Design of a Piezoelectric-based Structural Health Monitoring System for Damage Detection in Composite Materials

Seth S. Kessler

S. Mark Spearing

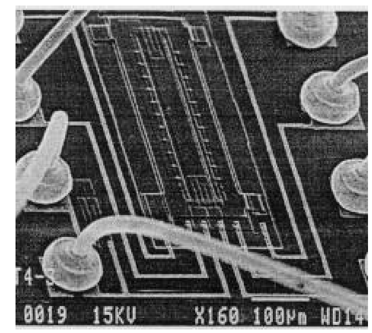
Technology Laboratory for Advanced Composites
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

SHM Motivations

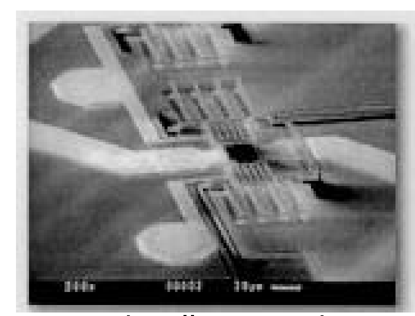
- Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to improve reliability and reduce life-cycle costs
- Inspection and maintenance expenses could be reduced by SHM
  - currently, about 25% of aircraft life cycle cost 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

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

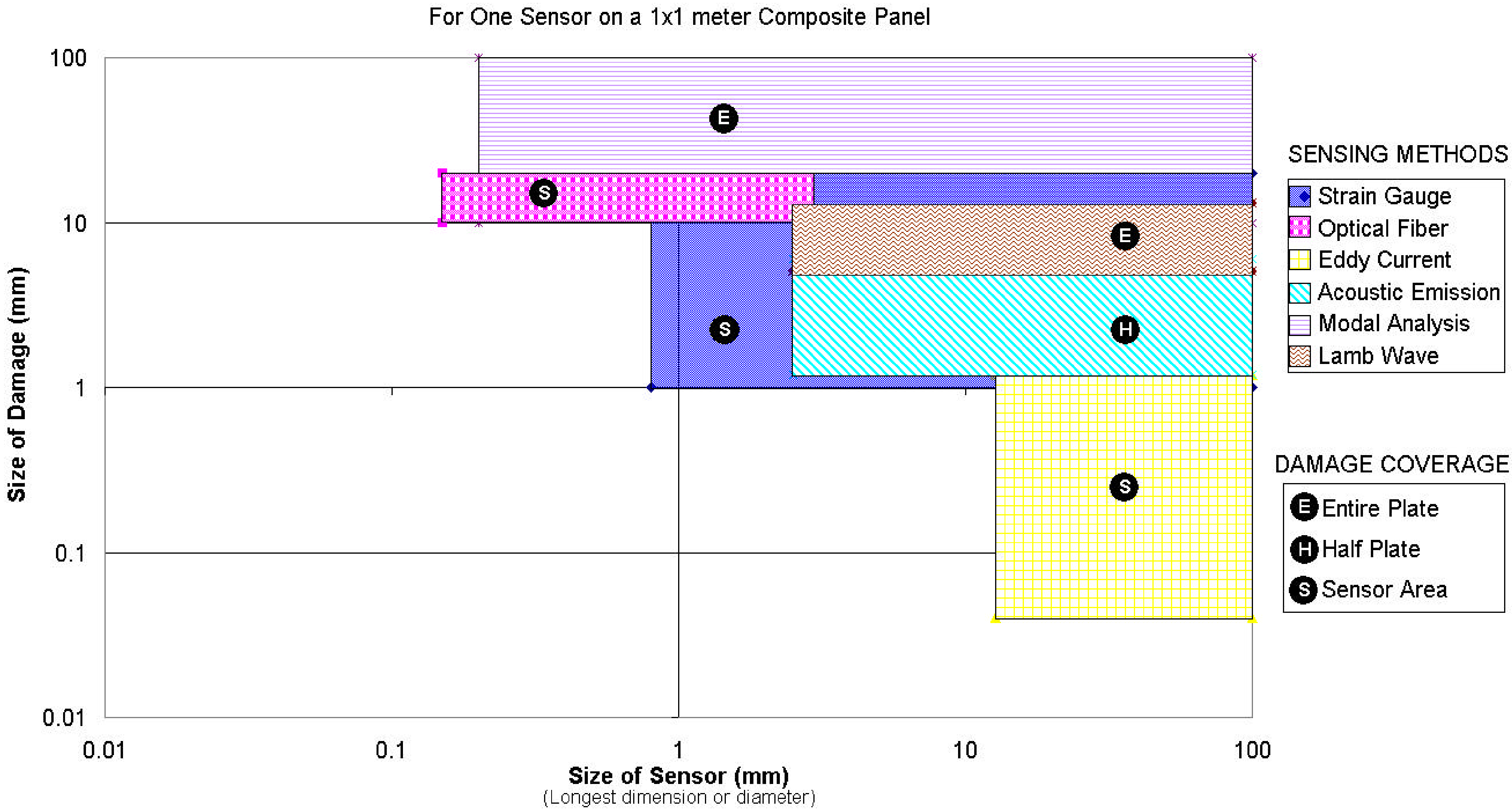
SHM in Composites

- 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

Summary of Detection Methods

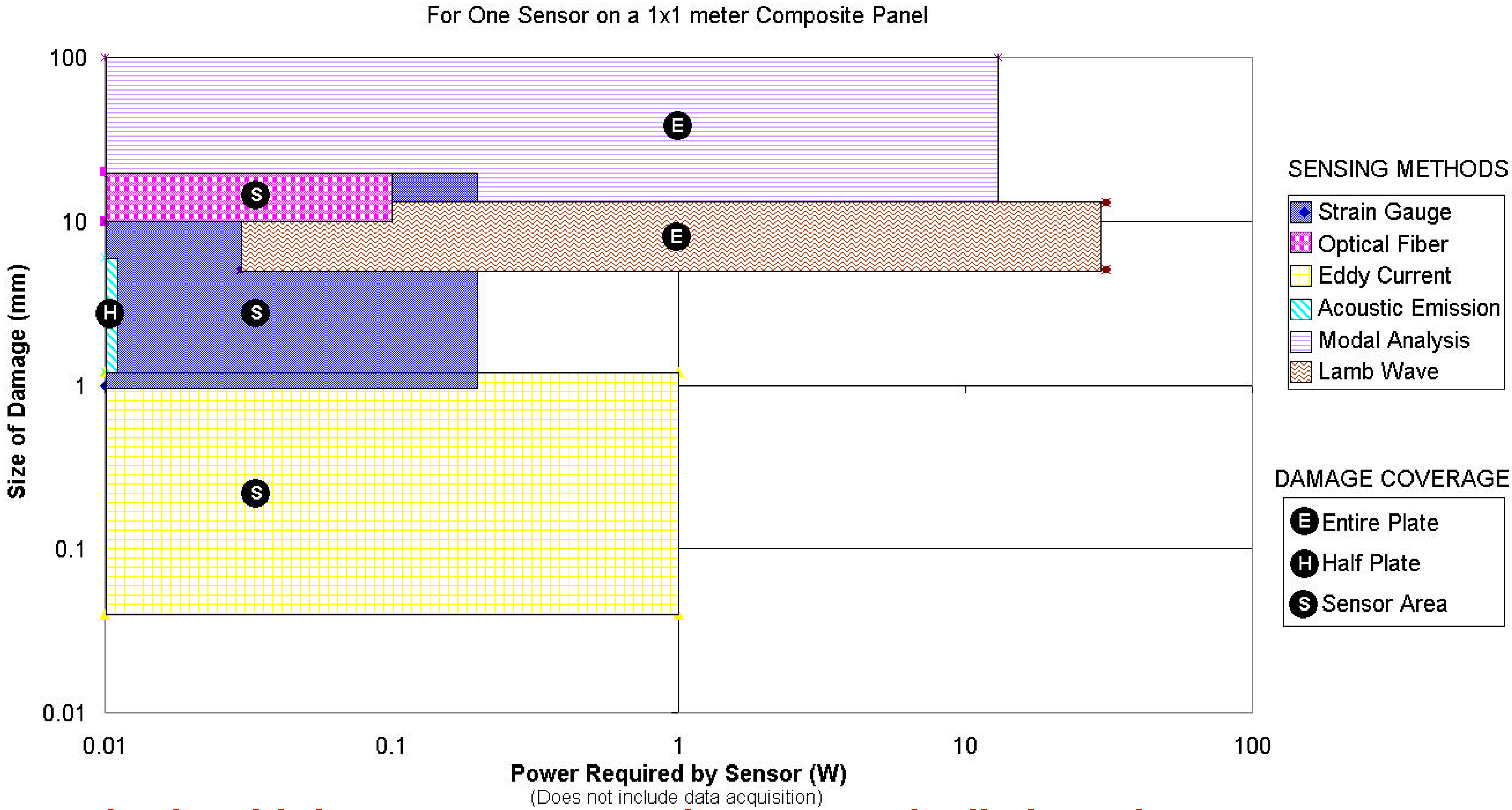
Method	Strengths	Limitations	SHM Potential
Strain gauge	embeddable simple procedure low data rates	expensive limited info	low power localized results
Optical fibers	embeddable simple results very conformable	expensive high data rates accuracy?	requires laser localized results
Eddy current	surface mountable most sensitive	expensive complex results safety hazard	high power localized results damage differentiation
Acoustic emission	inexpensive surface mountable good coverage	complex results high data rates event driven	no power triangulation capable impact detection
Modal analysis	inexpensive surface mountable good coverage	complex results high data rates global results	low power complex structures multiple sensor types
Lamb waves	inexpensive surface mountable good coverage	complex results high data rates linear scans	high power triangulation capable damage differentiation

Size of Detectable Damage vs Sensor Size



Methods with best damage/sensor size ratio typically have low coverage, only Lamb wave and FR methods cover entire area, AE covers most

Size of Detectable Damage vs Sensor Power



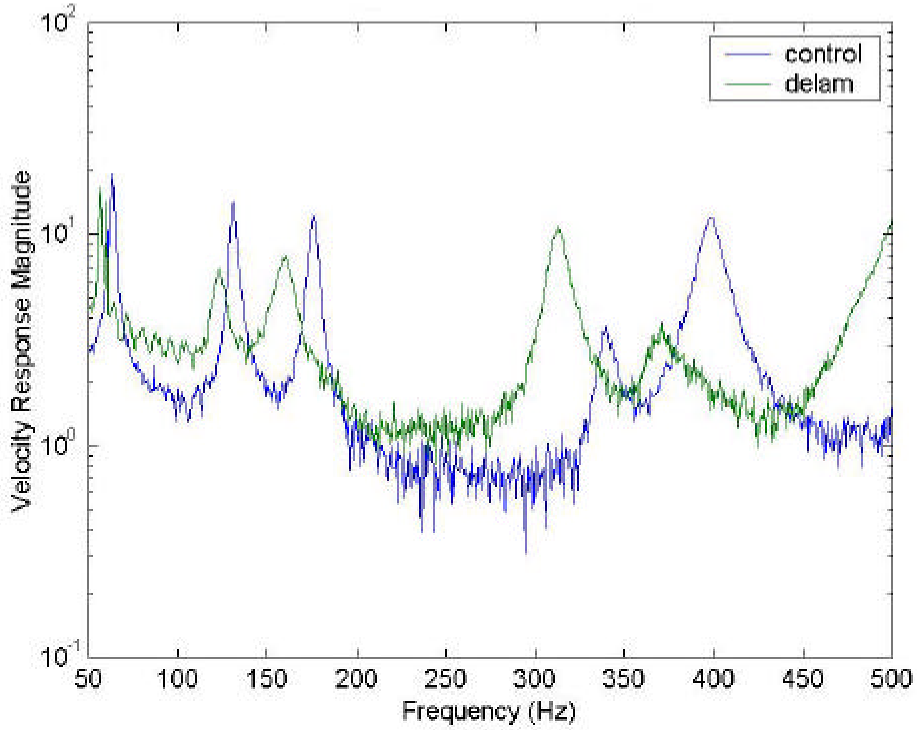
Methods with lowest power requirement typically have lowest coverage; for Lamb wave and FR methods sensitivity scales with power level

Frequency Response Methods

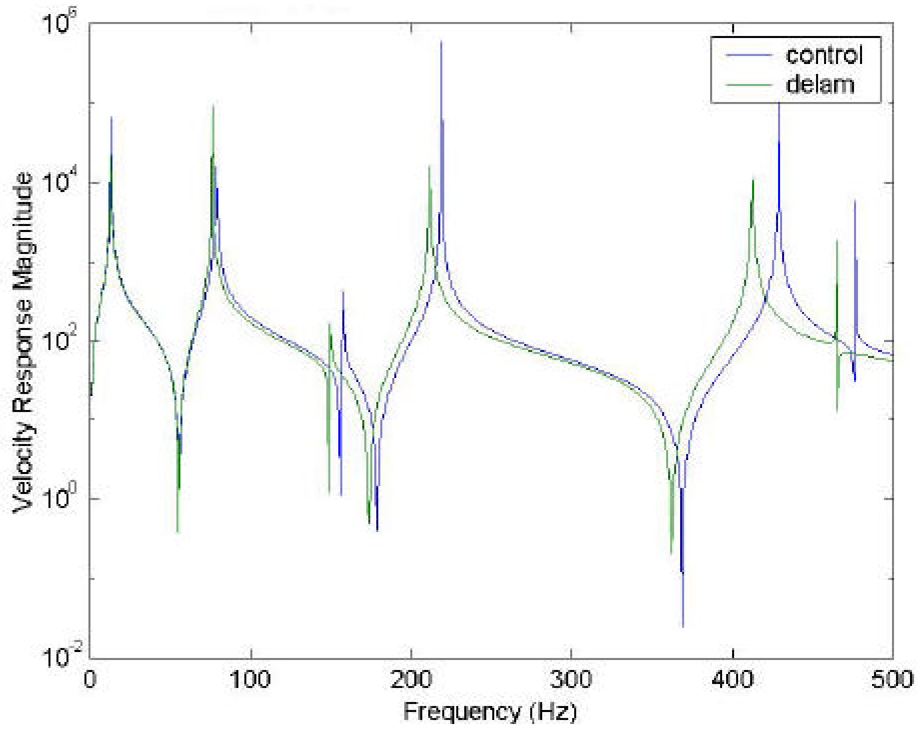
- Simple to implement on any geometry, global in nature
- Can be applied actively or passively
  - active method uses transfer function between two actuator/sensors
  - can passively monitor response to ambient or operational vibrations
- Natural bending frequencies for beams: $? \; ? \; ? \; ^{?}\sqrt{\frac{EI}{m}} \; ? \; ? \; ^{2}\sqrt{\frac{Et^2}{?}}$
  - 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



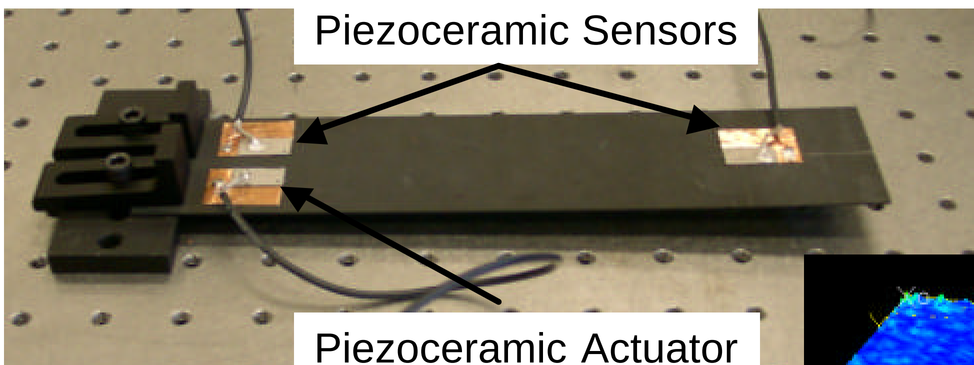
Clearly identifiable shift in frequencies due to delamination

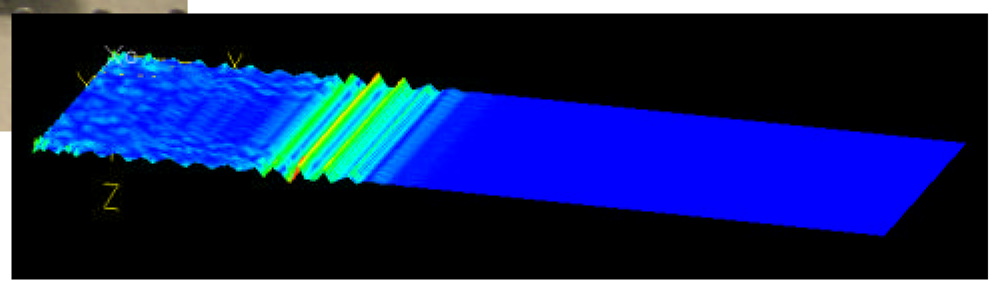
Frequency Response Method Conclusions

- 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

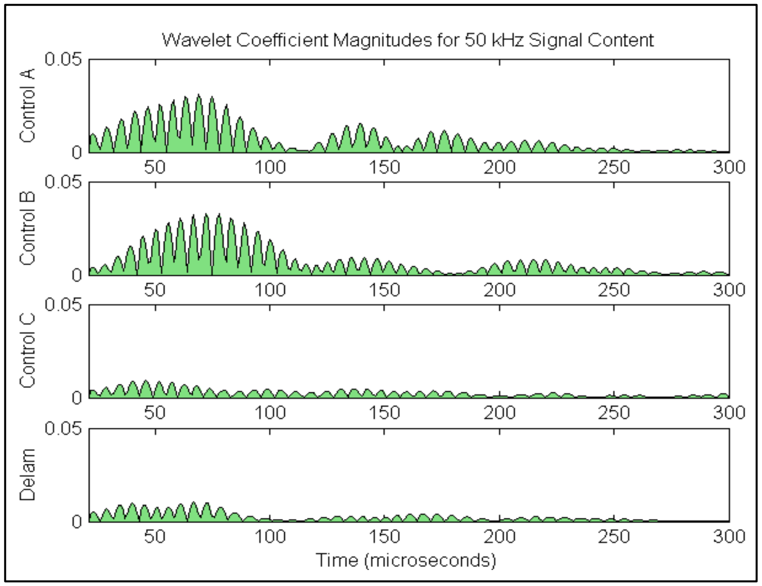
Lamb Wave Methods

- 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

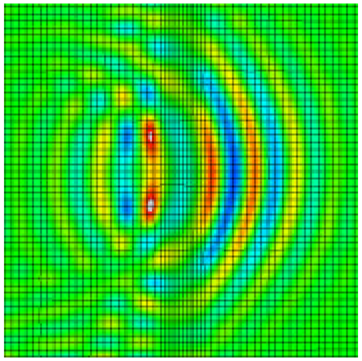


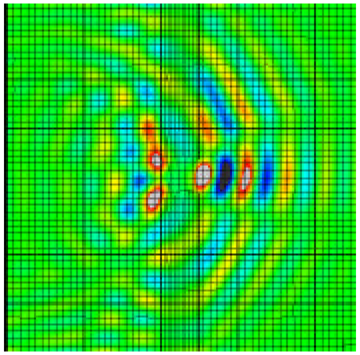


Damage Detection Results



- 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

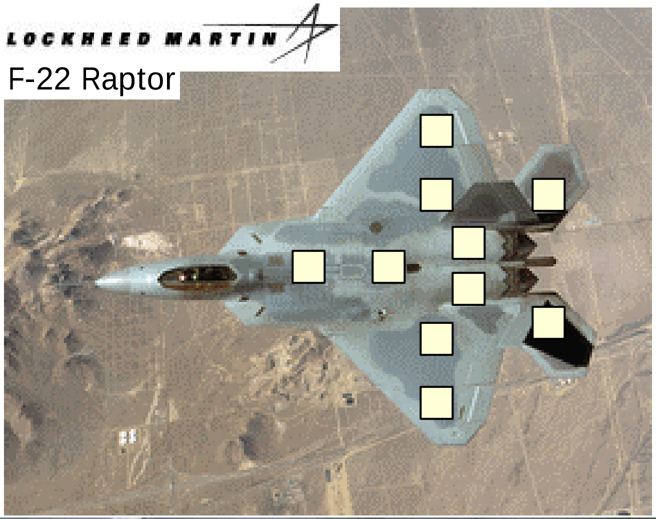
Other Piezo-Based Methods

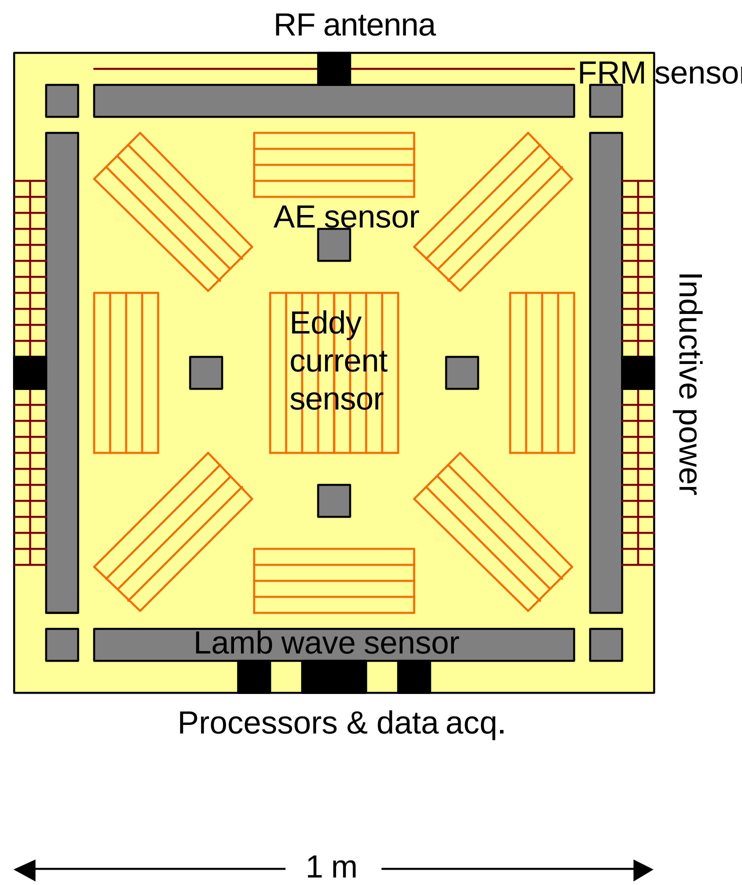
- Piezo sensors used for FRM and Lamb wave methods can be used to implement other methods passively
- Strain monitoring
  - programs at NASA and Boeing have used piezo's to monitor strain
  - Hautamaki *et al* (1999) have fabricated MEMS piezoelectric sensors
  - can use strain records to calculate stresses 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