Structural Health Monitoring for Life Management of Aircraft

-SHM System for Composite Structures –

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The Joint Advanced Materials and Structures Center of Excellence

SHM System for Composite Structures

- **Motivation**:
  Impact damage in composite structures followed by continued cyclic loading can lead to structural failure and an SHM system to monitor these will be useful.

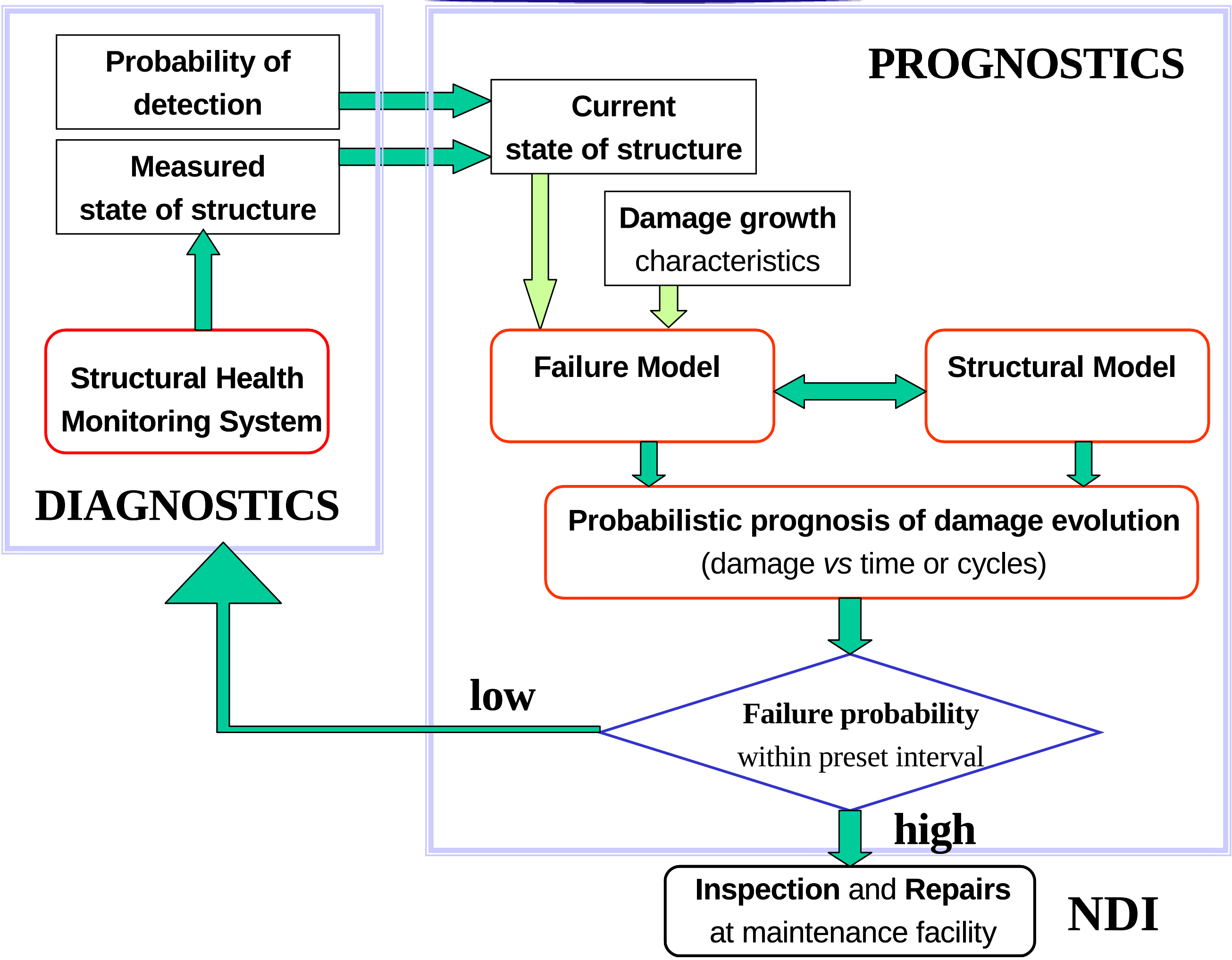
- **Objective:**
  Develop an SHM system to detect and size impact damage and predict remaining lifetime of a laminated composite component.

- **Approach:**
  Modally-selective Lamb wave sensors coupled with **damage growth laws** and **probabilistic lifetime calculations**

FAA Sponsored Project Information

- Principal Investigators & Researchers
  - J.D. Achenbach
  - Sridhar Krishnaswamy
  - Isaac M. Daniel
  - Gabriela Petculescu, Goutham Kirikera, Li Sun
- FAA Technical Monitor
  - Peter Shyprykevich, Curt Davies
- Industry Participation
  - Boeing, Honeywell, GE, Imperium, AlphaStar Corp

Structural Health Monitoring and Lifetime Prediction



- **SHM sensors** for unanticipated events (impacts etc)
- **SHM sensors** for aging (fatigue etc)
- **NDI tools** for flaw identification and characterization

SHM of Composite Structures

- **Monitor unanticipated events**:
  A laminated composite aircraft panel suffers impact damage.
- **Identify location of damage**:
  Impact is identified by on-board PZT and FBG ultrasonic SHM sensors which locate the point of impact.
- **Image damaged region**:
  Full-field NDI tool (Acoustocam) images the damage region (matrix cracks…delaminations).
- **Monitor damage growth:**
  Modally-selective SHM sensors are installed around the damage region to monitor further damage growth as the panel is subject to cyclic loading.
- **Predict damage growth:**
  Measured damage size is used in a probabilistic fatigue damage model which estimates the remaining lifetime of the structure.

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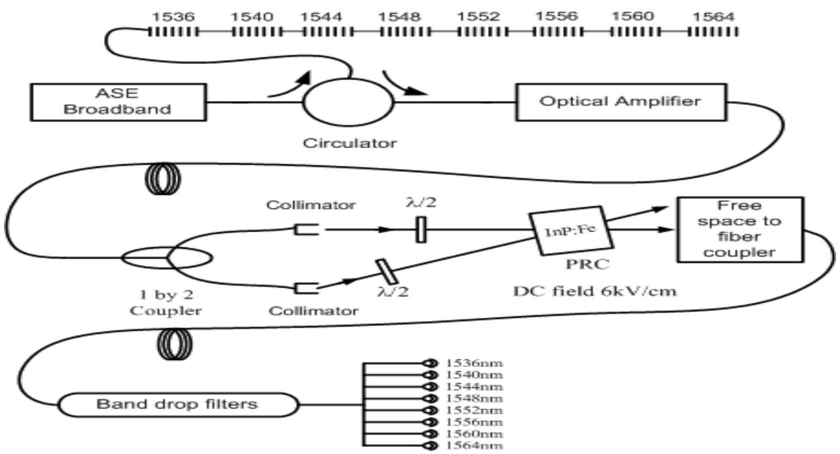
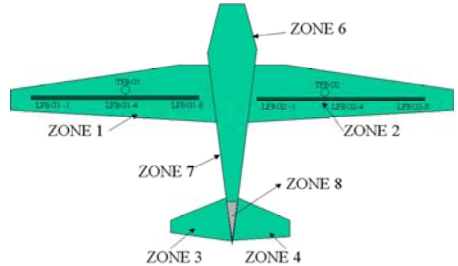
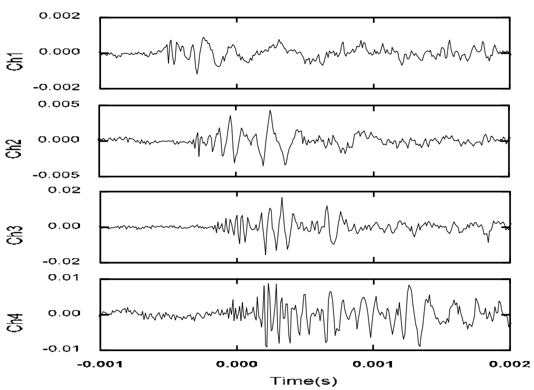
Monitor / Identify Impact Location

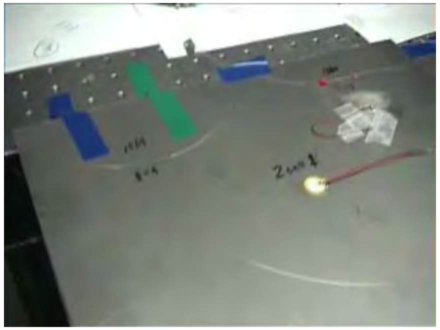


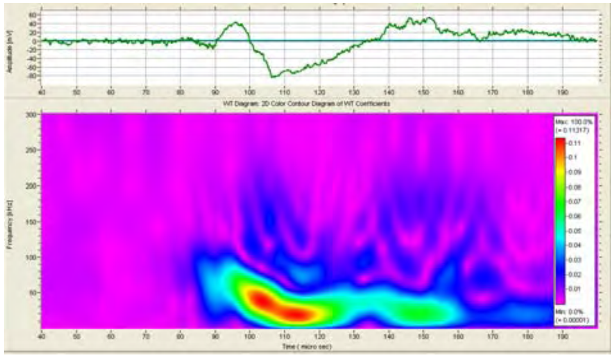


- FBG sensor network
- always ready
- multiplexable
- adaptive to low frequency noise



Lamb wave signals from several sensors due to impact





Time-frequency information to locate impact point

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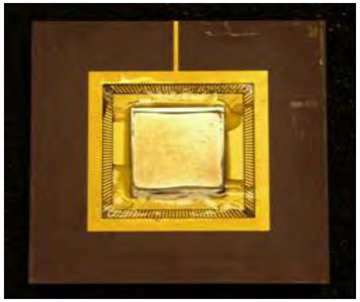
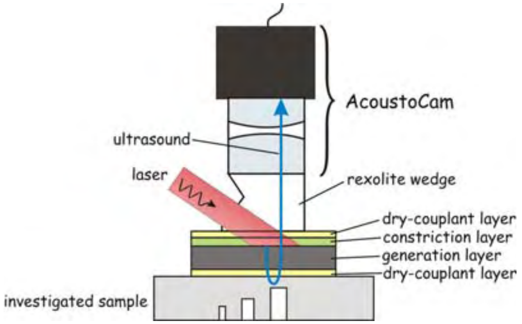
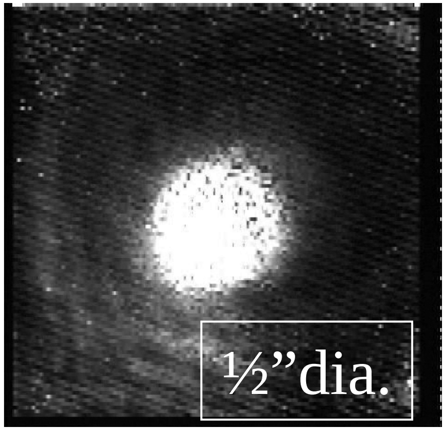
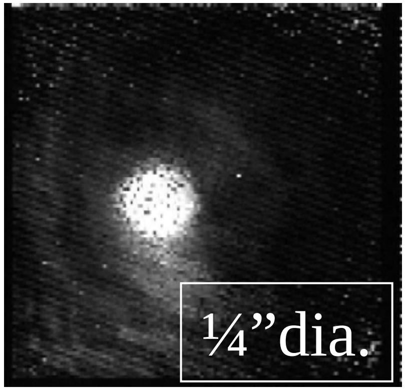
Image Impact Damage Region

- CCD array with piezo-sensitive coating
- Real time subsurface imaging –video rates
- Large area – 1-1.5 inch square
- High resolution – 120x120 pixels
- Non-invasive
- Multiple applications
- Faster and cheaper than current technologies









Delaminations in Woven composite panel

Manufactured by Imperium Inc

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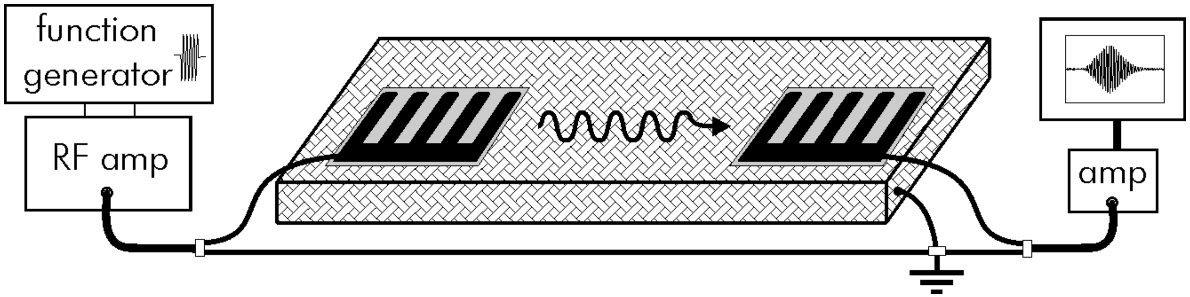
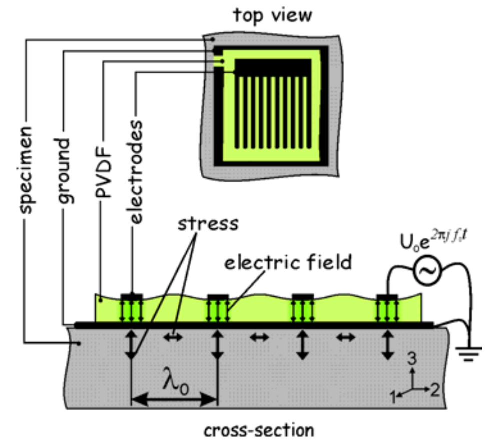
Sensor development

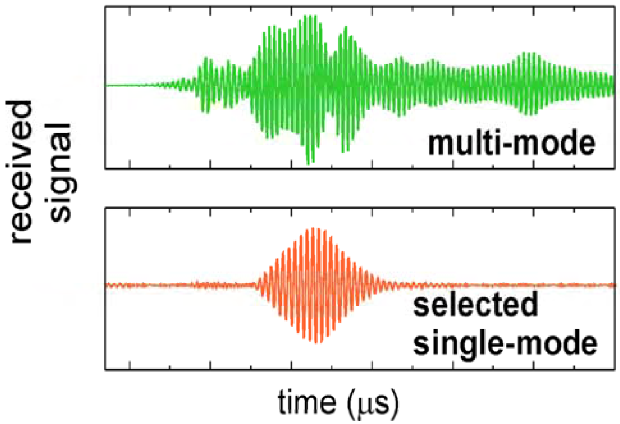
- Build a complete SSHM prototype that can perform Structure and Sensor Health Monitoring.
- Structural Health Monitoring: Excitation and reception of a single mode
- Investigation of various transducer configurations to optimize the SHM setup
  - Ultrasonic wave generation transducers
  - Ultrasonic wave reception transducers
- Sensor Health Monitoring
  - Understand the theory
  - Build an initial prototype

SHM: Mode-Selective Lamb-Wave Sensors for defect sizing



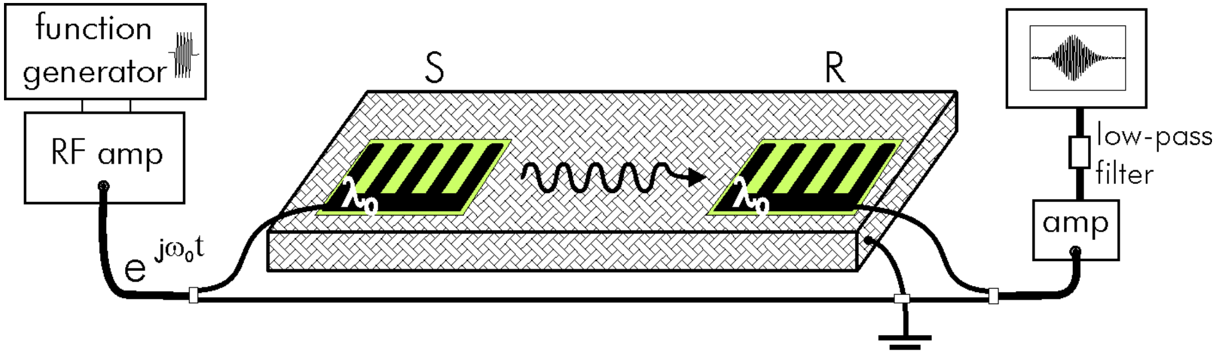


- matched-pair of modally-selective generators / receiver arrays
- delamination size correlates to measurable *time-delay* of the received signal.
- Time-delays are easier to measure than amplitude changes etc.

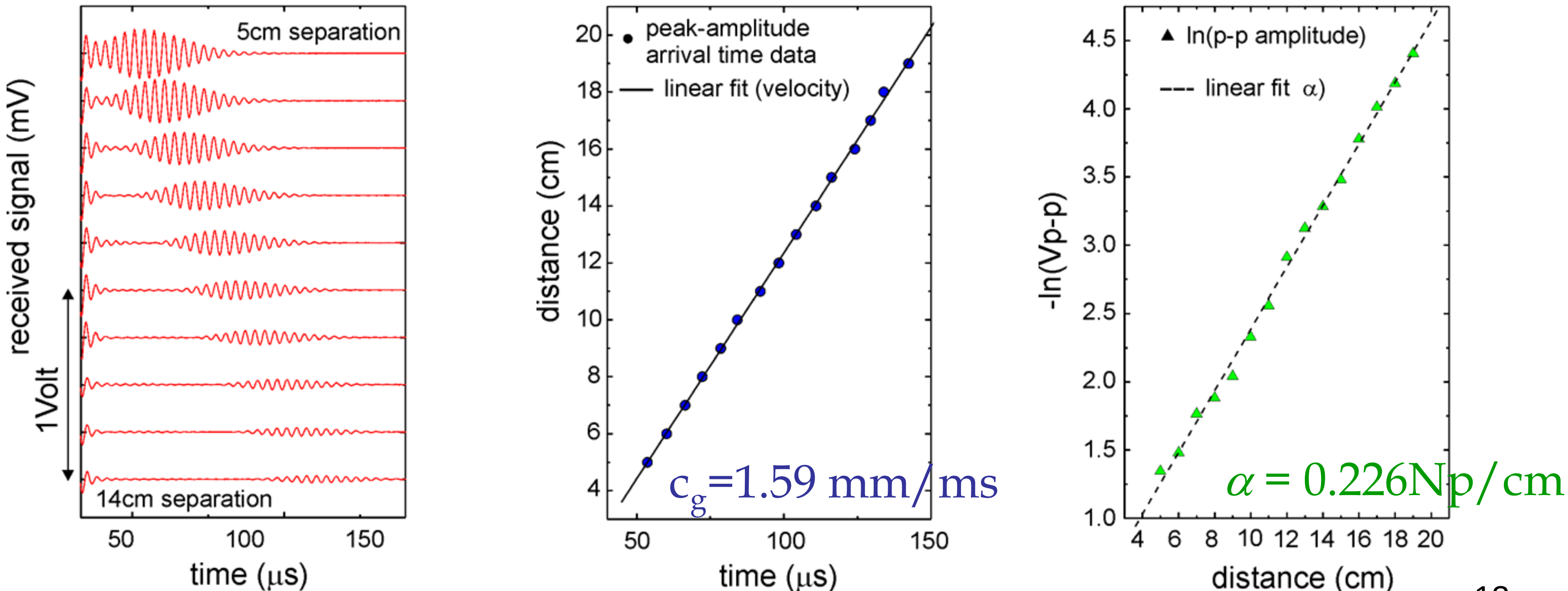


Mode Propagation

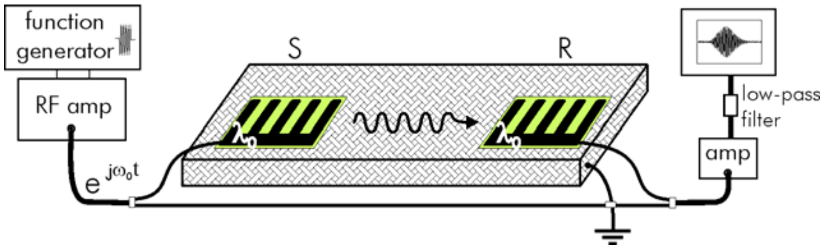
(minimal dispersion)



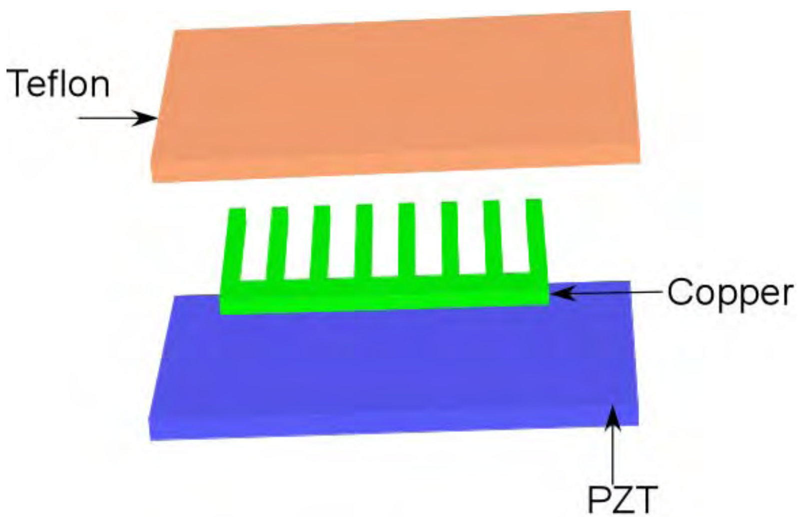
- 16 ply carbon-epoxy woven composite
- a_0 mode (f=0.31MHz, λ=4.5mm)



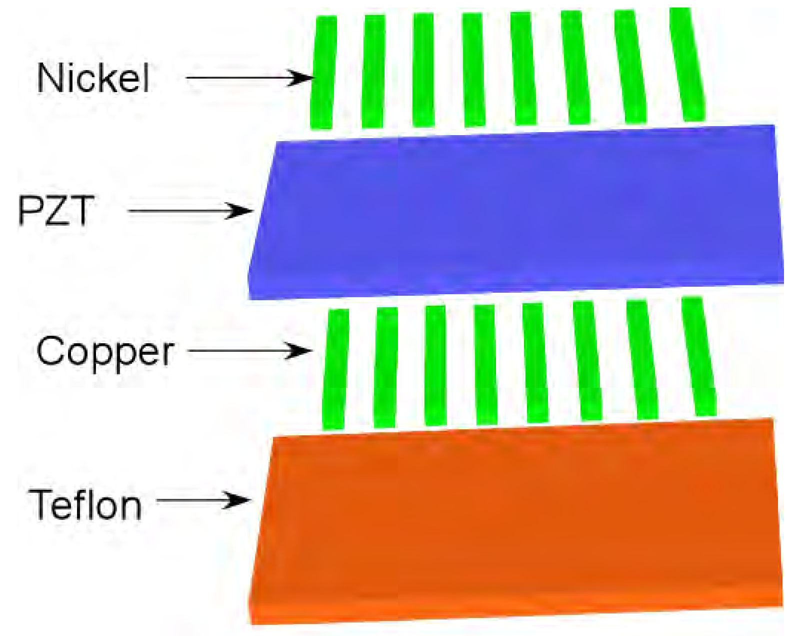
Array Design Configurations



- **Generator array** is best connected in **parallel**.
- **Receiver array** is best connected in **series**.

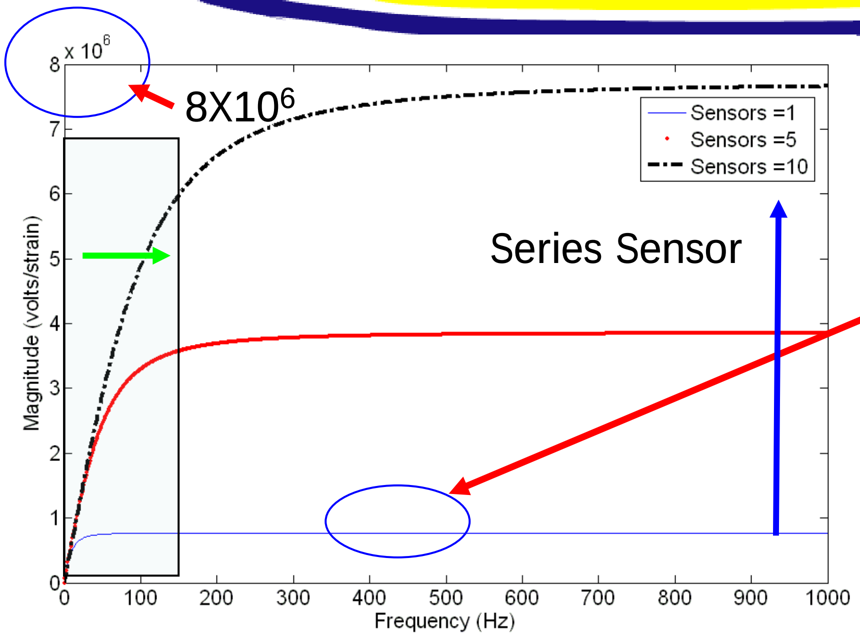


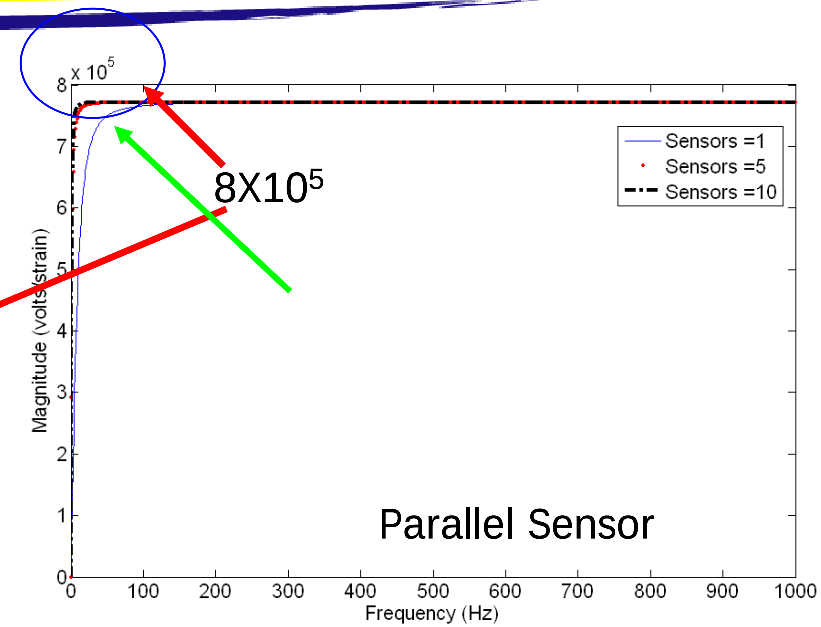
Generation Transducer array



Receiver Transducer array

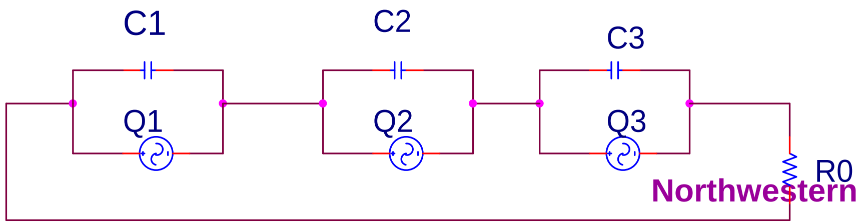
Series Vs Parallel Array Transducer

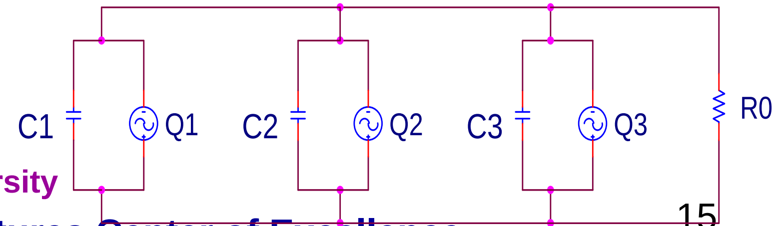




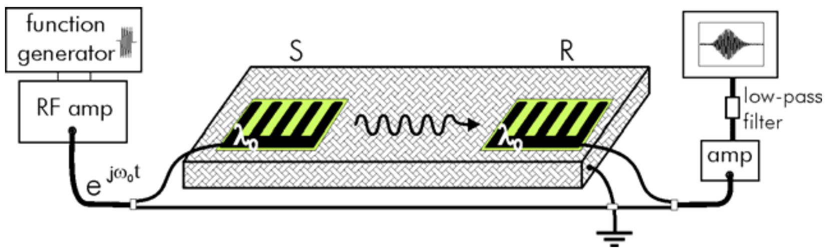
$$\frac{V_o}{S} = \frac{(e * A_e * R_o * n * j * \omega)}{n + (j * \omega * C * R_o)}$$

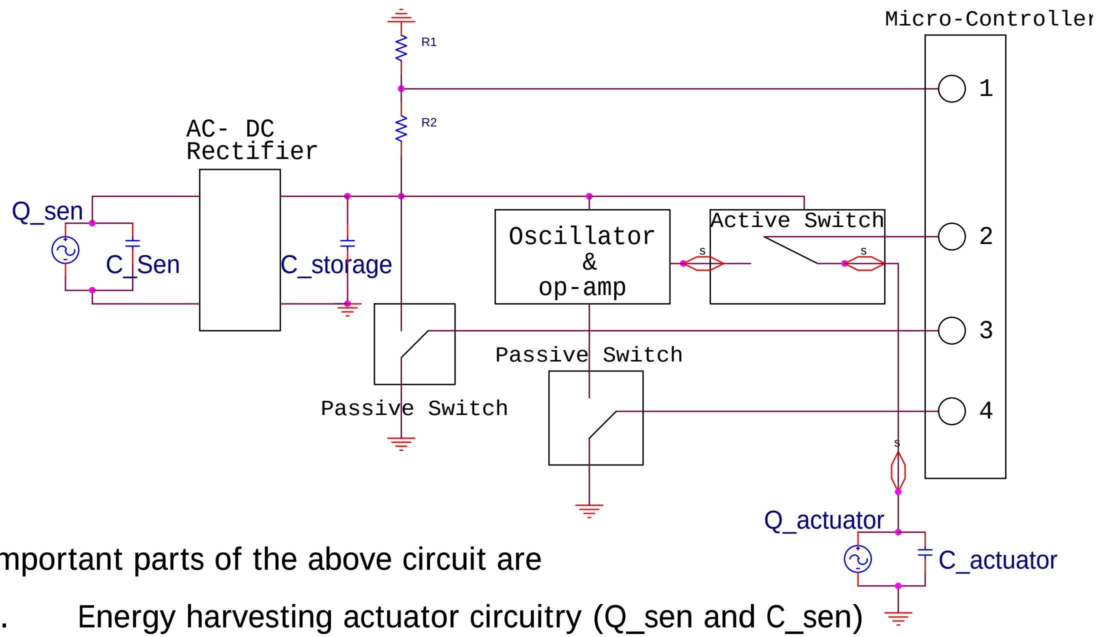
$$\frac{V_o}{S} = \frac{(-e * A_e * R_o * n * j * \omega)}{1 + (n * j * \omega * C * R_o)}$$





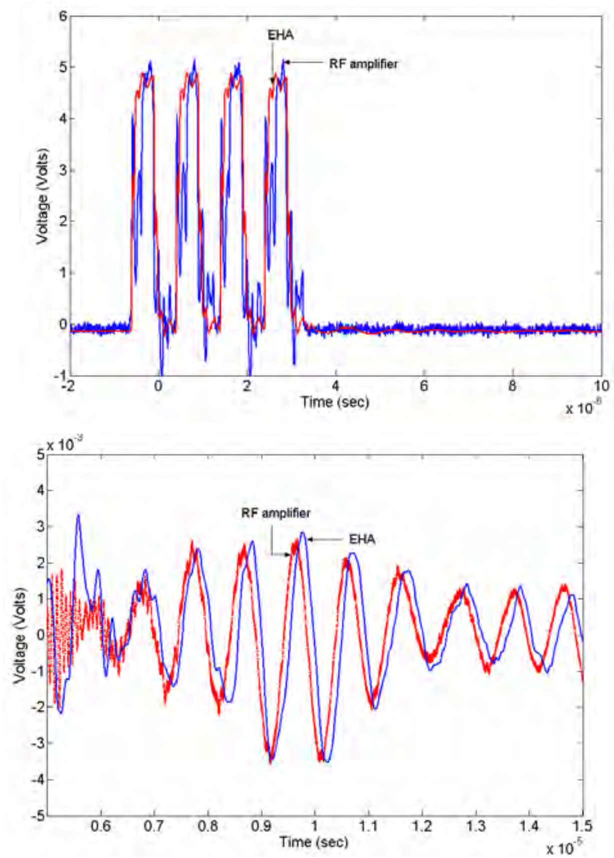
Energy harvesting circuit to power generating array





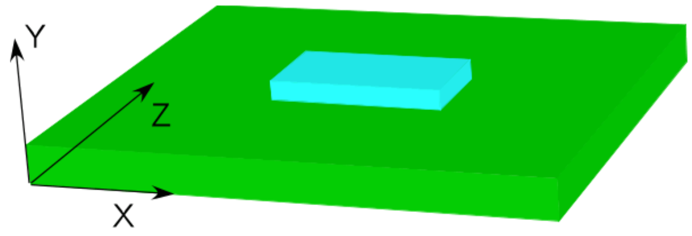
Important parts of the above circuit are

1. Energy harvesting actuator circuitry (Q_sen and C_sen)
2. Generation transducer array (Q_actuator and C_actuator)
3. Receiver transducer array (not shown)



Comparison of signals between RF generator and EHA (a) Excitation signal (b) Receiving signal

Transducer Health Monitoring



Free transducer

$$C_{free} = \frac{Q}{V} = \frac{\varepsilon_{33}^{T} A_e}{t}$$

Clamped transducer

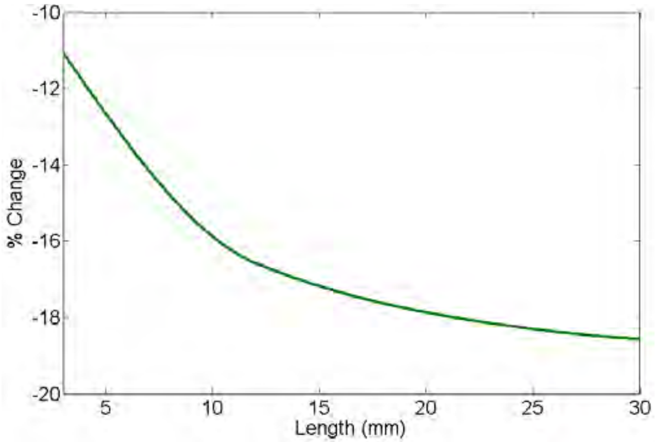
$$\left(\frac{Q}{V_3}\right) = \left(\frac{A_e}{t}\right)\varepsilon_{33}^{T}[1 + \frac{d_{31}T_1}{E_3\varepsilon_{33}^{T}} + \frac{d_{32}T_2}{E_3\varepsilon_{33}^{T}} + \frac{d_{33}T_3}{E_3\varepsilon_{33}^{T}}] = C_{BONDED}$$

Variation of capacitance is due to

- Change in the area of the transducer (A_e) (in this case it is assumed that the area is constant)
- Change in the stresses associated with the transducer and in turn relates to the change in the dielectric coefficient of the transducer
- Change in the thickness of the transducer

Finite element modeling using ANSYS is performed to understand the above changes

Stress Variation Study

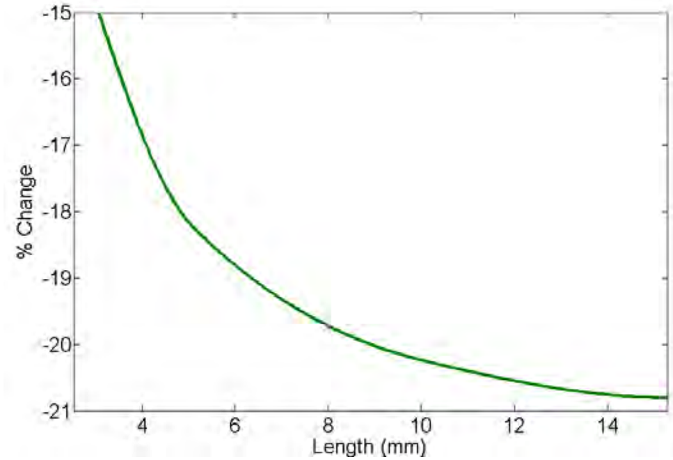


Variation of Capacitance as a function of transducers length

Host structure thickness: 5.1mm

Width of the transducer: 5mm

Thickness of the transducer: 1.02mm



Variation of Capacitance as a function of host structure thickness

Length of the transducer: 24mm

Width of the transducer: 5mm

Thickness of the transducer: 1.02mm

The in-plane stresses are the primary reason for the change in the capacitance. For a transducer completely embedded inside a rigid structure the maximum change in capacitance is about 60%. For a transducer surface bonded the maximum change is about 21%

Relative displacement variation

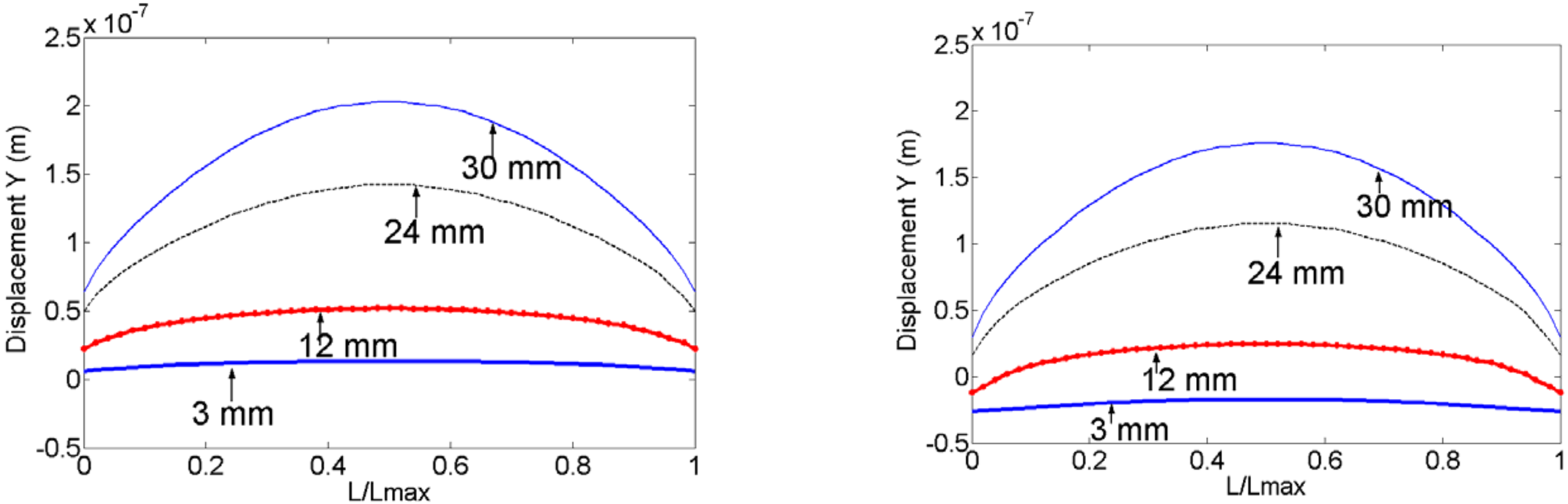
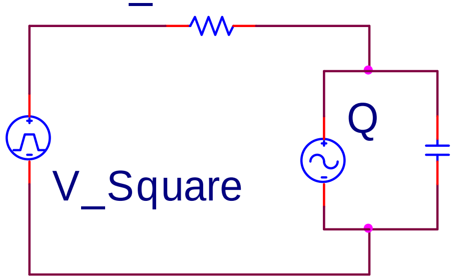


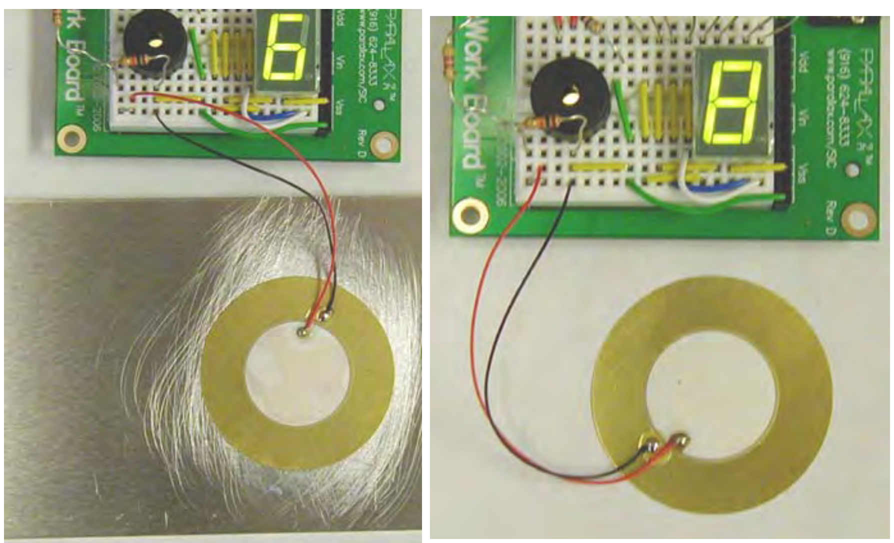
Figure Variation of displacement in the Y direction (a) Bottom layer of the transducer (b) top layer of the transducer

Host structure thickness: 5.1mm, Width of the transducer: 5mm, Thickness of the transducer: 1.02mm

The change in thickness between the top and bottom layers of the transducer is 20nm. Such a small change does not significantly alter the capacitance. Hence capacitance change is primarily a function of in-plane stresses.

Sensor Health Monitoring - Prototype





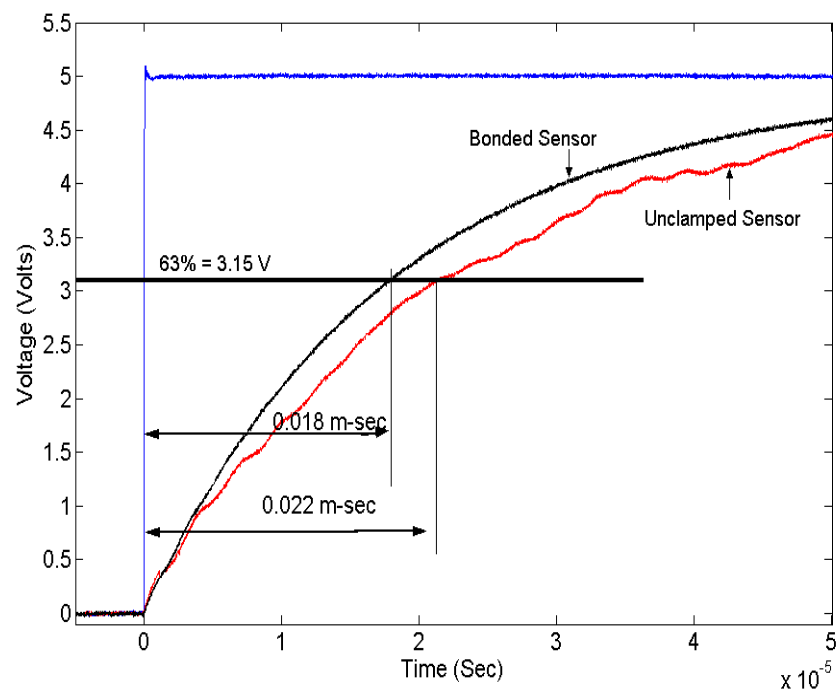
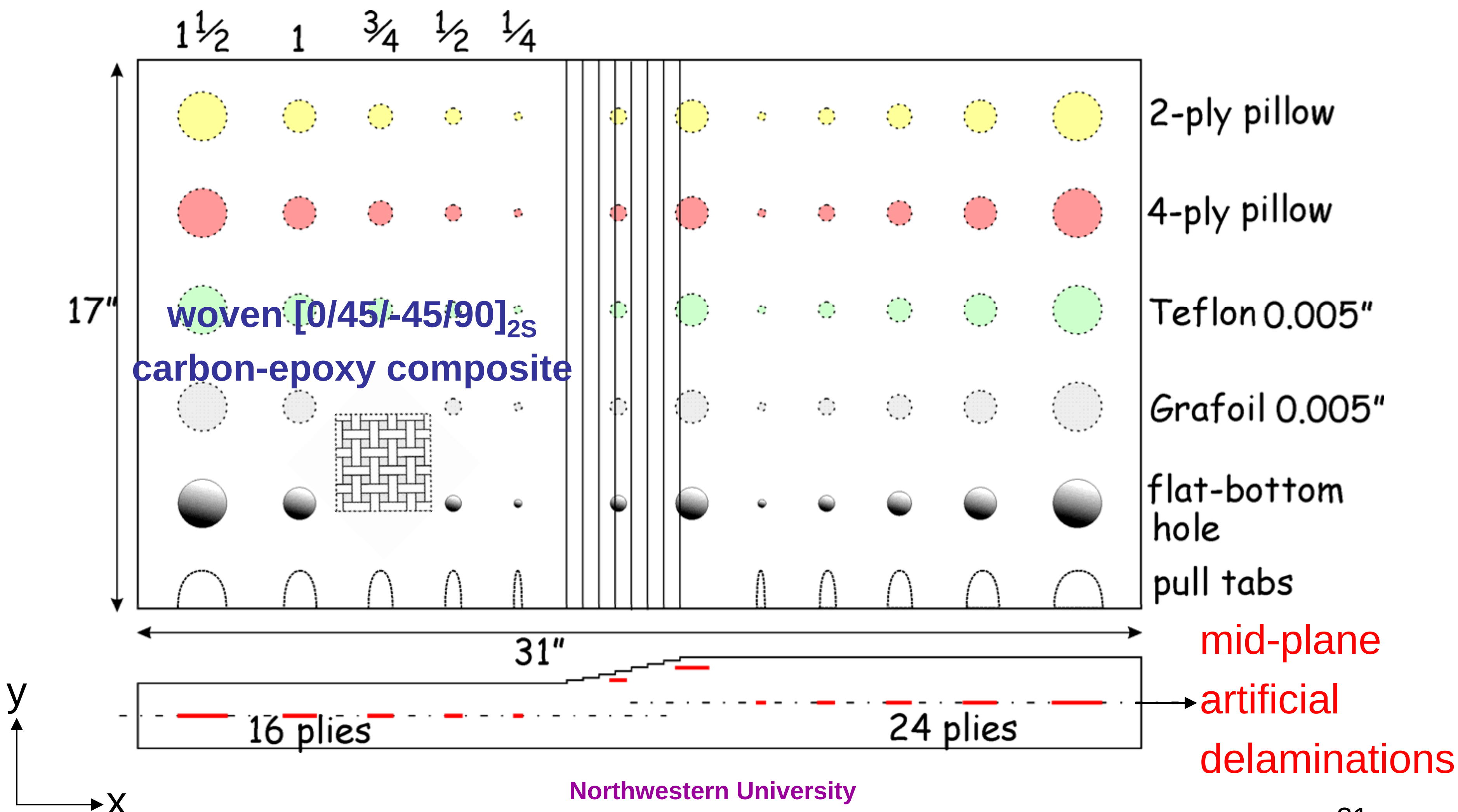


Figure. Transducer health monitoring based on a commercially available transducer (a) Microcontroller indicating “G” for a good transducer (b) Microcontroller indicating “B” for bonding issues with a transducer. The change in capacitance is 18%.

Delamination Detection

(simulated at mid-plane)

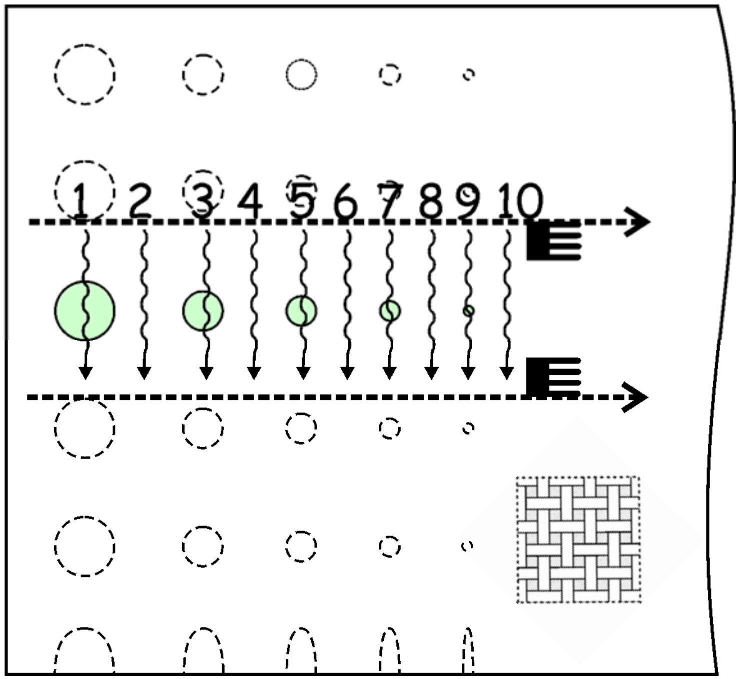


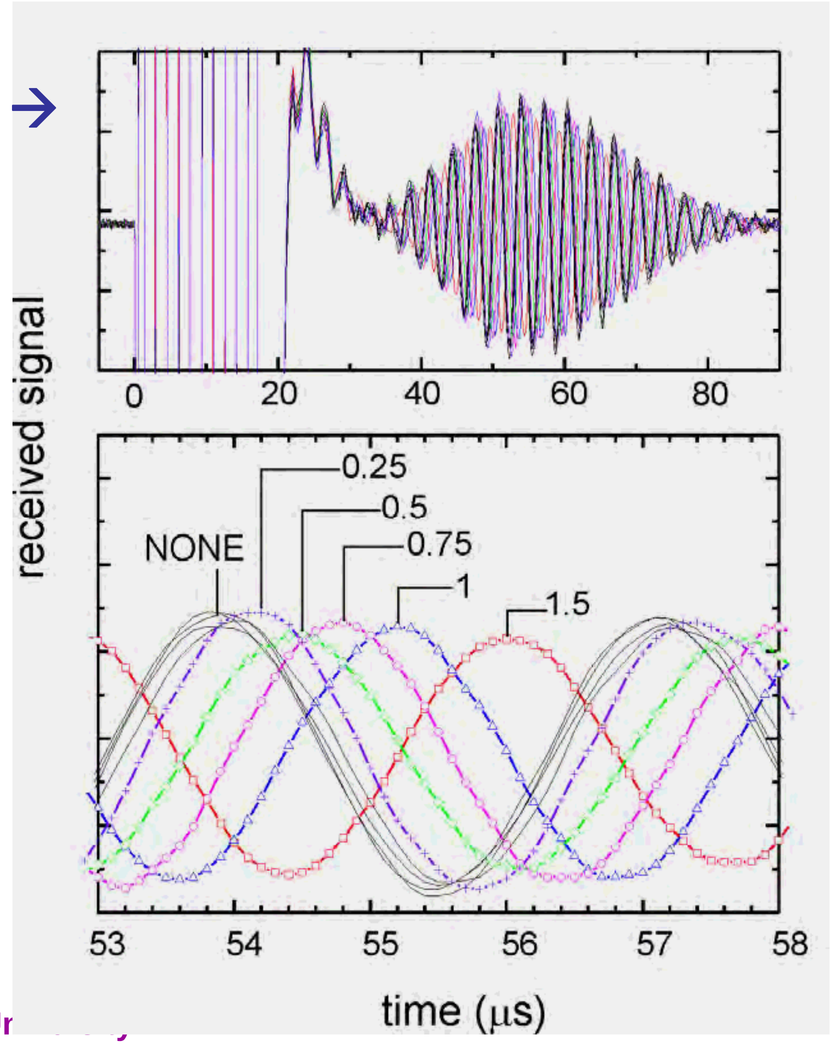
Delamination Signature

(decrease in group velocity)

single mode (a_0) tone-burst propagation →

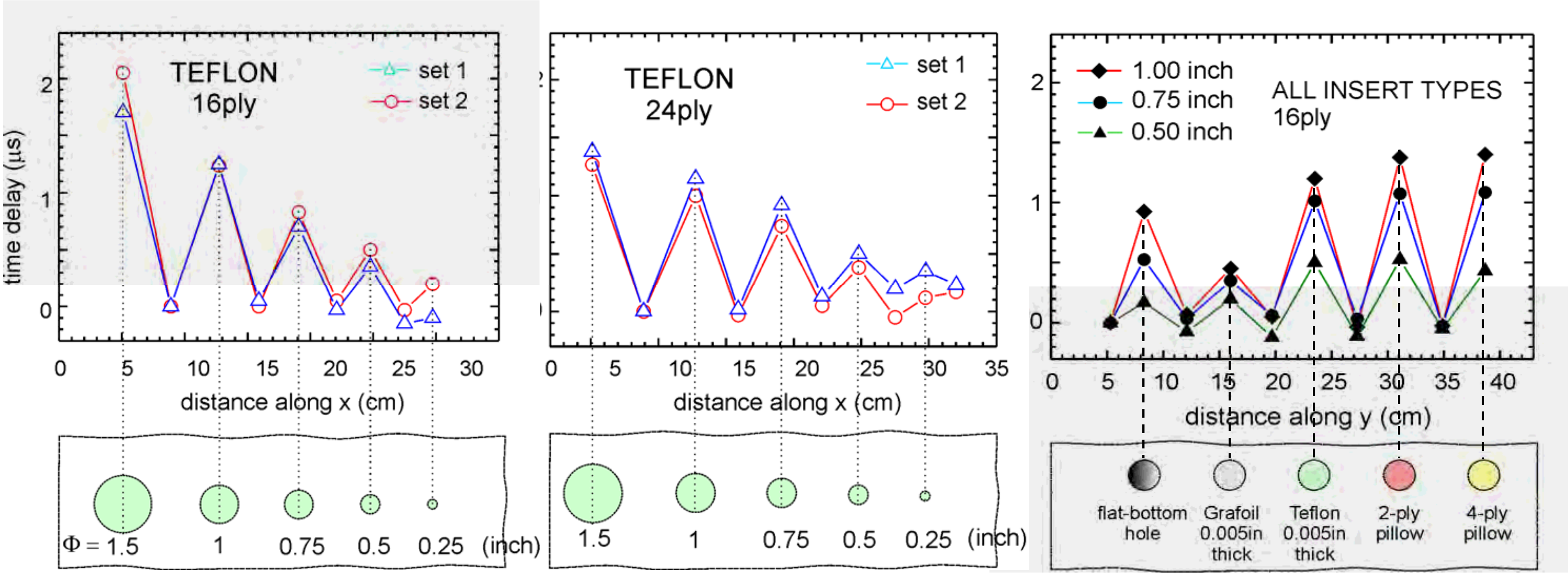
TEFLON inserts





Delamination Signature

Time-Delay



Impact Delaminations

Material:

Toray T800 BMS 8-276
manufactured by:
NIAR, Wichita, KS

→ cross-ply $[0/90]_{6S}$

→ carbon-epoxy composite

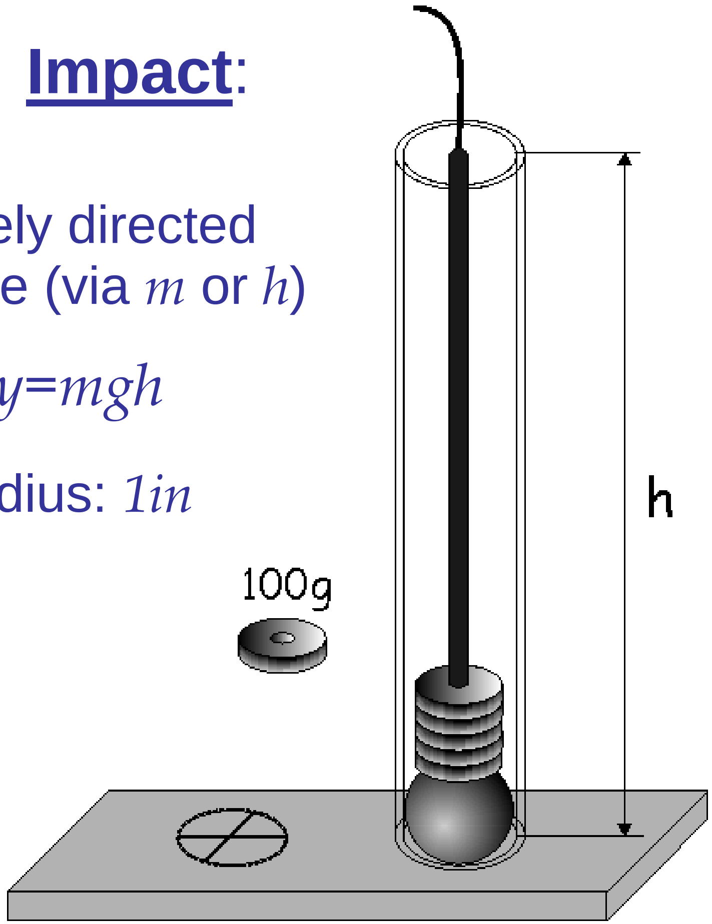
→ 4.6mm thick (24 plies)

Impact:

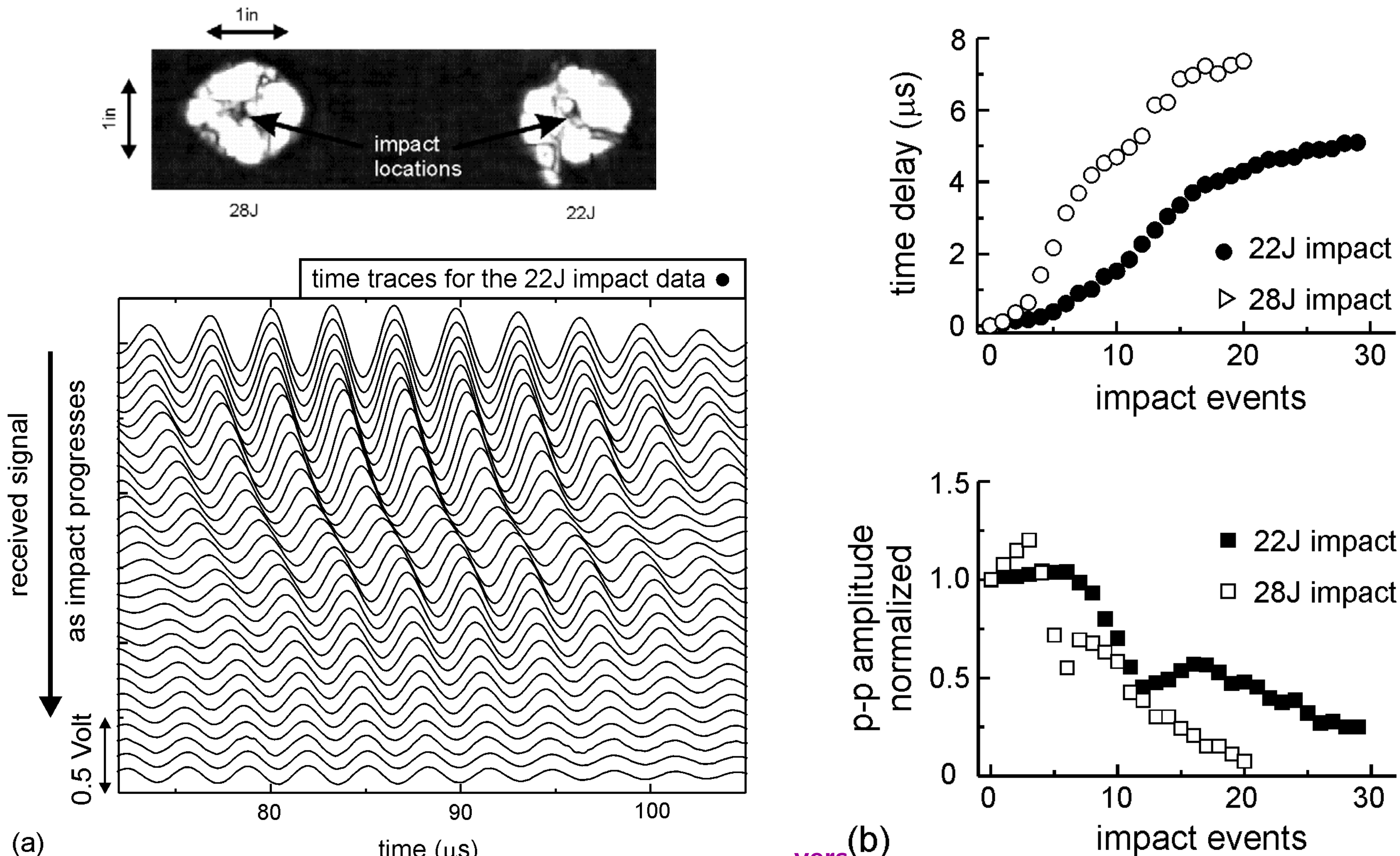
- precisely directed
- variable (via m or h)

$$Energy = mgh$$

- ball radius: *1in*



Impact Delaminations



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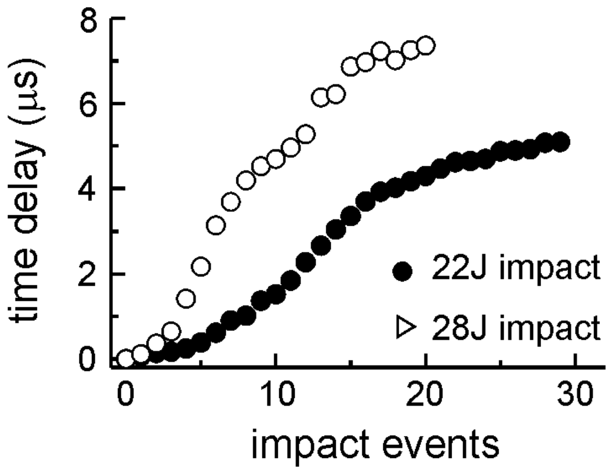
Damage Prognosis

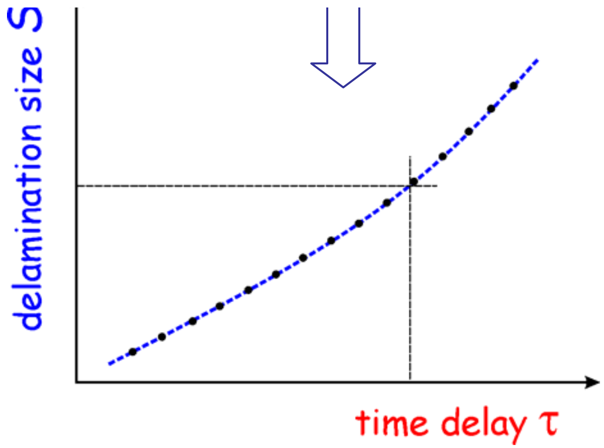
i) composite part suffers an impact and monitored with sensors;

ii) velocity changes ➔ **time-delay (τ)** ;

convert τ into **damage level (S)**



$$S(\tau)=a+b\tau^{m}$$



coefficients **a**,**b**, and **m**
are determined *empirically*
Note: S(τ) → impact-type specific

Damage Prognosis

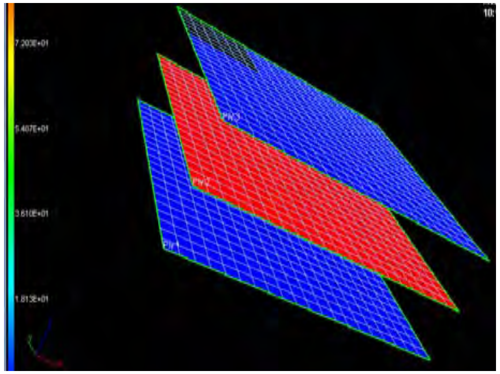
Evaluated Failure Analysis Software for Composites:

Alpha STAR's Generalized Optimization and Analysis (GENOA) software* is designed to evaluate the life, residual strength and damage/failure propagation in advanced materials and structures. GENOA performs progressive failure analysis (PFA) using finite element analysis (FEA) software (including commercial codes), full hierarchical modeling and materials engineering to determine:

- Material properties and property degradation
- Damage and fracture initiation/progression
- Failure mechanism contribution
- Effects of manufacturing anomalies, including in-service damage, and environment including moisture and temperature
- Component life and final failure load

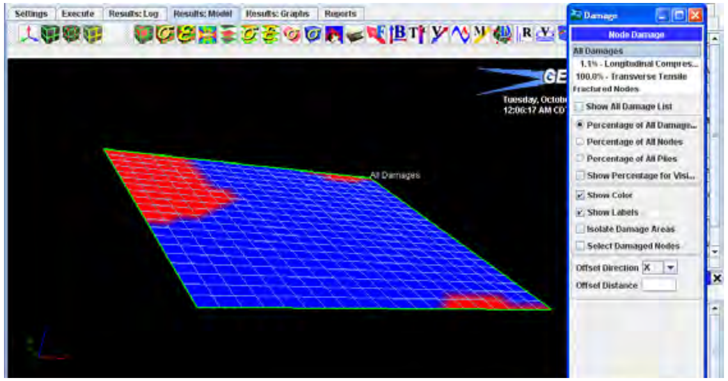
* ascgenoa.com

Damage Prognosis



The composite laminate

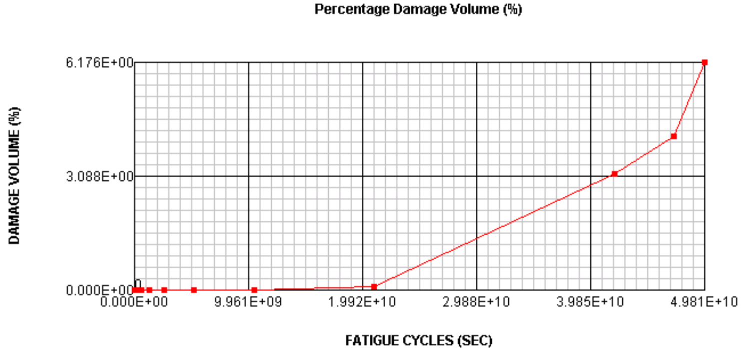
Fatigue analysis:
load amplitude = 1e3 N, R=0.1

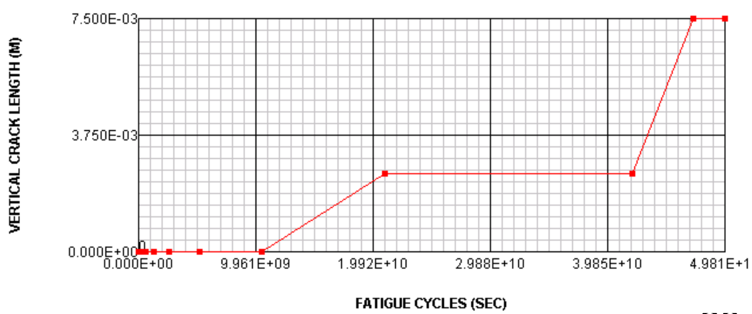


Delamination is provided in ply 3. The top ply is 3. Ply 1 and 3 are oriented in 0 degrees and ply 2 is oriented at 90 degrees.

View Equilibrium Iterations Only | View All Iterations

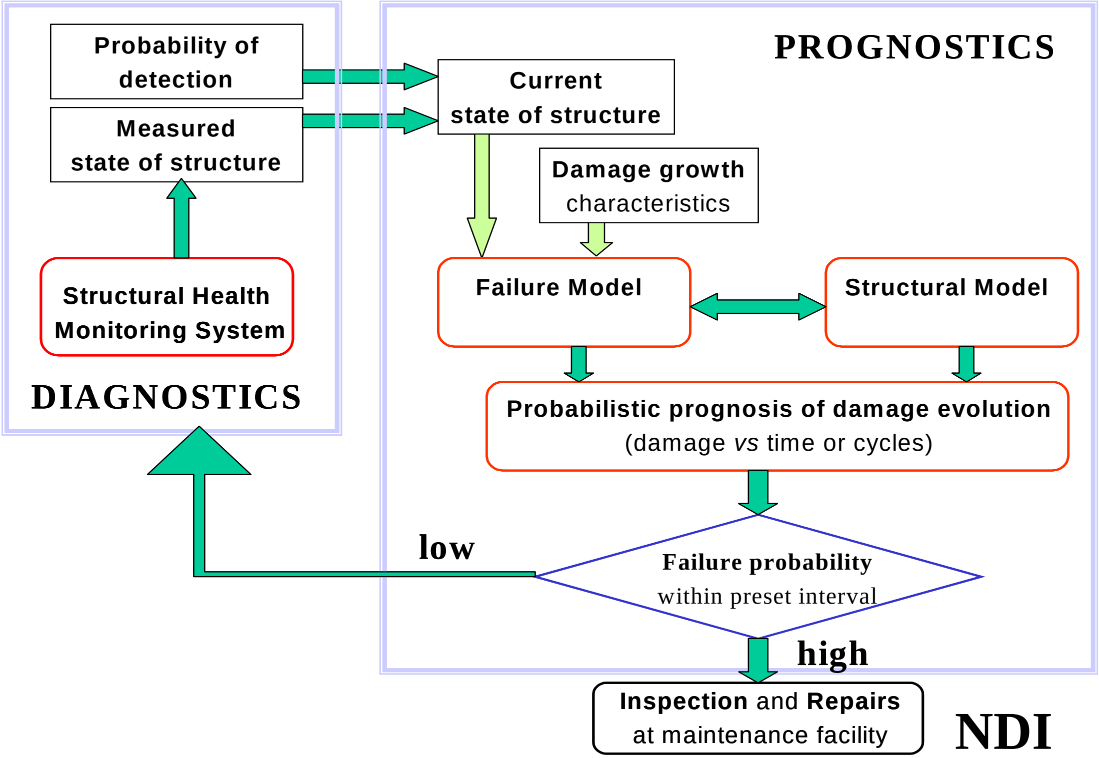
Iteration	Elements	Nodes	Force X	Force Y	Force Z	Moment X	Moment Y	Moment Z	Pressure	Cycle	Damage...	Fractured...	Status
17	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	6.554E+...	0	0	Equilibri...
18	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	1.311E+...	0	0	Equilibri...
19	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	2.621E+...	0	0	Equilibri...
20	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	0	0	Equilibri...
21	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	1.049E+...	0	0	Equilibri...
22	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	2.097E+...	2	0	Damage...
23	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	2.097E+...	3	0	Damage...
24	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	2.097E+...	3	0	Equilibri...
25	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.194E+...	38	0	Damage...
26	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.194E+...	43	0	Damage...
27	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.194E+...	47	0	Damage...
28	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.194E+...	47	0	Equilibri...
29	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.719E+...	56	0	Damage...
30	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.719E+...	61	0	Damage...
31	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.719E+...	61	0	Equilibri...
32	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.981E+...	75	0	Damage...
33	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.981E+...	84	0	Damage...
34	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.981E+...	88	0	Damage...
35	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	4.981E+...	88	0	Equilibri...
36	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	110	0	Damage...
37	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	127	0	Damage...
38	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	142	0	Damage...
39	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	159	0	Damage...
40	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	175	0	Damage...
41	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	194	0	Damage...
42	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	207	0	Damage...
43	400	441	2.100E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	0.000E+...	5.243E+...	218	0	Damage...





Work in Progress

Integrate the SHM sensor data with the damage growth software to form closed-loop prognostics for life-time assessment.



A Look Forward

- Benefit to Aviation
  - Maintenance calls based on need
  - Cost saving
  - Reduced downtime
- Future needs
  - Efficient wireless sensor systems for autonomous data acquisition and data management
  - Damage growth laws
  - Integration of diagnostics and prognostics