Vector-based Damage Localization for Anisotropic Composite Laminates

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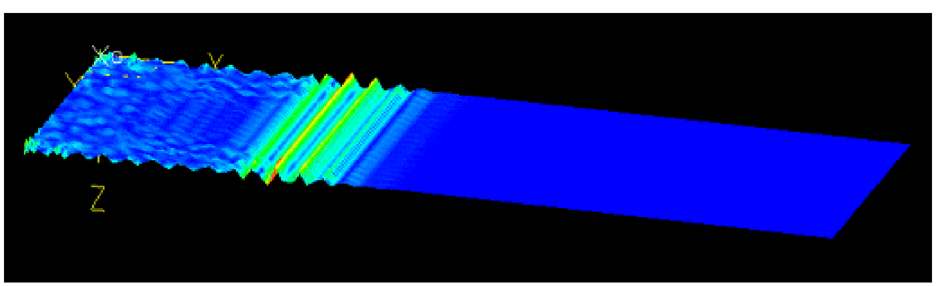
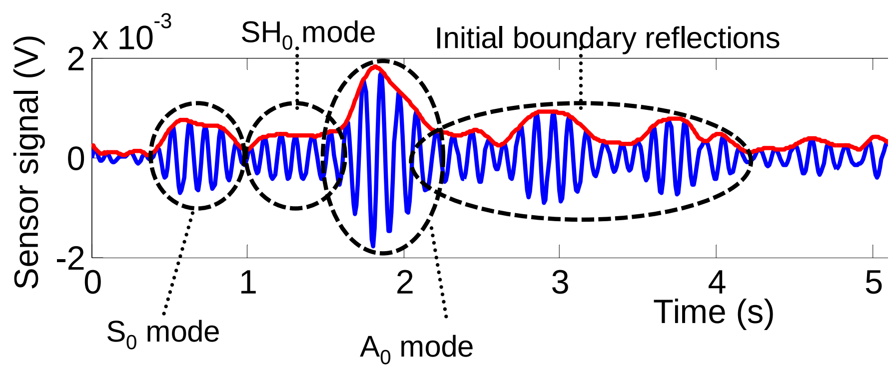
Guided Wave-Based SHM Methods

- Form of elastic perturbation that propagates in a solid medium
  - best damage size & detection range to sensor area ratio
  - sensitivity and range scales with input power level (with limitations)
  - advantages for detecting/characterizing local damage over large areas

- Research utilizes concentric piezoelectric actuator/sensor pairs
  - excitation shape and frequency can be optimized for particular geometry
  - pitch-catch: group velocity $\propto (E/\rho)^{1/2}$, damage slows down waves
  - pulse-echo: reflected wave used to determine damage locations

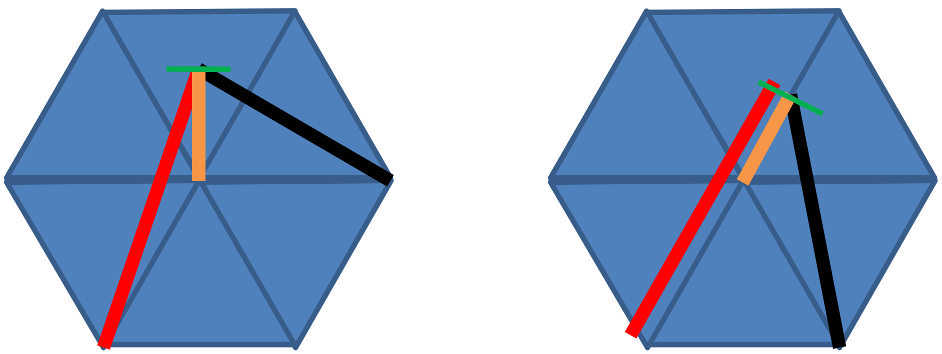




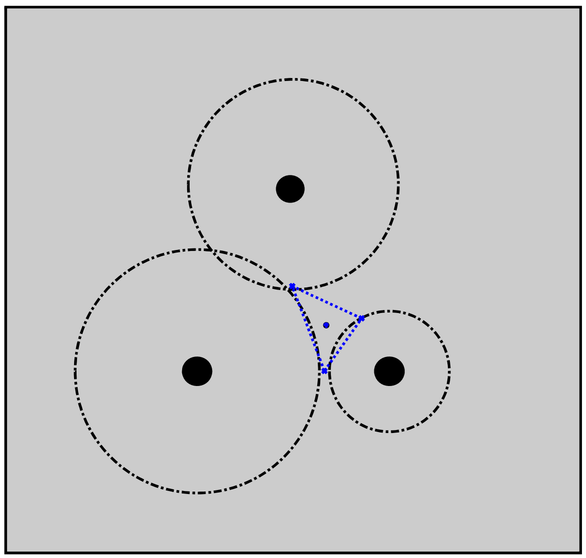
Motivations: Sensor Density

- Traditional methods need high sensor density for good location
  - pitch-catch measures delays and/or scatter along direct sensor line paths
  - pulse-echo determines reflected radius of damage from TOF
  - both cases require at least 3 nodes in close proximity to triangulate
- Prediction resolution scales w/sensor array proximity (density)

Pitch-Catch GW Methods



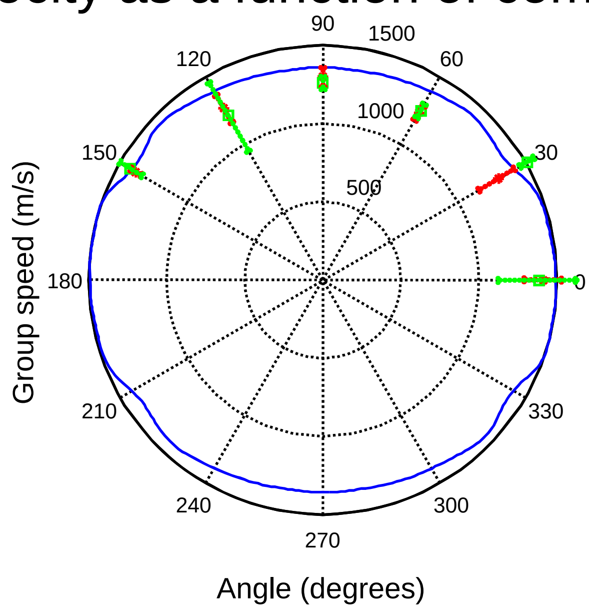
Pulse-Echo GW Methods



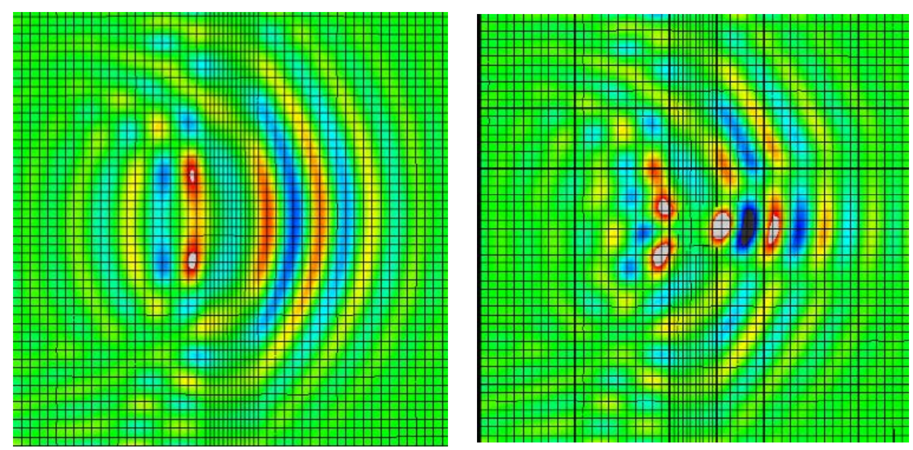
Motivations: Wave Velocity

- Complications arise in non-isotropic/homogeneous applications
  - composite & anisotropic materials present velocity ellipses & stars
  - stiffened regions with ribs or doublers exhibit local acceleration of wave
  - tapered or ply-drop-off regions yield continuously changing velocity
- Prediction resolution scales w/accuracy of wave velocity as f(θ)

Velocity as a function of composite θ

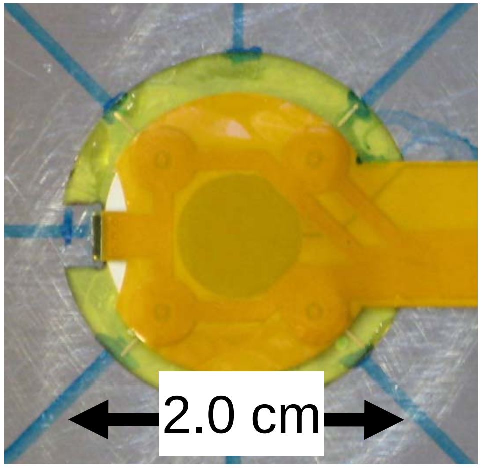


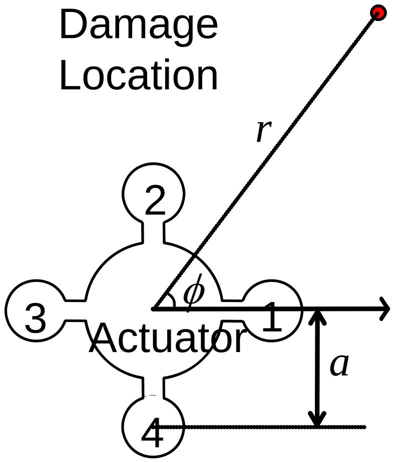
Wave acceleration through ribs



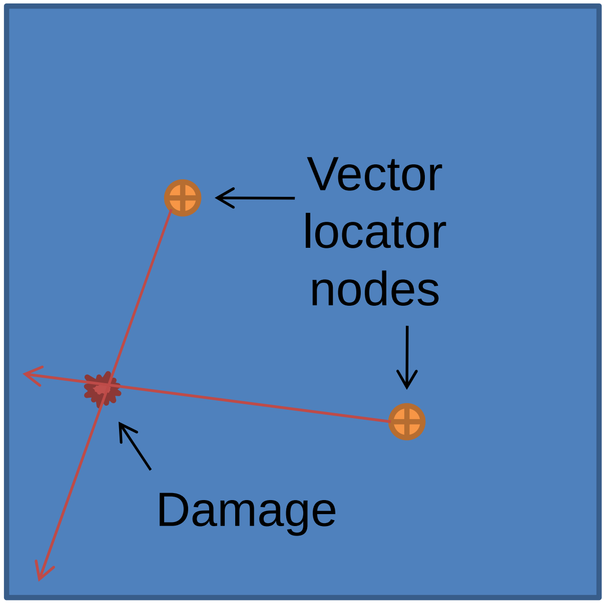
Damage Vector Locator™

- New method devised to resolve motivating issues
  - U.S. Patent No's 7,533,578 & 7,469,595
  - novel sensor coupled with innovative algorithm
- Single practical solution for real structures
  - high detection resolution with reduced minimized sensor density
  - velocity independence to locate damage in complex configurations





Method Description



- Method predicts damage location without structural details
  - vector from 1 node to damage location if velocity "$V_g(\theta)$" is known
  - rays from 2 nodes intersect to identify unique location without velocity
  - 3rd node provides triple redundancy by virtue of ray combinations
- Effective for both guided waves & acoustic emission
  - actively this method uses guided waves to seek out damage position
  - passively this method uses acoustic emission to indicate impact location

Theory & Algorithm

- Structure is excited omni-directionally by PZT actuator
  - 4 co-located concentric sensor elements measure reflection
  - results are plotted in cylindrical coodinates as a function of time
- Incident angle is determined by slight differences in phase
  - method relies on fast acquisition to resolve differences
  - multiple levels of peak-detection required (interpolation, oversampling)

$$\begin{aligned}\phi &= \operatorname{atan2}\left(t_4 - t_2, t_3 - t_1\right) \quad \text{if } \left|t_4 - t_2\right| \geq \left|t_3 - t_1\right| \\ &= \operatorname{atan2}\left(t_3 - t_1, t_2 - t_4\right) - \pi/2 \quad \text{otherwise}\end{aligned}$$

- Distance to damage determined by TOF or vector intersection

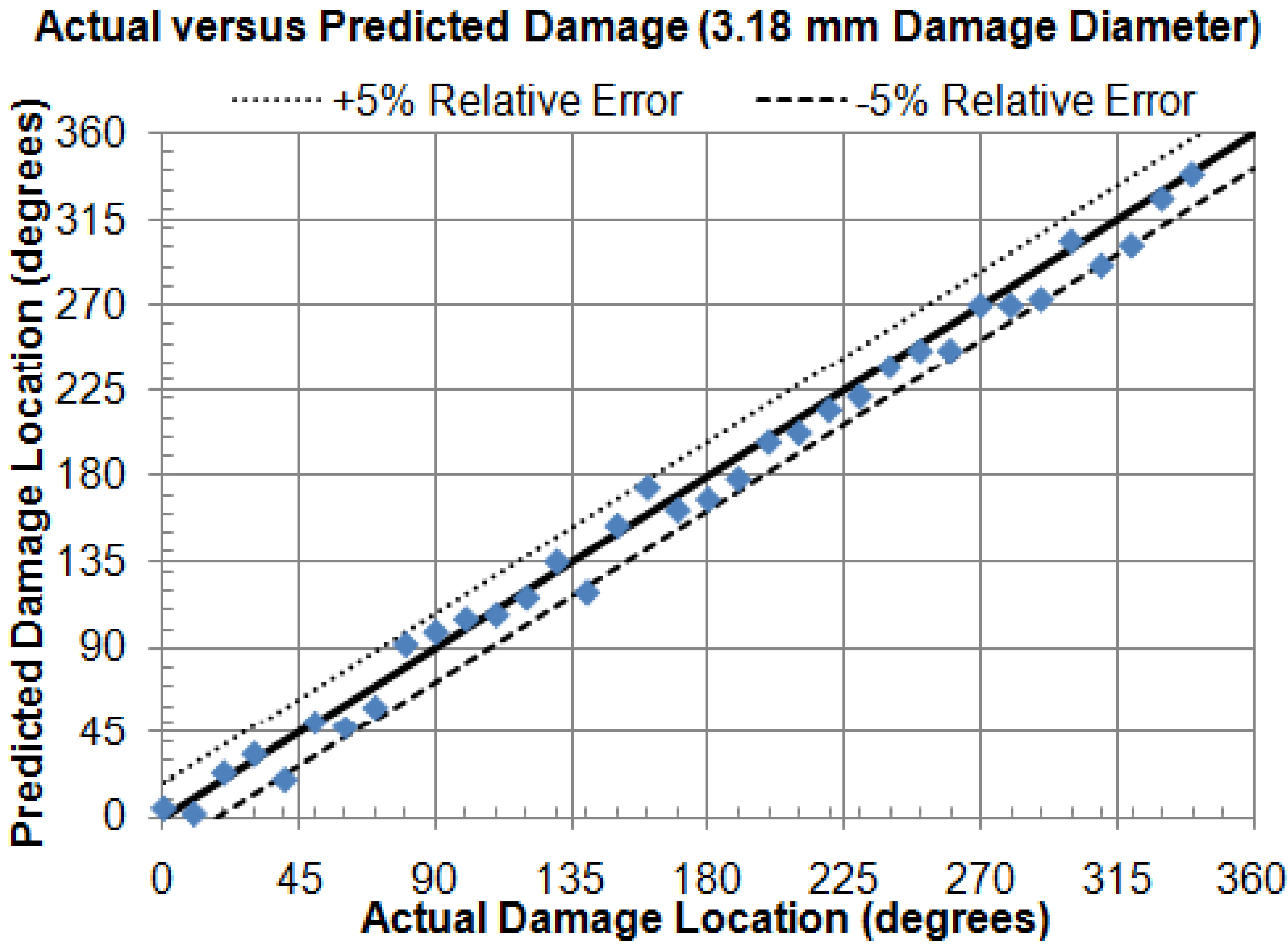
$$r = 0.5 c_g \left(\frac{t_1 + t_2 + t_3 + t_4}{4} - t_a \right) \text{ isotropic}$$

Single-Node Validation Tests

- Damage Vector Locator™ setup
  - PZT device laser fabricated & selectively electroded
  - geometry optimized for A_0 Lamb wave (fundamental antisymmetric)
  - 90 kHz 3.5-cycle toneburst signal modulated by a Hanning window
  - synchronously sampling 10 MHz data acquisition channels

- Test setup
  - 0.9 m square 3.2 mm thick 6061 aluminum plate (isotropic)
  - small magnets used to simulate "inverse" damage (increased stiffness)
  - 3 damage sizes: 3.2 mm, 6.4 mm and 12.7 mm diameter
  - 36 data collection points (10° increments) located around a 0.5 m circle

Experimental Results (3.18 mm)



Experimental Results (6.35 mm)

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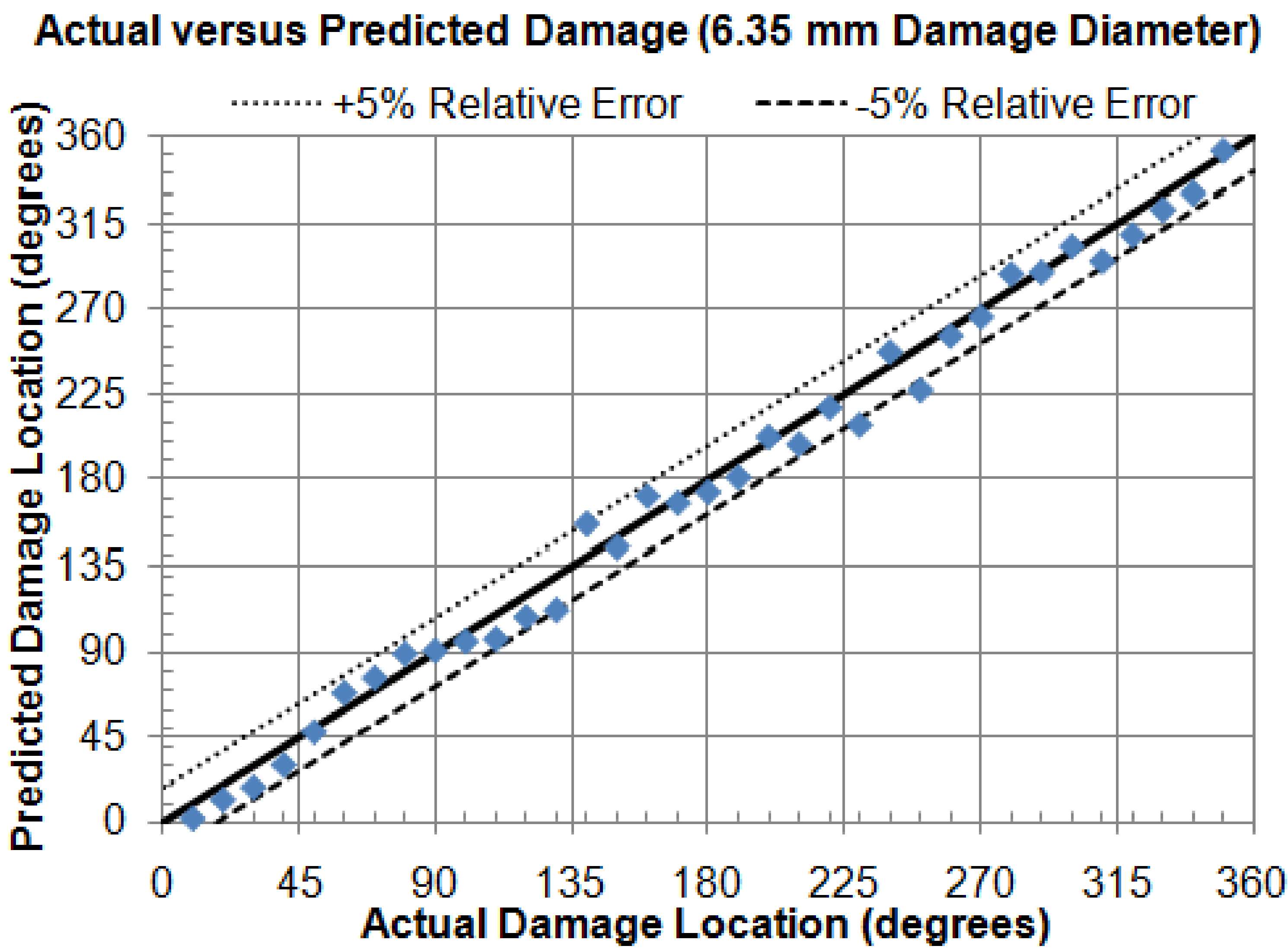
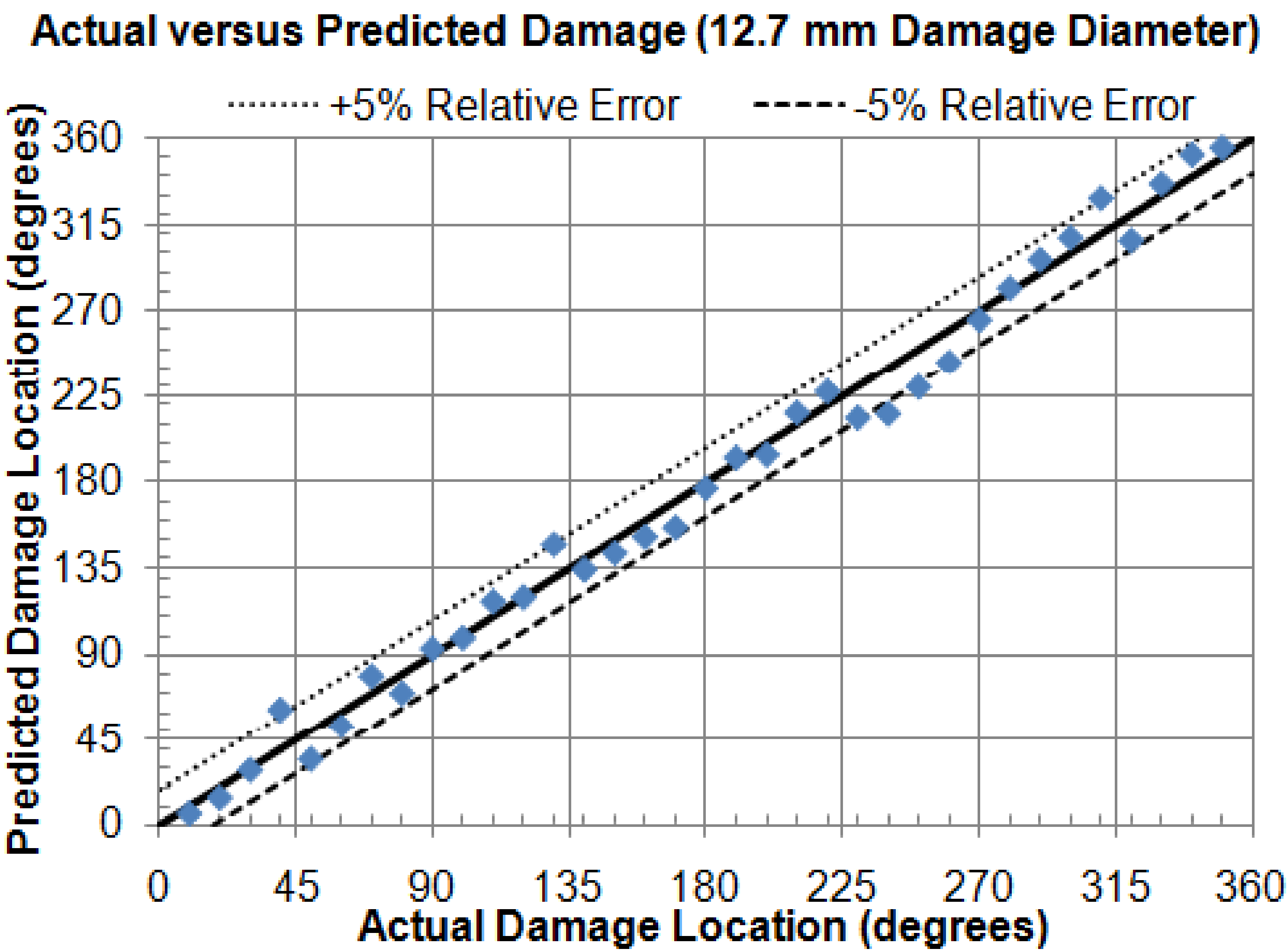
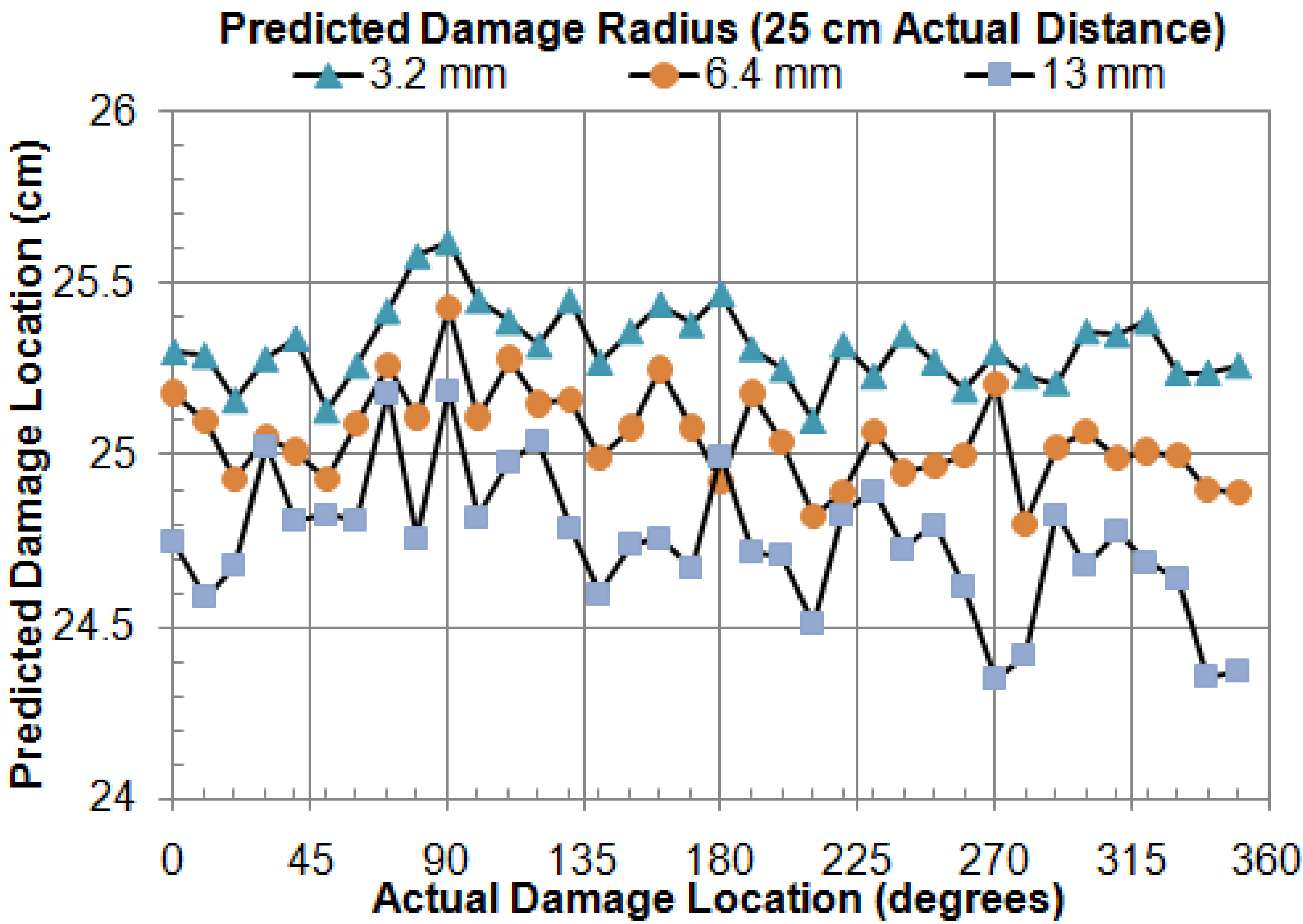


Experimental Results (12.7 mm)



Experimental Distance Results



Angular Position Error

- Overall average absolute angular error was 2.4% (8.6°)
  - highest error occurred at odd multiples of 45°
  - lowest error occurred at multiples of 90°
- Slight dependency on size, error increases with larger damage

Damage (mm)	Maximum (degrees)	Maximum (%)	Average (degrees)	Average (%)
3.18	21.1	5.9%	8.6	2.4%
6.35	22.9	6.4%	8.2	2.3%
12.7	24.3	6.8%	9.1	2.5%

Radial Position Error

- Overall average radial error was 0.9% (2.4 mm)
  - no apparent angular dependency
  - no apparent damage size dependency in the absolute sense
  - algorithm tended to under-predict distance as damage size increased

- Results obtained using isotropic aluminum wavespeed

Damage (mm)	Maximum (mm)	Max. Error (%)	Avg. Error (mm)	Avg. Error (%)
3.18	6.2	2.5%	3.2	1.3%
6.35	4.3	1.7%	1.1	0.4%
12.7	6.5	2.6%	2.8	1.1%

Single-Node Validation Discussion

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- Reconciling average methodology error
  - 2 cm diameter SHM node on a 0.5 m diameter circular area (1963.5 cm^2)
  - locate damage as small as 8 mm^2 with an area of uncertainty of <1.0 cm^2

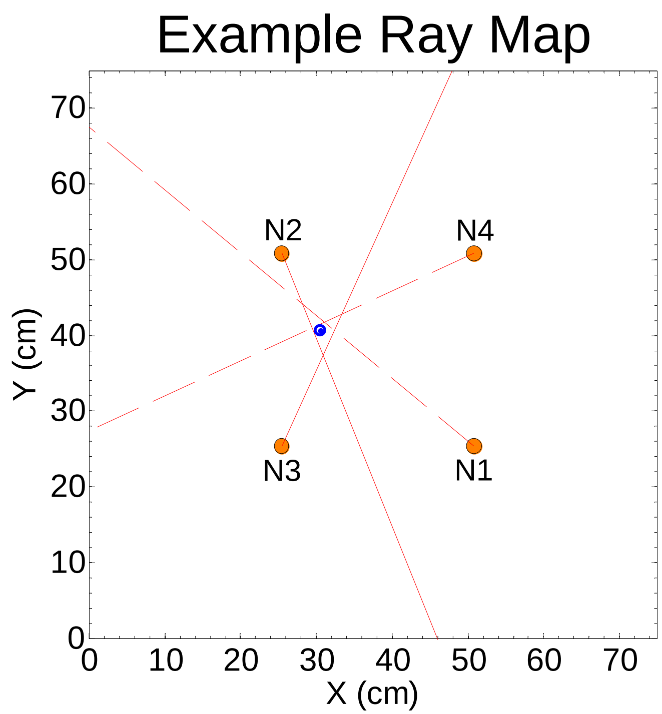
- Provides a path to reliable & efficient damage location detection
  - greatly reduced density & increased accuracy over pitch-catch methods
  - removes velocity dependency of pulse-echo methods
  - eliminates blind-spots & dead-zones produced by phased arrays

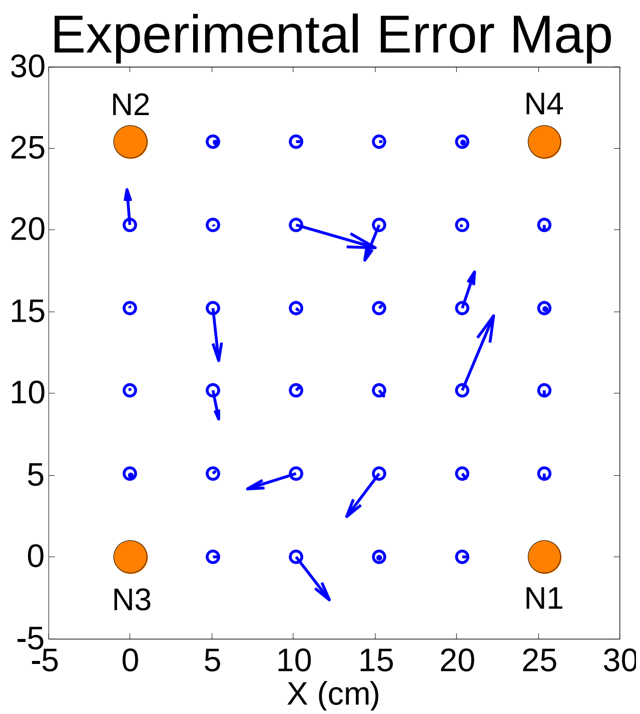
- Following single-node validation of sensor & algorithm, next step was to validate dual-node ray intersection concept

Dual-Node Tests on CFRP

- Composite plate tested w/4 nodes along diagonals
  - 75 x 75 cm graphite/epoxy plate, 2.5 mm thick
  - 6.4 mm damage in 32 locations within 25 cm square w/nodes at corners
  - identical test setup, data collected from each node asynchronously
- No properties were known for laminate (fiber, matrix, layup, etc)

Dual-Node Experimental Results





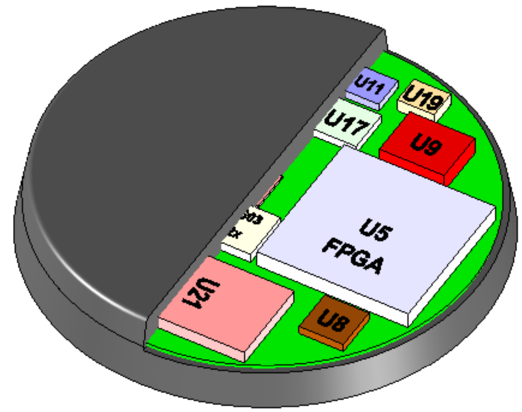
- Data processed in Matlab to produce velocity-independent rays
  - predicted location based on intersection of 2 strongest ray signals
  - error map shows distance between actual position (o) & prediction (↑)
- 32 mm^2 damage reliably located within 625 cm^2 detection zone
  - average positional prediction error was ~1 cm, 5 cm max error
  - 22 predicted locations had < 3 mm positional error

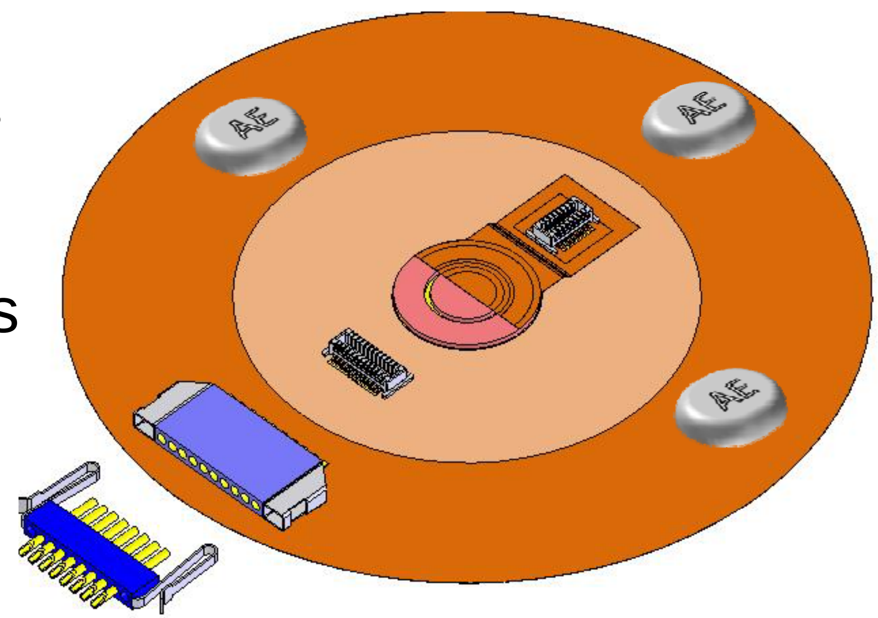
Continuing Research

- SHM improves reliability, safety & readiness @ reduced costs
  - adds weight, power consumption & computational bandwidth
  - analog cable runs introduce EMI susceptibility & signal attenuation
  - scaling SHM for large-area coverage has presented challenges
- Local sensor digitization
  - U.S. Patent No. 7,373,260 & Other Patents Pending
  - convert analog signals into digital data at point-of-measurement (POM)
  - eliminates EMI & attenuation, introduces distributed computation
  - can serially connect sensors on sensor-bus to minimize total cable length

Intelligent SHM Infrastructure

- Intelli-Connector™ HS hardware
  - ARB & oscilloscope replacement
  - 50 MHz 12-bit acquisition (6 channels)
  - 40 MS/s 12-bit excitation (20 Vpp)
  - 1 Gbit buffer & 16 Mbit static memory
  - synchronous to 10ns on CAN bus
  - MIL-810/DO-160 encapsulation
  - 40 mm diameter x 6 mm, 15 g mass
  - can house damage vector locator™
- Facilitates multiple SHM methods
  - guided waves & acoustic emission
  - improves accuracy w/EMI reduction
  - can integrate algorithms in FPGA





Summary

- Proof-of-concept results presented for damage vector locator™
  - novel SHM sensor design & innovative algorithm were developed
  - 1-node system demonstrated on isotropic aluminum plate
  - 4-node system demonstrated on unknown CFRP plate
- Method provides path to reliable & efficient damage location detection for large-scale complex composite structures
  - requires minimum sensor density
  - requires no material properties or structural configuration information
- Future work
  - integrated testing with Intelli-Connector™ HS electronics
  - embed algorithms within FPGA for digital position output
  - couple method with damage characterization algorithms