Optimization of Lamb Wave Methods for Damage Detection in Composite Materials

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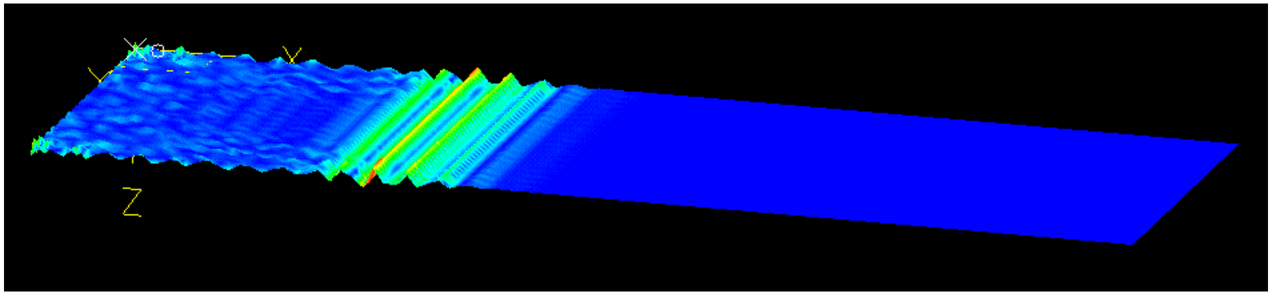
Motivation and Research Goals

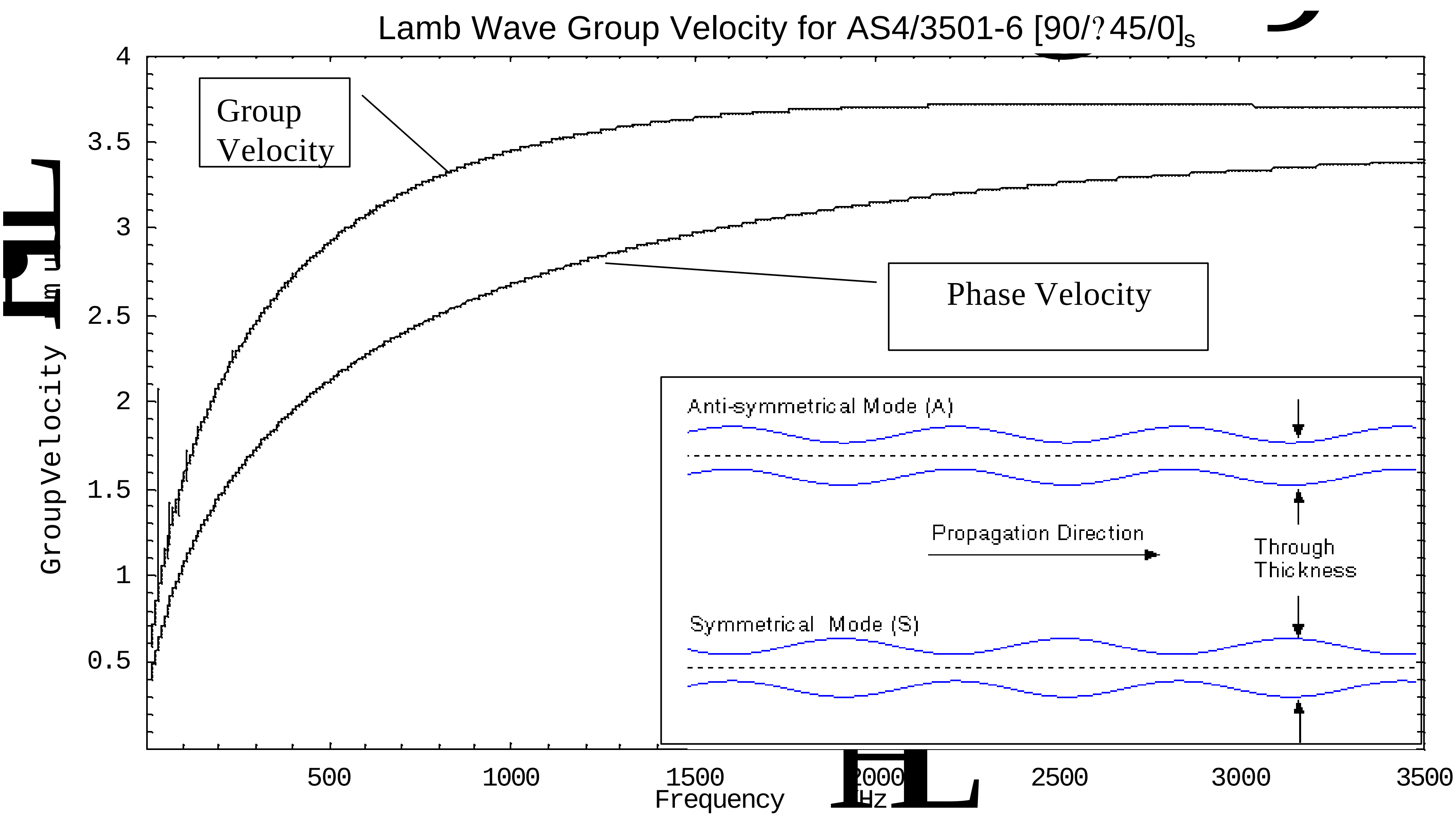
- SHM denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to improve reliability and reduce life-cycle costs
- Greatest challenge in designing a SHM system is knowing what “changes” to look for, and how to identify them
- Proposed research
  - investigate potential sensing methods and combinations
  - report on strengths and limitations of methods
  - implementation potential for a real structure (conformability, size, etc.)
  - show progression of detection reliability through building block
  - focus on composite materials — high pay-off area

Lamb Waves

- Form of elastic perturbation that propagates in a solid medium
- First described by Horace Lamb in 1917
- Described via dispersion curves
  - plot group or phase velocity versus frequency thickness product
  - function of elastic constants and density (often use Lamé’s constants)
- At a given frequency, two types of Lamb waves satisfy the wave equation – symmetric and anti-symmetric



Dispersion Curves and Wave Shapes



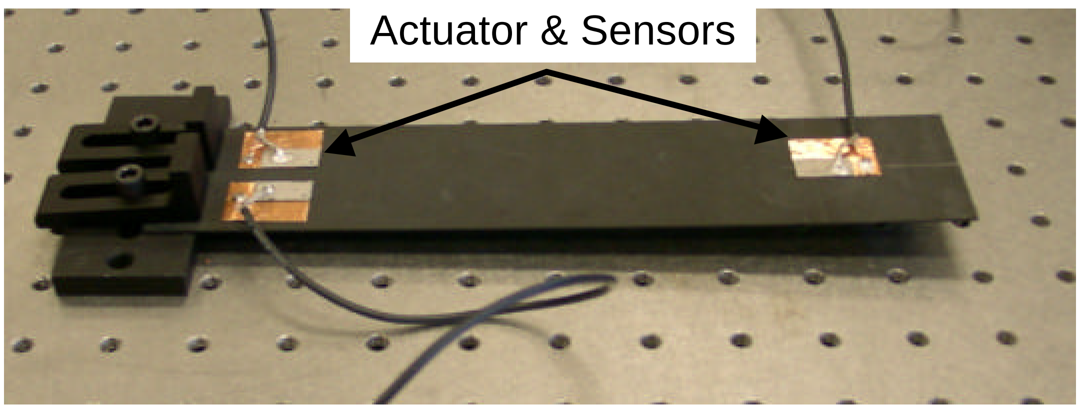
Damage Detection using Lamb Waves

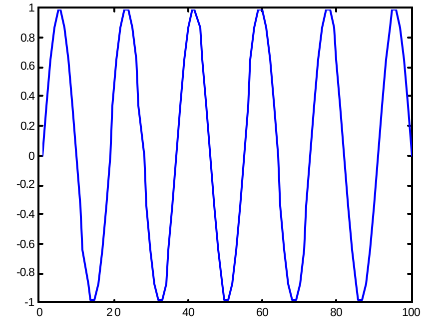
- Levels of damage detection in a structure
  - identify presence of known damage in specimens
  - quantify extent of damage
  - estimate damage location on specimen
  - differentiate between types of damage

- Damage can be found in several ways
  - velocity determined by $\sim(E/?)^{1/2}$, cracks slow down waves
  - reflected wave from damage site, can use to determine locations

Experimental Setup

- Use specimens from previous work, improve detection capability found using frequency response methods
- Determine parameters for reproducible and reliable testing
  - specimen configuration
  - actuator and sensor configuration
  - driving frequency





Driving Signal?

Lamb Wave Studies

- Experiment with sensitivity of setup parameters
  - effect of altering boundary conditions
  - sensing in transmission, reflection and using actuator
  - location of actuator on width of specimen
  - geometric and electrical configuration of actuator
- Signal optimization
  - driving frequency
  - signal shape (and type of window)
  - number of pulses
  - material properties effects
- Accurately and easily send and receive Lamb waves

Sensitivity Results I

- Boundary conditions
  - changes in BC's outside of wave path have no effect
  - restraints in the through-thickness dimension cause damping
  - boundaries and abrupt stiffness changes (i.e. holes, bonded materials) between actuator and sensor have greatest effect
- Transmission vs reflection
  - transmitted signals have much greater amplitude than reflections
  - difficult to measure reflections in this configuration, since waves are actuated in all directions, wave from adjacent piezo dominates
  - reflected waves hold key to damage triangulation

Sensitivity Results II

- Location of actuator
  - actuator and sensor must be far enough apart to separate signal of sent wave from received wave; electronics problem
  - within the width of the tested specimen, location had little effect

- Configuration of actuator
  - length in propagation direction affects amplitude sinusoidally with maximum at $2a=?(n+{}^{1}/_{2})$, larger width for more uniform wavefront
  - 5-10V sufficient for driving, must use coax cable to avoid crosstalk through equipment; important SHM system issue

Optimization Results I

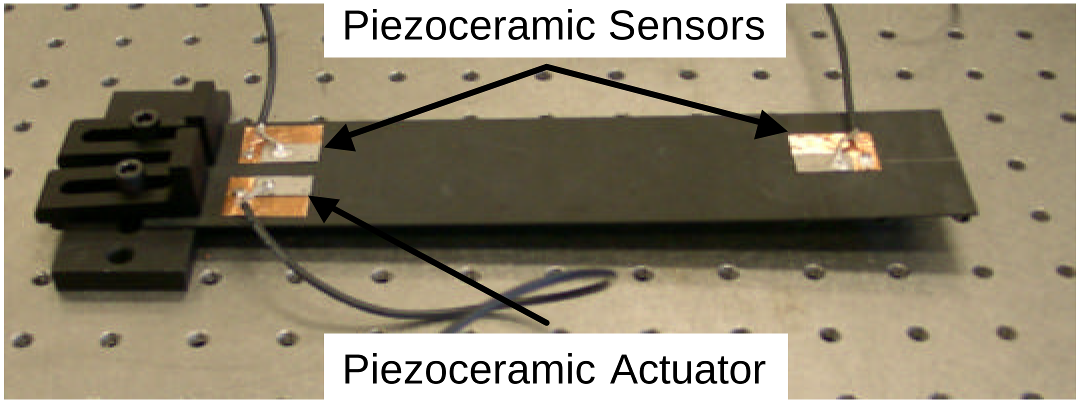
- Driving frequency
  - probably the most important characteristic to excite proper wave
  - use dispersion curve to guide upper and lower bounds
  - tune with oscilloscope to find particular solution, natural frequencies of structure plays a role
  - 15 kHz here for thin laminates, 50 kHz for sandwich panels
- 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

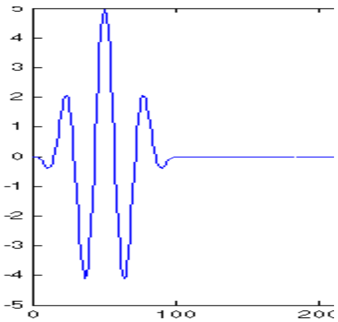
Optimization Results II

- Number of pulses
  - 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
- Material properties effects
  - modulus and density affect wave velocity similarly to normal modes
  - specimen thickness has an linear effect on velocity
  - curvature in materials as well as thickness causes higher dispersion rates

Optimized Testing Procedure

- Setup determined from conclusion of studies
  - from material properties dispersion curves are calculated
  - from group velocity dispersion curve, operating frequency selected
  - from operating wavelength, actuator size is selected
- PZT piezoceramic patches used for actuators and sensors
- Excite A_o wave for long travel distances and to minimize clutter
- Driving signal of 3.5 sine waves under a Hanning window
  - 15 kHz for narrow specimen
  - 50 kHz for sandwich beams

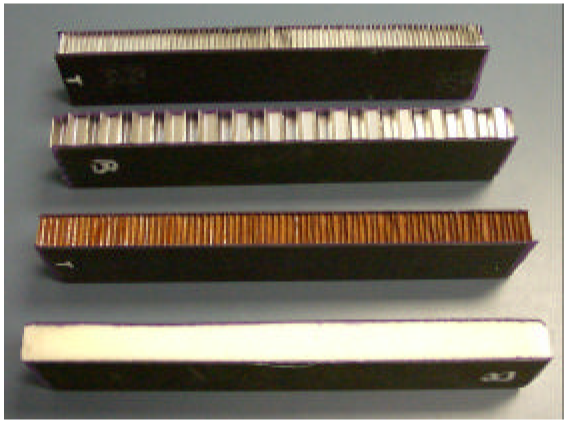




Sent Signal

Building Block Approach

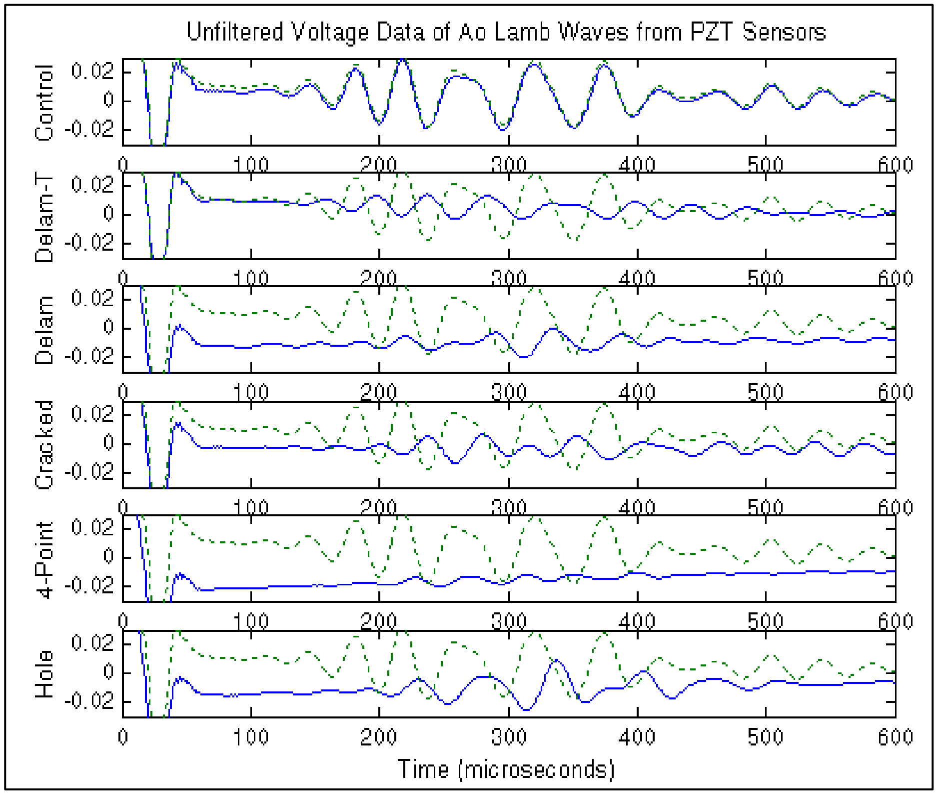
- Coupon level laminate tests
  - consistency amongst control specimens
  - effects of various types of damages



- Narrow sandwich beam specimens
  - effects of various types of cores
  - delamination between laminate and core in different locations

- Complex structures
  - micro-satellite tube with honeycomb core
  - built-up structures with bonded ribs
- Future work with flat plate specimens
  - actuating in center with sensors around edges
  - “self-sensing” actuators in corners

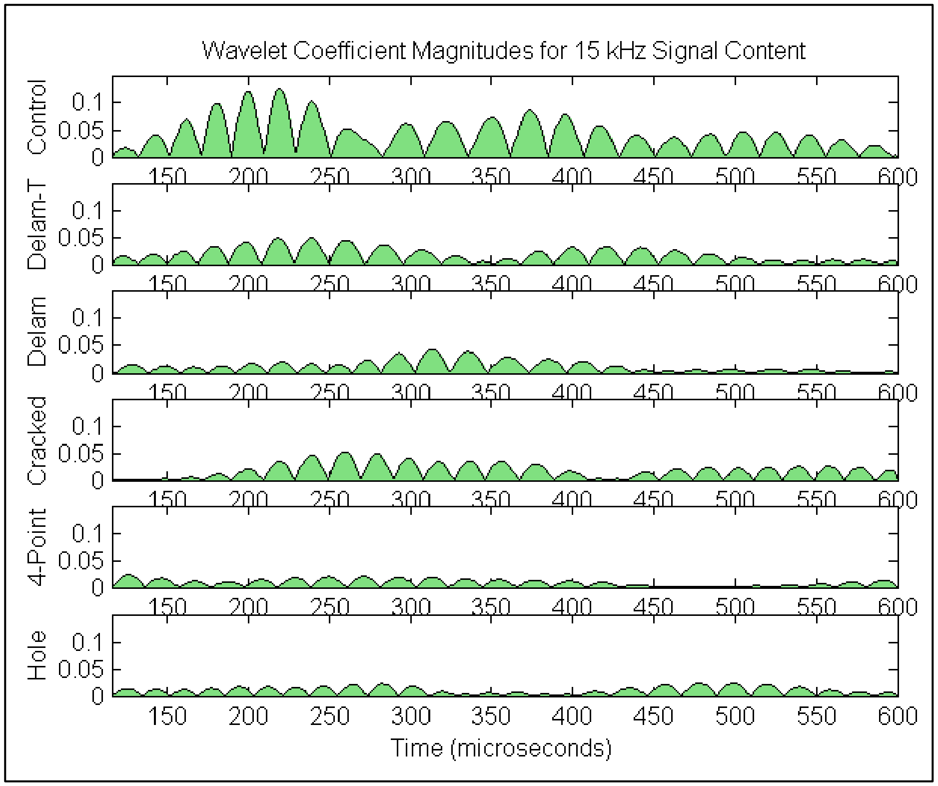
Thin Laminate Results: Time of Flight



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

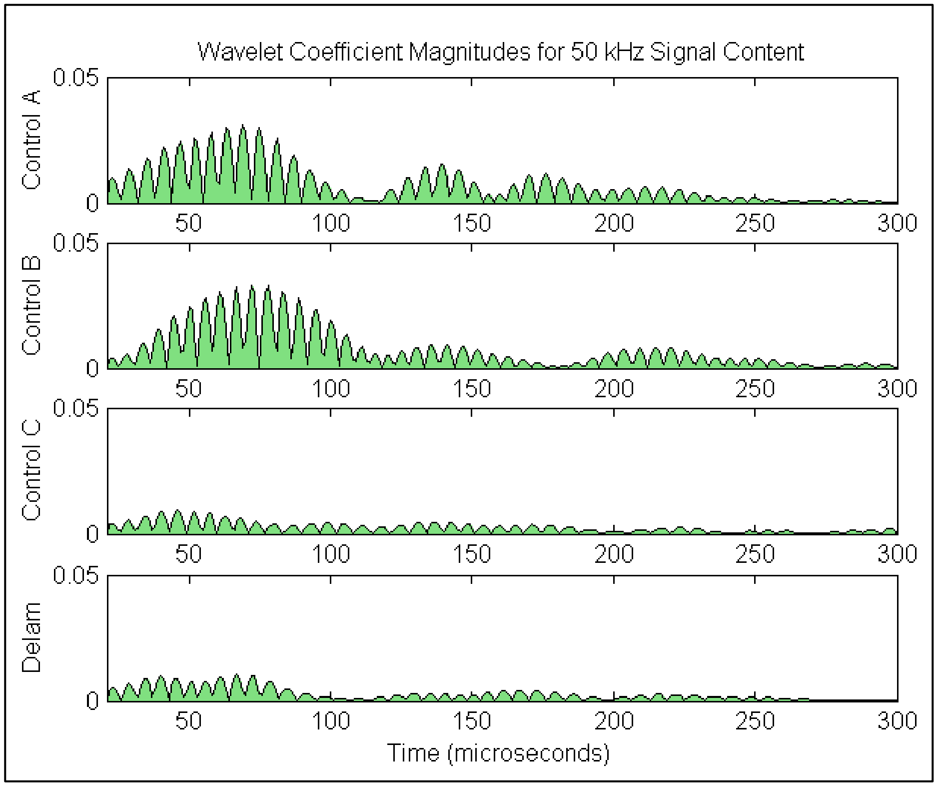
Thin Laminate Results: Wavelet Analysis



- 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 severity

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 specimen

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

Preliminary Lamb Wave Conclusions

- Method shows great detection sensitivity to damage
  - has demonstrated presence and severity of damage capabilities
  - potential for damage location with self-sensing actuators
- Method must be tailored for particular material and application
  - combination of models and tests to determine driving frequency
  - patch size and location depends upon material, thickness, curvature
- Several limitations exist
  - active power requirement
  - complex results caused by need for high sensitivity
  - results are localized to straight path and max traveling distances
- Possible strategy for implementation in SHM system
  - also light, conformal, but requires small voltage for actuating
  - could use same sensors as FRM and AE to produce Lamb waves
  - groups of sensors to be placed in areas of concern for triangulation

Future Work

- Further actuator and sensor optimization
  - other piezoelectric materials
  - patterned electrodes
  - geometry
- Finite element representations of all tests
- Combined testing using several co-located methods
  - Lamb wave
  - frequency response
  - acoustic emission
  - strain based
- Refine analysis procedures for reliable automated detection of presence of damage
- 2-D testing of plate sections