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Recent advances at CEA LIST for the development of guided waves HM solutions: Techniques, imaging and simulation

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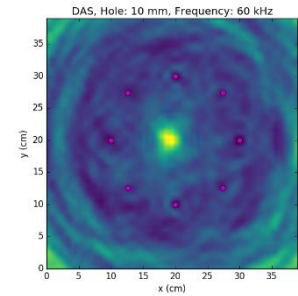
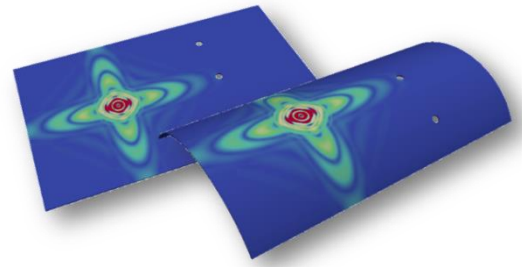
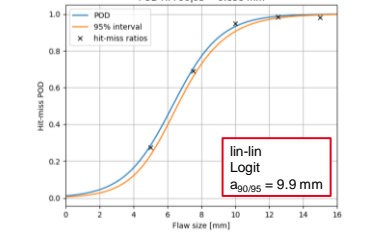
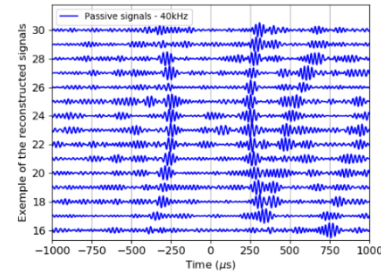
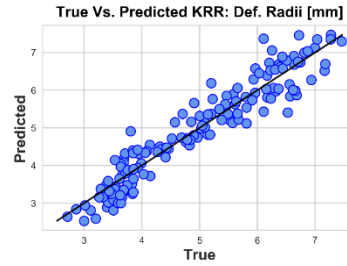
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Submitted on 25 Mar 2024

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RECENT ADVANCES FOR THE DEVELOPMENT OF GUIDED WAVES SHM SOLUTIONS : TECHNIQUES, IMAGING AND SIMULATION

Pierre CALMON and coll.

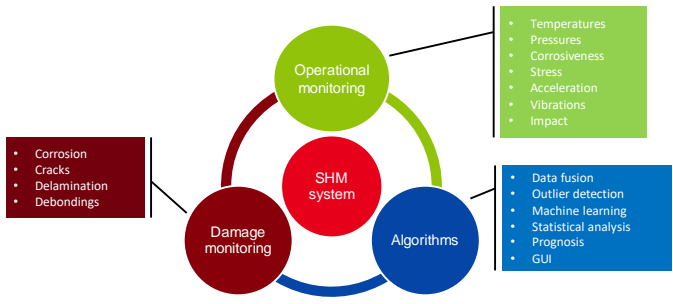
- Introduction: from NDE to GW-SHM techniques for SHM
- GW Imaging requiring a reference state
- More sensors: GW tomography (active & passive)
- Passive techniques and the use of FBGs as GW sensors
- Reliability assessment of SHM systems: MAPOD estimation

INTRODUCTION

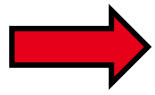
Structural Health Monitoring = “The process of acquiring and analyzing data from on-board sensors to evaluate the **health of a structure**”



First guideline for aircraft industry:
 “Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft”, standard n°[ARP6461](#), published by SAE International, 2013

- Sensors attached to the structure to detect damage
- Damage monitoring replacing periodic inspections
- Decision making algorithms
- Predictive maintenance



Significant benefits expected and technical challenges



BENEFITS

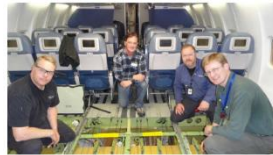
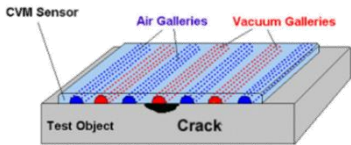
- Monitoring of inaccessible / complex area / harsh environment
- Minimize Human factors using automated data collection and analysis
- Global monitoring: large inspected area
- **Reduction of operation time and cost**
- Possible measurements on demand
- Correlation with data from operational monitoring
- Possible monitoring of the damage evolution
- Predictive maintenance- RUL evaluation
- **Life extension**

CHALLENGES

- **SHM = NDE in situ : Common technical challenges + specific ones**
- Design and system integration
- Power consumption, weight, cost, ...
- Durability of sensors
- Environmental/operational compensation
- Algorithms & simulation
- Reliability assessment
-

- Among other technical solutions ...

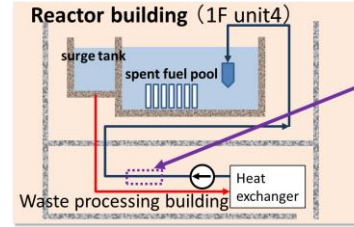
Comparative Vacuum Monitoring (CVM) system



First SHM system certified in 2016 by the US FAA

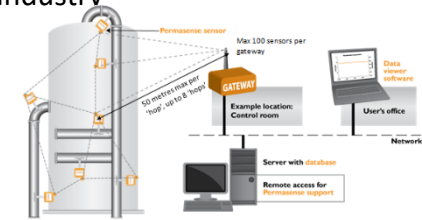
<http://airlines.org/wp-content/uploads/2014/10/231030-Paul-S.pdf>

EMAT sensors for the monitoring of pipes (nuclear)



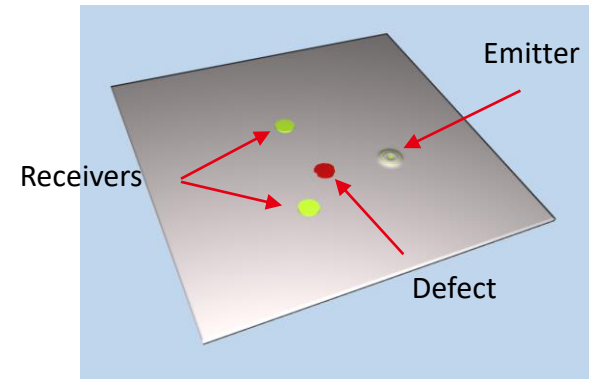
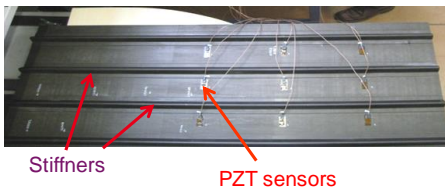
From T. Takagi and coll,

Permanently installed corrosion monitoring ultrasonic sensors in Oil and gas industry

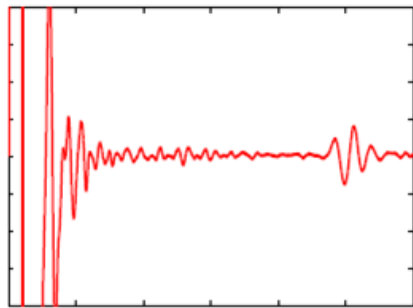


From P. Cegla and coll,

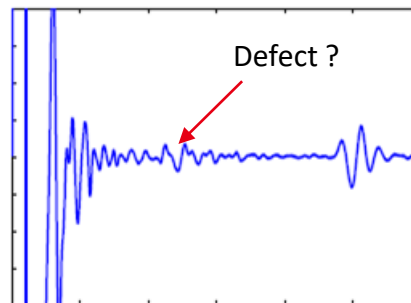
- Guided waves SHM is one of the most promising techniques for the monitoring of large structures (plate-like, pipes, ...)



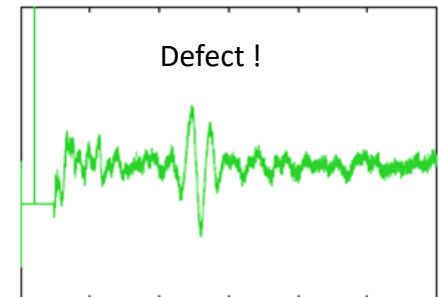
- GW can propagate along large distances with low attenuation
- But... the physic is complex (multiple and dispersive modes) and (often) low sensitivity to localized heterogeneities
- Classical solution: Use of baseline signal and detection criterion on residual signals



GW signal (with defect)



Baseline signal (pristine)



Residual signal (defect)

- Drawbacks: sensitivity to environment conditions, robustness, risk of false alarms...

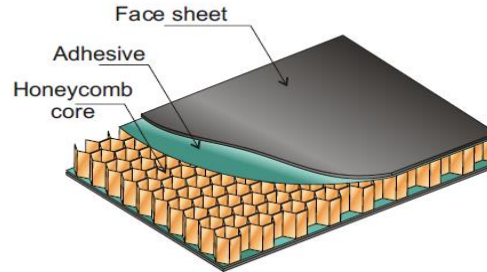
Guided Wave imaging for SHM (with reference state)

AN EXAMPLE OF APPLICATION TO PLATE-LIKE STRUCTURE

Collaborative work in progress

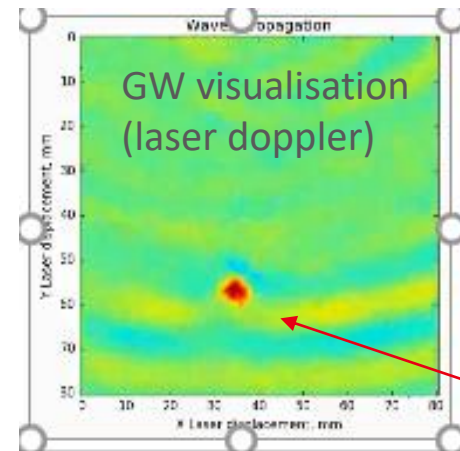


3 m



Sandwich composite.

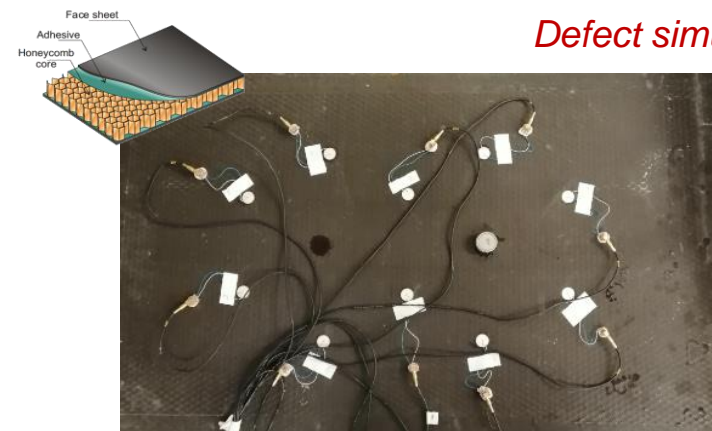
Goal: To develop of a GW SHM solution in order to detect **delaminations** of the composite face sheets and **disbonds** between face sheets and honeycomb core



GUIDED WAVE IMAGING TECHNIQUE

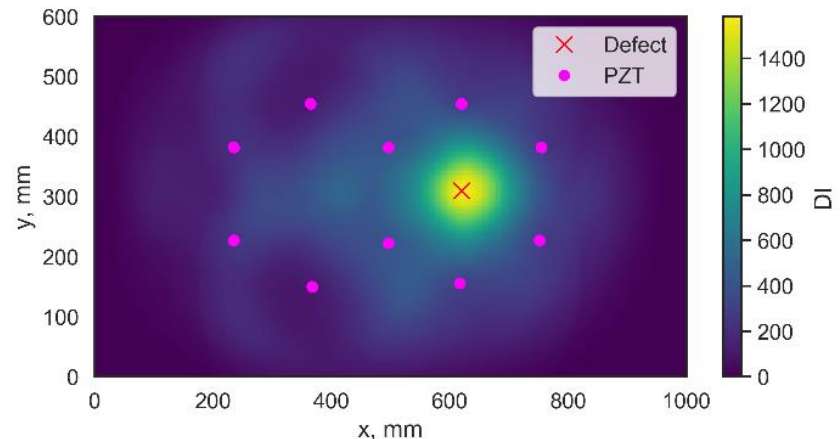
Proposed technique (first step):

- Network of PZT sensors paving the structure
- Low-frequency GW propagation for honeycomb (~10-40 kHz)
- Collection of response of sensors: Residual signals (unknown – pristine)
- Model-based imaging (DAS, Excitelet,...) of the residual signals



30-mm thick honeycomb

Defect simulated by an attached mass

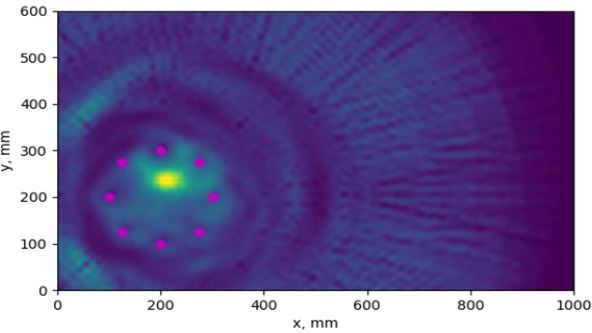


Possible not only to detect but also to localize (size see after) the defect

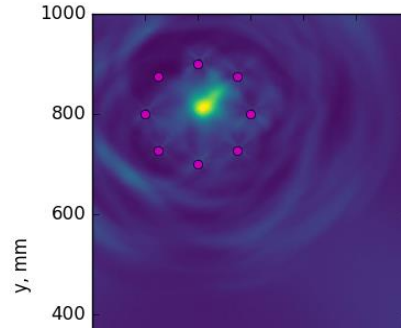
From A. Kulakovskiy PhD thesis, 2018

CFRP plates

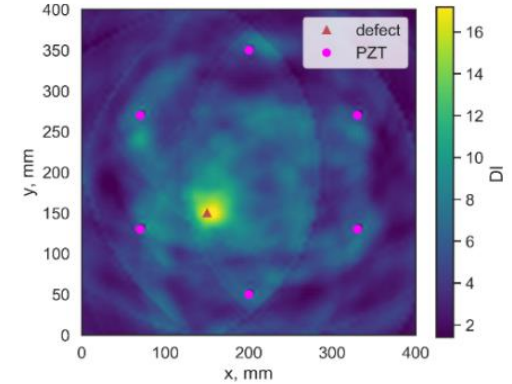
Defect simulated by one attached mass



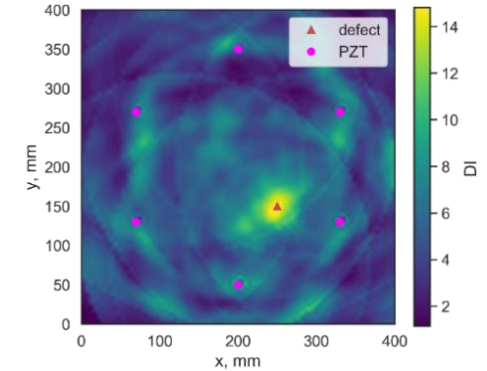
Through-hole $\varnothing = 15 \text{ mm}$



Impact 5J

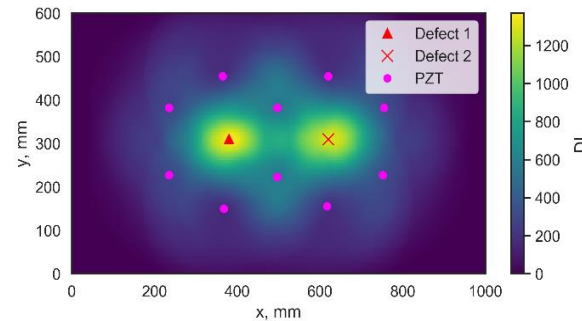
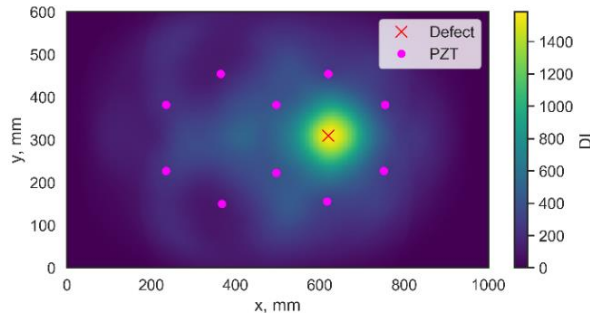
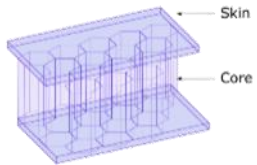


Impact 11J



Honeycomb composite plate

Defect simulated by one and two attached mass



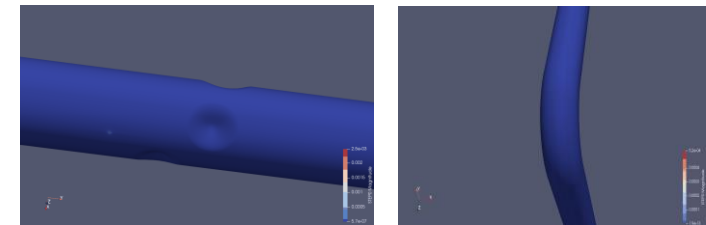
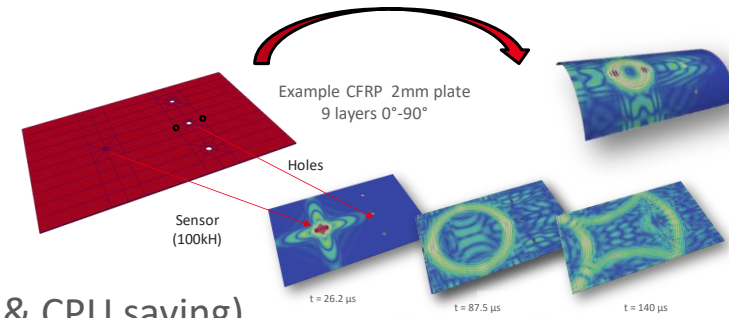
Availability of efficient simulation tool is **ESSENTIAL** in order to propose solutions to SHM technical challenges:

- Design of the system (**location/numbers of sensors**)
- Reliability assessment: **POD estimation**
- Damage index definition
- Design of **automatic diagnostics** (training of ML algorithms)

Development of a CIVA-SHM module

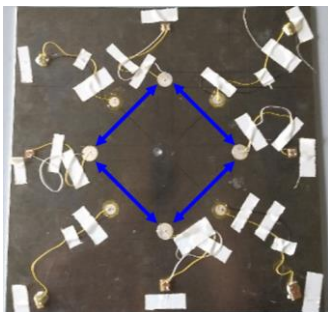
- Computes transient GW in plate-like or pipe-like structure
- Optimized for SHM (sensor array approach)
- **3D High order FEM** (fewer elements) + Macromesh (memory & CPU saving)
- **Metamodelling: Generation of numerical data basis**
- Supports imaging/tomographic algorithms
- Coupled to statistical tools (POD)

CIVA
N·D·E·I

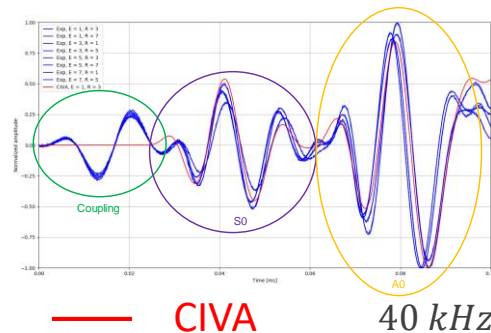


Experimental validation (signals + images)

Al plate, 3 mm

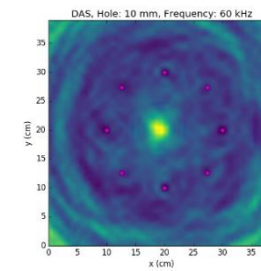


Comparison of signals in pristine

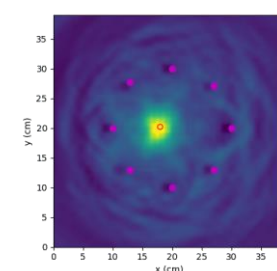


Simulation of imaging algorithms

Experimental



Simulated

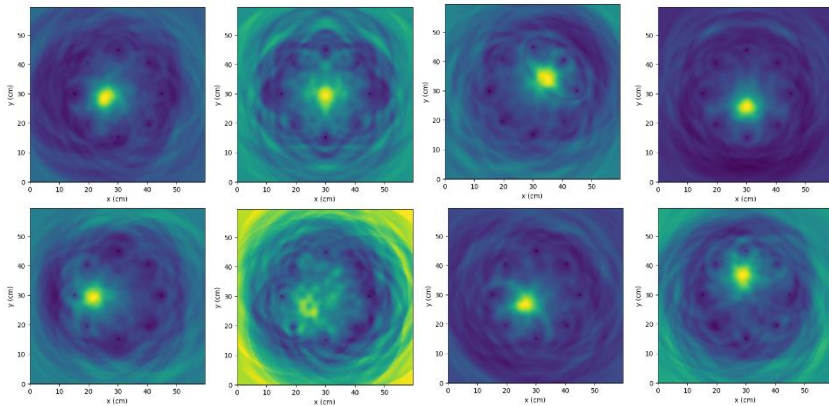


SIMULATION ASSISTED MACHINE LEARNING

Purpose: Automatic diagnostic (location and size of the defect)

Method : Machine learning on a numerical data set

Offline (training) phase: Learning the « inverse model »

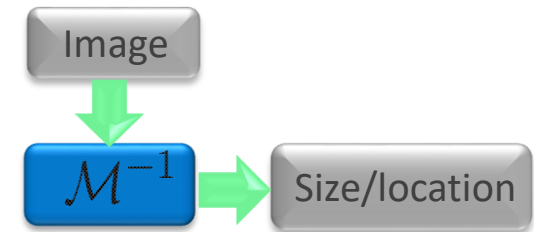


Machine
learning

Inverse model
(\mathcal{M}^{-1})

Numerical database (350 simulated images)
Various defect size and position

- Data: Guided wave images (DAS, Excitelet) of holes
- Training of CNN (convolutional neural network) algorithm

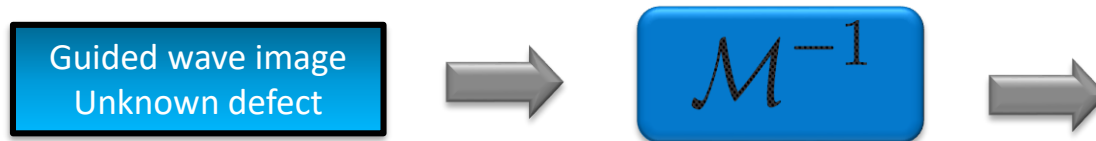


SIMULATION ASSISTED MACHINE LEARNING

Purpose: Automatic diagnostic (location and size of the defect)

Method : Machine learning based inversion trained on a numerical data set

Online phase: Exploitation of the « Inverse model »



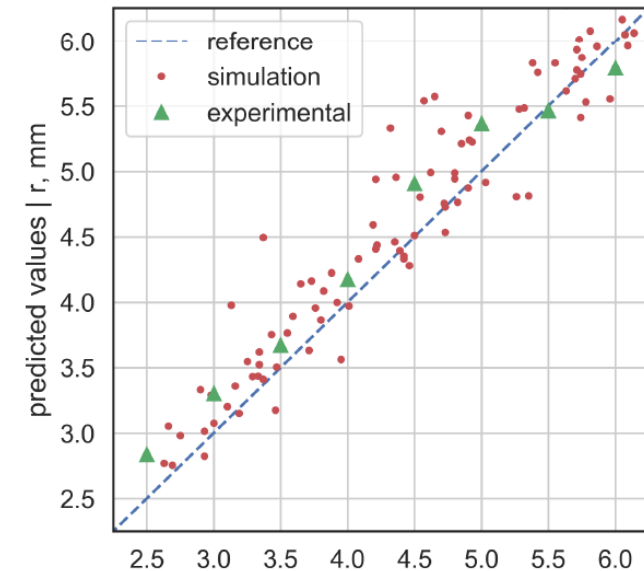
Results

Proof of concept:

- Application to numerical data base (test base, 150 images)
- Average absolute error of 0,3mm in sizing

First results on experimental data:

- Excellent prediction (here CNN algorithm)



Predicted size VS true size

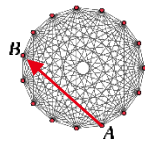
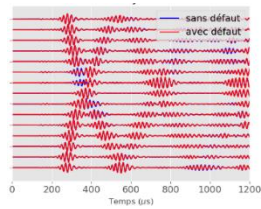
Red: Numerical data
Green : Experimental

Guided Wave Tomography and Passive techniques

GW TOMOGRAPHY : TO DO WITHOUT REFERENCE SIGNAL

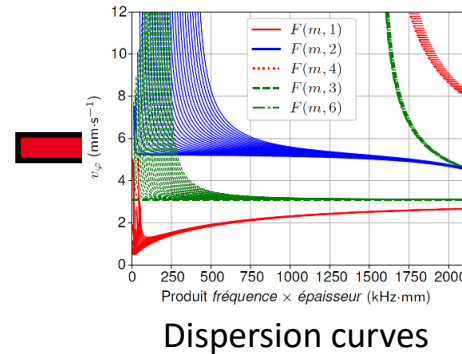
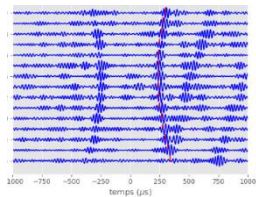
To overcome the limitations of baseline signals based techniques one solution: to increase the number of sensors and apply tomography

- Concept :
 - Arrays of sensors encircling the critical zone (corrosion)
 - GW velocity dependance on part thickness
 - Application of tomographic algorithm on signals



Tomography

Velocity map



Thickness map

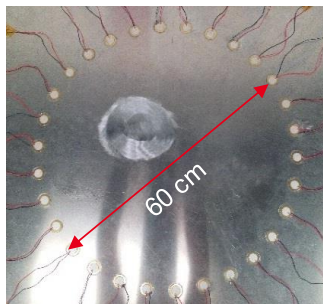
Image= quantitative map of thickness

To overcome the limitations of baseline signals based techniques one solution: to increase the number of sensors and apply tomography

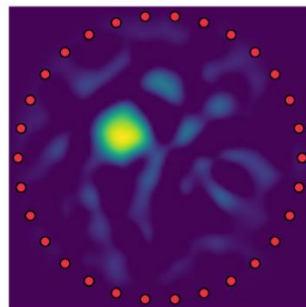
- Concept:

- Arrays of sensors encircling the critical zone (corrosion)
- GW velocity dependance on part thickness
- Application of (ToF) tomographic algorithm

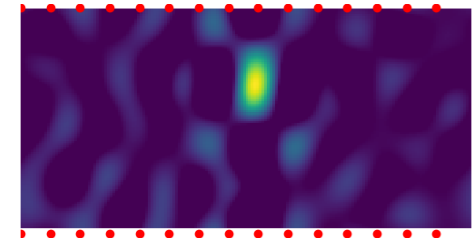
- Applied to plate-like structures



Al plate, 30 sensors



- Applied to pipe monitoring



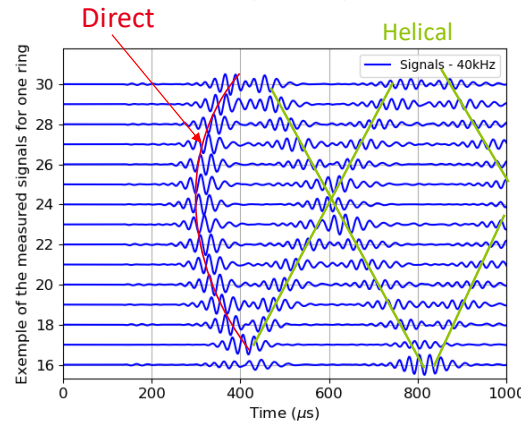
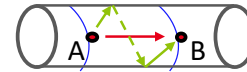
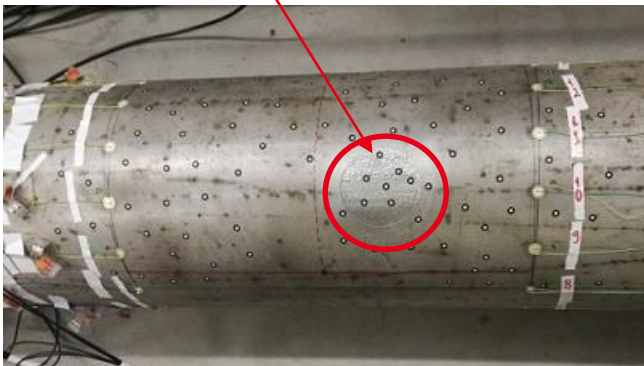
Image= quantitative map of thickness

- Corrosion is a major challenge for various industries.
Cause of leakage, failure of pipeline systems.
- Strong interest for online NDT technique (SHM) using permanently installed sensors allowing early detection.
- Collaboration with EDF for evaluating the potential of GW tomography for monitoring corrosion of pipes in the context of Nuclear Power Plant maintenance

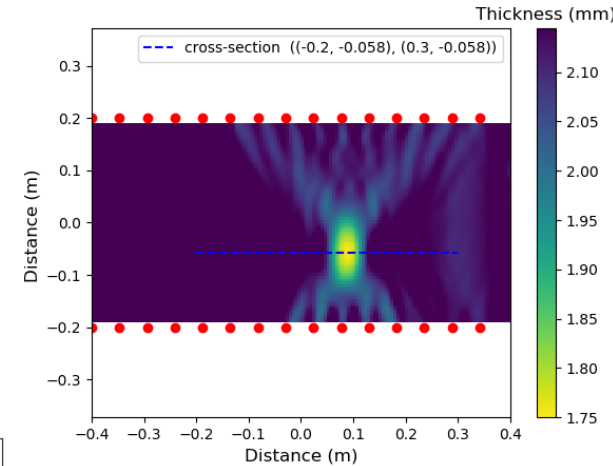
Experimental set-up

- Stainless steel tube (3 m, \varnothing 254 mm, $t= 2.1$ mm)
- Two rings of 15 PZT each
- Excitation: 40 kHz (generation of L01 mode)
- Collected data : signals for all the pairs of sensors
- Electro-eroded corrosion

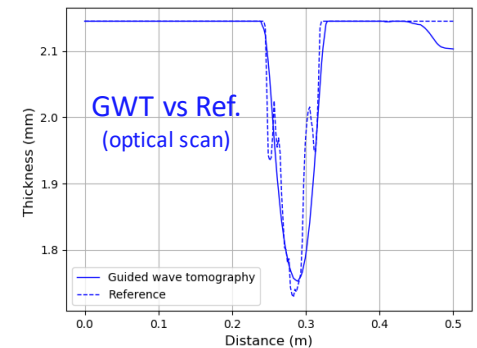
Corroded area



Tomographic image



Thinning profile

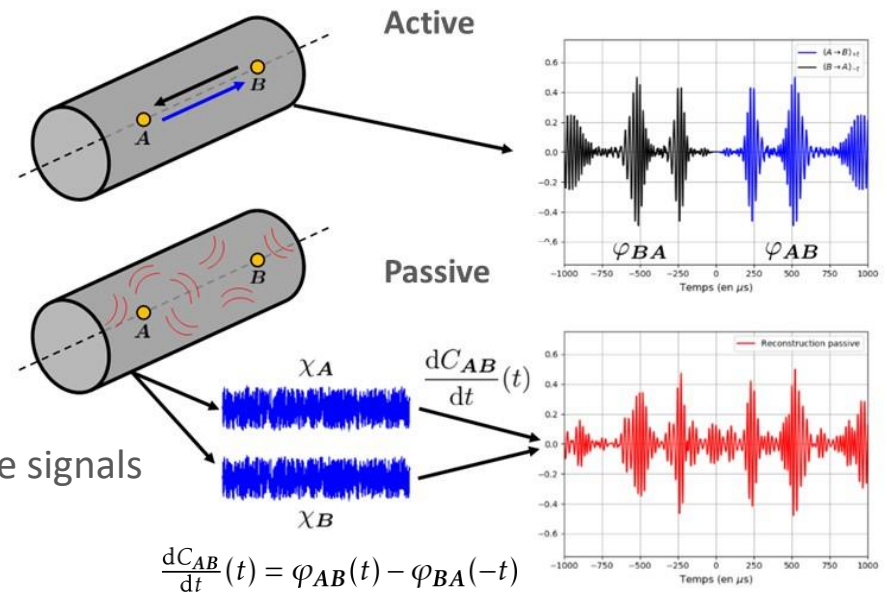


- Concept of passive Tomography:

Based on the measure of the ambient noise (turbulence, liquid flux, etc...)

Active: Emission at “A”, and reception at “B” (or conversely)

Passive: Measurement of the ambient noise at “A” and at “B”.



Underlying theory: The cross-correlation of the passive signals converges towards the Green function of the part A/B

➔ **No wave excitation:** low power and simplified electronics

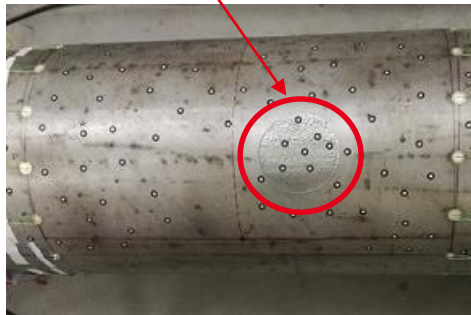
➔ **Makes possible the use of FBG** instead of PZT as ultrasonic sensors: robustness to harsh conditions (T° , radiation)



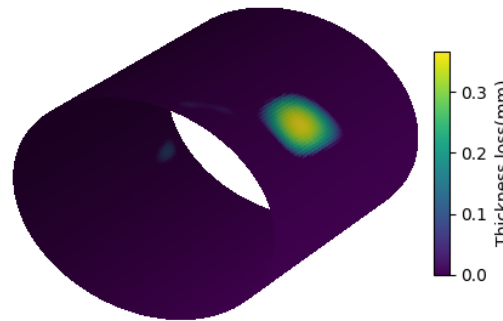
The ambient noise is produced by spraying compressed air inside the pipe
The noise signals are collected on the two arrays of PZT sensors



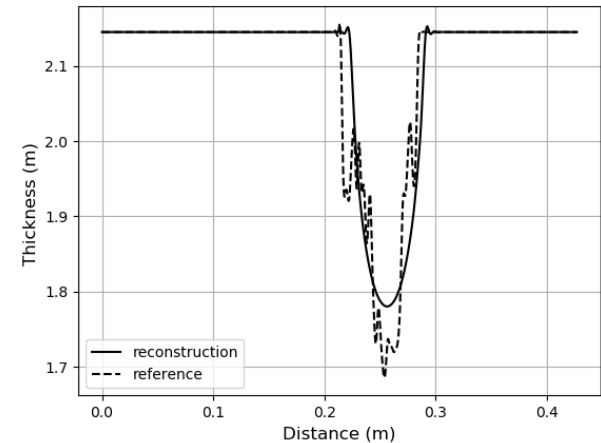
Corroded area



Tomographic image



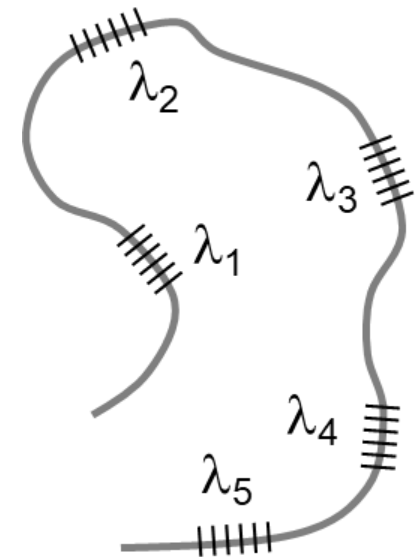
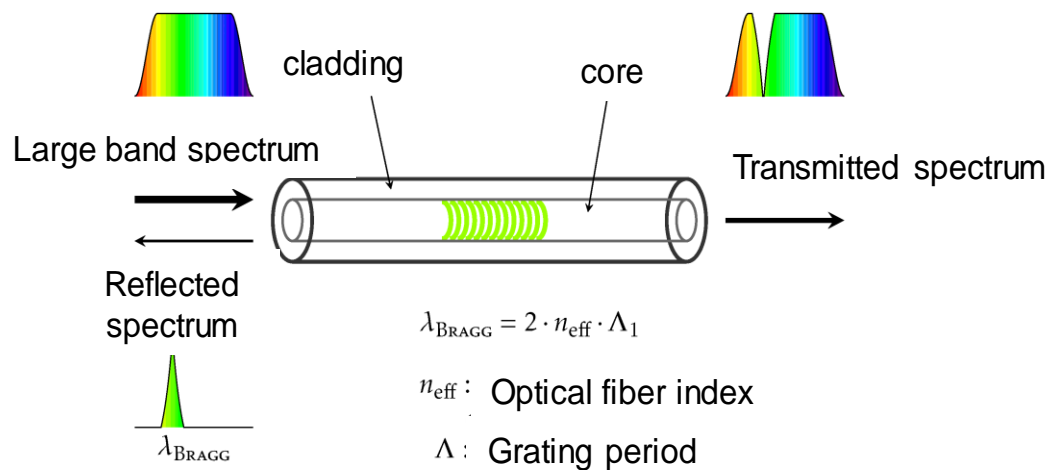
Comparisons of the profiles



Proof of the feasibility of the passive technique

USE OF FBG AS GW SHM SENSORS

Reminder: Fiber Bragg Gratings (FBG) are periodic variations of the refractive index inscribed in the core of an optical fibers. Can be used as strain sensors



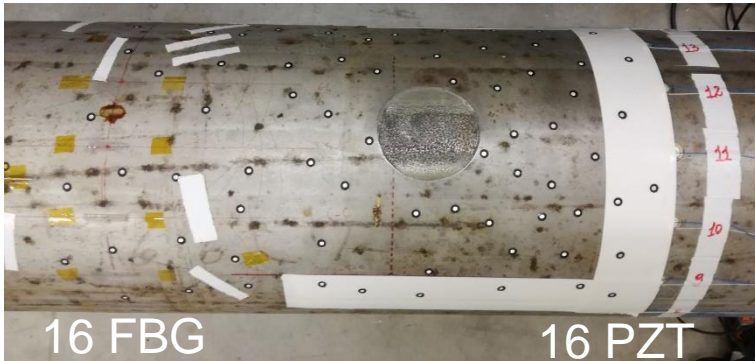
Principle: Measure of the frequency shift of the light reflected by the FBG

FBGs distributed along the fiber can be used as a network of GW sensor

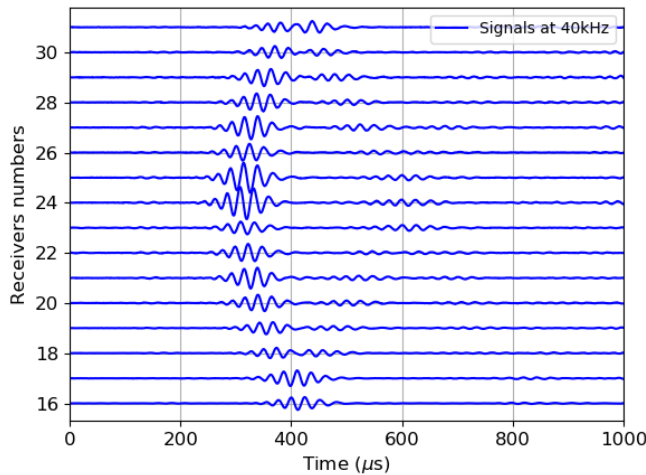
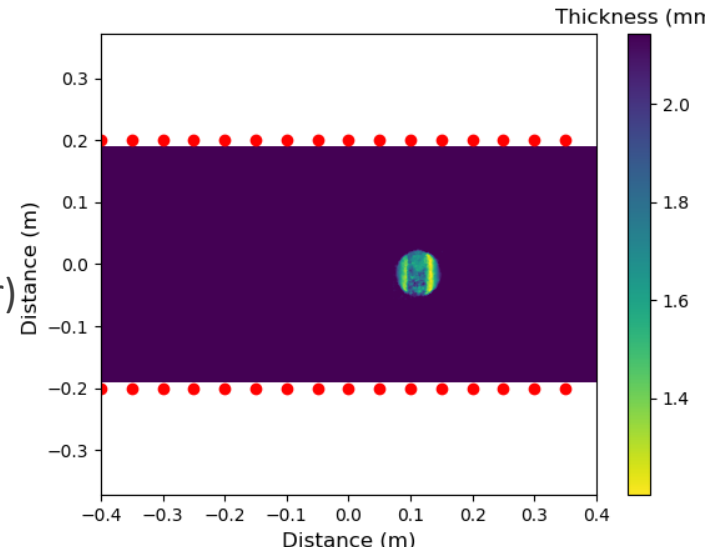
- ➔ High temperature (1000 °C), and radiation resistance
- ➔ Low intrusivity thanks to wavelength multiplexing

Hybrid (PZT /FBG) GW Tomography

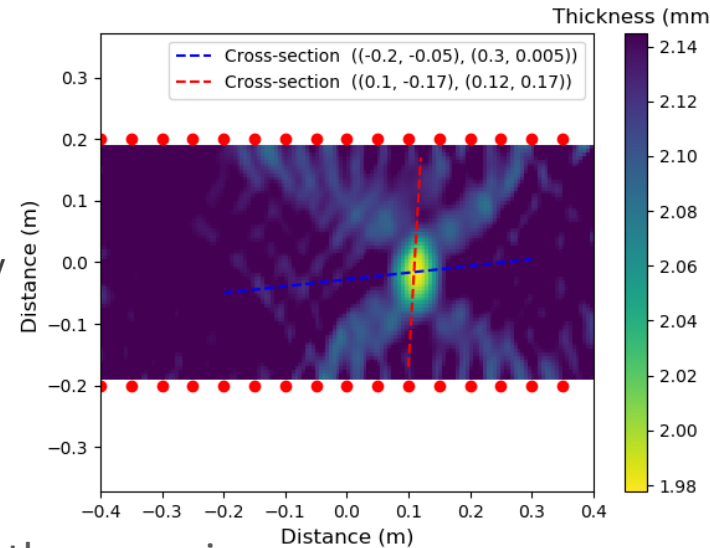
Excitation by PZT/Reception by FBG



Reference
(optical scanner)



GW tomography

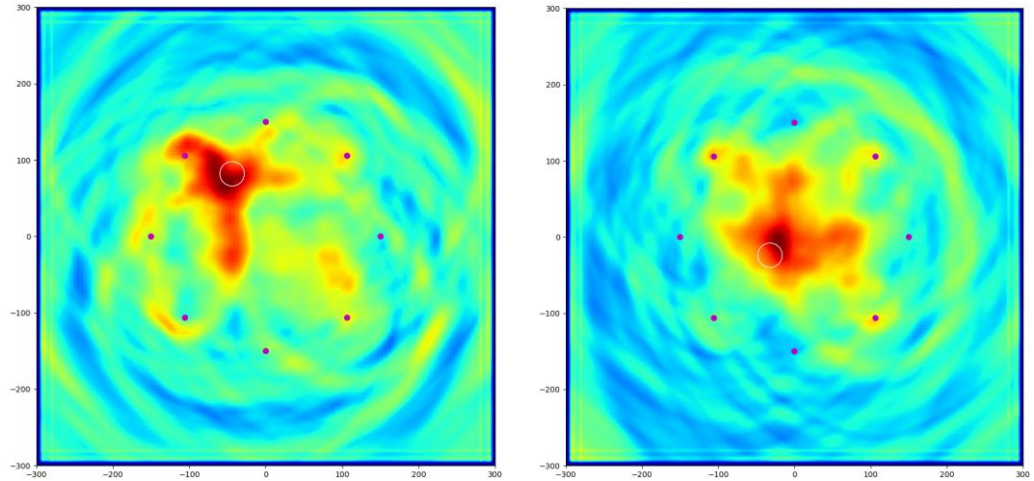


Proof of the feasibility of using FBG for imaging the corrosion

FULL PASSIVE GW IMAGING WITH FBG



GW passive imaging on a CFRP plate using only FBG

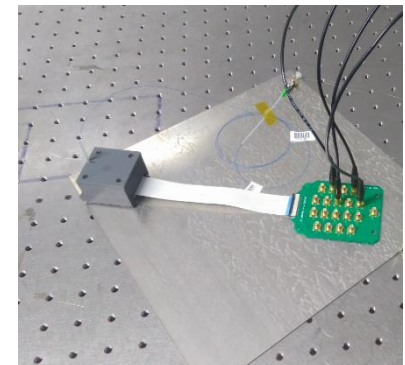


Guided wave imaging results with 2x4 FBGs.
Two defects (added mass) positions

Set up

- 2 sets of 4 FBG → 24 signals
- A_0 mode, around 40 kHz
- Noise (compressed air) acquisition: 50 s

Possibility to measure simultaneously on 8 FBGs at high frequency
(sampling rate 1MHz) on the same fiber (AWG device developed by CEA Leti)



Reliability assessment & POD

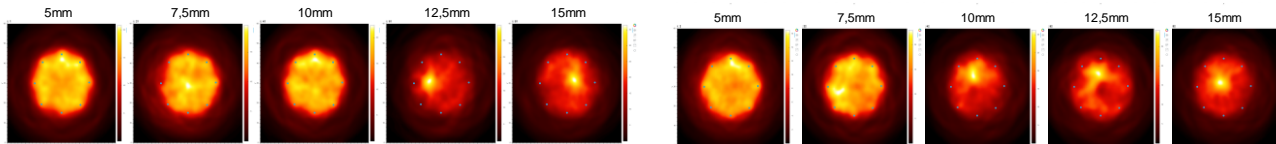
- **Reliability assessment of SHM systems is crucial for the development of SHM technologies.**
- The deployment of a SHM system requires to demonstrate equivalent performances as NDI.
- Often NDI reliability assessment relies on **estimation of POD** and numerous experimental trial (MILHDBK_1823 in Aircraft industry)
- **Due to SHM specificities a specific methodology for the estimation of POD for SHM systems is necessary:**
 - Sensors are attached to the part: Economical cost of numerous trials
 - Influential factors include: Environmental conditions (T° , applied stresses,...), location of the defect (for global techniques as GW), variability/degradation of sensors...
 - Detection criteria & damage index may rely on : comparisons with pristine state, sophisticated processing (GW imaging, ML), data from different sources
- Works in progress in the community to propose new methodologies. In Aircraft Industry an active WG of **AISC-SHM SAE** on this topic. In Nuclear Industry similar questions.
- **General agreement about the role that simulation will play a in a methodology which is to be established (MAPOD) .**

MAPOD FOR SHM: APPLICATION TO DETECTION OF IMPACT DAMAGE

MAPOD key idea: To estimate POD from a numerical data base obtained by introducing variability in the inputs of the models (influential factors)

Illustration on the previous example (Collab. SAFRAN):

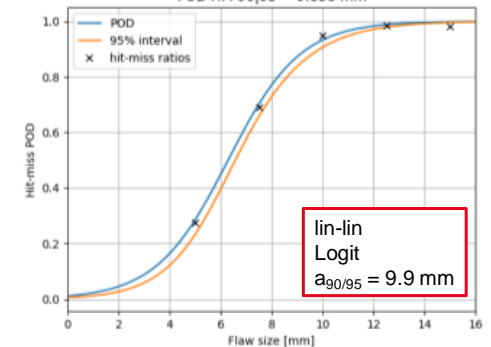
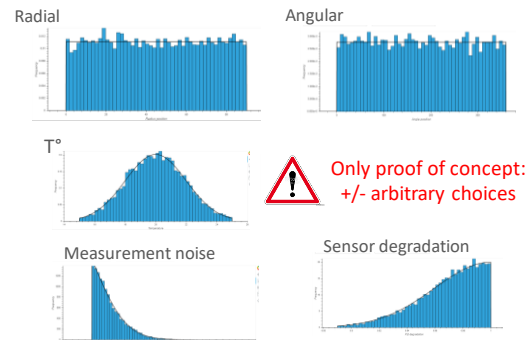
- Creation of a numerical data base of images (CIVA-SHM)



- Introduction of variability

- Estimation of POD (Hit miss)

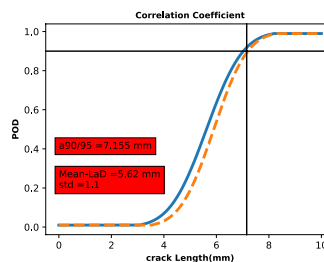
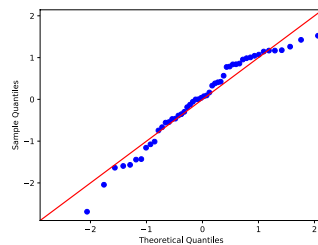
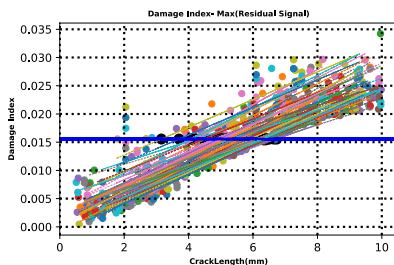
- Location of the defect
- Temperature: [15,25]°C
- Variable measurement noise
- Sensors ageing: Variable bias to sensors response (degradation)



SIMULATION TO EVALUATE POD STATISTICAL ANALYSIS DEVELOPED FOR SHM

SHM applied to the detection of fatigue cracks in metallic parts

- Natural idea: to estimate detection performances of sensors (PZT) by initiating cracks in a few specimen and collecting data during fatigue tests.
- Several authors (e.g. D. Forsyth 2016) have emphasized that such repeated **measurements on growing cracks do not provide « independant » data** and therefore do not verify assumptions of POD standard methodology.
- **Work in progress (AISC-SHM Group) to propose alternative POD statistical analysis (SEPOD) adapted to this type of data**
- **Simulation used to test POD statistical analysis and underlying hypothesis**



S. Sharma's talk
Today Session 4A

SOME CONCLUSIONS

- GW SHM techniques are mature and recent R&D works demonstrate their capability to detect but also to characterize damages.
- Their expected deployment should significantly contribute to paradigm shift in maintenance strategy. Coupled to ML : From detection to prediction.
- High potential of passive techniques in various contexts.
- Importance of the simulation for the design and acceptability of systems.

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