metis design

mechanical design
composites engineering
structural health monitoring

Experimental Application of Optimized Lamb Wave Actuating/Sensing Patches for Health Monitoring of Composite Structures

Seth S. Kessler and Christopher E. Johnson
Metis Design Corporation

Christopher T. Dunn
Massachusetts Institute of Technology

TELAC

Technology Laboratory for Advanced Composites
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

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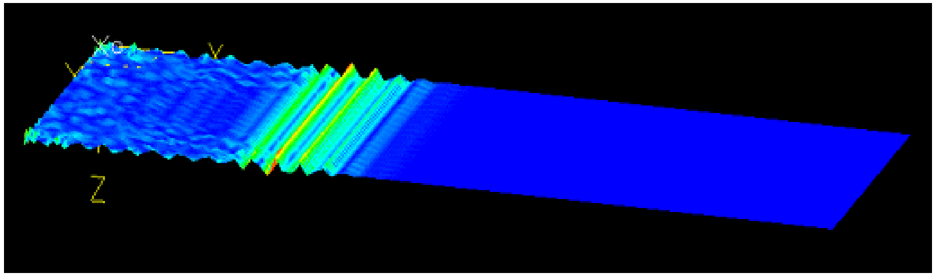
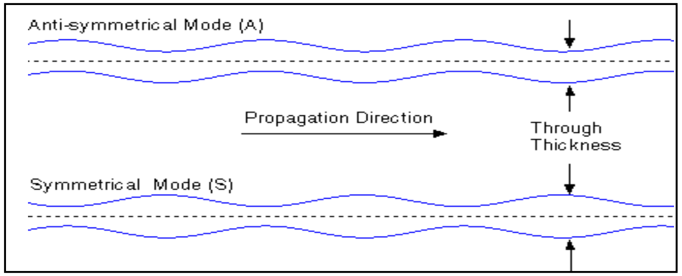
Lamb Wave Methods

- Form of elastic perturbation that propagates in a solid medium
  - actuation parameters determined from governing equations
  - excite A_o wave for long travel distances and to minimize clutter
- Damage can be identified in several ways
  - group velocity approximately $\propto (E/\rho)^{1/2}$, damage slows down waves
  - reflected wave from damage can be used to determine locations
- Present research utilizes piezoelectric actuators and sensors to detect energy present in transmitted and reflected waves

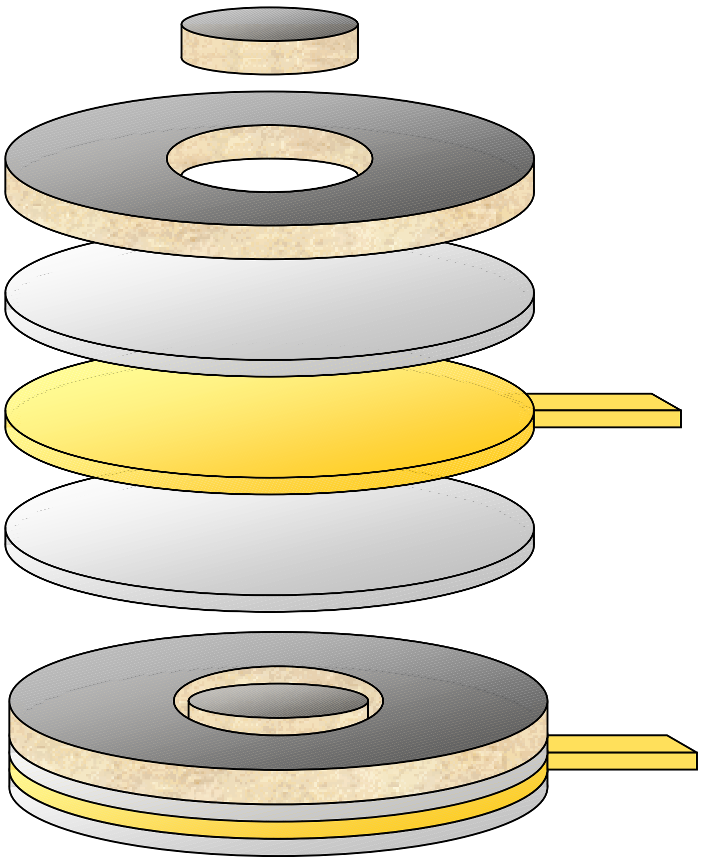




Recent Lamb Wave Research

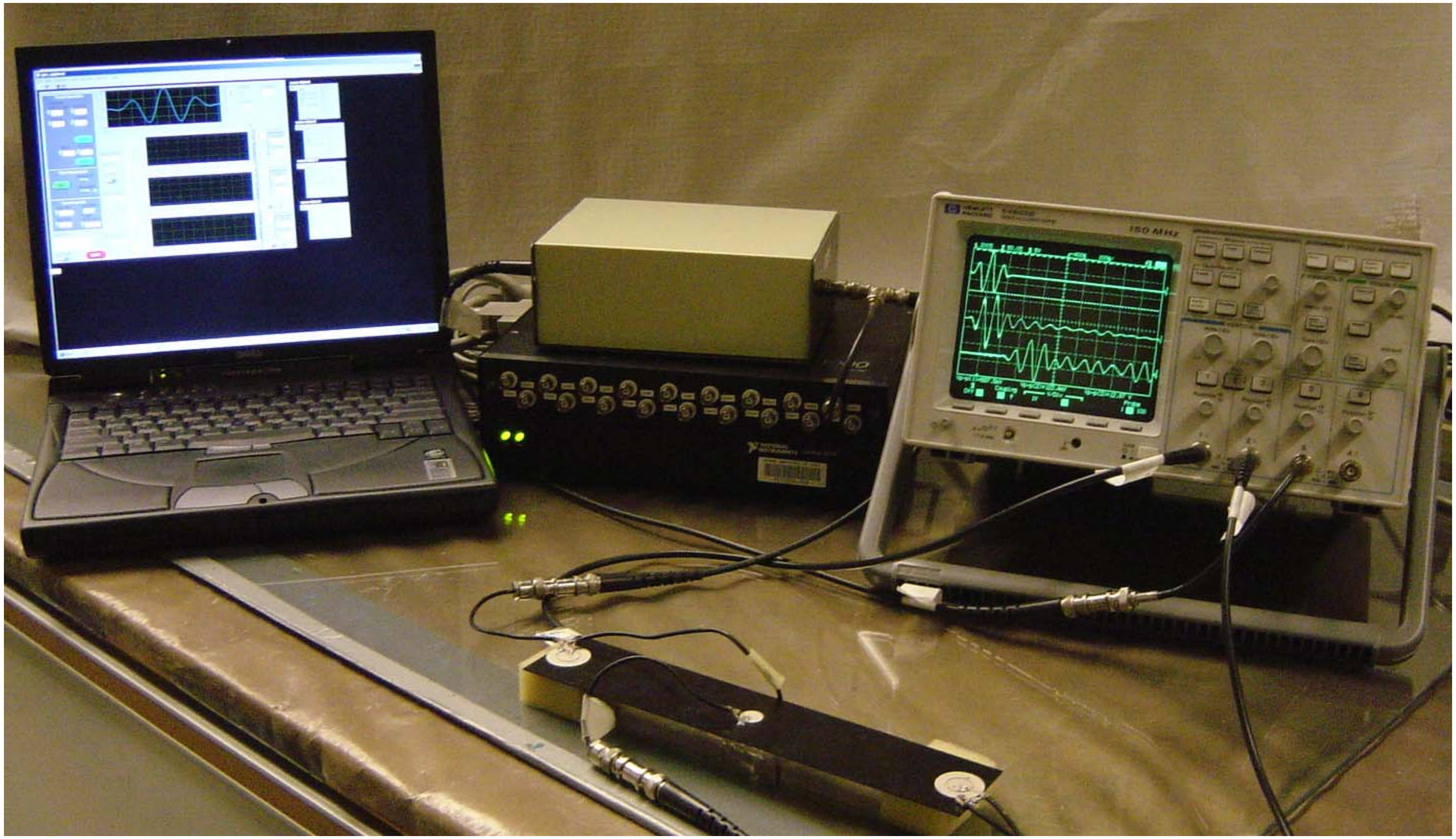
- Optimization of Lamb wave testing procedure
  - selection of best actuating/sensing materials, adhesives, electrodes
  - more efficient actuating/sensing scheme for transmission and reflection
  - increased reliability, robustness and signal strength by 4x
- Algorithm development
  - damage evaluation algorithms in MATLAB using filters and wavelets
  - tuned and validated by a large set of simple test results
  - Current software yields report on presence, location, and type of damage
- Test specimen database
  - testing sensors/algorithms on composite plates with variety of damage
  - testing sensors/algorithms complex sandwich structure specimens
  - observe effects of various core densities and thickness
  - observe effects of disbonds, delams, hardpoints and gaps

Actuator/Sensor Package



- PZT-5A material selected for actuator and sensor material
  - Highest actuating voltage
  - Temperature stability
  - Bandwidth of peaks
- Electrical & mechanical connections
  - 3M 9703 conductive tape (2 mil)
  - Brass Alloy 260 (1 mil)
- Increased signal strength 4x

Lamb Wave Test Setup



- Tests executed via PC laptop and NI data acquisition board
- Completely portable, simple to use and automated results
- HP oscilloscope and function generator have also been used

METIS_v1 Software Decomposition

metis design

```
%Damage detection software executable version 1.0

function metis_v1(y,x);
% (control, test)

% Setup values from user
values

% Initialize variables
init

% Filter and wavelet decomposition
data

% Piecewise max wavelet coefficients and plots
wavecoef
waveplots

% Computing
signalplot
energycompute
arrivalcompute
frequencycompute
reflectioncompute

% Reporting
energyreport
arrivalreport
frequencyreport
reflectionreport
finalreport
```

```
% Filter and wavelet decomposition
data

% Piecewise max wavelet coefficients and plots
wavecoef
waveplots
```

- Data subroutine uses custom Butterworth bandpass filters and truncates data into desired format
- Wavecoef subroutine performs custom wavelet decompositions using modified Morlet mother wavelet
- Waveplots initializes each of the subsequent plot formats
- At this point in the code, all of the useful data has been extracted and "messaged" to be readily analyzed

METIS_v1 Software Computation

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% Computing
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```

- Computation section is the “gut” of software
- Four separate but related physical phenomena used to interpret and compare
  - energy integration
  - wave speeds arrival times
  - frequency spectra
  - reflected wave patterns
- Each subroutine is independent for upgrade
- Share common function to locate wavepeak

METIS_v1 Software Output

METIS_v1 Damage Detection Software Report

Energy Analysis

	Control	Damage	Difference	Ratio
E Near Sensor	30.09	35.53	-5.44	0.85
E Far Sensor	10.95	9.88	1.06	1.11

There appears to be a 18% gain of energy at the near sensor
The structure may be damaged
Far energy losses are nominal. No damage has been detected with energy method

Wave Arrivals

	Control	Damage	Difference
Near Sensor	196.00	197.00	1.00
Far Sensor	529.00	560.00	31.00

Sensor report exceeds damage tolerance. There may be a delamination

Frequency Peaks

	Control	Damage	Difference
Peaks Act	14.00	14.00	0.00
Peaks Near	14.32	13.70	-0.62
Peaks Far	14.65	14.00	-0.65

Tested frequency shift of 0.00 compared to nominal frequency shift of 0.65
Band shift within tolerances.

Wave Reflection Report

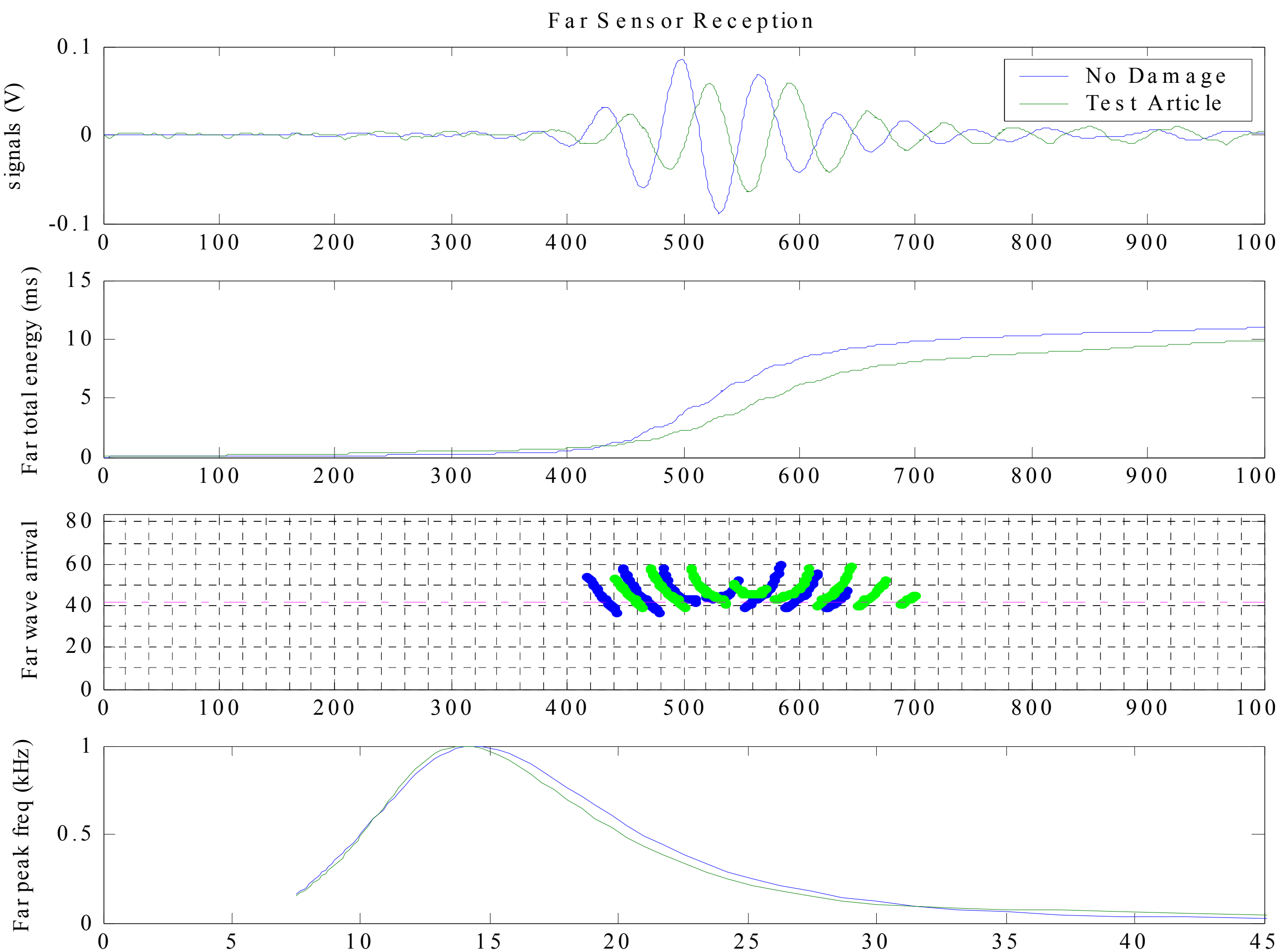
Reflected waves at 510.00 corresponding to 4.75 inches
Waves traveling at a speed of 23810 inches/second

DAMAGE SUMMARY

There may be a delamination at 4.75 inches
Actuator/sensors are functioning properly.

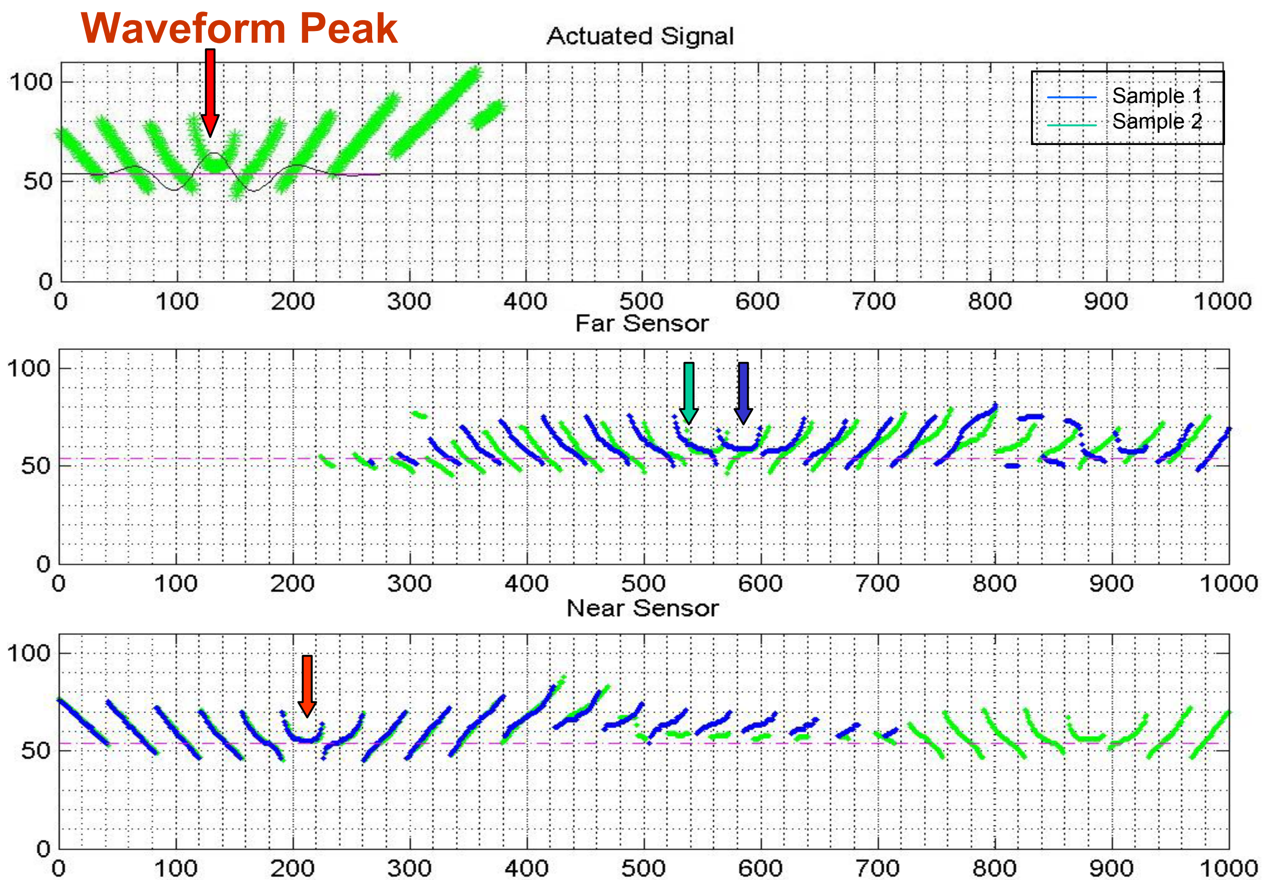
- Text output produced from Reporting section of code
- Reports for each method
  - integrated energy levels
  - wave arrival times
  - frequency bandwidth peaks
  - wave reflection locations
- Damage Summary combines reports to determine damage state
- Self-calibrating, uses wave between actuator and adjacent sensor to calculate wavespeed
- Self-diagnostic, several checks on actuating signal to confirm wafers are functioning properly

Delaminated Results: Far Sensor



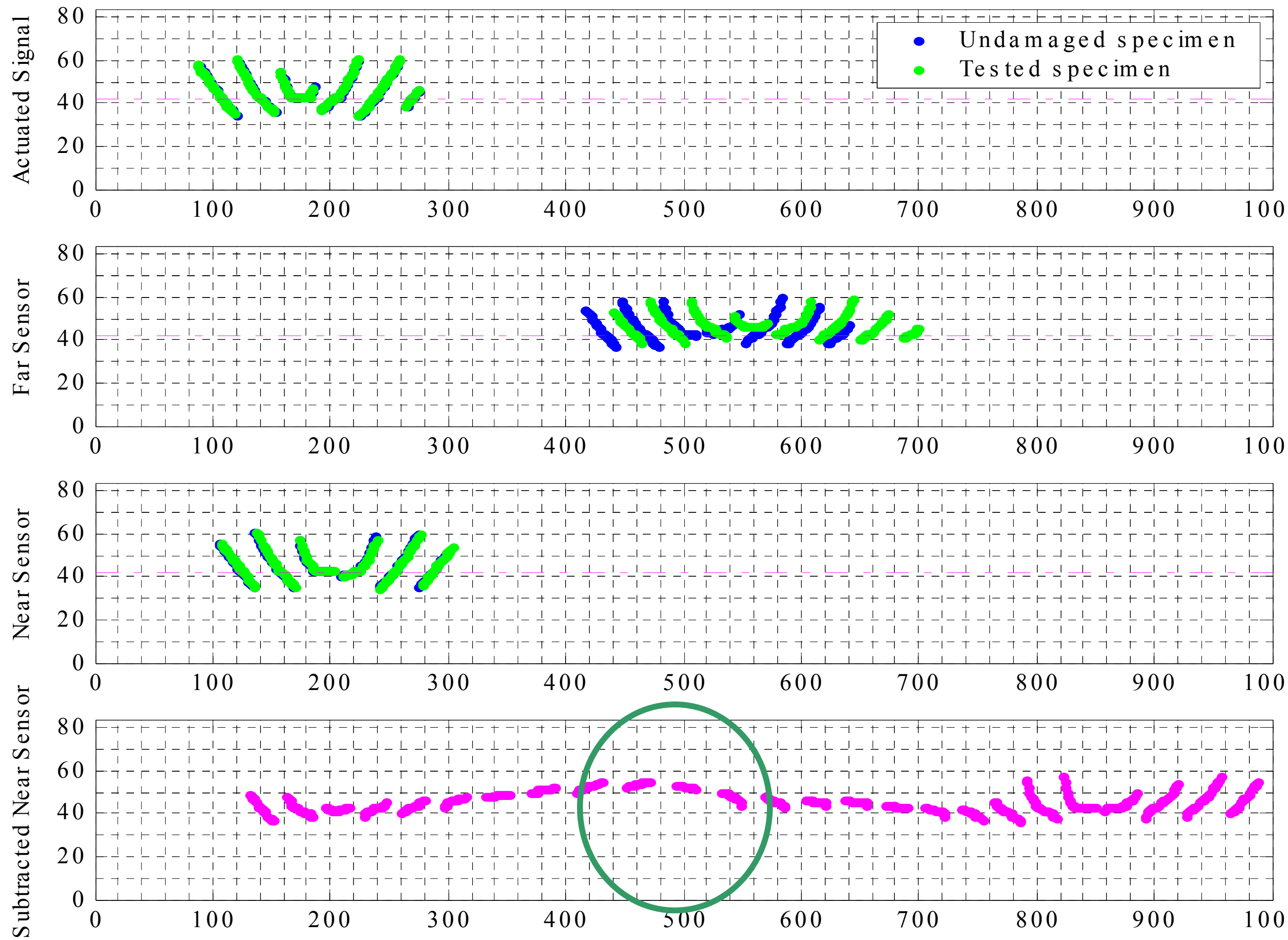
- Delaminated signal is time-lagged, slightly lower energy content
- Frequency bandwidth remains similar

Waterfall Plot Cross Sections



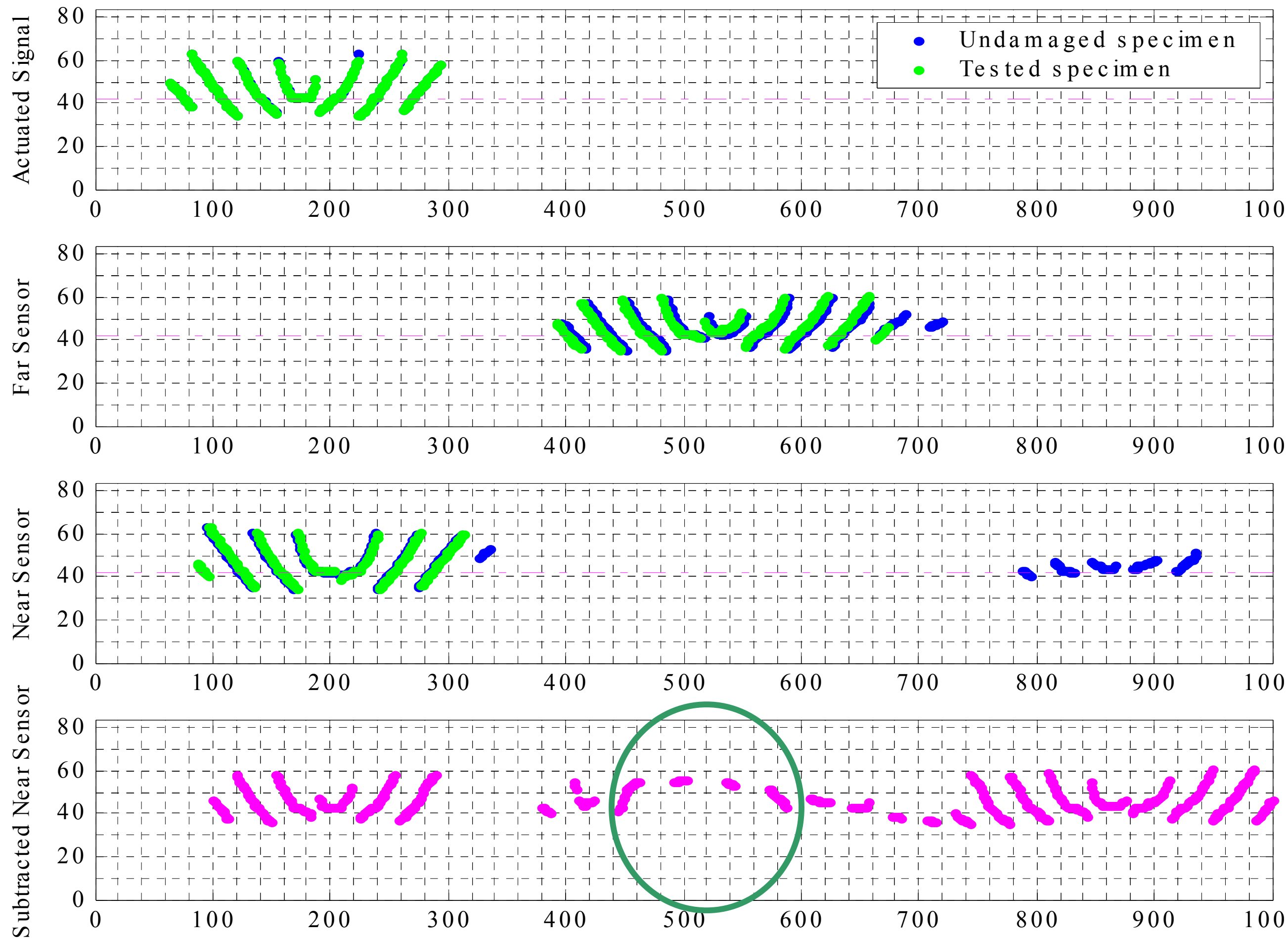
- Plotted for actuating frequency, points represent highest scales
- Troughs represent peak of waveform, threshold used for noise

Coupon w/Delamination Results



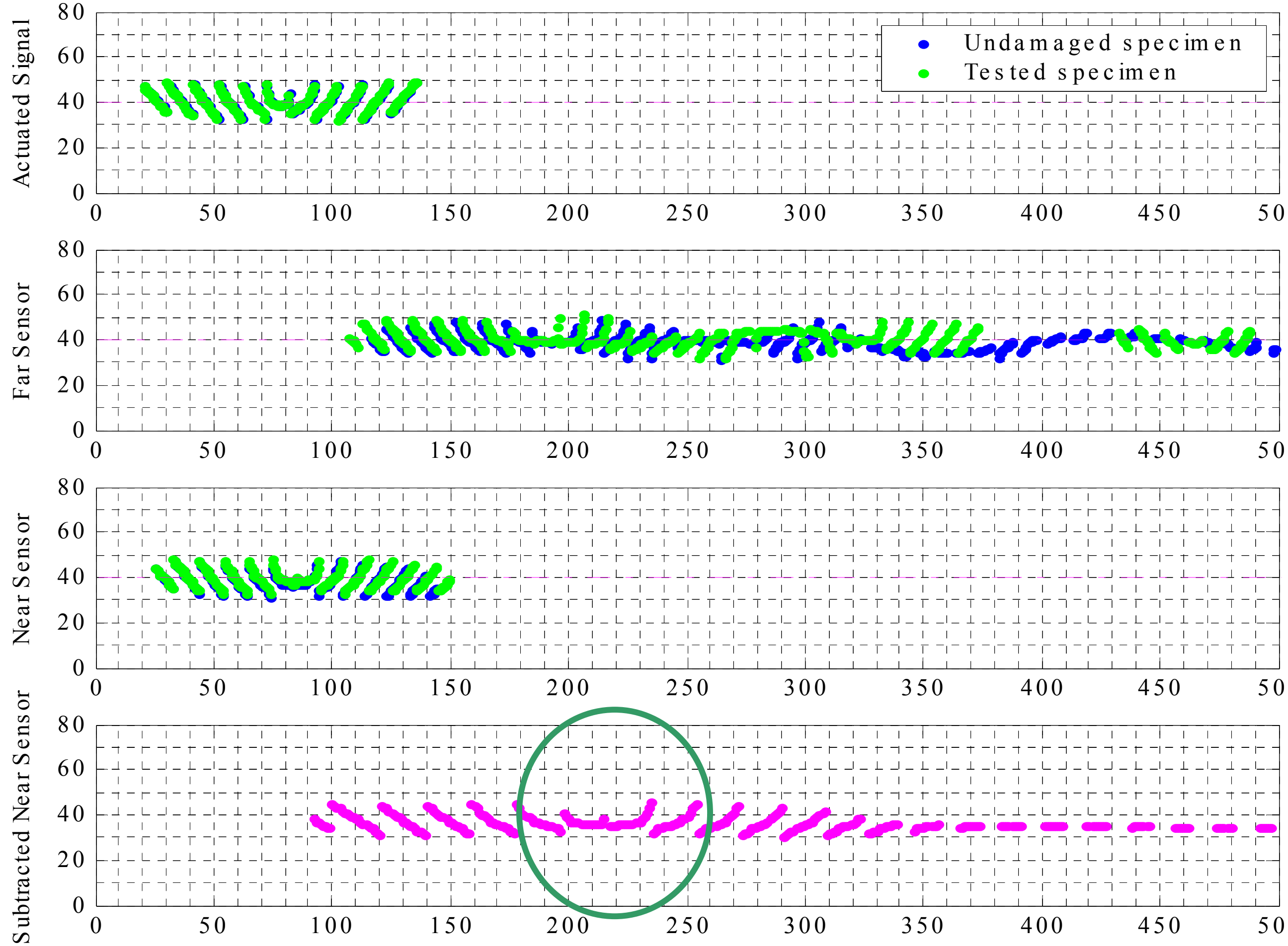
- Reflection revealed at around 510 us (also reflection from end)
- Corresponds to delamination at 4.75” (actual at 4.8”)

Coupon w/Matrix Cracks Results



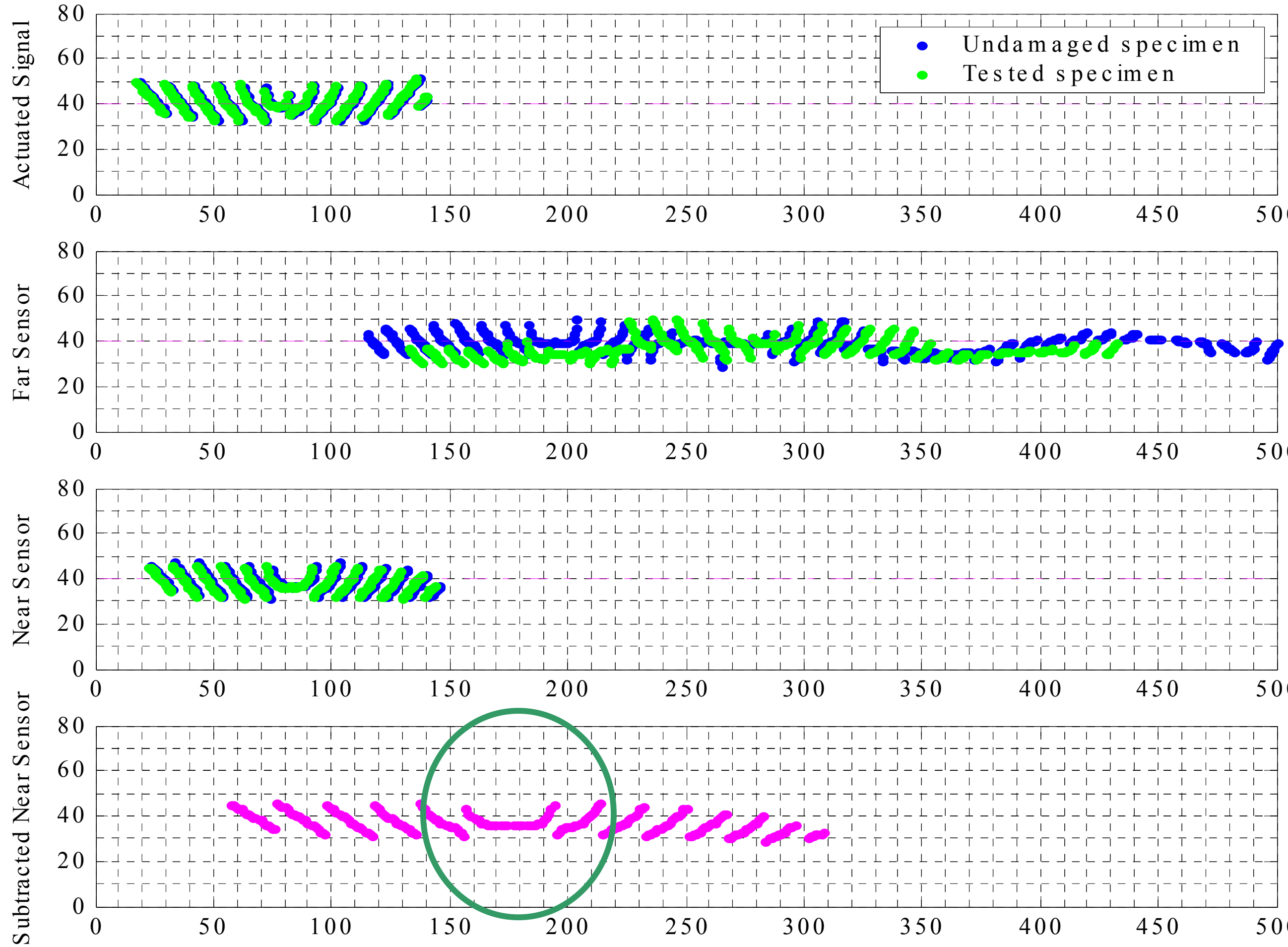
- Reflection revealed at around 493 us (also reflection from end)
- Corresponds to cracking at 4.72” (actual at 4.8”)

HD Al Core w/Disbond Results



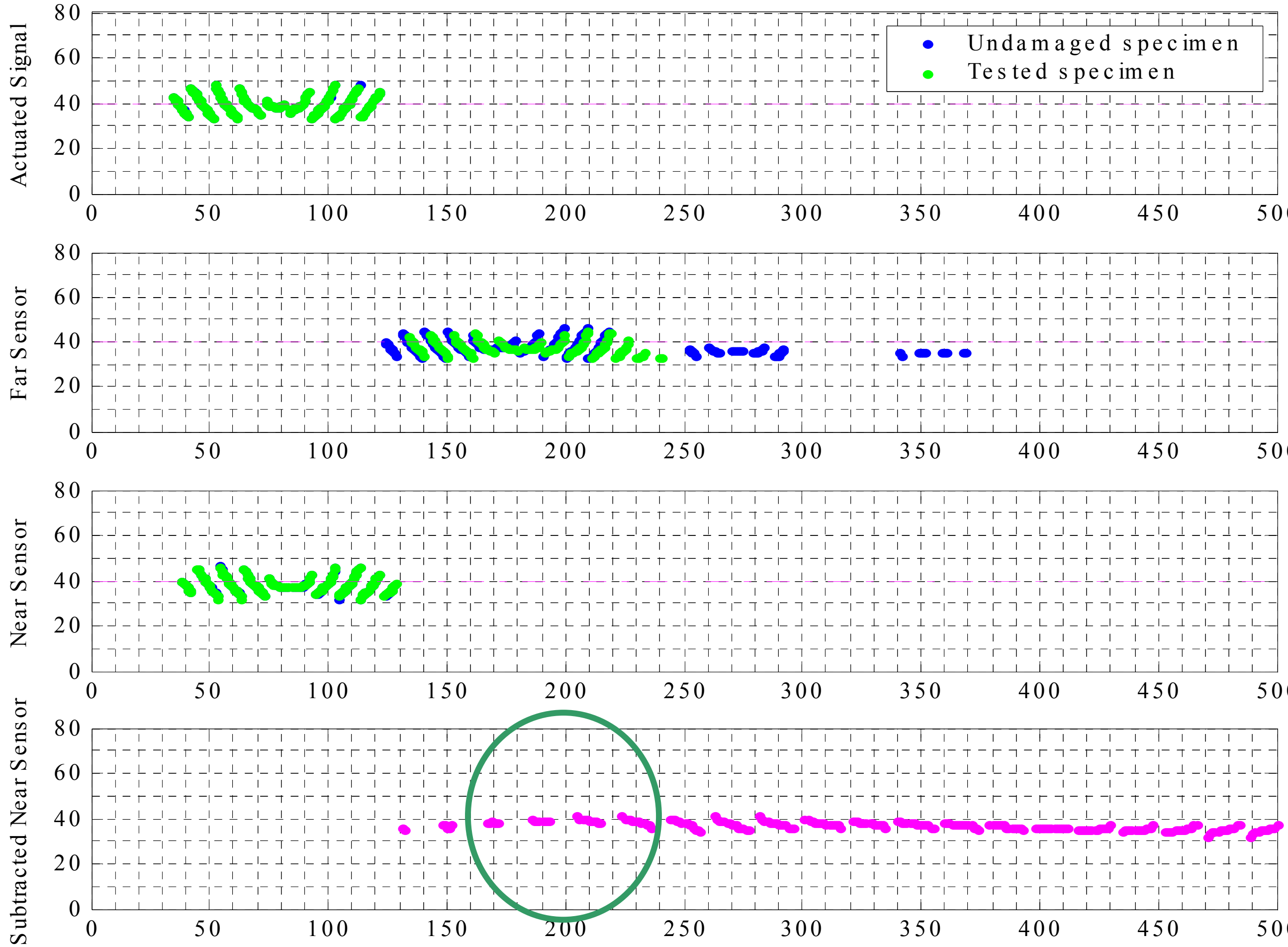
- Reflection revealed at around 238 us
- Corresponds to delamination at 4.76” (actual at 4.75”)

HD Al Core w/Impact Results



- Reflection revealed at around 178 us
- Corresponds to damage at 3.6” (actual center at 4.25”)

Hybrid Core w/Disbond Results



- Reflection revealed at around 202.5 us
- Corresponds to debond at 4.73” (actual at 4.75”)

Lamb Wave Testing Conclusions

- Thin laminates
  - control laminates are very reproducible, used to calibrate thresholds
  - delaminated specimens yield reflections with little change to bandwidth
  - matrix cracks yield frequency changes with some reflections
- Sandwich structures
  - high density Al core specimens easily show disbond and impact damage
  - low density Al core specimens yield similar results, slightly damped
  - Nomex & Rohacell core specimens are further damped
  - solid thick and thin Al core have faster waves speeds, cleanest signals
- Mixed sandwich structures
  - high density Al core with center gap easily differentiated from disbond
  - half high density half solid Al produces wave with reflection at interface
  - half high density half solid Al and disbond can be measured over joint

Recent Research Conclusions

- Optimized Lamb wave actuator/sensors and test configuration
  - increased signal strength nearly a factor of 4 over prior research
  - currently working on packaging to robustness of piezoceramic assembly
- METIS_v1 damage detection software
  - exhibits 83% accuracy, nearly 100% for delamination (over 200 tests)
  - eliminates most subjectivity with automation and thresholds
  - threshold levels used to tune algorithms based on control specimen
- Experimental results
  - several combinations of small and controlled damage still yields measurable effect, the more damage, the more dramatic the results
  - overall highly successful project, able to detect damage in all specimens

Future Research

- Development of a thin-film polymer rechargeable battery
  - matching size and power specifications for an SHM system
  - AFOSR funded project, w/MIT Material Science & Microstrain Inc.
- Study of packaging techniques
  - isolate from harsh natural, mechanical,and electrical environments
  - NSF funded project, w/MIT Aero/Astro department
- Comparison of behavior and reliability of SHM NDE methods
  - different materials (metals, CFRP, GFRP)
  - manufacturing processes (uni-tape, woven fabric, filament wound)
- Increase complexity of tests
  - test on built up section
  - use multiple sensing methods at once to increase reliability
  - integrate multiple SHM components