State-of-Art of Structural Health Monitoring and Prognostics

Never Stand Still | Faculty of Engineering | School of Mechanical and Manufacturing Engineering

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Acknowledgement

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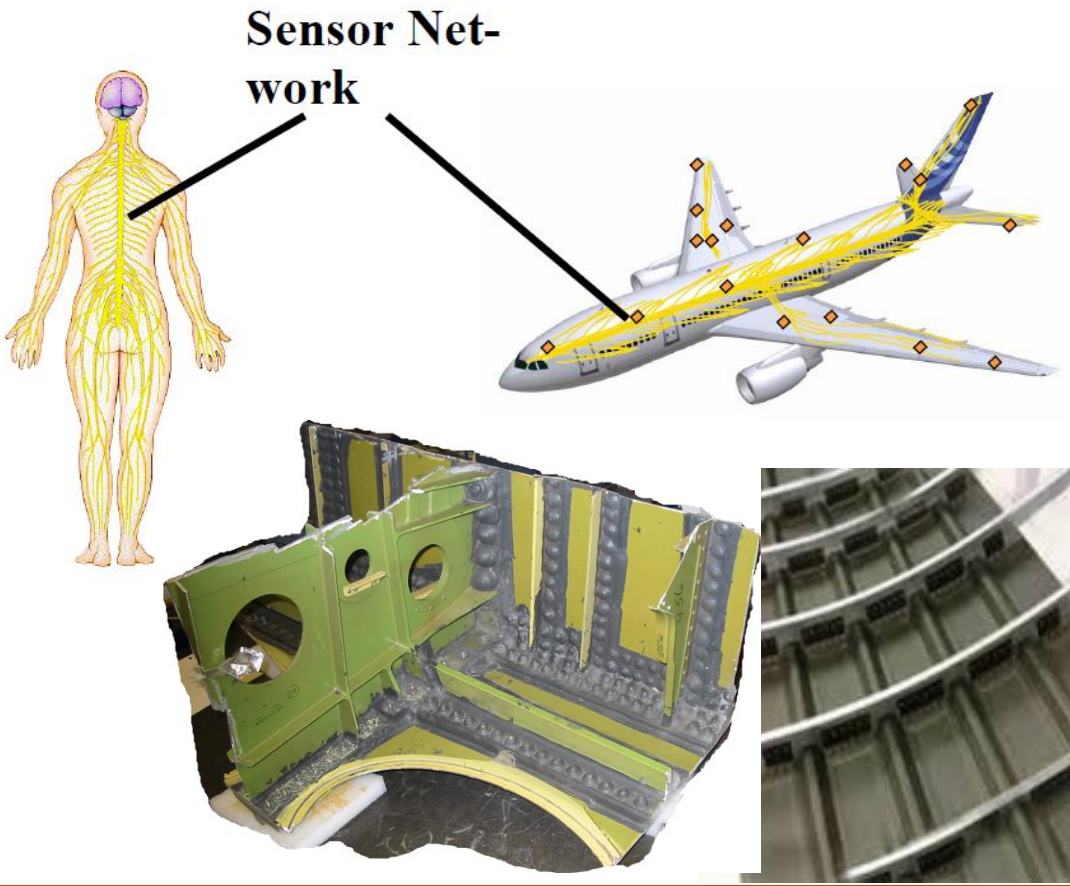
Outline

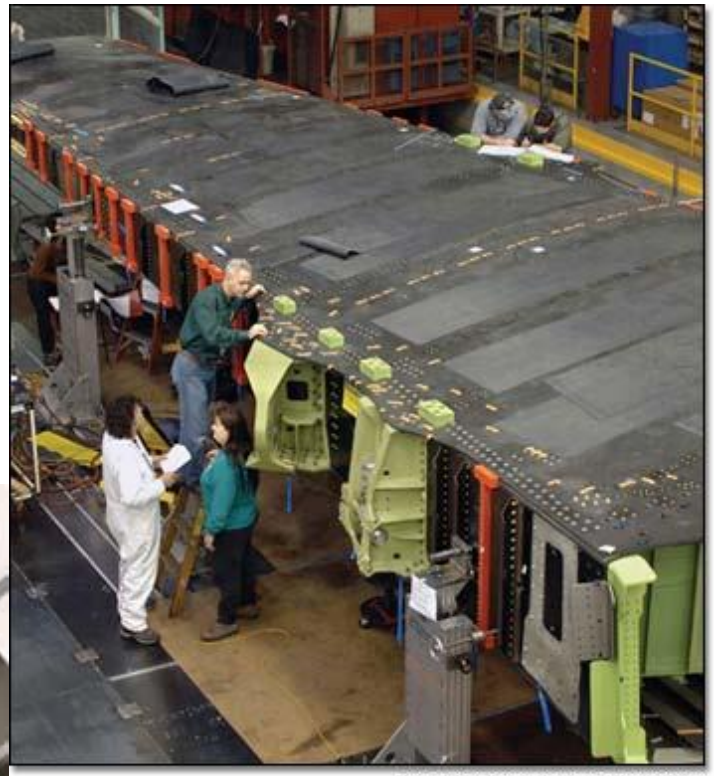
- Structural health monitoring and prognostics
- Damage types and system requirements
- Methods
- Applications: devices and system
- Future outlook

Structural Health Prognostics

- Objective:

  A paradigm shift: Actuarial ⇒ Medical





MARIAN LOCKHART PHOTO
Members of the 787 Dreamliner wing team prepare the wing box for its move to its test location. At the bottom (from left) are Steve Reames, Tim Colligan and Lamar Dearth; at the top (from left) are Wes Davis and Vince Romero.

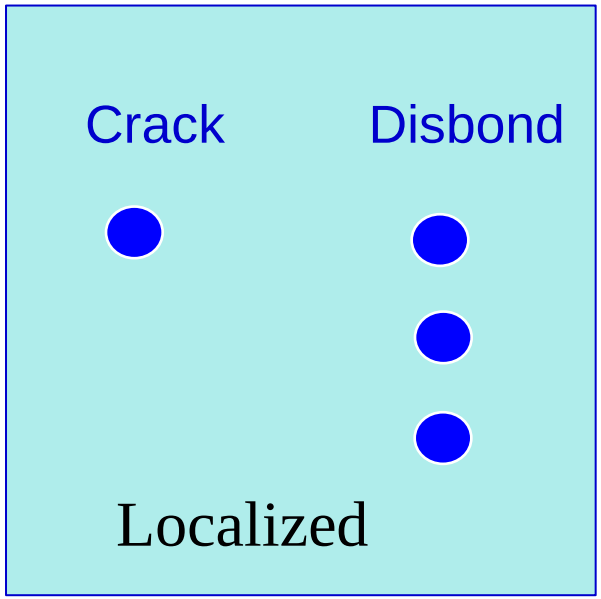
Damage types

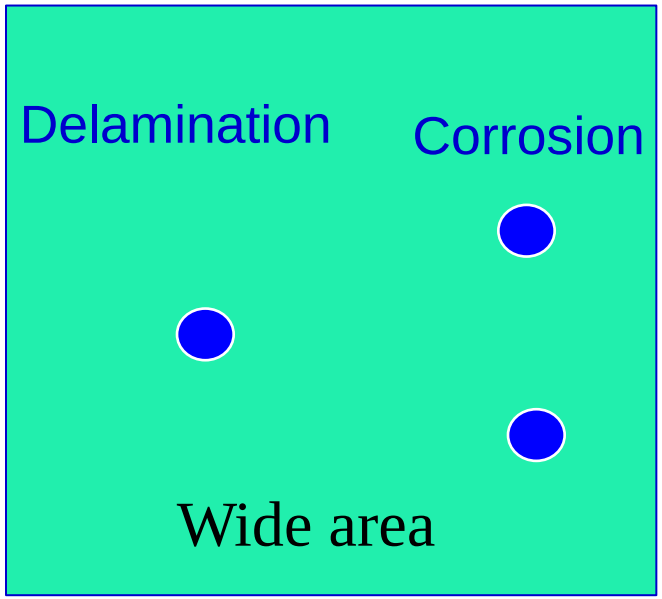
Aircraft Structures

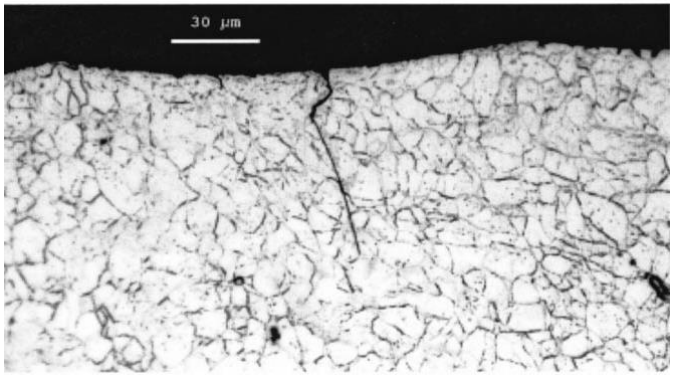
Metallic/honeycomb

Composite/honeycomb

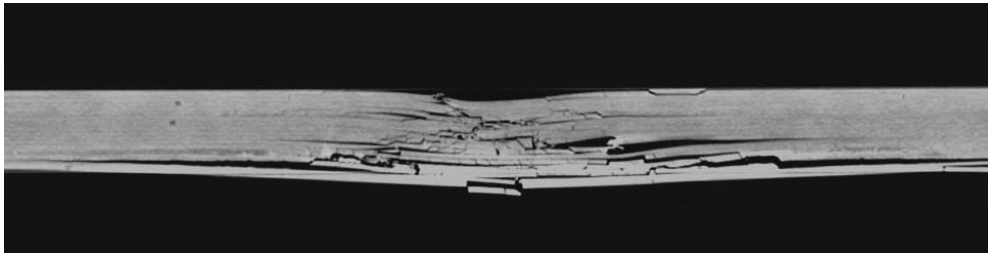
Bonded metals



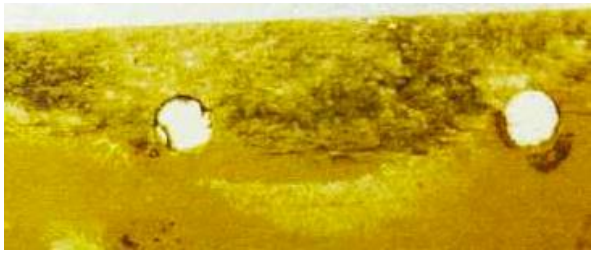


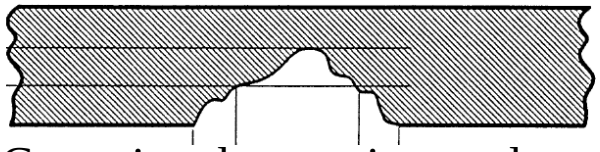


Fatigue crack



Composite delamination due to impact

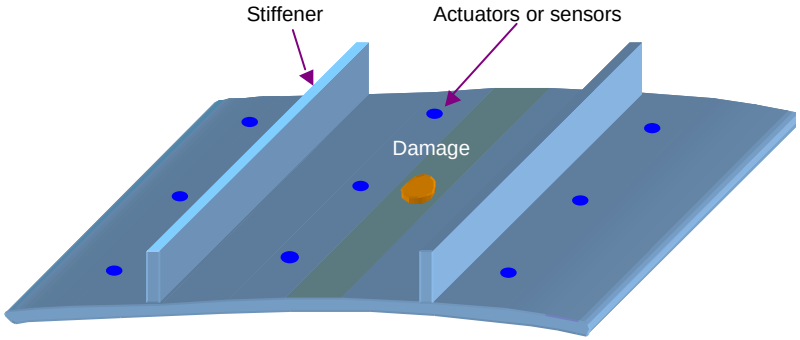


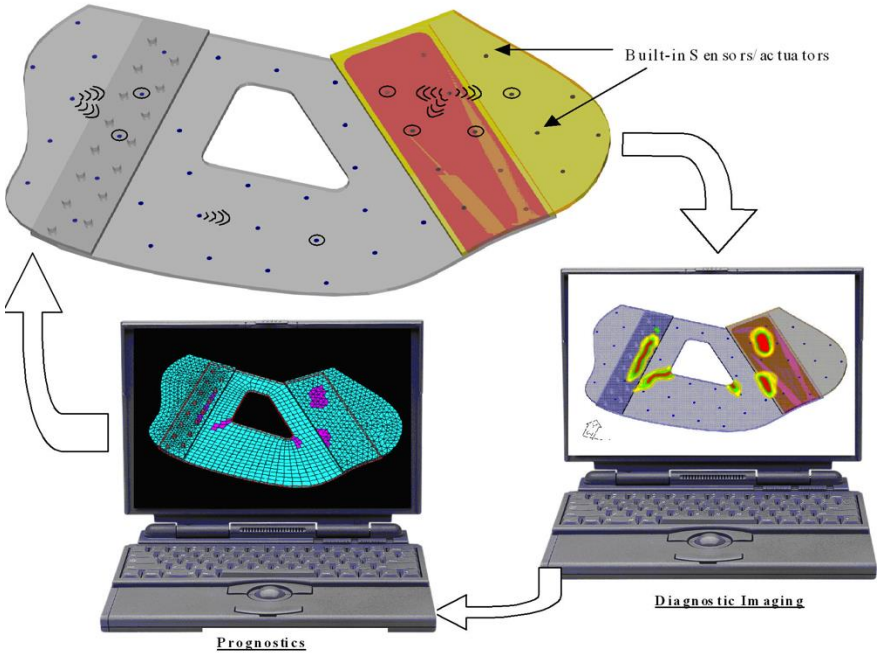


Corrosion damage in metals

Structural Health Prognostics

- Objective:
  - Level 1: State awareness (detecting & locating damage)
  - Level 2: Quantification of damage and safety prognosis





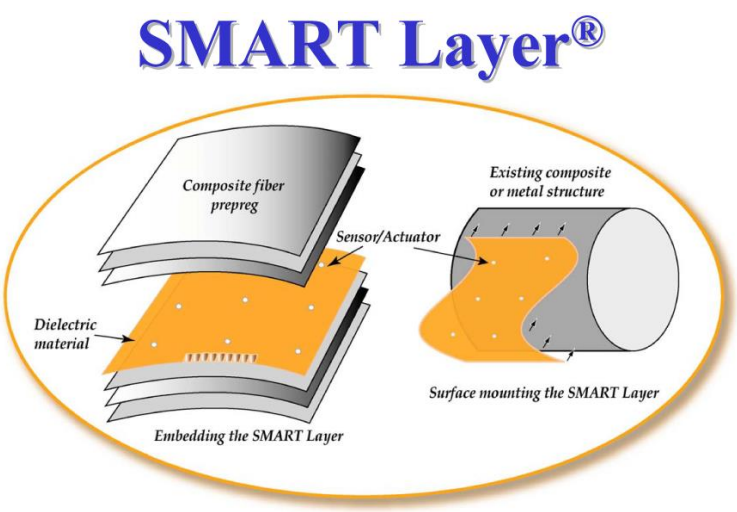
Potential benefits (significance)

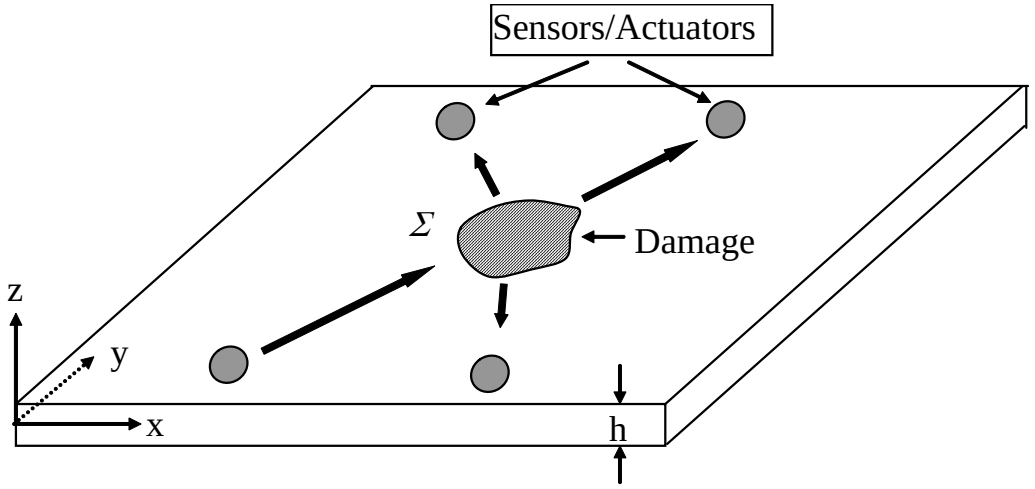
- **Existing aircraft management: highly conservative**
  - Safety-by-retirement (safe-life components):
    - more than 50% of retired parts can last one more lifetime.
  - Safety-by-inspection (damage tolerance components):
    - for every 1000 inspections, fewer than one flaw is supposed (often the case) to be found.

- **US Air Force commits 63% of its capital budget to the sustainment of existing fleet**
  - Significant cost savings
    - Reduced conservativeness in design
    - Reduced cost of inspections
    - Reduce un-necessary replacement

Methods

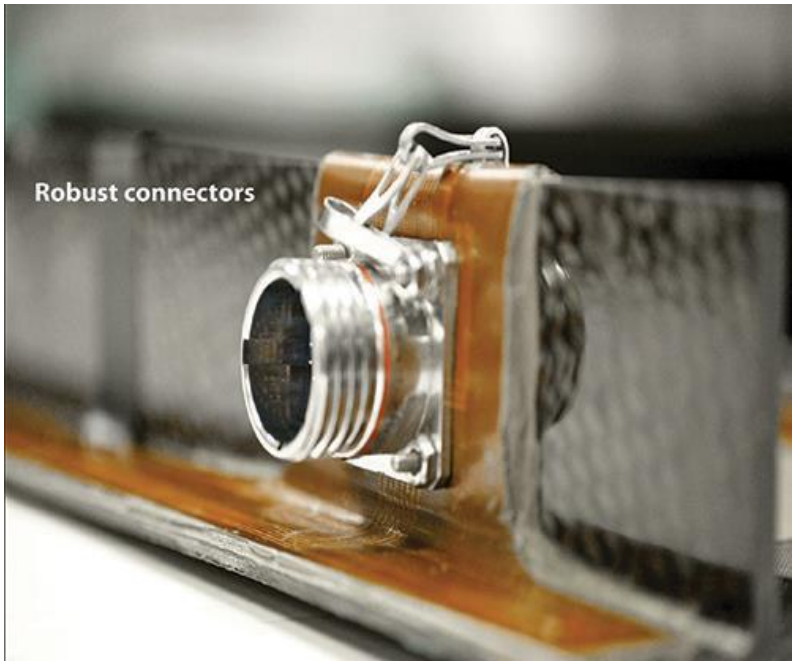
- On-board (in-situ) system capable of autonomously characterise damage and make decision
  - Embedded sensor and communication network
  - Early work focused on
    - Event (impact, cracking) monitoring
    - Simple algorithm (triangulation) to detect damage





Triangulation based on time of flight

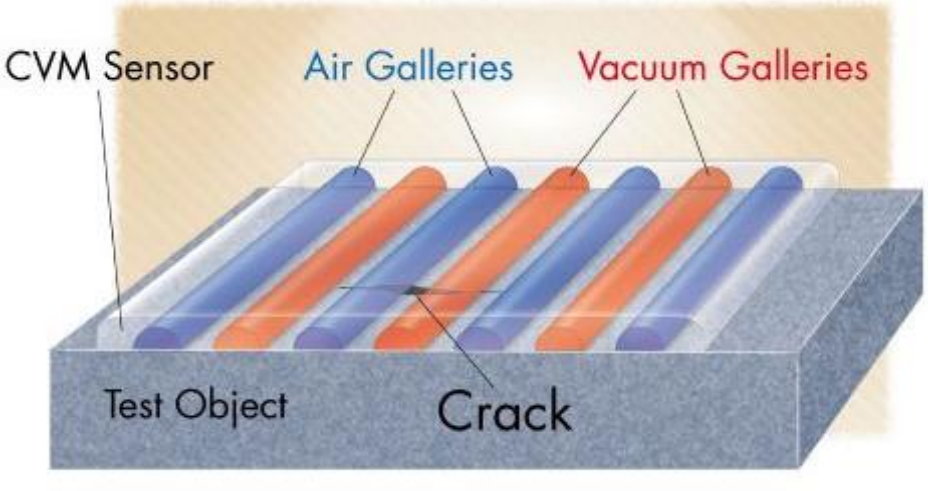
Impact (event and damage) detection



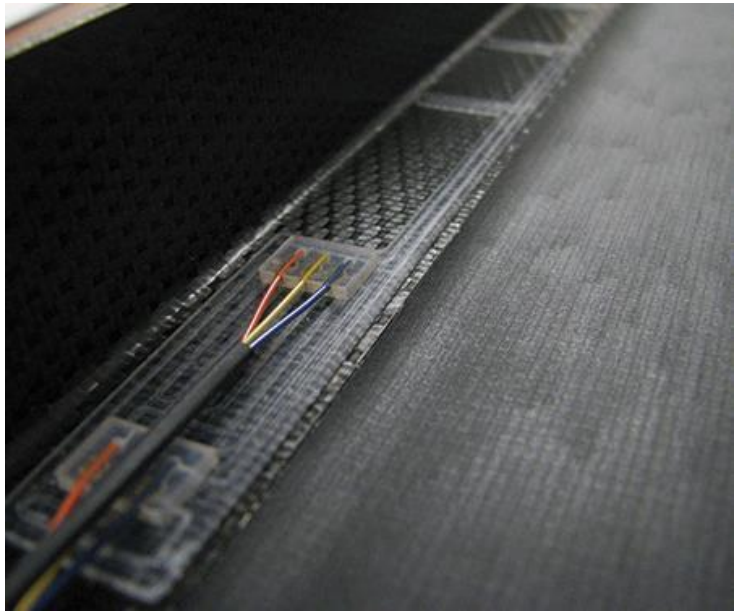
Network of SMART Layer sensors is currently undergoing flight testing as a local SHM system for impact detection on an A350 CFRP door surround panel.

Source: Airbus

Crack detection



Source: Structural monitoring systems

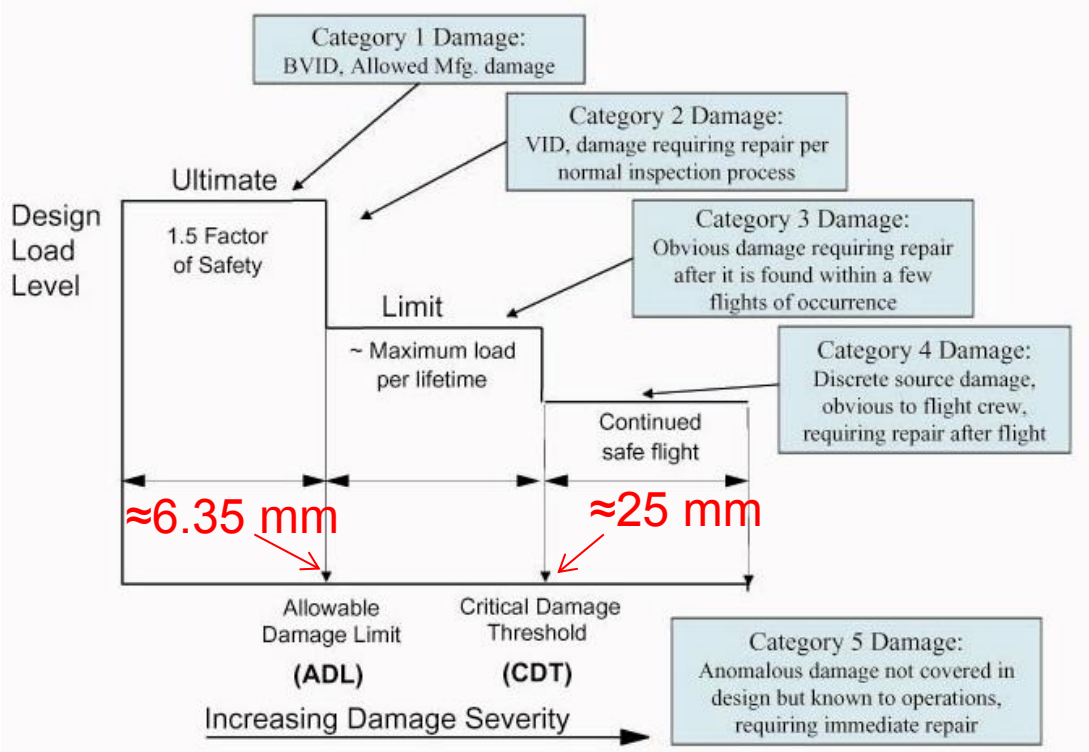


CVM sensors (see photo above) are flying on Delta Air Lines 737 aircraft like this one as part of a program aimed to approve structural health monitoring as an alternative inspection technique to manual disassembly and visual inspection for commercial aircraft by 2016.

Source: Sandia/Photo: Randy Montoya

Requirements

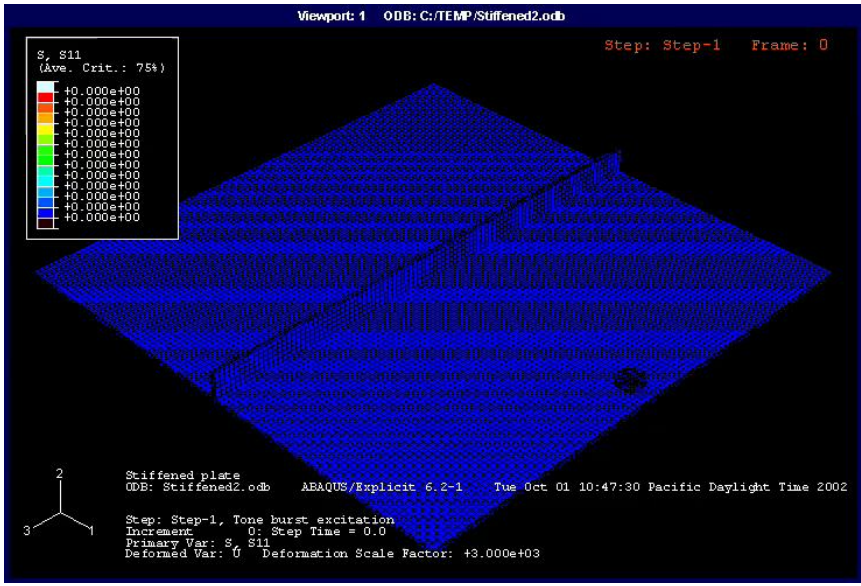
- Quantitative in-situ Damage Imaging
  - Damage size and severity
- Predictive model
  - Forecasting system's future performance
- Autonomous system
  - Embedded power, sensor, and intelligence



FAA: AC 20-107B

Techniques

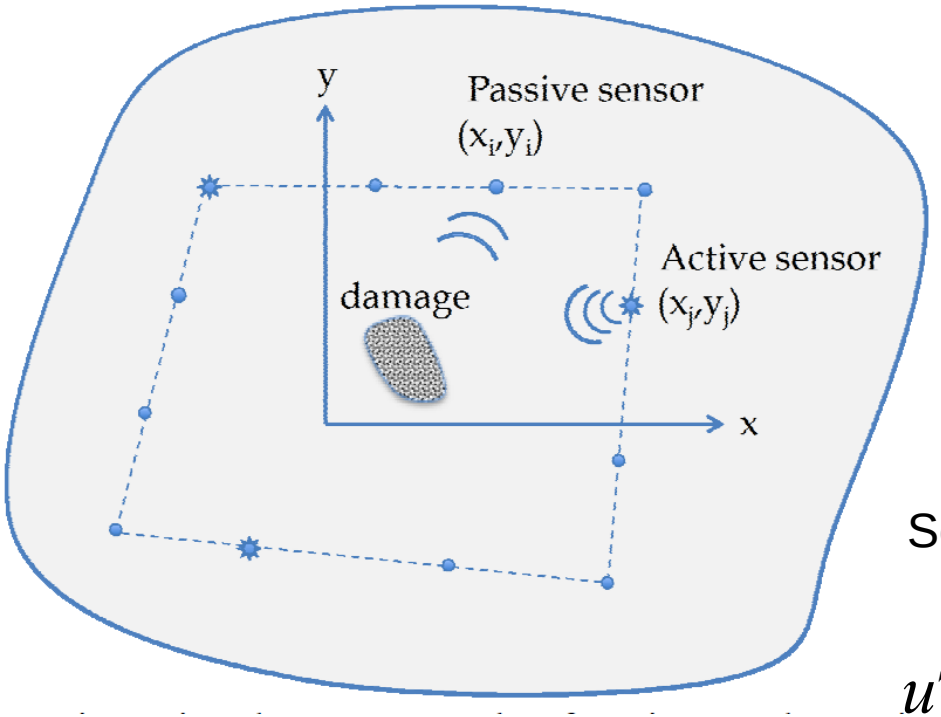
- Guided wave (propagating wave)
- Vibration (standing wave)
- Pressure loss
- Electromagnetic
- Electrical conductivity
- Thermal conductivity

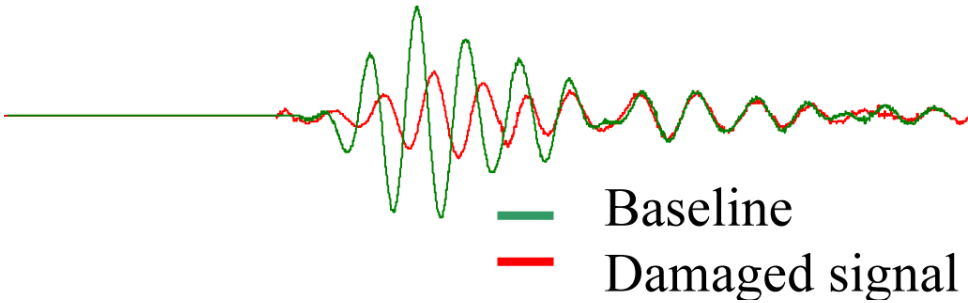


- Guided and standing waves directly interrogate mechanical properties (stiffness)

Guided wave technique

- Distributed sensors



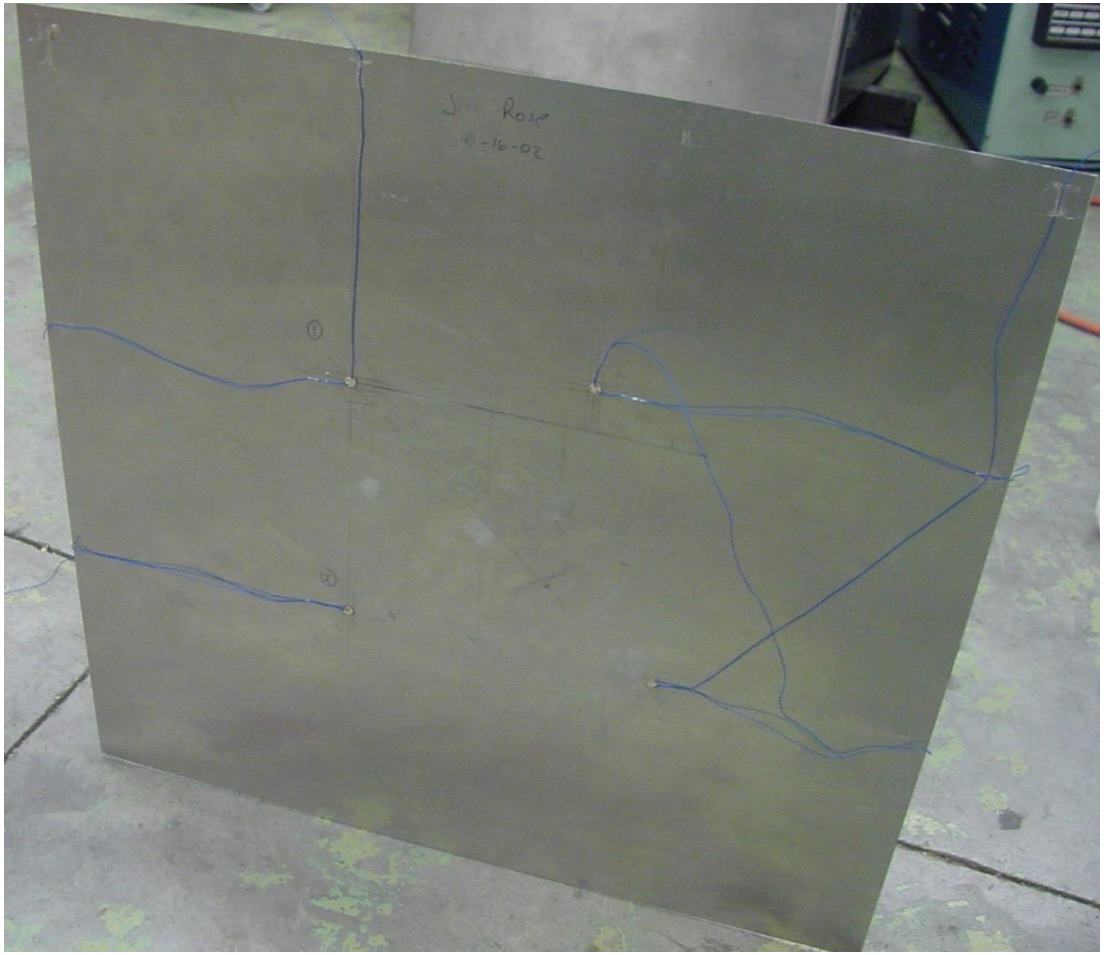


Scattered signal = Damaged signal – Baseline

$$u^S(t) = u^T(t) - u^I(t)$$

Time-reversal imaging

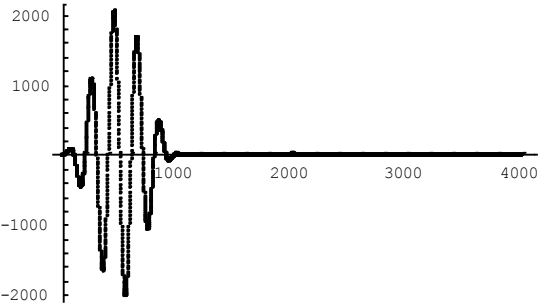
Aluminum plate with EDM cut (crack)

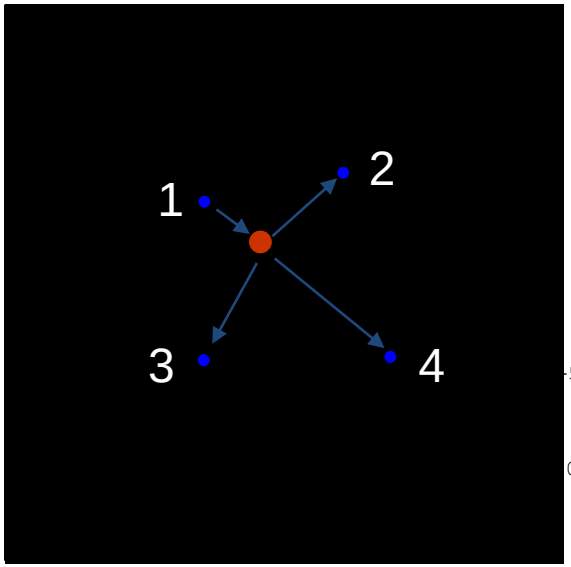


Wang, C.H. Rose, J. T. and Chang, F.-K. *A synthetic time-reversal imaging method for structural health monitoring, Smart Materials and Structures, 2004.*

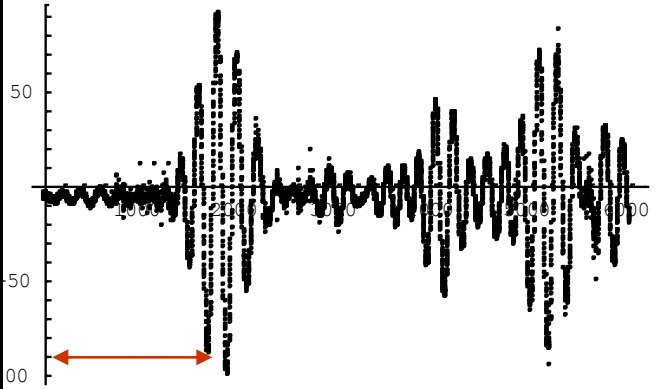
Focusing by time-reversal

Actuator 1

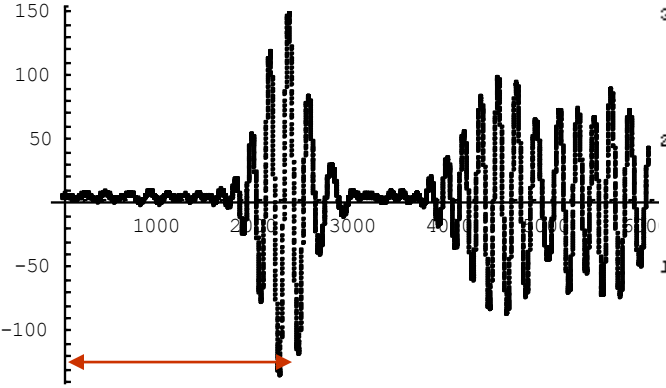


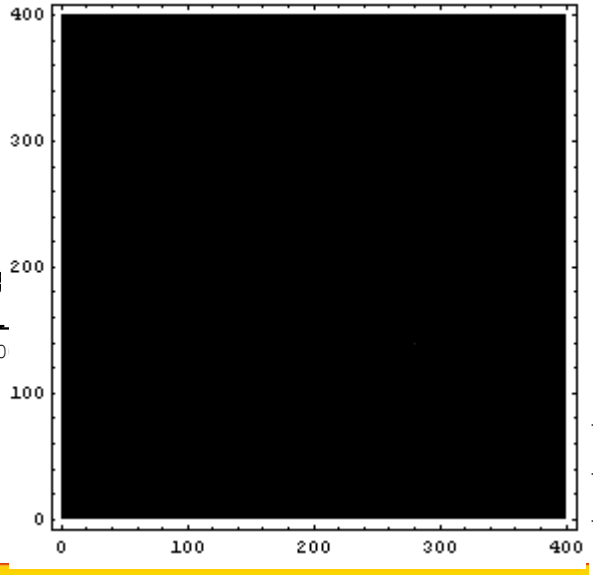


Scattered response at sensor 2

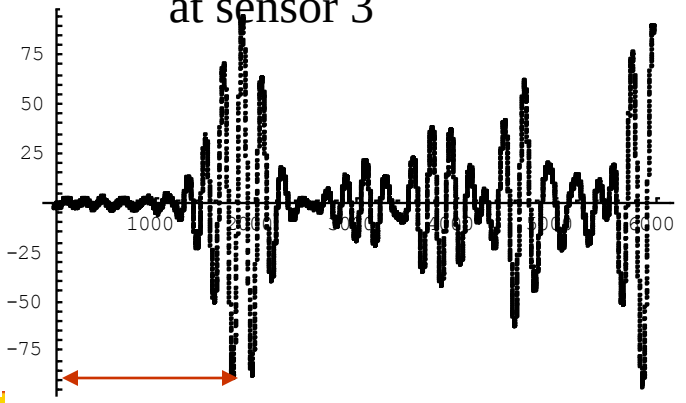


Scattered response at sensor 4





Scattered response at sensor 3



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Time-reversal imaging

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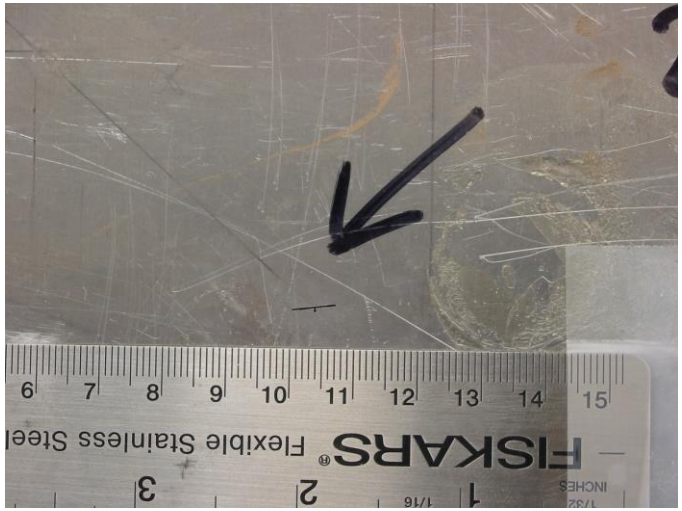

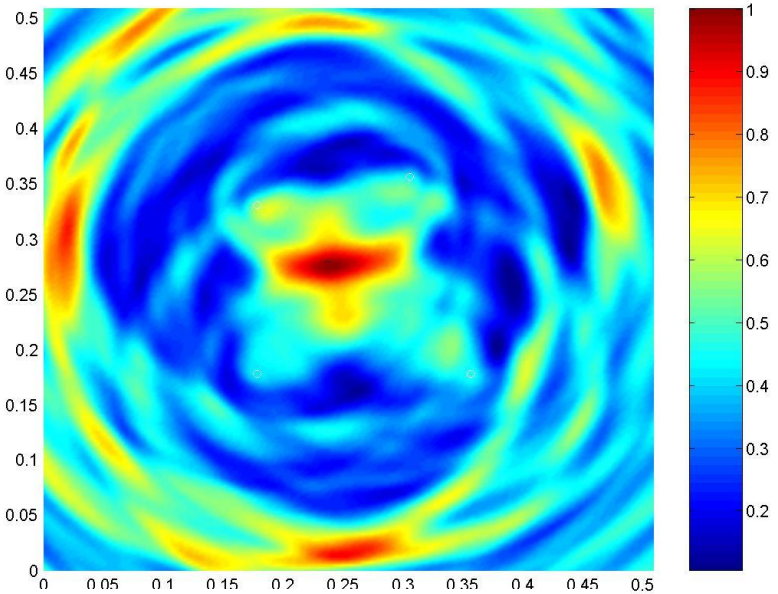

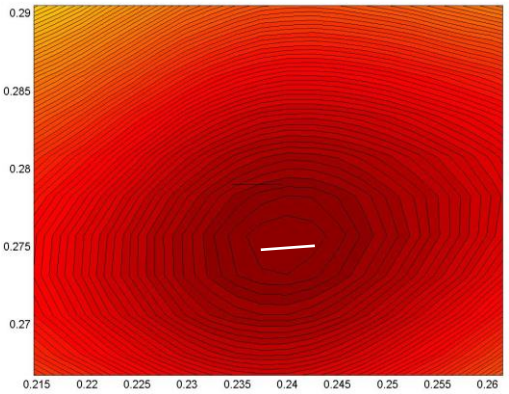

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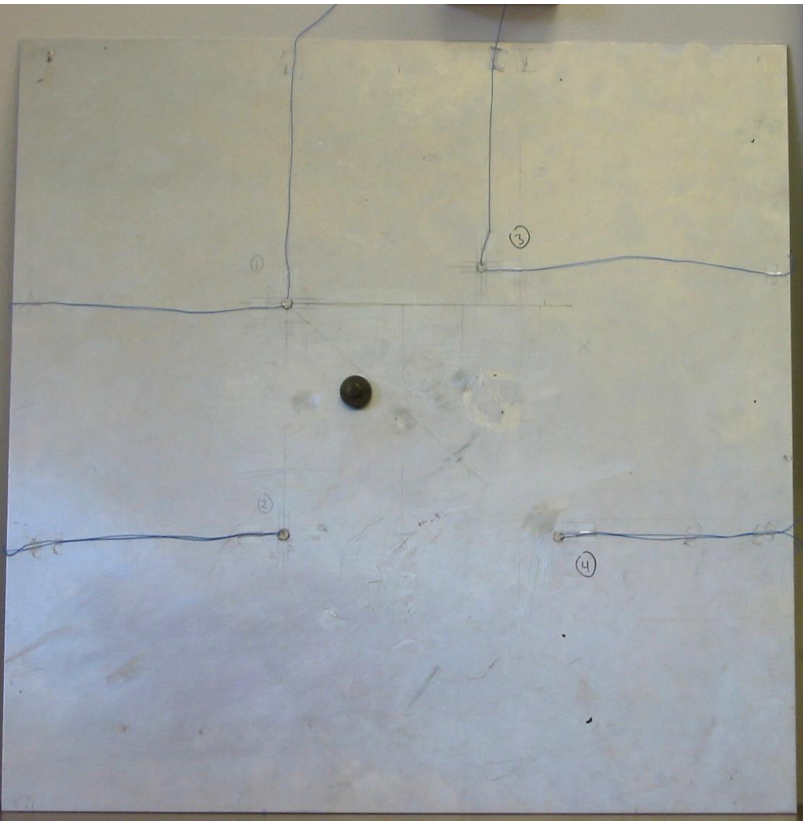
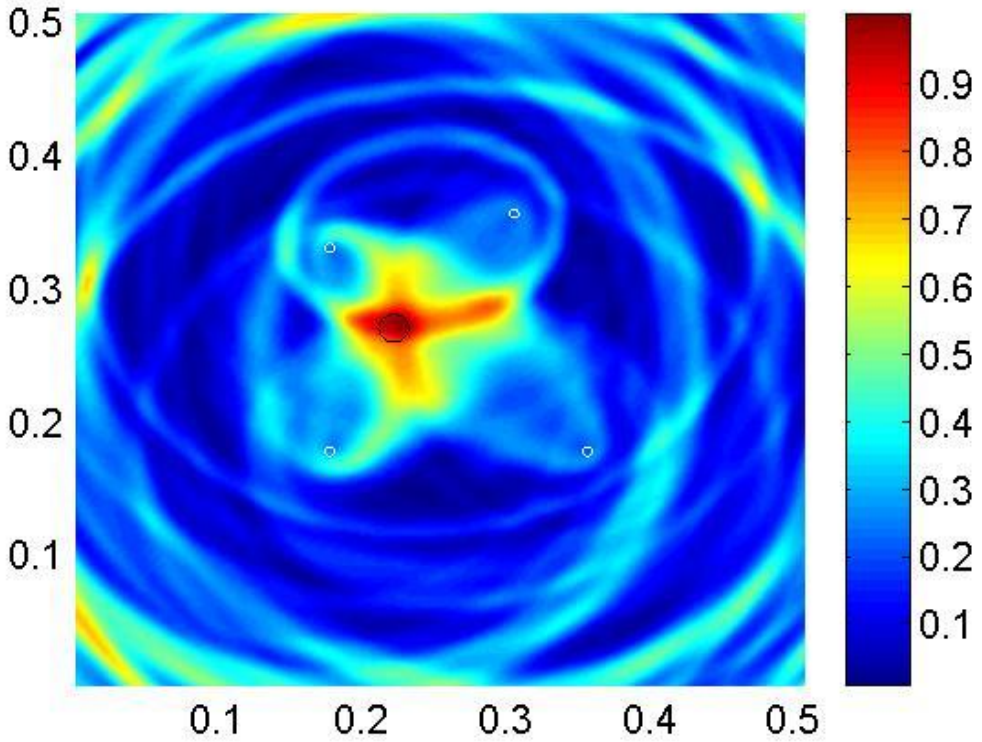
Results

Aluminum plate with bonded mass





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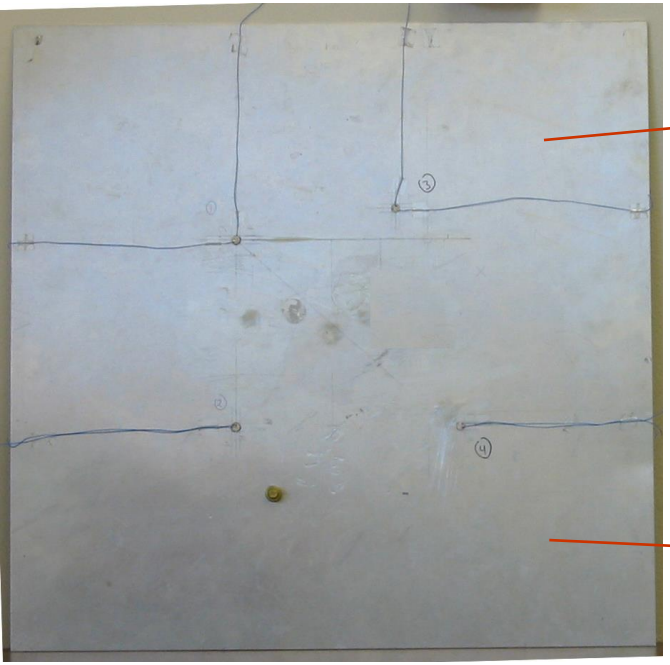
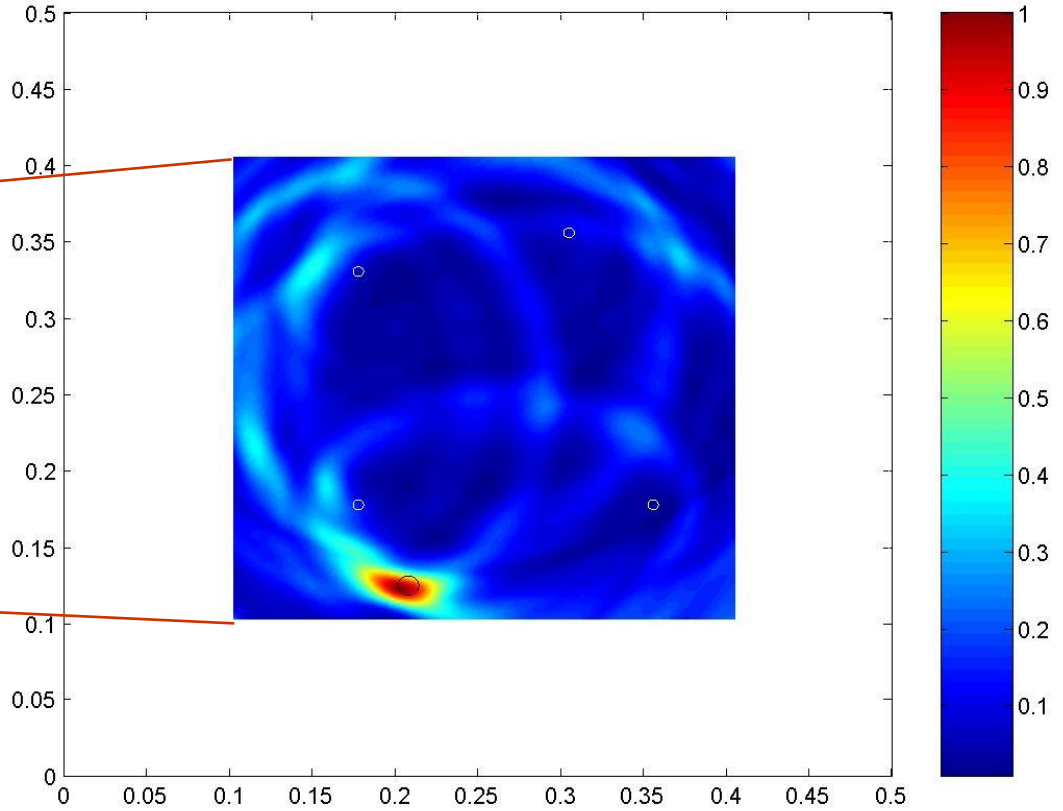
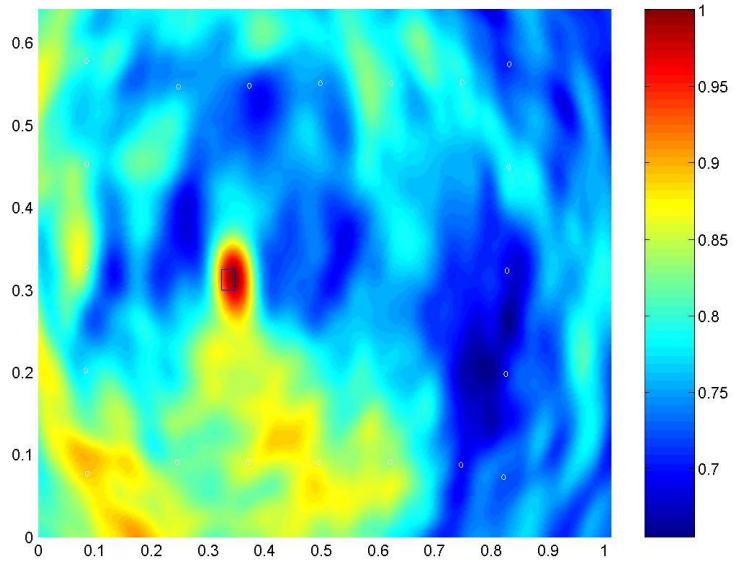


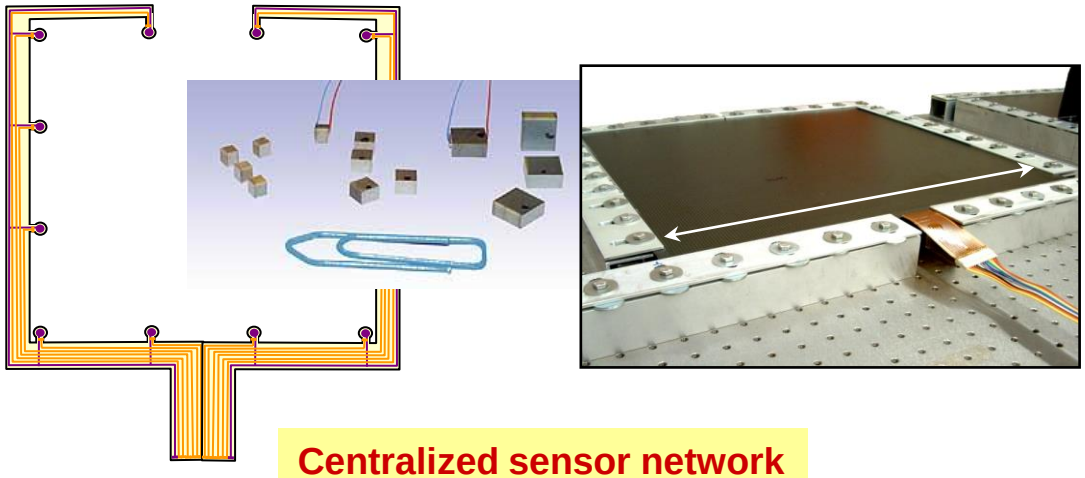


Results

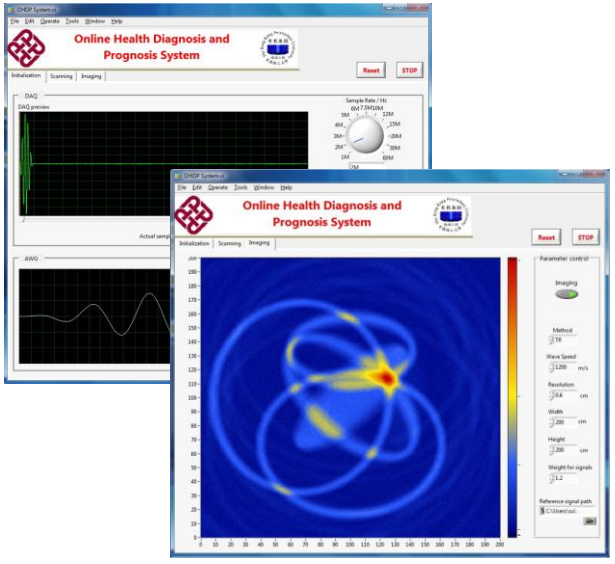
Composite plate with bonded patch



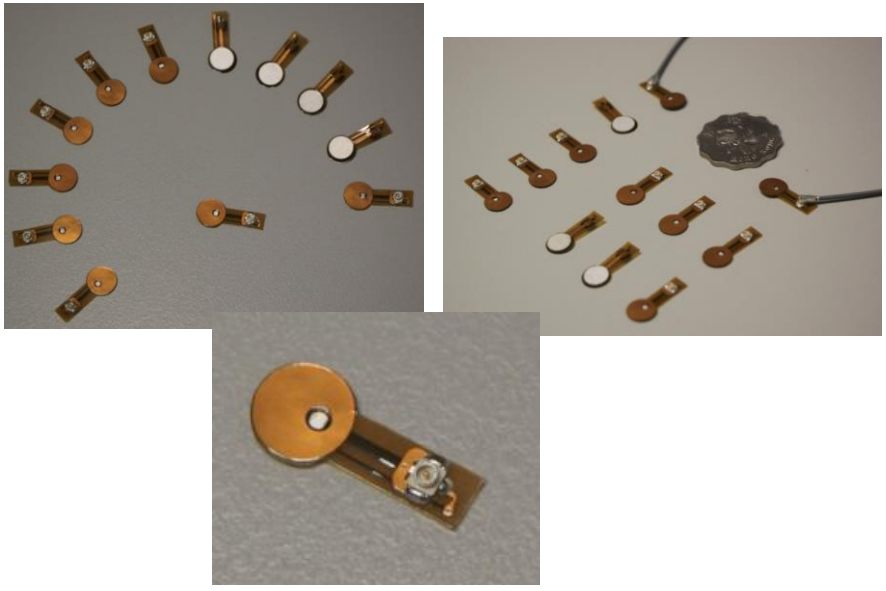
Courtesy of Professor Zhongqing Su (Hong Kong Polytechnic University)



Centralized sensor network



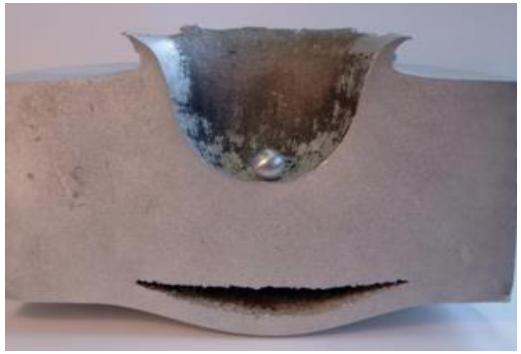
SHM software

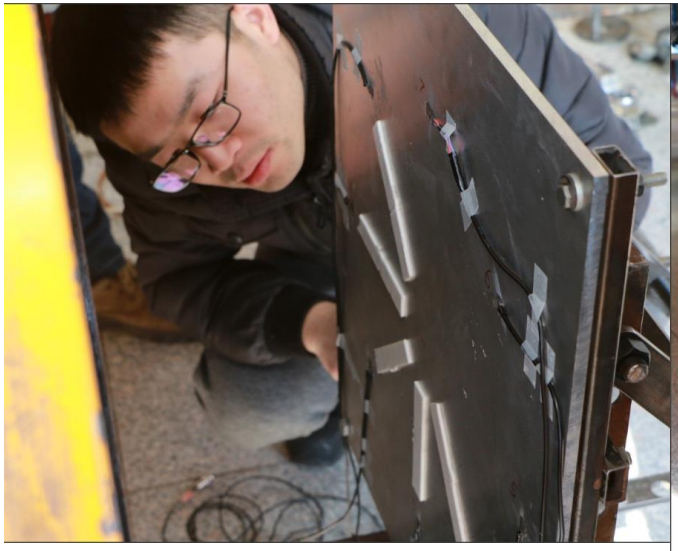


Decentralized sensing unit

Self-developed online SHM system

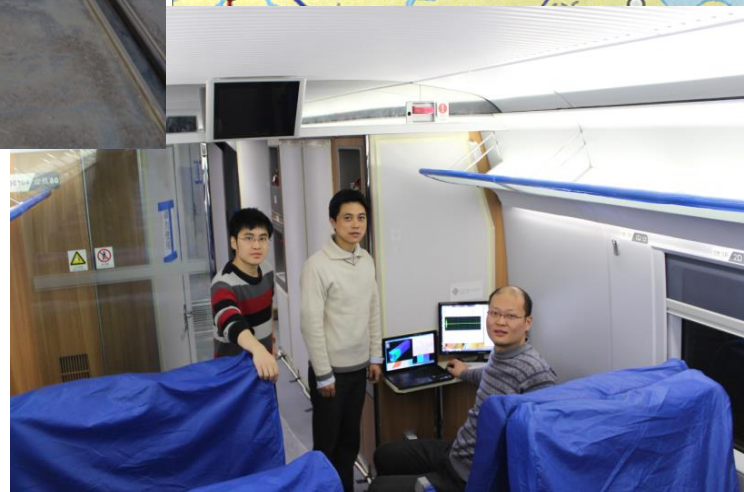
Online SHM for Satellite Structures under Hypervelocity Impact in Outer Space (>4 km/s) (with China Academy of Space Technology)





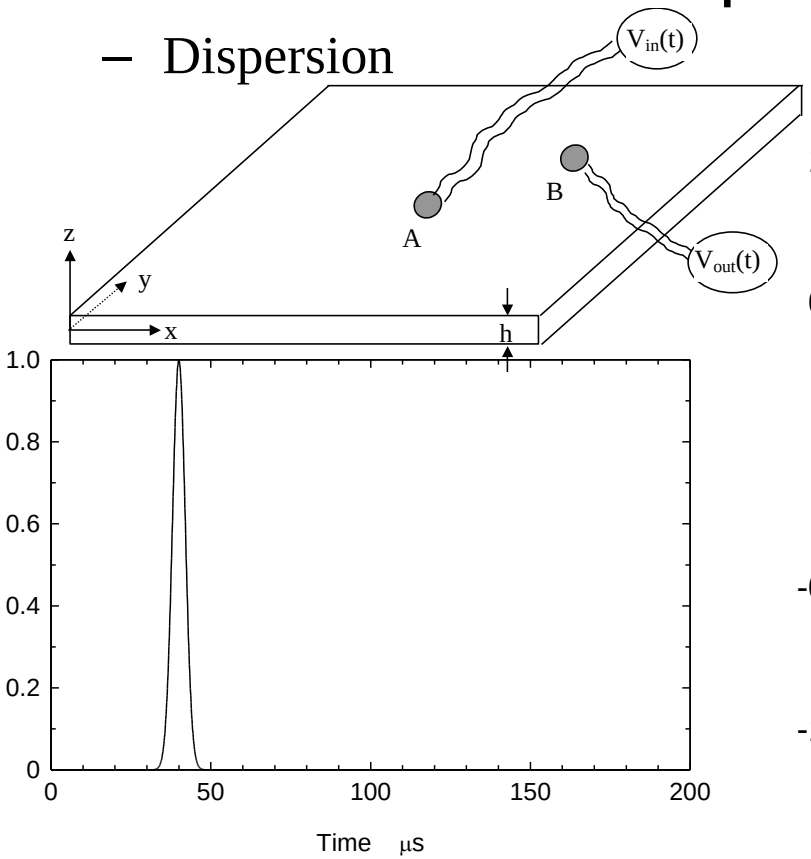
Courtesy of Professor Zhongqing Su (Hong Kong Polytechnic University)

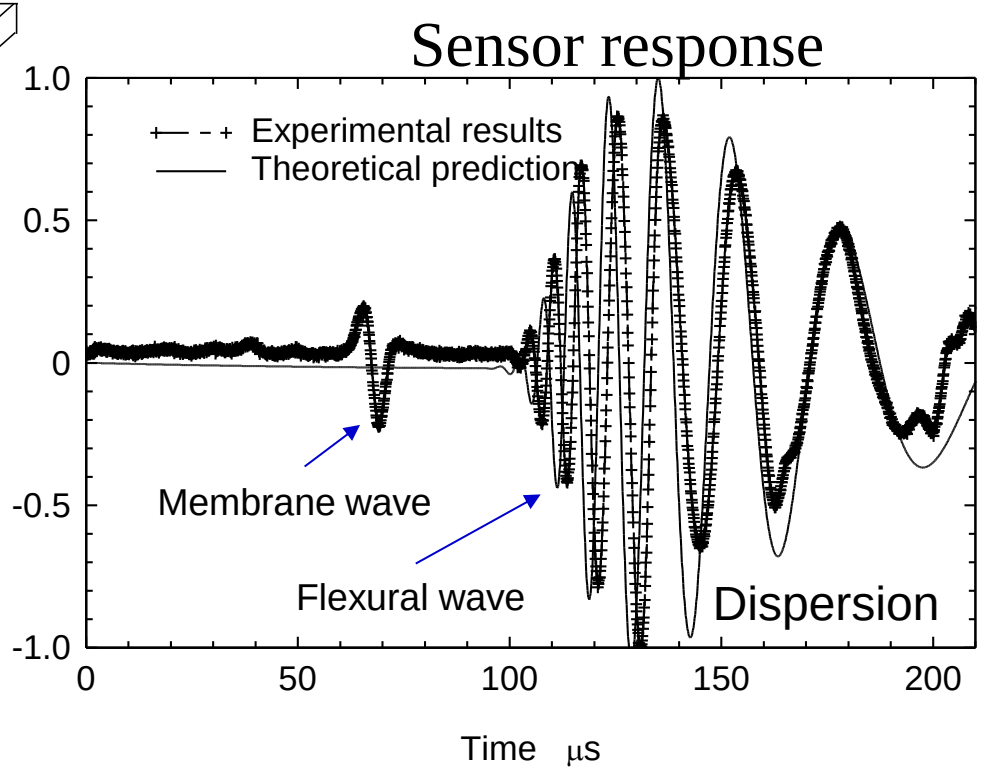
Online SHM for High-speed Train (Beijing-Shanghai, 300 km/h)



Level 2: Quantitative Evalution

- Damage size and shape for prognostics
  - Direct relationship with scattered wave
  - Dispersion





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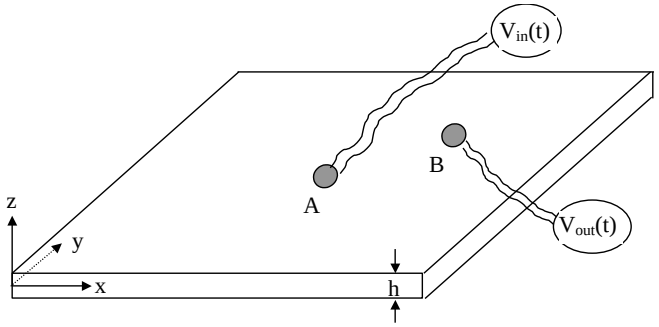
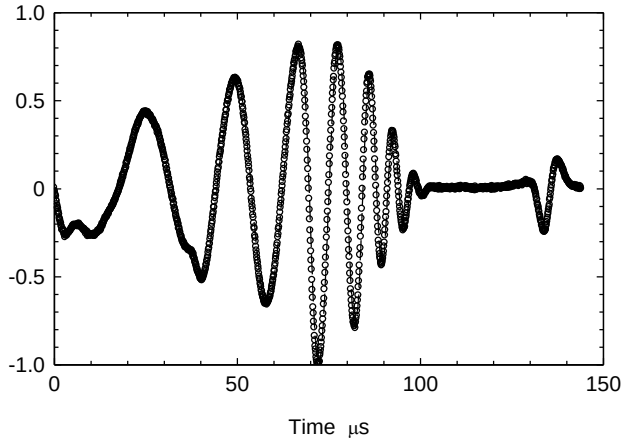
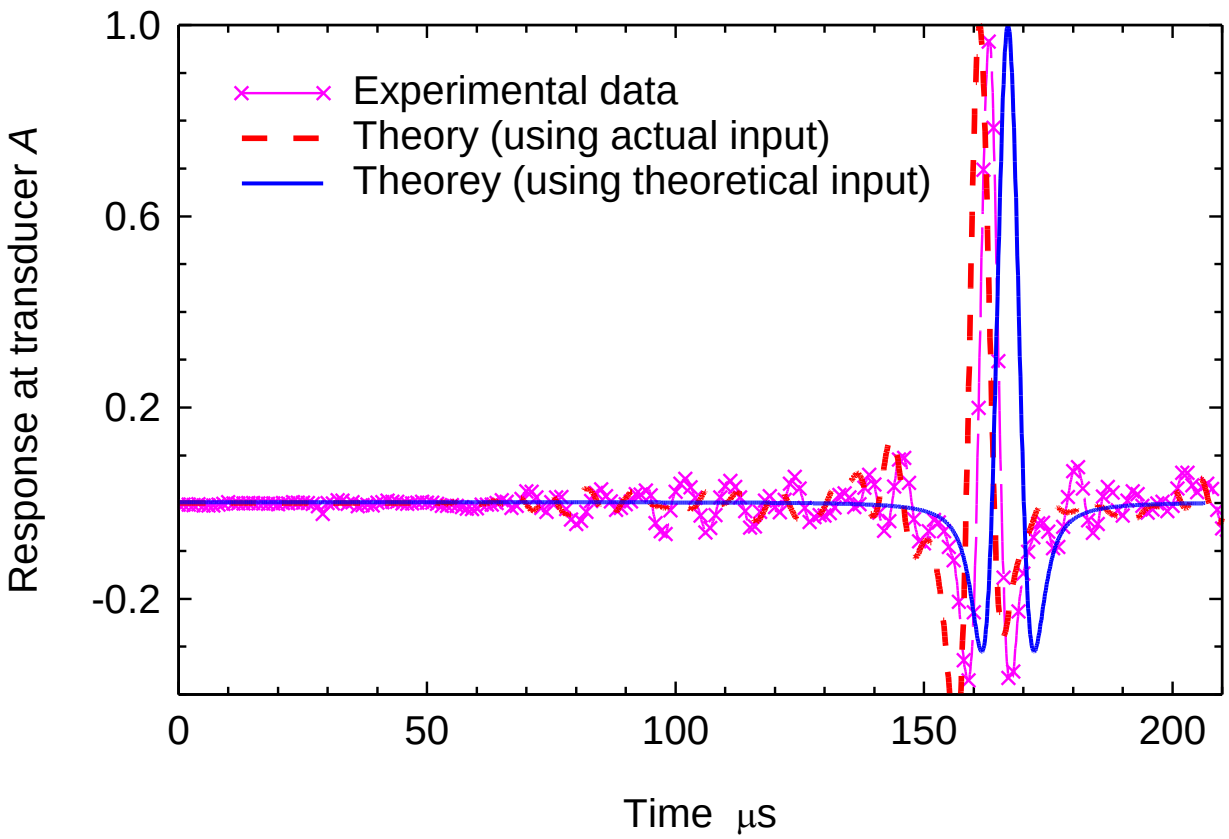
Experimental Results

- Time-reverse the response and resend:
  Recover the sharp pulse







- Basis for time-reversal imaging technique

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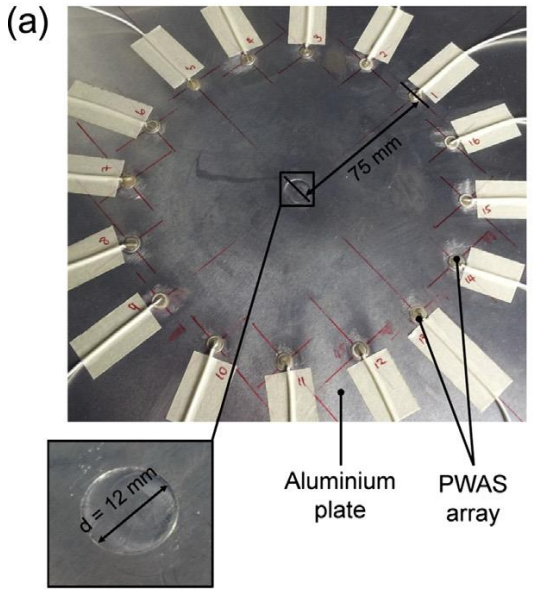
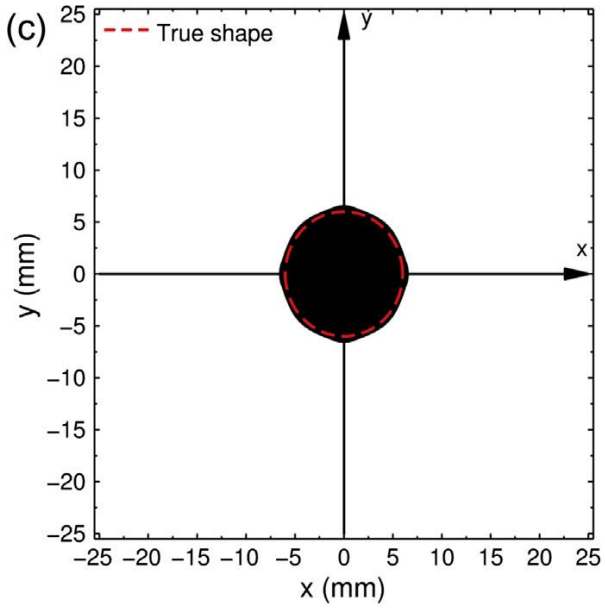
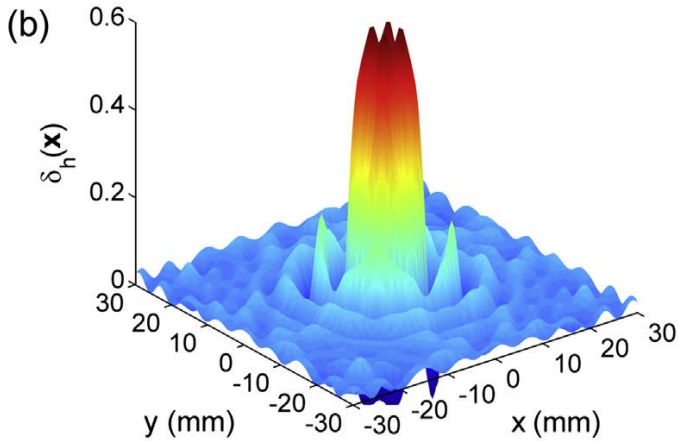
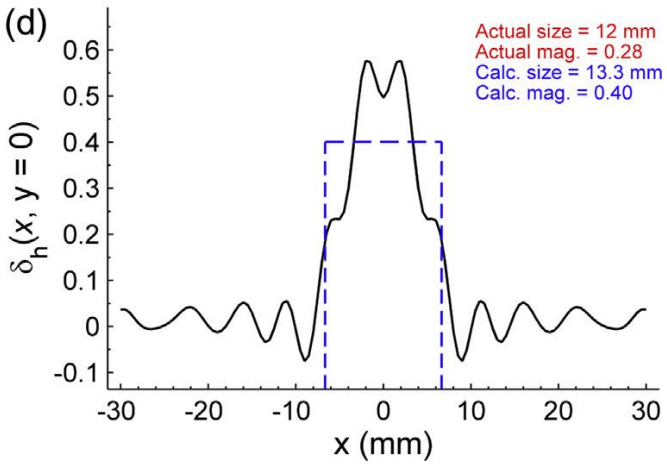
Quantitative imaging









Chan, E., L.F. Rose, and C.H. Wang, *An extended diffraction tomography method for quantifying structural damage using numerical Green's functions.* Ultrasonics, 2015. **59**: p. 1-13.

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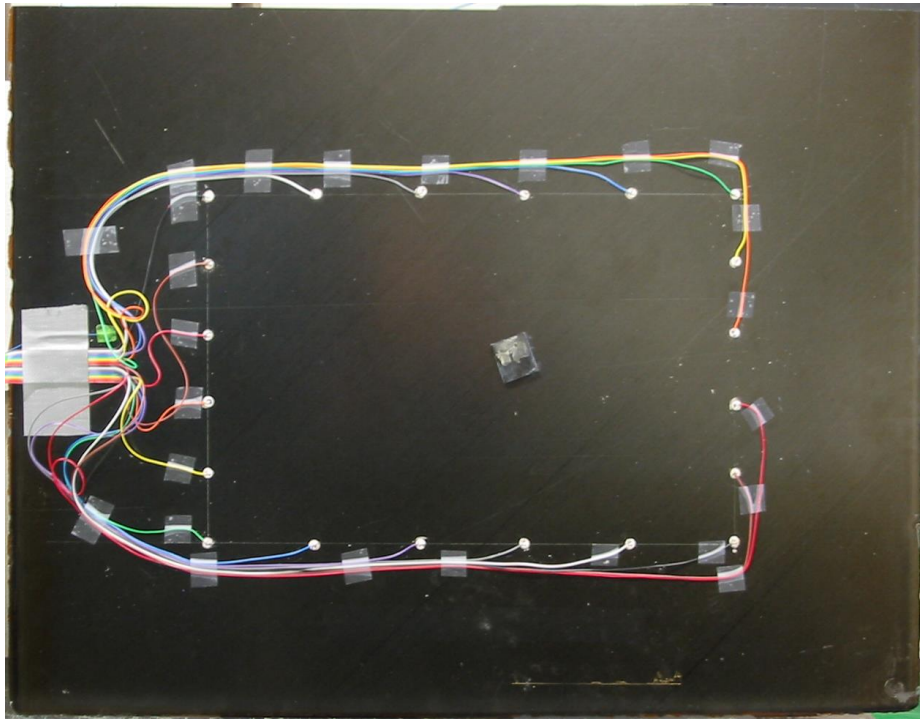
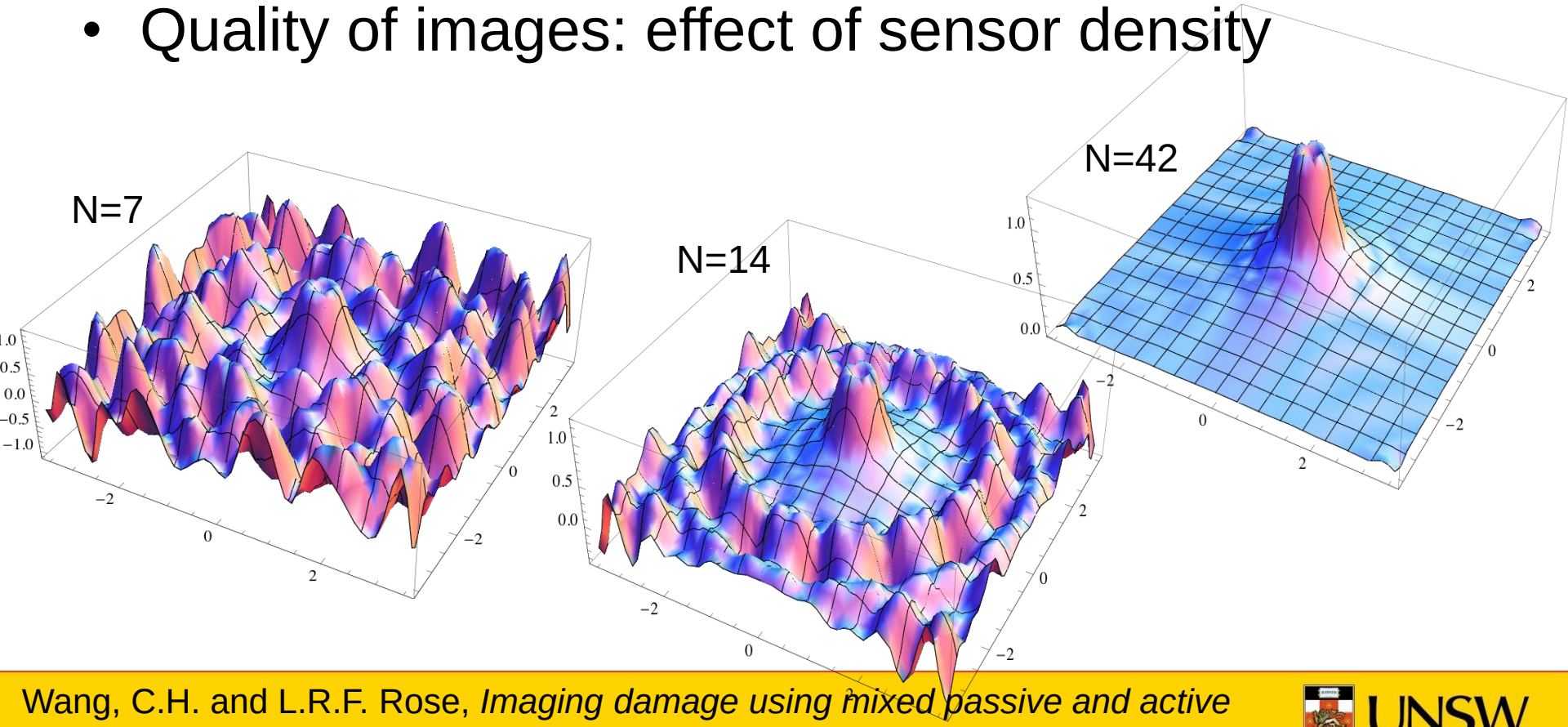
Practical issues



- How to quantify damage size and shape?
- How many sensors?
- How to deal with boundaries and substructures?

Minimising Size of Sensor Network

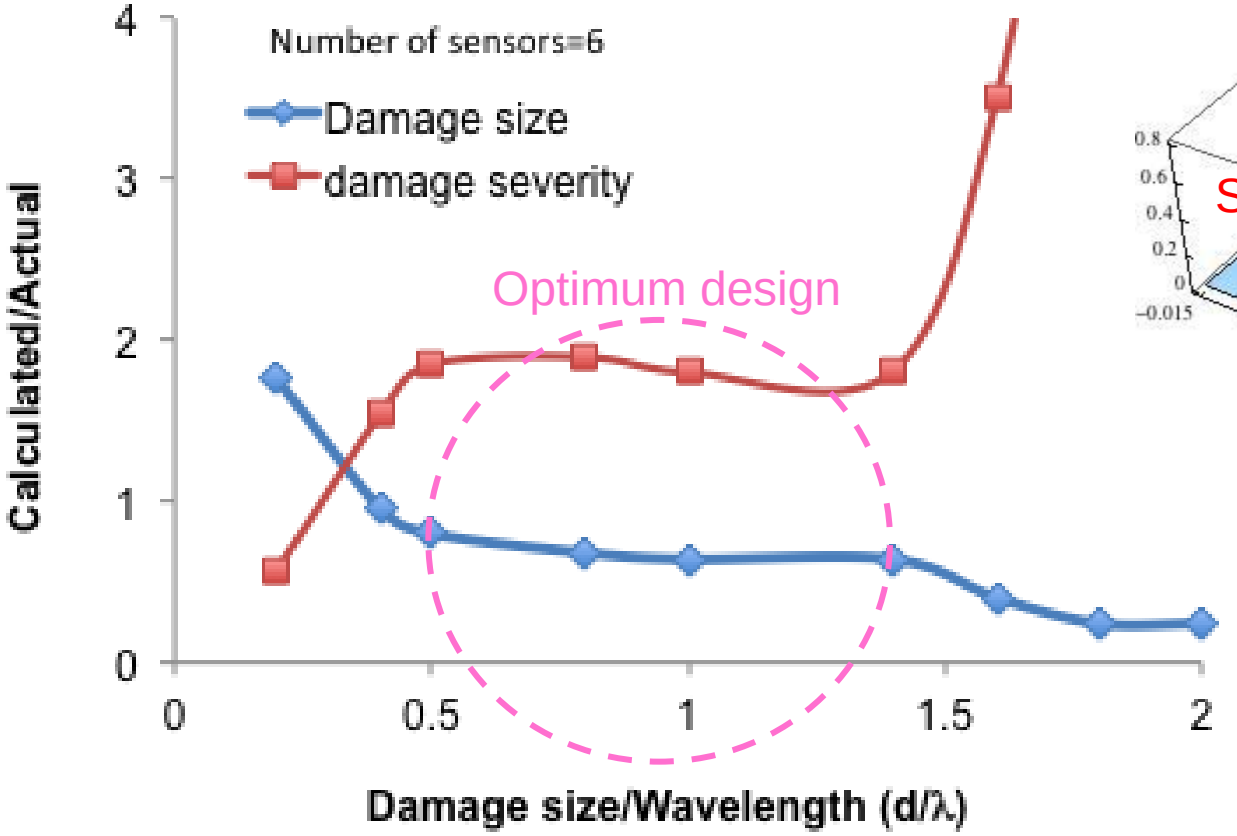
- Numerical method
  - Scattering results from eigenfunction expansion
  - Shown to agree with FEM and experiment
- Quality of images: effect of sensor density

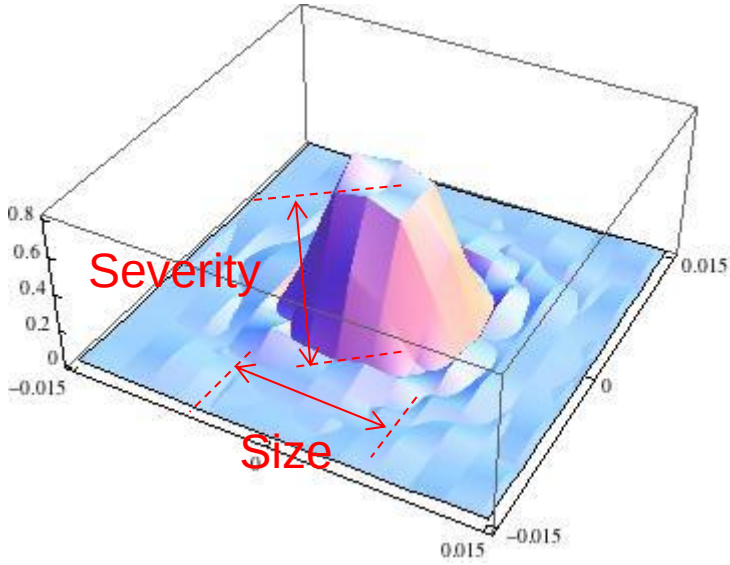


Wang, C.H. and L.R.F. Rose, *Imaging damage using mixed passive and active sensors*, in *Key Engineering Materials*. 2013. p. 244-251.

Optimum Frequency (for minimum sensors)

- Step 1: Long wavelength to locate damage
- Step 2: Short wavelength to quantify damage (size and severity)





Wang, C.H. and L.R.F. Rose, *Imaging damage using mixed passive and active sensors*, in *Key Engineering Materials*. 2013. p. 244-251.

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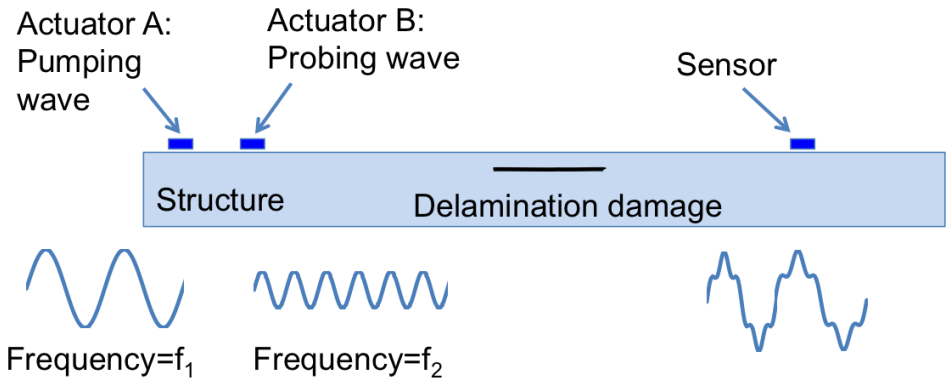
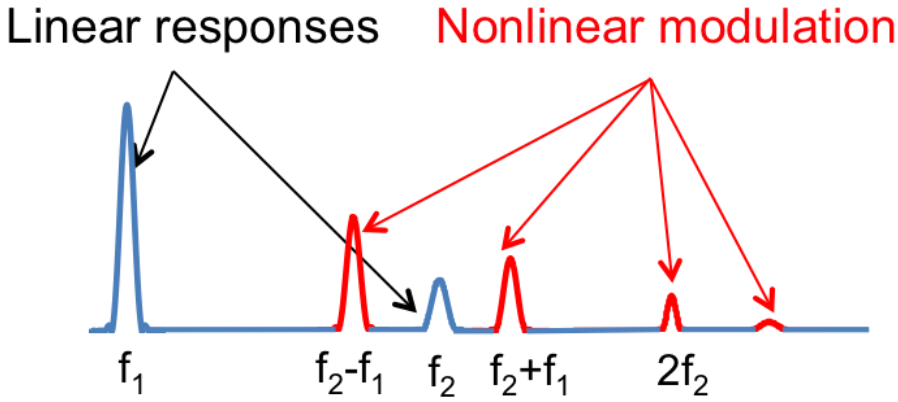
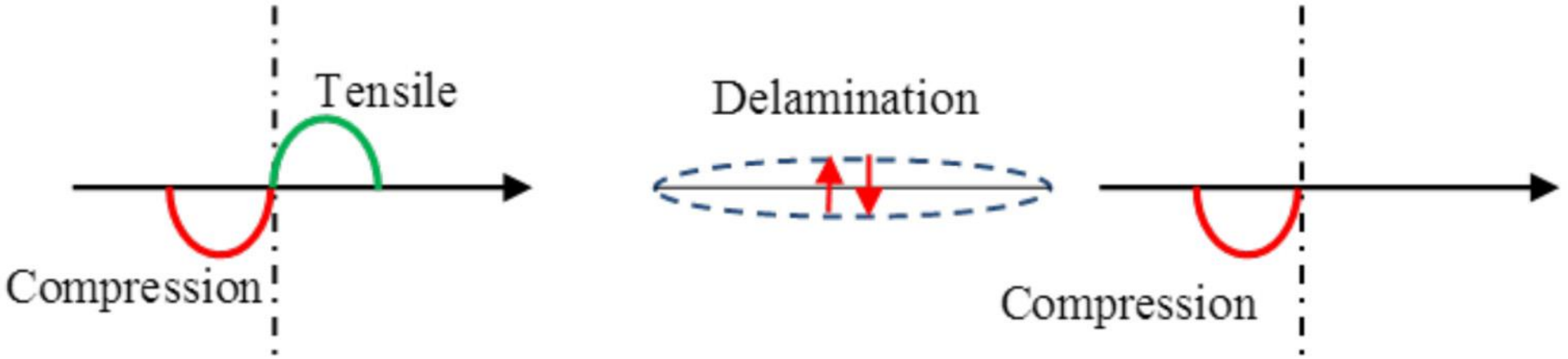
Recent Research

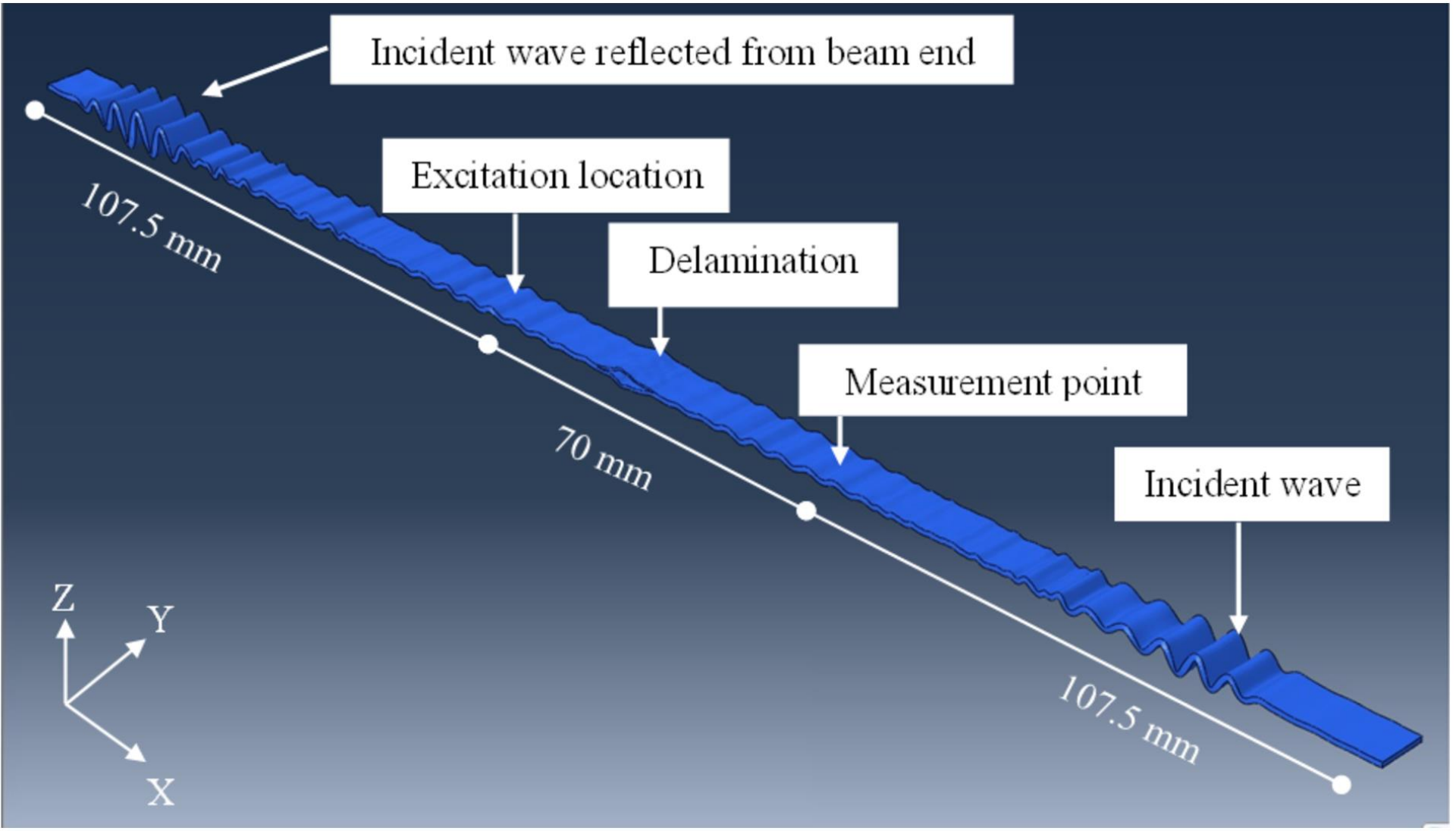
- Nonlinear techniques







Nonlinear response from delamination



Soleimanpour, R., C.-T. Ng, and C.H. Wang, *Higher harmonic generation of guided waves at delaminations in laminated composite beams.* Structural Health Monitoring, 2016

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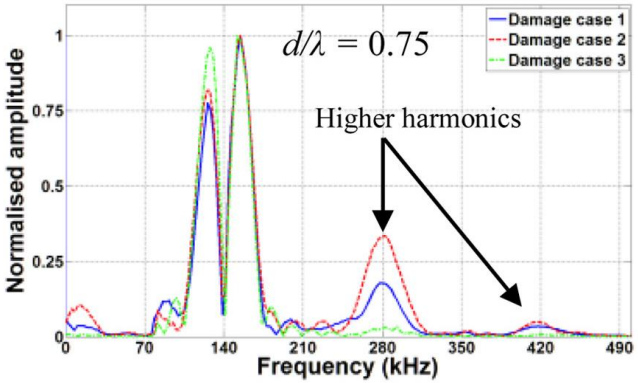
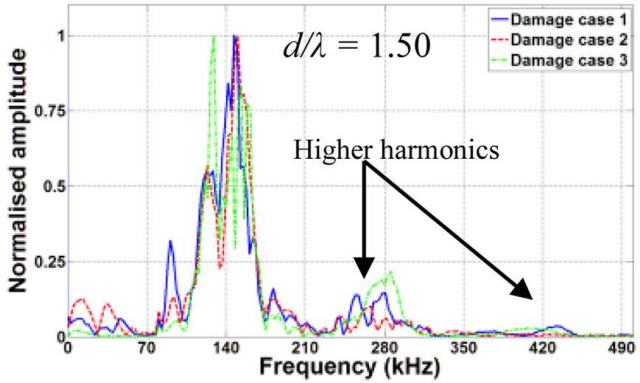
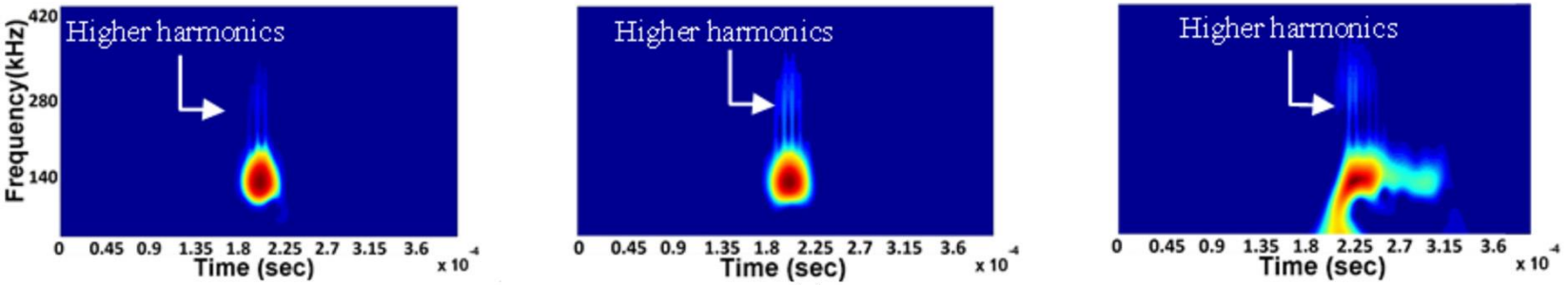
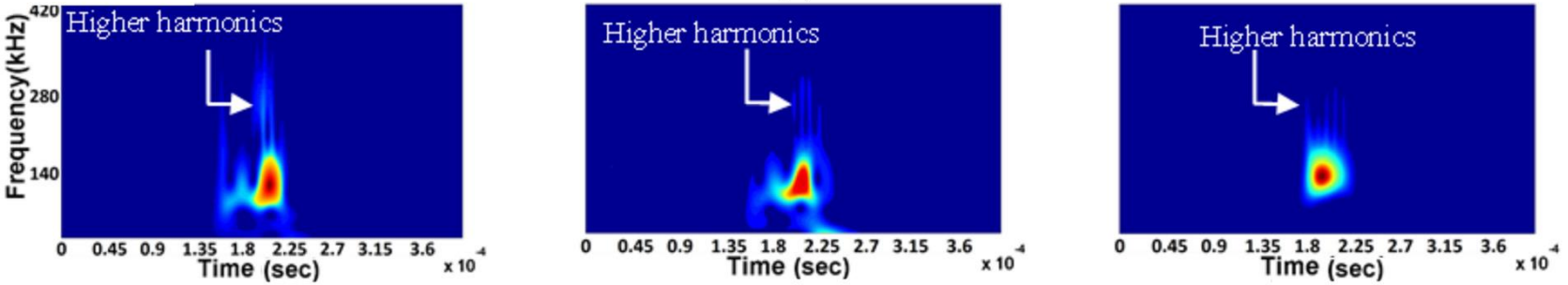
Nonlinear response from delamination







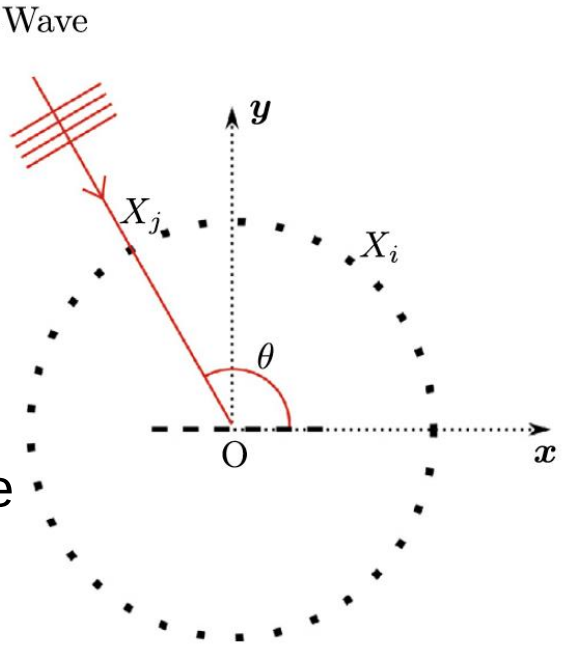
(a)



(b)

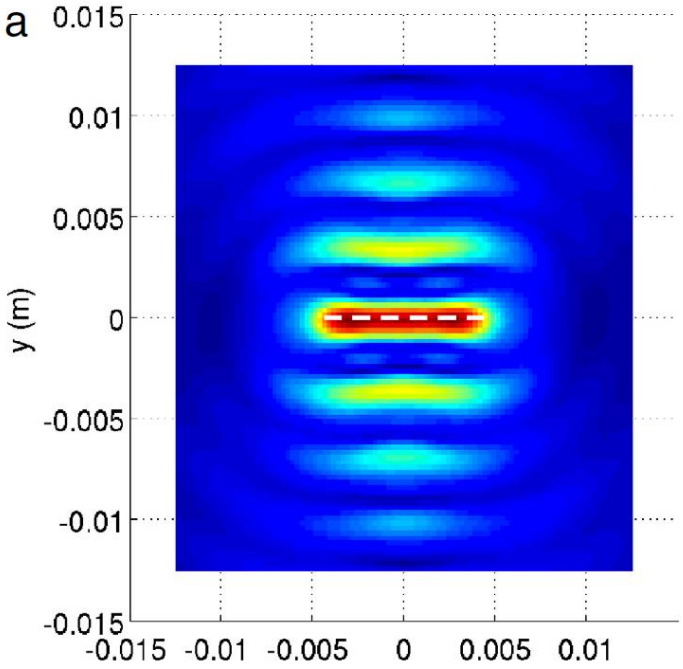
Soleimanpour, R., C.-T. Ng, and C.H. Wang, *Higher harmonic generation of guided waves at delaminations in laminated composite beams.* Structural Health Monitoring, 2016

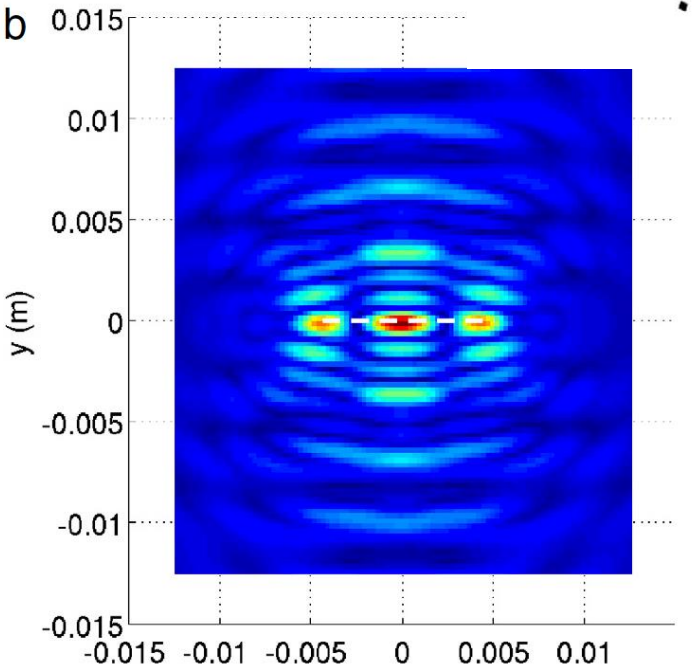
Nonlinear wave imaging: crack



Linear response
(needing baseline)

Nonlinear response
(no baseline)





Blanloeuil, P., L.R.F. Rose, J.A. Guinto, M. Veidt, and C.H. Wang, *Closed crack imaging using time reversal method based on fundamental and second harmonic scattering.* Wave Motion, 2016.

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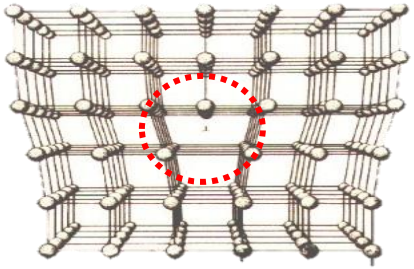
Source of Nonlinear Modulations

Classical | **Non Classical**

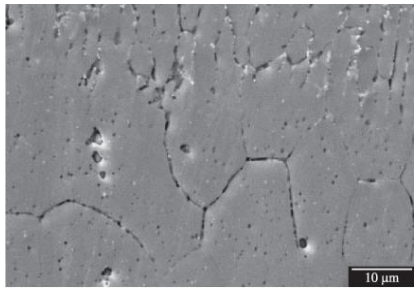
Material's Intrinsic Nonlinearity

A crystallographic defect, or irregularity, within a crystal structure such as dislocation



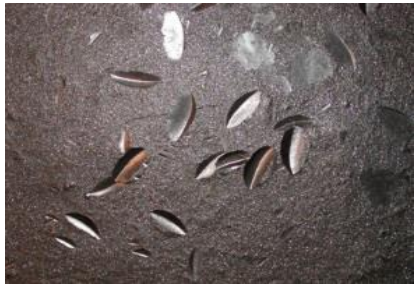
Initial Micro Cracks / Voids

Initial micro cracks/voids act as precursors of macro cracks under repeated loading



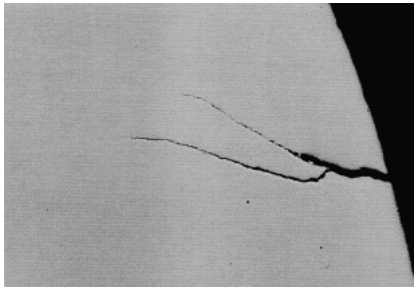
Local Plasticity

Local plastic from impact, overloading or stress concentration can generate nonlinearity



Fatigue Crack

Fatigue cracks can generate nonlinearity due to friction, clapping contact, hysteresis and thermoelectricity at the crack surfaces

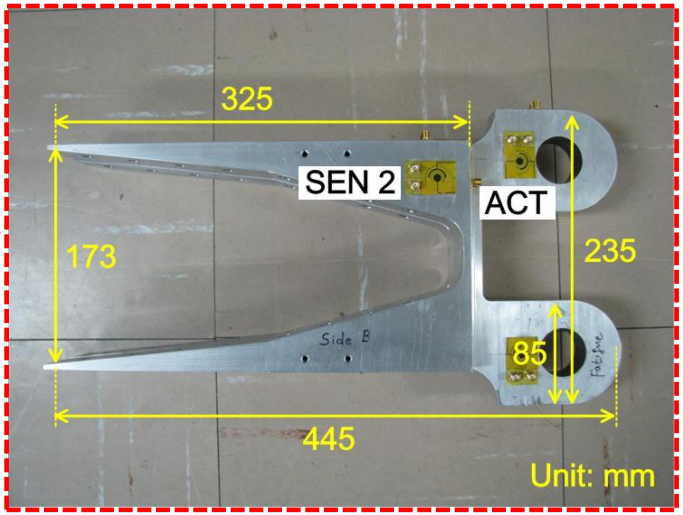


Distributed | **Localized**

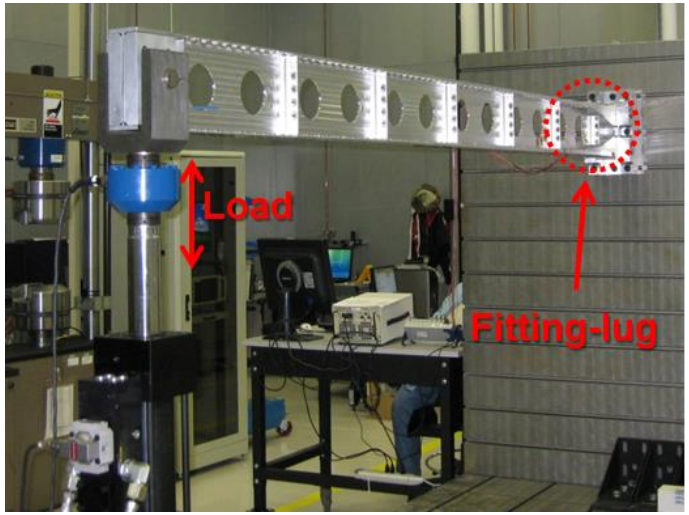
Fatigue Crack Detection in Fitting-lug Specimen

(Supported by US Air Force Research Laboratory)

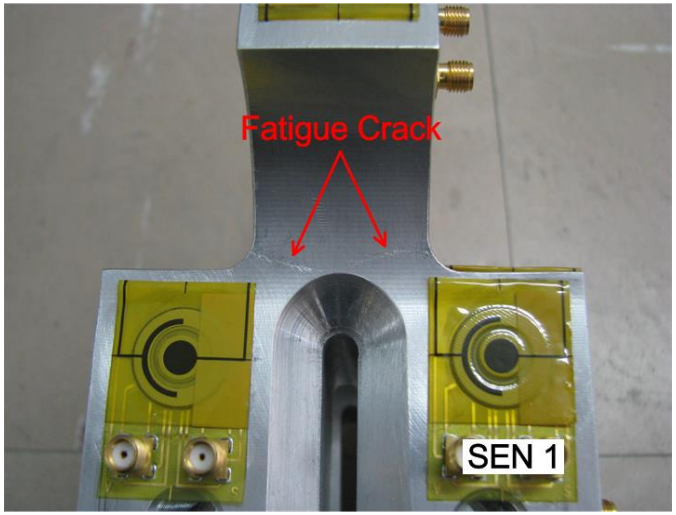
F-15 aircraft



Fitting-lug mock up specimen



Fatigue test



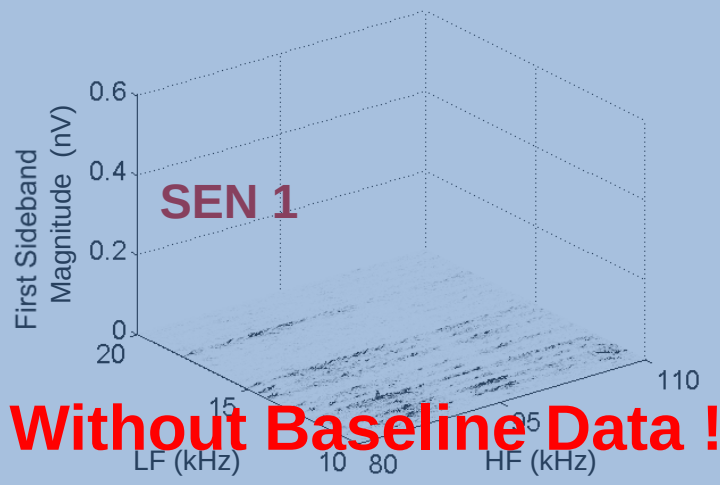
Fatigue crack on the specimen

Courtesy of Professor Hoon Sohn (KAIST)

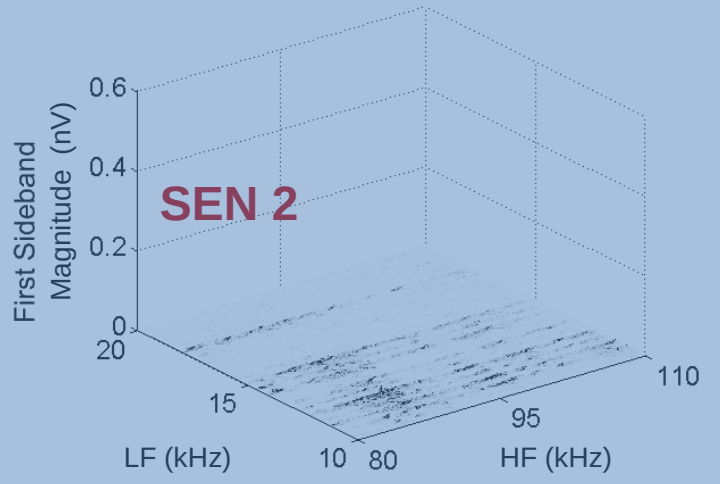
Fatigue Crack Detection in Fitting-lug Specimen

(Supported by US Air Force Research Laboratory)

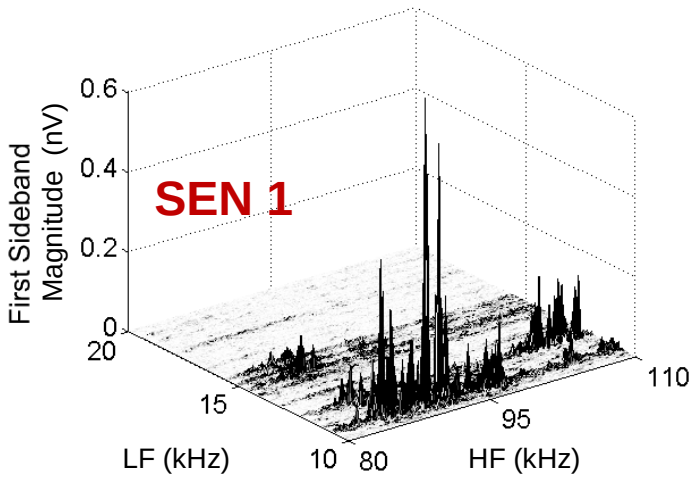
Intact

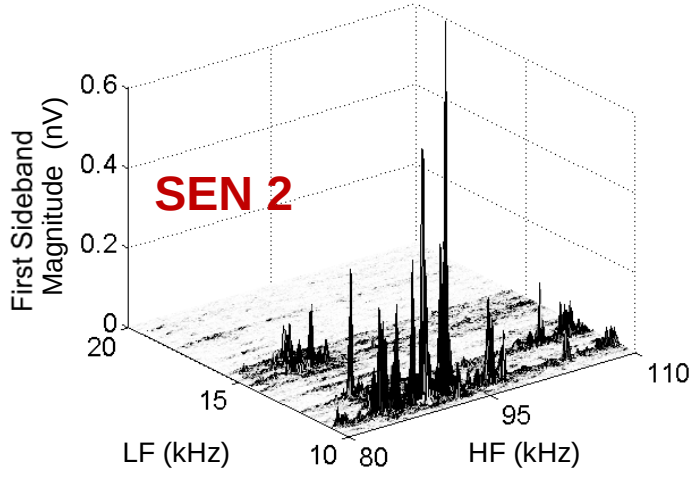


Without Baseline Data !!



Damage





Hoon Sohn, Hyung Jin Lim, Martin P. DeSimio, Kevin Brown, Mark Derriso, "Nonlinear ultrasonic wave modulation for online fatigue crack detection," *Journal of Sound and Vibration*, 333(5), pp. 1473-1484, 2014

Summary

- Quantitative damage imaging is now possible for sizing damage in plate- and shell-like structures
- Sensors and portable devices have been developed and demonstrated on aircraft components
- Nonlinear techniques are emerging to remove the need for baseline data
- Ease of system integration remains a practical challenge
  - Wireless power and communication
  - IoTs

Human Health Monitoring

- Actuarial ⇒ Medical ⇒ Augmented Actuarial