SHM Detection Capability Demonstration
The POD - DoE relationship

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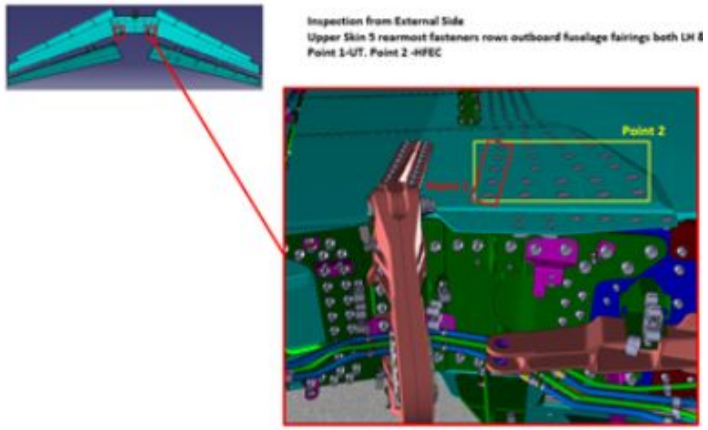
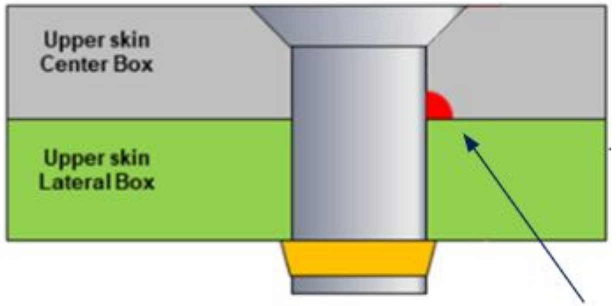
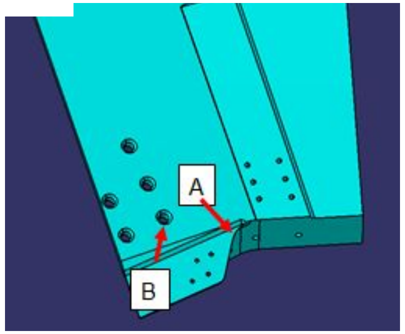
Crack detection with UT Phased Array

SHM use-case

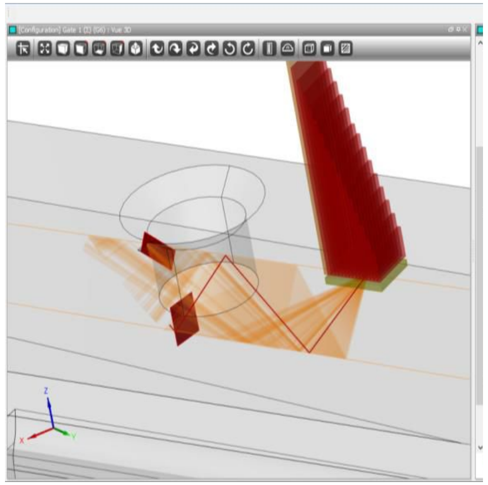
- Cracking around fastener hole







- UT Phased Array in sectorial scan



Crack detection with UT Phased Array

Workflow of the study

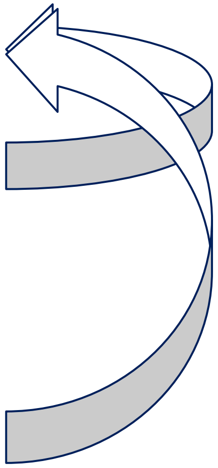
1. <u>SHM Design & Feasibility phase</u>
    a. Show technical feasibility of detection on coupon with the SHM technology
    b. Explore capabilities and limits by understanding variability sources

→ Inspection procedure v1

2. <u>Demonstration phase</u>
    a. Define POD approach and Design experiments for that purpose
    b. Execute tests
    c. Compile and analyze tests results

→ Inspection procedure

→ SHM POD result

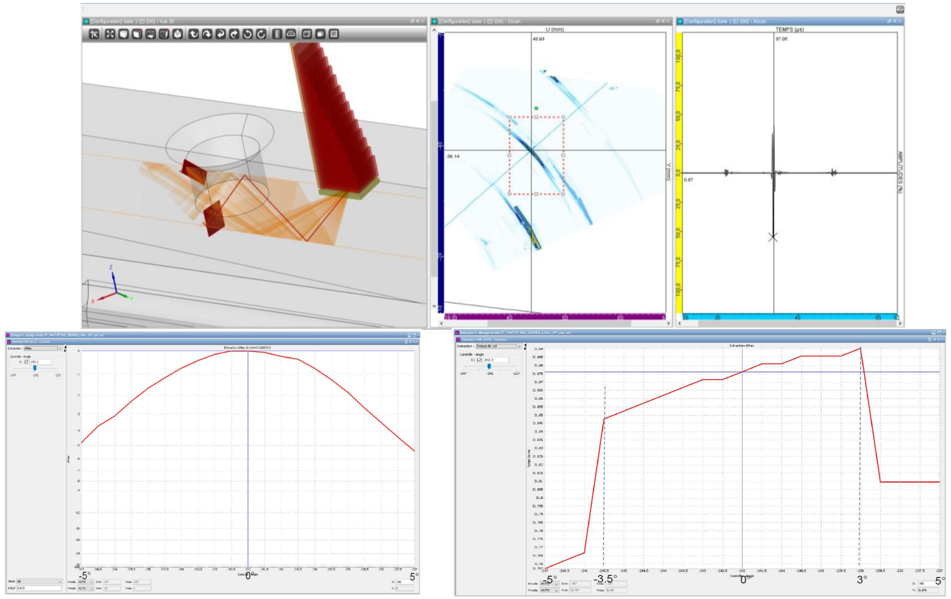


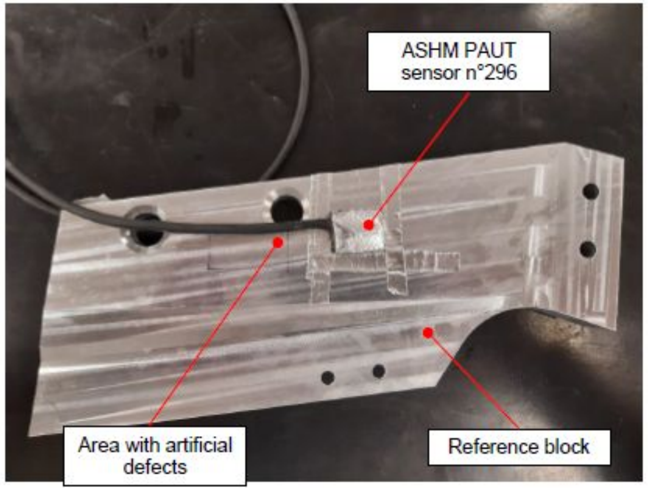
Crack detection with UT Phased Array

Feasibility phase

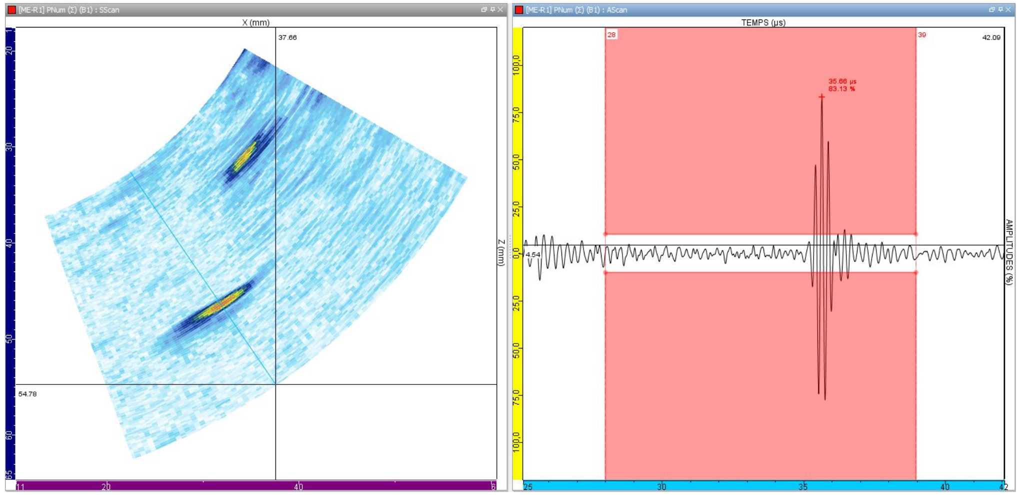
Parametric (simulation) study to

- **Evaluate influence of potential variability sources**
- **Pre-assess detectable crack length**





Detection demonstrated on feasibility block (Experiments)

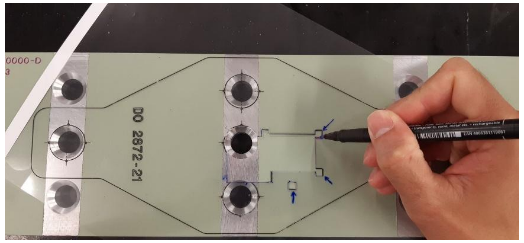
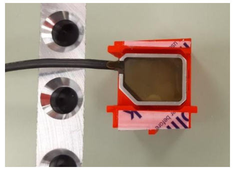
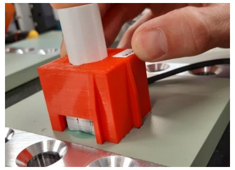


Also check some key characteristics (larger cracks yield better detection)

Crack detection with UT Phased Array

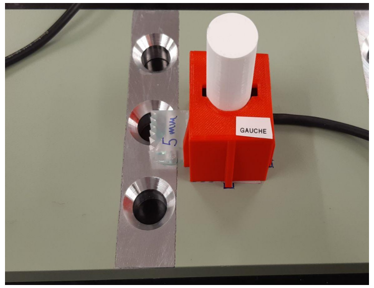
SHM solution Design

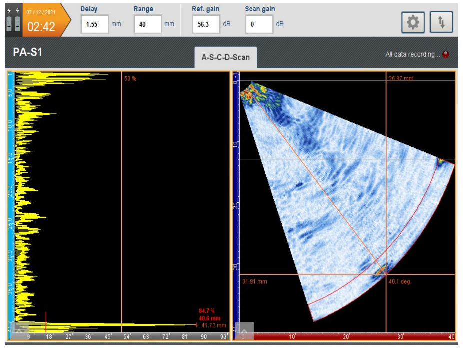
Sensor installation

The <u>installation process is key</u>
- Positioning shall be accurate and reproducible
- The process shall be applicable on aircraft
- The bonding of the sensor shall be durable and robust to environmental factors

Sensor calibration after installation



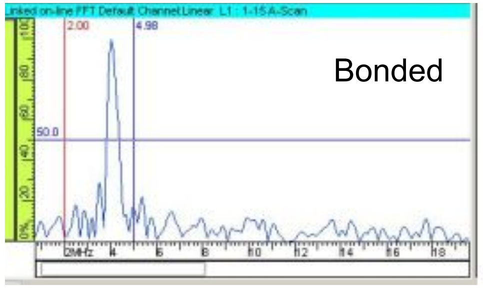


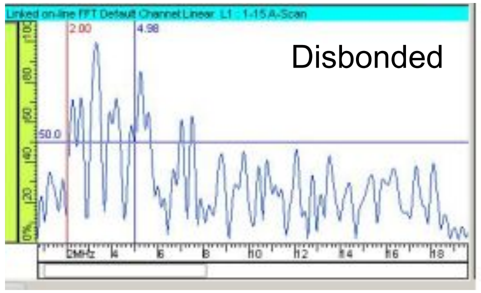
Sensor calibration when no geometrical echo is available

*Patent application n° 5405.148592

Sensor functional tests

- Elements check on wedge echo
- Bonding test with frequency analysis





→ Full procedure ready

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Demonstration phase

The SHM solution is expected to become an alternative to the current inspection, which is an NDT (HFET) procedure, covered by a Probability of Detection (POD).

- The SHM solution will have to prove at least equivalent (in terms of detection) to the current NDT procedure.

The SHM POD study shall cover main variability sources.

The SHM solution, being permanently installed on the aircraft, shall demonstrate detection capability for the full duration of the expected use.

Durability and environmental factors are essential to SHM damage detection capability demonstration

Demonstration phase

- **Main identified variability sources**
  - Defect (*size*, angle, initiation site)
  - Sensor installation (positioning, bonding)
  - Sensor to sensor variability
  - Interrogation: calibration, signal interpretation
  - Durability and environmental factors

- **POD statistical approach**
  - MIL-HDBK 1823?
  - LaD / OSTI or Random Effects Model?
  - 29/29?

Design of Experiments
(DoE)

From variability to DoE

Main variability sources	How to practically experiment variability in a DoE?
Defect (*size*, angle, initiation site)	☐ Several defects ☐ Artificial defects to explore angles and initiation sites
Sensor installation (positioning, bonding)	☐ Several sensors permanent installation ☐ Several installation process implementations to explore effect of positioning
Sensor to sensor variability	☐ Several sensors / batches of sensors
Interrogation: calibration, signal interpretation	☐ Several interrogations of the sensors and signal analysis with different inspectors
Durability and environmental factors	☐ Application of environmental factors and durability cycles to the flawed samples equipped with sensors + signal acquisition and analysis

The DoE for POD shall enable to experiment the effect of the variability sources

From POD statistical approach to DoE

POD statistical approach	Type of DoE
MIL-HDBK 1823 (Berens Signal Response & Hit-Miss)	● No need to run a POD campaign on a growing cracks test bench ● Large number of flaw sites (> 40 to 60 for NDT), of different sizes (same nb of sensors) ● Single data per “sensor(s) - flaw site” couple
Length at Detection **One Sided Tolerance Interval** **Random Effects Model**	● Need to run the POD campaign on a growing cracks test bench ● Reduced number of flaw sites (TBD on a case by case - 15? Convergence approach?) ● Multiple data per “sensor(s) - flaw site” couple (data dependency caution) ● How do we know the real crack length associated to the measurements?
29/29	● No need to run the POD campaign on a growing cracks test bench ● Reduced number of flaw sites (29 max if campaign successful) ● Single data per “sensor(s) - flaw site” couple

The choice of the POD approach strongly influences the specific Design of Experiments

POD / DoE analysis for UTPA crack detection	MIL-HDBK 1823	LaD / OSTI / RPM	29/29 Airbus Amber
Possibility to have several defects	Yes	Yes	Yes
Possibility to have artificial defects to explore angles and initiation sites	Yes (modulo gain compensation and conservatism)	No	Yes (modulo gain compensation and conservatism)
Possibility to experiment several permanent installation of sensors	Yes	Yes	Yes
Possibility to test effect of sensor positioning on a given flaw site?	Yes (modulo conservatism - ex. gel coupling for UT)	No	Yes (modulo conservatism - ex. gel coupling for UT)
Possibility to experiment several sensors / batches of sensors	Yes	Yes	Yes
Possibility of several interrogations of the sensors and signal analysis with different inspectors	Yes	Yes	Yes
Possibility to test durability & environmental effects on the same samples?	Yes, in a second phase	No	Yes, in a second phase
Need to record data on a growing crack bench	No	Yes	No
# data per “sensor-flaw site” couple	1	Multiple	1
# of flawed sites	>> 40 to 60	? Reduced, 15? Convergence approach?	29
Conclusion	Rich information, but very expensive test campaign	Attractive in number of samples but limited for design of space exploration	Conservative result but lean DoE

POD & DoE: scenario analysis

Reasons to choose 29/29 for the UTPA case

- Possible to cover all main variability sources, including durability and environmental factors
- Reduced number of cracked samples and sensors
- Conservatism is understood and accepted
- Equivalent practice to a well known and widely used POD approach for NDT

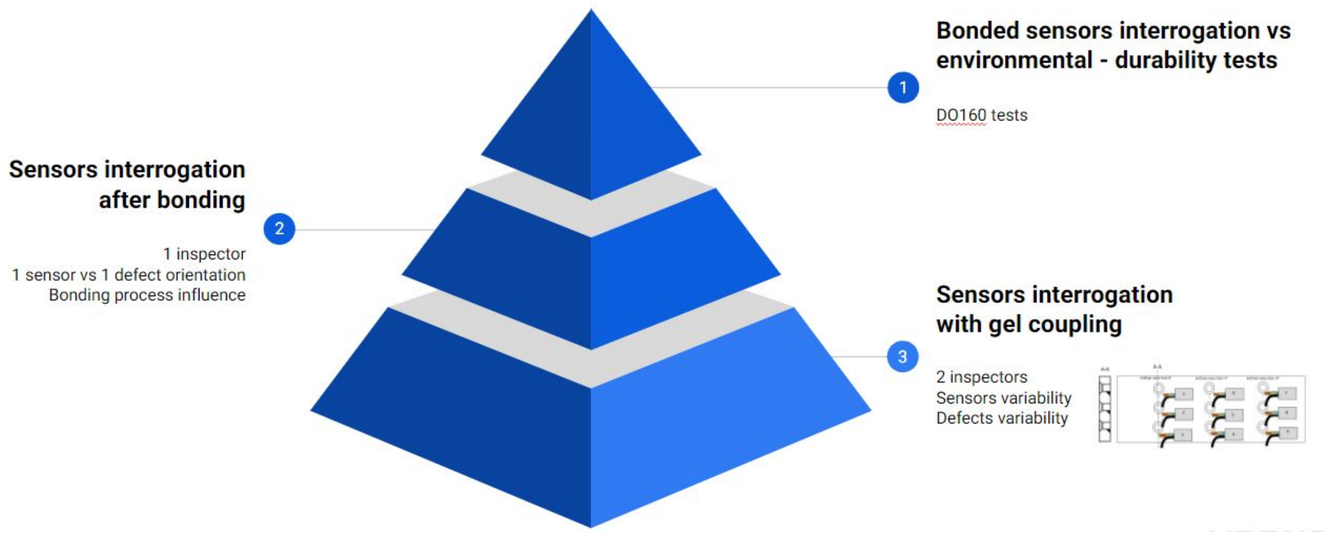
Warning! the choice of the POD approach also depends on the SHM technology

Ex. the CVM technology requires a growing crack test bench to move from “no crack situation” to “crack situation”

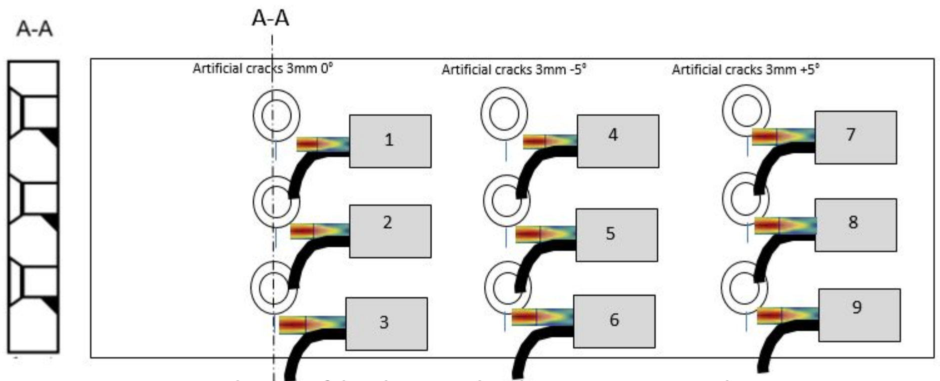
POD & DoE: application to our UTPA use-case

POD test pyramid

For each stage (Recording of UT signal & Statement on crack detection or not)



POD tests specimen



Number of holes: 9 holes per sample
Crack size 3 x 3 mm with an orientation from -5 to + 5°

POFC (pristine samples) tests specimen as well!

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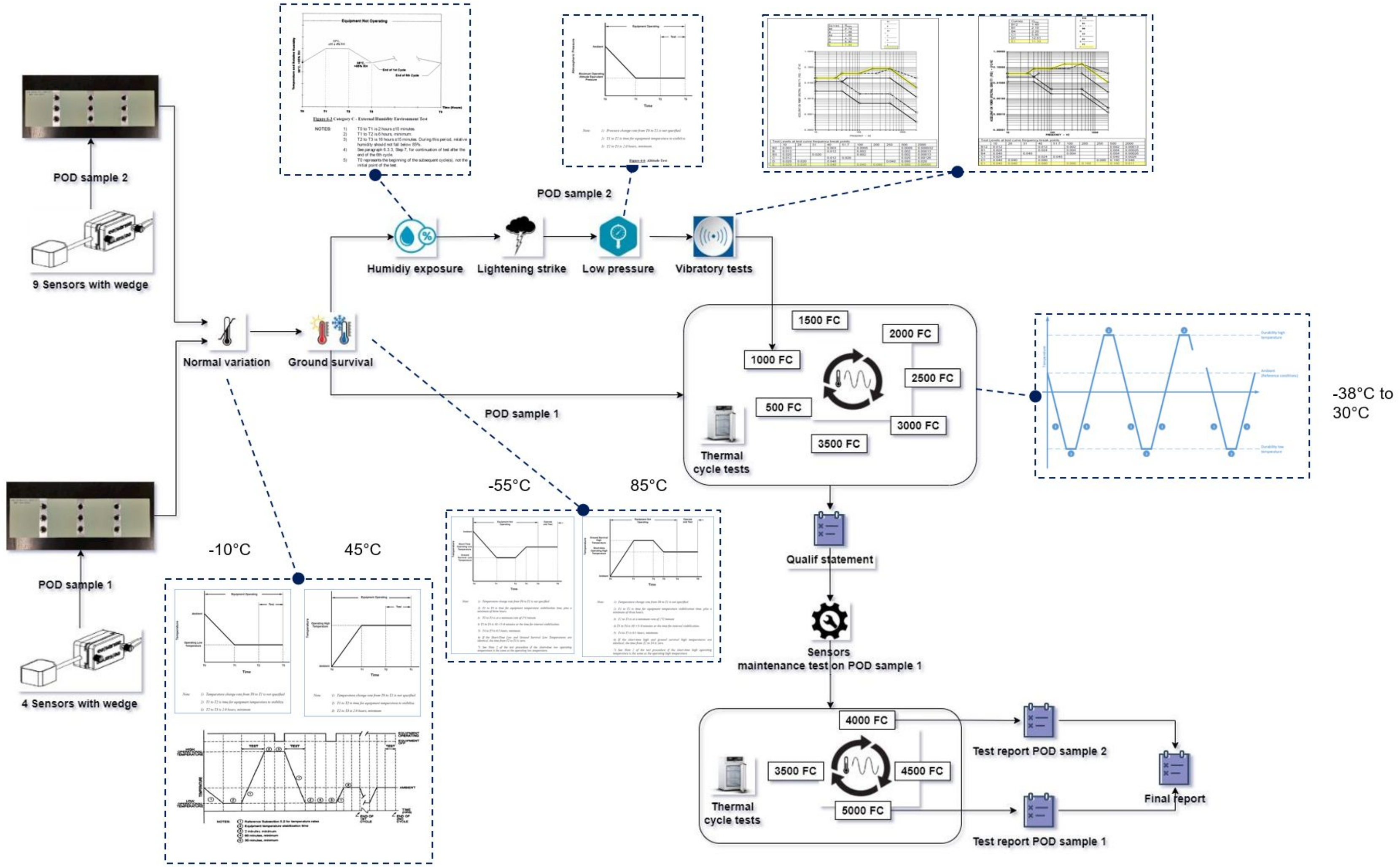
POD & DoE: application to our UTPA use-case

Focus on environmental and durability tests: derived and adapted from DO160



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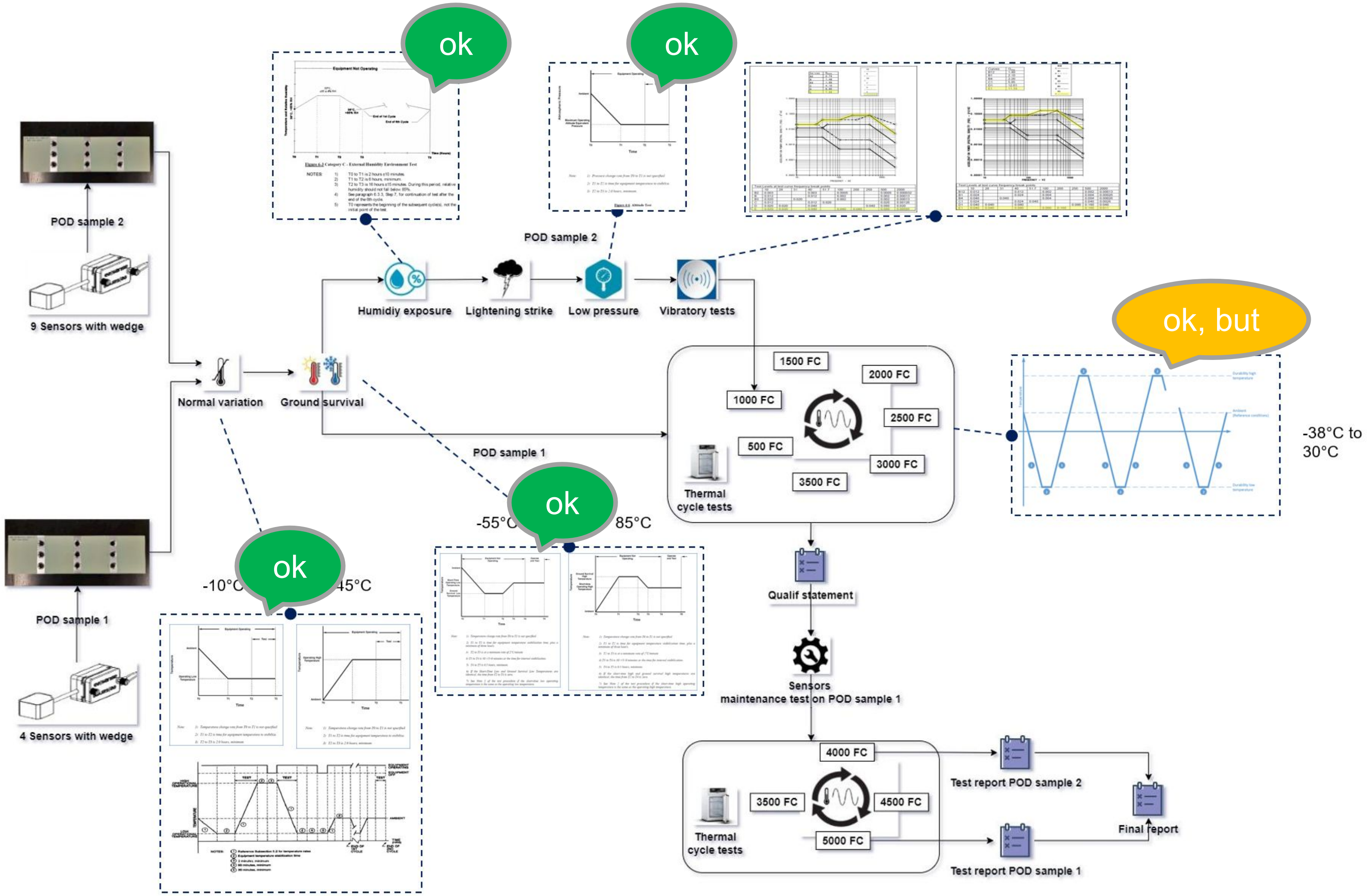
UTPA use-case: environmental and durability results



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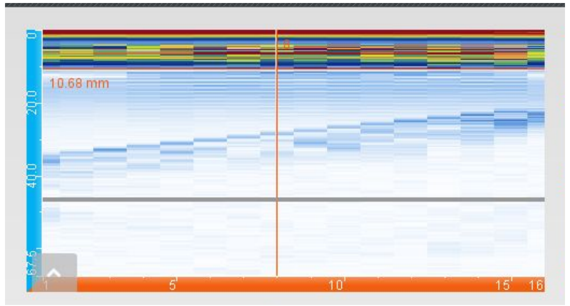
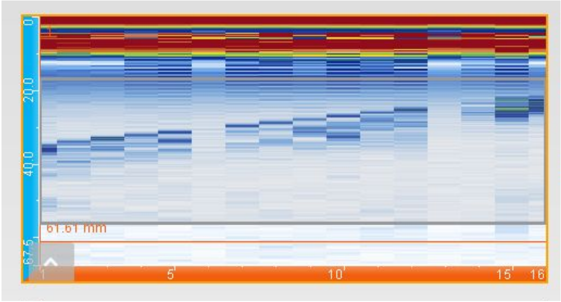
UTPA use-case: environmental and durability results

Fatigue thermal cycling shows effect on some sensors performance.

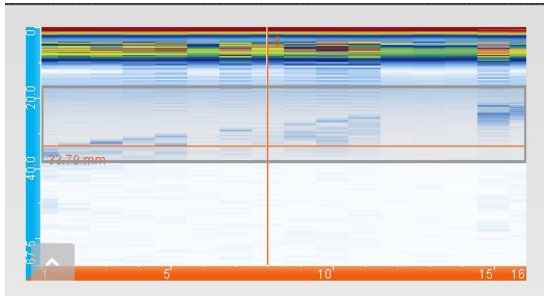
Detection is ok, but signals degrade (elements loss)… investigations on-going.



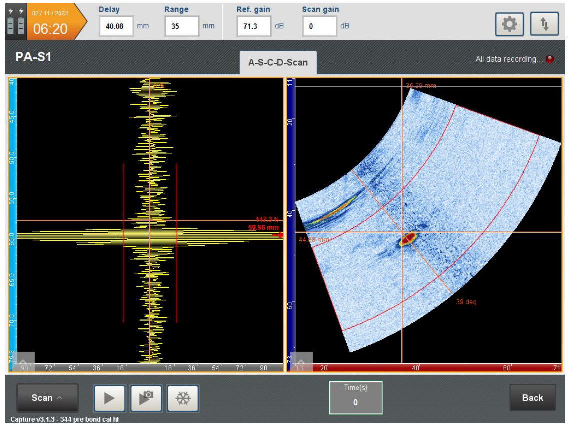
0 cycle



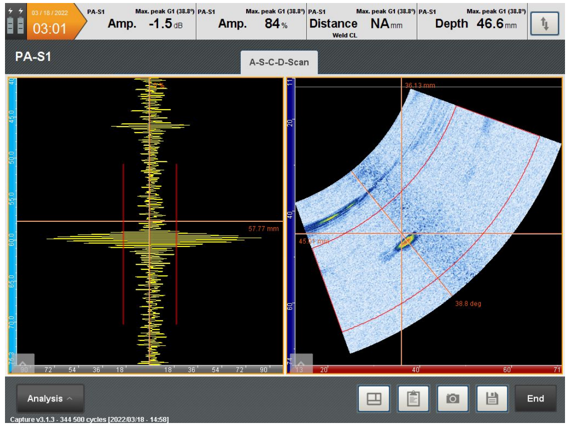
500 cycles



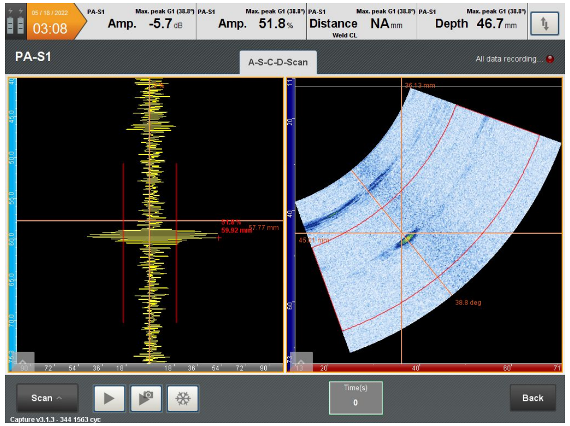
2000 cycles



Detection OK



Detection OK



Detection OK

SHM POD & DoE: discussion / conclusions

- The choice of a POD approach has a major impact on the Design of Experiments for POD
  → POD approach and DoE should be considered all together

- Durability and environmental factors accountancy should be considered when choosing the POD approach
  - The 3 families of approach have very different implications regarding durability and environmental factors in the Design of Experiments

- The choice of the "most appropriate" POD approach is use-case dependent (structure, damage and SHM solution)

It is important to manage several SHM POD demonstration options in front of the diversity of potential SHM use-cases and technologies

Thank you