Piezoelectric-Based In-Situ Damage Detection in Composite Materials for Structural Health Monitoring Systems

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Composites Engineering ? SHM ? Mechanical Design
http://www.MetisDesign.com
Agenda

• SHM motivations and goals
• Approach
• Modal analysis methods
• Lamb wave methods
• Other piezo-based sensing methods
• SHM system design
SHM Motivations

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

• Applicable to any field – highest payoff in air/spacecraft

• 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 aircraft, 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
Goals for SHM

• Minimize life-cycle costs
  – use CBM over damage tolerant design – reduce weight up to 25%
  – eliminate scheduled inspections
  – reduce operational down-time, thereby capturing more revenue
  – improve efficiency and accuracy of maintenance

• 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 $[90/\?45/0]_s$ 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

25 cm

5 cm
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

• One of the most common means of damage detection
• 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
• Background work from literature
  – Zou et al (2000) published a review paper on model dependant FRM
  – Zhang (1999) and Zimmerman (1995) both published work on active FRM using transmittance functions to compare to a healthy structure
  – Soutis (2000) demonstrated linear relationship between delamination area and frequency shifts using piezo sensors in a composite laminate
• Present work monitors specimen response using transfer function method, measuring piezo impedance due to “sine-chirp” actuation
Detecting Damage using FRM

- Natural bending frequencies for beams:  \[ \omega \sqrt{\frac{EI}{m}} \]  
  - stiffness reduction decreases ?
  - density/mass reduction increases ?
  - boundary conditions most directly affect ?

- Mode shapes are altered by damage locations
  - bending modes affected by damage near nodes
  - torsion modes affected more by asymmetric damage
  - bending and torsion modes begin to couple

- Response amplitude increases with more damage
Averaged Velocity Response
Experimental Low Frequency Range

Clearly identifiable shift in frequencies due to delamination
Experimental Mode Shapes

Mode shapes of control specimen from scanning laser vibrometer
Transfer Function Response
Predicted Low Frequency Range

Predicts small shift in frequencies due to delamination at low frequencies
Transfer Function Response
Predicted High Frequency Range

Shifted peaks are difficult to match with control model at high frequencies
First four mode shapes of control specimen plotted in I-DEAS post-processor
## Modal Analysis Results: Frequency Comparison

<table>
<thead>
<tr>
<th>Shape</th>
<th>(All Hz)</th>
<th>Control</th>
<th>Hole</th>
<th>Impact</th>
<th>Delam</th>
<th>Crack</th>
<th>Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mode 1:</strong> 1(^{st}) Bending</td>
<td>FEA</td>
<td>12.5</td>
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Modal Analysis Results: 
Analytical Percent Error

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<tr>
<th>Shape</th>
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<td>8.2%</td>
<td>8.5%</td>
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</table>

Good correlation between FEA and experimental results at frequencies < 500 Hz
Modal Analysis Results: Effect of Damage

<table>
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<th>Shape</th>
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<tr>
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<td>Mode 2: 2\textsuperscript{nd} Bending</td>
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Small differences between control and damaged models at frequencies < 500 Hz
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
  - 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 $\sqrt{\frac{E}{\rho}}$, damage slows down waves
  – reflected wave from damage can be used to determine locations
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
Thin Laminate Results: Time of Flight

- 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
Thin Laminate Results: Finite Element Analysis

- Figure on left shows FEA results for coupon without damage
- Figure on right shows FEA results for coupon with 25 mm disbond
- Movie files show z-displacement at 100 microsecond intervals
- Can use to measure time-of-flight and observe reflections
Blind-Test Beam Results

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

Indicates viability of wavelet method for use in at least simple structures
Stiffened Plate FEA Results

- Figure on left shows FEA results for stiffened plate without damage
- Figure on right shows FEA results for rib with 25 mm disbond
- Movie files show z-displacement at 100 microsecond intervals
- Disbond yields fringe pattern in both reflected and transmitted wave
Cylindrical Control Region

- CFRP tube, 4-plies surrounding low-density anticlastic Al core
- Test two apparently undamaged areas and compare to known impact damage region
- Axial signal transmission limitation appears to be about 0.5 m
- Circumferential transmission limit of 0.2 m; curvature causes more dispersion in signal (not shown)
- Wavelet coefficient plot compares energy content for 40 kHz

Lamb waves are capable of traveling at least 0.5 m in sandwich structure
Cylindrical Damaged Region

- Known impact damage region in tube of 2.5 cm diameter (damage visible on surface of outer ply)
- Energy content in first 10 cm is greatly reduced
- Signal is practically lost due to dispersion after 20 cm
- Can readily confirm presence of damage from integrated energy
- Lamb waves could potentially travel even further in a large structure without damping core

Small impact damage near actuator deflects much of the sent energy
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
Acoustic Emission Results

- Pencil break test used same setup and sensors from 2-D Lamb wave test
- Break graphite point counter clockwise around plate as shown in figure
- Obvious event occurrence, highest energy at sensor nearest break point
- Potential impact-event detection—higher data rate for location (>1MHz)
# Summary of Detection Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Strengths</th>
<th>Limitations</th>
<th>SHM Potential</th>
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<tbody>
<tr>
<td>Strain gauge</td>
<td>embeddable simple procedure low data rates</td>
<td>expensive limited info</td>
<td>low power localized results</td>
</tr>
<tr>
<td>Optical fibers</td>
<td>embeddable simple results very conformable</td>
<td>expensive high data rates accuracy?</td>
<td>requires laser localized results</td>
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<tr>
<td>Eddy current</td>
<td>surface mountable most sensitive</td>
<td>expensive complex results safety hazard</td>
<td>high power localized results damage differentiation</td>
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<tr>
<td>Acoustic emission</td>
<td>inexpensive surface mountable good coverage</td>
<td>complex results high data rates event driven</td>
<td>no power triangulation capable impact detection</td>
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<tr>
<td>Modal analysis</td>
<td>inexpensive surface mountable simple procedure</td>
<td>complex results high data rates global results</td>
<td>low power complex structures multiple sensor types</td>
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<tr>
<td>Lamb waves</td>
<td>inexpensive surface mountable good coverage</td>
<td>complex results high data rates linear scans</td>
<td>high power triangulation capable damage differentiation</td>
</tr>
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</table>
Methods with best damage/sensor size ratio typically have low coverage, only Lamb wave and FR methods cover entire area, AE covers most.
Methods with lowest power requirement typically have lowest coverage; for Lamb wave and FR methods sensitivity scales with power level.
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
Papers and Publications

• Frequency response methods
  – SPIE 2001 NDE conference paper (3/01)
  – Composites: Part B journal (accepted 6/01)

• Lamb wave methods
  – ASC 2001 conference paper (9/01)
  – Stanford SHM workshop paper (9/01)
  – European SHM workshop (6/02)
  – Smart Materials and Structures journal (accepted 1/02)
  – Intelligent Materials Systems and Structures journal (submitted 1/02)

• SHM system design
  – SPIE 2002 smart structures conference paper (3/02)
  – SDM 2002 SHM conference paper (4/02)
  – Materials Evaluation journal (submitted 1/02)
Backup Slides
Frequency Selection

- Collect material properties and representative geometry
- From $E$, $\rho$, $\tau$, $t$ 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 $A_0$ mode phase velocity travels as $w^{1/2}$ 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
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
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 $2a = \lambda (n+\frac{1}{2})$
    where $\lambda$ is the wavelength and $n=0,1,2,3…$

• 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
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
Electrical Noise

- Unknown electrical noise and drift present in all tests
- “Parasitic capacitance”
  - data acquisition device uses multiplexer (MUX) that checks each channel by charging a small capacitor
  - if sampling time is too fast at high voltage, will still be discharging from previous reading while taking next one
- Can partially circumvent this problem by using an attenuating circuit to trigger the sensing channels
Sandwich Beam Results

- Time-trace of voltage signal from PZT sensor 20 cm from actuator driving at 50 kHz
- Stiffer panel requires higher driving frequency for clear results
- Core causes damping in the signal, softer core? smaller signal
- Again, good consistency between all control traces
- Very small signal in all damaged cases, difficult to compare with undamaged specimen

![Graph showing time-trace of voltage signal from PZT sensors](image)
Bonded Stiffener Results

- Quasi-isotropic laminated plates with thick Gr/Ep strips bonded in center of laminates
- One plate with teflon strip inserted between adhesive and stiffener
- Observe transmitted wavelet energy passing through stiffener
  - measurement taken in center
  - measurement taken on side (S)
- Delaminated region slows wave
- Similar results observed with metallic c-channel stiffener

Lamb wave method viable for detecting delamination in built-up structure
2-D Plate Results

- Quasi-isotropic 25 cm square plates with sensors in the center of each side around perimeters
- Actuator from one side, sense from other three for each test
- Reproducible waveform transmitted from opposite sides, different velocity on adjacent sides
- Also attempted to implement self-sensing actuator
Self-Sensing Circuit

- Full bridge circuit inspired by Anderson (MIT A/A PhD ’94)
- Allows for large driving voltage to pass through piezo without affecting the small reflected signal (10V compared to 10 mV)
- Circuit also extracts drift and much noise with parallel legs
- Reduces complexity, cost and weight of a SHM system
Strain Monitoring Results

- Tensile test with a strain gauge on front side and piezo on back
- One control specimen and one with center hole, sample at 50 Hz
- Piezo strain results were non-linear, probably due to thermoplastic
- A few acoustic events present, correlate with audible damage
Eddy Current

- Jentek sensors, company in Cambridge w/MIT ties
- Different techniques to separate damage modes
  - conducting to detect damage in fibers
  - capacitive to detect damage in matrix
- Have demonstrated detection of small damage in metals