In-Situ Damage Detection of Composites Structures using Lamb Wave Methods

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SHM Motivations

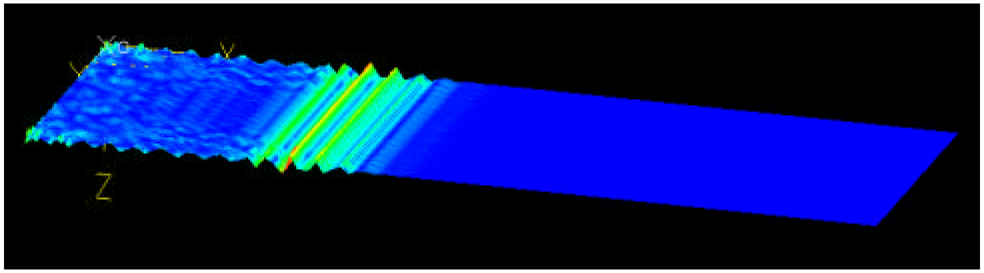
- Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to improve reliability and reduce life-cycle costs

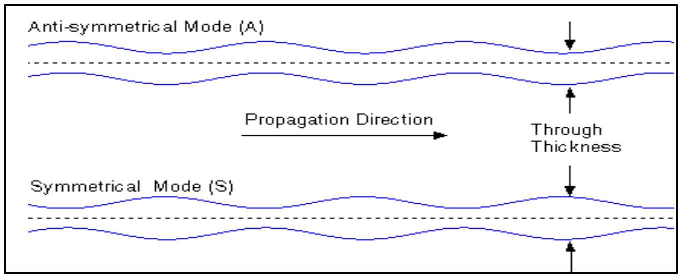
- Inspection and maintenance expenses could be reduced by SHM
  - currently, about 25% of aircraft life cycle cost is spent in inspections
  - commercial airlines spend a combined $10 billion/year on maintenance
  - condition based maintenance could reduces these costs by 33%

- Reliability of damage detection and failure prediction increased
  - much of the airline and military fleet are ageing aircrafts, fatigue issues
  - can catch damage that may have occurred between scheduled intervals
  - most inspection is currently visible, forms of damage can be overlooked

Lamb Wave Methods

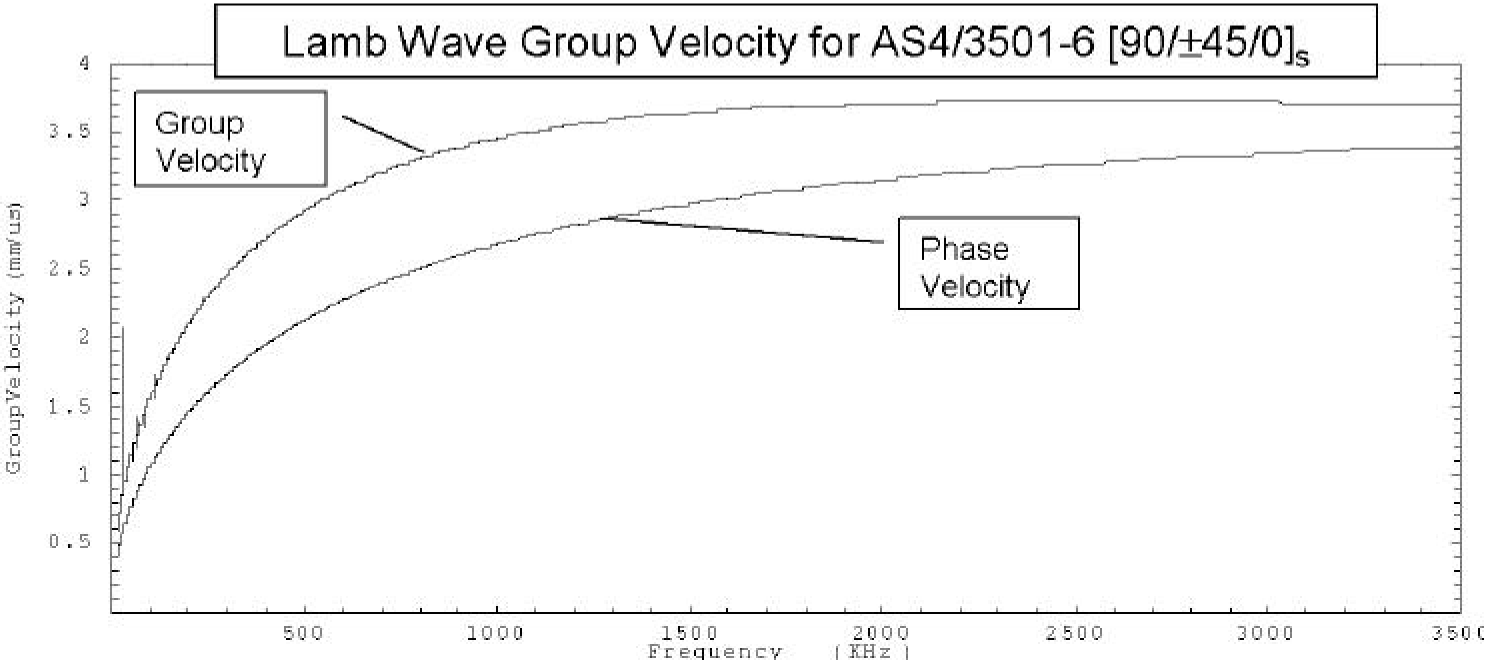
- Form of elastic perturbation that propagates in a solid medium
  - function of elastic constants and density (often use Lamé’s constants)
  - two waves satisfy equation at ? – symmetric and anti-symmetric
- Background work from literature
  - Described by Horace Lamb (1917), developed by GE for NDE in 1960
  - most significant work published by Cawley (2000), detecting damage using interdigitated Lamb wave sensors in complex metallic structures
  - Soutis (2000) demonstrated relationship between delamination area and time of flight shifts using piezo sensors in a composite laminate
- Present work uses piezo sensors in pulse-transmission mode to detect energy present at driving frequency, some self-sensing work





Damage Detection using Lamb Waves

- Dispersion curves are the best way to describe Lamb waves
  - phase or group velocity versus frequency thickness product
  - can use to select actuating frequency and predict attenuation behavior
- Damage can be identified in several ways
  - group velocity approximately ? $(E/?)^{1/2}$, damage slows down waves
  - reflected wave from damage can be used to determine locations



Frequency Selection

- Collect material properties and representative geometry
- From E, ?, ?, t plot phase velocity and group velocity curves (use corrections to derivations from literature of group velocity calcs)
- Want to choose $dc_g/dw=0$ (nearly constant group velocity)
  - for A_o mode phase velocity travels as $w^{\frac{1}{2}}$ and begins $c_g=2c_p$ and tends to Rayleigh velocity, so $c_g=c_r$ is the optimal value
  - Often A_1 will occur at a frequency below c_g, so choose highest value within 10% of A_1
- Must also take into account actuator and data acquisition capabilities in choosing highest frequency
- Lastly, structural natural frequencies play a small role in sinusoidally amplifying the signal, from FEM can choose particular operating frequency to coincide with normal mode

Pulse Shape Selection

- Signal shape
  - sinusoidal waves works much better than anything else
  - Hanning window helps to minimize spillover frequencies
  - induced strain on PZT resulting from waves is at a magnitude of about 1/250 of actuating voltage

- Number of periods
  - probably most complicated decision in specifying system
  - more pulses yield a narrower bandwidth of frequencies actuated
  - too many pulses can cover damage signal if close to sensor
  - since specimens for this experiment were short, 3.5 cycles used

Actuator Dimensions

- Actuator Length (2a)
  - once operating frequency is selected and phase velocity is calculated the optimal actuator lengths can be specified
  - amplitude sinusoidally amplified with maximum at $2a=?(n+{}^{1}/_{2})$ where ? is the wavelength and $n=0,1,2,3\ldots$

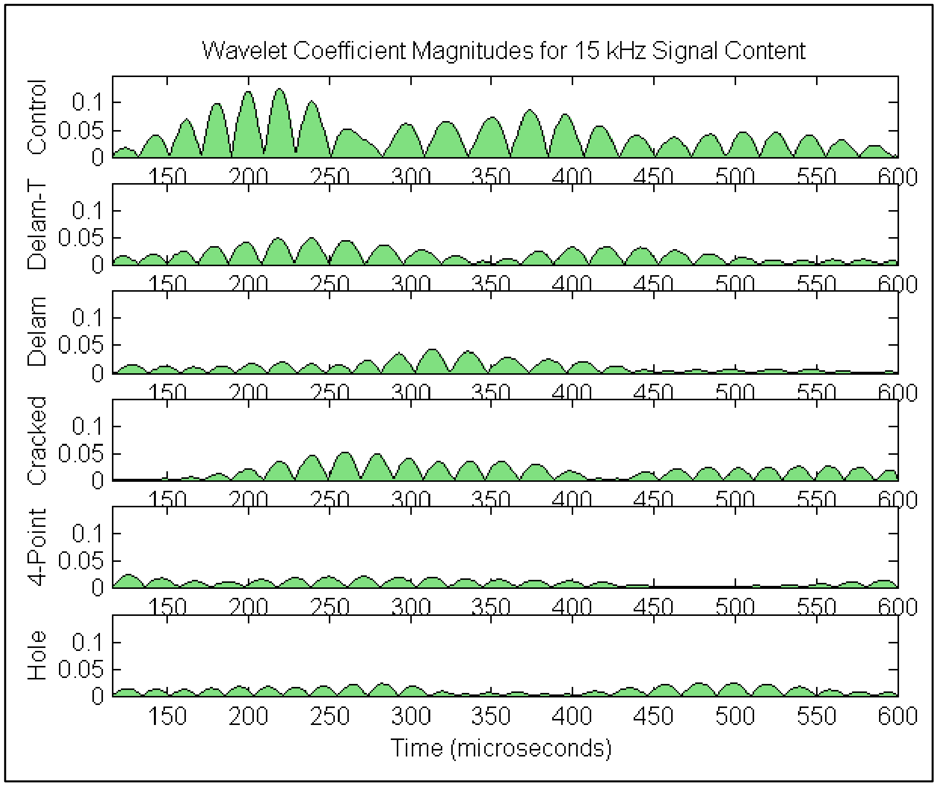
- Large actuator width yields more uniform wavefront
  - can design as a minimum from the above equation to suppress propagation in off-axis direction
  - for circular actuators, diameter=2a

Lamb Wave Limitations

- Dispersion is the change in slope of the phase velocity curve
  - curved sections experience higher dispersion, especially at lower frequencies
  - anisotropy typically yields more dispersion
  - discontinuities and damage causes increased dispersion as well

- Attenuation is the loss factor in displacement amplitude in the propagating wave
  - generally follows $A=1/KL$
  - thicker specimens tend to Rayleigh value of $1/(KL)^{1/2}$
  - higher dispersion causes increased attenuation
  - fluids have a significant effect on the attenuation of S modes, but an insignificant effect of the A modes

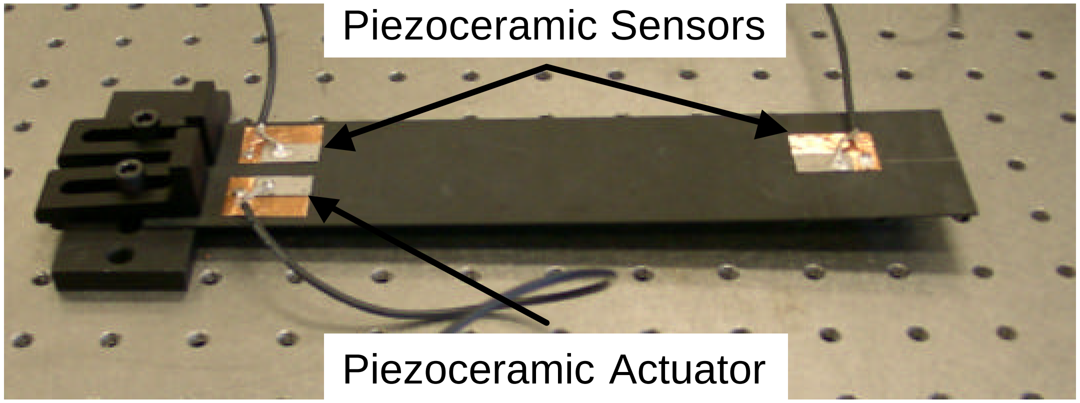
Wavelet Analysis



- Wavelet decomposition performed using Morlet signal
  - select mother wavelet
  - scale and shift using basis
- Found in 1910, complex algorithms not until 1988
- Compare received signal's energy content at dominant frequency
- More efficient than FFT because closer signal shape
- In practice use discrete wavelet decomposition in software, since often there is no closed form solution for continuous equality

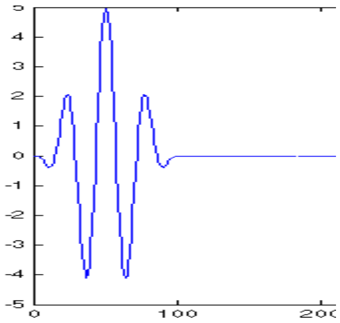
Parameter Optimization

- Actuation parameters determined from governing equations
  - from material properties dispersion curves are calculated
  - from group velocity dispersion curve, operating frequency selected
  - from operating wavelength, actuator size is selected
  - number of pulses to be sent determined by distance between features
- Excite A_o wave for long travel distances and to minimize clutter
- Experimental procedure for present work used these equations
  - frequencies between 15-50 kHz
  - utilizes 3.5 sine waves under a Hanning window



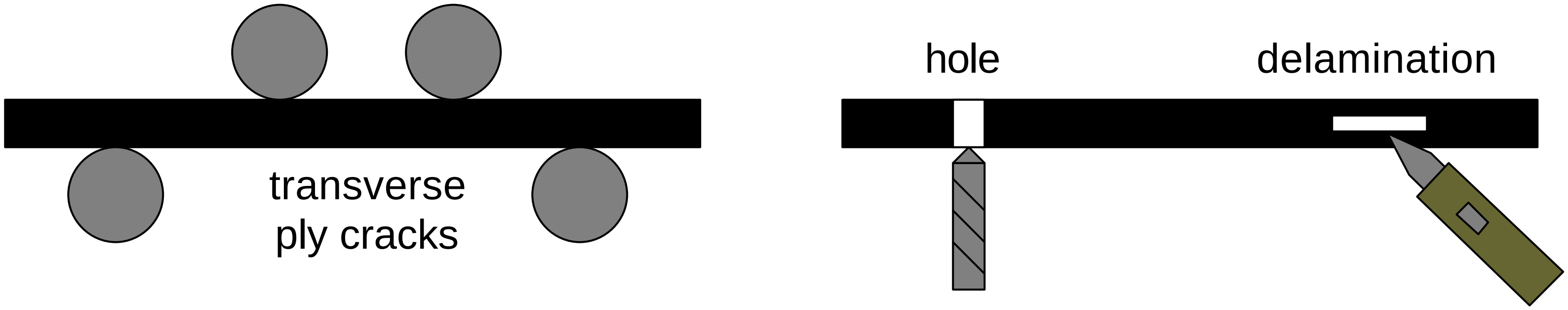
Piezoceramic Sensors

Piezoceramic Actuator



Sent Signal

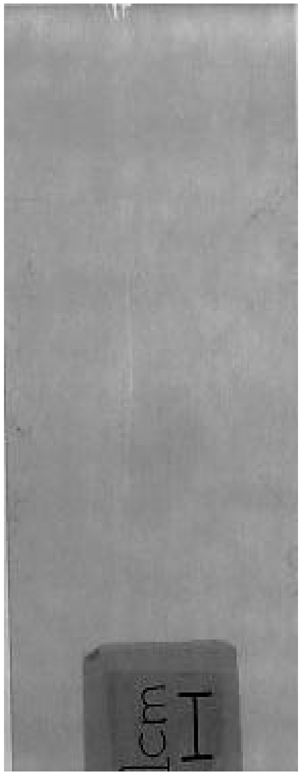
Representative Damaged Coupons



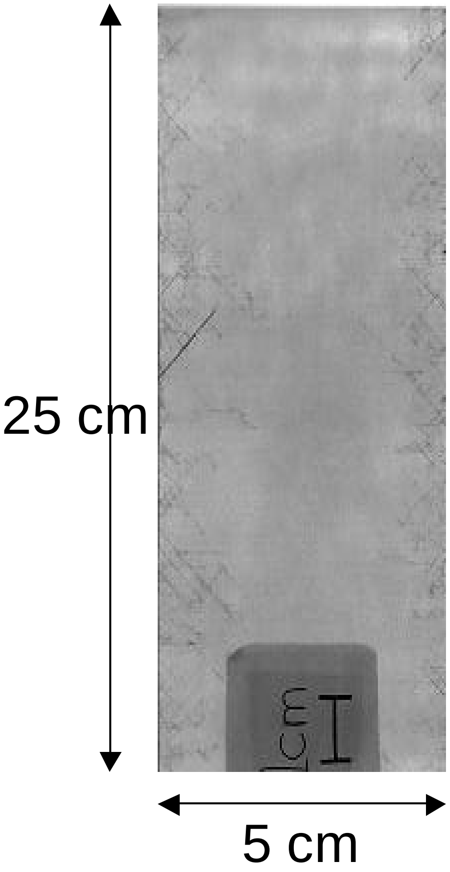
- AS4/3501-6 quasi-isotropic $[90/?45/0]_s$ laminates
- Introduced representative damage to composite specimens
  - delamination — 2.5 cm cut w/utility knife, or Teflon strip in middle
  - transverse ply cracks — 4-pt fatigue on center of specimen
  - fiber fracture — 4-pt bend until audible damage
  - stress concentration — drilled hole through specimen
  - impact — hammer struck against steel plate in center of sample
- Radiographs taken to verify damage

X-Ray Damage Verification

Control
Specimen

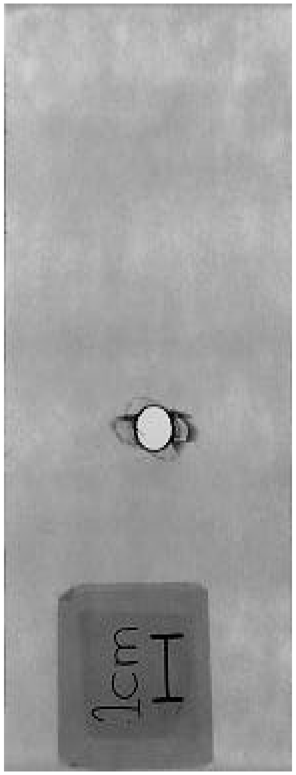


Matrix Crack
Specimen

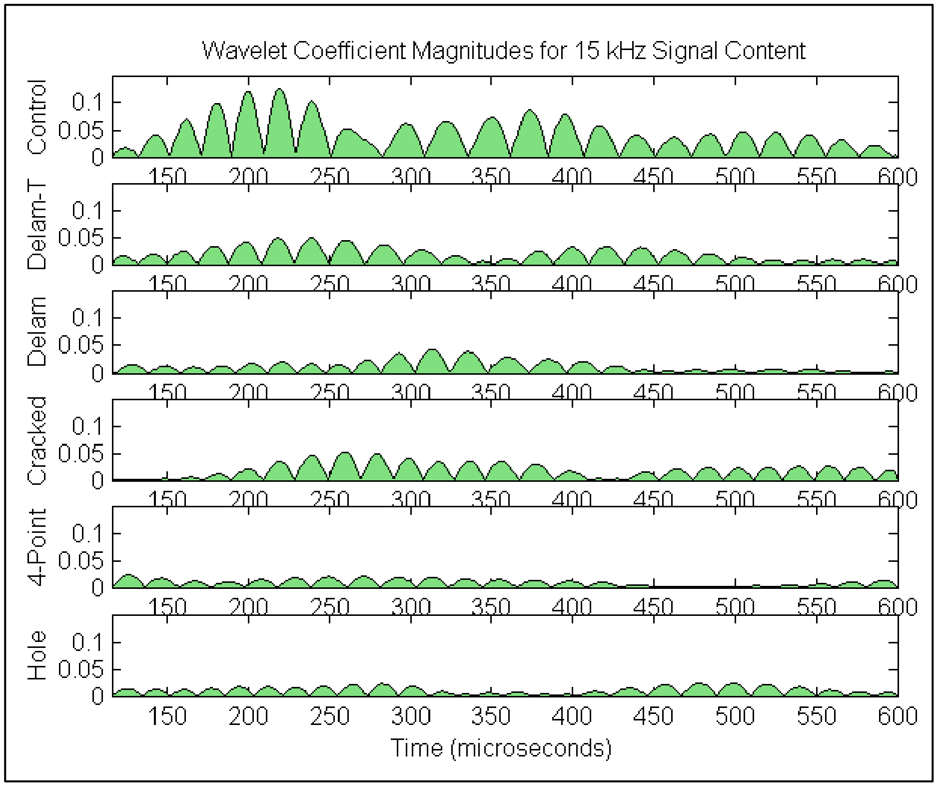


Delamination
Specimen

Core Drilled
Specimen



Thin Laminate Results

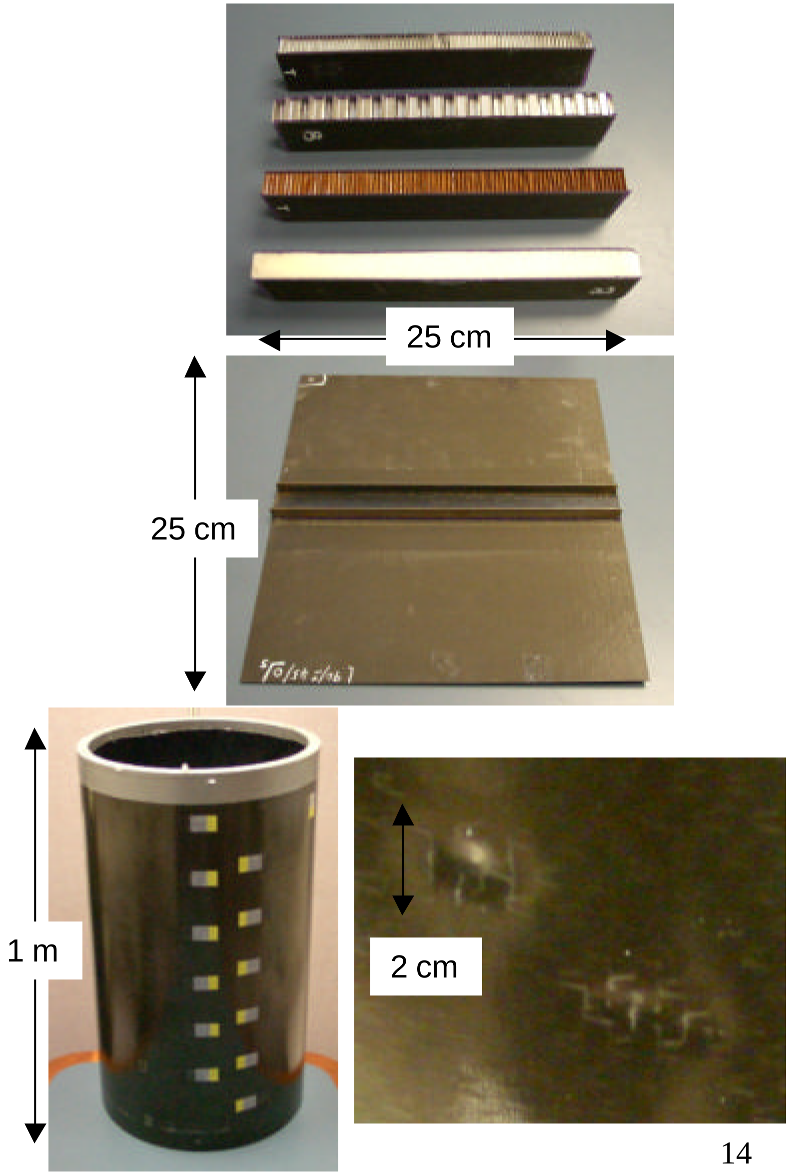


- Wavelet plots from PZT sensor 20 cm from actuator driving at 15 kHz
- Control specimen clearly has the most energy transmitted
- Appears that as damage becomes more severe, more energy is lost
- Differences seem obvious enough for process to be automated
- High degree of consistency between all control traces
- All damaged traces show a delay in time of arrival

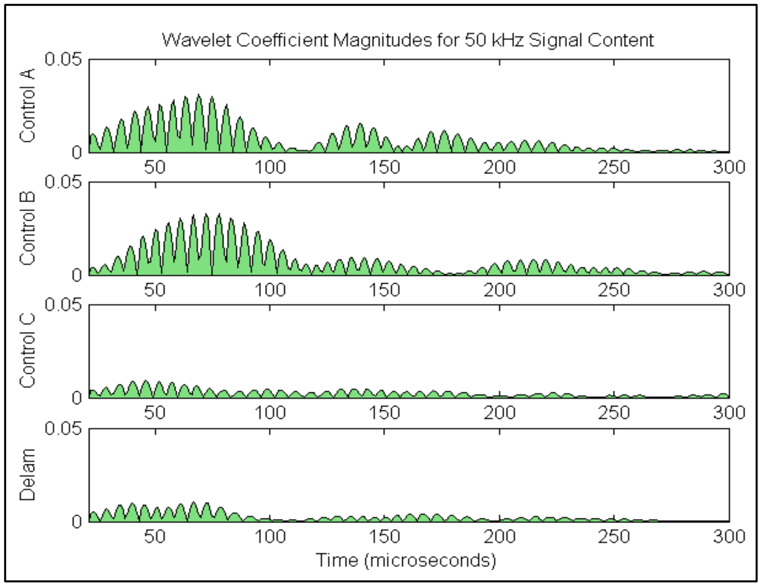
Demonstrates ability to detect presence of damage and judge extent

Building Block Approach

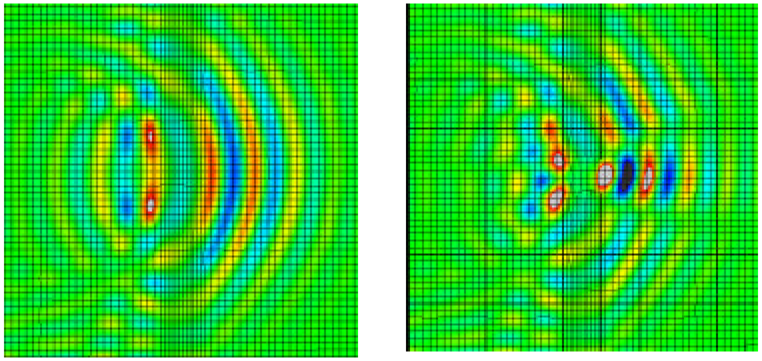
- Narrow coupon laminates
  - same specimen used for FRM
  - several types of damage
- Narrow sandwich beams
  - various types of cores tested
  - disbonds between laminate and core
- Stiffened plate
  - various types of bonded ribs
  - disbonds between laminate and rib
- Composite sandwich cylinder
  - 0.4m diameter cylinder with core
  - low velocity impacted region



Damage Detection Results



- Wavelet coefficient plot for beam “blind test” compares energy content for 50 kHz
- Three “control” specimens with Al core, one has an unknown delamination
- Compared to a damaged specimen
- Top two clearly have more energy
- Bottom two with little energy present are debonded specimens



- Two composite plates with stiffening ribs compared, one with disbond
- Disbond yields fringe pattern in both reflected and transmitted wave

Indicates viability of wavelet method for use in at least simple structures

Lamb Wave Method Conclusions

- Strengths
  - shows great sensitivity to local presence of many types of damage
  - potential for damage location calculation with self-sensing actuators
- Limitations
  - method must be tailored for particular material and application
  - patch size and location depends upon material, thickness, curvature
  - high power requirement compared to other methods
  - complex results by comparison to other methods
  - results are localized to straight paths and max traveling distances
- SHM implementation potential
  - could use same sensors as FRM to produce Lamb waves
  - can integrate and compare transmitted and reflected energy
  - groups of sensors to be placed in areas of concern for triangulation

Proposed SHM Architecture

- Several piezoceramic sensors and other system components on a generic 0.5x0.5 – 1x1 m patch with a thermoplastic backing
  - strain, vibration, acoustic emission, Lamb waves
  - some on chip processing
  - wireless relay from patch
  - to be placed in key locations
- Neural network behavior (ant colony scenario)
  - system to be calibrated pre-operation to understand orientations
  - several “dumb” sensors collectively making “smart” decisions
  - sensors behave passively with AE and strain, occasional FRM
  - when event occurs, will actively send Lamb waves to quarry damage, determine type, severity and triangulate location
  - upon verification of damage convey to central processor
- Could gather information through ethernet port upon landing, run full vehicle test pre-flight as a preliminary insertion step

Future Recommended Research

- Similar studies for other potential detection methods
  - acoustic emission
  - eddy current
- Similar studies for other SHM components
  - wireless communication systems
  - data acquisition and processing
  - powering devices
- Increase complexity of tests
  - test on built up fuselage section or helicopter blade
  - test in service environment, noise and vibrations
  - use multiple sensing methods at once
  - integrate multiple SHM components
  - use MEMS components