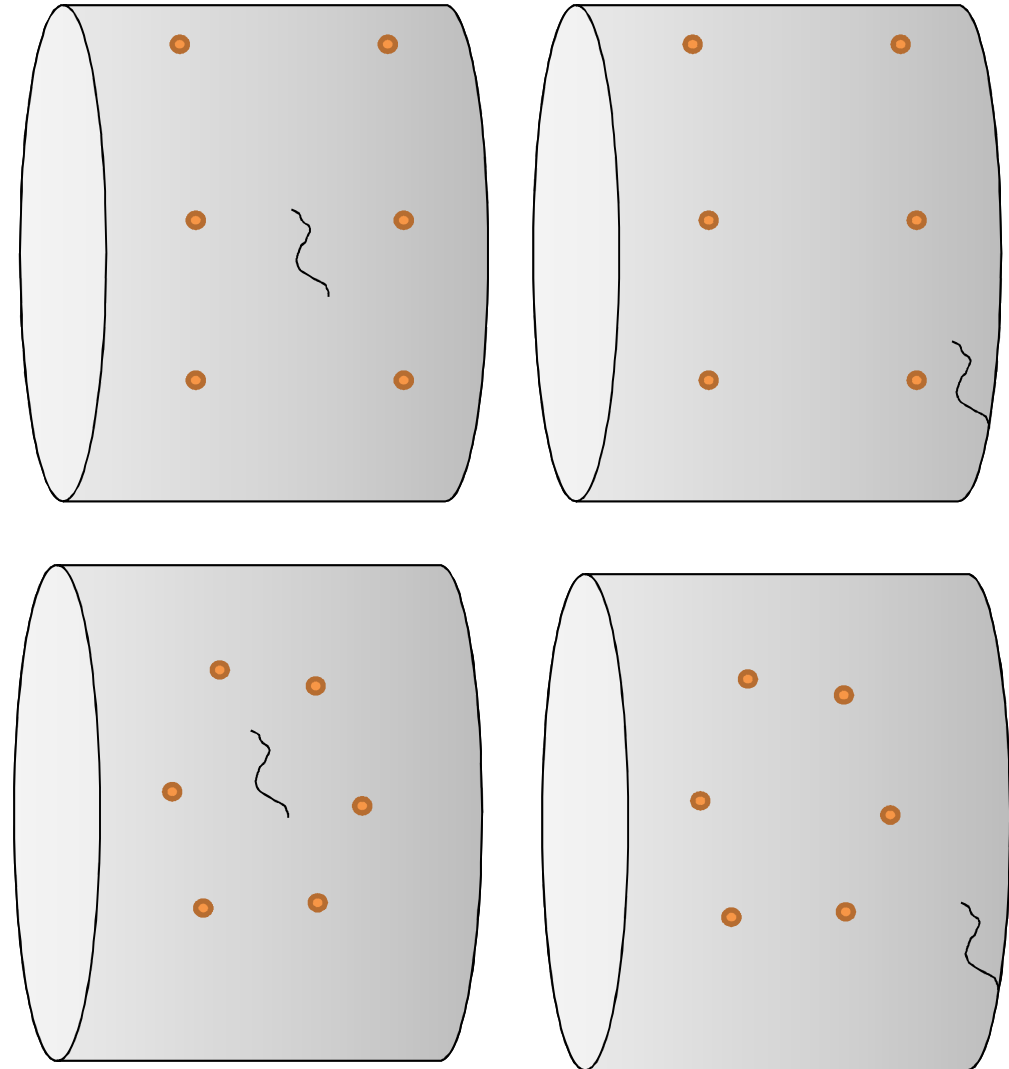
- Forward modeling
 - Simulate specific inspection scenario with specific defect case
 - Inform interpretation of data or inform optimization of inspection



- Inverse modeling
 - Start with experimental signal
 - Use modeling to predict what created that signal



- Forward modeling:
 - Investigate a large number of defect scenarios vs. detectability
 - Investigate sensor arrangement vs. detectability
- Inverse modeling:
 - Improve determination of defect location
 - Improve quantification of defects



EFIT - Elastodynamic Finite Integration Technique

- 2nd order Finite Difference scheme
- Works well for isotropic and orthotropic materials
- $\Delta x \leq \lambda / 10$

$$\Delta V_x = \frac{\Delta t}{\Delta n \frac{(\rho + \rho[x+1])}{2}} (S_x[x+1] - S_x + T_{xy} - T_{xy}[x-1] + T_{xz} - T_{xz}[x-1]) + F_x$$

$$\Delta V_y = \frac{\Delta t}{\Delta n \frac{(\rho + \rho[y+1])}{2}} (S_y[y+1] - S_y + T_{yz} - T_{yz}[y-1] + T_{xy} - T_{xy}[y-1]) + F_y,$$

$$\Delta V_z = \frac{\Delta t}{\Delta n \frac{(\rho + \rho[z+1])}{2}} (S_z[z+1] - S_z + T_{xz} - T_{xz}[z-1] + T_{yz} - T_{yz}[z-1]) + F_z$$

$$\Delta S_x = \frac{\Delta t(\lambda + 2\mu)}{\Delta n} (V_x - V_x[x-1]) + \frac{\Delta t\lambda}{\Delta n} (V_y - V_y[y-1]) + \frac{\Delta t\lambda}{\Delta n} (V_z - V_z[z-1]),$$

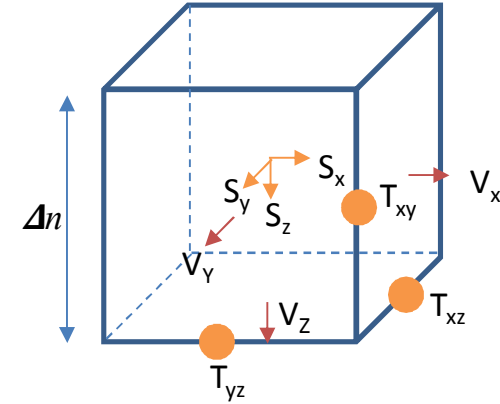
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$$\Delta T_{xy} = \frac{4\Delta t}{\Delta n \left(\frac{1}{\mu} + \frac{1}{\mu[x+1]} + \frac{1}{\mu[y+1]} + \frac{1}{\mu[z+1]} \right)} (V_y - V_y[x-1] + V_x - V_x[y-1]),$$

$$\Delta T_{xz} = \frac{4\Delta t}{\Delta n \left(\frac{1}{\mu} + \frac{1}{\mu[x+1]} + \frac{1}{\mu[y+1]} + \frac{1}{\mu[z+1]} \right)} (V_z - V_z[x-1] + V_x - V_x[z-1]),$$

$$\Delta T_{yz} = \frac{4\Delta t}{\Delta n \left(\frac{1}{\mu} + \frac{1}{\mu[x+1]} + \frac{1}{\mu[y+1]} + \frac{1}{\mu[z+1]} \right)} (V_z - V_z[y-1] + V_y - V_y[z-1]),$$



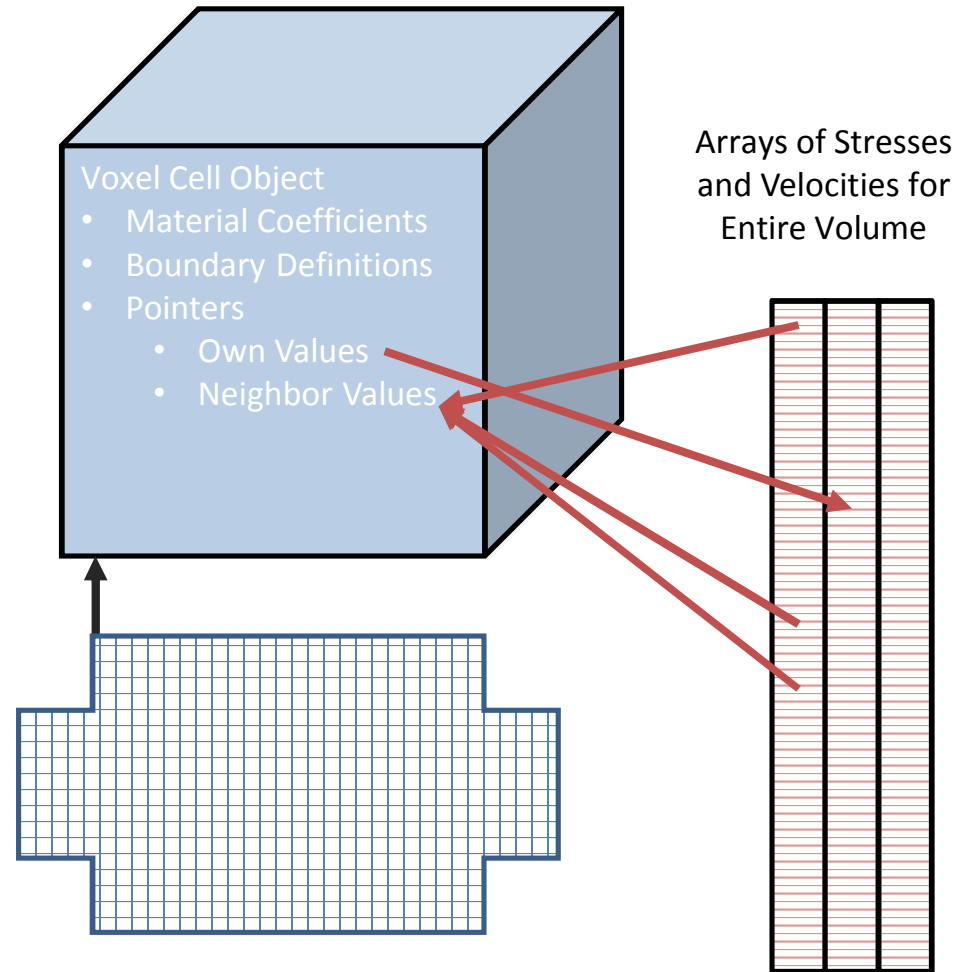
Velocities, Normal and Shear Stresses

ρ = density

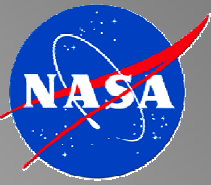
λ & μ = Lamè parameters

‘CompCell’ EFIT

- 3D ‘Computational Cell EFIT’ is modular code version of EFIT aimed at complex geometries and written in C++
- Allows easy discretization of complex geometry
- Prevents wasted memory on empty space (i.e., memory efficient)
- Uses pointers to modularize the EFIT equations
- Uses MPI and OpenMP for parallelization



EFIT CompCell Goals



Efficiently handle
complex geometry

CompCell
structure

Pointer chasing

Minimal data
copying

Optimized for
speed

MPI for Node to
Node
communication

OpenMP for on
Node
calculations

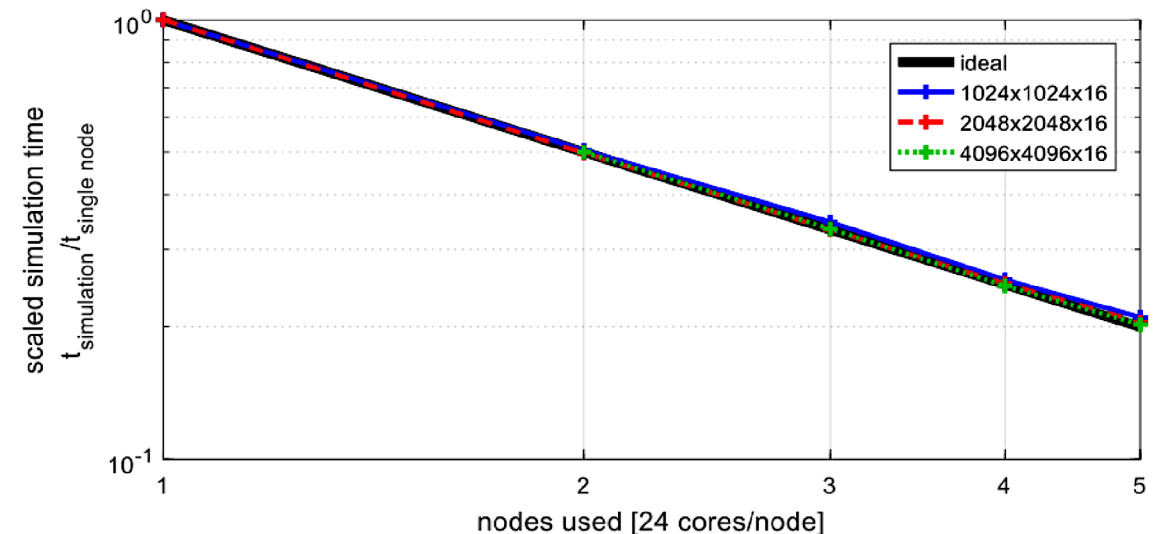
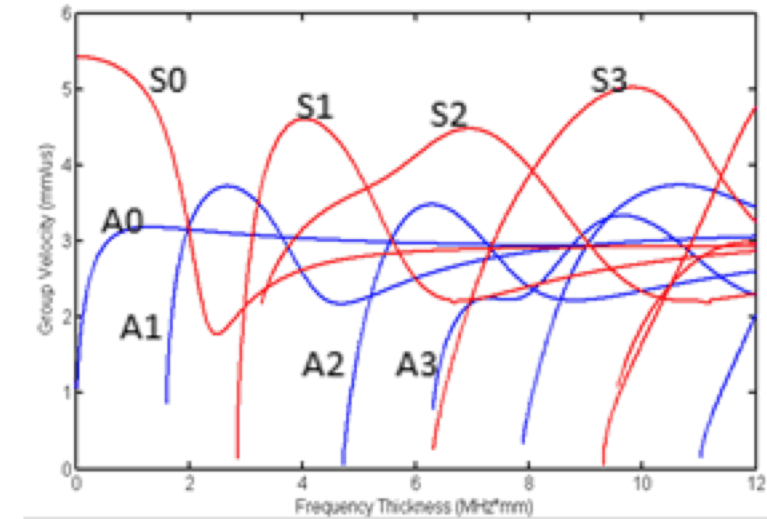
Reusable API

Modular
Approach

Interfaces are
clearly defined

Human readable
inputs

- Example: Error of 0.822% compared to the theoretical group velocity of A0, 2675 m/s calculated for waves in 1.6mm aluminum and 200 kHz excitation
- Scales well with increasing number of cores (i.e., decreased simulation time with increased core count – strong scaling)



FAA Aircraft Panel with SHM Testing



- FAA goal for experimental testing: assess capability of commercial SHM system



<http://www.acellent.com/en/products/sensors/>

FAA Panel & Simulation Case

- FAA AL 2024-T3 panel
 - 3.175 m (125 in) long by 1.85 m (73 in) wide
 - Skin thickness = 1.6 mm
 - 0.1 mm wide 60 mm long vertical cut ('crack')
- Simulation case: 2-bays of the panel
 - $\Delta x = 0.1$ mm, $\Delta t = 7.9$ ns
 - 200 kHz excitation
 - 8 hour run time on 400 cores Xeon 6148 Skylake

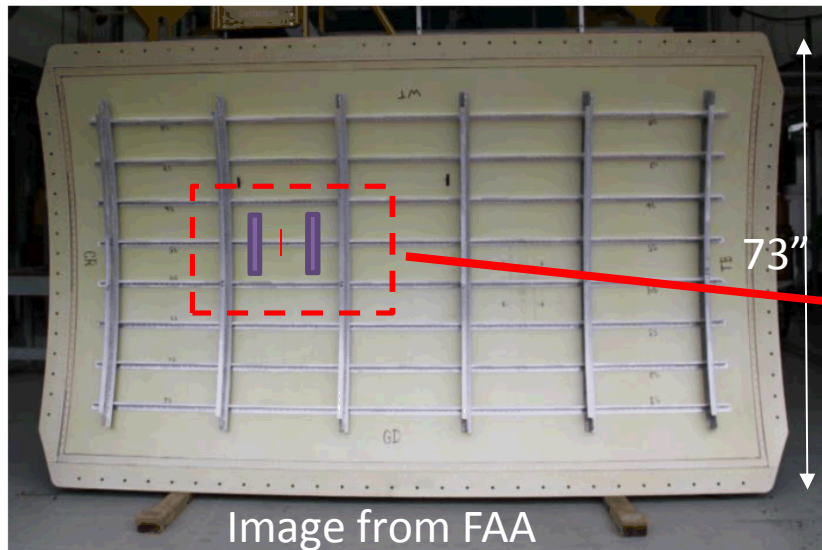
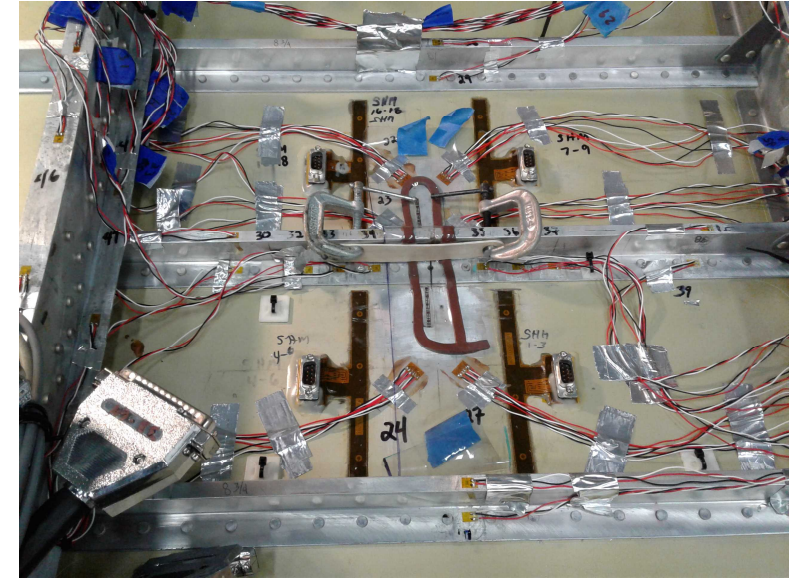
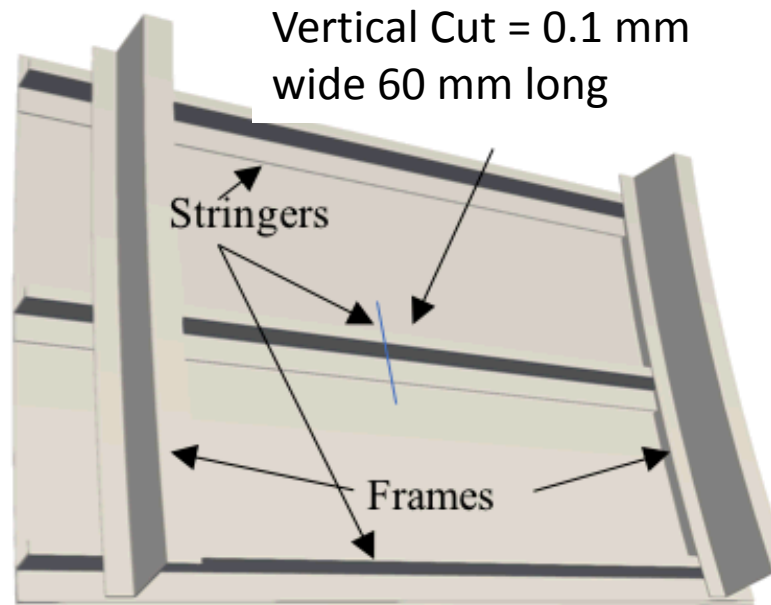


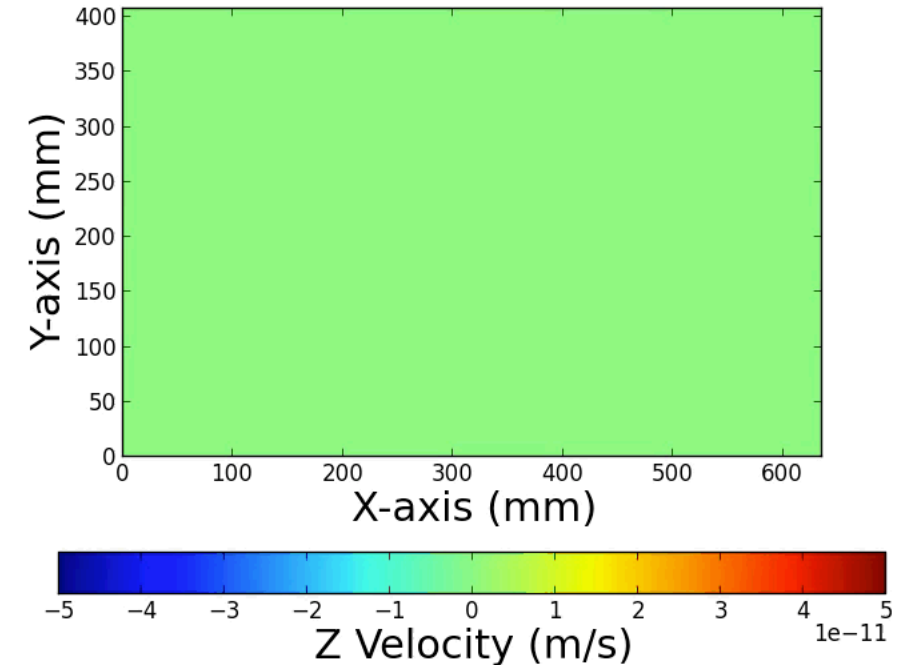
Image from FAA



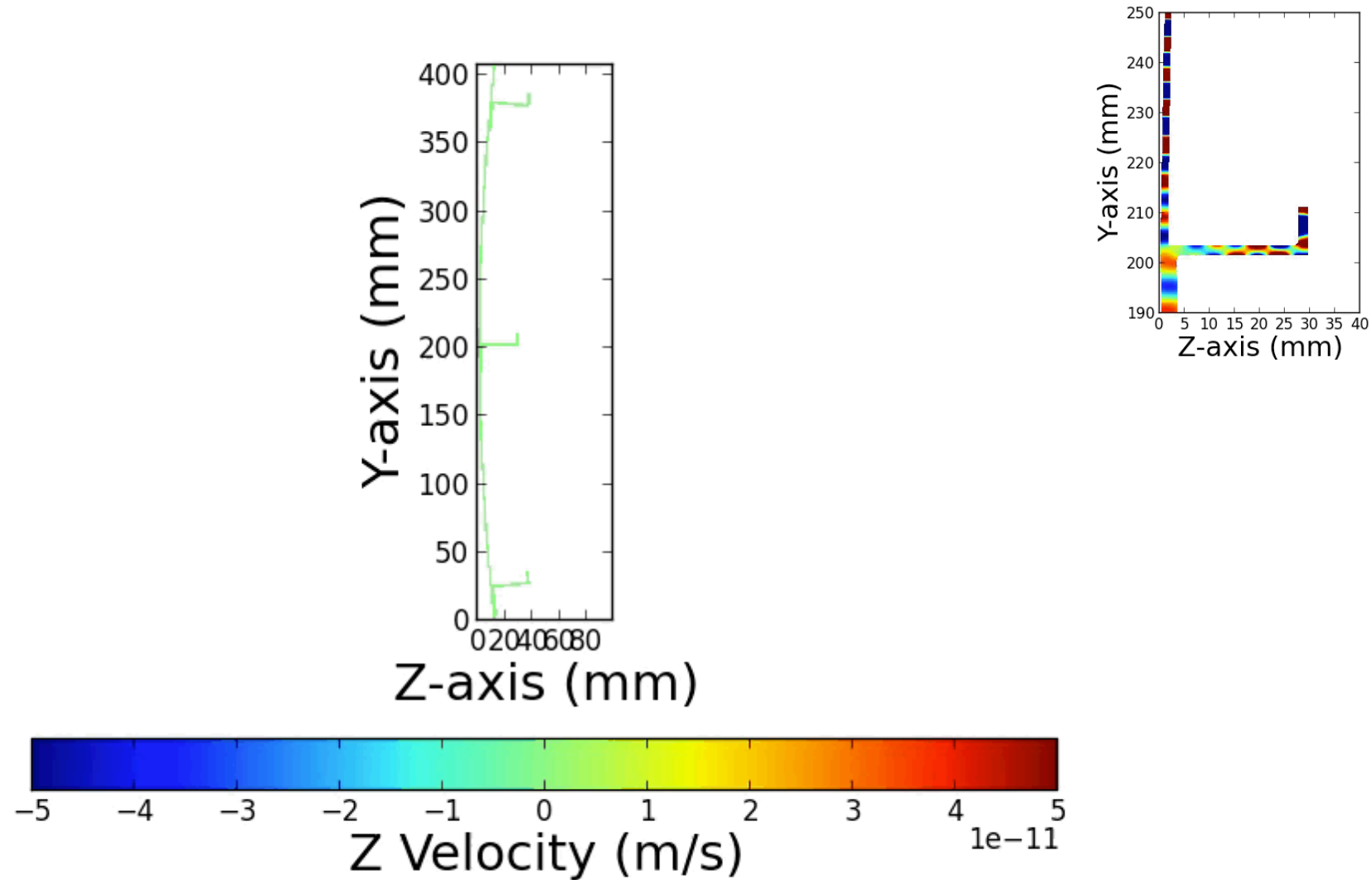
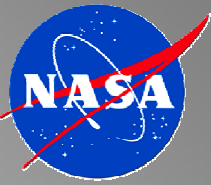
Simulation for Improved SHM System Assessment

- Use NASA simulation code to simulate FAA experimental setup
 - Run both data sets through the same defect detection/location algorithm
 - Acellent software (proprietary algorithm)
- Perform comparison between experiment and simulation
- If simulation accurately represents the key features of experiment, then proceed with simulating various defect/sensor scenarios

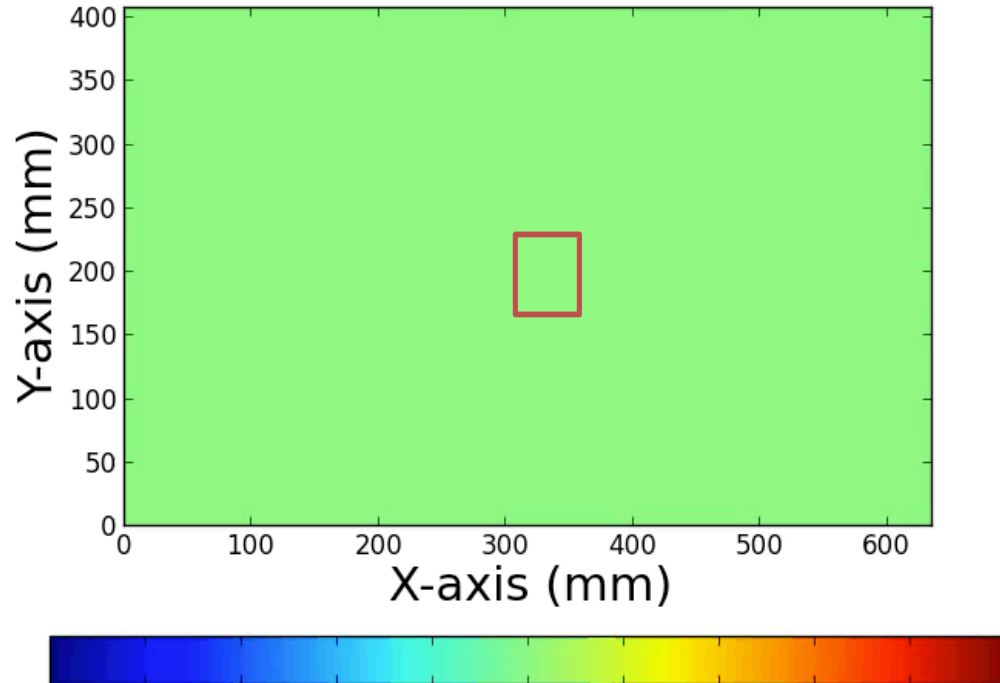
Pristine Panel Simulation:



Simulated Pristine

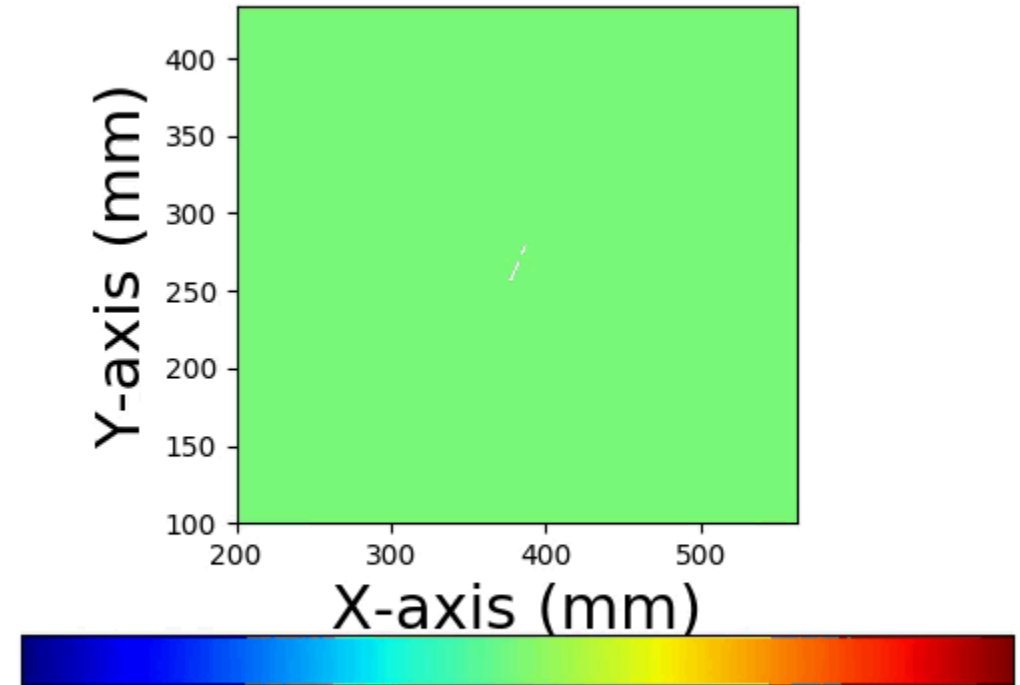


Simulated Crack



Z Velocity

Normal Crack

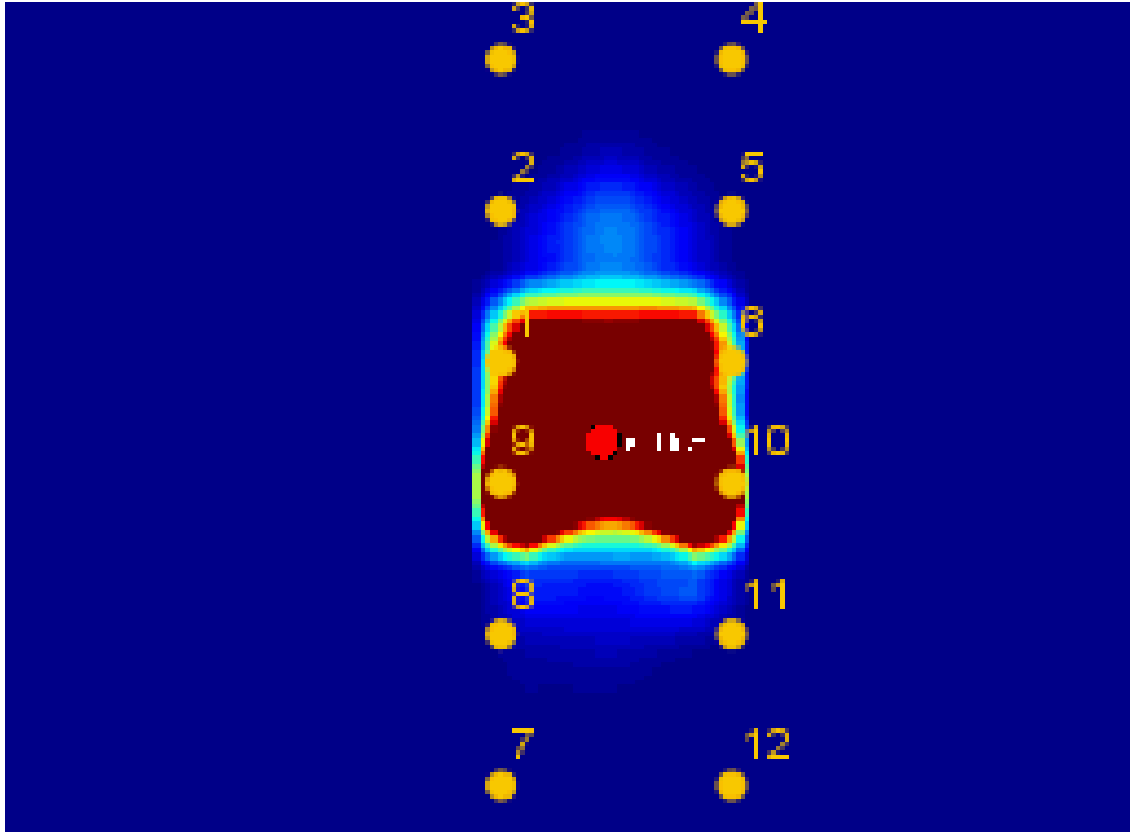


Z Velocity

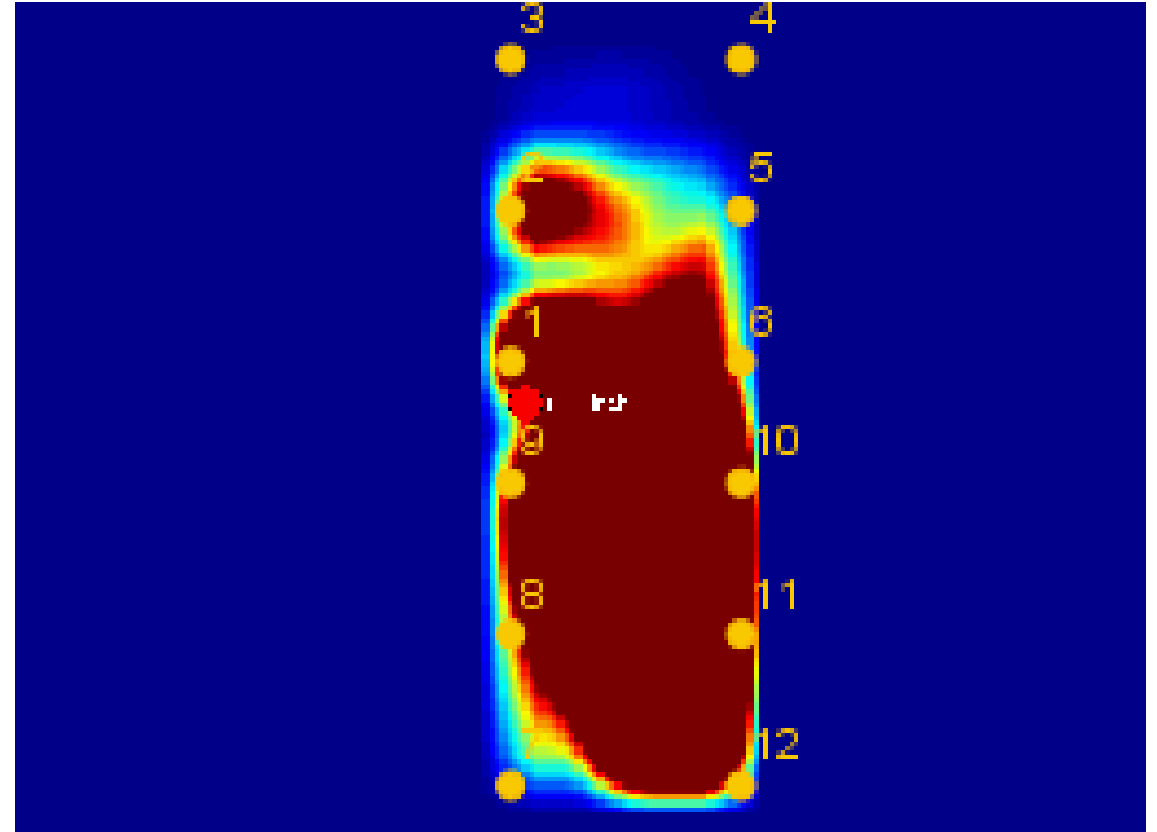
Angled Crack

Comparison between simulation and experiment

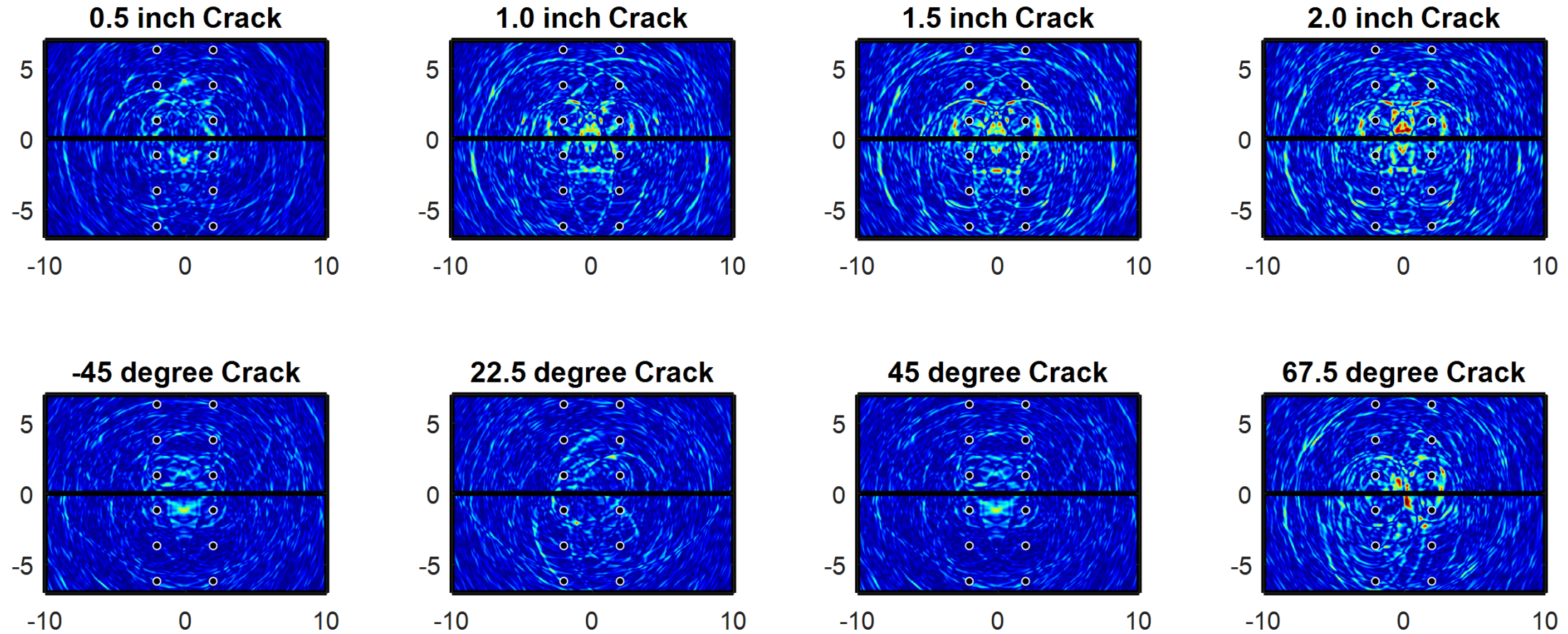
Simulation Result



Test Result



Damage Index Maps of Various Simulated Crack Configurations



Damage Index Maps

- Verify correctness of computational pipeline demonstration
- Investigate use of realistic GW ultrasound simulation for SHM system validation / 'POD'
- Continue to populate more defect scenarios
 - Varying: defect size, angle, width

Questions?