Needs and trend for NDT and SHM in the Aerospace Industry

- NDE/NDI Methods in Aeronautics
- Replacement of Penetrant Dye Test during manufacturing of metallic parts
- Structural Health Monitoring

by Hervé TRÉTOUT

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NDE/NDI Methods in Aeronautics

- Composite Fuselage
  - In-situ process control
  - Robotised Ultrasonic Inspection System (phased arrays, water jets...)
  - Laser Ultrasonics
  - IR Thermography / Shearography / THz
  - X-Rays
  - Monolithic Structures
  - Sandwich Structures (Hybrid)
  - Inserts
**NDE/NDI Methods in Aeronautics**

- Composite Wing
  - Ultrasonic Techniques
    - Reflexion mode
  - Laser Ultrasonics
    - Embedded transducers for in situ or/and in service inspection
  - Phased Arrays + Signal processing

Integrated monolithic structures with variable thicknesses, curvatures and difficult access.
Development and validation Plan for in service inspection

Composite and metallic materials structures

In situ systems: UT, EC, Acoustic emission

Optical systems

Multitechniques robotized systems

- Laser ultrasonics
  - Air coupled UT
- Eddy currents
- Thermography / Shearography

Inservice damages:

- Impact
- Corrosion
- Debonding
- Crack

Detéction
Localisation
Identification
Sizing

Monolithic structures

Metallic structures

Sandwich structures
# Ultrasonic Inspection State of the Art in Aeronautics

<table>
<thead>
<tr>
<th>Total Immersion</th>
<th>Local Immersion</th>
<th>Others</th>
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</thead>
<tbody>
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<td>Water tank</td>
<td>Water jet</td>
<td>6 axes robot</td>
</tr>
<tr>
<td>Water box</td>
<td>Water jet</td>
<td>Wheel probe</td>
</tr>
</tbody>
</table>

**Methods**
- Water tank
- Water jet
- Water box
- 6 axes robot
- Wheel probe
- Laser Ultrasonics
- US Air
- Contact

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**Contact**
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- Water jet
- Water box
- 6 axes robot
- Wheel probe
- Laser Ultrasonics
- US Air
« New» NDT / NDE methods: Robotics issues

Main issues:
- Part geometry different from CAD model
- Part rigidity
- Complex geometry part

• Simulation objectives
  - Set-up configuration (robot, effector, sensors)
  - Trajectory simulation
  - Robot programming

• Simulation tools
  - CATIA + DELMIA + Fast surf (Dassault systems)
  - CADFIBER (CORIOLIS)
  - CIMSTATION (ructif.)

• Synchronisation of trajectories and NDT data
• Effector compliance
« New» NDT / NDE methods: Maintenance issue

Current manual inspection with single element probe and RΘ system
Conventional Ultrasonics inspection systems

- Immersion C-scan
  Airbus Nantes

- Water Jet System « Sara VIII »
  Airbus Spain

- Water Jet System ARGUS
  Raytheon « Premier »

- Water Jet System – ATK

- Water Jet System
  Bell Helicopter
« New» NDT / NDE methods: Phased Arrays Systems

- Airbus Nantes
- Size: \( X = 12\,000 \)
  \( Y = 6\,500 \)
  \( Z = 1\,000 \)
- Automatic scanning for skin and stringers
- Local immersion
- Scanning time about 3 to 4 hours
- Data processing time about 30 hours
« New» NDT / NDE methods: Phased arrays Techniques

**SAUL Technique (Surface Adapting Ultrasound)**

Step 1

Step 2

Wave front is perpendicular to the surface
« New» NDT / NDE methods: Conformable Phased arrays

CEA 3D smart flexible phased arrays

Matrix distribution of 5x12 piezoelectric elements moulded in a soft resin

Transducer dimension:
- Diameter = 50 mm
- Length = 110 mm

Elbow with 75 mm diameter, bending radius : 50 mm

3D Profilometer : Matrix distributions of springs and displacement sensors
« New» NDT / NDE methods: Laser Ultrasonics

1990 - LUIS
Scanning Unit on rolls

2000 - Ω, β, α
Scanning Unit on gantry

2010 - LUCIE
Scanning Unit on robot + linear track
"New" NDT / NDE methods: Laser Ultrasonics

LUCIE – Robotized Laser Ultrasonics System
Developed by Tecnatom (ES) and I-Photon (USA)
AIRBUS - Tecno Campus Nantes
« New » NDT / NDE methods: Laser Ultrasonics

Airbus - Radome (Glass fibre sandwich)

Rafale – Vertical Tail apex

Time of flight and amplitude cartographies
« New» NDT / NDE methods: *Laser Peening or Laser shock*

- Use of Laser Peening (short pulse with high intensity) to generate shock wave.
- Shock wave disbands 'weak bonds', detected by Laser US or conventional US.

Alternative for small thicknesses: *Laser tapping*
« New» NDT / NDE methods: Acousto ultrasonics

An elastic wave (lamb and surface waves) generated by a transducer is detected by a sparse array of transducers or a vibrometer

Radome:
- Composite sandwich
- Magnetostrictif excitation,
- Vibrometer detection

Processed image of an impact
« New» NDT / NDE methods: Air Coupled Ultrasounds

Facts
- Emerging method, low cost
- Very much relying on transducer technology:
  - Composite
  - Capacitive
- Arrays available for increased speed of inspection (otherwise low)
- Several providers in USA (QMI, ULTRAN,..) and Europe (Dr Hilger, SONAXIS, ..)
- Several laboratories
- Main users = Wood Industry, Airbus Nantes and ASTRIUM

Perspectives
- Alternative to water jet systems
- Space applications (dry coupling)
- Maintenance
- Improved bandwidth,
- Focussing capabilities
« New» NDT / NDE methods: Air Coupled Ultrasounds

- CESAR - US –Air System
  Dassault Aviation

- Pitch and catch system
  DASA Manching

- Sandwich panel

- LOLITA – US –Air System - ASTRIUM

- Impact damage
« New» NDT / NDE methods: On Line NDT

Objectives:
For RTM and LRI Composite material manufacturing processes, by sensors integration in a mould monitoring of the
• Compaction
• Infusion
• Curing
« New » NDT / NDE methods: Tomographic inspection

Multiaxes, multi sources Industrial system

Taille pièce 2.50x 3 m > Résolution 200µm
Taille pièce 0.8x1.5m > Résolution 10µm

Medical Scanner mono-source

Perspectives: Robotised Limited Angle X-ray Tomography v X-Ray Laminography
µ-Computed tomography for micro-structure characterization of CFRP by EADS Munich

- Impact damage characterization
- Inner CFRP structure characterization
- Main orientation characterization in CFRP
- Porosity evaluation in 3D
- Qualitative and quantitative CFRP characterization
- Repair and sandwich structures
« New» NDT / NDE methods : Tomographic inspection

• « Grand Tomographe » Astrium
  ➢ Handling part volume: Ø2,2mxH3,5m,3t
  ➢ Scan volume : Ø0,6mxH0,2m
    (Ø to be extended to 1 m)
  ➢ Resolution : 0,2mm

Falcon Winglet
  ➢ 1 scan = 3x (rotation 360°)
    yield 45 Gpixel
  ➢ 4 scans for 800 mm height
« New » NDT / NDE methods: Laminography X

Large Scanning X-ray Tube

Electron Beam

Raster Motion

Object

Undetected Scatter

Point Detector

Data is digitized at computer

Large Scanning X-ray Tube

First mm

Résolution h/v: 12/25 µm

Slice of 0.2 mm

First cm
### New NDT/NDE methods verses new and remaining Issues

<table>
<thead>
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<th>New methods</th>
<th>Remaining Issues</th>
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<tr>
<td>X-Ray Tomography</td>
<td>Thick Composites (&gt; 50 mm)</td>
</tr>
<tr>
<td>X-Ray Laminography</td>
<td>Curved Composites</td>
</tr>
<tr>
<td>Phased Arrays</td>
<td>Bonded materials</td>
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<tr>
<td>Laser Ultrasonics</td>
<td>Heterogeneous Composites</td>
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<tr>
<td>Laser Peening / Laser Shock</td>
<td>Data treatment</td>
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<tr>
<td>Laser Tapping</td>
<td>Remote Sensing</td>
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<tr>
<td>Acousto Ultrasonics</td>
<td>Paint thickness measurement</td>
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<tr>
<td>On line NDT / Embedded sensors</td>
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<tr>
<td>Air Coupled Ultrasound</td>
<td></td>
</tr>
<tr>
<td>Terahertz</td>
<td></td>
</tr>
</tbody>
</table>
Replacement of Penetrant Dye Test during manufacturing of metallic parts

Objectives:

- Green alternative proposal as a replacement for Liquid Penetrant and Magnetic Particle Inspections,
- Replacement of the Chromium Anodic Oxidation corrosion protection scheme (OAC by 2017)

At two stages:
- Intermediate stages after forming before shot peening
- Final stage

Alternative methods are evaluated and developed:
- to eliminate non-renewable and noxious substances,
- to reduce the high volumes of water consumed and wastes,
- to reduce pollution, energy consumption, cost, long cycle and hazardous transportation from the manufacturing sites to the inspection sites (200 km)
- to eliminate manual inspection
- For automation of the manufacturing line
Replacement of Penetrant Dye Test - Defects expected

• **Defects in the raw material**
  – Material quality assessed by the aluminium plate manufacturer,
  – Ultrasonic inspection, criteria as a function of the quality paid for,
  – Current criteria = equivalent to a 0.2 mm diameter flat bottom hole (scarce)

• **Defect occurring during the part manufacturing process**
  • Metallurgical defects open by machining,
  • Open crack due after forming and closed by shot peening,
  • Open crack after stress corrosion,
  • Scratches.

• **Defects criterias**

<table>
<thead>
<tr>
<th>Defect type</th>
<th>Intermediate Stage</th>
<th>Final stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack</td>
<td>length 2 mm x width 0.1 mm x depth 0.5mm</td>
<td>length 1 mm x width 0.5 mm x depth 0.5mm</td>
</tr>
<tr>
<td>Void:</td>
<td>1.25mm diameter</td>
<td>1.25mm diameter</td>
</tr>
<tr>
<td>Scratch</td>
<td>hight less than 0.2mm</td>
<td>hight less than 0.2mm</td>
</tr>
</tbody>
</table>
Replacement of Penetrant Dye Test - Wing Pannel

- Stiffened panel without cells (14m long)

- Particular areas
  - Curved pannel
  - Radius
  - Steps
  - Stiffener end
Replacement of Penetrant Dye Test – Central Wing Box – Real Defects

In a radius

In a draining hole
Replacement of Penetrant Dye Test - Test Sample

Classe 2 Penetrant Dye Test – Test Sample CR85 with EDM notches

Crack 3A:
- Length 1 mm
- Width 0.025 mm
- Depth 0.1 mm
Replacement of Penetrant Dye Test - Test Samples with EDM notches v EC probe types

1: Skin (both sides) - Flexible probe with coils

2: Stiffeners - Flexible probe …

3: Edges – Rigide probe –static mode

4: Steps - Rigide probe –static mode

5: Cell walls & bottom Flexible probe

6: Cell corner - Rigide probe – static mode

7: Holes – Flexible rotative probe

8: Double radius - Rigide probe –static

9: Conductivity - Conformable probe with coils
<table>
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<th>Alternative NDT methods</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Issues</th>
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<td><strong>High Definition Vision</strong></td>
<td>Simplicity</td>
<td><strong>TRL 4</strong></td>
<td>Resolution</td>
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<tr>
<td>Semi-global Method</td>
<td>Cost</td>
<td>Scanning speed, Volume of data, depth of field</td>
<td>Surface aspect, Artifact sensitivity</td>
</tr>
<tr>
<td><strong>Laser Triangulation</strong></td>
<td>Cost</td>
<td><strong>TRL 4</strong></td>
<td>Resolution</td>
</tr>
<tr>
<td>Pinpoint Method</td>
<td>Scanning speed</td>
<td>Pinpoint Method</td>
<td>Surface aspect, Artifact sensitivity</td>
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<tr>
<td></td>
<td>Miniaturization</td>
<td>Coverage (holes)</td>
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<tr>
<td></td>
<td>Automation</td>
<td></td>
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<tr>
<td><strong>Surface Acoustic Waves – Phased Arrays – Laser US</strong></td>
<td>Scanning speed</td>
<td><strong>TRL 4</strong></td>
<td>Resolution</td>
</tr>
<tr>
<td>Pinpoint Method</td>
<td>Cost</td>
<td>Safety requirements</td>
<td>Coverage (holes)</td>
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<tr>
<td></td>
<td>Automation</td>
<td></td>
<td>Setting - up</td>
</tr>
<tr>
<td><strong>Eddy Current Arrays</strong></td>
<td>Resolution</td>
<td></td>
<td>Coverage (number and types of probes vs. part geometry)</td>
</tr>
<tr>
<td>Semi-global Method</td>
<td>Scanning speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TRL 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Digital X-rays</strong></td>
<td>TRL 7</td>
<td>Cost</td>
<td>Resolution</td>
</tr>
<tr>
<td>Semi-global Method</td>
<td>Resolution</td>
<td>Set-up</td>
<td>Coverage (in plane defect)</td>
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<tr>
<td></td>
<td></td>
<td>Safety requirements</td>
<td>Scanning speed</td>
</tr>
<tr>
<td><strong>Thermosonics</strong></td>
<td>Cost</td>
<td><strong>TRL 4</strong></td>
<td>Setting-up</td>
</tr>
<tr>
<td>Global Method</td>
<td>Coverage</td>
<td>Scanning speed</td>
<td>Resolution</td>
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<tr>
<td><strong>Flying Spot Camera</strong></td>
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<td></td>
<td>Automation</td>
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<tr>
<td>Pinpoint Method</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Microwaves</strong></td>
<td>Resolution</td>
<td></td>
<td>Resolution</td>
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<td>Pinpoint Method</td>
<td>Automation</td>
<td></td>
<td>Scanning speed</td>
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SHM & NDT – INSA Lyon (FR) – 29/11/2013

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Replacement of Penetrant Dye Test - High Definition Vision (TOCATA)

Crack 3A x 50

Crack 3A x 200

Camera Keyence
Replacement of Penetrant Dye Test - High Definition Vision (TOCATA)

- Linear camera - image 50Mpxls (5000 x 1000)
- Real part – Wing spar
- Crack width ranging from 15µm to 100µm, 2pxls to 15pxls.

Good detection with radial lighting however sensitive to surface aspect
Replacement of Penetrant Dye Test – Passive Infrared Thermography

Heating $T^\circ = 120 \, ^\circ C$
Replacement of Penetrant Dye Test – Vibrothermography

Infrared camera

Sonotrode

Thermal waves

Defect

Vibrations

Elastic waves
Replacement of Penetrant Dye Test - Flying Spot Camera (AREVA)

Crack 3A: 4 pixels (spatial resolution 0.28 mm), extrapolated length 1.12 mm, S/N 10

Double radius
Corner
Curved skin
Replacement of Penetrant Dye Test - Laser ultrasonics – Surface waves

Sound area

Crack

Potential 25 µm (laser / laser)
Replacement of Penetrant Dye Test - Laser Diffraction

Laser profilometer – Keyence – Crack 3A
Replacement of Penetrant Dye Test – Microwaves
(EDF – LEST Université de Bretagne Ouest)

Dual Behavior 13GHz Resonator Sensor

\[ d = 50 \, \mu m \] above EDM crack

\[ w_e = 0.2 \, mm, \, h_e = 3 \, mm, \, l_e = 10 \, mm \]
Industrialization: EC probes

- **Original flexible probe from CEA**
  - 128 elements, organised in 64 patterns of 2 coils
  - Coverage: 100 mm.
  - Step: 1.5 mm.
  - Coils inprint on kapton film

- **Flexible probe for flat areas (Eddyfi)**
  - 4 rows of 32 coils (2.5mm) aligned 2 à 2,

- **Stratic probe for edges (Eddyfi)**
  - Coverage 56 mm, 2 x 2 rows of 32 coils (1.5mm)

- **Flexible probe for stiffeners (CEA - Statice)**
  - Coverage 91mm, 128 patterns, coil 2mm 10 turns

- **Stratic probe for double radius (Eddyfi)**
Test: Flexible probe for flat areas (Eddyfi)

- Micro coils
- Defect: L 1mm x P 0.5mm x O 0.1mm
- Coverage 82mm, 4 rows of 32 coils (2.5mm)
- 3 modes of detection:
  - absolute,
  - transmitter / receiver
  - Single transmitter axial / transversal
Industrialization: « Dassault Iron »

- Manual scanning of skin with Dassault Iron (28 coils probe from STATICE)
- Manual scanning of skin, stiffener and radius with 64 elements imprint flexible probe (CEA-STATICE)
Robotised EC inspection with flexible sensor

• Endurance wear test > interchangeable PTFE film
• PHL solution based on CATIA DELMIA Robotique V5 + OLP + CENIT FASTSURF
• Effectors made by 3D Direct Manufacturing
• 3+1 or 6+1 axes synchronization solutions developed

Issues:
• Edge effect
• Lift off variations

Film protecteur Téflon 120 um
Conclusion

• High Resolution Vision is not appropriate as long as the depth of field remains so small (1mm)

• Flexible Eddy Current Arrays:
  – are available however they integration is not quite settled,
  – are quite convenient to tackle complex geometry parts,
  – sensitivity is appropriate, resolution is high
  – however requires too many probes

• Modelling as for Ultrasonic phase Arrays is necessary and available (CIVA10) to design your EC sensors

• Complementary method is required = Flying spot evaluation is undertaken

• Most of the tested methods detect the Crack N°3A

• Further evaluation tests should be undertaken with smaller cracks (provided by fatigue testing)
A priori Benefits of SHM

Continuous and autonomous monitoring of the structural integrity by means of permanently attached or imbeded sensor systems.

**Improved Maintenance**

- Reduction of inspection time
- Deferred maintenance / repair
- Maintenance on demand
  - DOC

**Improved Design**

- Structural efficiency
  - Weight saving
Airbus applications for 1st SHM generation

Debonding in sandwich structures

Detection of cracked/failed element (ie: stringer in upper fuselage shells sized in DT)

Impact damage detection

Water ingress in sandwich structures

Corrosion detection (ie lavatories, joints)

Crack detection in metallic structures (ie main frames)

Hardlanding detection
# Sensing technologies under investigation

<table>
<thead>
<tr>
<th>Technology</th>
<th>Type of Default</th>
<th>Type of Installation</th>
<th>Target Material</th>
<th>Detection Area</th>
<th>Detection Mode</th>
<th>Illustrations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comparative Vacuum Monitoring (CVM)</strong></td>
<td>Crack initiation &amp; propagation, Debonding</td>
<td>Surface (or embedded in between 2 parts)</td>
<td>Metal, Composite</td>
<td>Local</td>
<td>Off-line Passive</td>
<td><img src="image1" alt="CVM Illustration" /></td>
</tr>
<tr>
<td><strong>Acousto-Ultrasoundics (AU)</strong></td>
<td>Delam, Debond, Crack, Core damage</td>
<td>Smart layer on the surface</td>
<td>Metal, Composite</td>
<td>Global</td>
<td>Off-line Active</td>
<td><img src="image2" alt="AU Illustration" /></td>
</tr>
<tr>
<td><strong>Acoustic Emission (AE)</strong></td>
<td>Impact, Crack, Delamination, Debonding</td>
<td>PZT transducer + equip. on board</td>
<td>Metal, Composite</td>
<td>Global</td>
<td>On-line Passive</td>
<td><img src="image3" alt="AE Illustration" /></td>
</tr>
<tr>
<td><strong>Foil Eddy Current Sensors (ETFS)</strong></td>
<td>Crack initiation and propag., Corrosion</td>
<td>Surface (or embedded in between 2 parts)</td>
<td>Metal</td>
<td>Local</td>
<td>Off-line Active</td>
<td><img src="image4" alt="ETFS Illustration" /></td>
</tr>
<tr>
<td><strong>Micro Wave Sensors (µW)</strong></td>
<td>Water Ingress</td>
<td>Antenna in the structure</td>
<td>Sandwich</td>
<td>Global</td>
<td>Off-line Active</td>
<td><img src="image5" alt="µW Illustration" /></td>
</tr>
</tbody>
</table>
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<tbody>
<tr>
<td>Fibre Bragg Gratings (FBG)</td>
<td>Stress, Strain, Impact, Delamination, Debonding</td>
<td>Surface, Embedded in the lay-up</td>
<td>Metal, Composite</td>
<td>Local</td>
<td>On-line Passive</td>
<td>![FBG Illustration]</td>
</tr>
<tr>
<td>Crack wire</td>
<td>Element failure (ie : stiffener)</td>
<td>Surface</td>
<td>Metal, Composite</td>
<td>Local</td>
<td>On-line Passive</td>
<td>![Crack Wire Illustration]</td>
</tr>
<tr>
<td>Environm. Degradation Monitoring Sensors (EDMS)</td>
<td>Corrosion</td>
<td>Surface</td>
<td>Metal, Composite</td>
<td>Local</td>
<td>On-line</td>
<td></td>
</tr>
<tr>
<td>Imaging Ultrasonics</td>
<td>Crack, Delamination, Debonding</td>
<td>Surface</td>
<td>Metal, Composite</td>
<td>Global</td>
<td>Off-line</td>
<td></td>
</tr>
<tr>
<td>Sensitive coatings</td>
<td>Corrosion, Crack</td>
<td>Surface, Embedded</td>
<td>Metal, Composite</td>
<td>Global</td>
<td>Off-line</td>
<td></td>
</tr>
</tbody>
</table>
Dassault Aviation requirements

Maintenance Issue Status both civil and military:

- 2 maintenance types:
  - Usual maintenance = visible defects
  - Visits (IF)/ageing studies = non visible defects

- 2 different maintenance approaches:
  - Military (fighter) - Systematic repairing or replacement
  - Civil - Damage tolerance philosophy (fail safe)
Dassault Aviation requirements

• **Visits / ageing studies – Definition approach**
  
  • Mainly concerns loaded areas and bore edge = "fuse zones"
  • 3 types of defect causes:
    
    • Fatigue (metallic parts):
      • issued from specific tests and calculation (DJD - Dossier de justification et de définition)
      • Retour d'expérience
    • Accidental (impact on fiber composite parts)
    • Environmental (wear and corrosion)

• **Current Maintenance Issues both civil and military:**
  
  - Only a few inspection points, about 10 on current fleets:
    Example (Falcon 2000): X-ray (1), Eddy current (4), Ultrasounds (5)
  - Impact damage detection ruled by visual inspection

• **Conceptual Issue on composite structure mainly civil one's**
  
  - Optimised design, no weight reduction foreseeable
Prediction, Defect detection, identification, location and sizing

- Fatigue Crack
- Plastic strain

Priority 2

- Corrosion:
  - Structural
  - Bacterial

Priority 1

On board recording

On site monitoring

Autonomous or energy slaved detection

Autonomous environmental parameters recording system

Autonomous or energy slaved environmental parameters recording and detection system (s)
Objectives:
Evaluation of in situ corrosion prediction detection, localisation and sizing sensors, and procedure for an Environmental Index

STANAG System
Corrosion detection and prediction through environmental parameters measurement

- BAES data logger
- ISD data logger

Sensors:
- Temperature,
- Humidity,
- Pressure,
- Sentinel,
- TOW (Time of wetness)
SHM – Conclusion

• Many sensors available at different TRL for many SHM application, most of them are commercialised
• Numerous laboratory studies and applications for mechanical testing monitoring but not wireless
• Many EC research and other governemental projects
• Several environnemental paramaters Data Loggers available for corrosion prediction
• No application softwares
• Data exploitation philosophy not settled down
• Airbus seems to slow down

Requirements:

• Sensor durability to be assessed
• Autononous and wireles systems to be developed
• *Data Transfer and exploitation to be validated (security issues : frequency bands availibility)*
• Physical models and simulation tools must be developed for inspection case design
Merci pour votre attention
Thank you for your attention