IN-SITU SENSOR-BASED DAMAGE DETECTION OF COMPOSITE MATERIALS FOR STRUCTURAL HEALTH MONITORING

Seth S. Kessler

S. Mark Spearing

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

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

Airline Inspection Practice

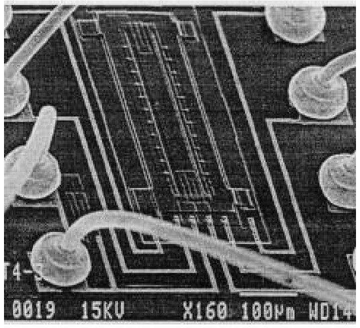
- Current requirements from FAA
  - “walk-around” pre-flight for obvious visual damage
  - detailed visual inspection of most components every 150 flights
  - tear-down of critical metallic components every 6,000-12,000 flight hours, ultrasonic or eddy-current inspection
  - composite parts designed to survive with any invisible damage, visually inspect for no growth over two scheduled intervals

- Example: Airbus A300/310
  - composite vertical stabilizer
  - no specific inspection requirement
  - Airworthiness Directive (FAA-AD) immediate visual inspection for “delamination, cracks, splitting, moisture damage or frayed fibers”

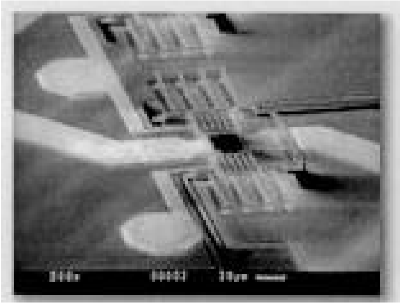
NTSB report on American Airlines Flight #587

SHM System Components

- **Architecture:**
  - integration of system components for efficiency, redundancy and reliability
  - real-time VS discontinuous monitoring
- **Damage characterization:**
  - identification of damage types for target application
  - quantification of damage signature and effect on structural integrity
- **Sensors:**
  - strain, vibration, acoustic emission, impedance, magnetic field, etc.
  - active VS passive sampling methods
- **Communication:**
  - both between neighboring sensor cells and global network
  - wired VS wireless
- **Computation:**
  - locally control sensing systems and acquire data
  - process and combine local and global data
- **Algorithms:** interpretation of damage location, severity, likelihood of failure
- **Power:** supply electricity to each component
- **Intervention:** actively mitigate damage, repair damage



Honeywell MEMS sensor



Rockwell RF receiver

Goals for SHM

- Minimize life-cycle costs
  - eliminate scheduled inspections
  - improve efficiency and accuracy of maintenance
  - reduce operational down-time, thereby capturing more revenue
  - increase fuel efficiency and range by reducing structural weight
- Improve failure prevention
  - retrofit SHM systems into existing vehicles to monitor damage growth
  - integrate SHM networks into new vehicle designs to guide inspections and dictate maintenance and repair based upon need
  - intelligent structures are a key technology for quick turnaround of RLV’s
- Greatest challenge in designing a SHM system is knowing what “changes” to look for, and how to identify them

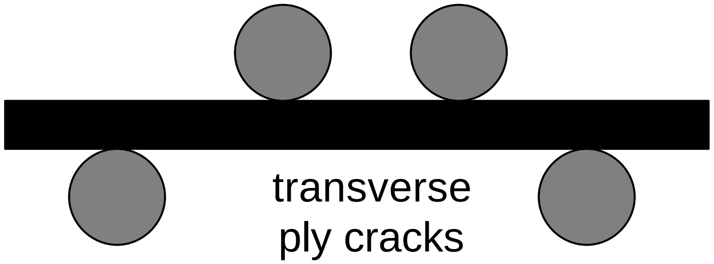
SHM in Composites

- Most new vehicles include advanced composite materials in structural components due to their high specific strength and stiffness
- Different areas of concern for NDE
  - metals: corrosion and fatigue
  - composites: delamination and impact damage
  - damage below the visible surface is most important for composites
- Composite generally allows a more flexible SHM system
  - ability to embed to protect sensors or actuators
  - can tailor structure with SMA or E&M conductive materials
  - higher likelihood of sensors initiating damage however
- May help relax peoples' fear of commercially using composites if they are continuously monitored

Procedure Outline

- Reviewed candidate damage detection methods in literature
  - most investigators focus on a single particular method
  - ideal specimens are used, non-representative geometry and damage
  - little presented on limitations of methods or pertinence to SHM
- Architectural considerations
  - focus on composite materials as a high pay-off area
  - examine effects several damage types and geometric complexities
  - investigate combinations of sensing methods using same sensors
  - report on strengths, limitations, and SHM implementation potential
- Experimental approach
  - generic specimens manufactured and tested by various methods
  - piezoelectric sensors selected for versatility and simplicity
  - thermoplastic tape used to attach sensors for re-usability
- Analytical approach
  - optimize testing procedures with governing equations
  - build finite element models to predict response, judge sensitivity

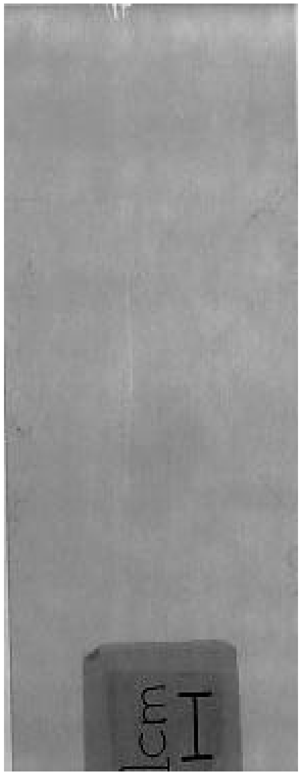
Representative Damaged Coupons



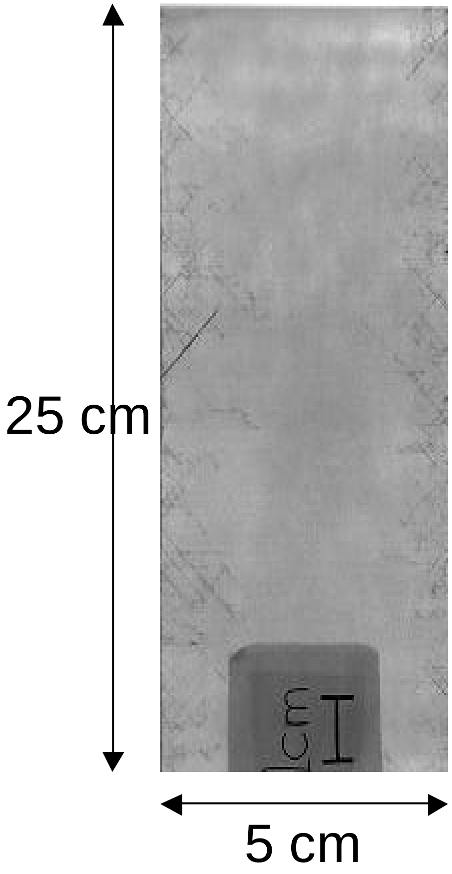
- AS4/3501-6 quasi-isotropic $[90/\pm 45/0]_s$ laminates
- Introduced representative damage to composite specimens
  - delamination — 2.5 cm cut w/utility knife, or Teflon strip in middle
  - transverse ply cracks — 4-pt fatigue on center of specimen
  - fiber fracture — 4-pt bend until audible damage
  - 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

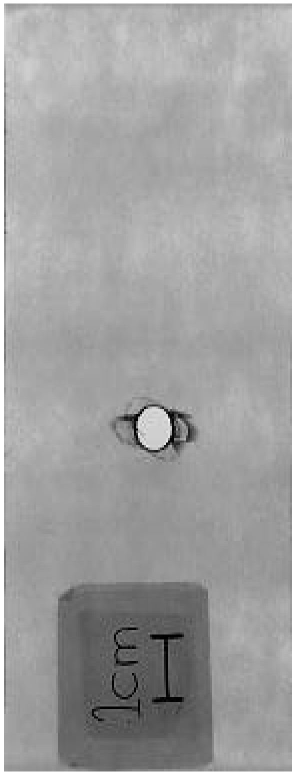


Matrix Crack
Specimen



Delamination
Specimen

Core Drilled
Specimen



Finite Element Models

- Modeled and processed in ABAQUS?
  - 25x5cm quasi-isotropic laminate
  - 2000 - 5mm square 9-noded shell elements
  - Clamped-free boundary conditions
  - 0-20 kHz dynamic excitation for modal analysis method
  - loading by a nodal coupled moment for Lamb wave method

- Several models representing various damage types
  - delamination — 2 layers of half laminate elements in damage region
  - fatigue cracks — 20% reduction in E of region (Tong et al., 1997)
  - fiber fracture — 10% reduction in E of region (Whitney, 1999)
  - hole — physically modeled holes in appropriate location

Frequency Response Methods

- Simple to implement on any geometry, global in nature
- Can be applied actively or passively
  - active method uses transfer function between two actuator/sensors
  - can passively monitor response to ambient or operational vibrations

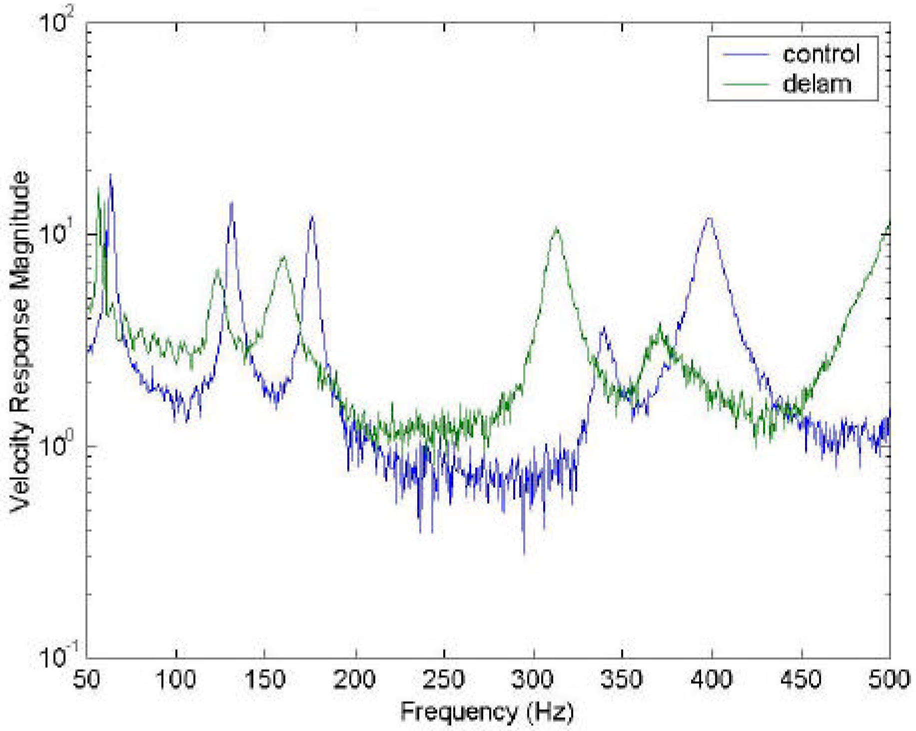
- Natural bending frequencies for beams: $? \; ? \; ? \, {}^{?}\sqrt{\frac{EI}{m}} \; ? \; ? \, {}^{2}\sqrt{\frac{Et^{2}}{?}}$
  - stiffness reduction decreases ?
  - density/mass reduction increases ?
- Mode shapes are altered by damage locations
- Response amplitude increases with more damage

- Present work monitors specimen response using transfer function method, measuring piezo impedance due to “sine-chirp” actuation

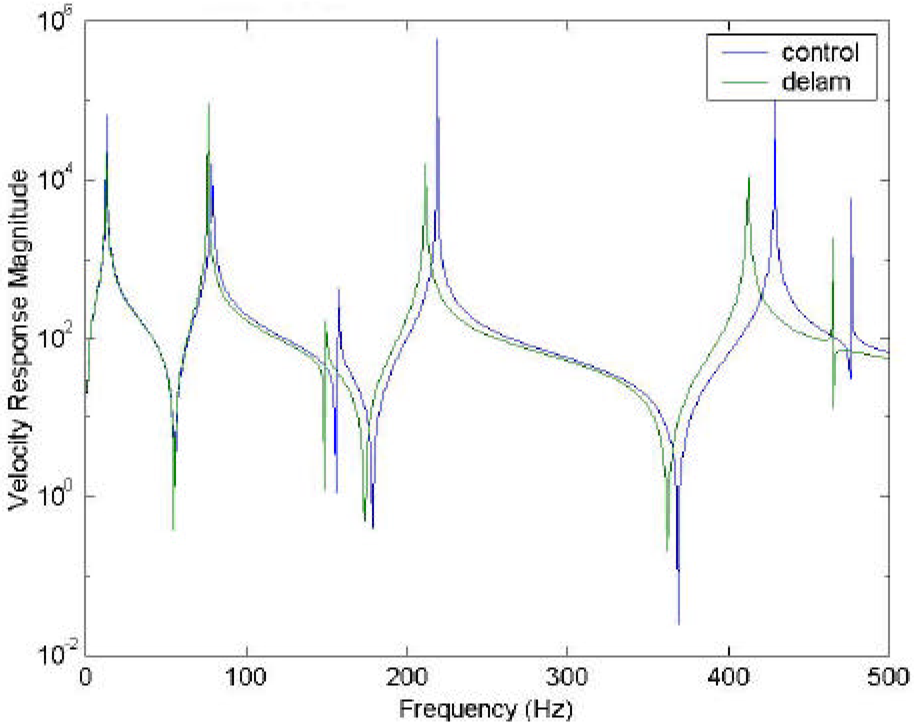
Averaged Velocity Response

Low Frequency Range

Experimental Results



Finite Element Results



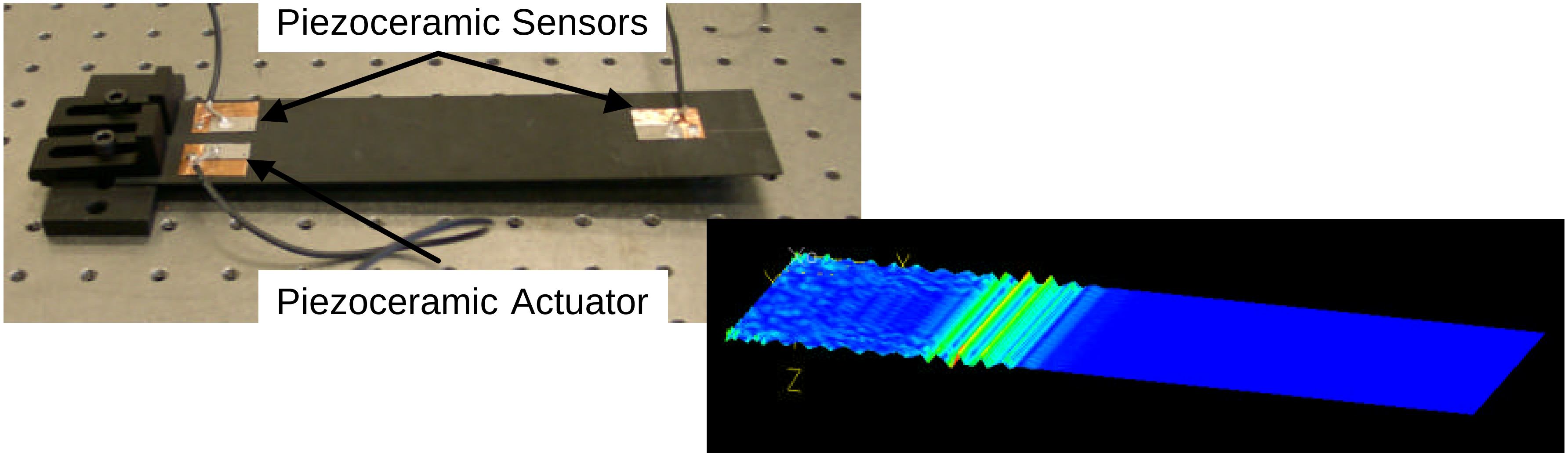
Clearly identifiable shift in frequencies due to delamination

Frequency Response Method Conclusions

- Strengths
  - method shows useful detection sensitivity to global damage
  - testing can be passive, variety of light and conformal sensors work
- Limitations
  - small changes in characteristics at low frequencies
  - modes combine and new local modes appear at high frequencies
  - altering one variable linearly is not practical for real applications
  - model-based analysis is impractical
  - little information on damage type or location (6cm hole ? 5cm delam)
- SHM implementation potential
  - first line of defense for detecting global changes caused by damage; use active sensing methods for more detail
  - last line of defense for widespread fatigue damage on global modes; can set limit on modal resonance change from healthy state

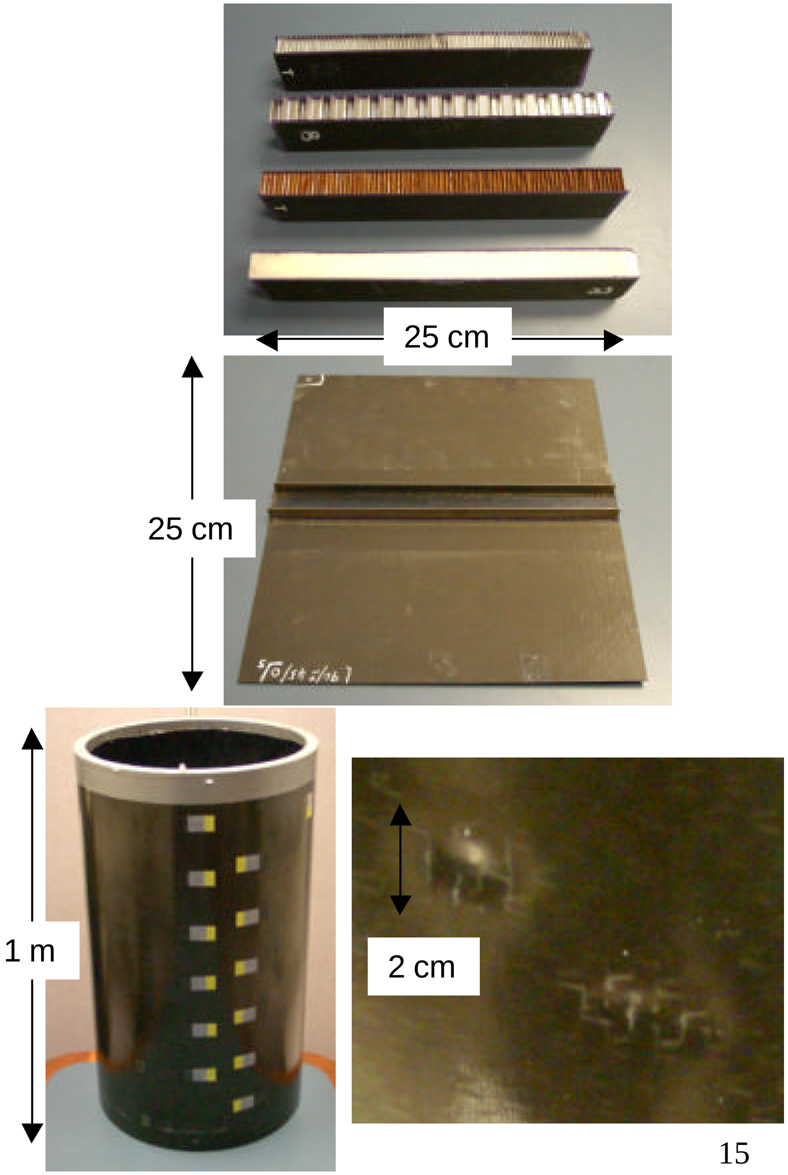
Lamb Wave Methods

- 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 ? $(E/?)^{1/2}$, damage slows down waves
  - reflected wave from damage can be used to determine locations
- Present work uses piezoelectric sensors to detect energy present in transmitted and reflected waves using self-sending actuators



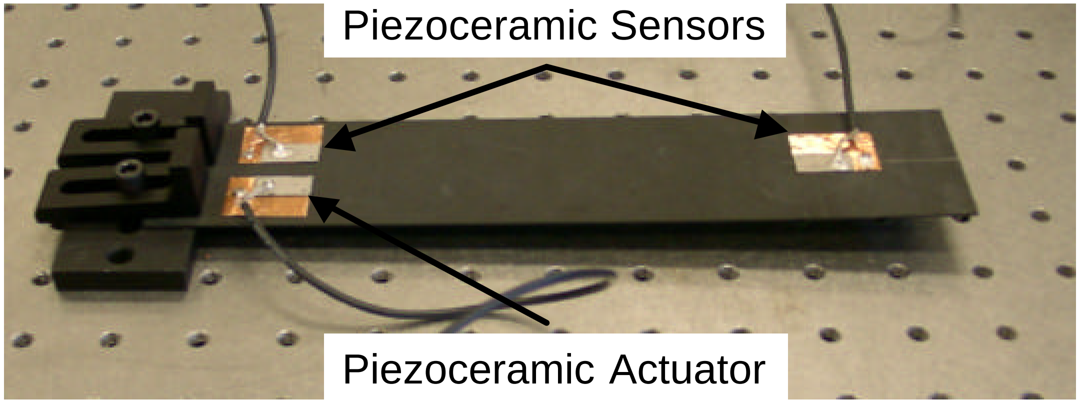
Building Block Approach

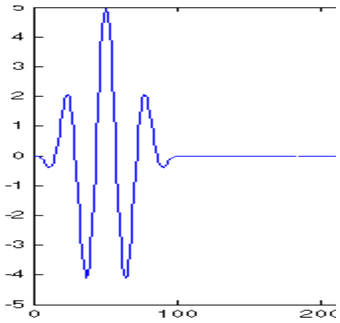
- Narrow coupon laminates
  - same specimen used for FRM
  - several types of damage
- Narrow sandwich beams
  - various types of cores tested
  - disbonds between laminate and core
- Stiffened plate
  - various types of bonded ribs
  - disbonds between laminate and rib
- Composite sandwich cylinder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



Parameter Optimization

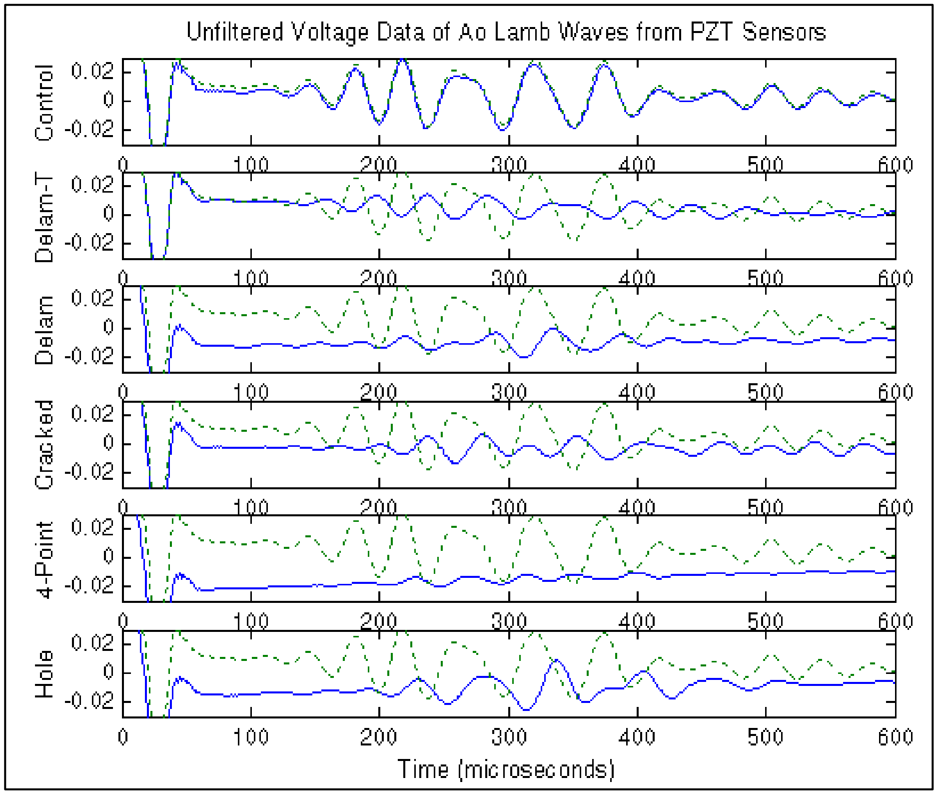
- Actuation parameters determined from governing equations
  - from material properties dispersion curves are calculated
  - from group velocity dispersion curve, operating frequency selected
  - from operating wavelength, actuator size is selected
  - number of pulses to be sent determined by distance 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





Sent Signal

Thin Laminate Results: Time of Flight

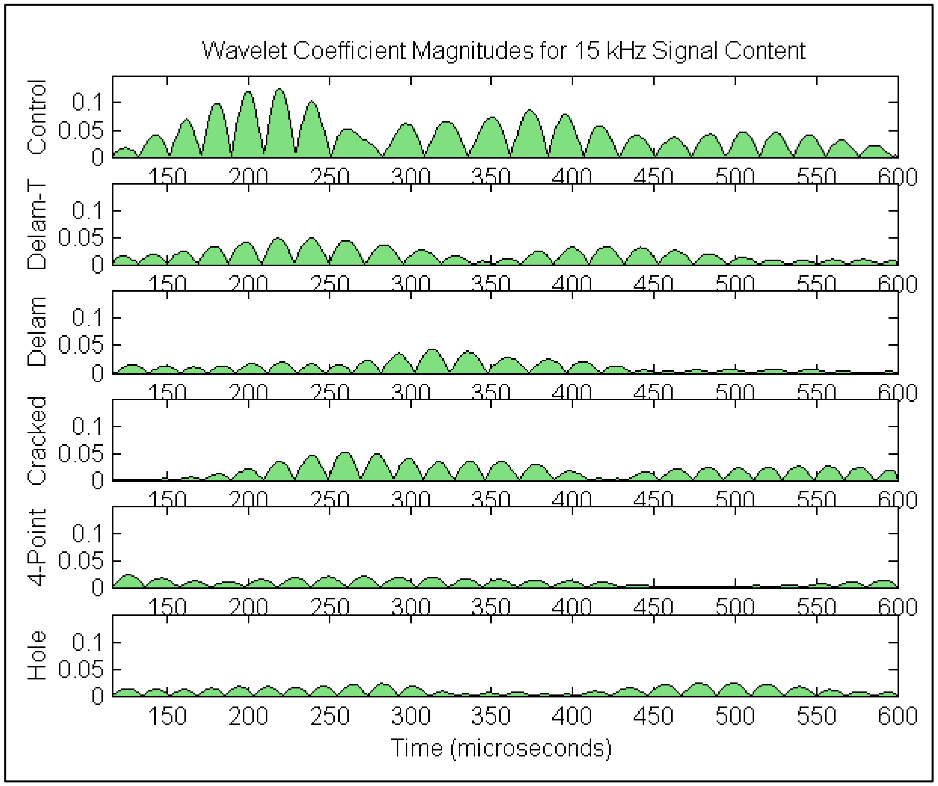


—— Specimen labeled on plot

- - - - Superimposed control specimen

- Time-trace of voltage signal from PZT sensor 20 cm from actuator driving at 15 kHz
- High degree of consistency between all control traces
- All damaged traces show a delay in time of arrival, and smaller amplitude responses
- Since these are short specimens, many reflections combine quickly
- While TOF is easily reproduced, difficult to measure accurately

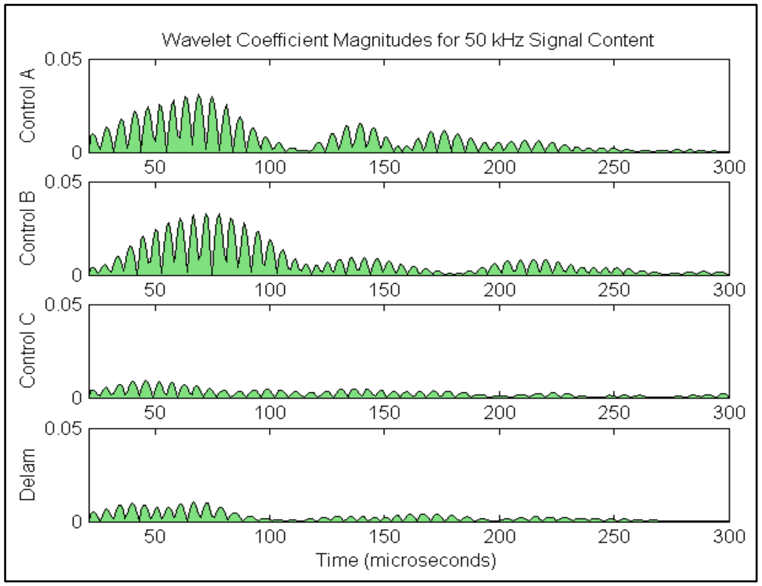
Thin Laminate Results: Wavelet Analysis



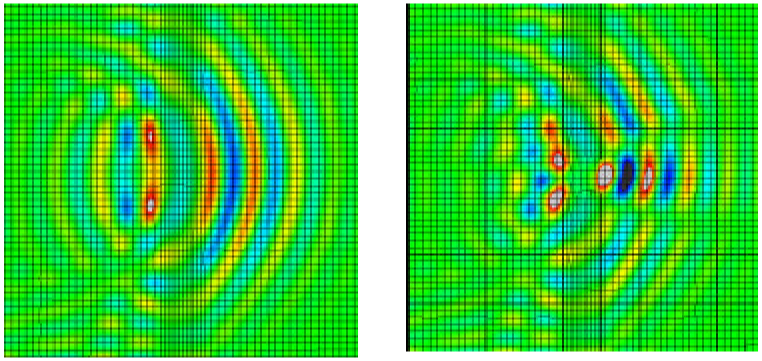
- Wavelet decomposition performed using Morlet signal, similar to FFT
- Compare received signal's energy content at dominant frequency
- Control specimen clearly has the most energy transmitted
- Appears that as damage becomes more severe, more energy is lost
- Differences seem obvious enough for process to be automated
- Still not much information about damage type and location

Demonstrates ability to detect presence of damage and judge extent

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

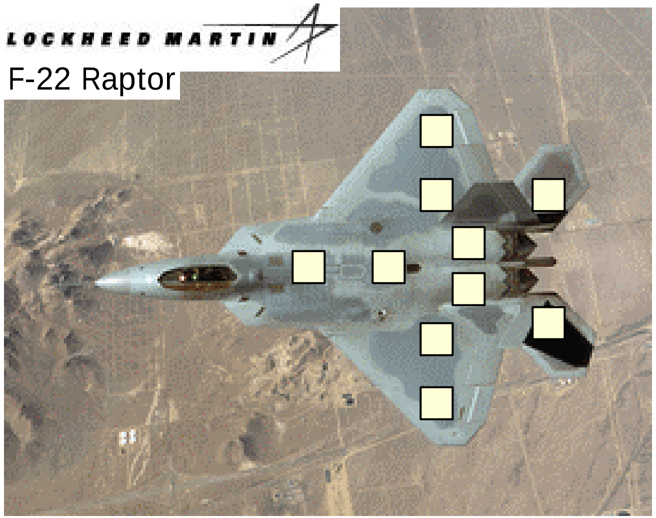
Other Piezo-Based Methods

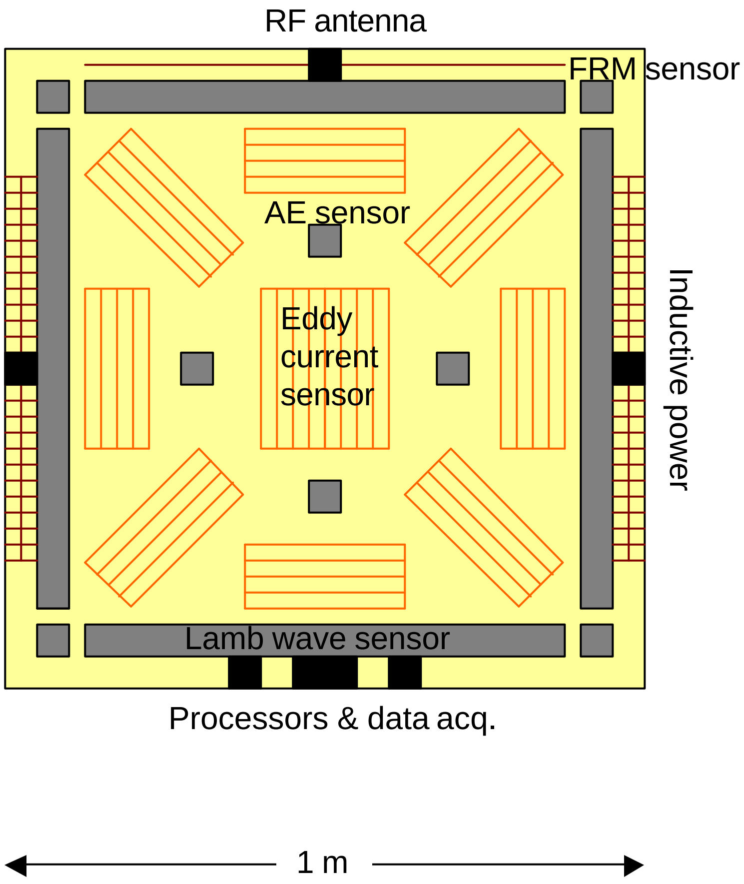
- Piezo sensors used for FRM and Lamb wave methods can be used to implement other methods passively
- Strain monitoring
  - programs at NASA and Boeing have used piezo's to monitor strain
  - Hautamaki *et al* (1999) have fabricated MEMS piezoelectric sensors
  - can use strain records to calculate stresses seen in operation
  - present work used tensile test to compare strain in piezo and foil gauge
- Acoustic emission (AE)
  - work performed at Honeywell, Northrup and Boeing with this method
  - much work performed at MIT by Wooh (1998)
  - most elaborate demonstration is Chang's "smart-panel" (1999)
  - can determine damage event occurrence and estimated location based on time of flight for impacts and fiber/matrix cracking
  - present work performed pencil-break test on laminated plate

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

Architecture Schematic





Concluding Remarks

- Piezoelectric materials are ideal for SHM applications
  - can be used to implement a variety of NDE test methods
  - both actuating and sensing capabilities
  - light, low cost, low power, flexible, can be deposited
- Frequency response methods
  - useful detection sensitivity to global damage
  - little information on damage type or location
  - can be used for first or last line of defense
- Lamb wave methods
  - sensitive to local presence of many types of damage
  - requires more power than most sensors, most tailor to application
  - potential for triangulation of damage location and shape
- Recommendations for SHM system architecture
  - based on experiment and analytical results
  - use of multiple detection methods to gain maximum information

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