JAMS

Structural Health Monitoring for Life Management of Aircraft

-SHM System for Composite Structures –

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A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

NORTHWESTERN UNIVERSITY

CECAM
center of excellence for composites and advanced materials

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 a SHM system to detect and size impact damage and predict remaining lifetime of a laminated composite component.

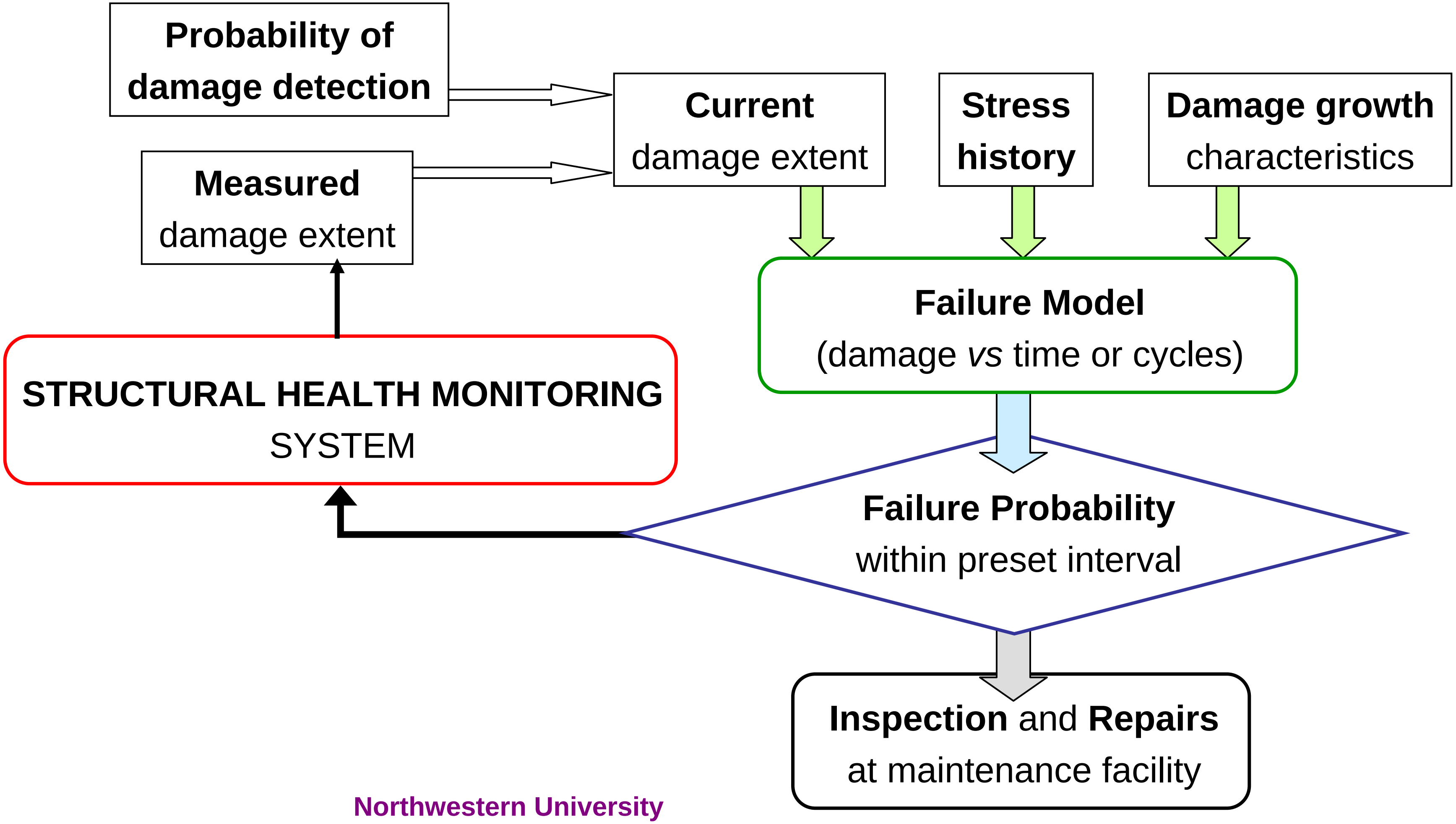
- **Approach:**

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

Structural Health Monitoring and Lifetime Prediction



Probability of damage detection

Measured damage extent

Current damage extent

Stress history

Damage growth characteristics

Failure Model
(damage *vs* time or cycles)

STRUCTURAL HEALTH MONITORING SYSTEM

Failure Probability within preset interval

Inspection and **Repairs** at maintenance facility

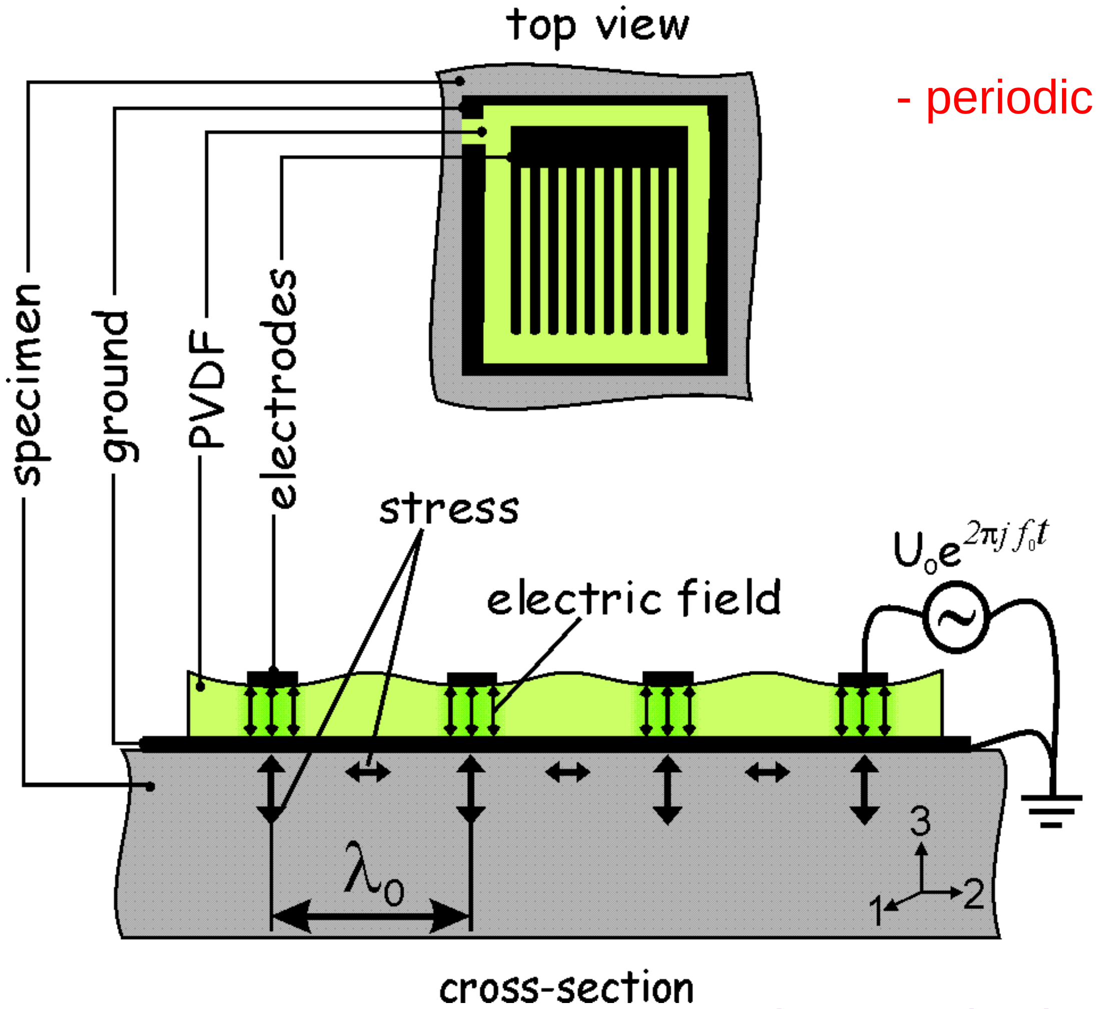
SHM of Composite Structures

- A laminated composite panel suffers impact damage → matrix damage and delaminations.
- The panel is subject to cyclic loading which causes the damage to grow.
- A permanently installed SHM system comprising ultrasonic probes detects/sizes the damage.
- A probabilistic fatigue damage model estimates the remaining lifetime of the structure.

SHM of Composite Structures

- **Sensor Development:**
  - – Modally-selective Lamb wave sensors
    - Measurement of distributed damage via changes in propagation due to the dispersive nature of the Lamb-waves
    - Mapping of delaminations with Lamb-wave tomography
- **Damage growth laws**
- **Probabilistic estimation of remaining lifetime**

Mode-Selective Lamb-Wave Sensors

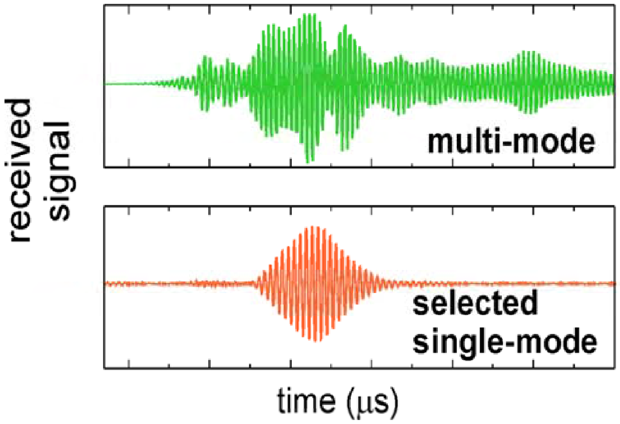


The comb design:

- 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,density, layup)

➔ determine the dispersion curves

2) identify a region with minimal dispersion ➔

known velocity c and frequency (f_0)

3) design a comb mask with finger spacing $\lambda_0 = c / f_0$

4) fabricate the electrodes

5) assemble the transducers

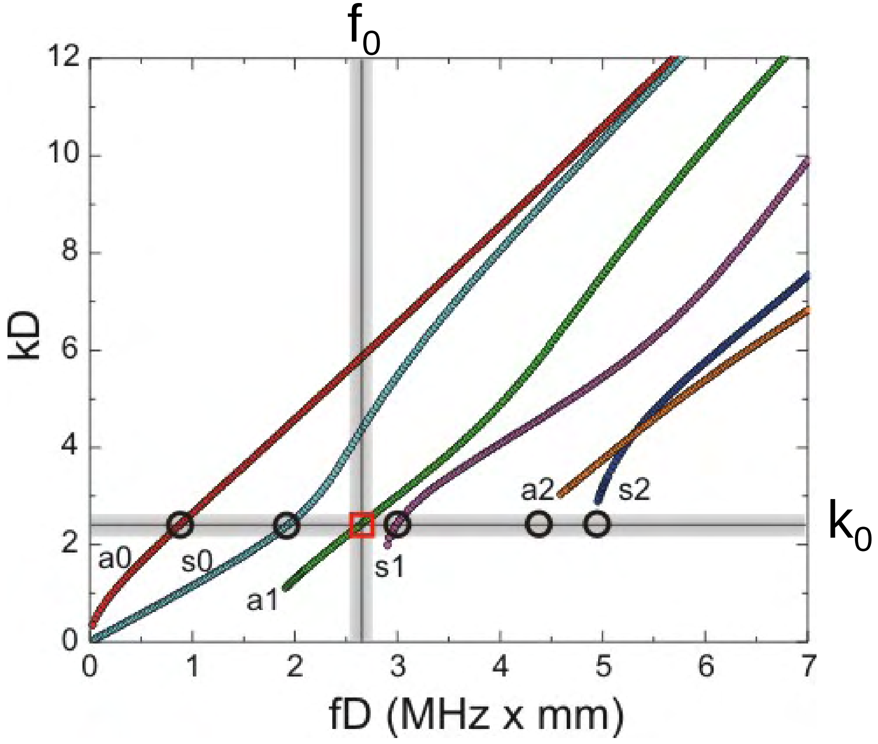
Note: it is desirable to design a sensor which, at a fixed λ_0*, can excite individual modes at specific frequencies:* $\lambda_0 = c_1/f_1 = c_2/f_2 = c_3/f_3 \ldots$

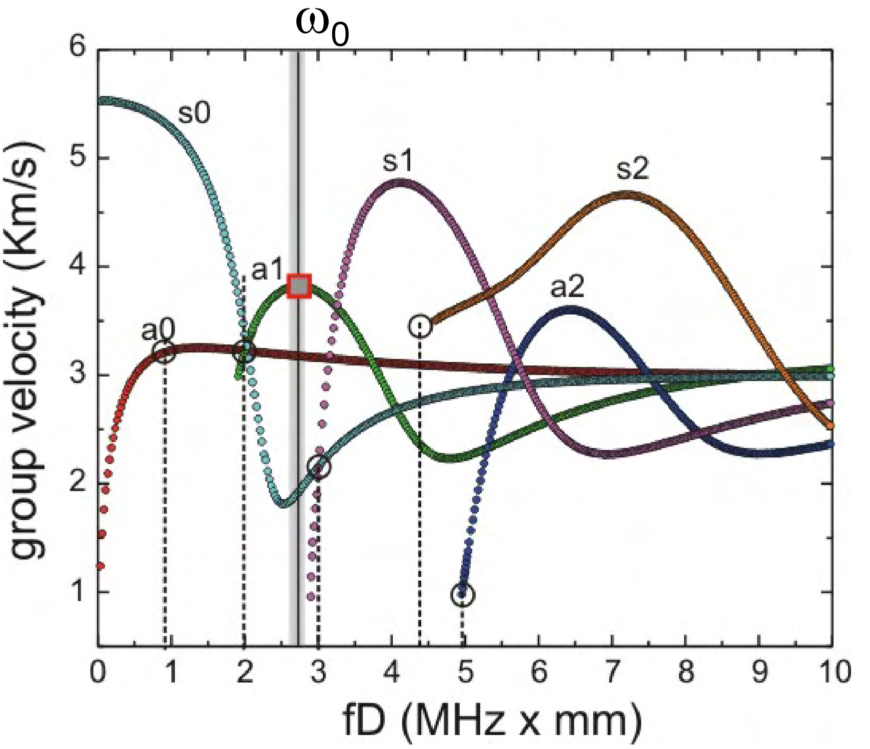
Sensor Design

- dispersion curves -

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

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

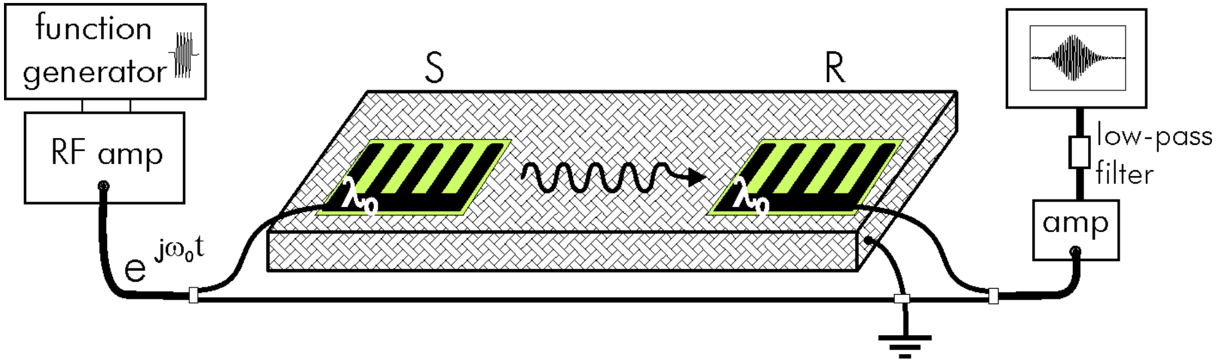




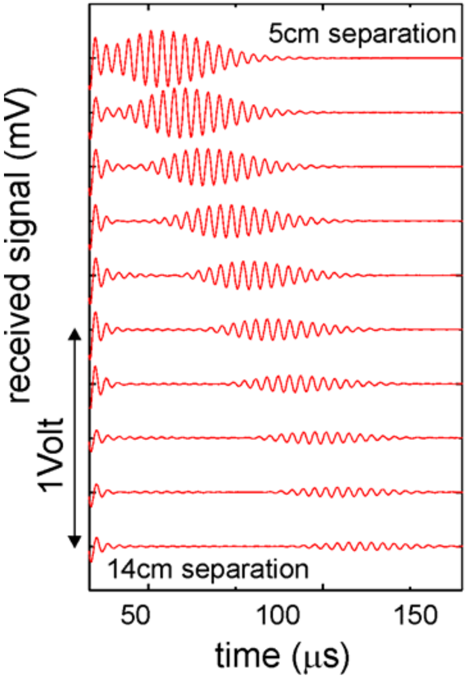
Excitation: in a low-dispersion domain

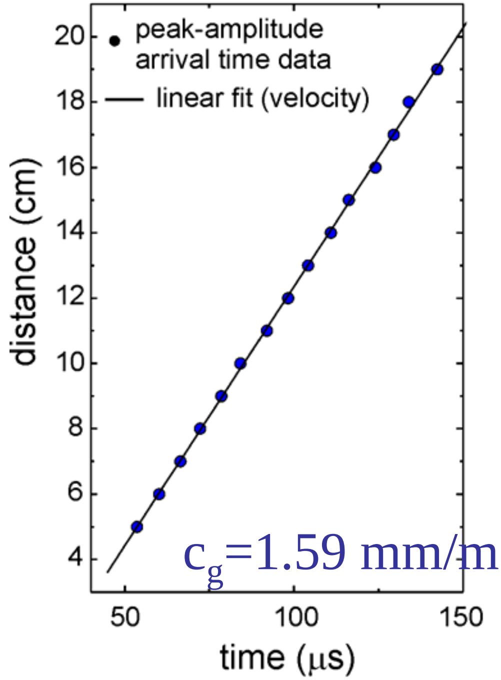
Mode Propagation

(minimal dispersion)

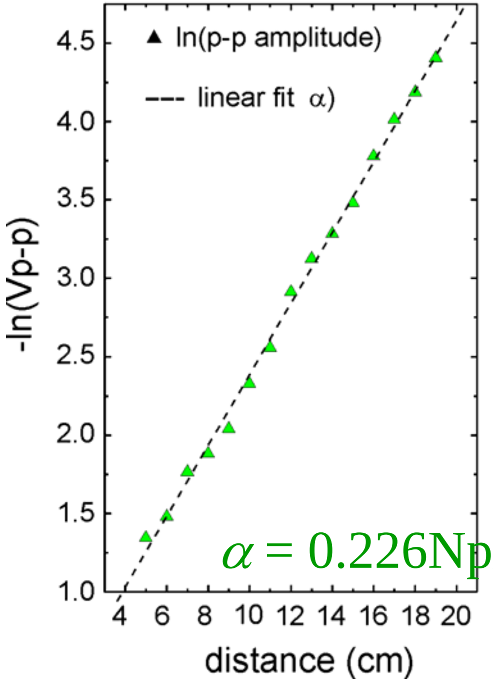


- 16 ply carbon-epoxy woven composite
- a_0 mode (f=0.31MHz, λ=4.5mm)



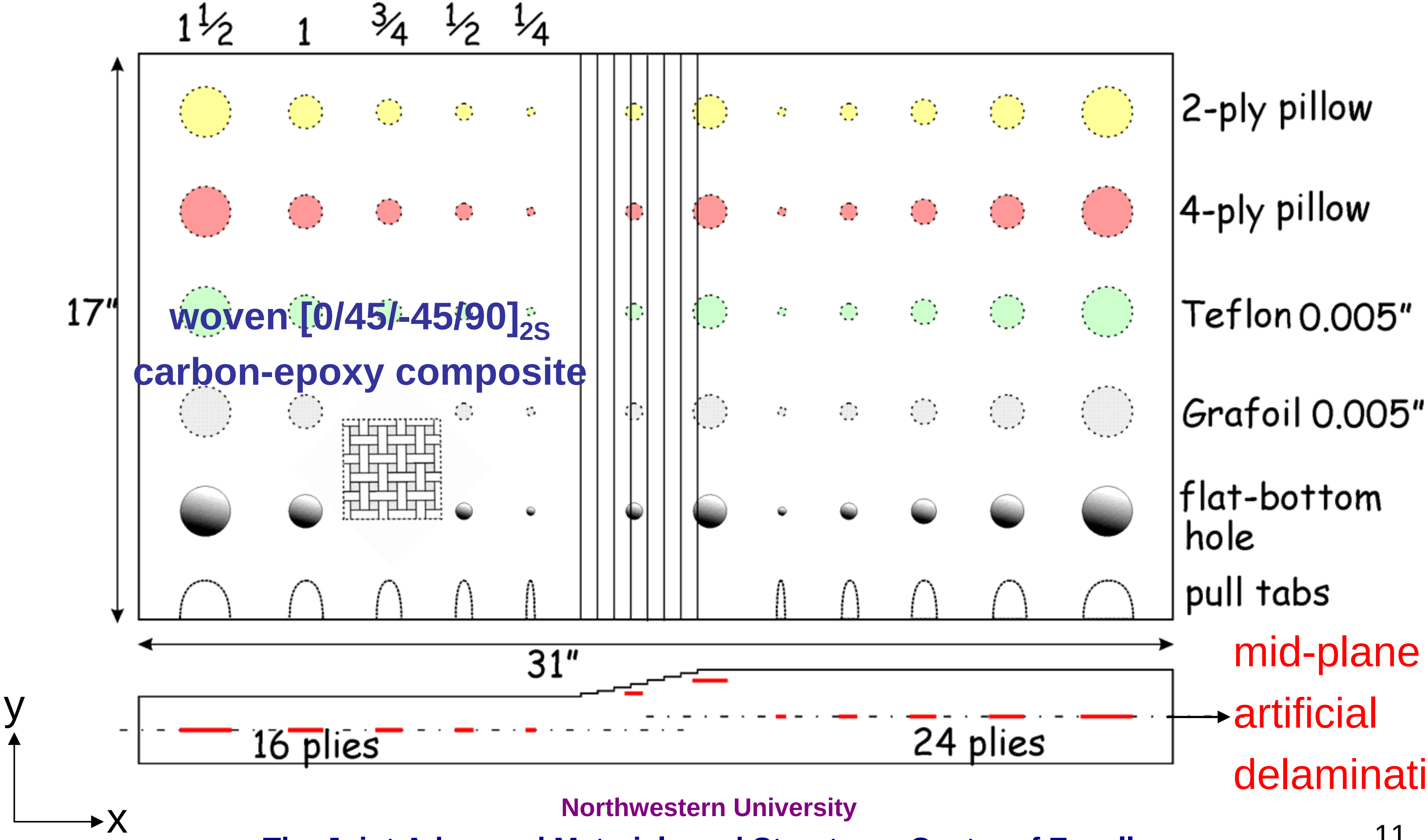


c_g=1.59 mm/ms



α = 0.226Np/cm

Composite Specimen with Seeded Delaminations



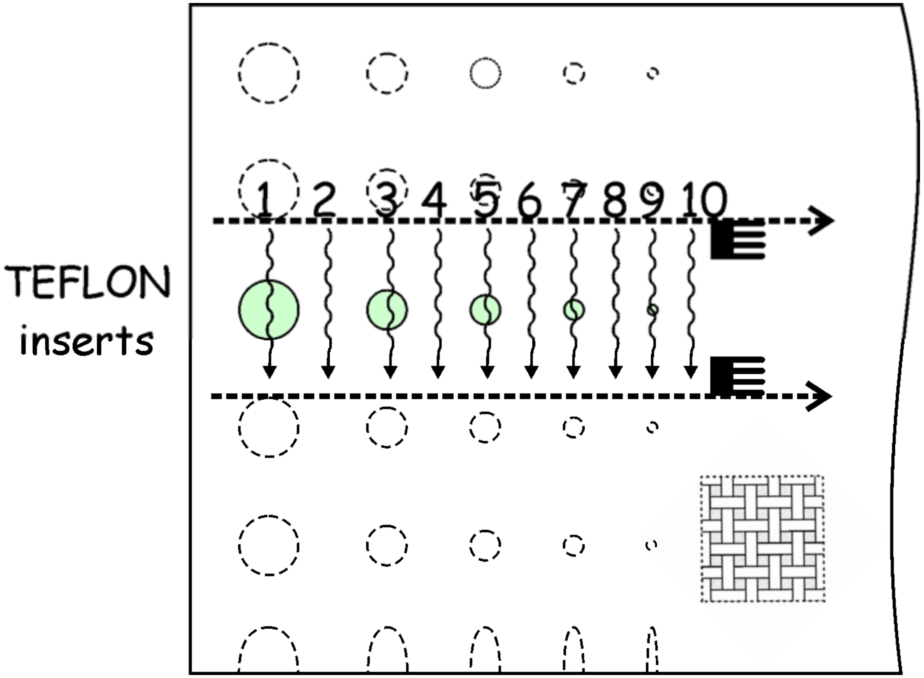
woven $[0/45/-45/90]_{2S}$ carbon-epoxy composite

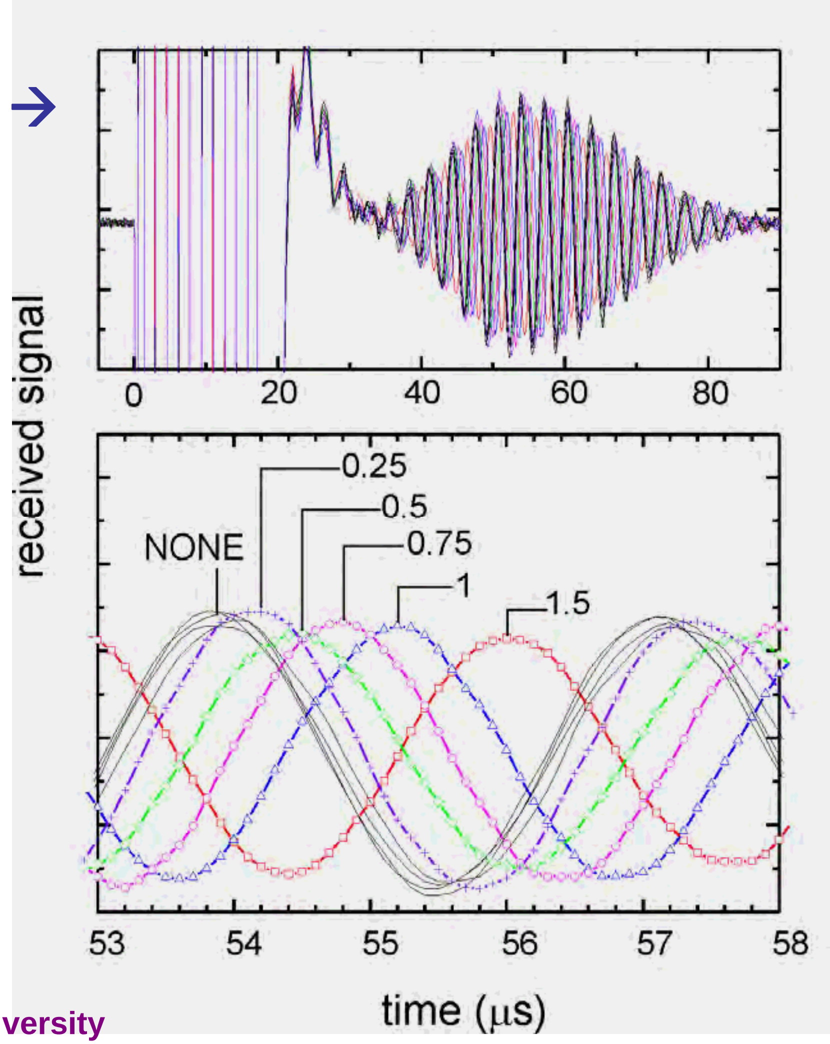
mid-plane artificial delaminations

Delamination Signature

(time delay)

single mode (a_0) tone-burst propagation →



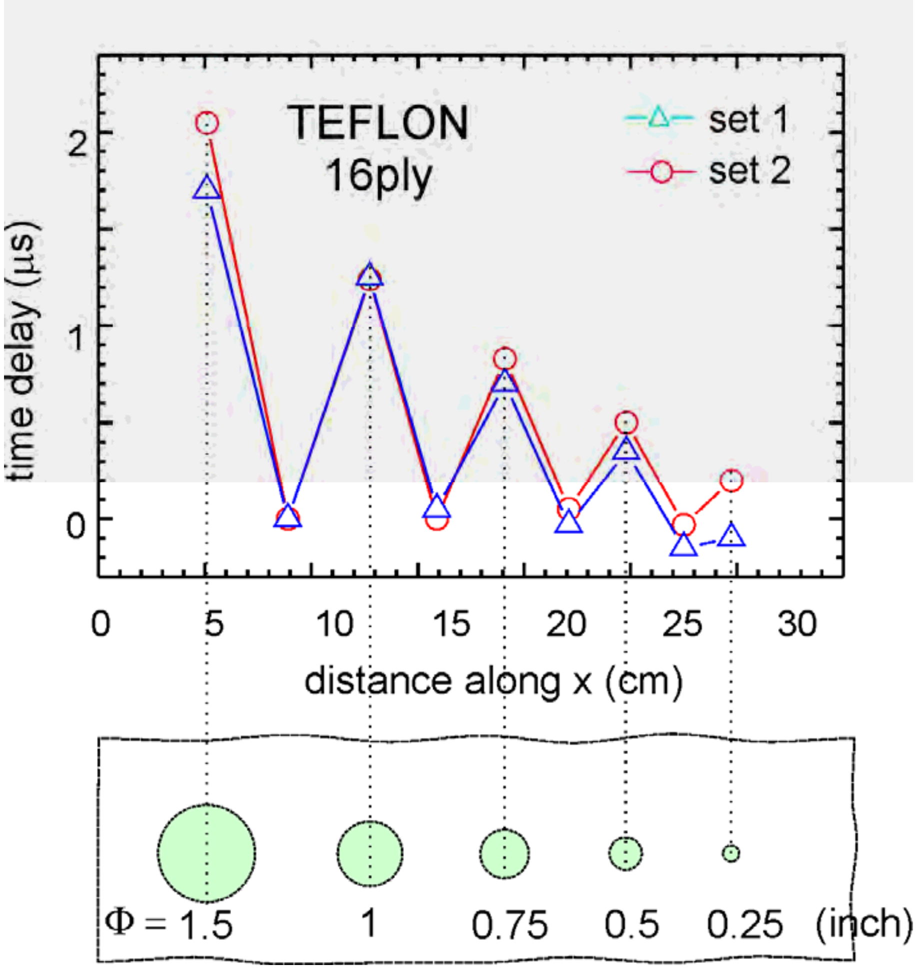


Delamination Signature

Time-Delay

thinner part

(16 ply)



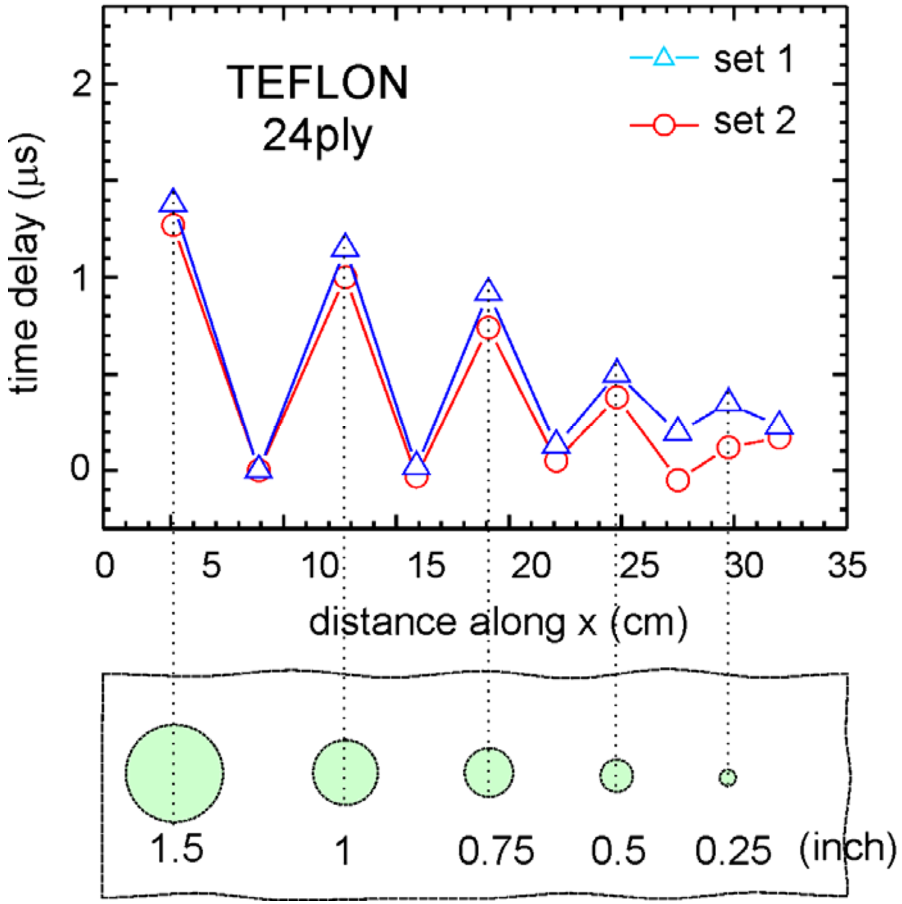
Delamination Signature

Time-Delay

thicker part

(24 ply)

larger fD → smaller Δc_g



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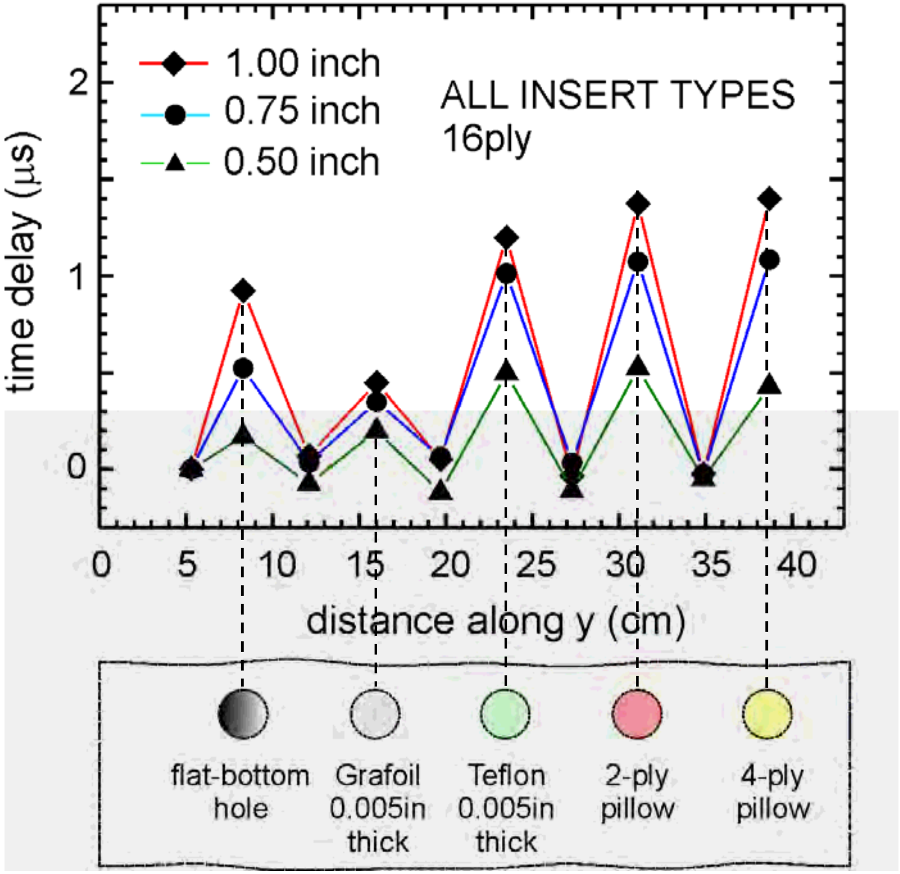
Delamination Signature

Time-Delay



Impact-Induced Delaminations

Material:

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

→ cross-ply $[0/90]_{6S}$

→ carbon-epoxy composite

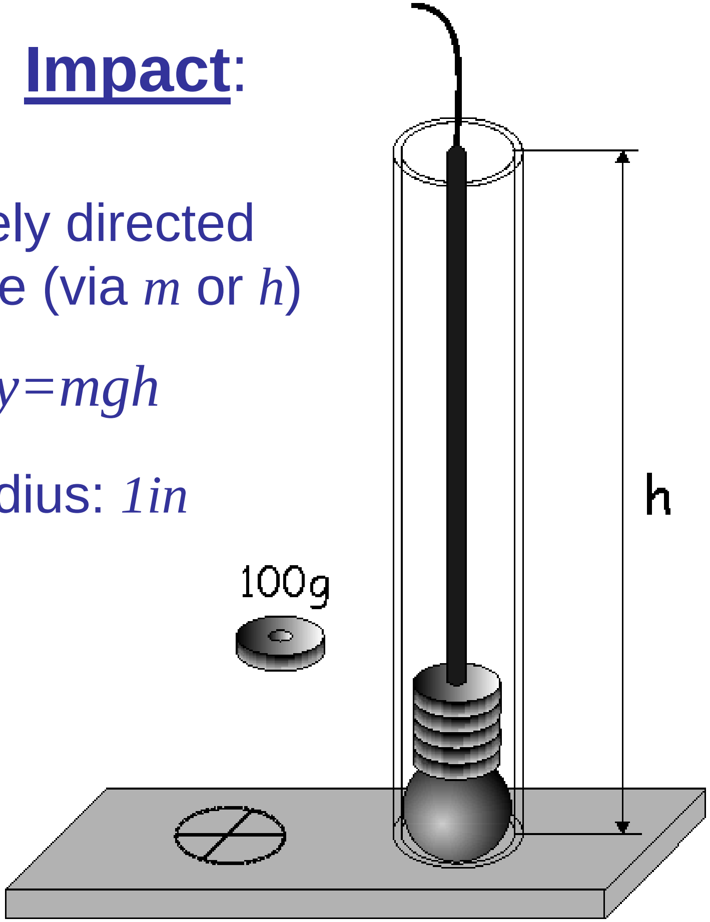
→ 4.6mm thick (24 plies)

Impact:

- precisely directed
- variable (via m or h)

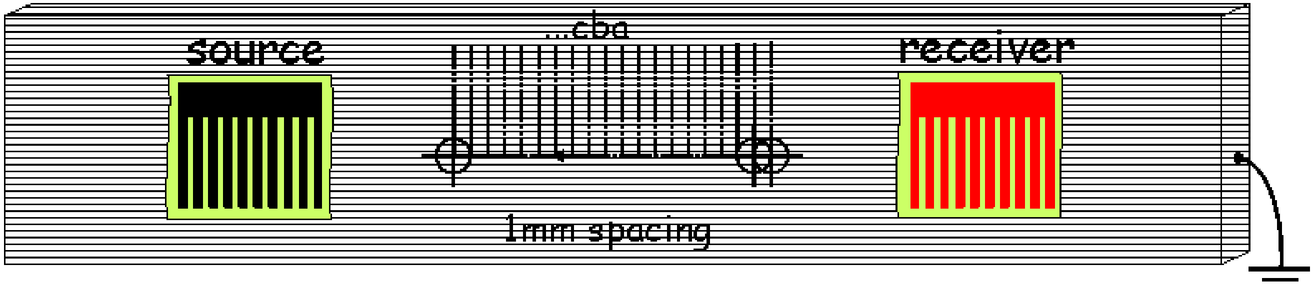
$$Energy = mgh$$

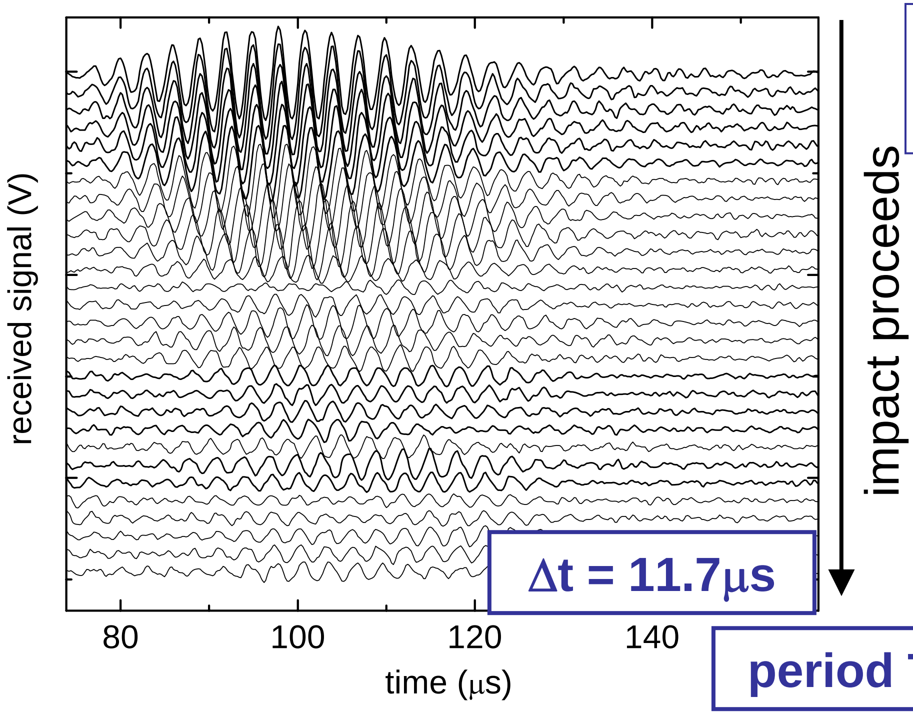
- ball radius: $1in$



Impact Delaminations

- test I -

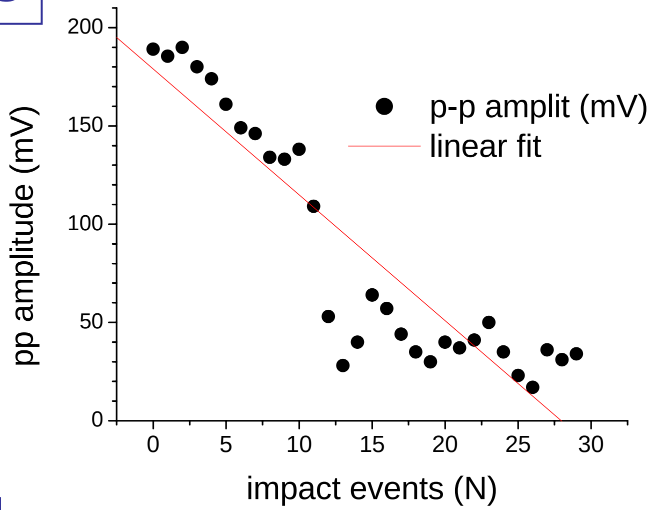




Impact: 17 Joules

Δt = 11.7μs

period T = 3.2μs

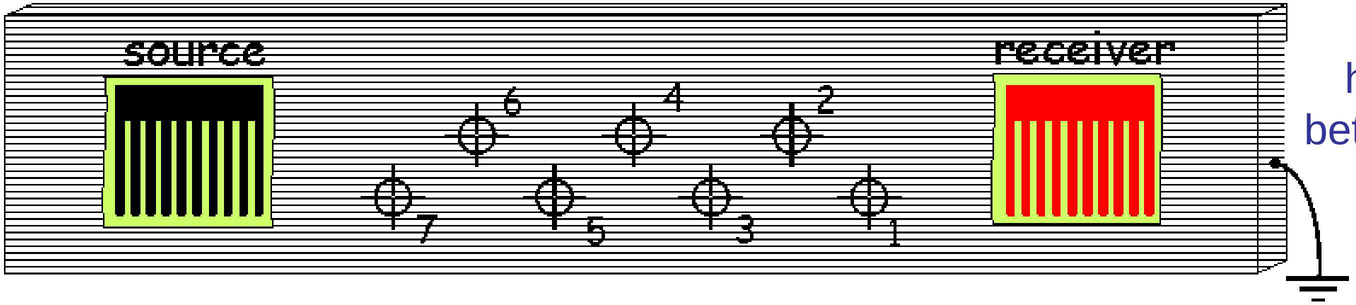


Impact Delaminations

- **test I** ; C-scan image of damage -

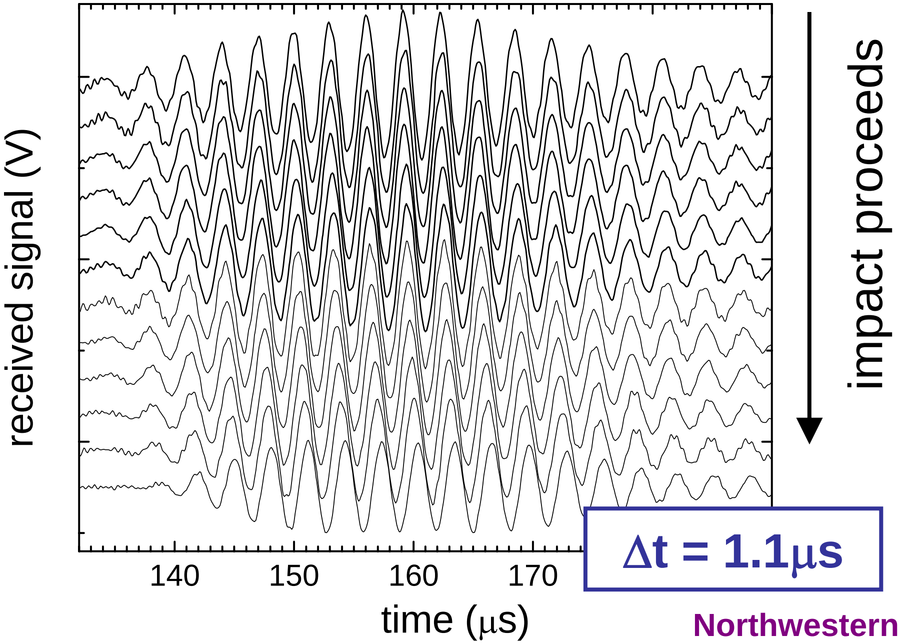
Impact Delaminations

- test II -



horizontal spacing between impacts: 3cm

signal received after impact at pos1

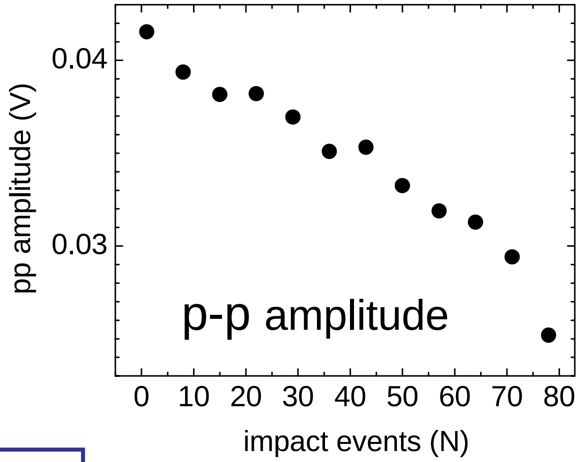


Impact:

13J
↓
15J
↓
16J

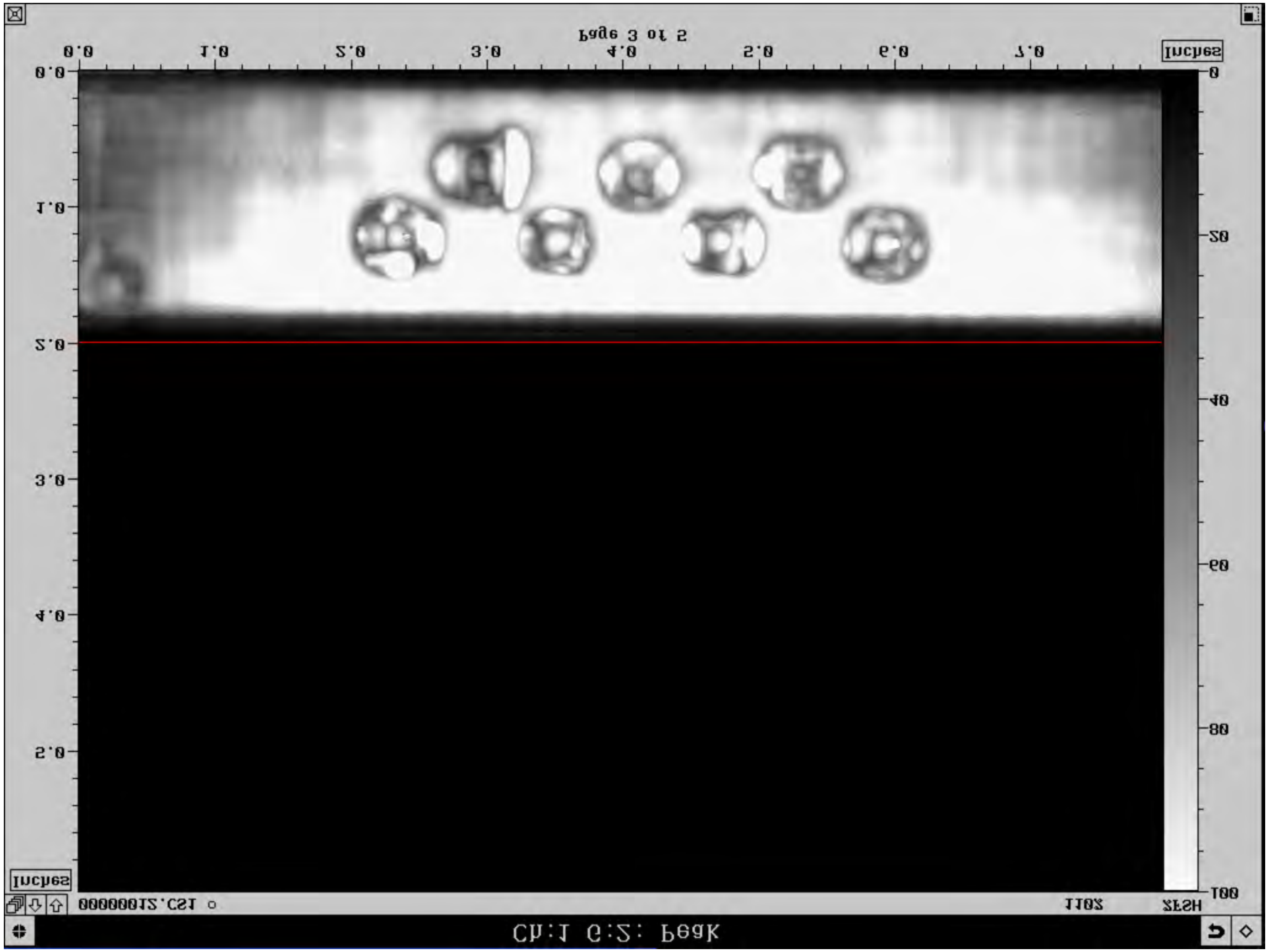
Δt = 1.1μs

period T = 3.2μs



Impact Delaminations

- **test II** ; C-scan image of damage -



1 inch

Impact Delaminations

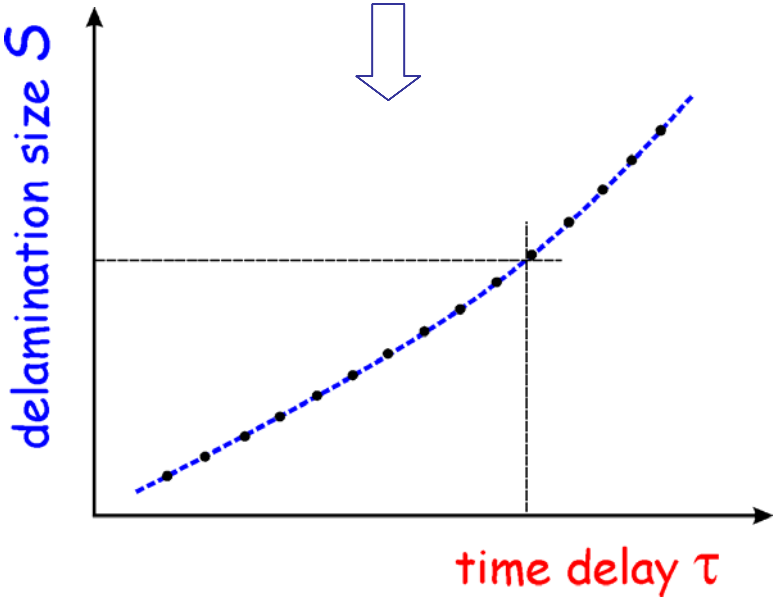
- time-delay *vs* size **correlation** -

Scenario: **i)** composite part instrumented with sensors suffers an impact; **ii)** velocity changes ➔ **time-delay (τ)** ; **iii)** $\underbrace{\text{convert } \tau \text{ into } \textbf{damage level (S)}}$

How is S determined?

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

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



1) continuously increase the impact load
2) C-scan image to determine delamination size *after each impact*
3) measure time delay *after each impact*

Damage Parameters

Time-delay τ

- sensitive damage parameter
- **RELIABLE**: damage dependent **only**

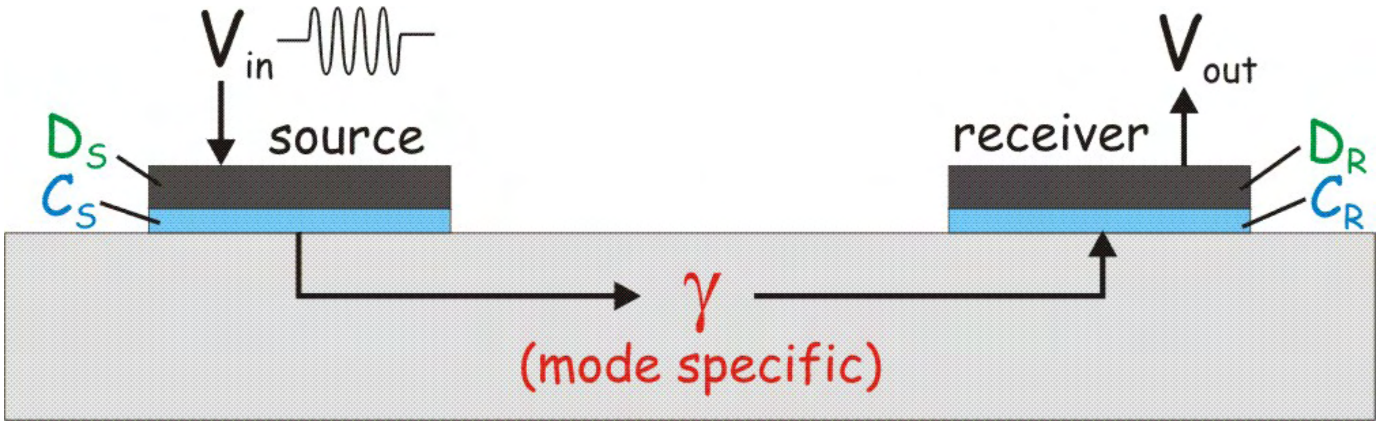
Amplitude A

- sensitive damage parameter
- **UNRELIABLE**: couplant dependent

IF coupling/insertion loss variations can be eliminated or corrected for

$[\ \tau + A\ ]$ would make a **strong and reliable damage parameter**

Couplant Cancellation



Received amplitude:

$$\boxed{V_{out} = D_R\, C_R\, \gamma(\text{propagation})\, C_S\, D_S\, V_{in}} = \gamma\, T$$

coupling

piezoelectric effect

Couplant Cancellation

$$V_{out} = \gamma\, T$$

1) damage: change in $\gamma \rightarrow \gamma'$

* affects every mode in a **unique** way

2) variations **other than damage**: change in $T \rightarrow T'$

e.g. coupling insertion losses changes

e.g. changes in the input energy V_{in}

* affects every mode the **same** way

using two modes a and b

$(i - impact\ event)$

$$\Phi(i) = \frac{V^{b}_{out}(i)}{V^{a}_{out}(i)} \Bigg/ \frac{V^{b}_{out}(0)}{V^{a}_{out}(0)} = \boxed{\frac{\gamma^{b}(i)}{\gamma^{a}(i)} \Bigg/ \frac{\gamma^{b}(0)}{\gamma^{a}(0)}}$$

damage-dependent ONLY

Couplant Cancellation

using two modes
a and *b*

(i – impact event)

$$\Phi(i)=\frac{\mathrm{V}^{\mathrm{b}}{}_{\mathrm{out}}(i)}{\mathrm{V}^{\mathrm{a}}{}_{\mathrm{out}}(i)}\Bigg/\frac{\mathrm{V}^{\mathrm{b}}{}_{\mathrm{out}}(0)}{\mathrm{V}^{\mathrm{a}}{}_{\mathrm{out}}(0)}=\boxed{\frac{\gamma^{b}(i)}{\gamma^{a}(i)}\Bigg/\frac{\gamma^{b}(0)}{\gamma^{a}(0)}}$$

damage-dependent
ONLY

Φ: a measure of the detected signal amplitude as a function of damage, independent from *coupling* or any other factor, as long as that factor affects all the modes <u>equally</u>.

<u>Note</u>: empirically determined Φ is used in the prediction algorithm.

Work in Progress

- improve the transducer sensitivity by replacing the PVDF with flexible *piezo-composite* (from Smart Material Inc.)
- verify the consistency of the measurements
- instrument a large panel with sensors for X-Y tomography
- having defined a damage-parameter, study the influence of *fatigue* on specimens with seeded delaminations; determine the *growth-law*

A Look Forward

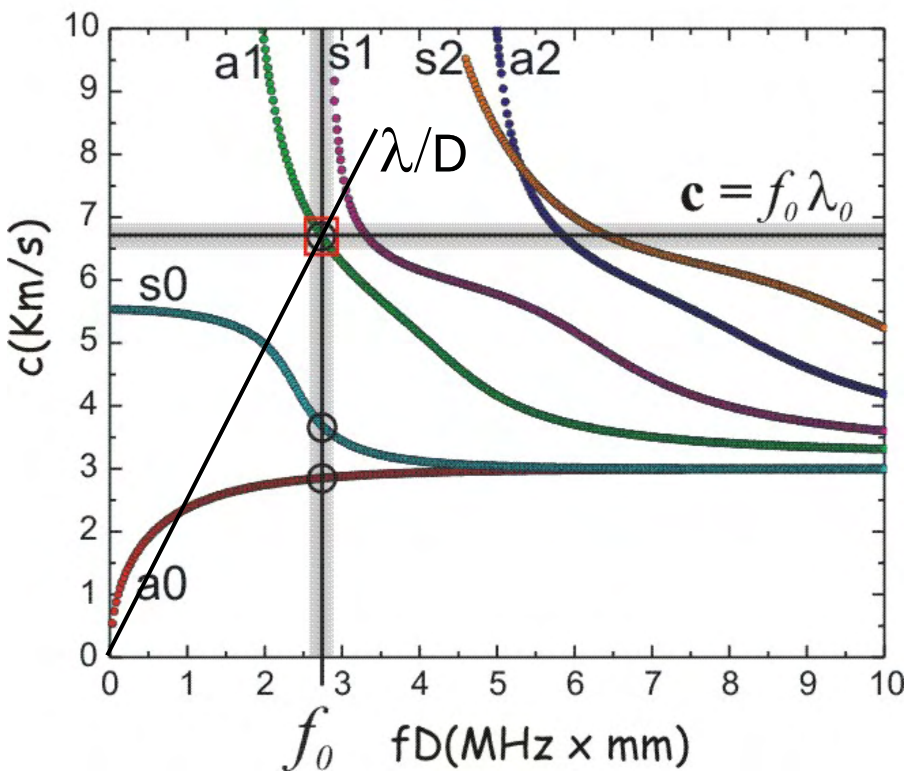
- Benefit to Aviation
  - Maintenance calls based on need
  - Cost saving
  - Reduced downtime
- Future needs

  - sensor powering… energy harvesting?

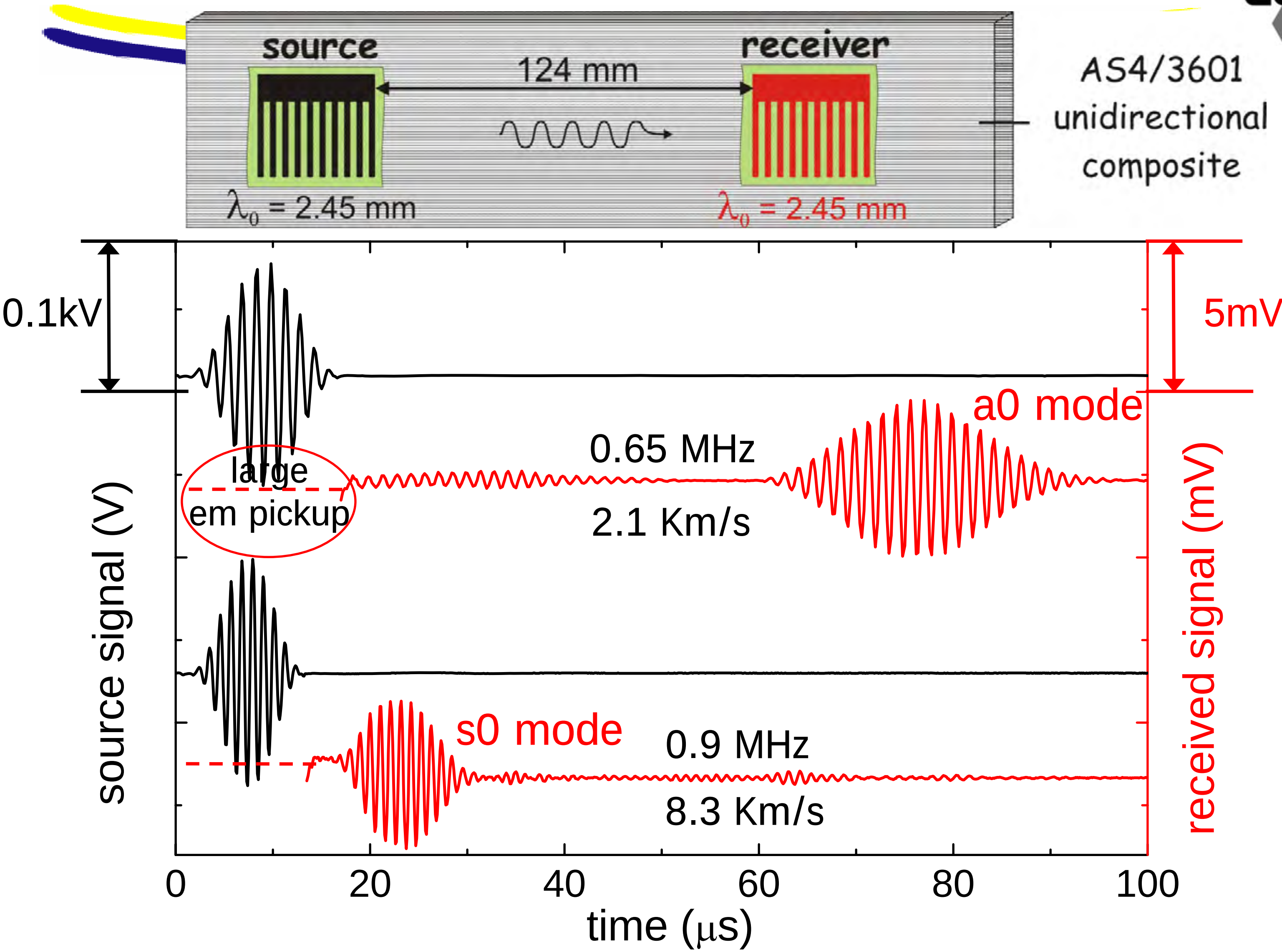
  - sensor data transmission…telemetry

additional

phase velocity *vs.* fD

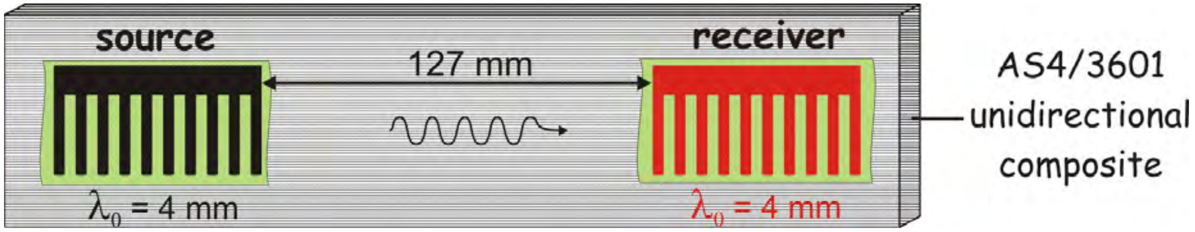


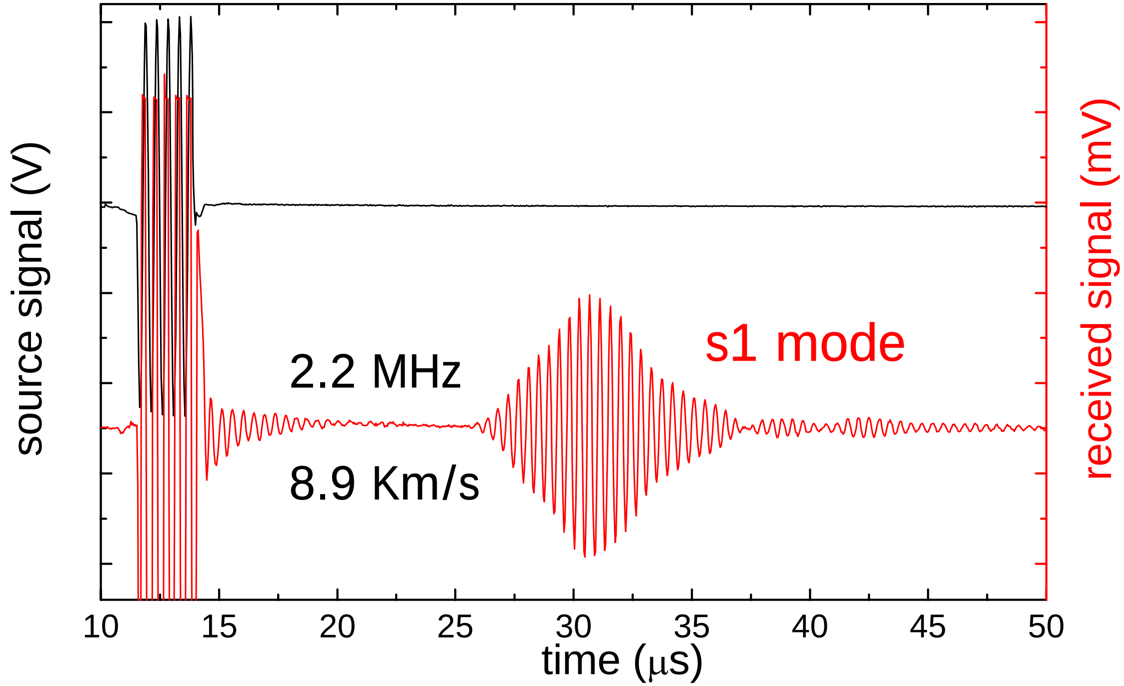
additional



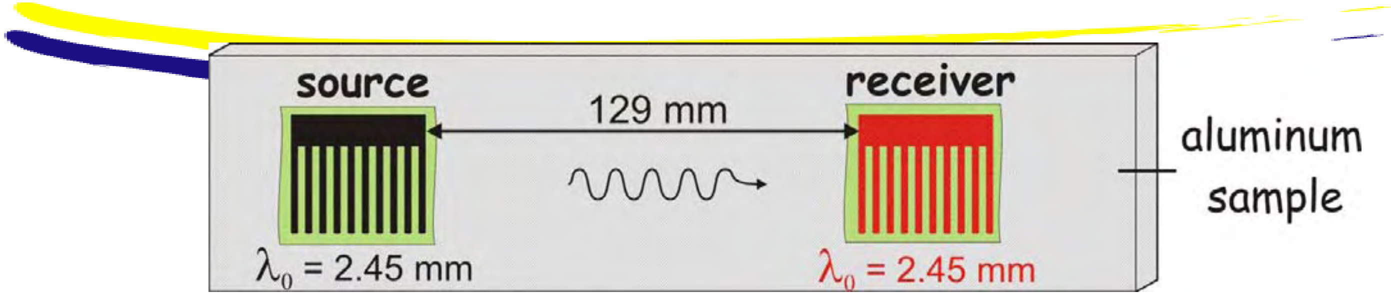
source
124 mm
receiver
λ_0 = 2.45 mm
λ_0 = 2.45 mm
AS4/3601
unidirectional
composite
0.1kV
5mV
a0 mode
0.65 MHz
2.1 Km/s
large
em pickup
s0 mode
0.9 MHz
8.3 Km/s
source signal (V)
received signal (mV)
0
20
40
60
80
100
time (µs)

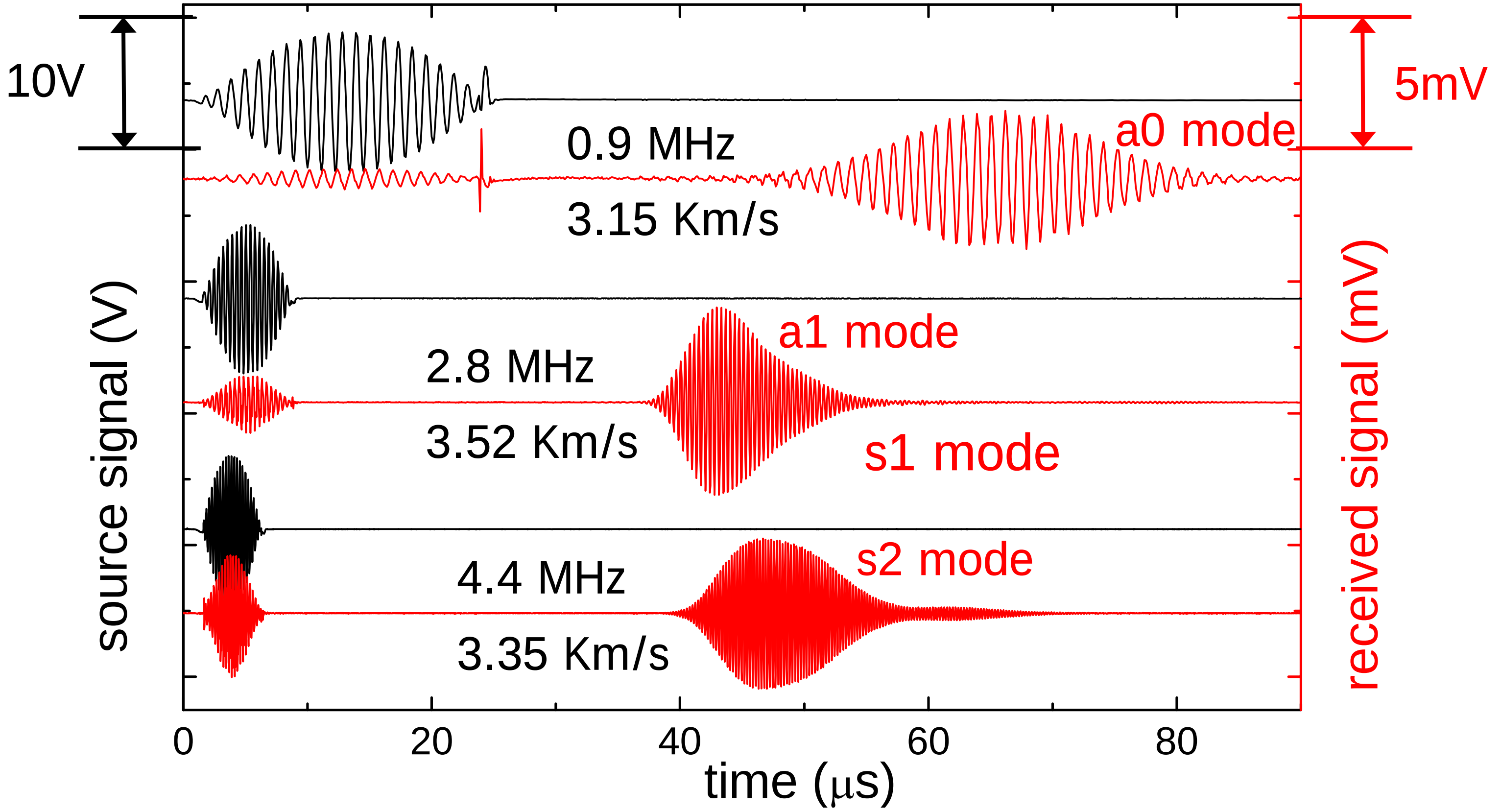
additional


source
127 mm
receiver
λ_0 = 4 mm
λ_0 = 4 mm
AS4/3601
unidirectional
composite


2.2 MHz
8.9 Km/s
s1 mode
source signal (V)
received signal (mV)
time (μs)
10
15
20
25
30
35
40
45
50

additional


source
receiver
129 mm
aluminum sample
λ_0 = 2.45 mm
λ_0 = 2.45 mm


10V
5mV
a0 mode
0.9 MHz
3.15 Km/s
a1 mode
2.8 MHz
3.52 Km/s
s1 mode
s2 mode
4.4 MHz
3.35 Km/s
source signal (V)
received signal (mV)
0
20
40
60
80
time (μs)

additional

measurement event: N	mode	Received signal amplitude	Normalization to mode a	Normalization to first meas. event
0	a	$\gamma_a(0)\ T_a$	1	1
	b	$\gamma_b(0)\ T_b$	$\left.\frac{\gamma_b}{\gamma_a}\right\vert_0 \frac{T_b}{T_a}$	1

↓

damage and coupling insertion losses occur

↓

measurement event: N	mode	Received signal amplitude	Normalization to mode a	Normalization to first meas. event
i	a	$\beta\ \gamma'_a(N)\ T_a$	1	1
	b	$\beta\ \gamma'_b(N)\ T_b$	$\frac{\cancel{\beta}}{\cancel{\beta}}\ \left.\frac{\gamma'_b}{\gamma'_a}\right\vert \frac{T_b}{T_a}$	$\underbrace{\frac{\gamma'_b}{\gamma'_a}(i)\ \frac{\gamma_a}{\gamma_b}(0)}_{\Phi}$