JAMS

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.

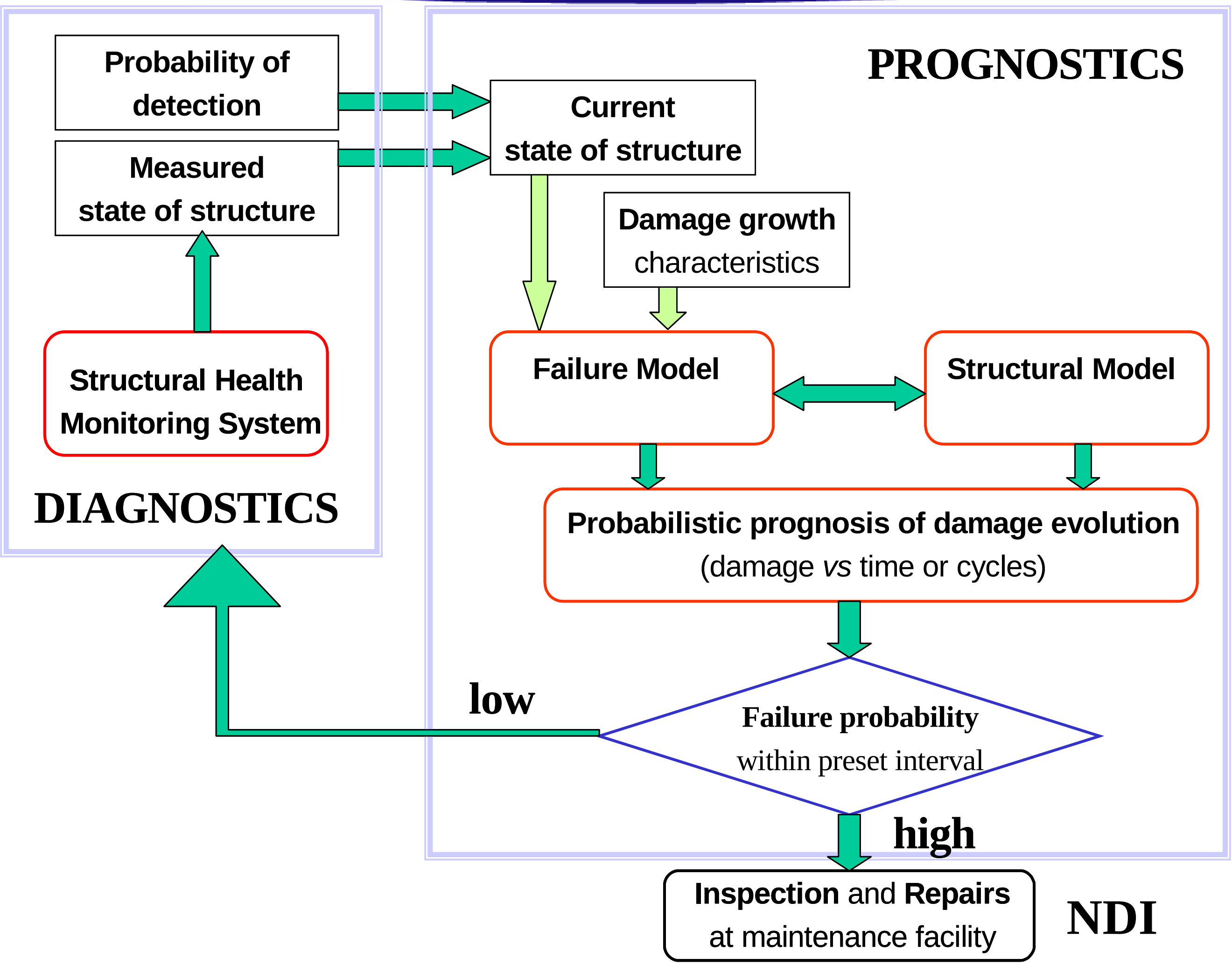
- **Approach:**

  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
- FAA Technical Monitor
  - Peter Shyprykevich, Curt Davies
- Industry Participation
  - Ed White, Boeing Phantom Works

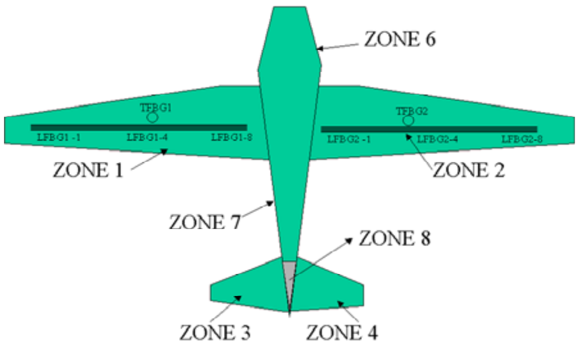
Structural Health Monitoring and Lifetime Prediction



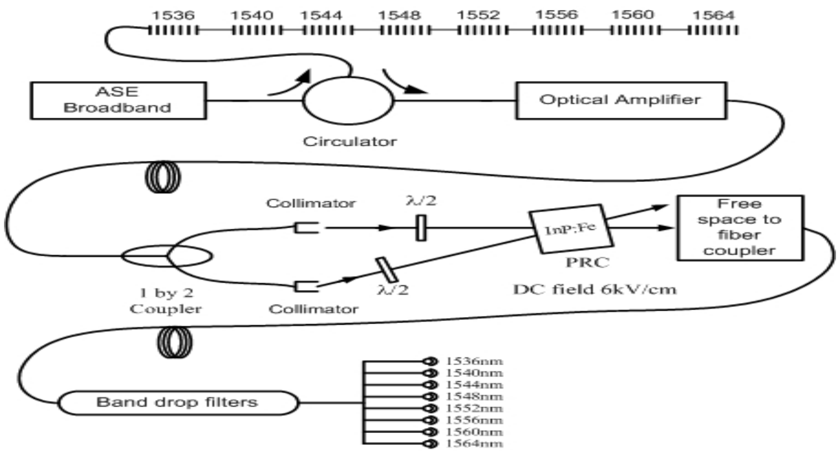
- SHM sensors for unanticipated events (impacts etc)
- SHM sensors for aging (fatigue etc)
- NDI tools for flaw identification and characterization

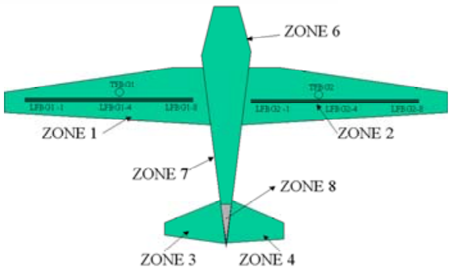
SHM of Composite Structures

- **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.

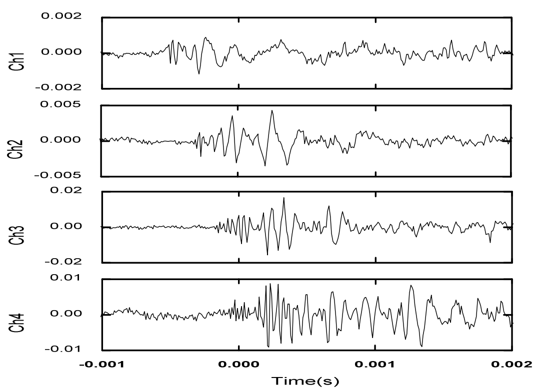


Monitor / Identify Impact Location

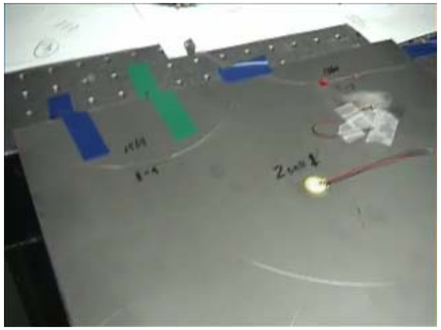


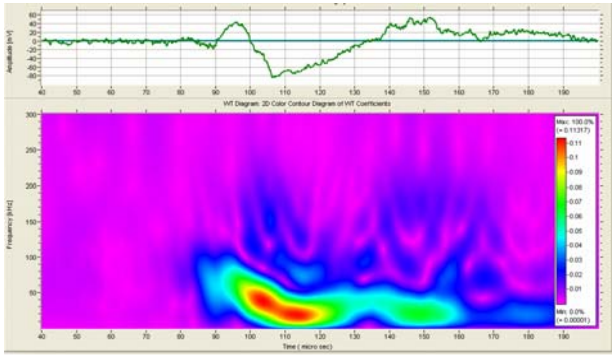


- FBG sensor network
- always ready
- multiplexable
- adaptive to low frequency noise



Lamb wave signals from several sensors due to impact

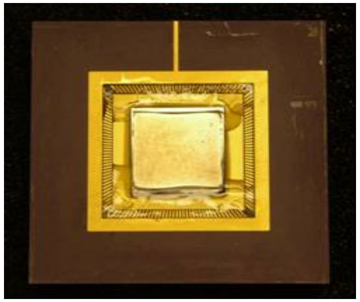


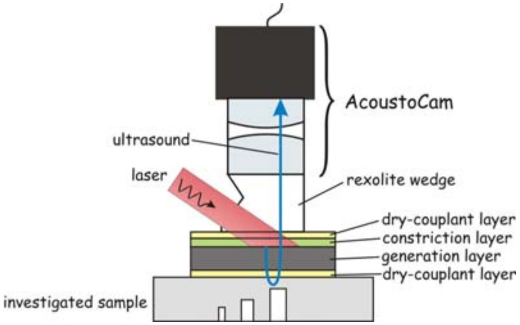


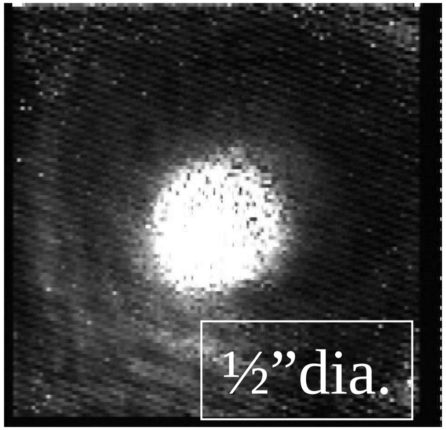
Time-frequency information to locate impact point

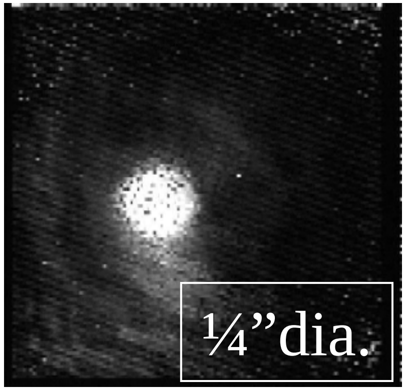
Image Impact Damage Region

- 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





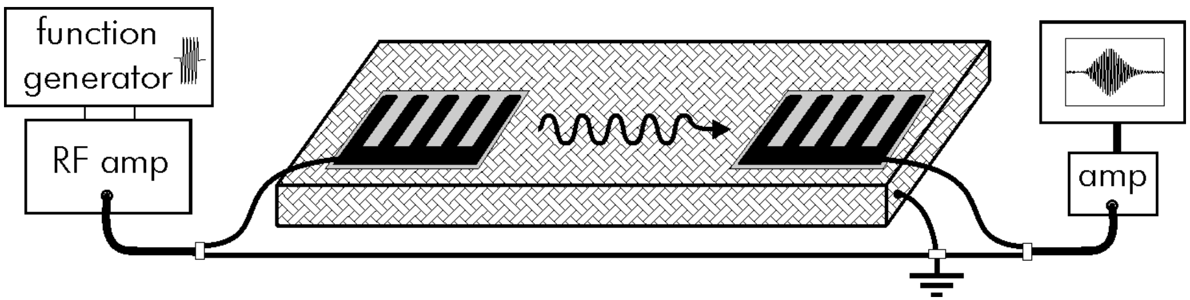


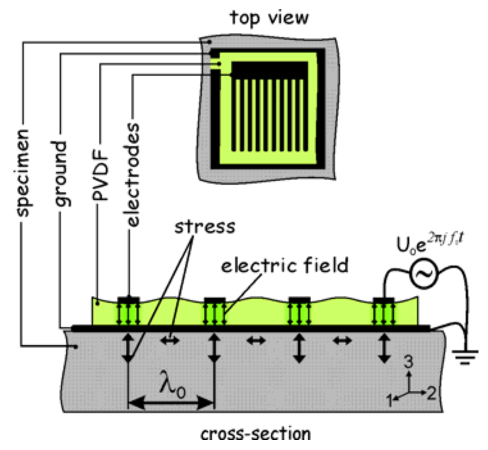


Delaminations in Woven composite panel

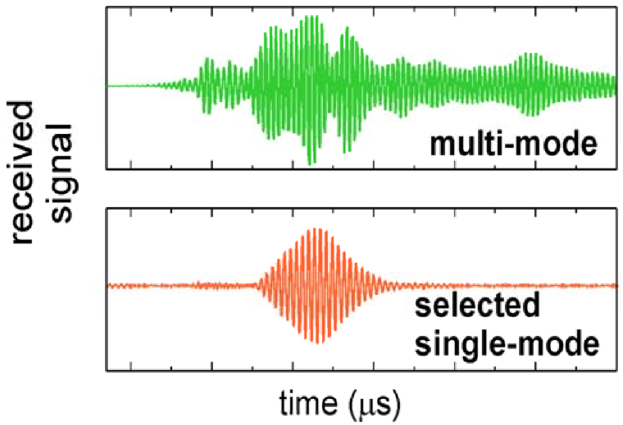
Manufactured by Imperium Inc

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

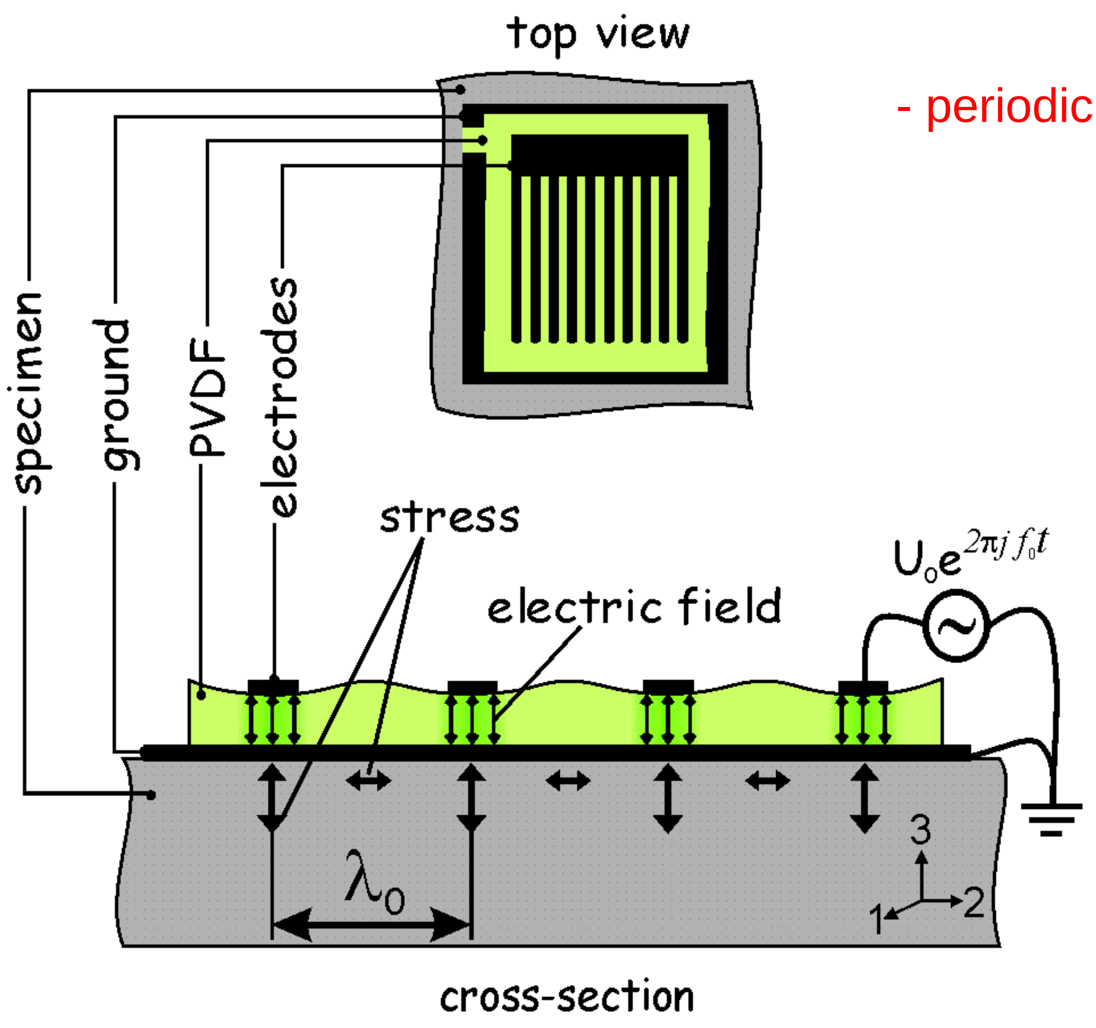




- matched-pair of modally-selective generators / receiver arrays
- delamination size correlates to measurable *time-delay* of the received signal.
- Time-delays are easier to measure than amplitude changes etc.



Mode-Selective Lamb-Wave Sensors

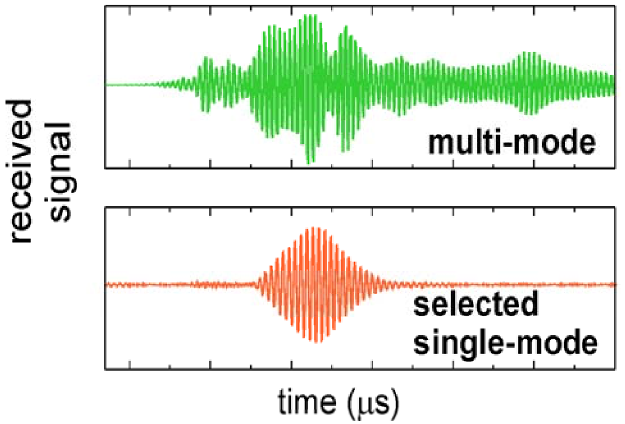


The comb design:

- periodic array of sources (period=λ_0) -

Characteristics:

- **unobtrusive: 0.3 mm thick**
- **malleable**
- **inexpensive**
- **mode-selective**



Sensor Design

STEPS in designing/fabricating transducers for the desired **Lamb mode**:

1) from the composite properties (elastic tensor, ρ, lineup)

  ➔ determine the dispersion curves

2) identify a region with minimal dispersion ➔ known group velocity (c_{group}) and frequency (f_0)

3) design a comb mask with finger spacing $\lambda_0 = c_{group}/f_0$

4) fabricate the electrodes

5) assemble the transducers

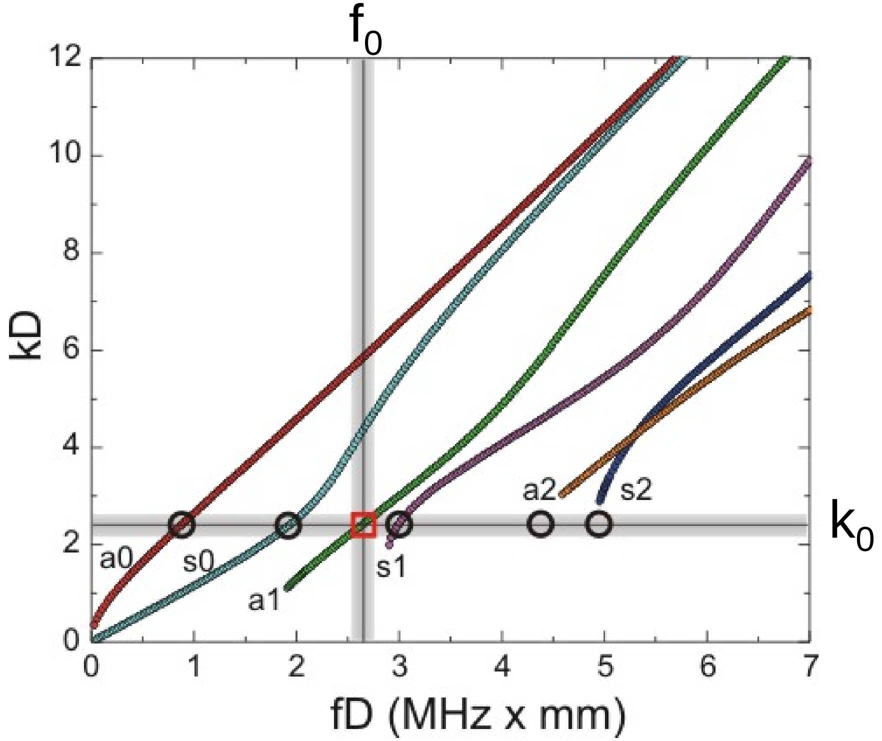
Note: it is desirable to design a sensor which, at a fixed λ_0, can excite individual modes at specific frequencies: $\lambda_0 = c_1/f_1 = c_2/f_2 = c_3/f_3 \ldots$

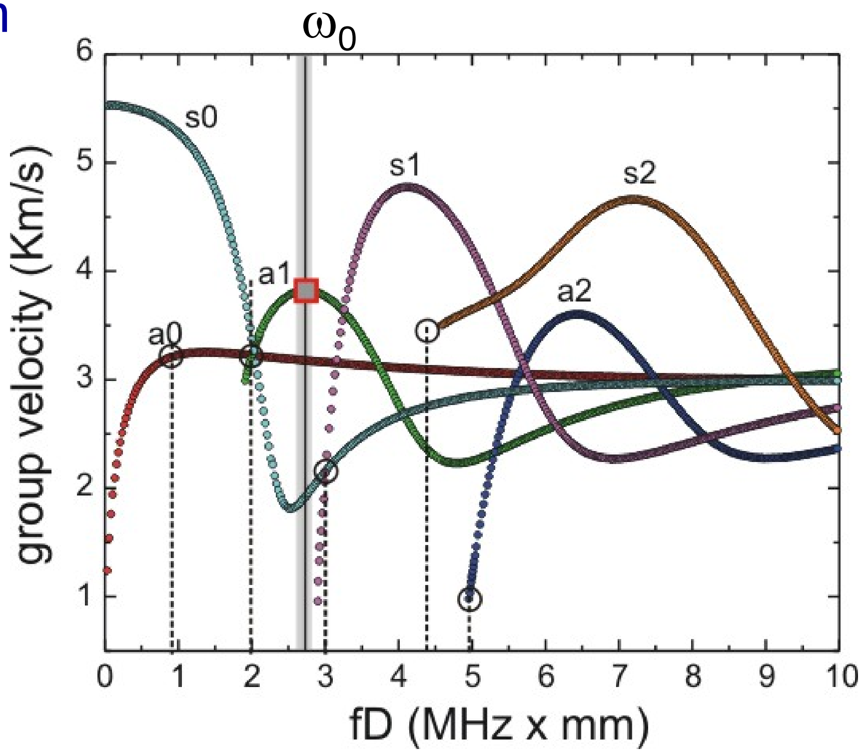
Sensor Design

- dispersion curves -

Wavelength λ_0 ($2\pi/k_0$) imposed by design

=> only one mode can satisfy $c_0=\omega_0/k_0$.

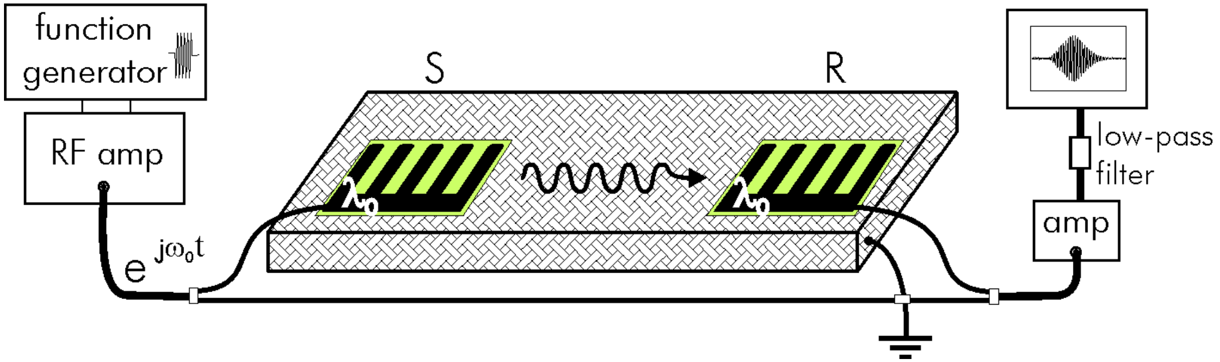




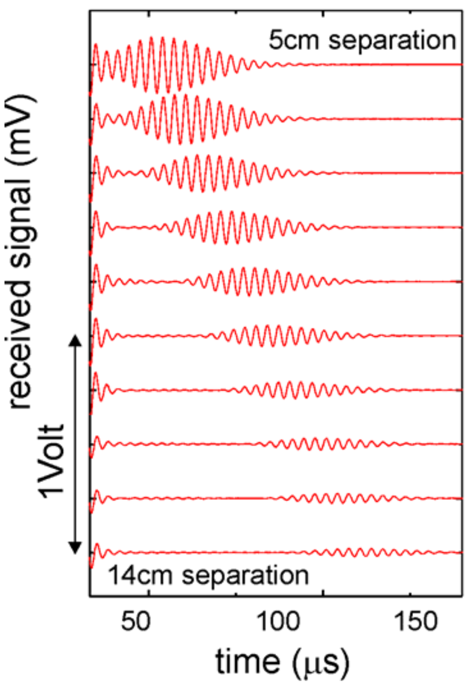
Excitation: in a low-dispersion domain

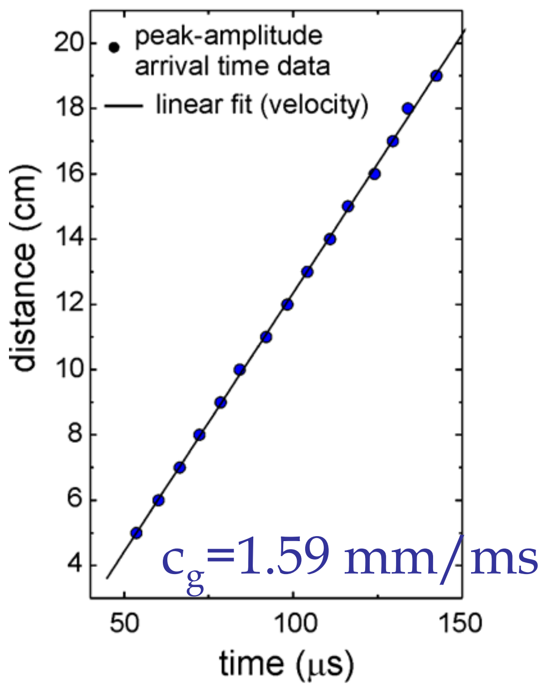
Mode Propagation

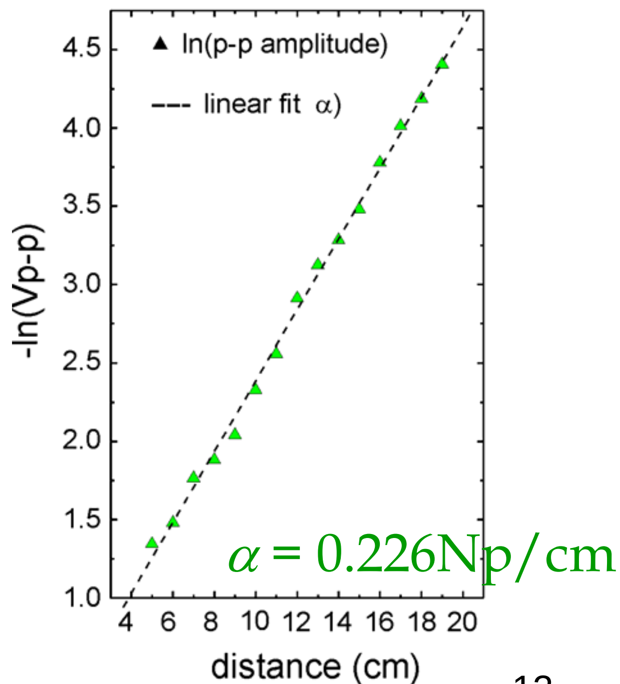
(minimal dispersion)



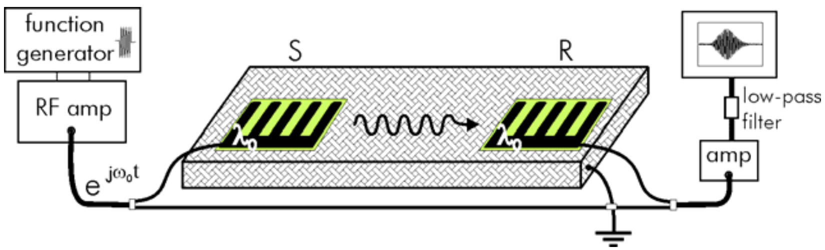
- 16 ply carbon-epoxy woven composite
- a_0 mode (f=0.31MHz, λ=4.5mm)



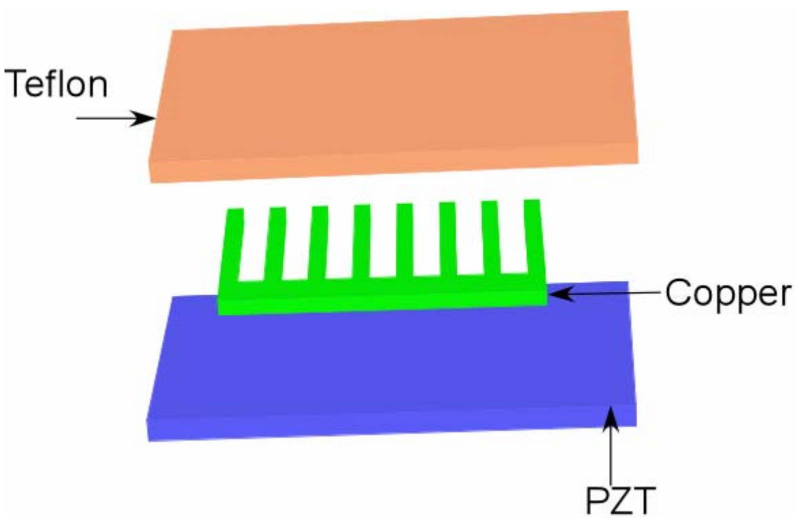




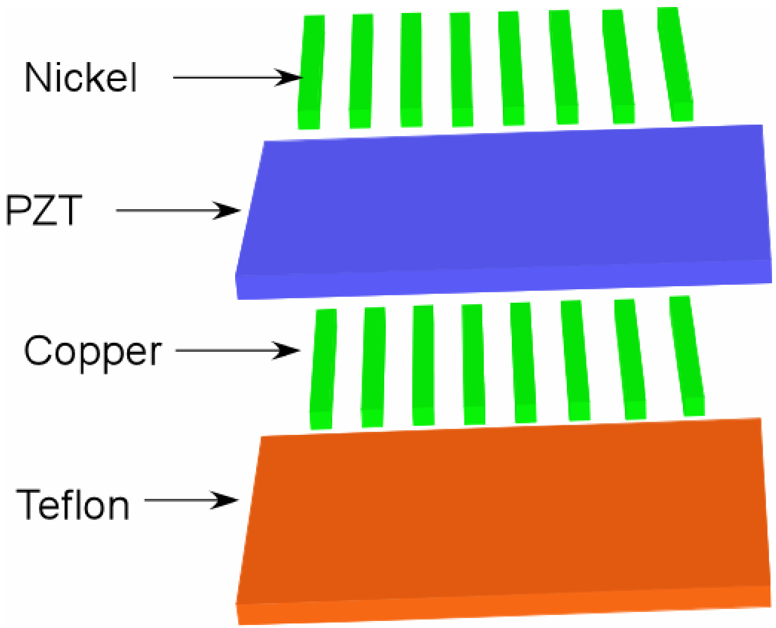
Array Design Configurations



- Generator array is best connected in parallel.
- Receive array is best connected in series.

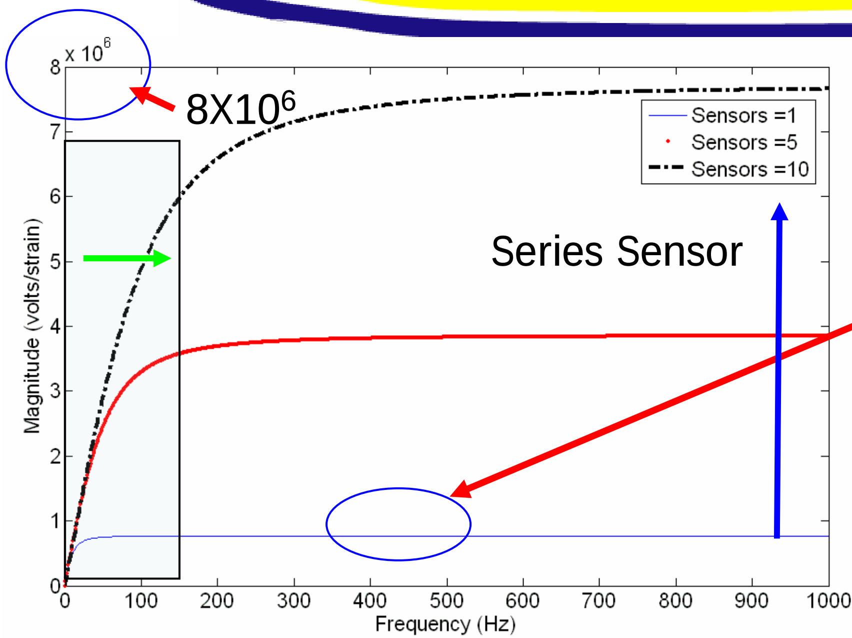


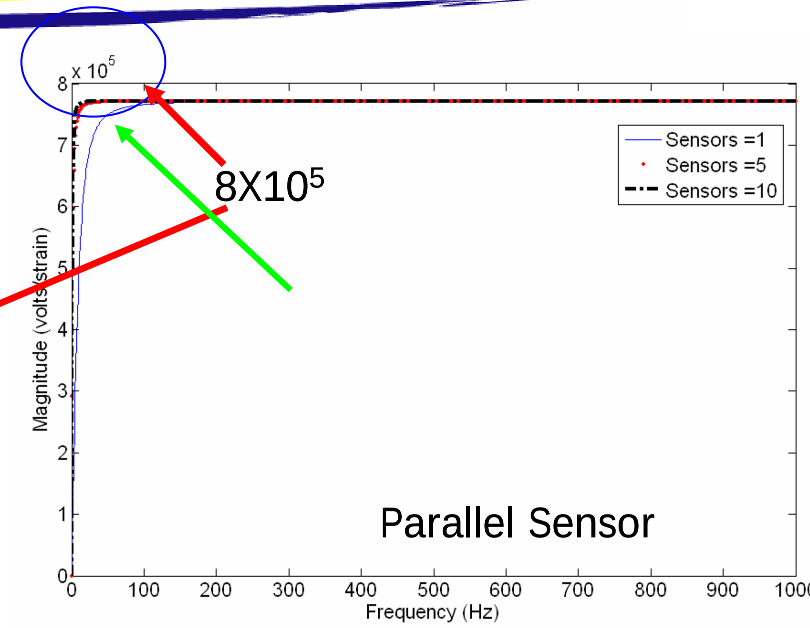
Generation Transducer array



Receiver Transducer array

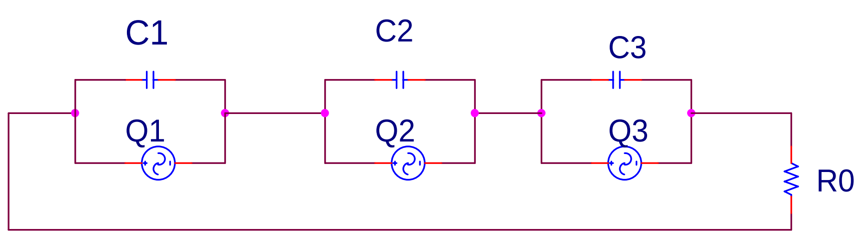
Series Vs Parallel Transducer

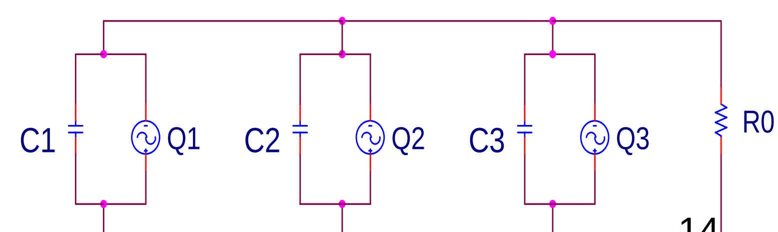




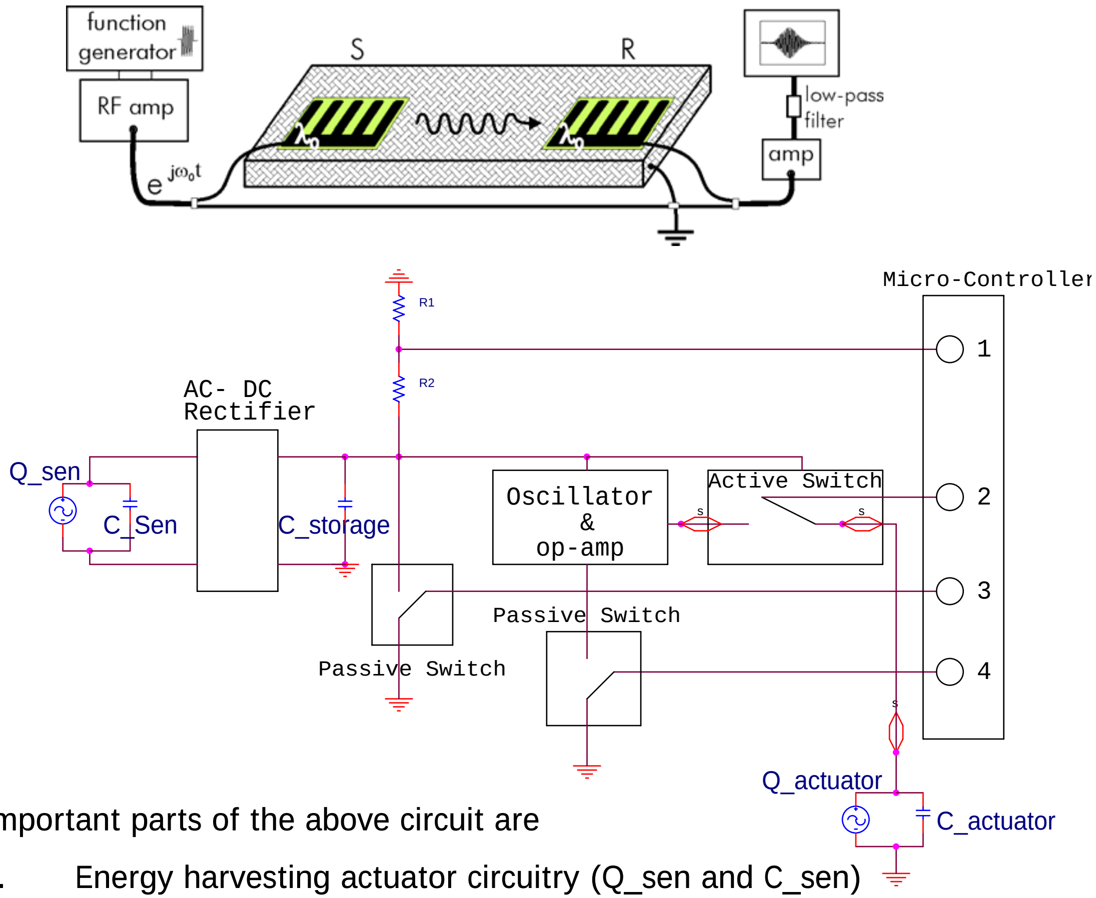
$$\frac{V_o}{S} = \frac{(e * A_e * R_o * n * j * \omega)}{n + (j * \omega * C * R_o)}$$

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



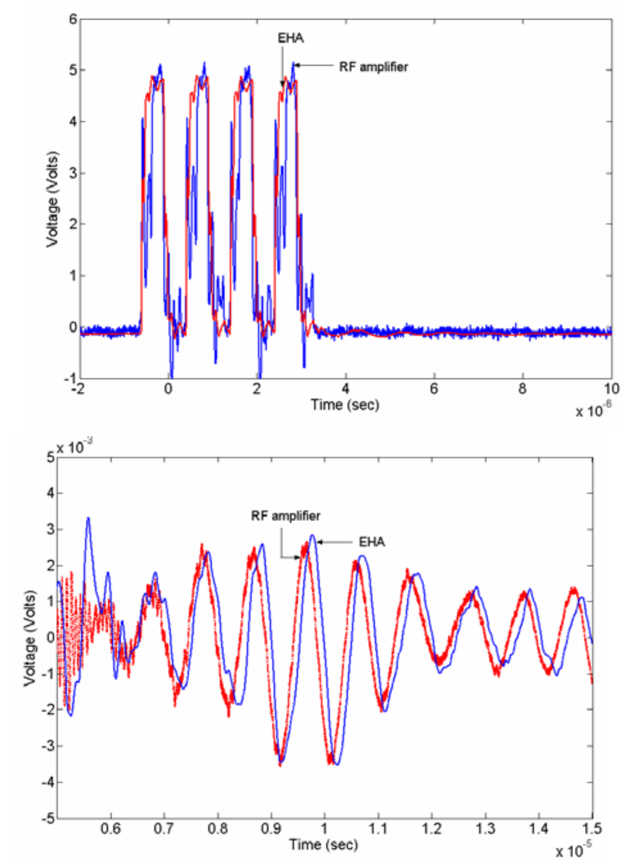


Energy harvesting circuit to power generating array



Important parts of the above circuit are

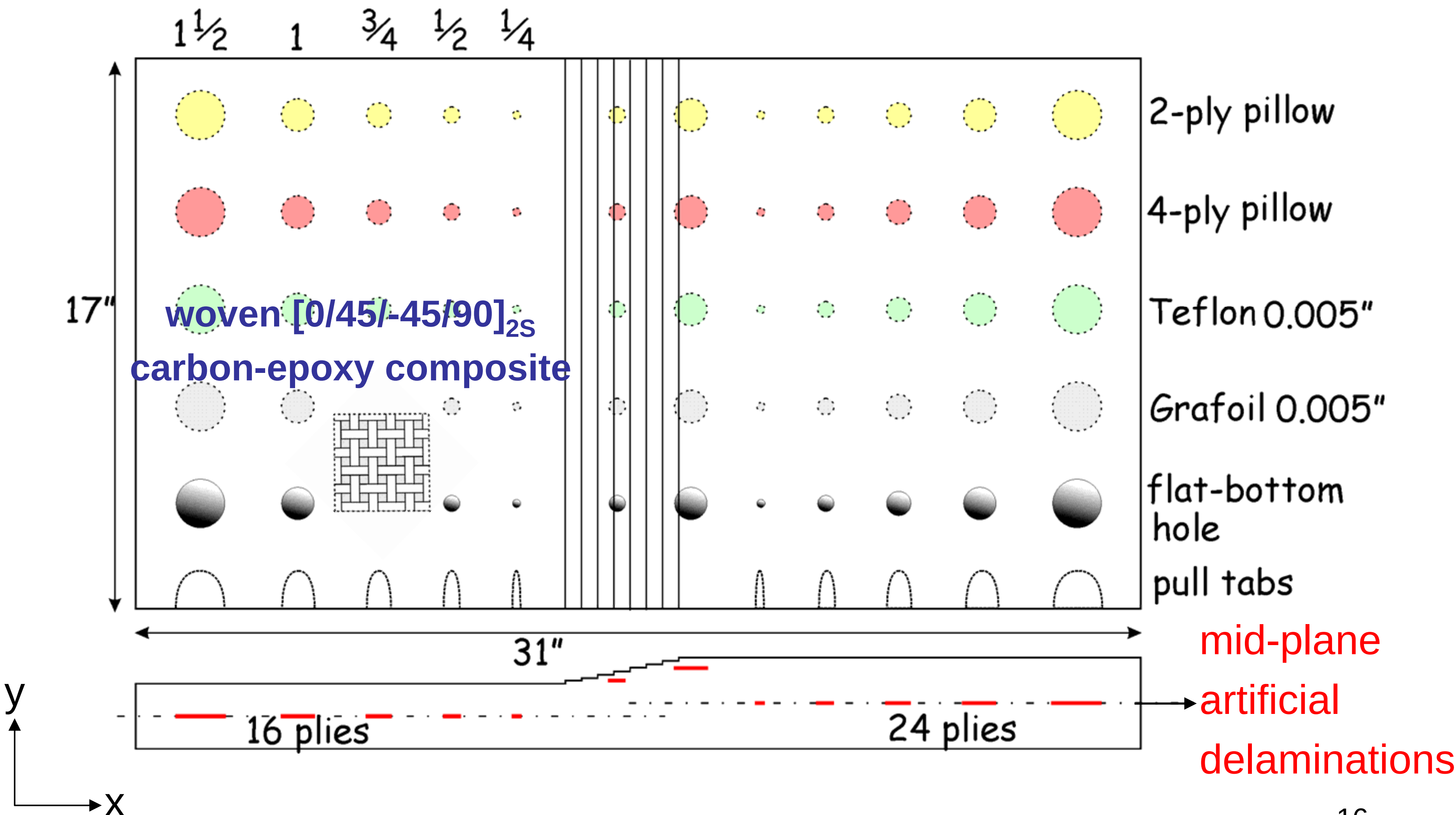
1. Energy harvesting actuator circuitry (Q_sen and C_sen)
2. Generation transducer array (Q_actuator and C_actuator)
3. Receiver transducer array (not shown)



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

Delamination Detection

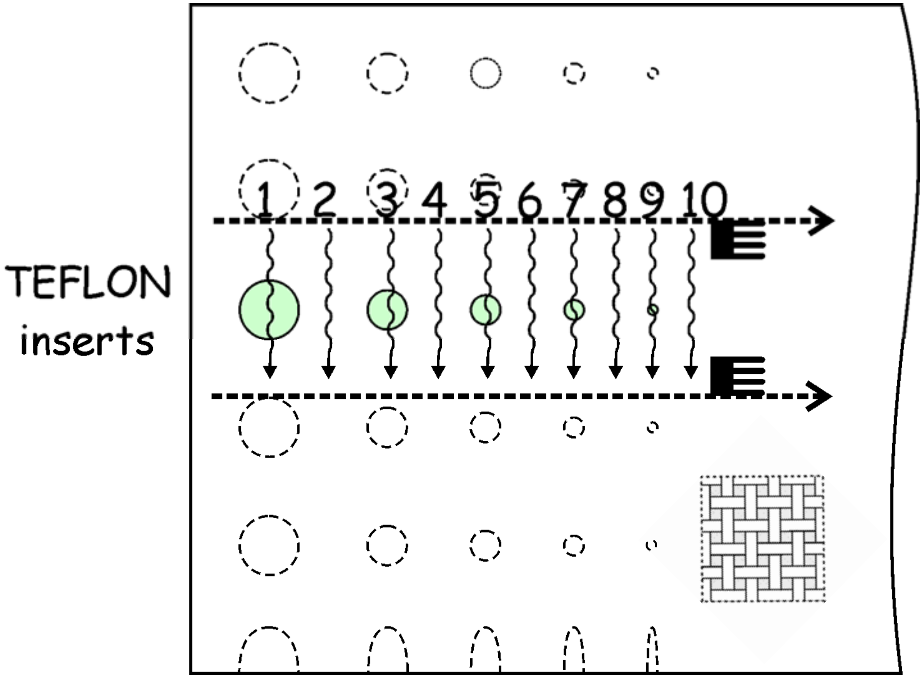
(simulated at mid-plane)

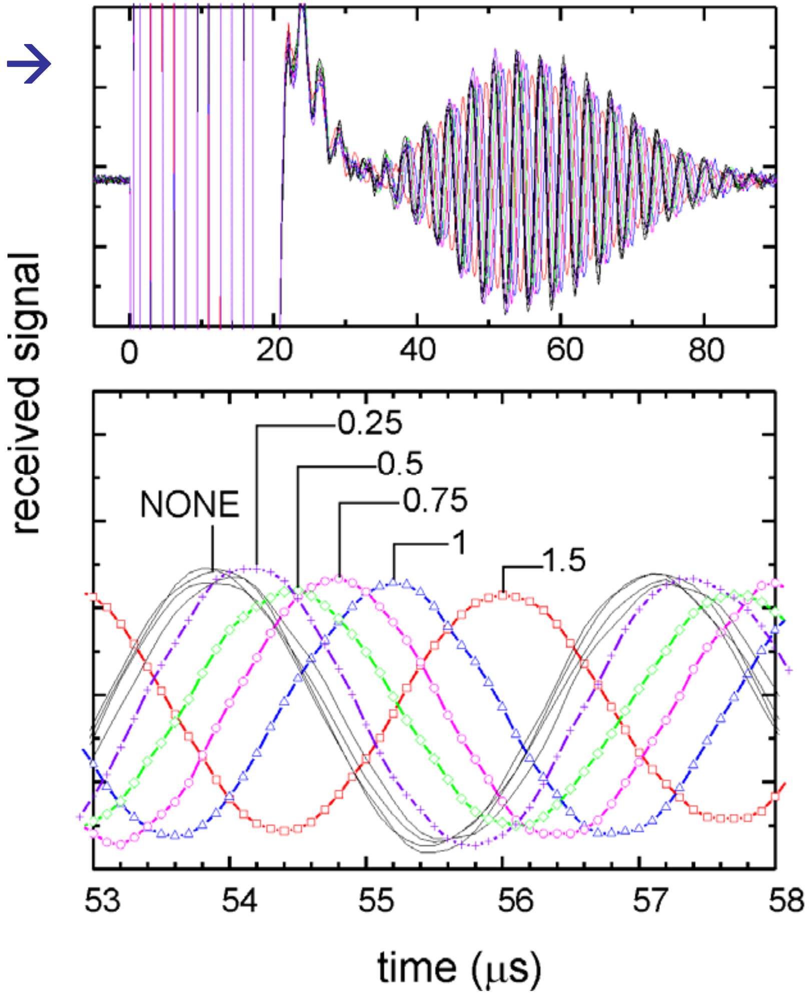


Delamination Signature

(decrease in group velocity)

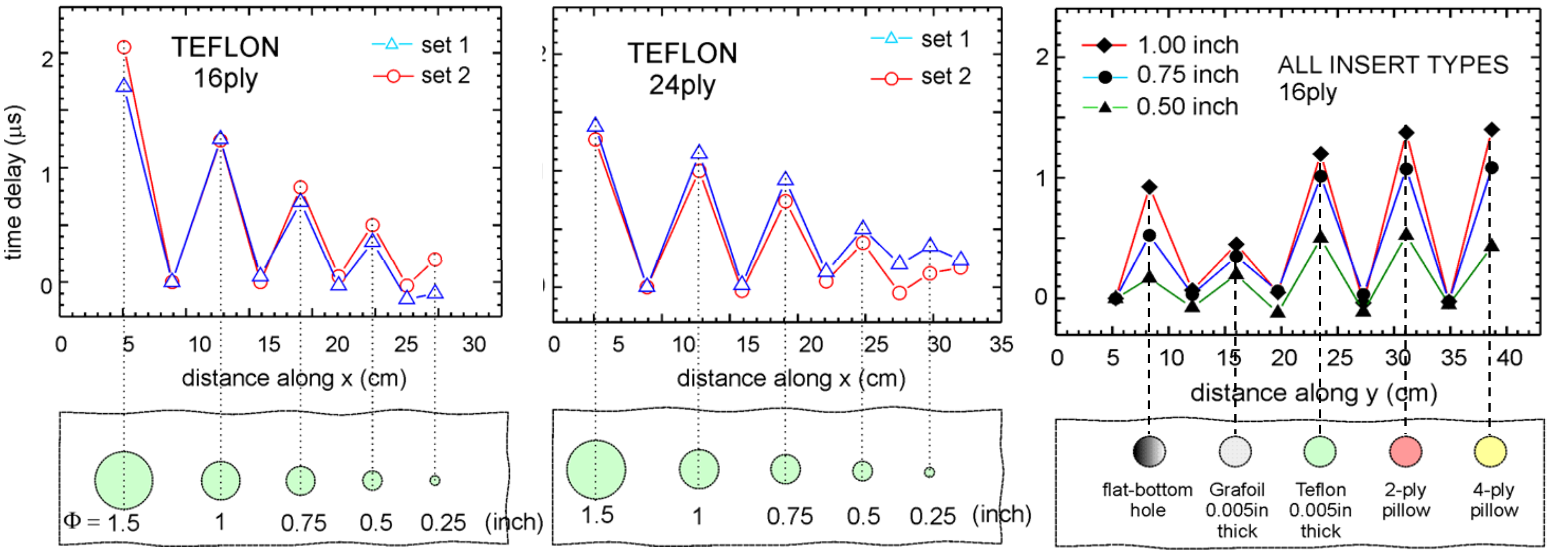
single mode (a_0) tone-burst propagation →





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

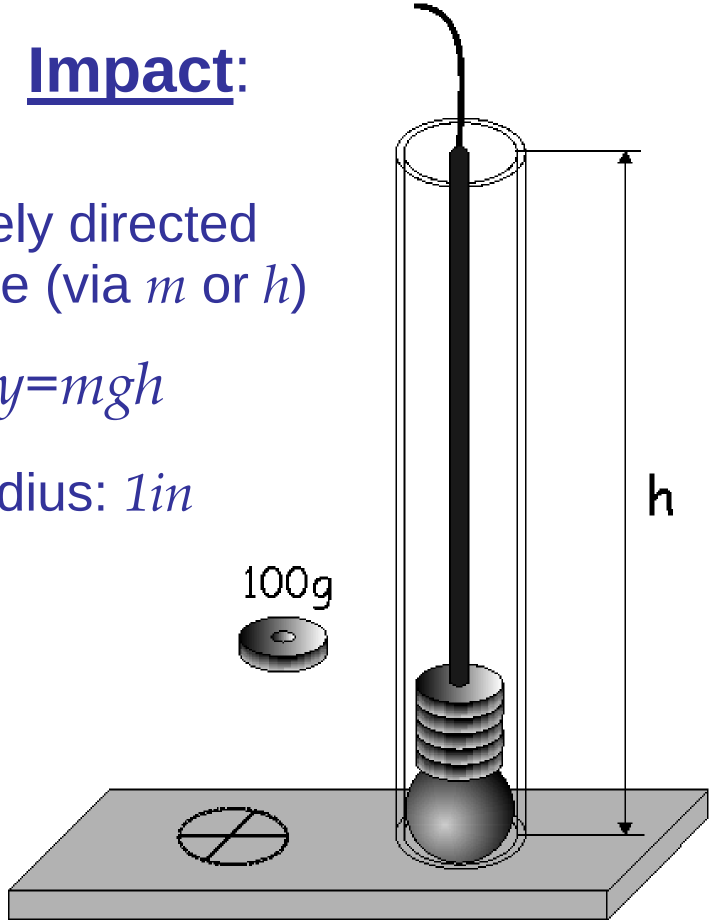
→ 4.6mm thick (24 plies)

Impact:

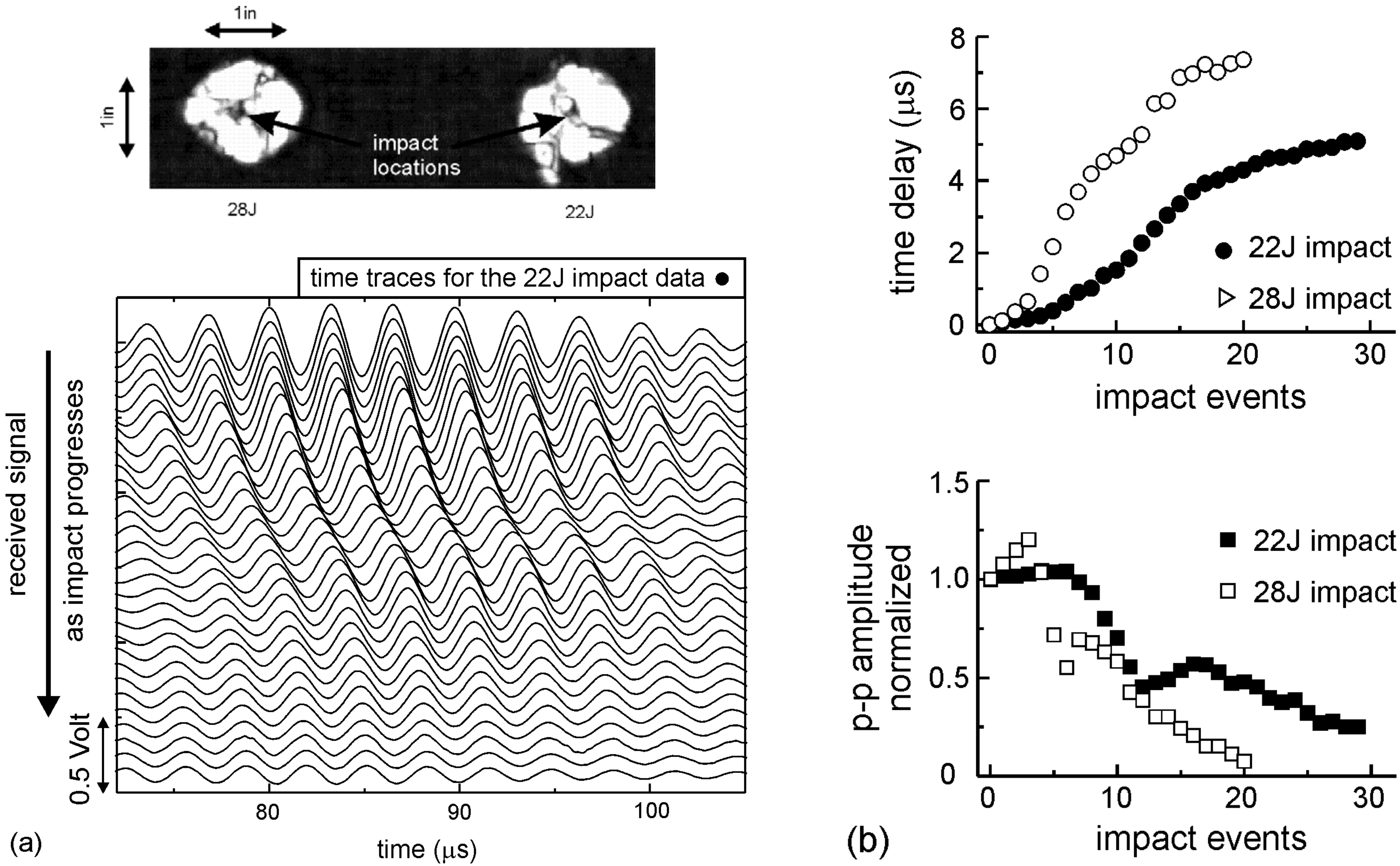
- precisely directed
- variable (via m or h)

$$Energy = mgh$$

- ball radius: *1in*



Impact Delaminations



Impact Delaminations

- prognosis -

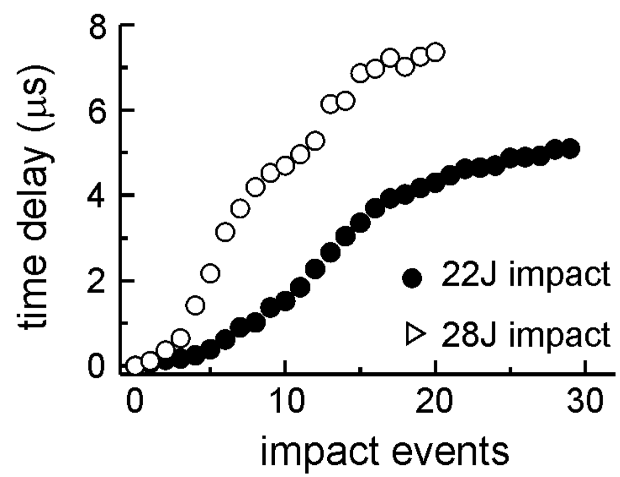
i) composite part suffers an impact and monitored with sensors;

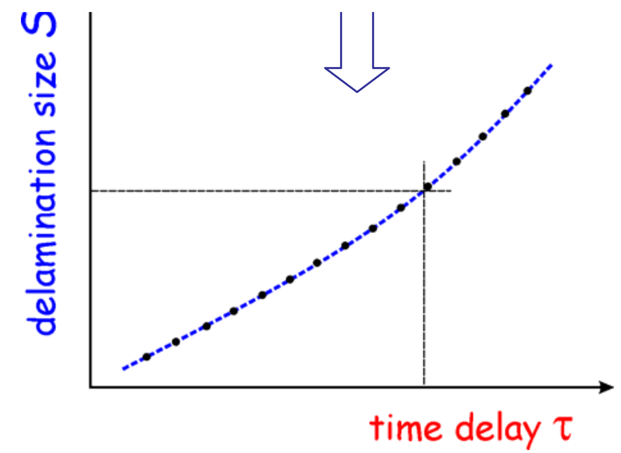
ii) velocity changes → **time-delay (τ)** ;

convert τ into **damage level (S)**

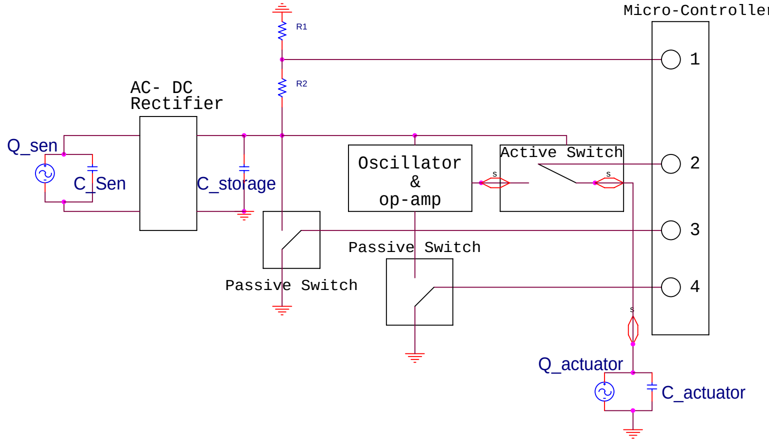
$$S(\tau)=a+b\tau^{m}$$

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

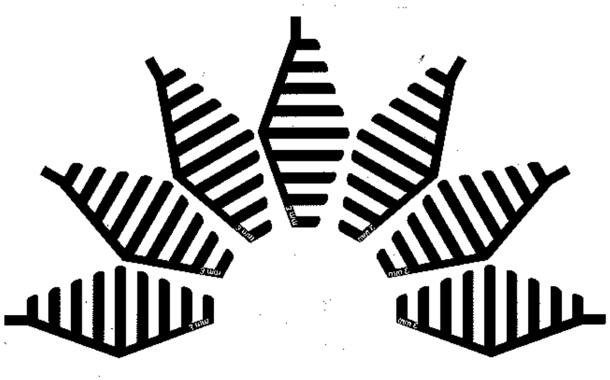




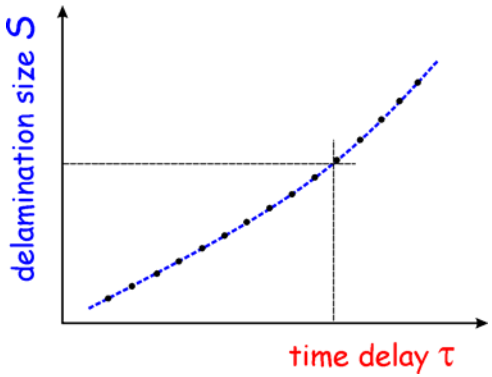
Work in Progress



Energy-harvested generation transducers



Radial transducer arrays



Prognosis

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