Recent Research on Damage Detection Methods for Helicopter Rotor Systems

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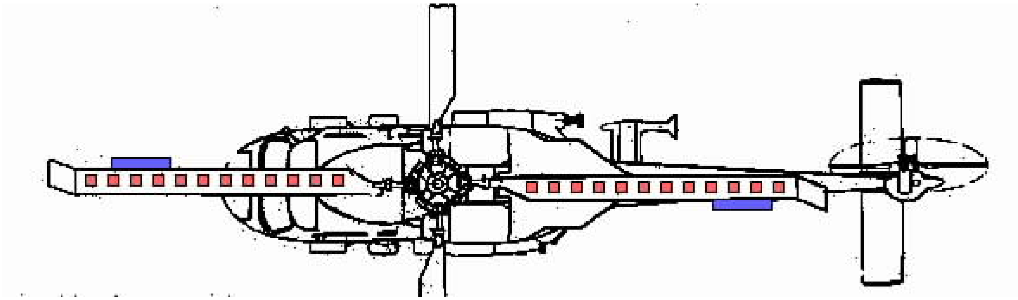
Background

- Common Damage encountered in helicopter & tiltrotor blades:
  - o Leading edge erosion damage and related cracks
  - o Delamination & fiber failure (following low speed impact)
  - o Ballistic impact
  - o Fatigue cracks (matrix)
  - o Bearings and linkages



Overall Goal (Subtasks)

Develop suite of Damage Detection methodology and systems:

1) **Impedance Methods**
2) **Guided waves**
3) **Structural Intensity Sensing**

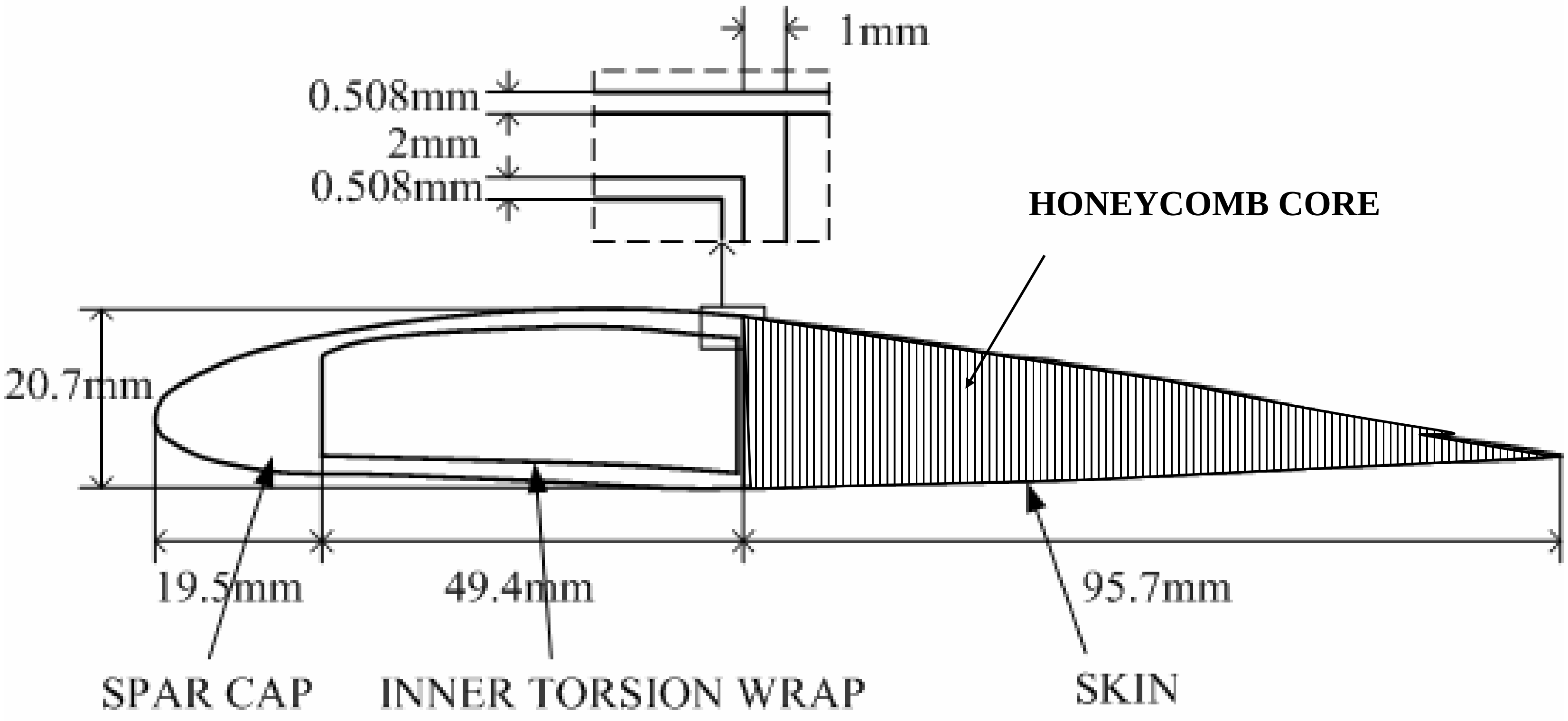
Interrogation signals

- Embedded transducers
- Signal processing

Structure of a typical composite helicopter rotor blade

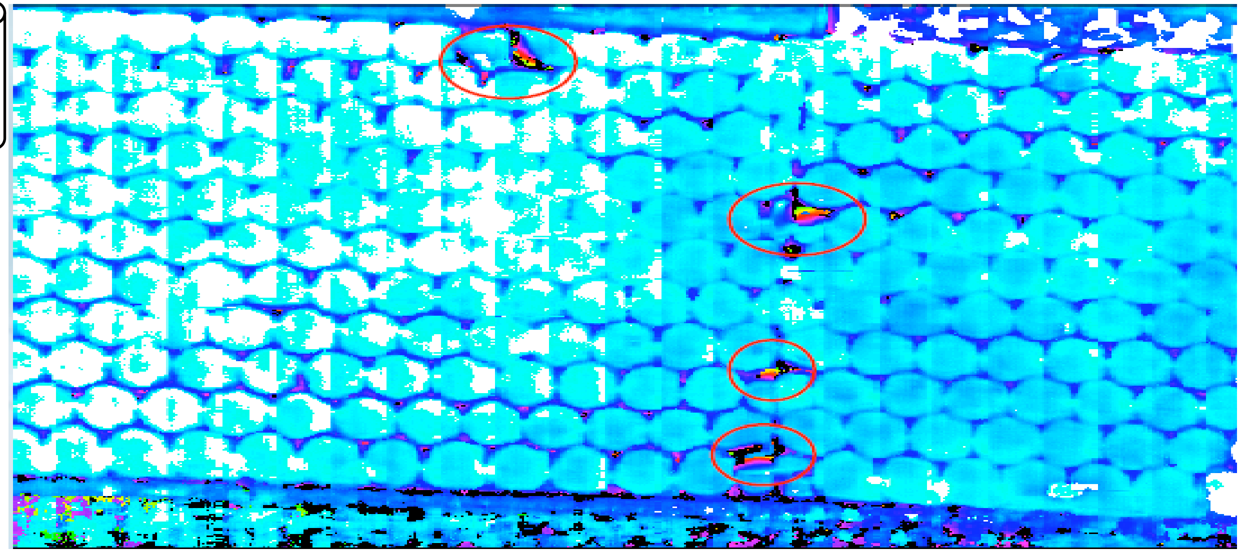
Metal blades (c 1960-70s): Finite fatigue life ($20-$30K/blade for med helo)

Composite blades (1980s +): "Infinite" fatigue life ($200-$300K/blade)

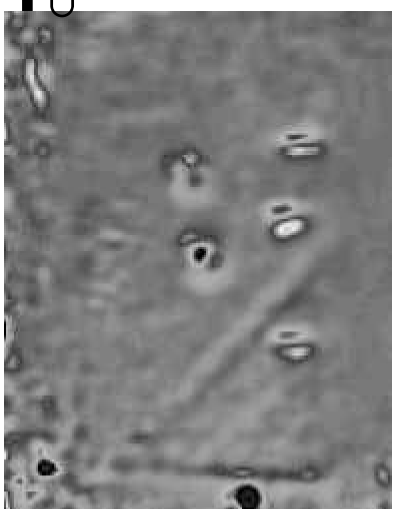


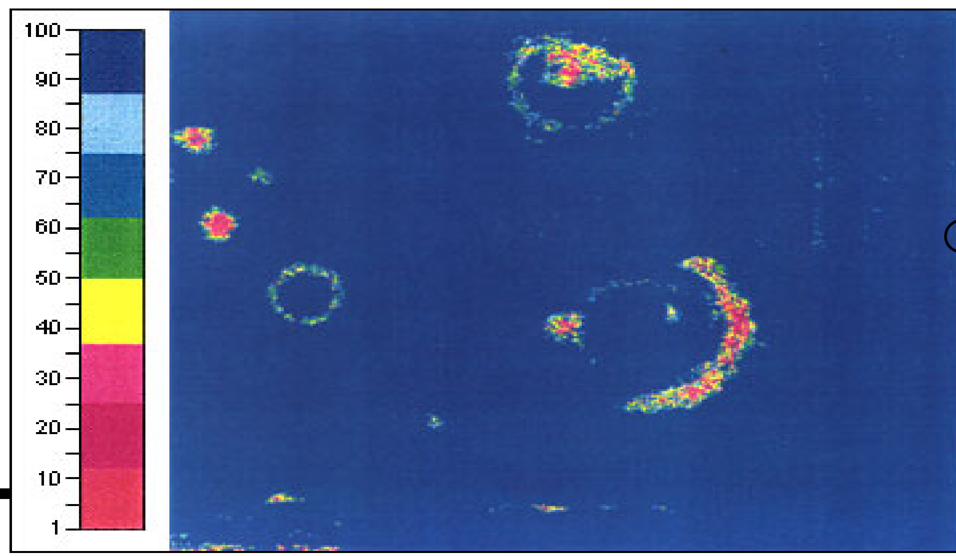
Damage Database: Skin-Core Delamination

Delamination
Ultrasound PA



Local Delamination
Shearography





Delamination
C Scan

Damage Database: Erosion/Corrosion

Skin Erosion

Erosion leading to delamination

Moisture leading to corrosion under the doubler

Damage Database: Skin Cracks

Root end blade crack
Dye Penetrant

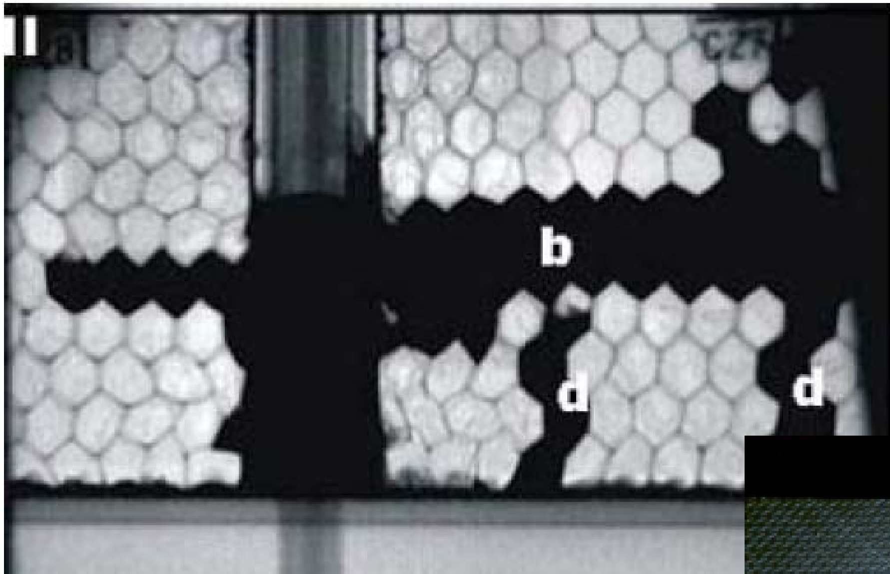
Leading Edge crack
Dye Penetrant

Damage Database: Ballistic Impact

Ballistic

Impact

Damage Database: Moisture



Moisture

Neutron Radiography (NR)

Moisture

X-Ray

Motivation - HUMS for Weight Savings

CURRENT DESIGN APPROACH*:

1) Factory NDE Inspection for “”small” flaws
2) No subsequent capability to find “small” flaws
3) Must assume they exist and prevent from growing

Lower strain allowables = heavy weight (e.g. 1000 lbs/blade heavy lifter)
(3000 micro-strain)

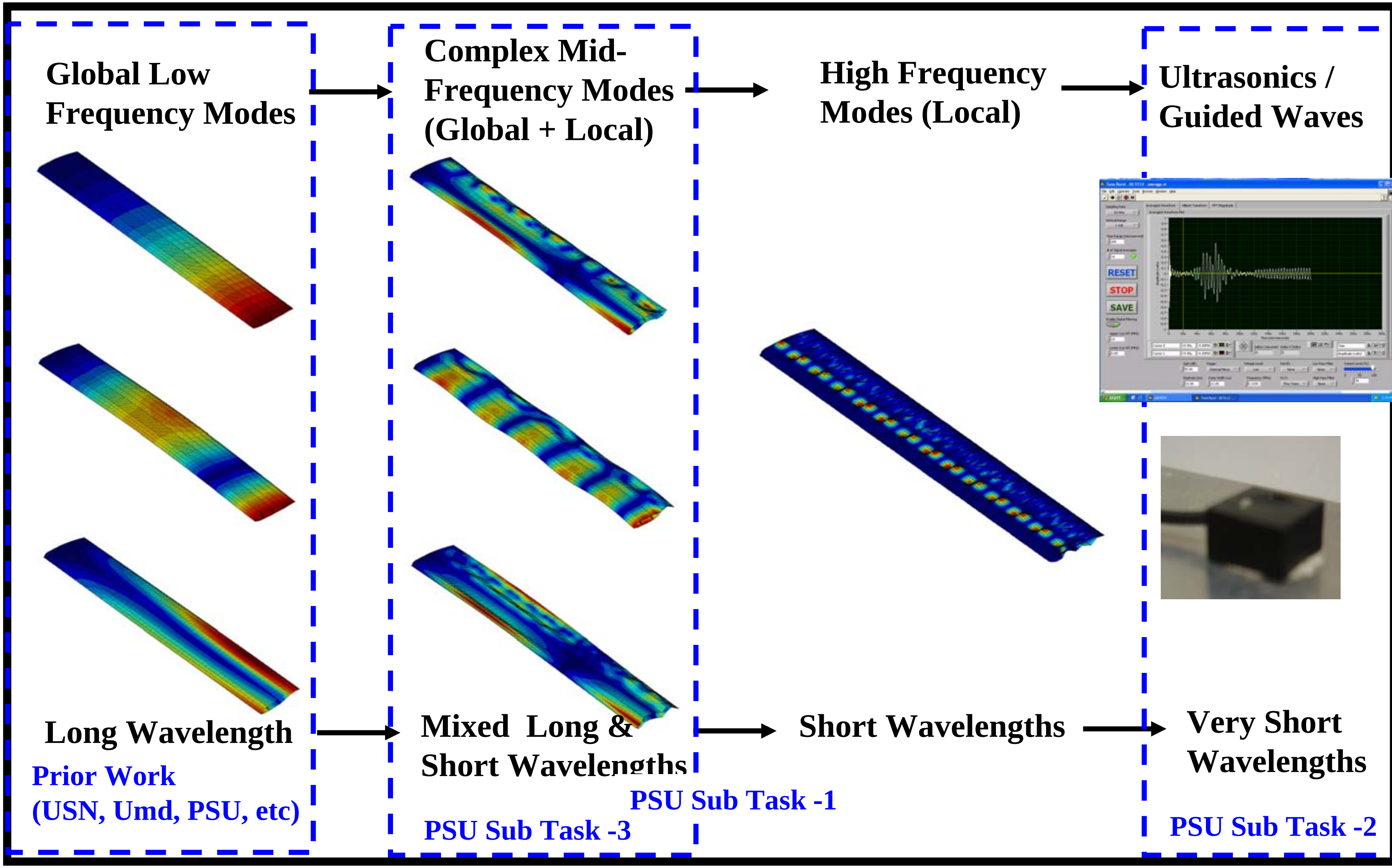
DESIRED FUTURE DESIGN APPROACH:

1) Factory NDE Inspection for “”small” flaws
2) NEW capability to find “small” flaws using high fidelity embedded sensors
3) NEW Capability to repair composite structures before flaws grow (healing)

Higher strain allowables = reduced weight (perhaps 15-20% savings)

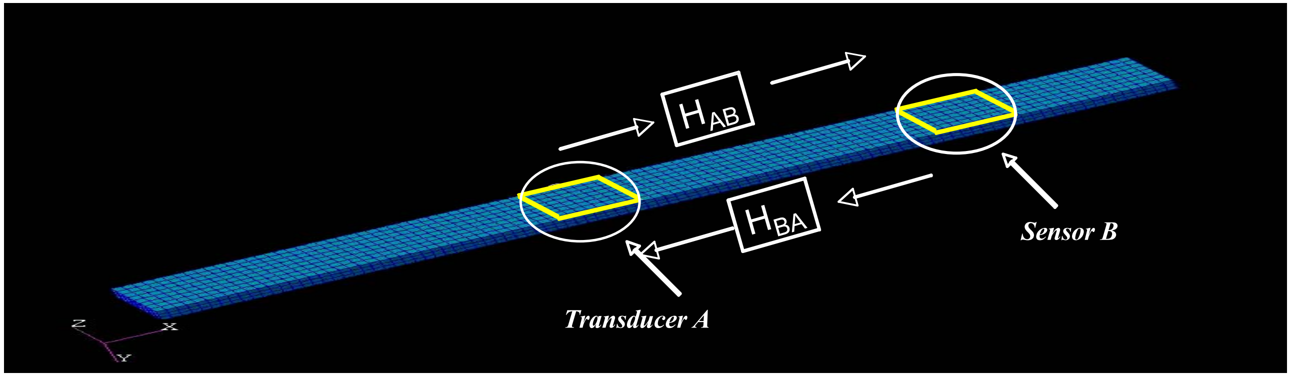
* Based on 2004-2005 NASA-Industry Heavy Lift Study (Smith & Zhang, et al)

Notional Blade Design:
Vibration Classification & Damage Detection Approaches



Electro-mechanical Impedance Methods

Prof. Kon-Well Wang, Prof. Edward Smith
PhD Student: Fabio Semperlotti



Electro-Mechanical Impedance : General Considerations

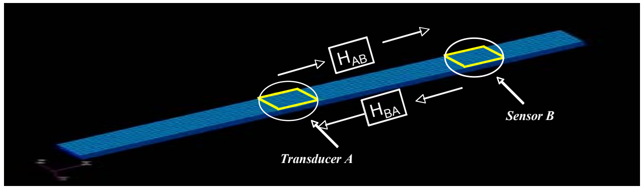
- ***Advantages:***
  - ✓ High Sensitivity to small defects
  - ✓ Do not need any FE model of the host structure
  - ✓ Easy Interpretation of the results
- ***Disadvantages:***
  - ✓ Limited Sensing area (Local damage detection)
  - ✓ EMI with co-located sensors does not provide any information about the location of the damage.
- ***General Constraints:***
  - ✓ Do not rely on a FE model of the host structure
  - ✓ Minimize the number of sensors needed

Transfer-Impedance

- The Transfer Impedance is defined as the impedance measured through a sensor 1 while exciting the structure by a Transducer 2 (*Non-co-located transducers*).
- In a linear domain, the Cross Transfer Functions between the two transducers are exactly the same;

this results in the same value for the Cross-Transfer Impedance.

$$H_{AB}=H_{BA}$$



The transfer impedance in the linear domain can be used only compared with the Pristine state signal of the host structure.

A nonlinear FE model must be used to calculate the mechanical impedance of the host structure.

Electro-Mechanical Impedance Theory

- **The electrical impedance of an electric circuit is defined as:**

$Z=V/I$ *(1)*

V=Volt
I=Electric Current

The effective mechanical impedance is defined as:

$Z_{eff}=F/u'_{eff}$ *(2)*

F=Applied Mechanical Load
u'_{eff}*=effective velocity*
u_{eff}*=effective displacement*

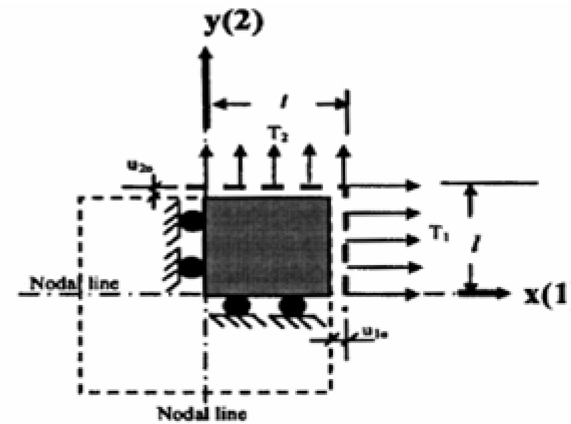
The mechanical impedance of the PZT rectangular patch can be derived through the equation (2) expressing the effective velocity as the first derivative of the displacement of the patch in the in-plane directions. Displacements can be obtained through the solution of the wave equation for a rectangular plate.

Electro-Mechanical Impedance Theory

- **The effective mechanical impedance of the patch will result in:**

$$Z_{a,eff} = \frac{2klh\,\bar{Y}^{E}}{j\omega(\tan kl)(1-\nu)}$$

$$k = \omega\sqrt{\frac{\rho}{\bar{Y}^{E}}}$$



***l* =PZT patch length**

***H* = PZT patch width**

***v*= Poisson's ratio**

***Y^E* = complex Young modulus**

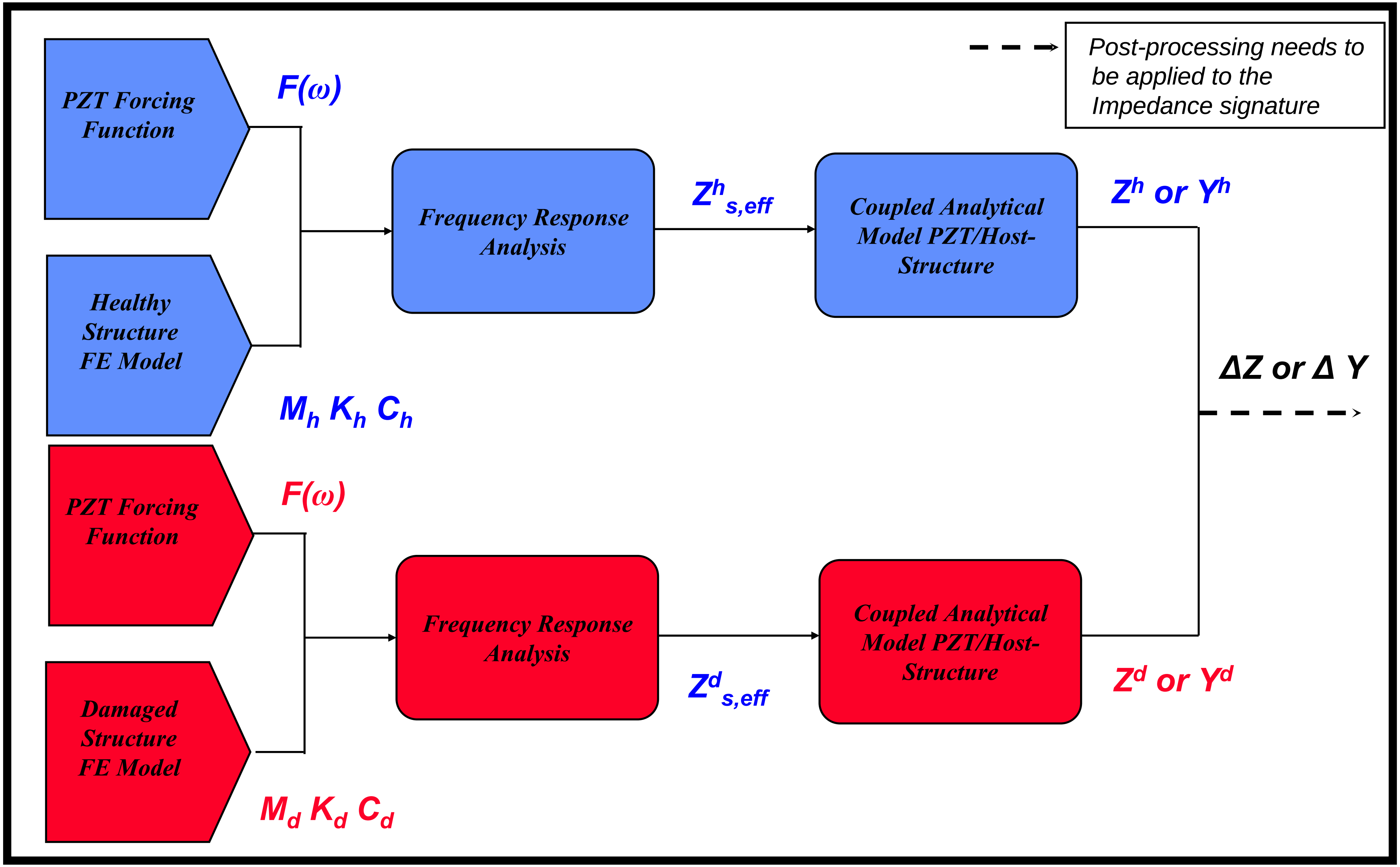
Using the linear constitutive equation for the piezoelectric material along with equation (1) we obtain the electromechanical impedance of the coupled system:

$$Y = \frac{1}{Z} = \frac{I}{V} = j\omega\frac{l^2}{h}\left[\varepsilon_{33}^{T} - \frac{2d_{31}^{2}\bar{Y}^{E}}{(1-\nu)} + \frac{2d_{31}^{2}\bar{Y}^{E}Z_{a,eff}}{(1-\nu)(Z_{s,eff}+Z_{a,eff})}\left(\frac{\tan kl}{kl}\right)\right]$$

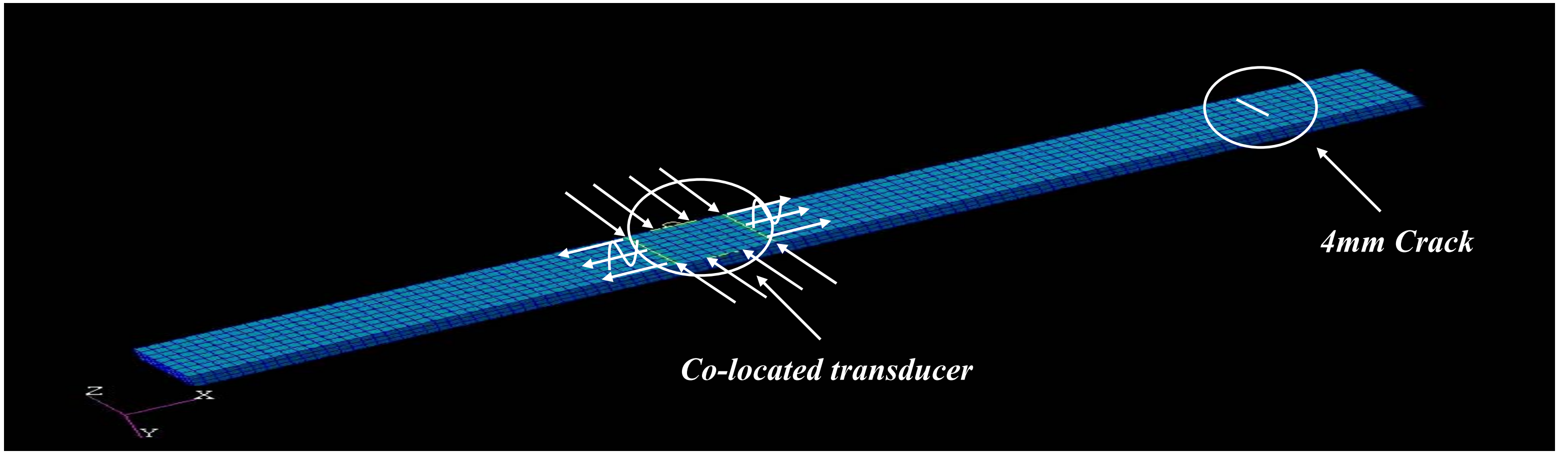
***d_{31}* = Piezoelectric constant**

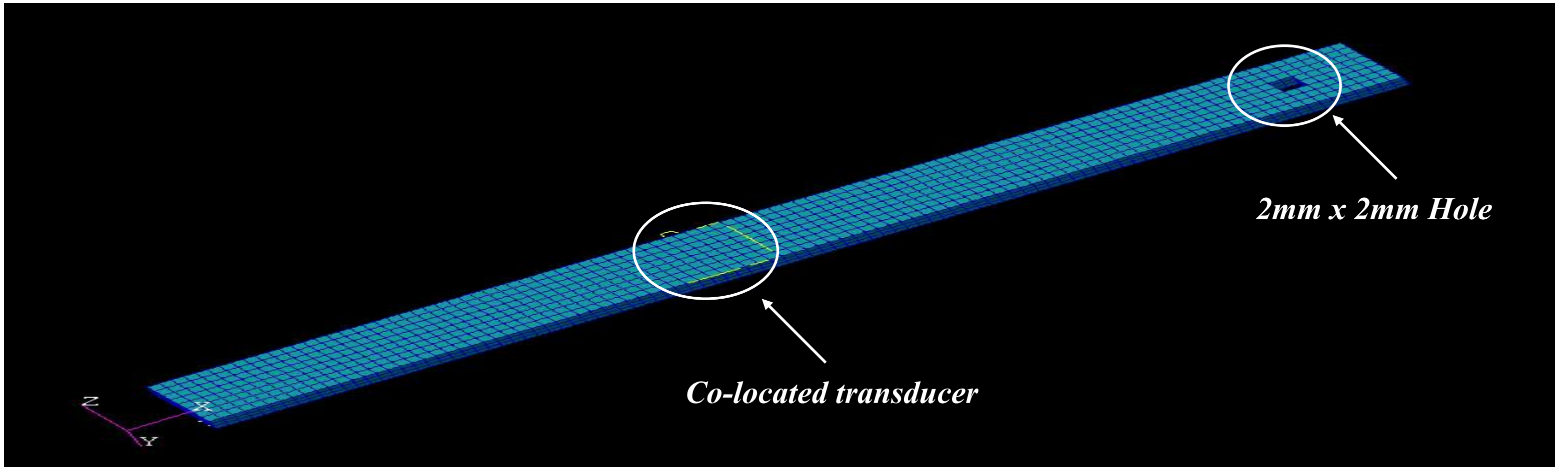
***ε_{33}* = Constant piezoelectric permittivity at constant stress**

FLOW CHART: DETECTION PHASE 1
(Existence of damage)

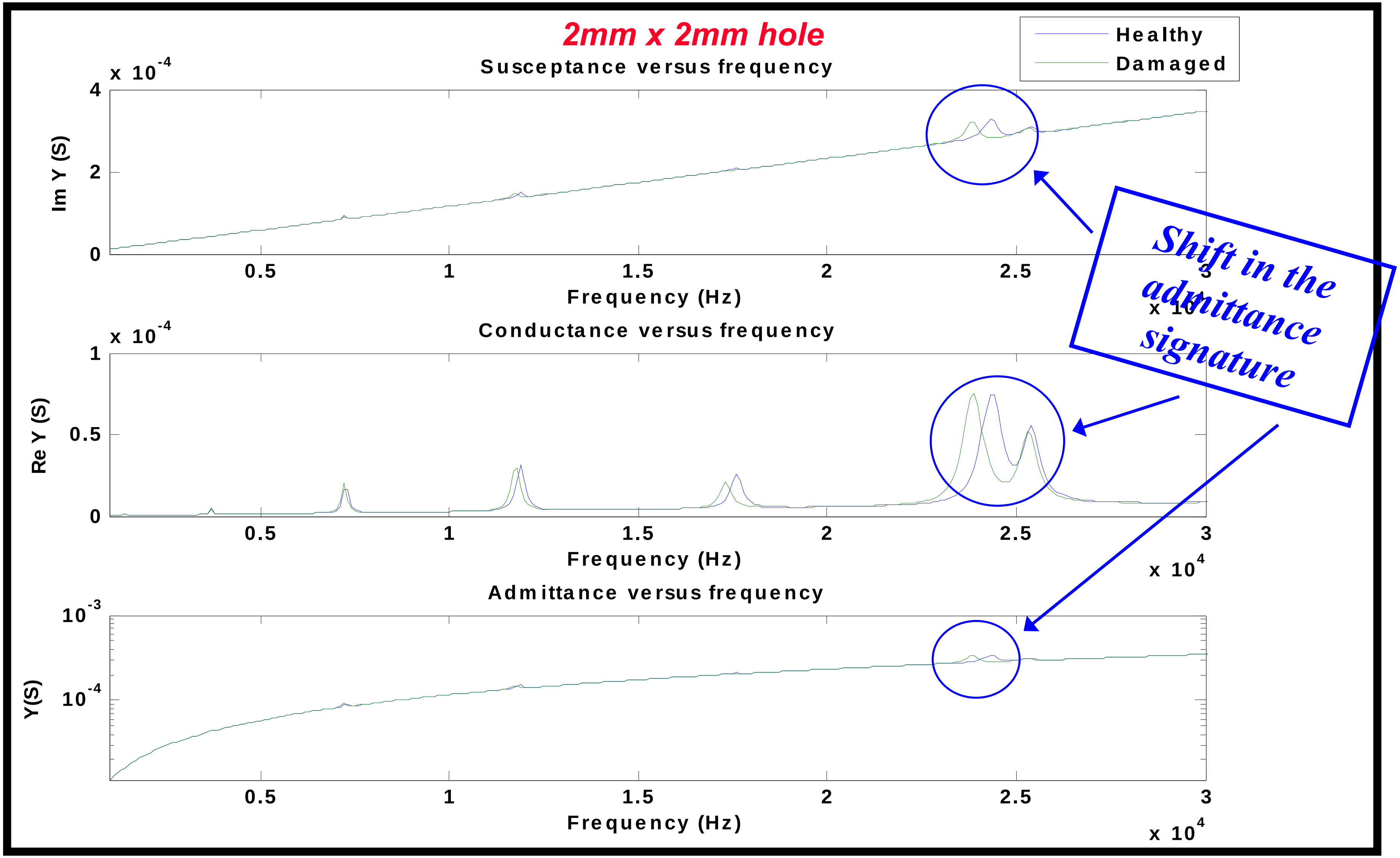


Preliminary Results: FE Model





Preliminary Results: Admittance Signature



Current Objectives of Work

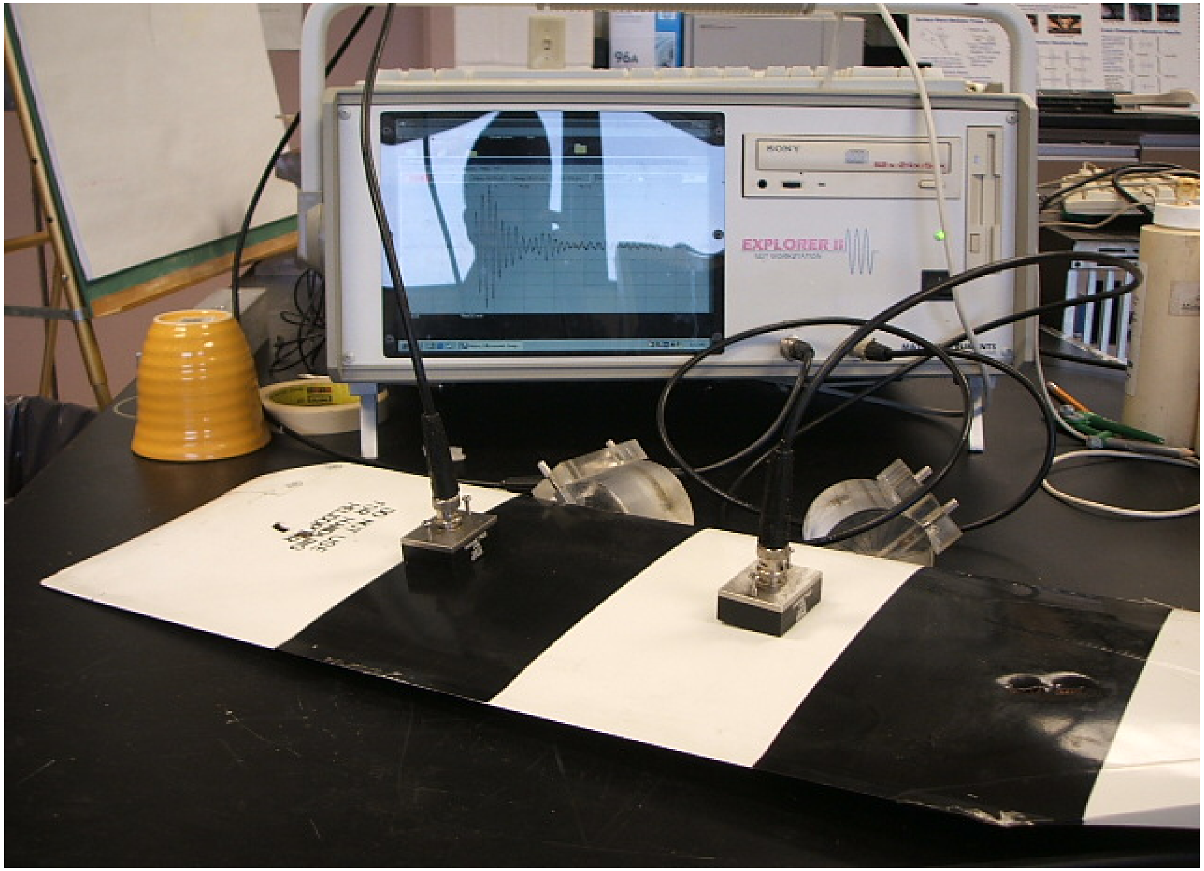
- **Developing the EMI coupled semi-analytical model with co-located sensors.**
  - ✓ Parametric study and sensitivity analysis to different defects on simple structures (beam and/or plates).
  - ✓ Compare the analytical results with experimental measurements obtained through a Precision Impedance Analyzer.
- **A post-processing technique will be applied in order to analyze the data.** (*Wavelets Transform and Hilbert-Huang Transform are under evaluation)*
- **Evaluating the feasibility of a Nonlinear Transfer Impedance Approach to perform phase 2a detection.**
  - ✓ Developing a coupled semi-analytical model with non-co-located sensors.
  - ✓ Identifying empirical or semi-empirical relations to detect the damage location.
  - ✓ Compare the analytical results with experimental measurements.
- **Evaluating the performance of the proposed Damage Detection System on a scale d rotor system.**
- **Evaluating the effect of the centrifugal force on the PZT analytical model.**

Guided Wave Sensing Based SHM

Prof. Joe Rose
PhD Student: Xue “Kevin” Qi

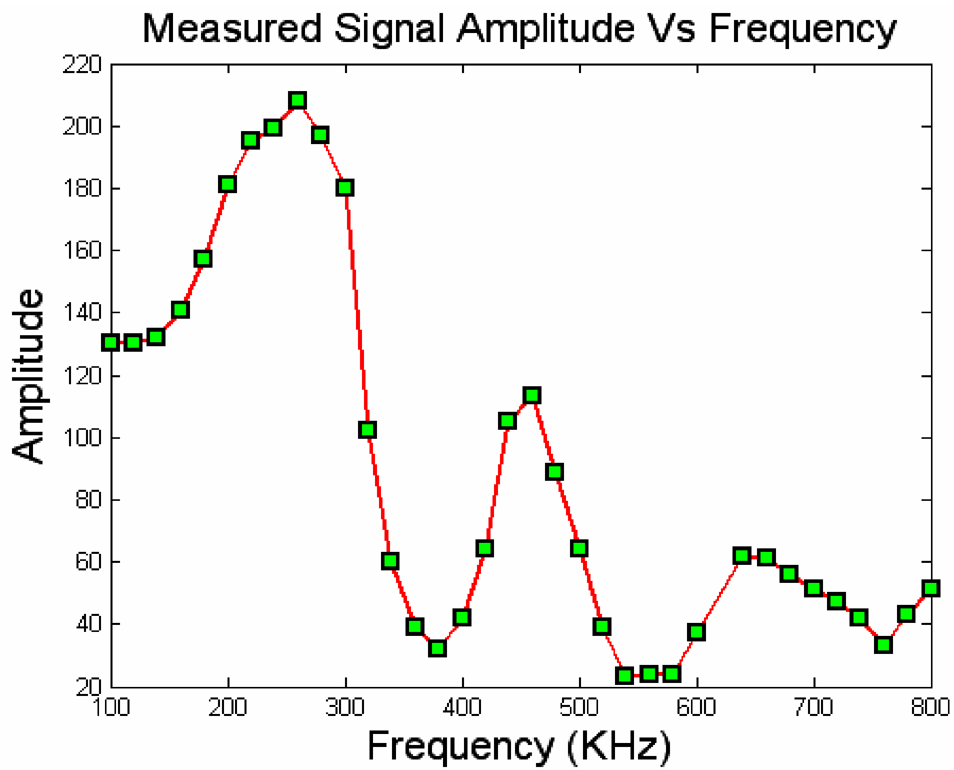
- **Initiating packaging efforts on PZT ceramic sensor design, fabrication and evaluation. (Packaging enhances the safety and stability of the sensor.)**
- **Penetration power measurements for angle beam transducers and normal beam transducers on the leading edge and trailing edge of a portion of a rotor blade:**
- **Experiments proved that the ultrasonic wave excited by a pair of transducers could cover a reasonably large area on the surface of the rotor blades.**
- **Initiated FEM simulation for ultrasonic wave propagation in the sandwich structure of a helicopter rotor blade.**

Experiment setup of helicopter rotor blade A

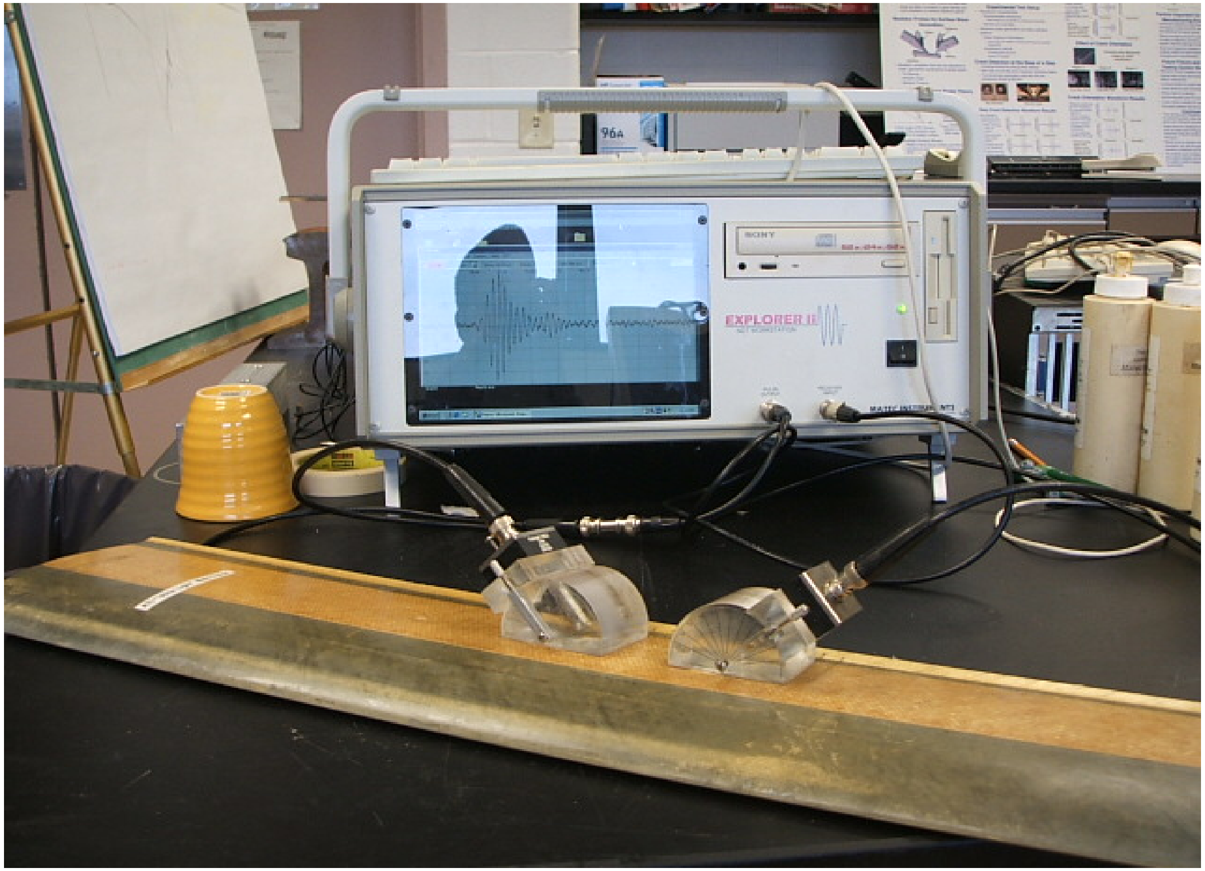


A109
TR (metal)

Amplitude of ultrasonic guide wave Vs frequency in blade A, measured with a normal beam transducer

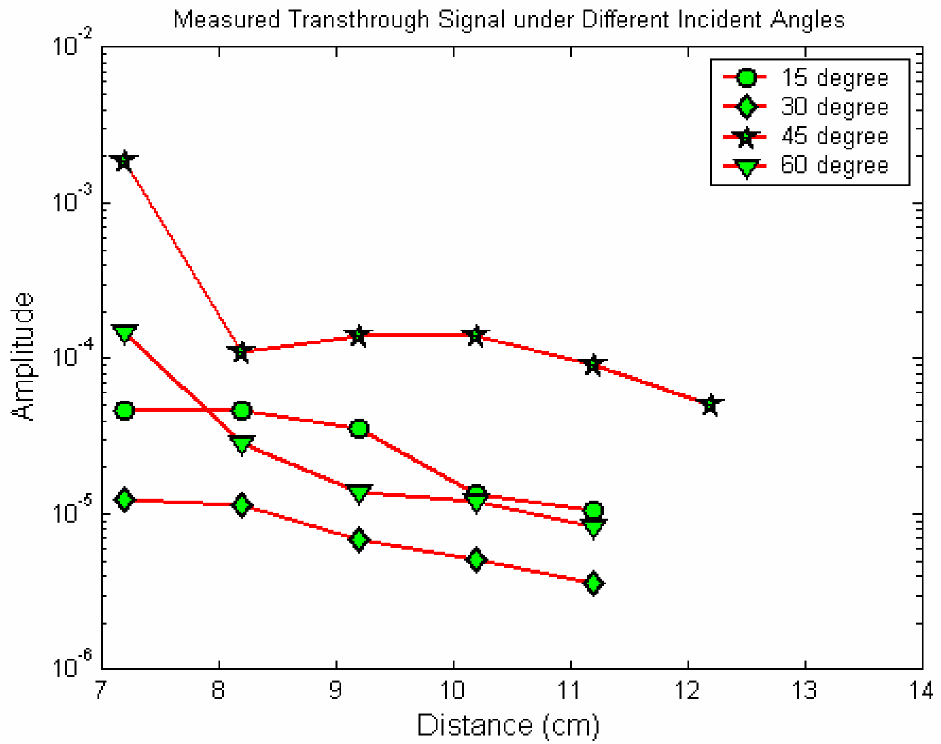


Experiment setup of the helicopter rotor blade B



ATI
UltraLight MR

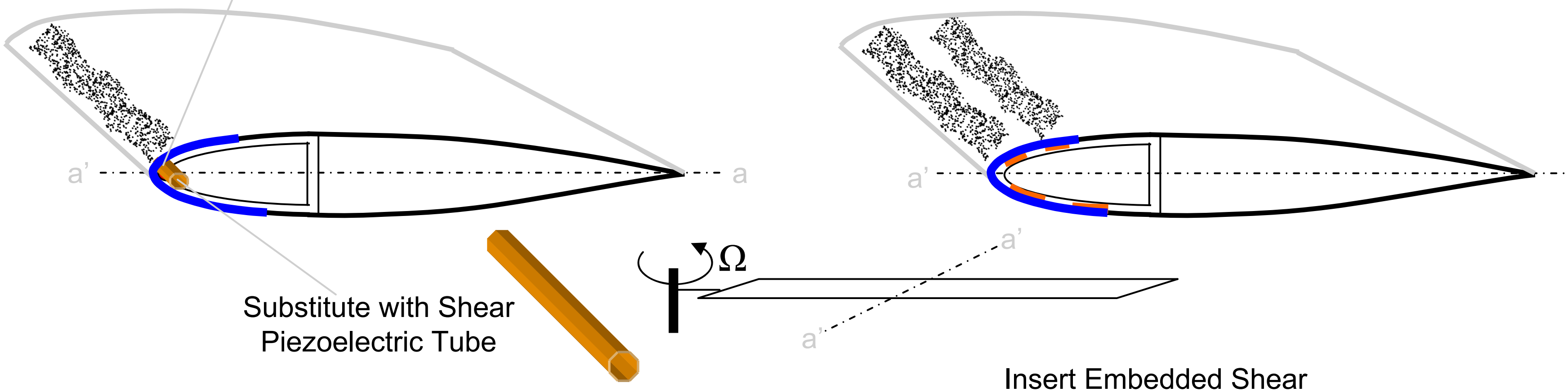
Peak-peak amplitude of ultrasonic guide wave in the trailing edge of blade B



Anti-Icing Conceptual Design (2004-2006)

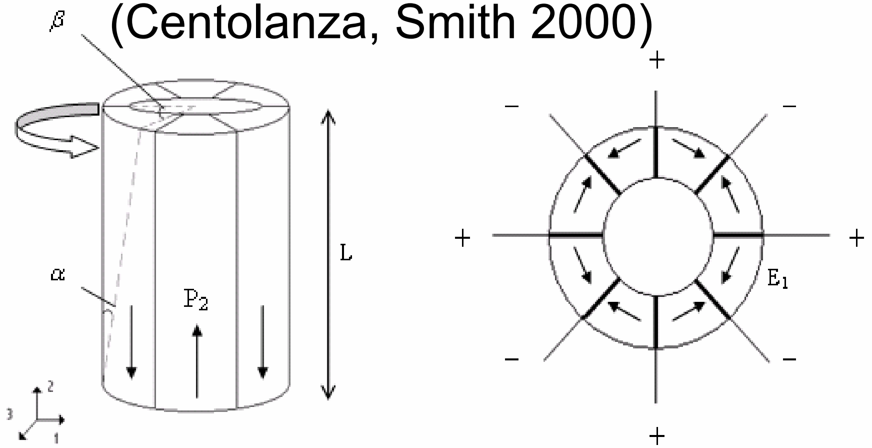
1 Leading Edge Mass (10 – 20% Weight of the Blade)

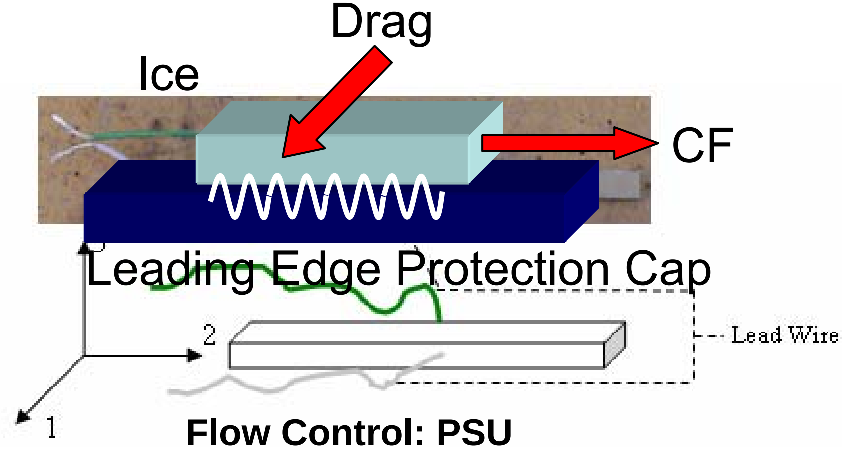
2



Insert Embedded Shear Actuators

(Centolanza, Smith 2000)



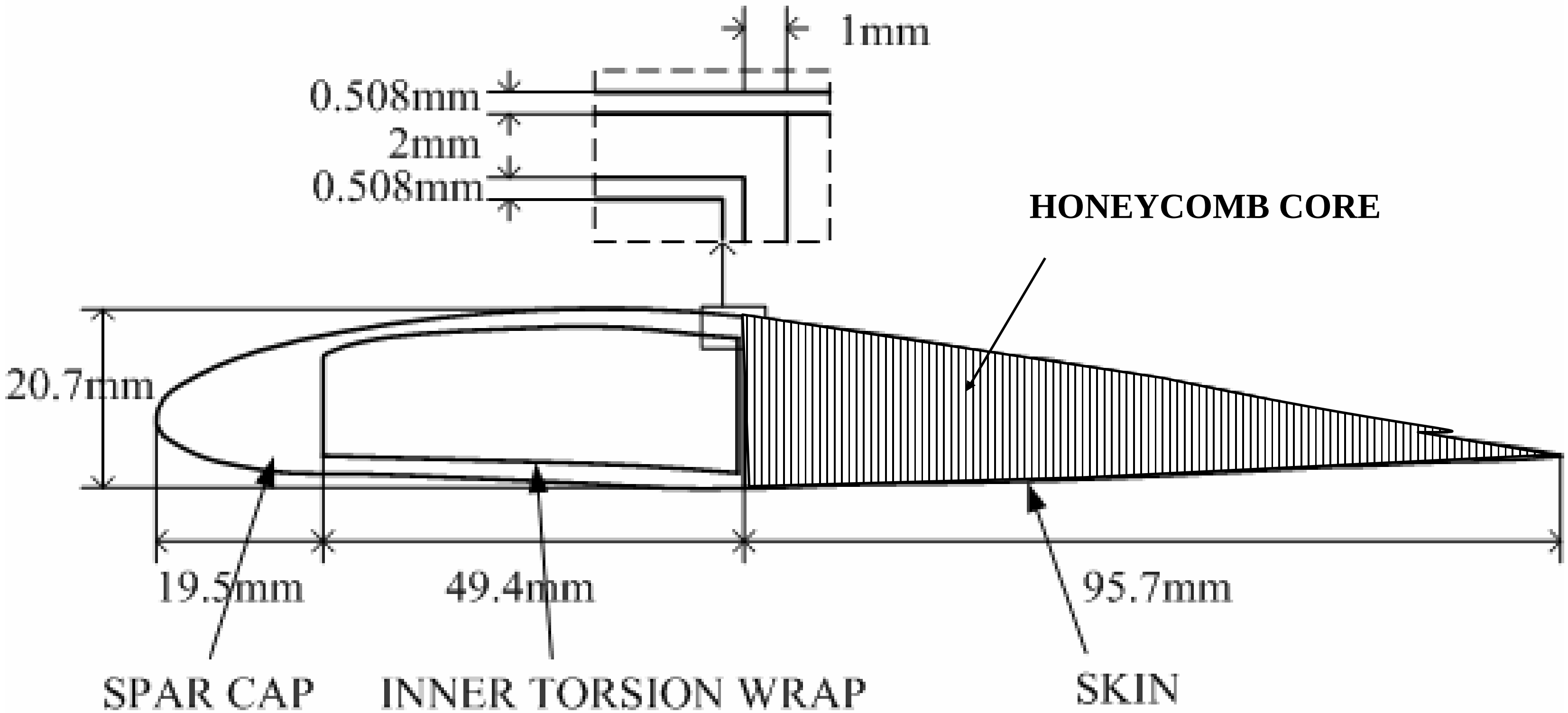


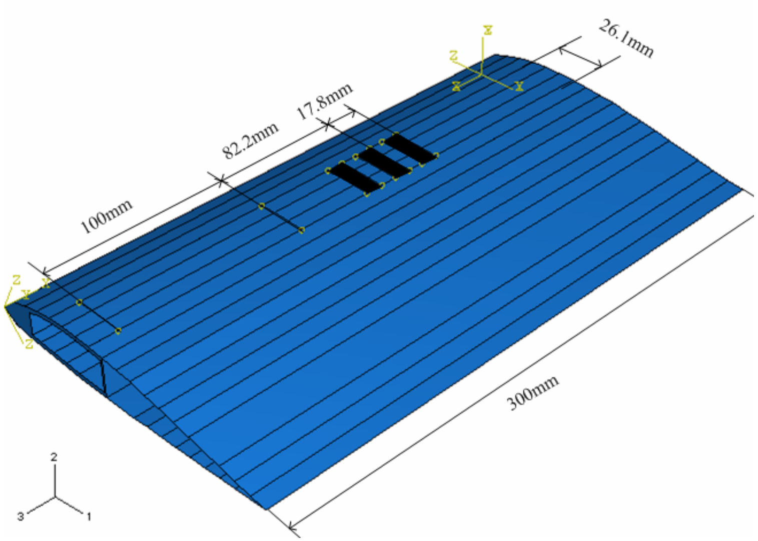
- Segments poled along longitudinal direction, P_2
- Electric field applied in the width direction, E_1

Flow Control: PSU

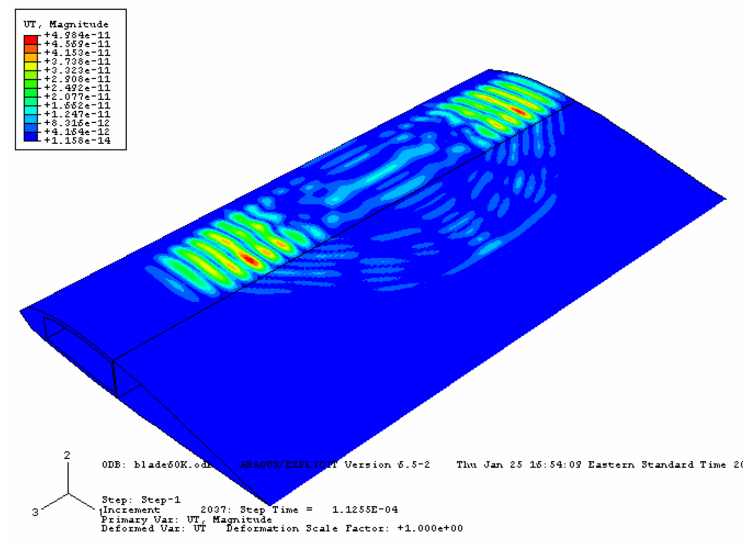
Damage Detection: Rose, Smith, Wang, Conlon CRI

Structure of a typical composite helicopter rotor blade





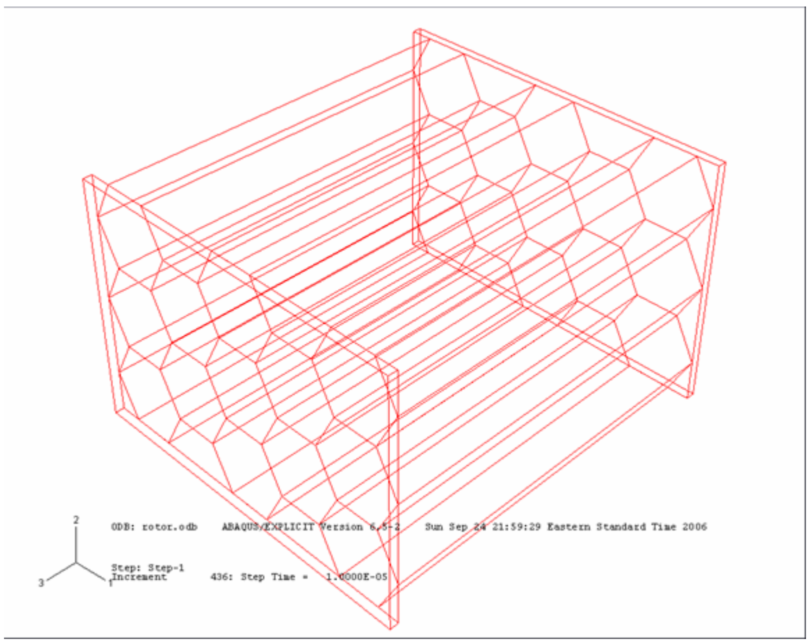
FEM model of a composite rotor blade with a comb transducer (the black region)

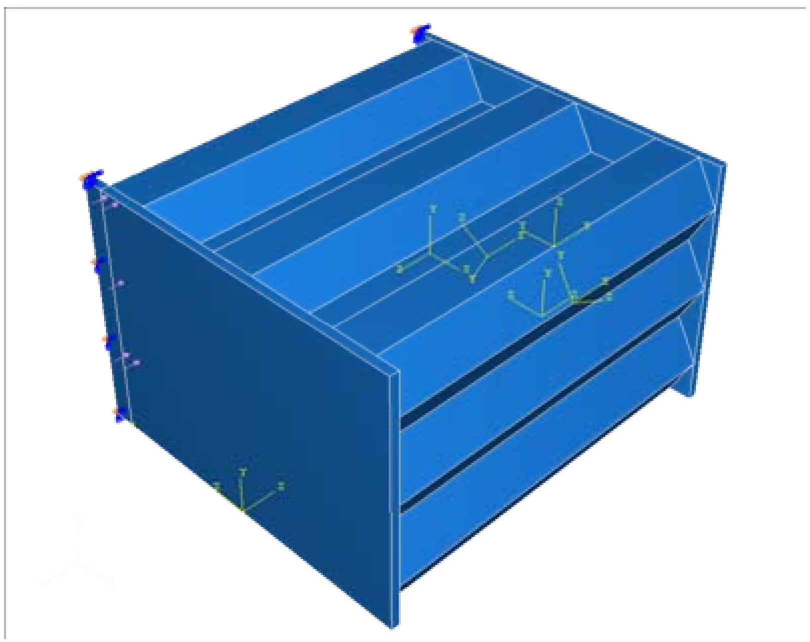


Simulation of wave propagating in the rotor blade

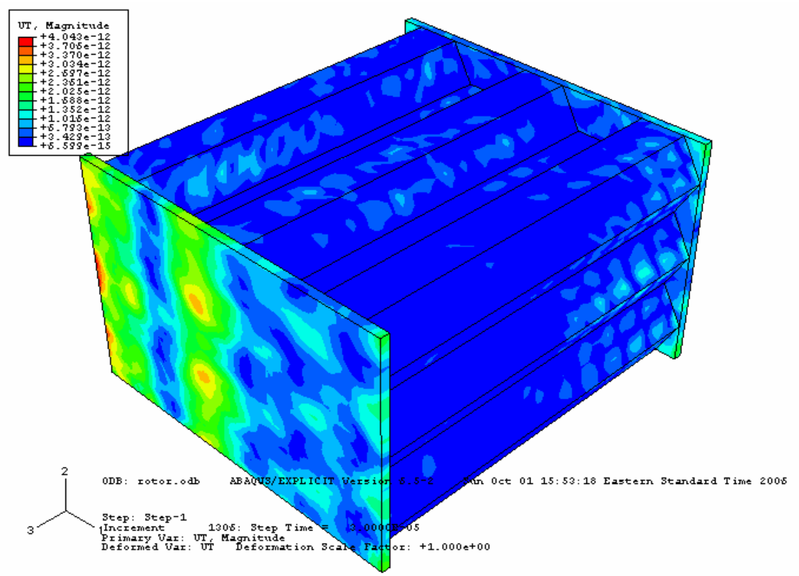
- From the FEM model, we can get the wave structure at any point of the blade
- Wavelength is adjustable by changing the size & space of the comb transducer
- Our purpose is to choose a suitable mode where the acoustic energy is focused at the required region.

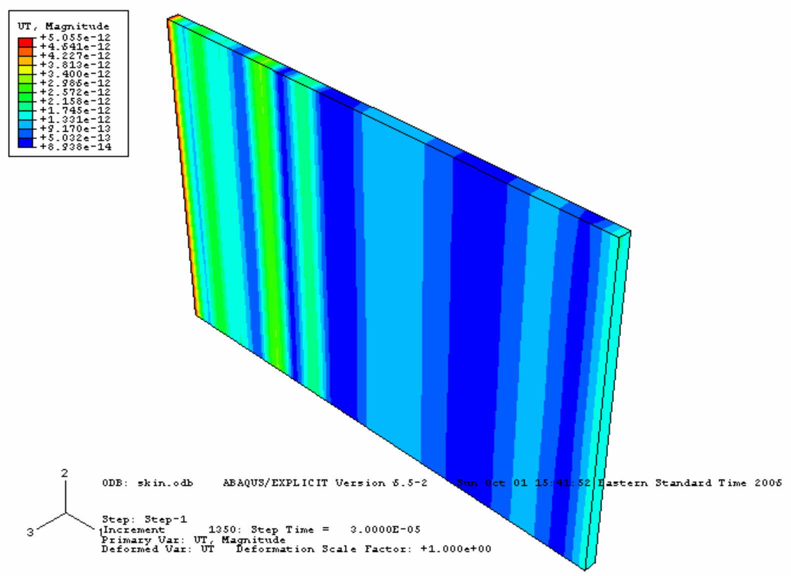
FEM simulation of honeycomb structure in the trailing edge



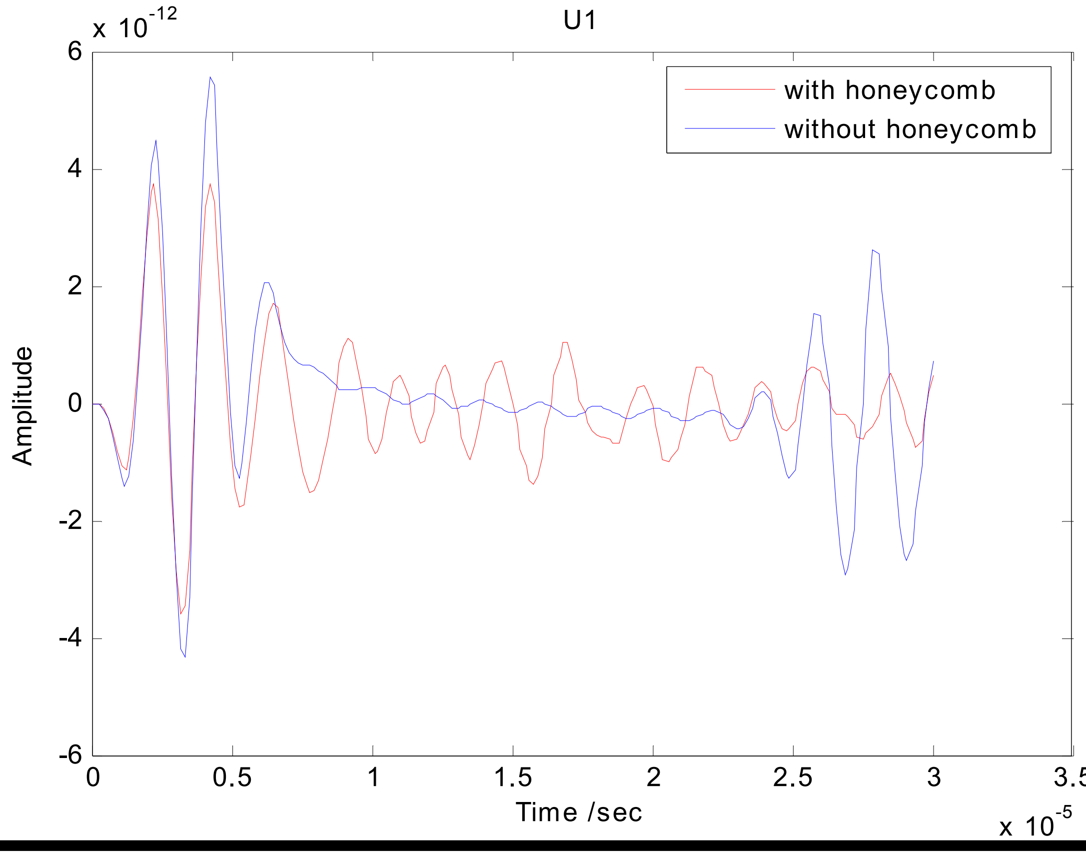


Comparison of signal with honeycomb and without honeycomb structure





Comparison of signal with honeycomb and without honeycomb structure



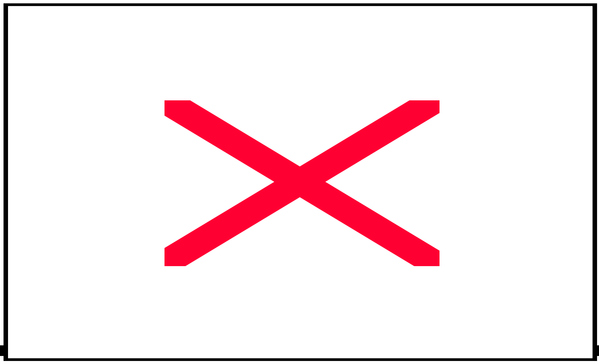
Damage Detection Using Structural Intensity Sensing

Prof. Steve Conlon
MS Student: Randy May

•**Developed Finite Element Models and performed structural intensity simulations for undamaged and damaged simplified structures**

• **Defined demonstration hardware for simplified structure, experiments are underway examining structural intensity / energy flow signal processing concepts**

•**Developed representative rotor blade model for detailed damage detection simulations**

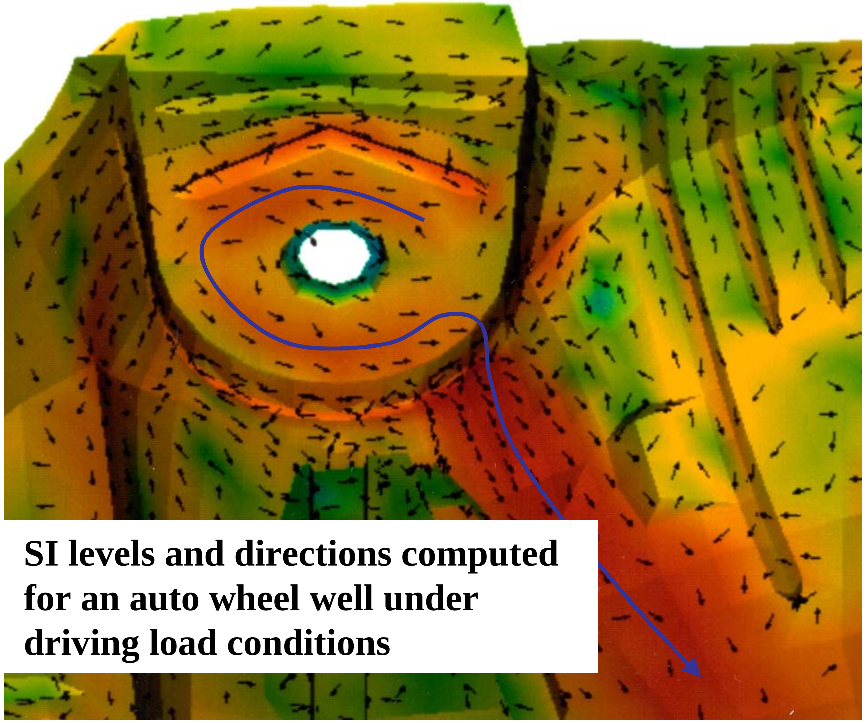


Structural Intensity Based SHM

Simulation using FE based models

Structural Intensities and total power (or energy) flow can be computed for complex "healthy" and "damaged" structures

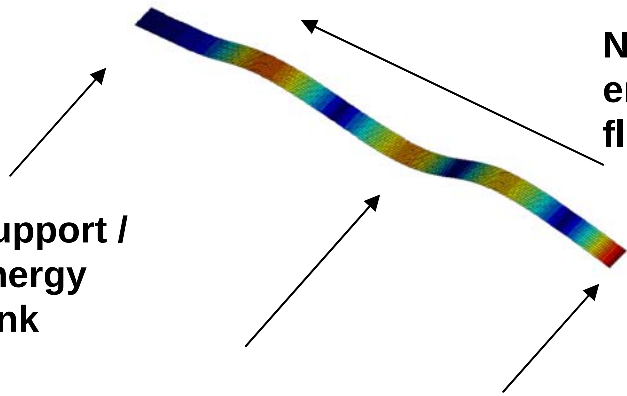
- Post processing forced response results.
  - Bar elements
  - Plate (Quad) elements
  - Solid elements

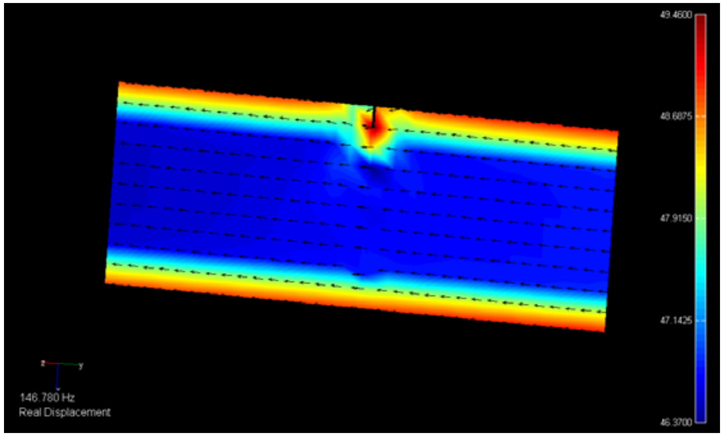


SI levels and directions computed for an auto wheel well under driving load conditions

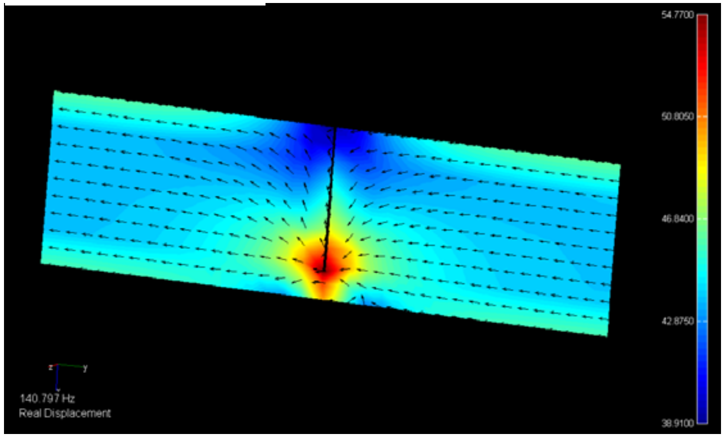
Structural Intensity Based SHM

- Simulation using FE based models





SI Small Notch



SI Large Notch

Structural Intensity Plots of Damaged Beam Section

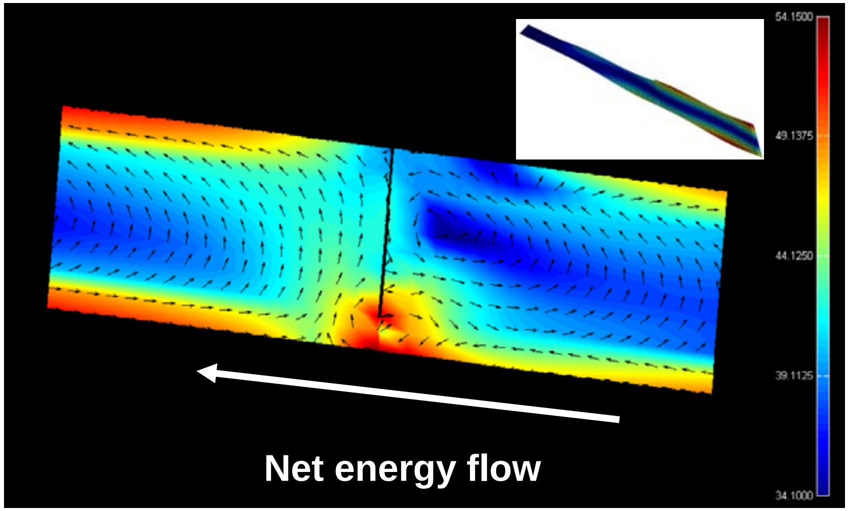
- **Unit vectors indicating intensity direction**
- **Color bar indicating intensity magnitude**
    - **Note: Scales not the same on two plots**
- **Net energy flow right to left**
- **Pure Bending vibration for these two cases**

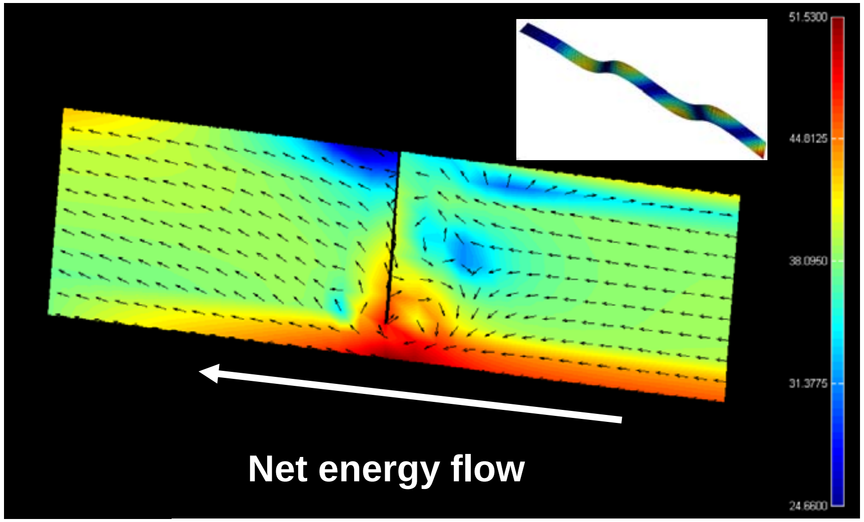
Structural Intensity Based SHM

- Simulation using FE based models

Structural Intensity Plots of Damaged Beam Section

- **Unit vectors indicating intensity direction**
- **Color bar indicating intensity magnitude**
- **Coupled bending / torsional vibration**
- **Significant energy recirculation at damage and away from damage location**
  - **Strongly detectable from SI phase change**



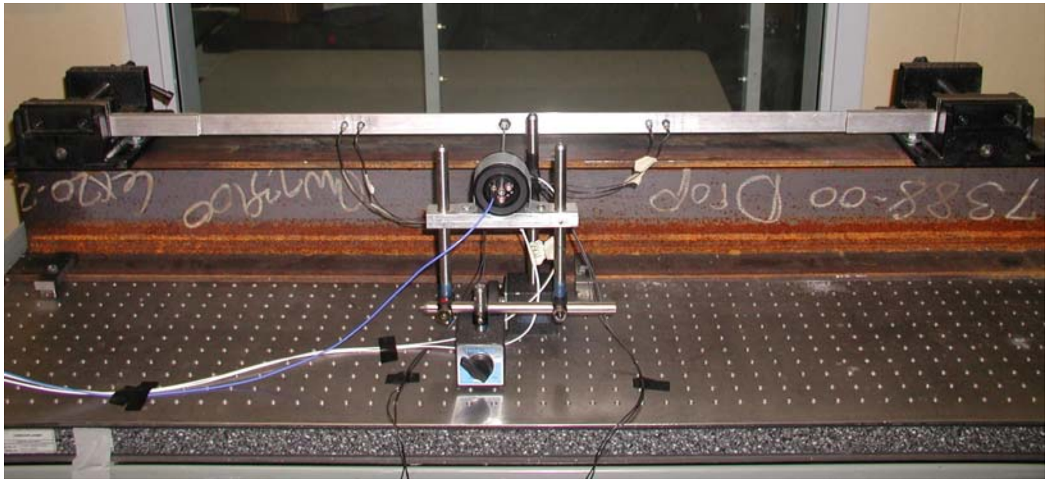


Structural Intensity Based SHM

- **Simplified Structure Experiments: Signal Processing Techniques Development – Notched Beam Experiments**

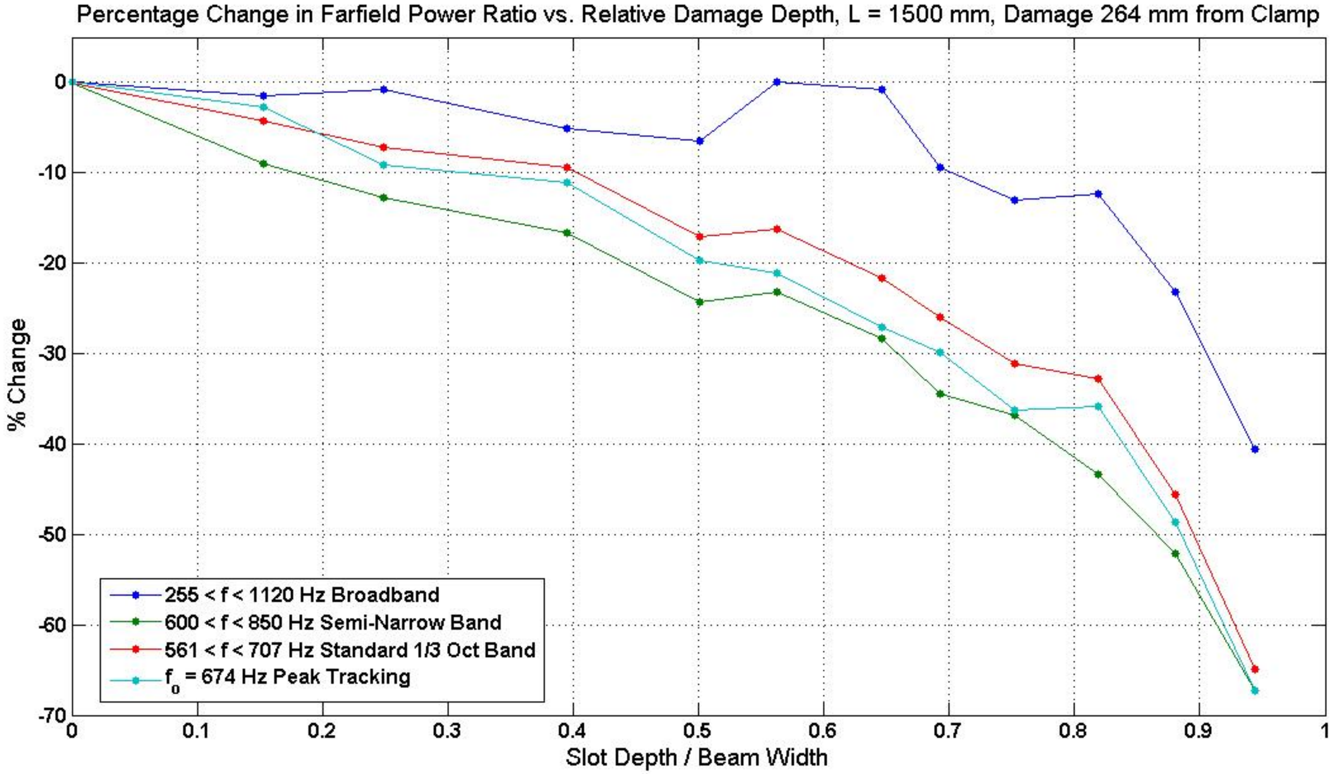
- Monitor changes in relative amount of power flow on either side of drive as Single Edge Notch (SEN) depth increased
- Test with varying damage locations
- Power measured with far-field limited two accelerometer finite difference technique

$$P = \frac{2\left(Bm\right)^{1/2}}{\Delta} \int_{f_1}^{f_2} \frac{\mathrm{Im}\left\{\overline{G}_{a_2 a_1}\left(f\right)\right\}}{\omega^2} df$$



Structural Intensity Based SHM

- **Simplified Structure Experiments: Signal Processing Techniques Development**



- Each band type reflects significant power flow changes
- Semi-Narrow, 1/3 Oct, and Peak Tracking band trends typically develop at lower severities than Broadband trends
- Broadband results dominated by high powers at low frequencies → masking of high frequency, low power effects
- **Typical healthy to fully damaged power ratio changes ~ 20 – 70%**
  Typical healthy to fully damaged resonance frequency shift ~ 1 – 7%

Summary - Rotor Blade Damage Detection

- **An In-Flight Damage Detection System is necessary:**
  - ✓ **reduce the blade's weight: Heavy Lift Application**
  - ✓ **Increase safety and reliability of the mechanical system**

- **Current HUMS in use on Helicopter are too rudimentary to detect small flaws.**

- **Numerous unique challenges**
  - **Highly flexible, fatigue loaded structures**
  - **Centrifugal loading**
  - **Various materials, tightly coupled**
  - **Nonlinear and highly damped structural dynamics**
  - **Weight critical**

- **Concentrated multi-year effort has been initiated in 2006:**
  - **Electro-mechanical Impedance methods**
  - **Guided wave mechanics with custom tailored embedded transducers**
  - **Structural Intensity methods**

- **Industry-University collaborative research environment**

  (Bell, Boeing, Sikorsky Goodrich, FBS, etc)

Project Overview

➢ **The Component Based Maintenance (CBM) Technology Project is a cooperative NRTC/CRI effort in concert with Bell Helicopter, Boeing, Sikorsky Aircraft, Goodrich, Georgia Institute of Technology (GIT), University of Illinois (UIC), University of Maryland (UMD), and Penn State University (PSU).**