Implementation of SHM at Delta Air Lines

David Piotrowski
Senior Principal Engineer
Enabling Technologies
Delta TechOps
OUTLINE

• What is SHM?
• Why SHM?
• Timeline
• Near-term Applications
• Pieces of the Puzzle
  o Technical
  o Procedural
  o Financial
  o Regulatory
• Policy updates, Industry Committee work
• Philosophical change needed
• Future
What is SHM?

From AISC-SHM

• STRUCTURAL HEALTH MONITORING (SHM): The process of acquiring and analyzing data from on-board sensors to determine the health of a structure.

• "Inputs" to the SHM system are obtained from on board sensors that provide operational and/or damage monitoring. The "outputs" are information processed from this data that provide a health assessment of the aircraft structure, which lead to the highlighted benefits.

• ‘S-SHM is the act of using/running/reading out a SHM device at an interval set at a fixed schedule.’ Also known as Scheduled SHM

• A-SHM: ‘is any SHM technology which does not have a pre-determined interval at which mtc action must takes place, but instead relies on the system to inform mtc personnel that action must take place’. Also known as Automated SHM
Larger view – Health Management

Integrated Vehicular Health Mgmt (IVHM)/
Integrated Aircraft Health Mgmt (IAHM)

Structural Health Monitoring is generally recognized as an element of the Structural Health Management, which is an element of the Aircraft Health Management.

S = sensing
A = acquisition
T = transfer
A = analysis
A = action

SHM is a segment of overall IVHM

Courtesy: AISC-SHM, HM-1
SHM variations & contents

SHM has many variations of use cases
There are 3 fundamentally different concepts of AHM/SHM

- **Conventionally scheduled tasks making use of AHM/SHM equipment**
  - Go to the aircraft at scheduled occasions (fixed threshold / interval)
  - Run / read out / use equipment to determine the condition of the aircraft
  - Act if required (repair, replace)

- **Conventional tasks scheduled by smart usage parameters**
  - Monitor usage of the aircraft and determine time when action is required
  - Perform conventional task (lubrication, inspection, check, restoration, discard) at that time

- **Continuous monitoring of the structure/systems**
  - Continously collect, process and analyse data
  - Act when required (potentially never during the life of the aircraft)

 Courtesy: EASA
Examples of Sensor Technologies

- A large scope of sensing technologies:
  - CVM (Comparative Vacuum Sensors)
  - Acoustic Emission
  - Foil eddy current sensors
  - Acousto Ultrasonic
  - Fibre Bragg Gratings (FBG)
  - ...

Delta has used CVM, PZT sensors

Courtesy: Holger Speckmann
Maintenance Application

- Damages caused by corrosion
- Fatigue Cracks
- Inspection of Hidden areas without removal of installations
- At inconvenient Mtc visits

SHM used to avoid access requirements
Why SHM? Today’s Maintenance

- Let problems control you
  - $$$$$$$$$
  - Delays
  - Cancellations
  - Operational Disruptions
  - Poor customer service scores
  - Personnel in crisis mode

- Premature replacement
  - $$$$$
  - Waste of time
  - Personnel ‘busy’ work
  - Avoid some D&C, Disruptions
  - Better customer scores
Why SHM? How we will do Maintenance

• Intelligent Maintenance
  o Digital Twin
    ▪ Aircraft damage file (3D)
    ▪ Augmented reality
    ▪ Glasses/tablets
  o Machine learning algorithm
  o Neural networks
  o Only work what is needed
  o Personnel 99% efficient

• Data-driven, tail specific maintenance program
  o Condition Based Mtc
  o Unscheduled to scheduled
  o Monitoring
  o D&C, disruptions prevented
  o $$$$$$$$$$ Savings
  o Efficient use of resources
Why SHM? Industry trend

SHM fits nicely into this trend
History & Timeline: Delta SHM

- FAA Funding: CVM Lab Work (POD, contamination)
- Boeing NDT Manual publish
- Delta/NW CVM Durability trial
- Delta/NW CVM Durability trial end
- ‘In-service’ find AC CRJ
- FAA program for ‘guidance’ - B737 Center Wing Fittings
History & Timeline: Delta SHM

<table>
<thead>
<tr>
<th>Year</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>FAA Program: B737 Center Wing Fittings</td>
</tr>
<tr>
<td>2016</td>
<td>Boeing SB includes CVM option</td>
</tr>
<tr>
<td>2017</td>
<td>B757 Door Frames Install</td>
</tr>
<tr>
<td>2018</td>
<td>B737 APB Install</td>
</tr>
<tr>
<td>2019</td>
<td>Delta PZT Trial</td>
</tr>
<tr>
<td>2020</td>
<td>Gogo Wifi Antenna</td>
</tr>
</tbody>
</table>

- New technologies
- More applications
- Policy discussions
SHM panel today: “Where are the applications of SHM?”
737NG Wing Center Section Front Spar Fitting

**Boeing SB 737-57-1309:**
- Cracking between 21K-36K
- Visual/eddy current for cracking
- Optional Preventative mod after one-time inspection
- Mod requires fuel tank entry; inspection doesn’t
- Recommend inspection at next opp.
- Recommend all 10 fittings changed

737NG application selected for FAA program
737NG Center Wing Box, Shear Fitting
737NG Center Wing Box – Accumulating Successful Flight History

Aircraft Parked at Gate After Final Flight of the Day

Access to SLS Connectors Through Forward Baggage Compartment

Connecting SLS Leads to Monitor Sensors and Logging Inspection Completion at Aircraft Gate

FAA William J. Hughes Technical Center
This revision is sent to add a Comparative Vacuum Monitoring (CVM) inspection as an alternative inspection method for the front spar shear fitting. In addition, illustrations in figures are changed to show correct views, footnotes are added in fastener tables for clarification and footnotes in figures are changed to clarify sealing instructions.
Incorporation into B737 NDT Manual
Summing it up - FAA briefings

FAA Program

- FAA-SACO, FAA Transport Directorate reviewed
- FAA: SHM ok as ‘alternate inspection’, but on case-by-case basis
- ‘Local’, or ‘hot spot’
- Transition from ‘prototype’ to ‘mainstream’
- Proved the ability for airline/MRO to install sensors and adopt into Mtc Program
- Certification path identified = SB revision
- Valuable flight trails = Inspection occurs at gate, overnight
  - 6 years (~42 total years!)
  - >115,000 flight hours
  - >60,000 cycles accumulated
  - 166 inspection events
- Prior ‘environmental durability trail’ = sensors flew 2005-2012

All programs: ~100 years, >1.5M flight hours for CVM
Boeing B757 applications found!

BS 1640 and BS 1681 Frame Inspections Are Typically Accomplished Together

Galley, Lavatory covering inspection area
Boeing B757 application Frame 1640

757 Fus Section 46 - Body Station 1640 Frame Inspection

AD 2018-06-07
- SB 737-53A0108
  - Threshold: 20,000 flight cycles
  - Repeat Intervals 3,000 – 6,000 FC

CVM Installed on 3 aircraft
Boeing B757 application Frame 1681

757 Fus Section 46 - Body Station 1681 Frame Inspection

AD 2017-26-07
- SB 757-53A0100
  - Threshold: 31,000.
  - Repeat Intervals: HFEC
    ~3,200 FC Repeat Intervals

CVM sensors Installed on 3 aircraft
Boeing B737 application - APB

737 Fus Aft Pressure Bulkhead

- SB 737-53A1248
  - Threshold 25,000 FC
- Repeat Intervals
  - LFEC  1,200 FC
  - HFEC  3,800 FC
- Airworthiness Directive AD 2016-18-15
- Airplane Models: 737-600, 737-700, 737-700C, 737-800, 737-900

Aft Galley covering inspection area
Boeing B737 application - APB

• CVM Installation on 21 aircraft
  o External, 3rd party MRO providers
  o Language barrier

• AMOC in progress at Boeing

Installs have occurred – AMOC in progress
Acellent SMART Layer

**SHM system for 737**

Acellent

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**Data Acquisition and data analysis software platform**
- Connects to SMART Layer
- Controls diagnostic data collection
- Manages resulting data and multiple monitoring areas
- Processes data and provide quantified damage results

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**SMART Layer sensors**
- Integrated piezoelectric sensor network
- Ease of installation using flexible thin film technology - enables installation on complex aircraft structures
- Uses a network of sensors - entire area can be monitored not just discrete points
- Sensor protection and durable coatings to ensure longevity
- Connects to diagnostic unit

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Aft pressure bulkhead

**Onboard the aircraft**

**Offboard the aircraft**
B737 APB – Convenient routing
STC applications found!

- Wifi/SAT TV structural modifications
  - Panasonic
  - Gogo
  - Viasat
- Different approval path
- Instructions for continued Airworthiness (ICA)

STC ICAs can be onerous
Putting it all together:

What it takes to implement
Piece of the puzzle - Technical

- Probability of Detection
- Damage Tolerance
- Defects/Criticality knowledge
- Design applicable?
- Durability/Environmental
- Flammability
- Lightning strike protection (if applicable)
- Electromagnetic (EMI)
- EWIS – Electrical Wiring Interconnect System
- SFAR 88/ MIL-STD-810/ DO-254 / DO-178

Technical piece is often the ‘easy’ part
Comparative Vacuum Monitoring (CVM)

- Sensors with fine channels on the adhesive face - applies a vacuum to a thin film sensor with embedded galleries open to the surface
- Leakage path between the atmospheric and vacuum galleries producing a measurable change in the vacuum level
- Doesn’t require electrical excitation or couplant/contact
- Sensors ducted to convenient access point
- POD data accomplished; False calls quantified (low)
- Placed into Boeing NDT manual as ‘general’ procedure
CVM – Probability Of Detection

CVM - Quantified Probability of Crack Detection for a Range of Variables

Test Scenarios:

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Coating</th>
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</thead>
<tbody>
<tr>
<td>2024-T3</td>
<td>0.040”</td>
<td>bare</td>
</tr>
<tr>
<td>2024-T3</td>
<td>0.040”</td>
<td>primer</td>
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<td>2024-T3</td>
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<td>primer</td>
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<td>2024-T3</td>
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<tr>
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<td>0.100”</td>
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<td>primer</td>
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<tr>
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<td>0.071”</td>
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</tr>
<tr>
<td>7075-T6</td>
<td>0.100”</td>
<td>primer</td>
</tr>
</tbody>
</table>

Cumulative Distribution Function of Detectable Flaw Lengths (0.040” th. primer panels)

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Field Evaluation of CVM Sensors

**Environmental Durability Testing** - To assess the long-term viability of CVM sensors in an actual operating environment, 22 sensors were installed on the following civil aircraft for functional evaluation:

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Tail</th>
<th>Operator</th>
<th>Date</th>
<th># Sensors</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-9</td>
<td>9961</td>
<td>NWA</td>
<td>Feb 04</td>
<td>6 (remaining)</td>
<td>2 sensors removed by NWA</td>
</tr>
<tr>
<td>DC-9</td>
<td>9968</td>
<td>NWA</td>
<td>Apr 05</td>
<td>6</td>
<td>3 sites</td>
</tr>
<tr>
<td>B757</td>
<td>669</td>
<td>Delta</td>
<td>Apr 05</td>
<td>8</td>
<td>4 sites in empennage on stringers, frames &amp; near APB</td>
</tr>
<tr>
<td>B767</td>
<td>1811</td>
<td>Delta</td>
<td>Apr 05</td>
<td>6 (connected)</td>
<td>3 sites in empennage</td>
</tr>
</tbody>
</table>

CVM Sensors in DC-9 Tail

AC 1811 APB
Piece of the puzzle - Procedural

- Design with Damage Tolerance, defects (thresholds); Instructions for Cont’d Aw (ICA)
- Process for install
- Validation of system
- What ifs?
  - Sensor fail – Minimum Equipment list?
  - Indication – verify how?
- Training
- Process (monitor via active or passive)
- During manufacture vs in-service mod
- Manufacturing approvals
- SAE documents

Procedural piece can be tricky
SAE has many applicable documents

- ARP6275A - Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System
- ARP5987 - A Process for Utilizing Aerospace Propulsion Health Management Systems for Maintenance Credit
- AIR 6900 - Applicable Aircraft Integrated Vehicle Health Management (IVHM) Regulations, Policy, and Guidance
- ARP 6821 - Guidance for assessing the Damage Detection Capability of Structural Health Monitoring Systems
- AIR 6245 - Perspectives on Integrating Structural Health Monitoring Systems into Fixed-Wing Military Aircraft
- AIR6892 - Guidelines for Implementation of Structural Health Monitoring on Rotorcraft
- ARP 4754 - Development Assurance Level
- DO178 - Airborne Software Development Assurance
- D0-254 – Airborne Electronic Hardware
Piece of the puzzle - Financial

- **End-user Payback period**
  - Hard to access area
  - Not at convenient mtc visits
  - Short repetitive intervals

- **Fuel cost/weight**
- **Dual process likelihood?**
- **Creative business deals, Collaborations, etc.**
- **Prioritization of financial & personnel resource allocations**

It’s all about the $/€/£/¥
Piece of the puzzle - Regulatory

- Maintenance Steering Group (MSG-3) document
- A4A MPIG (Mtc Programs Industry Group)
  - AHM working group
- IMRPB (Int’l Mtc Review Board & Policy Board)
- Issue Papers 92, 180, 105
- SHM IP
- Advisory Circular 43-218
- Maintenance ‘Credits’
- ReMAP = Real-time Condition-Based Mtc for Adaptive Aircraft Planning ([https://h2020-remap.eu/](https://h2020-remap.eu/))

Regulators are key
Commercial Aviation Mtc Process

- 90% of scheduled tasks result in no findings

MSG-3 leads the entire regulatory process chain
Commercial Aviation Mtc Process

Entire industry involved: Operators, OEMs, Regulators
SHM – Next Evolution?

MSG-3 revisions in process; Time for MSG-4?
IP 180 proposes revising MSG-3 to include AHM
Regulatory Changes – Upcoming

AC 43-218 Operational authorization of integrated aircraft health management systems (IAHM)
Provides guidance for developing an operator’s IAHM program
Approved, waiting for review before publication

FAA Order 8900.1
Provides guidance for inspectors to approve IAHM-related tasks
Approved, waiting for publication

IP-180 – Aircraft Health Monitoring (AHM) Integration in MSG-3 Analysis
Provides guidance for design holders to apply IAHM to the MSG-3 analysis process as an alternate procedure, action, or task - Published April 2018, currently being revised

SHM IP
Includes guidance and requirements to applicant of one particular application
Draft copy received by AISC-SHM – pushing for generic publishing
More guidance is being written right now
OEM Timeline for Implementation of SHM

Near Term
- Replace inspection tasks with SHM to reduce maintenance burden
- Enable flexible maintenance intervals via operational monitoring using existing aircraft & ground capabilities
- Assess conditional events

Mid Term
- Integrated airplane-level solutions and conditional maintenance based on SHM information
- Enable SHM based optimized design and weight savings
- Certification of maintenance credit

Long Term
- Optimize design rules for integrated F&DT and maintenance philosophy based on SHM monitored structures
- Longer economical airframe utilization
### Introduction of Scheduled SHM into Mtx Programs

#### Challenges:

- Replacement of traditional structural inspections: POD (Detection Capability)
- MRB process adjustments: MSG-3 Revision 2009.1 and IP 105
- Changes on the Instructions for Continued Airworthiness:

```
<table>
<thead>
<tr>
<th>MRBR Task Number</th>
<th>Zones</th>
<th>Type Category</th>
<th>Title Description Note Access Panels</th>
<th>Applicability</th>
<th>Interval (I: Interval, T: Threshold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55-20-001-0407</td>
<td>337</td>
<td>SDI</td>
<td>ELEVATOR STRUCTURE - INTERNAL Special Detailed Inspection of Elevator Structure, LH/RH, by using a Borescope - Internal Side of Elevator.</td>
<td>ALL</td>
<td>T: 96 MO I: 96 MO</td>
</tr>
</tbody>
</table>
```
Are There Regulatory Roadblocks?

• No roadblocks for SHM introduction
  – Existing mindset presumes scheduled task-based approach
  – Design philosophy considers range of threats generally without regard to likelihood of occurrence
  – Lack of familiarity with SHM technologies may lead to unclear or inconsistent regulatory requirements levied on applicants

• Three primary aspects for certification
  – System installation/qualification using existing requirements
    ➢ Defining the declared application intent
    ➢ Determining the appropriate criticality
    ➢ Applying 25.1301, 25.1309 integrity requirements
  – Protocols to validate certification credit
  – Instructions for Continued Airworthiness using existing requirements
Are There Regulatory Roadblocks? (con’t)

- In order to exploit full potential of SHM
  - Allowance to fly with known defects
  - Flexibility in inspection thresholds / intervals
    - Not on case by case basis
    - Based on usage/fatigue or crack severity index
Challenge - adverse to change

No thanks!

We are too busy
Philosophical Change Required

- Philosophical change is needed to use SHM as part of a Condition Based Maintenance program.
  - “Find it, fix it” mentality must change
  - “Monitoring” vs “Management”

- Therefore, SHM will involve progressive step-changes in the future.

3 phases envisioned:

- Phase 1: S-SHM for ‘alternate inspection approvals’
  - “Hot spot monitoring”
  - Perform SHM reading at same scheduled interval (S-SHM)

- Phase 2: Blend of S-SHM and ‘predictive/prognostics’
  - Early warning system (Proactive mtc.)
  - Extension of intervals (escalation)

- Phase 3: ‘Condition based maintenance’
  - Philosophy shift to allow ‘monitoring’ or CBM; heavy OEM input
  - AD 2007-10-04 AMOC – Monitoring stop drilled holes.

Seismic philosophy change underway
Future Innovative Steps

- SHM with RFID tags
- Wireless Sensors, Systems
- Energy Harvesting
- More Active systems
- “Global” Systems
- Artificial Intelligence
- Integrated with other HM systems (OEM?)
- Using Health Status to Calculate the Value of Leased Aircraft/Engine/Component
Summary

• Delta has implemented several SHM applications
  o More coming, dependent upon business case
  o Approvals and AMOC in process, TBD

• Pieces of the Puzzle
  o Technical
  o Procedural
  o Financial
  o Regulatory

• Policy updates, Industry Committee work

• Philosophical change needed
  o Step changes envisioned
  o Data driven, tail specific maintenance program

• Lots of industry activity
  o IP 180/ 105/ MSG-3 revision/ AC 43-218/ SHM IP
  o AISC-SHM Reliability work