**AEROSPACE RECOMMENDED PRACTICE**

| ARP6461™ | REV. A |
|---|---|
| Issued 2013-09<br>Revised 2021-08<br><br>Superseding ARP6461 | |

# Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft

RATIONALE

The development of structural health monitoring (SHM) technologies to achieve vehicle health management objectives in aerospace applications is an activity that spans multiple engineering disciplines. It is also recognized that many stakeholders—i.e., regulatory agencies, airlines, original equipment manufacturers (OEM), academia and equipment suppliers—are crucial to the process of certifying viable SHM solutions. Thus, a common language (definitions), framework of SHM solution approaches, and recommended practices for reaching those solutions are needed to promote fruitful and efficient technology development. Revision A of this document provides updated guidance based on a Five-Year Review.



TABLE OF CONTENTS

# 1. SCOPE

This document is applicable to civil aerospace airframe structural applications where stakeholders are seeking guidance on the definition, development, and certification of structural health monitoring (SHM) technologies for aircraft health management applications.

Inputs to the structural health management are obtained from SHM equipment and/or from onboard sensors, delivering the detection and characterization of damage, load, or environmental parameters for operational and damage monitoring.

For the purpose of this document, SHM is defined as “the process of acquiring and analyzing data from on-board sensors to characterize the health of a structure.” The suite of on-board sensors could include any presently installed aircraft sensors, as well as new sensors to be defined in the future.

## 1.1 Purpose

The document has these major purposes:

- Provide guidance on the implementation of SHM in aircraft applications to assist developers in specifying the measurements, accuracy, reliability and other requirements of the system to be designed.
- Provide information on structural maintenance practices and provide guidance on how SHM can be incorporated within or as modifications to current maintenance and airworthiness documents.
- Standardize and harmonize worldwide understanding about SHM (including terminology).
- Provide basic requirements to guide SHM technology development.
- Recommend certification matters that are relevant to SHM.



## 1.2 Field of Application

This document may be applied by SHM stakeholders to assist with, among other things:

- Definition, development, maturation, design, and guidance on certification of SHM systems for application in civil fixed-wing aircraft. Note that guidance for military fixed-wing aircraft is found in AIR6245, while rotorcraft guidance is found in AIR6892.
- Modification of aircraft maintenance and aircraft structural health management to use and benefit from SHM systems.
- Improving maintenance practices by utilizing alternative tools to conventional NDI.
- Execution of scheduled and/or unscheduled maintenance tasks in a more time and cost-effective manner.

NOTE: Although guidance such as this may be crucial to successful implementation of an SHM system, use of this guidance alone cannot be assumed to constitute or ensure regulatory agency acceptance. Any regulatory accepted use to fulfill inspection requirements will require negotiation and agreement with the appropriate regulatory agency. This SAE document is not a regulatory document and neither the applicants nor the regulatory agency is compelled to follow them unless there is associated regulatory agency policy.

1.3 An Overview of This Document

1.3.1 General Approach

This document provides key definitions, guidelines, and examples that can assist civil stakeholders in the development, validation, verification, and certification of SHM systems. The approach adopted in developing the guidelines was to maintain harmony with existing applicable regulations, standards, and guidelines, and to augment them with specific interpretations or extensions pertaining to SHM, as necessary. Where existing definitions and processes were available from industry accepted publications, they have been adopted without modification; interpretations specific to SHM have been added for clarity. Additional definitions and processes have been collated or developed only where their equivalents did not clearly exist. In this way, consistency is maintained with existing regulations, standards, and industry-accepted practices. Applicable documents from which the SHM key guidelines and definitions were collated are listed in Section 2. This document does not replace any existing FARs, regulations, or certification requirements currently in existence.

1.3.2 Designing and Maintaining Airworthy Structures

Referring to FAA publications, Section 3 reviews the main airworthiness regulations for design and maintenance of structures. Equivalent EASA regulations can be extracted from the applicable documents presented in Section 2. As summarized in Figure 1, maintenance regulations and processes are introduced to overcome the threats to structural integrity, which can arise from the damaging effects of fatigue, environments, and accidents. Section 3 gives more details about these regulations and processes and briefly introduces SHM.

Having introduced SHM, Section 3 illustrates how SHM can assist in overcoming the threats to structural integrity using existing processes without violating relevant airworthiness regulations. Section 4 describes SHM as an improved means for maintaining structural integrity and classifies potential SHM-intended functions under two main headings: operational monitoring and damage detection. Operational monitoring functions maintain regular surveillance over the factors that can lead to or indicate fatigue damage (FD), environmental damage (ED), and/or accidental damage (AD). Damage detection functions directly detect FD, ED, and/or AD if they occur. Section 4 describes the outputs, potential benefits, and operational considerations of SHM. Section 4 also summarizes specifications for the use of SHM systems in aircraft maintenance that have been recommended and proposed by Airlines for America Maintenance Steering Group 3 (A4A MSG-3) in recent and pending document revisions (Revision 2009.1, Issue Paper 92, Issue Paper 105, Issue Paper 180), as well as regulatory guidance found in AC 43-218 and SHM IP.

Having described how SHM can assist in overcoming the threats to structural integrity and highlighted the A4A MSG-3 recommended specifications for SHM, the evolution phases of SHM are briefly discussed to identify the main processes that are recommended to approve/certify SHM systems.



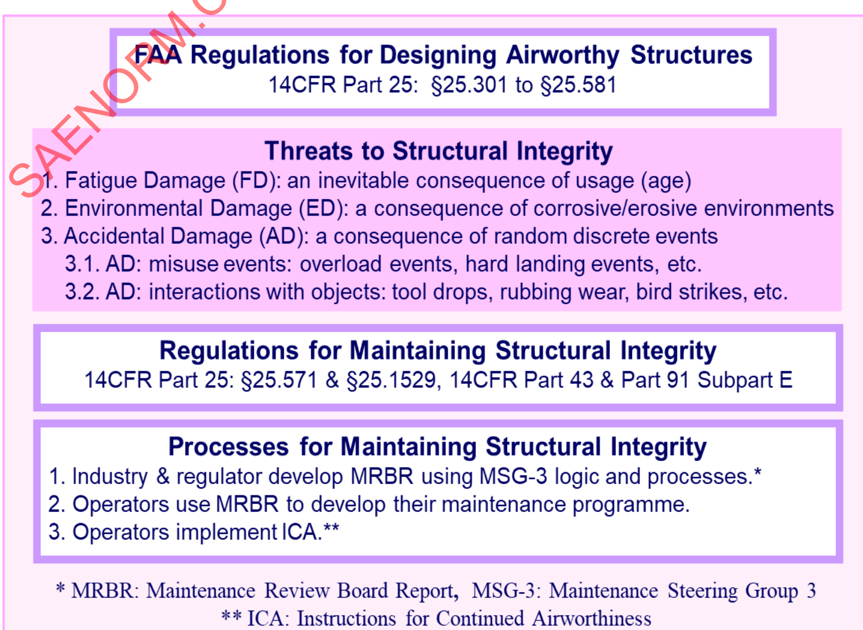


*Figure 1 - Designing and maintaining airworthy structures*

1.3.3 Evolution of Aircraft Products Including Structures and SHM Systems

Figure 2 illustrates the evolution phases of any aircraft product, which span maturation, development, production, installation/integration, certification, utilization, and maintenance. The evolution phases start with identifying intended functions that address emerging demands. The SHM technology maturation efforts are motivated by demands for improving maintenance practices, underwriting new aircraft materials/designs, and improving aircraft operational practices. Once suitable SHM technologies are identified, a development process will be followed that addresses architecture, requirements, test and validation, aircraft integration, and instructions for continued operation. Figure 2 identifies the sections of this document, by their numbers, that provide information about these activities.

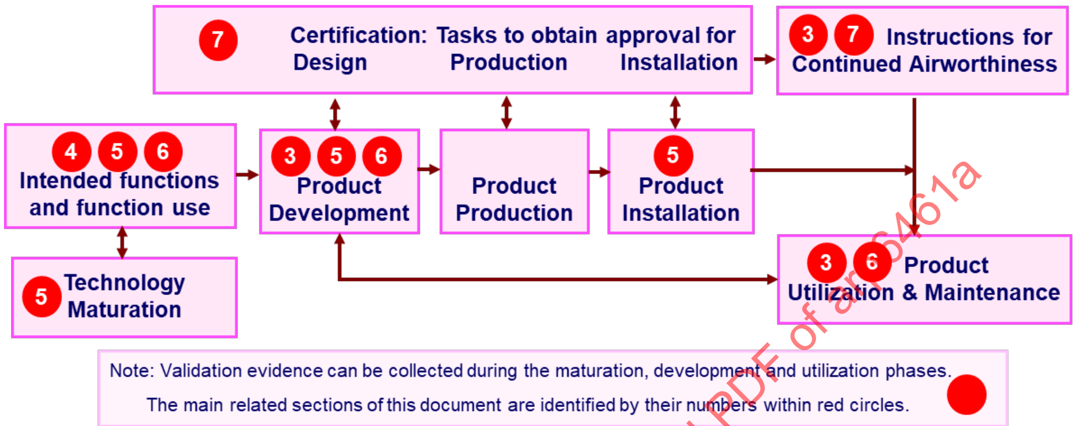


*Figure 2 - Evolution of aircraft products including SHM systems*

As indicated throughout this document, any SHM system uses data acquired by on-board sensors fitted in each individual aircraft to directly detect and/or monitor damage and to monitor the factors that can lead to or indicate damage. Other entities of an SHM system (for example, signal conditioning and information processing subsystems) can be located on-board the aircraft or within ground-based systems. Some or all of these entities may be designed specifically for SHM or can be shared entities from other pre-existing systems. Any given SHM-intended function may be realized by a variety of different system architectures.

1.3.4 Requirements, V&V, and Certification

Section 5 focuses on identifying SHM requirements. In this section, it is noted that the development of the system architecture and the allocation of requirements are tightly-coupled, iterative processes. The architectures of two SHM systems that provide the same intended function may have different design approaches, such as differences in: items shared with existing aircraft systems versus items designed specifically for SHM, ground-based items versus airborne items, similar airborne items installed into different aircraft location and, hence, exposed to different environmental conditions.

Section 6 presents typical methods used to validate and verify aircraft products and introduces interpretations and extensions specific to SHM systems. Section 6 recognizes that the rigor, and hence the assurance level, required for validation and verification depends on the chosen architecture and the consequence of the failure conditions of each SHM item on safe operations, if any. The more severe the consequence, the more rigor required. For SHM systems that have negligible effects on aircraft structures and systems, the validation and verification methods presented in Section 6 may not be required to support certification; such systems may be approved by a manufacturer qualified representative. However, SHM systems that have major effects can be approved only by the appropriate regulator after witnessing development, validation, and verification activities conducted with rigor proportionate to the consequence of SHM failure conditions.

For the purpose of this document, Section 7 considers certification as the processes required for obtaining approval from the appropriate Regulatory Authority (FAA, EASA, UK MOD, DOD, etc.) that the applicable airworthiness regulations, operating rules, and system requirements are met. Formal definition of certification taken from ARP4761 is presented in 2.3. The certification efforts involve the regulator, the product developer and the aircraft manufacturer along with any other stakeholders such as airlines and MROs. The certification efforts are initiated through an application made by the aircraft OEM, operator, or equipment vendor to the appropriate regulator, typically before the start of the product development phase; these efforts are performed in parallel to the other evolution phases and can overlap with the maturation phase. The outputs of successful certification phases include: design approval, production approval, installation approval, and Instructions for Continued Airworthiness (ICA). Section 7 presents more details about the certification phases, their outputs, and associated approval forms.

# 2. REFERENCES

## 2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific examption has been obtained.

### 2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.


AIR6245 Perspectives on Integrating Structural Health Monitoring Systems into Fixed-Wing Military Aircraft

ARP4754 Guidelines for Development of Civil Aircraft and Systems

ARP4761 Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

ARP5150 Safety Assessment of Transport Airplanes in Commercial Service

ARP5987 A Process for Utilizing Aerospace Propulsion Health Management Systems for Maintenance Credit

AIR6892 Structural Health Monitoring Considerations and Guidance Specific to Rotorcraft




### 2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.


14 CFR Part 21 Certification Procedures for Products and Parts

14 CFR Part 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes

14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes

14 CFR Part 26 Continued Airworthiness and Safety Improvements for Transport Category Airplanes

14 CFR Part 27 Airworthiness Standards: Normal Category Rotorcraft

14 CFR Part 29 Airworthiness Standards: Transport Category Rotorcraft

14 CFR Part 33 Airworthiness Standards: Aircraft Engines

| | |
|---|---|
| 14 CFR Part 35 | Airworthiness Standards: Propellers |
| 14 CFR Part 121 | Operating Requirements: Domestic, Flag, and Supplemental Operations |
| 14 CFR Part 135 | Operating Requirements: Commuter and On Demand Operations and Rules Governing Persons On Board Such Aircraft |
| AC 20-115 | Radio Technical Commission for Aeronautic, Inc. Document RTCA DO-178 |
| AC 20-107 | Composite Aircraft Structure |
| AC 20-152 | RTCA, Inc., Document RTCA DO-254, Design Assurance Guidance for Airborne Electronic Hardware |
| AC 20-156 | Aviation Data Bus Assurance |
| AC 25-571-1 | Damage Tolerance and Fatigue Evaluation of Structure |
| AC 25-19A | Certification Maintenance Requirements |
| AC 29-2C MG 15 | Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems |
| AC 43-218 | Operational Authorization of Integrated Aircraft Health Management Systems |
| AC 121-22 | Maintenance Review Board Report, Maintenance Type Board, and OEM/TCH Inspection EASA Publications |
| FAA CPI Guide | The FAA and Industry Guide to Product Certification |
| FAA Issue Paper | Comparative Vacuum Monitoring (CVM) for Damage Detection in Structure of Antenna Installations, Project Number: ODA-2499-01 |
| Order 8110.37E | Designated Engineering Representative (DER) Guidance Handbook |
| Order 8100.8D | Designee Management Handbook |

### 2.1.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

| | |
|---|---|
| CS-23 | Certification Specifications for Normal, Utility, Aerobatic, and Commuter Category Aeroplanes |
| CS-25 | Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes |
| EC 748/2012 | Annex Part 21: Certification of Aircraft and Related Products, Parts and Appliances, and of Design and Production Organizations |

2.1.4 Transport Canada Publications

Transport Canada documents are available from Transport Canada, Tower C, Place de Ville, 330 Sparks Street Ottawa, Ontario K1A 0N5, Tel: 1-800-305-2059, www.tc.gc.ca.

CARs 2012-1 Part I - General Provisions, Subpart 1 - Interpretation (CARs 101.01)

CARs 2012-1 Part V - Airworthiness, Regulations, Subpart 21 - Approval of the Type Design or a Change to the Type Design of an Aeronautical Product (CARs 521.01 to 521.456), Division IV - Changes to a Type Design (CARs 521.151 to 521.161)

AC 521-004 Changes to the Type Design of an Aeronautical Product

2.1.5 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

DO-178 Software Considerations in Airborne Systems and Equipment Certification

DO-200 Standards for Processing Aeronautical Data

DO-201 Industry Requirements for Aeronautical Information

DO-254 Design Assurance Guidance for Airborne Electronic Hardware

DO-278 Guidelines for Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) System Software Integrity Assurance

2.1.6 Airlines for America (A4A) Publications

Available from Airlines for America (A4A), 1301 Pennsylvania Avenue, NW, Suite 1100, Washington, DC 20004, Tel: 202-626-4000, www.airlines.org.

A4A MSG-3 Operator/Manufacturer Scheduled Maintenance Development

2.1.7 U.S. Government Publications

Copies of these documents are available online at https://quicksearch.dla.mil.

MIL-HDBK-1823 Nondestructive Evaluation System Reliability Assessment

MIL-STD-461 Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment

MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests

MIL-STD-1472 Design Criteria Standard: Human Engineering

CMH-17 Composite Materials Handbook 17 (Vol. 3 Chapter 12 Damage Tolerance)

2.1.8 ISO Publications

Copies of these documents are available online at http://webstore.ansi.org/.

ISO 5725 Accuracy (Trueness and Precision) of Measurement Methods and Results

2.1.9 Other Publications

ENV13005 Guide to the Expression of Uncertainty in Measurement

JAA JAR145 Aviation Maintenance Human Factors

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR4175 A Guide to the Development of a Ground Station for Engine Condition Monitoring

Azzam, H. and McFeat, J., "A Validation Methodology for Structural Health Monitoring," SAE Technical Paper 2011-01-2608, 2011, https://doi.org/10.4271/2011-01-2608.

2.2.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 39 Airworthiness Directives

14 CFR Part 43 Maintenance, Preventive Maintenance, Rebuilding and Alteration

14 CFR Part 91 General Operating and Flight Rules

AC 20-65 U.S. Airworthiness Certificates and Authorizations for Operation of Domestic and Foreign Aircraft

AC 20-77 Use of Manufacturers Maintenance Manuals

AC 20-107 Composite Aircraft Structure

AC 25.1309-1 System Design and Analysis

AC 25-1529-1 Instructions for Continued airworthiness of Structural Repairs on Transport Airplanes

AC 25.981-1 Fuel Tank Ignition Source Prevention Guideline

AC 500-002 Electromagnetic Compatibility Testing of Electrical and Electronic Equipment

AC 91-82 Fatigue Management Programs for In-Service Issues

Order 8110.54 Instructions for Continued Airworthiness Responsibilities, Requirements, and Contents

SFAR No. 88 Fuel Tank System Fault Tolerance Evaluation Requirements

Beard, S.J., Kumar, A., nad Ikegami, R., "Smart Patch System (SPS) for Condition Based Maintenance of Rotorcraft Structures," U.S. Department of Transportation, Federal Aviation Administration report for contract # DTFACT-05-C-00022, 2013.

Spencer, F., Borgonovi, G., Roach, D., Schurman, D., and Smith, R., "Reliability Assessment at Airline Inspection Facilities, Volume I: A Generic Protocol for Inspection Reliability Experiments," Dept. of Transportation Report, DOT/FAA/CT-92/12-I, March 1993.

2.2.3 ISO Publications

Copies of these documents are available online at http://webstore.ansi.org/.

| | |
|---|---|
| ISO 13374 | Condition Monitoring and Diagnostics of Machines - Data Processing, Communication and Presentation |

2.2.4 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

| | |
|---|---|
| AMC 20-29 | Composite Aircraft Structure |
| C.P006-01 | Continuing Airworthiness of Type Design Procedure |
| CM-SWCEH-001 | Development Assurance of Airborne Electronic Hardware |
| CM-SWCEH-002 | Software Aspects of Certification |
| CS-27 | Certification Specifications for Small Rotorcraft |
| CS-29 | Certification Specifications for Large Rotor |

2.2.5 NASA Publications

NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, 757-864-9658, Fax: 757-864-6500, http://ntrs.nasa.gov/.

| | |
|---|---|
| NASA/CR-2000-210643 | Analysis of Regulatory Guidance for Health Monitoring |

2.2.6 U.S. Government Publications

Copies of these documents are available online at https://quicksearch.dla.mil.

| | |
|---|---|
| ADS-79-HDBK | Aeronautical Design Standard Handbook for Condition Bases Maintenance Systems for U.S. Army Aircraft |
| MIL-HDBK-217 | Reliability Prediction of Electronic Equipment |
| MIL-HDBK-781 | Reliability Testing for Engineering Development, Qualification and Production |

2.2.7 Transport Canada Publications

Transport Canada documents are available from Transport Canada, Tower C, Place de Ville, 330 Sparks Street Ottawa, Ontario K1A 0N5, Tel: 1-800-305-2059, www.tc.gc.ca.

CARs Part V Airworthiness - Standards, Chapter 551 - Aircraft Equipment and Installation

CARs Part V Airworthiness - Regulations, Subpart 21 - Approval of the Type Design or a Change to the Type Design of an Aeronautical Product

CARs Part VI General Operating and Flight Rules

2.2.8 Other Publications

"Encyclopedia of Structural Health Monitoring," Boller, C., Chang, F.K., and Fujino, Y. (eds), John Wiley & Sons, Ltd., March 2009.

"Fault Tolerance Design and Redundancy Management Techniques," Advisory Group for Aerospace Research and Development Neuilly-Sur-Seine (France), Defense Technical Information Center, pp. 175, 1980.

Aldrin J.C., Medina, E., Santiago, J., Lindgren, E.A., Buynak, C.F., and Knopp, J.S., "Demonstration Study for Reliability Assessment of SHM Systems incorporating Model-assisted Probability of Detection Approach," Proceedings of the 31st Review of Progress in Quantitative Nondestructive Evaluation, AIP Press, p1543, 2012.

Aldrin, J.C., Medina, E.A., Lindgren, E.A., Buynak, C.F., and Knopp, J.S., "Protocol for Reliability Assessment of Structural health Monitoring Systems Incorporating Model-assisted Probability of Detection (MAPOD) Approach," Proceedings of the 8th International Workshop on Structural Health Monitoring, DEStech Publications, Inc., p2452, 2011.

Azzam, H., Gill, L., Beaven, F., and Wallace M., "A Route for Qualifying/Certifying an Affordable Structural Prognostic Health Management (SPHM) System," IEEE Aerospace Conference Proceedings, March 2004.

Beral, B. and Speckman, H., "Structural Health Monitoring for Aircraft Structures: A Challenge for System Developers and Aircraft Manufacturers," 4th International Workshop on Structural Health Monitoring, September 2003.

Berens, A.P., "NDE Reliability Data Analysis," Metals Handbook, Volume 17, 9th Edition: Nondestructive Evaluation and Quality Control, 1988.

Berens, Hovey, Donahue, and Craport, "User's Manual for Probability of Detection," University of Dayton Research Institute, UDR-TR-88-12, January 1988.

Brausch J. and Steffes, G., "Demonstration, Qualification and Airworthiness Certification of Structural Damage Sensing Systems for Air Force Applications," Air Force Research Lab report, Wright-Paterson AFB, unlimited distribution, August 2012.

Foote, P., McFeat, J., Heimes, F., Haugse, E., Duke A., Hochmann D., and Gordon, G., "Structural Health Monitoring Road Mapping Process," 2006, pgs. 68, Aerospace Vehicle Systems Institute.

Gordon, G. and Boller, C., "Commercial Fixed Wing Aircraft," in Encyclopedia of Structural Health Monitoring, Boller, C., Chang, F.K., and Fujino, Y. (eds), John Wiley & Sons Ltd., Chichester, UK, pp 1695-1710, 2009.

Kessler, S.S., Brotherton, T., and Gordon, G.A., "Certifying a Structural Health Monitoring System," Ch. 11 in System Health Management: with Aerospace Applications, Stephen B. Johnson, et al., eds. John Wiley & Sons Ltd., Chichester, UK, pp. 185-195, 2011.

Kumar, A., Zhang, D.C., Li, F., Beard, S.J., Chung, H., Pollock, P., Lee, S.J., Ikegami, R., Bordick, N., Hodges, C., and Jodon, J., "OH-58D Tail Boom Crack Detection System," Proceedings of Airworthiness, Condition Based Maintenance (CBM), and Health and Usage Monitoring (HUMS), February 11-13, 2013.

Lindgren, E.A. and Buynak, C.F., "The Need and Requirements for Validating Damage Detection Capability," Proceedings of the 8th International Workshop on Structural Health Monitoring, DEStech Publications, Inc., p2444, 2011.

MIMOSA OSA-CBM UML Specification 3.3.0, http://www.mimosa.org/?q=resources/specs/osa-cbm-330.

Roach, D. and Rackow, K., "Health Monitoring of Aircraft Structures Using Distributed Sensor Systems," DoD/NASA/FAA Aging Aircraft Conference, March 2006.

Roach, D., "Use of Distributed Sensor Systems to Monitor Structural Integrity in Real-Time," Quality, Reliability, and Maintenance in Engineering, Professional Engineering Publishing Ltd., Oxford, UK, 2004.

## 2.3 Definitions

AUTOMATED SHM (A-SHM): Automated SHM is any SHM technology which does not have a pre-determined interval at which maintenance action must takes place, but instead relies on the system to inform maintenance personnel that action must take place. (MSG-3)

AIRWORTHINESS: The condition of an aircraft, aircraft system, or component in which it operates in a safe manner to accomplish its intended function. (ARP4754)

APPROVAL: The act of formal sanction of an implementation by a certification authority. (ARP4754)

ASSURANCE: The planned and systematic actions necessary to provide adequate confidence and evidence that a product or process satisfies given requirements. (RTCA DO-178)

CERTIFICATION: The legal recognition that a product, service, organization, or person complies with the applicable requirements. Such certification comprises the activity of technically checking the product, service, organization, or person, and the formal recognition of compliance with the applicable requirements by issue of a certificate, license, approval, or other document as required by national laws and procedures. (ARP4754).

CERTIFICATION AUTHORITY: Organization or person responsible for granting approval in accordance with applicable regulations. (ARP4754)

CONDITION-BASED MAINTENANCE: Performing maintenance based on need (i.e., based on the condition or health of a component or system rather than on a periodic or scheduled basis).

CONDITION MONITORING: The process of observing the state of an asset in order to provide data, which can be used to determine a maintenance need. The observations can be continuous or intermittent.

CRITICALITY: Indication of the hazard level associated with a function, hardware, software, etc., considering abnormal behavior (of this function, hardware, software, etc.) alone, in combination, or in combination with external events. (ARP4761)

DAMAGE MONITORING: Any direct measurement methods that allow the detection of damages in the structure.

DAMAGE TOLERANCE: The attribute of the structure that permits it to retain its required residual strength for a period of use after the structure has sustained a given level of fatigue, corrosion, or accidental or discrete source damage. (AC 25-571-1)

FAILURE CONDITION: A condition caused or contributed to by one or more failures or errors that have either a direct or consequential effect on the airplane, its occupants, and/or other persons. In identifying failure conditions, the flight phase, relevant adverse operational or environmental conditions, and external events should be considered. (AC 25-19A)

FUNCTIONAL HAZARD ASSESSMENT: A systematic, comprehensive examination of functions to identify and classify failure conditions of those functions according to their severity. (ARP4754)

INDEPENDENCE: (1) A concept that minimizes the likelihood of common mode errors and cascade failures between aircraft/system functions or items. (2) Separation of responsibilities that assures the accomplishment of objective evaluation (e.g., validation activities not performed solely by the developer of the requirement of a system or item). (ARP4754)

INSTRUCTIONS FOR CONTINUED AIRWORTHINESS (ICA): Documentation that sets forth instructions and requirements for the maintenance that is essential to the continued airworthiness of an aircraft, engine, or propeller. (AC 25-571-1)

INTEGRITY: (1) Attribute of a system or an item indicating that it can be relied upon to work correctly on demand. (ARP4751) (2) Structural integrity is a performance characteristic which is applied to a component, a single structure, or a structure consisting of different components. Structural integrity assures that the construction will perform its designed function, during reasonable use, for as long as the designed life of the structure. Items are constructed with structural integrity to ensure that catastrophic failure does not occur, which can result in injuries, severe damage, death, or monetary losses.

PRELIMINARY SYSTEM SAFETY ASSESSMENT: A systematic evaluation of a proposed system architecture and its implementation, based on the functional hazard assessment and failure condition classification, to determine safety requirements for systems and items. (ARP4754)

OPERATIONAL MONITORING: Any indirect measurement methods that can contribute to the evaluation of structure's condition or utility.

PRODUCT: (1) Hardware, software, item, or system generated in response to a defined set of requirements. (ARP4754) (2) Aircraft, aircraft engines, propellers, as well as appliances and components or parts. (FAA CPI Guide)

QUALIFICATION: The processes of verifying that a product (system, hardware, and software) complies with a specified set of performance and airworthiness requirements.

SCHEDULED SHM (S-SHM): To use/run/read out a SHM device at an interval set at a fixed schedule. (MSG-3)

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

SYSTEM SAFETY ASSESSMENT: A systematic, comprehensive evaluation of the implemented system to show that the relevant safety requirements are met. (ARP4754)

VALIDATION: The determination that the requirements for a product are correct and complete (e.g., "Are we building the right aircraft/system/function/item?"). (ARP4754)

VERIFICATION: The evaluation of an implementation of requirements to determine that they have been met (e.g., "Did we build the aircraft/system/function/item right?"). (ARP4754)



## 2.4 Acronyms

| | |
|---|---|
| A4A | Airlines for America, formerly known as Air Transport Association of America, Inc. (ATA) |
| AC | Advisory Circular (FAA) or Airworthiness Certificate |
| ACO | Aircraft Certification Office |
| AD | Accidental Damage |
| AISC-SHM | SAE Aerospace Industry Steering Committee for Structural Health Monitoring |
| AL | Assurance Level |
| AMM | Aircraft Maintenance Manual |
| ARP | Aerospace Recommended Practice (SAE) |
| A-SHM | Automated SHM |
| CAR | Canadian Aviation Regulations |
| CCA | Common Cause Analysis |

| | |
|---|---|
| CFR | Code of Federal Regulations |
| COTS | Commercial Off-the-Shelf |
| CVM | Comparative Vacuum Monitoring |
| DAL | Development Assurance Level |
| DAR | Designated Airworthiness Representative |
| DER | Designated Engineering Representative |
| DET | Detailed Inspection |
| DoD | Department of Defense |
| EASA | European Aviation Safety Authority |
| EC | European Commission |
| ED | Environmental Damage |
| EMI | Electromagnetic Interference |
| EWIS | Electrical Wiring Interconnection System |
| FAA | Federal Aviation Administration |
| FAR | Federal Aviation Regulations |
| FBG | Fiber Bragg Gratings |
| FD | Fatigue Damage |
| FHA | Functional Hazard Assessment |
| FMEA | Failure Modes and Effects Analysis |
| GAMA | General Aviation Manufacturer's Association |
| GVI | General Visual Inspection |
| HUMS | Health and Usage Monitoring System |
| ICA | Instructions for Continued Airworthiness |
| IEEE | Institute of Electrical and Electronics Engineers, Inc. |
| IMRBPB | International Maintenance Review Board Policy Board |
| IP | Issue Paper |
| ISO | International Organization for Standardization |
| JAR | Joint Aviation Requirements |
| LOV | Limit of Validity |
| LRU | Line Replaceable Unit |

| | |
|---|---|
| MIL-HDBK | Military Handbook |
| MPIG | Maintenance Programs Industry Group (A4A) |
| MRB | Maintenance Review Board |
| MRBR | Maintenance Review Board Report |
| MRO | Maintenance, Repair, Overhaul (facility or company) |
| MSG-3 | Maintenance Steering Group 3 |
| MTBF | Mean Time Between Failures |
| NDI | Non-Destructive Inspection |
| NDT | Non-Destructive Testing |
| OEM | Original Equipment Manufacturer |
| OM | Operational Monitoring |
| PMA | Parts Manufacturing Approval |
| POD | Probability of Detection |
| PSCP | Project Specific Certification Plan |
| PSP | Partnership for Safety Plan |
| PSSA | Preliminary System Safety Assessment |
| PZT | Lead Zirconate Titanate |
| RTCA | RTCA, Inc. |
| SDI | Special Detailed Inspection |
| SHM IP | Structural Health Monitoring Issue Paper |
| SHM | Structural Health Monitoring |
| SSA | System Safety Assessment |
| S-SHM | Scheduled SHM |
| STC | Supplemental Type Certificate |
| TC | Transport Canada, Type Certificate (context dependent) |
| TCH | Type Certificate Holder |
| TL | Technology Level |
| TRL | Technology Readiness Level |
| TSO | Technical Standard Order |
| TSOA | Technical Standard Order Authorization |

UK MOD United Kingdom Ministry of Defense

USAF United States Air Force

XM Exceedance Monitoring

# 3. INTRODUCTION TO AIRCRAFT STRUCTURES DESIGN AND MAINTENANCE

This section introduces fundamental principles and references of aircraft structures design and maintenance. The understanding of these principles allows identifying opportunities, challenges, and benefits for structural health monitoring systems. The references will introduce key regulatory and recommended practices material associated with structures design and maintenance to consider when designing, developing, and certifying structural health monitoring systems.

## 3.1 Structures Design Principles

As a general principle, the aircraft structures are designed to carry all applicable loads and withstand all foreseeable conditions safely during its design service goal.

Certification requirements related to structural design for transport category airplanes is Part 25 - Airworthiness Standards within Title 14 of the Federal Aviation Administration in United States. The Electronic Code of Federal Regulations can be consulted for all details. Similar regulations are applicable for other aircraft categories and in other jurisdictions.

Subpart C (section § 25.301-§ 25.581) describes the different loads and conditions to consider in the design of structures. Maneuvers, gusts, pressurization, landing and lightning strike are few examples.

The section § 25.571 establishes the need for structural inspections to be included in the airworthiness limitations part of section § 25.1529 to be introduced later in this section.

Advisory Circular 25.571-1D provides guidance for compliance with the requirements for damage-tolerance and fatigue evaluation.

Damage tolerance is a property of a structure relating to its ability to withstand defects safely until detection and repair. The key steps of damage tolerance evaluation are introduced below along with additional notes relevant in the context of SHM.

a. Identification of the principal structural elements (PSE) that are considered essential in maintaining the overall structural integrity of the airplane.

   Examples are integrally stiffened plates, control surfaces, principal splices, and door frames. More than 200 PSEs are usually identified on a commercial aircraft.

b. Assessment of the extent of damage in terms of: (1) detectability with the given inspection techniques, (2) estimation of damage extent (e.g., crack size), (3) residual-strength capabilities, and (4) likely damage-extension rate.

   A SHM technology capable of reliably detecting damage of a specific nature and size over a specific line, area or volume is a candidate alternative to conventional non-destructive evaluation such as visual, eddy current, ultrasonic, and X-ray inspection methods.

c. Identification and minimization of inaccessible areas for inspection.

   The use of SHM technology for inspection of inaccessible areas may yield a range of structural benefits, including part count reduction, the potential for weight savings, and reduction of maintenance manpower to disassemble, inspect, and reassemble the inaccessible areas.

d. Fatigue test.

   The full-scale fatigue testing offers the opportunity to test the durability of the SHM installation subjected to representative loading conditions of the structure.

e. Identification of locations for damage-tolerance evaluation by determining the general damage locations and the critical damage areas.

A good understanding of the damage scenario is critical in the development of an SHM solution that will eventually meet the inspection requirements. Nonetheless, in-service experience has demonstrated that this analysis cannot anticipate all damage. Currently, inspectors have the flexibility to adjust quickly to new inspection instructions. Currently, most SHM systems do not afford this type of flexibility and hence is a potential limitation.

f. Damage-tolerance analysis supported by test evidences.

The ground testing campaign also offer the opportunity to demonstrate detection reliability of SHM technologies, particularly when artificial damage is introduced to initiate crack and characterize propagation rate.

g. Inspections or other procedures, as necessary, to prevent catastrophic failure from accidental, environmental, or fatigue damage.

Every aircraft type has specific inspection manuals describing the inspection methods approved by the OEM (e.g., visual, eddy current, ultrasonic, X-ray). There is already a documented example of a SHM technology that has been introduced in an inspection manual as accepted method by an OEM. Nonetheless, to date no inspection procedures were reported to offer this method.

h. Calculation of threshold for inspections.

Calculation of threshold for inspections is based on fatigue analysis and tests or slow-crack-growth analyses and tests. Generally, inspection thresholds are defined in terms of flight count, flight hour, or calendar days. SHM system for operational monitoring assesses parameters associated with the loads and conditions experienced in-service in order to further adjust inspection program rather than relying on past experience and projected utilization. This may yield in a lighter maintenance program for some operators. Additionally, the SHM system can influence the operation of the aircraft to reduce maintenance cost and optimize maintenance scheduling.

Figure 3 illustrates how the structural strength is maintained by damage tolerance for structure having slow-crack growth and no growth case. Limit load is defined as the maximum loads to be expected in service and the ultimate loads as the limit loads multiplied by prescribed factors of safety.



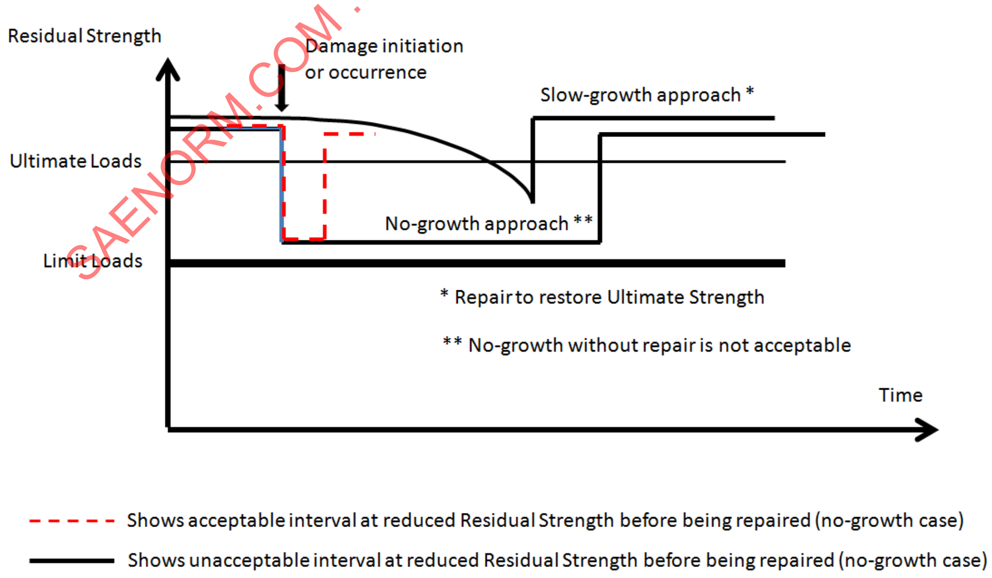


***Figure 3 - Damage tolerant structural life***

Damage tolerance evaluation § 25.571(b) is not required if it is considered impractical to apply to a specific structure. A classic example is the landing gear. In this case, the structure must comply to § 25.571(c). In this case, analyses supported by test evidence are required to demonstrate low probability of cracks for the service life of the structure, with the application of adequate safety factors (scatter factor). An SHM system for operational monitoring may be used to extend the service life of the structure in the case that the load spectrum experienced in-service is less severe than assumed in design.

More recently, section § 26.21 defines the requirement to establish a limit of validity (LOV) of the engineering data that supports the structural maintenance program. The LOV, in effect, is the operational life of the airplane consistent with evaluations accomplished and maintenance actions established to prevent widespread fatigue damages. The initial LOV defined during the certification process can be extended by additional analyses and/or tests. It is foreseen that SHM system for operational monitoring may also play a role in defining and extending the LOV.

## 3.2 Current Structures Maintenance Principles

### 3.2.1 A4A MSG-3 Document

The Airlines for America (A4A) MSG-3 Document is a result of combining more than 50 years of aircraft manufacturers, airlines, and regulatory authorities experience to create a minimum list of scheduled maintenance tasks for aircraft models under a given type certificate.

Through logical decision processes, A4A MSG-3 guides the development of scheduled maintenance programs with more effective tasks and intervals than the ones that would be generated directly from the engineering groups responsible for the aircraft design and certification.

The first version of this document was named Handbook MSG-1, "Maintenance Evaluation and Program Development," and concluded in July 1968. It was oriented only towards the Boeing 747 aircraft design and certification characteristics and therefore, it was necessary later to rewrite parts of its contents in order to turn it into a document that could be used by other aircraft types. The new version of the document was entitled MSG-2, "Airline/Manufacturer Maintenance Program Planning Document." It was used to develop scheduled maintenance programs for aircraft in the 1970s.

Around 10 years later, A4A airlines decided that a revision to existing MSG-2 procedures was necessary and with major participation of U.S. and European regulatory authorities and airlines as well as the U.S. Navy the MSG-3 document was developed. After the creation of the original A4A MSG-3, this document was revised several times (to be precise, nine times up to June 2012), in order to keep it up-to-date to the new regulations and maintenance processes as well as to clarify its contents. It was in the revision 2009.1 that the A4A MSG-3 document included for the first time SHM and scheduled SHM (S-SHM) concepts.

### 3.2.2 FAA AC 121-22, "Maintenance Review Board Procedures"

Understanding of the MSG-3 methodology is not sufficient for the approval of a maintenance program by a regulatory authority. An acceptable process is to coordinate the work of different groups with representatives from aircraft manufacturers, airlines and regulatory authorities. All these participants have distinct but complementary experiences on how to evaluate a given aircraft type, the model design documentation, and how to use their individual personal experience to reach agreements on what are the most applicable and effective maintenance tasks are and how to record them in an approved document.

Advisory circular (AC) 121-22 provides guidelines for what was mentioned above. Although it was developed by U.S. Federal Aviation Administration, it was adopted universally as a reference that may be used by industry during its development and revision of the initial minimum scheduled maintenance/inspection requirements for derivative or newly type-certificated transport category aircraft and power plants. These requirements constitute the Maintenance Review Board Report (MRBR) and after approval by the regulatory authorities, become a base or framework around which each airline develops its own individual maintenance program.

AC 121-22 provides a fairly detailed explanation about the process necessary to develop and approve an MRB Report, including roles and responsibilities of each group involved in this effort (Working Groups, Industry Steering Committee, etc.), and information about the MRBR format and contents.

As indicated in this AC, a maintenance review board report (MRBR) is generated as an expeditious means of complying in part with the maintenance instruction requirements of Appendix H to Title 14 of the Code of Federal Regulations (14 CFR) part 25. It is a means, in part, of developing instructions for continued airworthiness, as required by § 25.1529. Additional related regulations for this AC are: Title 14 of the Code of Federal Regulations parts 21, 23, 25, 27, 29, 33, 35, 121, 135; ss 21.50, 23.1529, 25.571, 25.1309, 27.1529, 29.1529, 33.4, 35.4, 121.25, 121.45, and 135.11.

3.2.3 Other Instructions for Continued Airworthiness

As mentioned before, the development and approval of a MRBR is necessary but not sufficient for an OEM to comply with requirements of Appendix H to 14 CFR part 25, "Instructions for Continued Airworthiness."

The complete set of instructions for continued airworthiness is listed below. ICAs, like MRBR, may be affected by the introduction of maintenance tasks based on SHM technologies:

- Airplane maintenance manual or section:
    - Includes an explanation of the airplane's features and data to the extent necessary for maintenance or preventive maintenance.
    - A description of the airplane and its systems and installations including its engines, propellers, and appliances.
    - Basic control and operation information describing how the airplane components and systems are controlled and how they operate, including any special procedures and limitations that apply.
    - Servicing information that covers details regarding servicing points, capacities of tanks, reservoirs, types of fluids to be used, pressures applicable to the various systems, location of access panels for inspection and servicing, locations of lubrication points, lubricants to be used, equipment required for servicing, tow instructions and limitations, mooring, jacking, and leveling information.
- Maintenance instructions:
    - Scheduling information for each part of the airplane and its engines, auxiliary power units, propellers, accessories, instruments, and equipment that provides the recommended periods at which they should be cleaned, inspected, adjusted, tested, and lubricated, and the degree of inspection, the applicable wear tolerances, and work recommended at these periods (normally covered by the MRBR).
    - Information describing the order and method of removing and replacing products and parts with any necessary precautions to be taken.
- Diagrams of structural access plates and information needed to gain access for inspections when access plates are not provided.
- Details for the application of special inspection techniques including radiographic and ultrasonic testing where such processes are specified.
- Information needed to apply protective treatments to the structure after inspection.
- All data relative to structural fasteners such as identification, discard recommendations, and torque values.
- A list of special tools needed.

- A section titled “Airworthiness Limitations.” This section must set forth:
    - The section must include a list of all mandatory maintenance tasks (e.g., any mandatory inspection/replacement/modification requirements) and should include all approved information, including limits, configurations, algorithms, and procedures that are required to perform the mandatory tasks by any designated maintainer independent of the OEM; for FAA regulations, refer to 14 CFR § 25.571 and 14 CFR § 25.981.
- Instructions for continued airworthiness applicable to EWIS as defined by 14 CFR § 25.1701.

### 3.3 Summary

Section 3 offers a brief summary of the regulatory requirements and recommended practices associated with the design and maintenance of aircraft structures. SHM is intended to impact maintenance and operations but does not replace the primary function of the structure. The essential aspects of structural health monitoring systems presented in the following sections are intended to be fully consistent with current regulation and the recommended practices for maintaining structural airworthiness.

## 4. ESSENTIAL ASPECTS OF STRUCTURAL HEALTH MONITORING

This section introduces the essential aspects of structural health monitoring that are generally recognized by the industry and the scientific community. These aspects cover the description of SHM, the motivations, architecture, and operational considerations. The material is presented for guidance purposes and should evolve as the technologies and the applications develop.

### 4.1 Description

SHM is the process of acquiring and analyzing data from on-board sensors to determine the health of a structure.

### 4.2 Motivations

The motivations for the use of SHM systems on aircraft structures are numerous. Presently the main motivations are for economic benefits through reduced downtime, labor, or repair cost. In the long term, SHM systems may also contribute to higher standards of safety and more efficient aircraft designs.

Before aiming for safety credits, the current demanding requirements for airworthiness need to be met. These requirements are introduced in the following section. A thorough understanding of the structure and its requirements can yield to identification of opportunities and benefits for SHM.

The main economic motivations for the use of SHM systems are to (a) reduce inspection time and cost, (b) improve repair planning, (c) increase, optimize, or customize inspection intervals, (d) extend the economic life of the structure, and (e) enable new design principles and maintenance concepts.

a. Reducing inspection time and cost can be achieved by using more automated equipment and reducing indirect tasks such as gaining access, preparing surface, or reporting.

b. Improving repair planning can be achieved by measuring conditions or parameters that are associated with potential structural defects prior to inspection. This information can be used to optimize maintenance planning and flight operation. An example is the detection of conditions that can lead to corrosion in a specific structural zone. This information can lead to conduct an inspection earlier than required by the maintenance manual. The benefit can be to perform a minor repair earlier (e.g., removing light damage and reapply coating) instead of a more significant repair later (e.g., replacing a part).

c. Inspection interval can be increased, optimized, or customized in the instances that the aircraft is being operated in conditions less severe than the structure was designed for. An example is the pressure cabin which may not reach cruise condition in the instance of short flights.

d. More common in military aviation, safe-life structures usage can be monitored to evaluate the remaining life more precisely than baseline parameters (i.e., flight count, flight hour, or calendar day). This improvement in precision can yield in the extension of the life of the structures when a structure is subjected to loads or conditions less severe than expected in design. The recent introduction of the limit of validity within the CFR Part 25 section § 26.21 may also offer opportunity for similar implementation within civil aviation.

e. The design and the maintenance procedures of a structure are the result of an optimization of multiple parameters such as loads, material, geometry, weight, manufacturability, maintainability and all associated costs. SHM systems are not expected to have direct impact on each of them individually, but may yield in a better optimization of structures (e.g., weight, cost, etc.). This benefit is expected in longer term when reliability and durability of SHM technologies will be well established.

## 4.3 General Structural Health Monitoring Architecture

As presented in Figure 4, structural health monitoring is generally recognized as an element of the structural health management, which is an element of the aircraft health management.

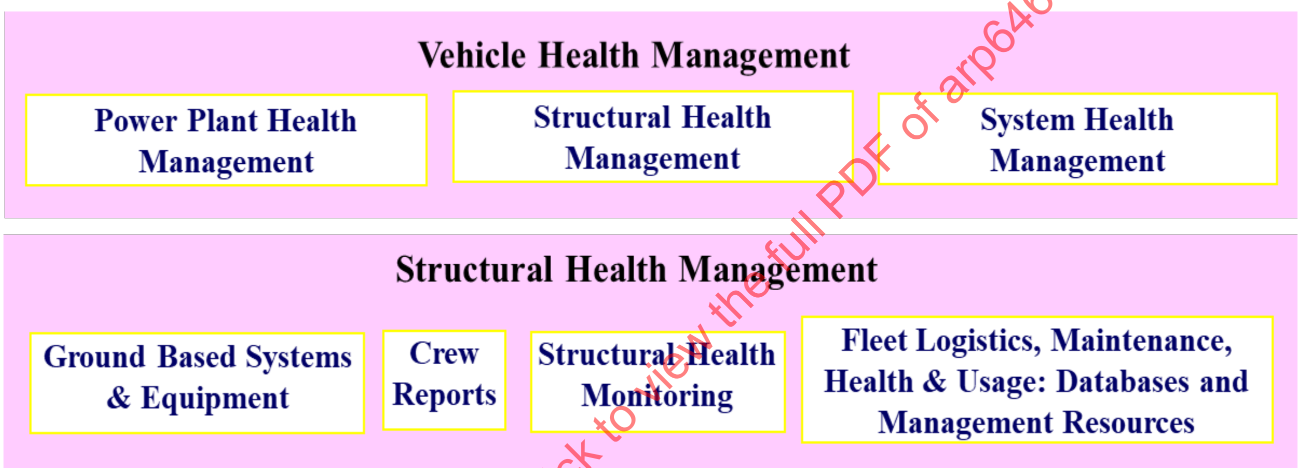


***Figure 4 - Structural health monitoring as a part of aircraft health management***

Structural health management intended functions use outputs from different sources as described in Figure 4. The "outputs" are information processed from this data that provide a health assessment of the aircraft structure, which lead to the highlighted benefits.

This SAE Recommended Practice section outlines the means to deliver inputs such that benefits can be derived. Figure 5 illustrates the main functional elements of structural health monitoring. Inputs to the structural health management are obtained from SHM equipment and/or from onboard sensors, delivering the detection, characterization of damage, load or environmental parameters for operational and damage monitoring.

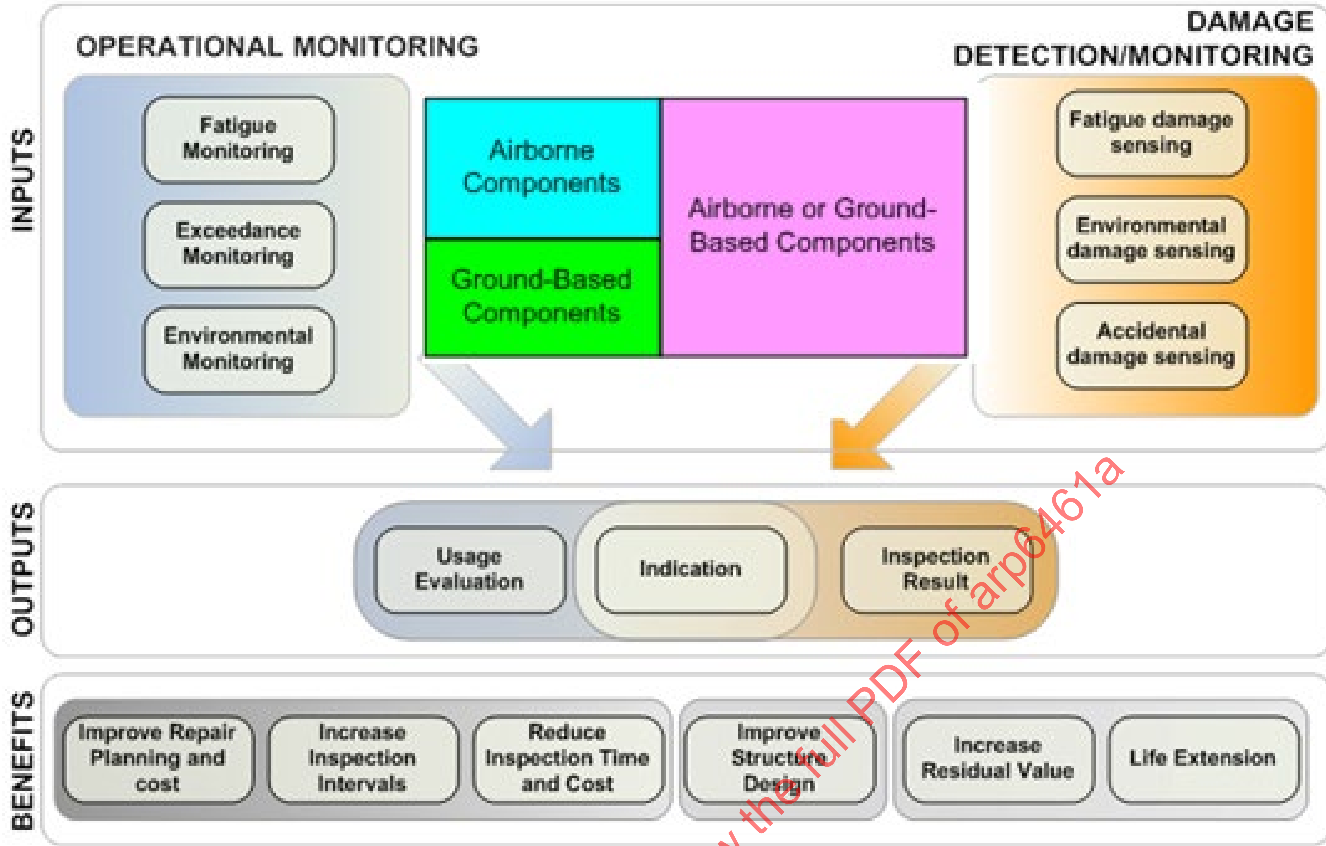


*Figure 5 - SHM-intended functions and benefits*



4.3.1 Inputs

Inputs can take many forms but all come from sensors installed onboard the aircraft. These sensors can be used specifically for SHM or be used primarily for other aircraft systems (e.g., accelerometers, altimeter, and flap position). The following describe the sub-function and benefit presented in Figure 5.

4.3.1.1 Operational Monitoring

Operational monitoring (OM) groups all indirect measurement methods that can contribute to the evaluation of structures condition or utilization. OM parameters can be derived from the damage tolerance and fatigue evaluation of structure. The output of OM can be an advisory indication or the structure usage evaluation. The advisory indication can report abnormal operating conditions that are usually reported by the flight or ground crew. The usage evaluation can lead to modify inspection intervals as a function of aircraft use.

i. Fatigue monitoring:

Fatigue monitoring (FM) evaluates structural fatigue based on any fatigue related parameters (e.g., flight parameters or strain measurements). FM can be applied at part, assembly or aircraft level. Output from FM is the structure usage evaluation or the necessary data required to conduct this evaluation. FM can contribute to increasing the inspection interval when load spectra in-service are less severe than the design spectra.

ii. Exceedance monitoring:

Exceedance monitoring (XM) identifies instances when loads in-service exceed the design spectra. XM can contribute to identify abnormal loads to the structure (e.g., hard landing or severe gust) based on any load related parameters (e.g., flight parameters, strain measurements). This information can reduce the rate of false negative and false positive indications related to these instances. XM output are advisory indications that can trigger maintenance actions.

iii. Environmental monitoring:

Environmental monitoring (EM) evaluates a structure's exposure to environmental conditions (e.g., temperature and humidity). EM can be applied at part, assembly, or aircraft level. Output from EM is the structural environmental evaluation or the necessary date required to conduct this evaluation. This evaluation can lead to improve preventive maintenance planning. EM can also contribute to increase inspection interval when environmental conditions are less severe than design criteria.

4.3.1.2 Damage Detection/Monitoring

Damage detection/monitoring (DM) encompasses all direct measurement methods that allow the detection of damages in the structure. DM can also include damage localization and damage size characterization. Sensors are generally installed in or near targeted areas. Damage monitoring can take the form of an alternate method of inspection. In this case, it implies that the damage sensing method meets the inspection requirements (i.e., detectable damage size and type, probability of detection, inspection area). The output is equivalent to an inspection report. If the inspection requirements cannot be met, damage monitoring could be complementary to the inspection program. In this later case, the output is an advisory indication that can contribute to improve repair planning.

i. Fatigue damage (FD) sensing:

Fatigue damage sensing detects mechanical properties degradation of the structure due to cyclic loading such as cracks.

ii. Environmental damage (ED) sensing:

Environmental damage sensing detects mechanical properties degradation of the structure due to environmental conditions such as corrosion.

iii. Accidental damage (AD) sensing:

Accidental damage sensing detects mechanical properties degradation of the structure due to accidental damage such as impact with ground service equipment and bird strike.



4.3.2 Outputs

The SHM system is expected to generate three types of output: usage evaluation, advisory indication, and inspection result.

4.3.2.1 Usage Evaluation

Basic usage evaluation of structure is achieved in flight hours, flight count, and calendar day. Usage evaluation output encompasses all forms of more sophisticated approaches to evaluate structure usage based on fatigue or environmental monitoring.

4.3.2.2 Advisory Indication

An advisory indication can take many forms. One of these forms is to report abnormal conditions or events that are generally assumed to be evident to the flight or ground crew (e.g., hard landing, severe gust, bird strike, hail storm). Another form is when damage sensors are used in a way such that the inspection requirements cannot be met. One example is when a SHM technology can detect crack growth or crack activity, but not crack size as generally required by inspection requirements.

4.3.2.3 Inspection Result

An inspection result is provided by a SHM system when the inspection requirements are met.

### 4.4 Operational Considerations

Section 3 summarized the current processes and regulations that are used to define the complete set of instructions for continued airworthiness (ICA) for a given aircraft type, and that part of these ICA are nothing more than traditional maintenance procedures (tasks) accepted by the regulatory authorities to be included in the MRBR, airworthiness limitation document (or equivalent), aircraft maintenance manual, and any other maintenance related documentation provided by the OEMs or its suppliers. It was also mentioned that some of the ICAs may be affected by the introduction of SHM systems.

The degree of interaction of a given SHM system in the ICA of an aircraft type certificate will vary in accordance with its intrinsic design and operation characteristics. Therefore, a standard classification of such systems, accepted by regulatory authorities, would make it easier to evaluate possible impacts on the standard ICA. This section will indicate possible ways to classify SHM solutions, highlighting their essential aspects.

SHM systems can be defined and classified in a number of ways. However, in order to simplify the process to introduce them as part of an approved maintenance plan, it is recommended that the classification adopted by the A4A MSG-3 document, as described in 4.2 and 4.3, be used.



#### 4.4.1 Scheduled SHM (S-SHM)

S-SHM is the act of using/running/reading out a SHM device at an interval set at a fixed schedule. The structure section of the A4A MSG-3 document was revised to select S-SHM tasks and interval in lieu of classic inspections. Structure inspection tasks for accidental damage (AD), environmental damage (ED), and/or fatigue damage (FD) can be replaced by a scheduled interaction with a SHM device demonstrated to be applicable and effective.

SHM is distinguished from other structure maintenance methods such as:

- General visual inspection (GVI).
- Detailed inspection (DET).
- Special detailed inspection (SDI).

An S-SHM task ideally would have the following general characteristics:

- Would be stated as part of the MRBR structural and/or corrosion prevention and control program sections in the same way as a traditional inspection.
- Would be listed as valid airworthiness limitation items inspections, if approved by regulatory authorities (not part of the MSG-3 process).
- Would have a correspondent and dedicated aircraft maintenance manual (AMM) task procedure.
- Can be carried out by a mechanic with aircraft type rating without additional training.
- Uses technology with built in go/no-go determination capability.
- Significantly reduces capacity for human factors based errors.

Some of the benefits of introducing SHM solutions into a maintenance programs using S-SHM inspections are listed below:

- There would be no unplanned operational interruptions, as the inspection will be carried out as part of scheduled maintenance checks.
- Once performed without indication of structural failure, the correspondent aircraft structure is considered airworthy until the next scheduled check by definition (as with any other traditional inspection).
- Potential S-SHM technology failure will be evident when performing the task.

With this, SHM is clearly separated from non-destructive inspection (NDI) principles/requirements, typically associated with SDI. Even if the technical definition of NDI and SHM may be compared, NDI principles are associated with dedicated training need (and cost) for the inspector performing the task, which ideally should be avoided in SHM applications.

#### 4.4.1.1 Maintenance Credits

Issue Paper 180 is being considered for incorporation into MSG-3. Specifically, it proposes that MSG-3 logic should be amended to realize the benefits from aircraft health monitoring (AHM) capabilities in scheduled maintenance development and to create a consistent industry approach. However, it is noted that it is limited for non-safety tasks. Structural tasks are deemed safety items and would not be applicable directly to IP 180, but the process could be expanded to include SHM at a later revision to MSG-3.

Other documents touch on this subject. As airline operators expand into this area, the FAA has published AC 43-218, to guide the industry on how to set-up a program of health monitoring, including SHM. ARP5987 has been approved and published. Between IP 180, AC 43-218, and ARP5987, a template for obtaining maintenance credits using SHM can be created for future MSG-3 incorporation.

### 4.4.2 Automated SHM (A-SHM)

As explained in the previous section, S-SHM tasks will be carried out as part of scheduled maintenance checks and therefore, can be classified as preventive maintenance. Although a preventive maintenance philosophy has several advantages, it has the negative aspect of forcing operators to perform maintenance activities to evaluate the condition of a given structure, regardless if there is a failure or degradation of it.

The SHM technologies have the potential of changing this scenario by providing information to operators, OEMs, and authorities to develop “on-condition” or “condition-based” maintenance programs, eliminating several scheduled maintenance inspection tasks. The industry presented a proposal of this type of SHM implementation, known as automated SHM (A-SHM), as an issue paper (IP 105) for the International Maintenance Review Board Policy Board in 2010. A-SHM is any SHM technology which does not have a pre-determined interval where maintenance action must take place, but instead relies on the system to inform maintenance personnel which actions must take place.

IP 105 provided additional considerations on SHM, defining structural health monitoring in general and more specifically the A-SHM concept, as well as clarifying the evaluation of SHM applications by MSG-3 System and Powerplant procedures. It presents the baseline considerations within the 2009.1 MSG-3 document revision, to address in more details SHM capabilities to replace, improve or complement classic inspection tasks.



### 4.4.3 SHM Application Categories

The proposed MSG-3 methodology avoids reference to specific SHM technology as it should cater for the full range of application scenarios. Nevertheless, it was considered relevant to classify SHM system in to generic categories (see Figure 6). The operation mode is classified as either “scheduled” or “automated.”

#### 4.4.3.1 SHM Operation Mode

- Scheduled SHM (S-SHM): As defined in 4.4.1.

- Automated SHM (A-SHM): SHM technology which does not have a pre-determined interval at which maintenance action much takes place, but instead relies on the system to inform maintenance personnel that action must take place.

#### 4.4.3.2 SHM Technology Type

- Damage detection/monitoring system: SHM technology that uses sensors to directly monitor structure for deterioration conditions.

- Operation monitoring system: SHM technology that uses sensors which do not directly check the structure for damage, but instead correlate various measurements (e.g., environment conditions, loads) to make an inference to the probability or likelihood of damage.

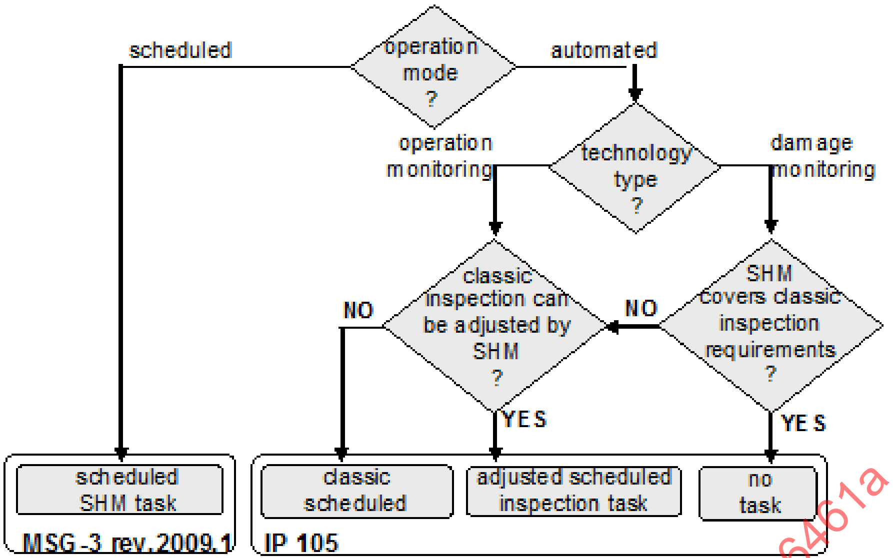


*Figure 6 - SHM evaluation procedure proposal (IP 105)*

There will be four types of SHM inspections, as indicated in Figure 7.

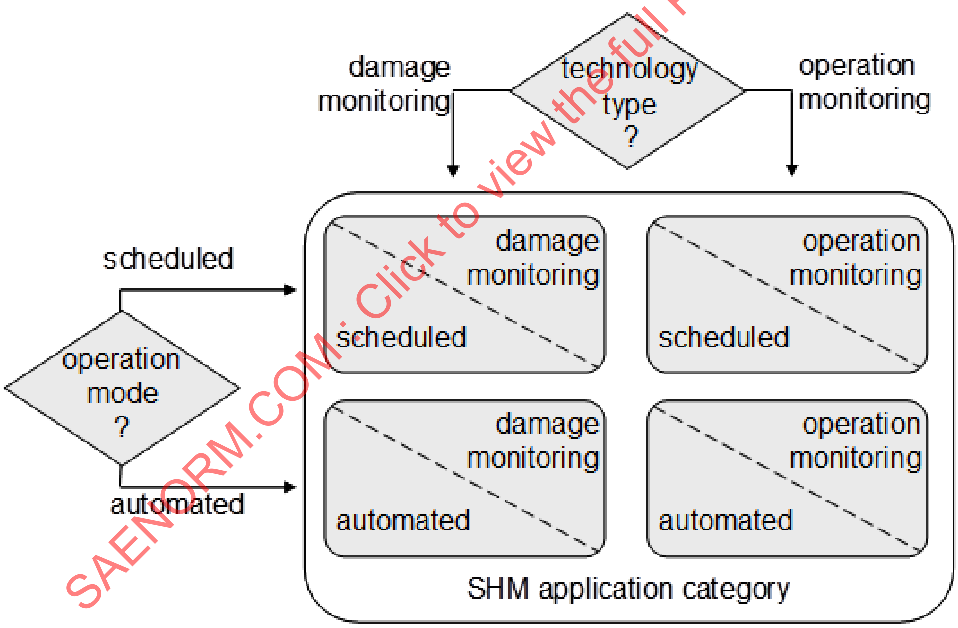


*Figure 7 - SHM possible application categories*

## 5. SHM SYSTEM REQUIREMENTS

The first step in developing requirements for an SHM system is to define the intended function and functional use for the system, Figure 8. Once the intended function and function use are defined, initial system architecture can be proposed to accomplish these objectives. As highlighted in Figure 9, the components that make up this SHM system architecture may be either on-board or ground support equipment, or a combination of the two. The function of the specific component, its location (i.e., onboard or on ground), functional interfaces with other components, and safety requirements will provide the basis for initial system requirements. Analysis of these initial requirements will often present conflicts or opportunities for optimization that will drive changes in the architecture and/or components. Thus, the development of SHM system requirements is an iterative process highly coupled with system architecture definition.

Figure 8 describes the main development activities that include development of SHM architecture, allocation of safety requirements, allocation of detailed requirements, design, implementation, test/evaluation, integration, test/evaluation of the integrated SHM, and flight tests. The development activities conclude with developments of instructions for production, installation, operation, and maintenance.

Figure 8 also presents brief descriptions of the essential processes required to develop a SHM system; these processes include safety assessment, validation, verification, and configuration management. The figure identifies the sections of this document, by their numbers, that provide information about aspects of these activities; these sections either give concise information and extensions applicable to SHM or refer the reader to existing industry accepted publications for more information.

As indicated throughout this document, any SHM system uses data acquired by onboard sensors fitted in each individual aircraft to (a) directly detect FD, ED or AD, or (b) monitor the factors that can lead to or indicate such damage types. The data can be acquired from sensors installed specifically for SHM or from existing aircraft sensors, (e.g., sensors that measure speed and acceleration). Other entities of an SHM system can be located onboard the aircraft or within ground-based systems, Figure 9.


*Figure 8 - The main development aspects of SHM systems*

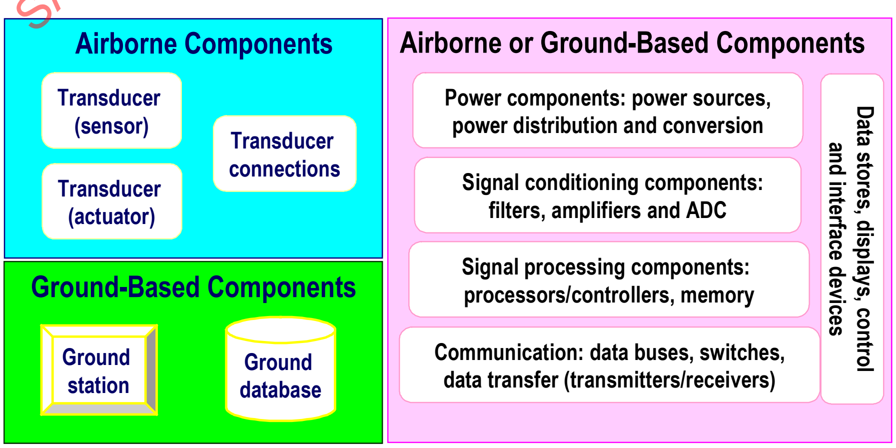


*Figure 9 - The main physical components of SHM architectures*

The entities can be (a) subsystems made of components, (b) components made of items, or (c) items, which are hardware or software objects having well defined interfaces. Depending on the chosen architecture, some or all of these entities may be designed specifically for SHM or can be shared entities from other pre-existing systems. Any given SHM-intended function can be realized by a variety of different system architectures. An optimum architecture can be chosen by assessing factors such as the technology readiness levels of entities, the associated safety requirements, development timescales, life cycle costs and weight. Architectural features of other existing aircraft systems can impose constraints on the SHM architecture.

Section 5 collates and comments on relevant existing standards, as well as adapts them for use on an SHM system. It further provides guidance on a set of requirements that a SHM system must meet. It is encouraged that SHM system developers use these unique and unequivocal definitions and requirements to define appropriate testing requirements for SHM components and systems.

The requirements are illustrative of notional SHM systems for generic application scenarios. The final requirement selection will be based on the specific application scenario for the chosen SHM system.

## 5.1 The Requirement Allocation Process

Having declared the SHM-intended functions, the architecture of a system that would deliver these functions can be developed: the architecture identifies hardware items, software items, items' functions and items' relationships necessary to deliver the intended functions.

Safety assessment methods are applied to identify the potential failures of the monitored items and functions; the methods classify the hazard associated with each failure condition and determine safety requirements: the hazard is classified as catastrophic (A), hazardous/severe-major (B), major (C), minor (D), or no safety effect (E); the safety requirements should reduce the probabilities of development errors and system failures to acceptable low levels that satisfy applicable airworthiness regulations and operating rules.

Along with the safety requirements, detailed requirements are assigned to each item and function. The detailed requirements include functional requirements (performance, operational, and customer requirements), physical, interface, installation, survivability, maintainability, and derived requirements arising from design choices.

## 5.2 SHM Function Classification

Details of the various technologies of SHM, their specific attributes and the means to test them are outside the scope of this document. However, some mention of the main features and attributes of the technologies and especially their relation to the implementation issues discussed in this document is appropriate. In reading the following, it is important to note that no accepted practices or standards for specifying and evaluating SHM systems for aerospace application exist yet. These important topics are the subject of on-going research, development and discussion and are expected to be the subject of future work and publications by AISC-SHM.

There are two major categories of intended functions for SHM systems mentioned in 4.3.1: operational monitoring and damage detection/monitoring. Operational monitoring is intended to monitor events associated with environments or operational conditions surrounding the structure such as strains, loads, temperature, humidity, etc. Damage detection/monitoring is intended to detect and monitor damage in the structure such as cracks, debond, corrosion, delamination in composites, impact damage, etc.

The inputs to the SHM systems are from the transducers (sensors or actuators) that are permanently mounted on the structures (see Figure 9). The sensor data are then processed and interpreted using hardware and software that could be hosted either on the aircraft or in ground-based systems as shown in Figure 9. The outputs of the SHM systems are the inspection results referred to in 4.3.1 based on the data from permanently mounted sensors and the software/algorithm interpretation.

Irrespective of the types of events (damage, defects, etc.) intended for monitoring, the location of the event may or may not be known prior to inspection by the SHM system. For instance, a fatigue crack may appear only at a known, fixed location, or it may occur anywhere within a region of a structure.

Because the sensors/actuators are permanently mounted on the structure in fixed locations, the selection and use of specific SHM technologies is dependent upon whether the event intended for monitoring is at a known fixed location (sometimes referred to as local monitoring) or is at an unknown location within a region (sometimes referred to as global monitoring). Whatever choice of SHM solution is selected it will be required to produce sufficient information to characterize the event to meet the intended function. Accordingly, depending upon the requirements of the intended function, an SHM system could possess the following capabilities for characterizing the event:

a. Detection of the occurrence of an event exceeding a specified threshold.

b. Identification of the location of the event if not known prior to inspection.

c. Determination of the magnitude or extent of the event such as impact force, defect size crack size.

d. Estimation of the influence of the event on the structure such as residual stiffness and strength or even remaining useful life.

As a minimum, an SHM system should be able to detect the occurrence of an event exceeding a prescribed threshold (cf NDT techniques). The outputs depend upon the sensor types, numbers of sensors, and their positions on the structure as well as the software and algorithms used in the SHM system.

5.3 Comments on Quantitative Requirements for SHM Outputs

Based on the four different levels of SHM capabilities characterized in 5.2, methodologies to validate and verify SHM for a specific application must incorporate the appropriate metrics and protocols. It is expected that the presently emerging methods to quantify SHM system performance with metrics, such as those that exist for NDT methods and manual based inspection protocols, will be influenced by future developments. Some features for consideration (not intended to be comprehensive) for each level are discussed in the following:

a. Detection of an event exceeding a threshold: Appropriate means for evaluating the detection capability of an SHM will be required. Evaluations must be used to quantify the capability of the system to detect a specified event. For example, the event could be specified as a minimum detectable crack size or impact force (energy). For a fixed known crack location, the procedures for determining the probability of detection (POD) with associated confidence levels traditionally used for NDT for crack detection might be adopted with appropriate modifications for the SHM system (see discussion in 6.10.4.1). However, for unknown event locations such as impact damage, the procedures similar to debond detection in NDT may be applicable and appropriately modified for SHM systems. Whatever methodology is developed to quantify the performance of SHM, it must be demonstrated to at least to match the standard, rigor, and robustness of the methods and protocols currently in use for manual inspections (visual and aided) in order to satisfy prevailing regulations, airworthiness authorities, and the aerospace industries.

b. Identification of location of the event: This would be required for an SHM application requiring surveillance of a region of structure in which events could happen at any location within that region (for example, detection of impact damage in composite structures). The accuracy of location would be entirely application specific and could range for example from event location (position of crack, defect, etc.) to location within a zone sufficient to trigger a maintenance action.

c. Determination of the severity of the event: Closely related to item (a) above, the SHM system may be required to measure the size of a defect as well as determining if an event has exceeded a specified threshold. The same comments made in item (a) apply, for evaluation of detection capability.

d. Estimation of possible influence of the event on the structure: Outcomes from an SHM system are usage evaluation, advisory indication, and inspection result (4.3.2). These could be combined to provide estimation of residual properties of the compromised structure in terms of stiffness and strength and updated remaining useful life resulting from the event.

## 5.4 The Requirements of Ground-Based Equipment

For many applications ground-based equipment represents an essential part of the SHM technology to support achieving the intended functions. The ground-based equipment fulfills multiple functions, such as providing power and managing data (which includes acquisition, processing, storage, or display) from the airborne SHM equipment.

Integrity attributes of ground-based items should be introduced to the assurance level required by the determined criticality; a design item criticality depends on the intended function, and, ultimately, the impact of the item failure on safety. The integrity and accuracy requirements of the various equipment items should be the same as those of existing or known equivalent items in the field of non-destructive testing (NDT).

Several standard requirements for ground-based equipment are already used for NDT equipment. The standards applicable to the environment of the ground-based SHM equipment may include the following:

- MIL-STD-810.
- MIL-STD-461.
- RTCA DO-278.

The operating environment of the SHM technology requires that the ground-based equipment may need to be tested against the following conditions:

- Vibration test.
- Drop test.
- Blowing rain test.
- Humidity test.
- Salt fog test.
- Sand and dust test.
- Icing/freezing rain test.
- Explosive atmosphere test.
- Electromagnetic interference test.
- Radiation emission/sensitivity test.

The corresponding test methods can be found in the MIL-STD-810, except for the electromagnetic interference and radiation tests, which are specified in the MIL-STD-461.

## 5.5 The Requirements of Airborne Equipment

Airborne equipment represents the core element of SHM technologies for many applications. In most cases, the airborne equipment of a SHM system is mainly composed of embedded or bonded SHM sensors, wires, interconnecting parts, or connectors, among others. Electronic devices for both wired and wireless data transmission and energy harvesting devices can also be parts of SHM airborne equipment. The airborne equipment fulfills at least the functions of interrogating the structure and transmitting the information to equipment, whether airborne or ground-based.

The reliability and integrity of the SHM airborne equipment during its whole useful life should be assured by requirements according to the operating conditions that may be applied throughout the life-cycle, including both daily operations and maintenance operations. The requirements are also set according to the assurance level determined from safety assessment at systems and aircraft levels. A design assurance level depends on the intended function and finally, the consequence of failure. This section offers a short description of the requirements regarding the airborne equipment and where to find more information within this guidebook or in available standard documents.

Environmental qualification is necessary to ensure product reliability regarding the expected environmental conditions endured by the SHM system. Section 5.6.6 is based on the standard RTCA DO-160 for systems regarding the environmental conditions of airborne equipment. The document does not cover all the requirements to fulfill the broader conditions to qualify a SHM system. Therefore, special considerations for SHM airborne equipment are added to the requirements or the respective requirement is modified to fit the SHM system requirements. The tests should cover representative structures with embedded or bonded SHM sensors, including special wires, connectors, or bonding materials (as well as the associated electronic devices).

The structures with embedded or bonded sensors, as well as other integrated components, should also fulfill the pertinent requirements relevant to the integrity of the structure. The requirements should ensure that the airborne equipment integrated/installed on the structure does not reduce the structure integrity beyond the limits set by design engineers when integrated into the aircraft environment. This subject is covered by structural requirements in 5.6.7.

Section 5.6.8 deals with the installation requirements of the airborne equipment which is permanently bonded to the structure. Sensors, wires, connectors and interconnecting parts are generally considered in this section. Electronic devices to exchange data wirelessly as well as energy harvesting devices could also be a part of the airborne equipment. The requirements are guidelines to set reliable and reproducible processes regarding the installation, protection, and calibration of the sensors.

The maintainability aspects of the airborne equipment are tackled in 5.6.9. The maintenance of the airborne equipment includes the inspection or self-diagnostic, the calibration and the repair process of the SHM system. Also refer to AC 20-152 (also known as RTCA DO-254).

The requirements also cover the avionics related to a given SHM system. The tests should, for example, demonstrate the presence of an adequate source of electrical power with integrity attributes commensurate with the determined equipment criticality. There should be no reduction in the level of safety or reliability for other equipment as a result of acquiring power for SHM equipment. Section 5.6.10 deals with this aspect, among other interface requirements.

Finally, the airborne software integrity attributes should be developed to the assurance level required by the determined criticality. The currently valid standards are based in the document RTCA DO-178, the standard for the development of software used in airborne systems.



## 5.6 Requirement Families

The requirements are captured in requirement families as described in ARP4754, according to the following requirement classification.

### 5.6.1 Safety and Reliability Requirements

- Functional requirements.
- Operational requirements.
- Performance requirements.
- Physical requirements.
- Environmental requirements.
- Structural requirements.
- Installation requirements.

- Maintainability requirements.
- Interface requirements.
- Safety and reliability requirements.

The requirements involve the minimum performance constraints for both availability (i.e., continuity of function), and integrity (i.e., correct behavior of the function). Safety requirements are determined through an FHA (functional hazard assessment).

5.6.1.1 Effect on Personnel

***Table 1 - Effect on personnel***

| Name of Requirement | Effect on Personnel |
|---|---|
| Statement of Requirement | The operation of the SHM system should not adversely affect the personnel when use in the intended manner and environment. |
| Reference | N/A |
| Rationale | The operation of the SHM systems should have no adverse effect on the personnel using it, should comply with appropriate safety standards and should not pose a hazard to the operator or other personnel. |
| Additional comments | N/A |



5.6.1.2 Effect on Structure

***Table 2 - Effect on structure***

| Name of Requirement | Effect on Structure |
|---|---|
| Statement of Requirement | The SHM system should not adversely affect the structure in any way whether when installing, applying, operating, or maintaining it. |
| Reference | N/A |
| Rationale | The application and operation of the SHM system should have no adverse effect on the systems or structural integrity of the structure, should comply with appropriate safety standards, should not pose a hazard to the structure, and should not result in any damage or deterioration of other systems or structures. |
| Additional comments | N/A |

5.6.1.3 Fault Tolerant Design of Equipment and Installations

***Table 3 - Fault tolerant design of equipment and installations***

| Name of Requirement | Fault Tolerant Design of Equipment and Installations |
|---|---|
| Statement of Requirement | SHM equipment and installations should incorporate fault tolerant designs as part of the means to achieve reliability requirements and intended functions. |
| Reference | ARP4754, ARP4761 |
| Rationale | Following functional hazard assessment and equipment/system reliability assessments it may be necessary to adopt fault tolerant design principles for SHM systems. This may entail special consideration of redundancy management techniques in complete SHM systems to achieve the required levels of reliability and performance. |
| Additional comments | SHM systems should be regarded as complex aircraft systems since they could entail combinations of structural, mechanical and electrical/optical subsystems each with their associated reliability characteristics. |

5.6.1.4 Software and Electronic Hardware

***Table 4 - Development assurance level***

| Name of Requirement | Development Assurance Level |
|---|---|
| Statement of Requirement | An assessment of the development assurance level (DAL) needed for the software functions of any on-board and/or off-board component of the SHM system should be made. |
| Reference | ARP5987, ARP4754, ARP4761 |
| Rationale | A DAL assessment for an SHM system can be determined based on its potential data effect through a standard hazard assessment. This process determines the assurance level that will be required during development or that will need to be mitigated by other means. ARP5987 has been produced to help guide engine health monitoring (EHM) system designers with a process to determine appropriate assurance levels (AL) for system software (SW) and appropriate airborne electronic hardware (AEH) firmware elements. Alternatively, each aircraft system functions can be systematically analyzed for failure condition according to ARP4754, ARP4761, and assigned a hazard classification which will dictate a development assurance levels (DALs). |
| Additional Comments | The ARP 5987 document addresses the various stages and functions of an EHM system (i.e., on-engine, on-aircraft, communications and ground-based elements) and also provides relevant guidance for the SHM designer. |

5.6.1.5 Mean Time Between Failure (MTBF)

There are many forms of the MTBF definition. In general, MTBF is the mean value of the lengths of time between consecutive failures, under stated conditions, for a stated period in the life of a functional unit. A more simplified MTBF definition for reliability predictions can be stated as the average time (usually expressed in hours) that a component works without failure.

***Table 5 - Mean time between failure (MTBF)***

| Name of Requirement | Mean Time Between Failure (MTBF) |
|---|---|
| Statement of Requirement | The minimum MTBF should be defined to achieve the operational reliability and design assurance requirements consistent with the intended function. |
| Reference | N/A |
| Rationale | The MTBF the complete SHM system should be sufficient for a high degree of operational reliability. |
| Additional Comments | N/A |

5.6.1.6 System Integrity

***Table 6 - System integrity***

| Name of Requirement | System Integrity |
|---|---|
| Statement of Requirement | The functional integrity of the structural health monitoring system should be sufficient to achieve the intended benefits. |
| Reference | N/A |
| Rationale | The structural health monitoring system must have a higher availability (i.e., an ability to perform its function when needed), than the underlying system that it is monitoring. |
| Additional Comments | N/A |

5.6.1.7 Software Development (On-Board)

***Table 7 - Software development (on-board)***

| | |
|---|---|
| Name of Requirement | Software Development (On-board) |
| Statement of Requirement | The SHM on-board software should be developed to meet the needs of the software assurance level assessment and to comply with airworthiness requirements. |
| Reference | AC 20.115, DO-178 |
| Rationale | DO-178 provides guidelines for the development of airborne systems software to give an appropriate level of confidence that it complies with airworthiness requirements.<br>FAA Advisory Circular (AC) 20.115 recognizes RTCA document DO-178 as a means of compliance for software approval for airborne systems installed on Parts 21, 23, 25, 27, 29, and 33 aircraft products. |
| Additional Comments | N/A |

5.6.1.8 Software Development (Ground-Based)

***Table 8 - Software development (ground)***

| | |
|---|---|
| Name of Requirement | Software Development (Ground-Based) |
| Statement of Requirement | The SHM on-ground software should be developed to meet the needs of the software assurance level assessment and to perform their intended functions while providing an acceptable level of safety. |
| Reference | DO-278 |
| Rationale | DO-278 constitutes the best set of guidelines that are available today for ground-based equipment, and uses an approach similar to DO-178. This standard is recommended when designing software for ground support equipment. It also provides guidance for the SHM designer. |
| Additional Comments | N/A |

5.6.1.9 Hardware Assurance Level

***Table 9 - Hardware assurance level***

| | |
|---|---|
| Name of Requirement | Hardware Assurance Level |
| Statement of Requirement | A hardware safety assessment should be conducted in conjunction with a system safety assessment (SSA) to demonstrate that the SHM on-board hardware can satisfy the applicable aircraft certification requirements. |
| Reference | AC 20.152, DO-254 |
| Rationale | AC 20.152 recognizes RTCA document DO-254 as a means of compliance for electronic hardware approval for airborne systems installed on Parts 21, 23, 25, 27, 29, and 33 aircraft products. |
| Additional comments | N/A |

5.6.2 Functional Requirements

The requirements involve the capabilities of a function (e.g., features to be monitored by overload monitoring, features to be monitored by a fatigue monitoring system, etc.). Functional requirements are necessary to obtain the desired performance of the system under the conditions specified.

#### 5.6.2.1 Data Acquisition

***Table 10 - Data acquisition***

| | |
|---|---|
| Name of Requirement | Data Acquisition (1): Sensor Data |
| Statement of Requirement | The sensor data should be transmitted securely and written without loss to a separate file (or set of files) for each data acquisition process in order to automatically create a unique data set to include complementary data. |
| Reference | N/A |
| Rationale | The recorded data need to be saved in a correct and complete manner in order to be able to analyze it and trace the measurement for further post-processing. |
| Additional Comments | There should be no data loss during data loading, saving, or reset. This can be checked by a capability such as self-test. |
| Name of Requirement | Data Acquisition (2): Complementary Data |
| Statement of Requirement | Complementary data (temperature, etc.) should be written to a separate file for each data acquisition process in order to automatically create a unique data set to include complementary data. |
| Reference | N/A |
| Rationale | The recorded data need to be saved in a correct and complete manner in order to be able to analyze it and trace the measurement for further post-processing. |
| Additional Comments | There should be no data loss during data loading, saving or reset. This can be checked by a capability such as self-test. |
| Name of Requirement | Data Acquisition (3): Configuration Data |
| Statement of Requirement | The configuration data file should contain all the settings of the system (e.g., channel allocation, gains, frequencies, wave shape, etc.) in order to record the system configuration and to allow tracing the data acquisition process. |
| Reference | N/A |
| Rationale | The recorded data need to be saved in a correct and complete manner in order to be able to analyze it and trace the measurement for further post-processing. |
| Additional Comments | There should be no data loss during data loading, saving, or reset. This can be checked by a capability such as self-test. |
| Name of Requirement | Data Acquisition (4): Consolidation Process |
| Statement of Requirement | Data acquisition file should be written (if possible) synchronously to a common time basis in order to make a consolidated data evaluation possible. (Combination of different monitoring methods.) |
| Reference | N/A |
| Rationale | The recorded data need to be saved in a correct and complete manner in order to be able to analyze it and trace the measurement for further post-processing. |
| Additional Comments | There should be no data loss during data loading, saving or reset. This can be checked by a capability such as self-test. |

### 5.6.3 Operational Requirements

The operational requirements specify the interfaces between the flight crew and an on-aircraft SHM component and between the maintenance crew and the on-aircraft/ground SHM components. Actions, decisions, information requirements, and timing constitute the bulk of the operational requirements. Both normal and non-normal operating conditions need to be considered when defining operational requirements. Development of operational requirements is supported by use cases.

5.6.3.1 Concept of Operations

**_Table 11 - Concept of operations_**

| Name of Requirement | Concept of Operations |
|---|---|
| Statement of Requirement | The concept of operations for the system should be briefly documented. How will the system be used, and what is its organizational setting? It is appropriate to include a graphic that depicts the system and its operation. Also describe data handling, processing and storing; the sensitivity and owner of the data. |
| Reference | N/A |
| Rationale | A concept of operation helps facilitate the systems engineering/integration process of the SHM system, and it serves as a reference in the validation process. |
| Additional comments | N/A |

5.6.3.2 Data Offloading

**_Table 12 - Data offloading_**

| Name of Requirement | Data Offloading |
|---|---|
| Statement of Requirement | The criteria for how, where, and when data are offloaded from the SHM system should be documented. |
| Reference | N/A |
| Rationale | As essential capability of the SHM system is to communicate its data and results. The method of that communication should be clearly established for every SHM system. |
| Additional comments | Considerations for this requirement include interval between data downloads, conditions for special data downloads (e.g., hard landings), data transmission time, and data transmission integrity assurance. |

5.6.3.3 System Airworthiness

**_Table 13 - System airworthiness_**

| Name of Requirement | System Airworthiness |
|---|---|
| Statement of Requirement | The structural health monitoring system should comply with 25.1309(b), (c), and (d) of the Federal Aviation Regulation (FAR). |
| Reference | 14 CFR Part 25.1309, AC 25.1309-1A |
| Rationale | A structural health monitoring system intended for use on transport airplanes must meet the airworthiness standards for that category of aircraft. |
| Additional comments | N/A |



5.6.4 Performance Requirements

Performance requirements for damage detection or operation monitoring use cases should be defined by the airframe designer, based on structural design and operation expectations. These requirements will influence the sensing solution selection, and contributing factors could include:

- Where on the airframe the sensors would be located.
- What environmental condition the sensors would be exposed to both while collecting data and while not in use through the expected life of the sensor system.
- What data rate is needed for structural health management.
- Measurement accuracy and/or detection capability.

NOTE: Operation monitoring and damage detection systems would be evaluated according to different type of performance criteria, namely measurement accuracy or detection capability. Therefore, those specific performances are detailed below.

5.6.4.1 Measurement Accuracy

This requirement is applicable when operation monitoring is identified as the monitoring feature of the present SHM system, including monitoring of environmental exceedance- parameters (temperature, pressure, humidity, etc.).

***Table 14 - Measurement accuracy***

| Name of Requirement | Measurement Accuracy |
|---|---|
| Statement of Requirement | The estimates of the repeatability, reproducibility and accuracy (trueness and precision) of the SHM measurement method should be provided, together with an estimate of measurement uncertainty of the specific measurement process associated with the trueness of the method. |
| Reference | ENV13005, ISO 5725 |
| Rationale | The SHM system capability should be tested against any influences on the measurement results and the variance associated with the results that could arise from these effects to be quantified. |
| Additional comments | One should elaborate that the accuracy of the measurement must be greater than or equal to that obtained (if available) by the method SHM is replacing. |

5.6.4.2 Detection Capability

This requirement is only applicable when damage detection (i.e., crack, delamination due to impact) is identified as the monitoring feature of the present SHM system.

This requirement represents one major criterion in the technical qualification of NDT inspection methods (commonly known as “POD tests”). It is important as well for technically qualifying an SHM system. Its evaluation must include the installation context and effects of environmental conditions.

Detection capability requirements have to be controlled differently depending on the respective SHM system. Herein, the difference between a global and local SHM system is of importance and is thus discussed as an introduction to the requirement. A local SHM system implies that the damage (structural state) can only be detected at the spot of the sensor application but the system cannot offer any statement about the structural state of the sensor surroundings. Global SHM systems are defined as a monitoring system covering an area greater than the dimension of the applied sensors. Most global technologies, such as the acousto-ultrasonic technique, use a spatially distributed sensor network.

Depending on whether it is a local or a global SHM system, the output to determine the monitored feature may be of a different type.

**Table 15 - Detection capability**

| Name of Requirement | Detection Capability |
|---|---|
| Statement of Requirement | For a specific application, probability of detection (POD) should be established for an SHM system with respect to damage size dependent on structural design and stress analysis. The minimum damage size that can be detected repeatability and reliability could be established as well. |
| Reference | MIL-HDBK-1823 |
| Rationale | For technical qualification of an SHM system, it is necessary to understand the system's ability to reliably detect, in a repeatable and reproducible manner, damage of a minimum size in a given application. |
| Additional comments | • The same sensing solution could exhibit different detection capabilities for different applications depending on application-specific context (e.g., structure material and design, environmental conditions, etc.).<br>• Results may be presented in different ways due to the measurement type based on the SHM system (global/local).<br>• In case that a spatial distributed sensor network is used, the results may vary due to and might be displayed as a function of system parameters (sensor network layout, number of sensors, size of monitored area, etc.).<br>• The accuracy and variance in damage localization (for global SHM systems) and damage size determination should also be considered and combined in the results.<br>Environmental and operational conditions should be incorporated in the analysis. |

5.6.5 Physical Requirements

The physical requirements include system/item attributes such as mass, size, cooling, power consumption, etc.

5.6.5.1 SHM System Weight

**Table 16 - SHM system weight**

| Name of Requirement | SHM System Weight |
|---|---|
| Statement of Requirement | The weight of the SHM system (including wires and sensors) should be established and documented, divided according to airborne and on-ground equipment. |
| Reference | N/A |
| Rationale | The cost-benefit analysis for use of an SHM system must consider the additional weight the SHM system may add to an aircraft. This additional weight influences factors including fuel requirements and payload capacity. |
| Additional comments | N/A |

5.6.5.2 SHM System Dimensions

**Table 17 - SHM system dimensions**

| Name of Requirement | SHM System Dimensions |
|---|---|
| Statement of Requirement | The dimensions of the SHM system should be established and documented, divided according to airborne and on-ground equipment. |
| Reference | N/A |
| Rationale | The impact of physical dimensions of the airborne SHM system on the aerodynamic surfaces, cargo space, and cabin should be calculated and included in the cost-benefit analysis. The dimensions of the airborne equipment should fit to the available amount of space and should not adversely influence the structural integrity of the aircraft. |
| Additional comments | N/A |

5.6.5.3 Power/Power Consumption

***Table 18 - Power/power consumption***

| Name of Requirement | Power/Power Consumption |
|---|---|
| Statement of Requirement | The power consumption of the complete SHM system, especially the airborne equipment should be determined. |
| Reference | N/A |
| Rationale | The power consumption of the airborne equipment should be adapted to the available power on the aircraft. If necessary, required power reduction or power transformation should be performed within the SHM system.<br>The power consumption for the airborne SHM system should be documented as a peak value and minimum value. |
| Additional comments | N/A |

5.6.6 Environmental Requirements

Environmental requirements capture the conditions in which an SHM system is required to perform and/or survive. These requirements are specified in RTCA DO-160. The aircraft manufacturer/operator may specify the environmental conditions to be met by the SHM system. Specific SHM system requirements (e.g., manufacturing and some special operational environments) may need specifications supplementary to DO-160. Table 19 provides a subset of environmental conditions relevant to SHM that are supplemental to and not necessarily covered by DO-160.

Applicable requirements from DO-160 for a particular SHM system depend strongly on the specific location of the SHM system within the aircraft. Table 19 lists the categories of DO-160 along with variations of the requirements specific to SHM systems. Unless otherwise stated, SHM equipment should be tested to the most severe conditions (categories) presented in RTCA DO-160.

Environmental testing consists of stressing the sensor (and its connecting components) to ensure they function properly in potential hazardous situations. Important to SHM systems is the connection between the sensor and the monitored structural component, which may be damaged during the environmental testing. This is especially the case when an adhesive is used to bond the sensors to the surface. When applicable, a mechanical bonding test should be performed according to 5.6.7.4 immediately after the environmental test has been completed. When stated, the functionality of the sensor with the SHM system (measurability, measurement accuracy, measurement capability, etc.) should be also controlled during the environmental test.

***Table 19 - DO-160 based environmental requirements and supplementary information***

| Requirement | Derivation from RTCA DO-160 with Respect to SHM |
|---|---|
| Temperature and Altitude | Covered by DO-160 |
| Temperature Variation | The SHM system might be installed during aircraft manufacturing (or in-service during repair work); accordingly, the system might have to withstand higher temperatures as they occur during the manufacturing process (e.g., CFRP curing up to 180 °C). |
| Humidity | The holding time at maximum heat and humidity defined in the reference document may need to be extended depending on the safety demands of the particular application scenario.<br>After humidity resistance testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. |
| Waterproof | After waterproof testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. |

| Requirement | Derivation from RTCA DO-160 with Respect to SHM |
|---|---|
| Fluid Susceptibility:<br>• Water<br>• Hydraulic fluid<br>• Kerosene<br>• Lubrication oils<br>• Cleaning and toilet fluids<br>• De-icing and anti-icing fluids<br>• Insecticides<br>• Disinfectants<br>• Coolant dielectric fluids<br>• Fire extinguishant | The duration of immersion may need to be extended and temperature of the bath may need to be increased depending on the safety demands of the particular application scenario. After fluid susceptibility testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. The test should be carried out straight after taking the specimen out of the container, avoiding re-drying by any means. |
| Salt Fog | The duration of exposure may need to be extended and temperature of the liquid may need to be increased depending on the safety demands of the particular application scenario. After spray resistance testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. The test should be carried out straight after taking the specimen out of the container, avoiding re-drying by any means. |
| Icing | After icing susceptibility testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. |
| Sand and Dust Test | After sand and dust susceptibility testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. |
| Fungus Resistance | After fungus resistance testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. |
| Vibration | The test should also include wind milling vibration test. After vibration susceptibility testing has been carried out, confirm mechanical bonding performance according to 5.6.7.4 when applicable. |
| Fire and Flammability | Covered by DO-160 |
| Explosion Resistance | Covered by DO-160 |
| Magnetic Effect | Covered by DO-160 |
| Power Input | Covered by DO-160 |
| Voltage Spike | Covered by DO-160 |
| Audio Frequency Conducted Susceptibility - Power Inputs | Covered by DO-160 |
| Induced Signal Susceptibility | Covered by DO-160 |
| Radio Frequency Susceptibility | Covered by DO-160 |
| Emission of Radio Frequency Energy | Covered by DO-160 |
| Lightning Induced Transient Susceptibility | Consider equipment targeted for use inside and outside the faraday cage separately. |
| Electrostatic Discharge | Covered by DO-160 |
| Lightning Direct Effects | Covered by DO-160 |

5.6.7 Structural Requirements

Structural requirements are correlated to the specified application scenario and its structural characteristics.

5.6.7.1 Sensor Integration

***Table 20 - Sensor integration***

| Name of Requirement | Sensor Integration |
|---|---|
| Statement of Requirement | The sensor integration should not significantly reduce the material and structure integrity beyond the limits set by design. |
| Reference | N/A |
| Rationale | The impact of the sensor system on the material and structure integrity should be investigated. The integration of the SHM sensors should be made considering the material and structural characteristics of the specific scenario. |
| Additional Comments | The structural integrity change should be within the allowable values provided by the stress and design offices and material specialists for a specific scenario. Approval from the stress office, design office and material specialists should be provided.<br>The sensor integration should comply with the aircraft design criteria needs from the scenario business case, proved by fatigue test, etc. A detailed report showing such compliance should be provided. This requirement is scenario specific (e.g., last the life of structure, last the loading level of the structure, etc.). |

5.6.7.2 SHM Equipment Integration

The SHM equipment may consist of, for example, an interrogation unit and cabling attachment points but it has to be defined depending on the SHM technology used.

***Table 21 - SHM equipment integration***

| Name of Requirement | SHM Equipment Integration |
|---|---|
| Statement of Requirement | The SHM equipment (interrogation unit and cabling attachment points) should not reduce the material structural integrity beyond the limits set by design when integrated into the aircraft environment (e.g., stress check when holes are required to install the interrogation unit and cabling). |
| Reference | N/A |
| Rationale | Any structure modification due to the installation of the equipment should be compliant with the structural design criteria. Investigations should be made to characterize how the SHM system integration impacts the material and structure integrity in various specific scenarios. |
| Additional Comments | Approval from the stress office, design office, and material specialists should be obtained. |

5.6.7.3 Sensor Network and SHM Equipment Design

***Table 22 - Sensor network and SHM equipment design***

| Name of Requirement | Sensor Network and SHM Equipment Design |
|---|---|
| Statement of Requirement | The overall SHM system should be optimized in terms of performance and minimal disturbance of the monitored area. The sensor network design should be pertinent to the application scenario and the SHM equipment should comply with the constraints of the specific scenario. |
| Reference | N/A |
| Rationale | Evaluate the sensor network and the overall SHM system design regarding the integration in the aircraft. A suitable prototype should comply with the physical dimension constraints of the specific scenario.<br>The SHM technology should comply with the design assurance level (DAL) for a given scenario. The appropriate DAL will be determined by the aircraft FHA. |
| Additional Comments | N/A |

5.6.7.4 Mechanical Bonding Performance

***Table 23 - Mechanical bonding performance***

| Name of Requirement | Mechanical Bonding Performance |
|---|---|
| Statement of Requirement | The mechanical bonding between sensors and the structure should withstand the corresponding tests described in the additional comments below. |
| Reference | N/A |
| Rationale | To function properly, SHM sensors require a high-integrity bond with the structure they are monitoring. The integrity of this bond must be maintained for the duration of use of the SHM sensors/system. |
| Additional Comments | For surface sensor: Test the bonding performance of the applied sensor under tensile (loading perpendicular to bond line) and/or shear loading or peeling test at room temperature. The correct functioning of the sensor should be demonstrated before and after each test (except for peel test).<br>For integrated sensor: The integrated sensor should withstand the same mechanical loading as the structural item in which it is integrated. Corresponding tests should be suggested from stress/design department. The correct functioning of the sensor should be demonstrated before and after each test.<br>The mechanical bond performance values have to be met also after environmental loading. Depending on the application scenario, a threshold value of a certain percentage of the ideal performance can be accepted. |

5.6.8 Installation Requirements

The installation requirements consider the airborne equipment which is permanently bonded to the structure. Sensors, wires, connectors, and interconnecting parts are generally considered in this section. Electronic devices to exchange data wirelessly as well as energy harvesting devices could also be a part of the airborne equipment. The requirements are guidelines to set reliable and reproducible processes regarding the installation, protection and calibration of the sensors.

5.6.8.1 Sensor Installation

***Table 24 - Sensor installation***

| Name of Requirement | Sensor Installation |
|---|---|
| Statement of Requirement | It should be assured that the way of sensor application to the structure (e.g., bonding, drilling, and bolting) and possible treatments (e.g., curing) are mastered and lead in a repeatable way to the same system performance. |
| Reference | N/A |
| Rationale | The sensor application should be performed through a reliable and reproducible procedure which ensures the integrity of the sensor, the structure and its surrounding components, as well as the quality of the structure-sensor interface. |
| Additional Comments | An accurate description of the installation procedure should cover, at least, the following topics:<br>• Surface preparation.<br>• Sensor positioning and placement.<br>• Description of the sensor application procedure as well as the adequate conditions for the sensor application to be performed (pressure, temperature, humidity, etc.). The means to provide these conditions should be also specified.<br>• The sensor application description should contain the application of sensors, connectors, and interconnecting parts.<br>• Application of protecting layers (sealant, top coat, copper foil, GFRP-layer, etc.).<br>• Security measures to be taken in each step (personal protective equipment or additional security devices).<br>• Detailed list of all substances, devices, tools, consumables, and other utilities needed during sensor installation.<br>• The datasheet of used substances and devices should be available.<br>• The procedure should have no adverse effect on the structure.<br>The influence of human factor during the installation procedure should be reduced to a minimum. |



5.6.8.2 Surface Treatment

***Table 25 - Surface treatment***

| Name of Requirement | Surface Treatment |
|---|---|
| Statement of Requirement | The surface treatment whereon the sensor is applied should be controlled and its continuous quality should be assured. |
| Reference | N/A |
| Rationale | During manufacturing and assembly there are several factors present which have a negative effect on the bond quality. The control of these factors and the subsequent determination of a suitable surface treatment should ensure a good bond quality. |
| Additional Comments | The surface treatment can contain one or more of the following steps:<br>• Surface finish. Before sensor installation, the surface should be uniformly smooth and free from any surface irregularities. Some examples are (primer crazing or pitting for metals and unevenness due to different prepreg layers for composites).<br>• Contamination removal. Several substances present during manufacturing and assembly can hinder the bond quality. Some of them are metal oxides, oil, grease, primer dust, corrosion and chemical surface contamination, sealants, humidity, or dust. Contamination should be removed with the approved tools and substances to avoid damaging the structure.<br>• Surface cleaning. The surface should be clean, the solvents used for contamination removal should dry off and recontamination before sensor installation should be prevented.<br>The surface treatment should have no adverse effect on the surface protection of the structure. A description of surface preparation should be included in the installation procedure document. |

5.6.8.3 Sensor Protection

***Table 26 - Sensor protection***

| Name of Requirement | Sensor Protection |
|---|---|
| Statement of Requirement | In certain cases the sensor installation is completed with a sensor protection. A suitable sensor protection prevents the sensors from being damaged without decreasing its performance.<br>The suitable sensor protection should be determined considering the conditions the sensors have to endure, including manufacturing, assembly, in-service time, and repairs. These conditions can include mechanical loading, temperature variations and chemically aggressive environments, among others. Some examples of sensor protection are GFRP-layers, sealant, fuel vapor barrier, and top coat. |
| Reference | N/A |
| Rationale | It has to be assured that the sensor is protected against external influences while the protection does not inhibit the correct functioning of the system in any form. |
| Additional Comments | For better results, the sensor protection should take place during or immediately after the sensor installation. A description of sensor protection should be included in the installation procedure document. |

5.6.8.4 Baseline/Sensor Initialization and Calibration

***Table 27 - Sensor initialization and calibration***

| Name of Requirement | Sensor Initialization and Calibration |
|---|---|
| Statement of Requirement | The acquisition of a baseline should be provided for the SHM technologies which need a reference value in order to evaluate damage. |
| Reference | N/A |
| Rationale | Some SHM technologies use relative values to assess the structure health (i.e., a reference value should be provided to evaluate damage). The data initialization deals with the acquisition of these reference values, also named baseline. The SHM system might need calibration while in-service.<br>These systems are sensitive to environmental conditions or changes in the mechanical stress field. This characteristic should be taken into account by either providing an adequate compensation method or acquiring a baseline that covers the environmental and mechanical conditions the aircraft will endure during its lifetime.<br>A certain sensor hysteresis during load change should be considered in some cases. In order to offset the hysteresis effect, the baseline acquisition could be repeated at planned intervals. |
| Additional Comments | The initial state of the structure should be controlled by means of conventional NDT methods before the acquisition of the baseline. Damaged parts in the structures should be recorded and further controlled. |

5.6.8.5 Manufacturing and Assembly

***Table 28 - Manufacturing and assembly***

| Name of Requirement | Manufacturing and Assembly |
|---|---|
| Statement of Requirement | The integrity of the sensor as well as the quality of the structure-sensor interface should be ensured for every specific scenario.<br>The system component materials (e.g., sensor, cabling, connector, adhesive, sensor protection) and sensor application process should be compliant and robust to the processes for manufacturing and assembly.<br>The SHM system should fulfill the additional requirements on the assembly and manufacturing processes driven by a specific scenario.<br>It should be verified that the sensor can be embedded, integrated or surface mounted during and/or after manufacturing.<br>• After manufacturing, the sensor functioning should be proven to remain within the specifications.<br>• The properties of the material and the structure with the embedded or integrated sensors should be proven to be within the values allowed by design.<br>It should be proven that the sensor can be embedded, integrated or surface mounted within the business case assumptions. |
| Reference | N/A |
| Rationale | It should be proven that the sensor in its application is withstanding any kind of mechanical, thermal, and chemical impacts during the manufacturing and assembly process. |
| Additional Comments | N/A |



5.6.9 Maintainability Requirements

Maintainability requirements include scheduled and unscheduled maintenance requirements of SHM system/functions and any links to specific safety-related functions. It should include self-test requirements for fault isolation to ensure integrity of SHM system/function and calibration requirements as required.

5.6.9.1 Self-diagnostic Capabilities

***Table 29 - Self-diagnostic capabilities***

| Name of Requirement | Self-Diagnostic Capabilities |
|---|---|
| Statement of Requirement | Sensor functionality should be controlled during installation and when in operation through self-test capabilities. The sensor output must not deteriorate below a certain allowable value, defined by the application scenario. |
| Reference | N/A |
| Rationale | If a sensor breaks, it must not be mistaken for a failure of the structure. Thus, the SHM system must be able to assess its monitoring abilities. This procedure is called self-diagnostics or simply self-test. |
| Additional Comments | It should ensure to state that an optimum interaction between the physical or chemical probe of the sensor(s) and the structure/material is enabled. This check should be possible to run at all times. |

5.6.9.2 Sensor Reparability/Maintainability

***Table 30 - Sensor reparability/maintainability***

| Name of Requirement | Sensor Reparability/Maintainability |
|---|---|
| Statement of Requirement | SHM sensors and equipment should ideally require no maintenance and be durable for the useful life of an aircraft.<br>By means of 5.6.9.1 or the like, required maintenance, repair, or replacement on the sensors should be identified.<br>Define procedures to overcome them if required within the scheduled maintenance check of the aircraft and applicable "return-to-service" testing that ensures the SHM system is fully operational, following a repair of the system itself, or other repairs to surrounding aircraft systems. |
| Reference | N/A |
| Rationale | Identify possible breakdowns of the SHM system.<br>• In case, that the sensors are not accessible after installation, there should be no scheduled or corrective maintenance.<br>• The SHM System should cause no additional maintenance check.<br>• In case, that the structural part is removed where sensors are installed or the structural part design changed due to repair actions, the SHM system should be recalibrated, repaired or reinstalled in order to fulfill its measuring task.<br>• The failure of a single sensor should not lead to the need to replace the monitored structure component for repair.<br>• Sensors should be exchangeable/downwards compatible in terms of version. |
| Additional Comments | |



5.6.10 Interface Requirements

Interface requirements include the physical system and item interconnections along with the relevant characteristics of the specific information communicated. The requirements should be defined with all inputs having a source and all outputs destinations defined.

5.6.10.1 Data Integrity

***Table 31 - Data integrity/assurance***

| Name of Requirement | Data Integrity/Assurance |
|---|---|
| Statement of Requirement | The data integrity of the system should be evaluated. |
| Reference | AC 20-156 |
| Rationale | Data that passes between LRUs, sensors, data concentrators, nodes, switches, modules, or other entities within the on-board SHM system must remain accurate and meet the data integrity of the intended SHM functions. |
| Additional comments | N/A |

5.6.10.2 Data Bus Performance

***Table 32 - Data bus performance***

| Name of Requirement | Data Bus Performance |
|---|---|
| Statement of Requirement | The performance of any data bus unique to the SHM system should be evaluated to establish its capabilities and limitations. |
| Reference | AC 20-156 |
| Rationale | The performance of a data bus must be capable of supporting the intended function of the SHM system and the applicable airworthiness requirements when maintenance or design credits are being sought. |
| Additional comments | N/A |

5.6.10.3 Data Availability

***Table 33 - Data availability***

| | |
|---|---|
| Name of Requirement | Data Availability |
| Statement of Requirement | The SHM system data bus and system architecture should be evaluated to establish the latencies associated with data collection, data processing, data transmission within an operational environment. |
| Reference | AC 20-156 |
| Rationale | The SHM architecture must be capable of producing alerts in a timely manner well ahead of the time taken for any monitored condition to propagate to a critical level. For example, if a ground station analysis is needed to provide a maintenance credit, then the time taken to provide the condition update must be shorter than time taken for the condition to manifest as a failure. |
| Additional comments | N/A |

5.6.10.4 System Interoperability

***Table 34 - System interoperability***

| | |
|---|---|
| Name of Requirement | System Interoperability |
| Statement of Requirement | The system's interoperability requirements with other systems should be described. |
| Reference | N/A |
| Rationale | SHM systems may connect with crucial air systems, including power and data systems. It is imperative to understand what the requirements of the SHM system are in the context of these other systems to ensure safe and correct operation. |
| Additional comments | Identify all requirements for the system to provide data, information, material, and services to and accept the same from other systems, and to use the data, information, materiel, and services so exchanged to enable them to operate effectively together. |

5.6.10.5 Human Machine Interface

***Table 35 - Human machine interface***

| | |
|---|---|
| Name of Requirement | Human Machine Interface |
| Statement of Requirement | Any SHM specific technical procedures should be designed and presented in accordance with good human factor principles that take into account human factors and human performance.<br>The broad cognitive, physical, and sensory requirements for the operators, maintainers, or support personnel that contribute to, or constrain, total system performance should be identified. |
| Reference | Joint Aviation Requirements JAA JAR145 |
| Rationale | All technical procedures should be designed and presented in accordance with good human factor principles to reduce the risk of human error.<br>Provide broad staffing constraints for operators, maintainers, and support personnel. |
| Additional comments | N/A |

5.6.10.6 Personnel Qualification and Training

The SHM system like the conventional NDT inspection system needs qualified personnel handling it and performing the inspection. Nevertheless, the actions of the “SHM inspector” differ from the known ones of a NDT inspector and they should be particularly defined case-by-case depending on the SHM system. The SHM inspector should cover the whole process containing:

- SHM system installation.
- SHM system initialization.
- SHM system usage (self-diagnostic test, measurement, calibration).
- Data analysis.
- SHM system maintenance and repair.

One should assure, depending on the SHM system, that special training can be provided when required and that required user manuals and troubleshooting manuals are provided. Additional information is found in AC 43-218.

***Table 36 - Personnel qualification and training***

| Name of Requirement | Personnel Qualification and Training |
|---|---|
| Statement of Requirement | Depending on the SHM system, special training, as well as user manuals and troubleshooting manual, should be provided. |
| Reference | AC 43-218 |
| Rationale | To achieve the intended benefit the SHM system must operate as designed. |
| Additional Comments | N/A |

5.7 SHM Maturity Assessment

5.7.1 Typical Maturation Efforts

The maturation efforts are often performed through research and development (R&D) programs guided by technology and product roadmaps: efforts are allocated to develop sensing technologies, algorithms, and software for SHM, and to enhance the performance of SHM in terms of increased accuracy, reduced weight, improved reliability, advanced communication, and efficient data transfer. Technology gaps and risks are identified, and efforts are allocated to fill the gaps and to mitigate the risks.

The use of SHM in parallel with common NDT methods might help to ease the transition process from highly approved and accepted technologies, such as NDT, to new emerging technologies, such as SHM for a given application scenario. Therein, the SHM system might be deployed on a trial basis, comparing its findings and results with those of traditional inspection methods. When differences appear, the SHM system might learn from those and thus, over a period of time, the SHM system has been essentially trained, and it is able to be used as a standalone system.

5.7.2 Technology Assessment

Technology readiness levels (TRL 1 to TRL 9) are used to assess the maturity of evolving aerospace technologies and, systematically, incorporate them into aerospace systems when they reach a high TRL. The risks, challenges, and gaps of an SHM technology should be re-assessed at the end of each TRL level. The actual SHM system development activities may start when the technology maturity has reached a level where the risks are significantly mitigated and challenges/gaps addressed; such a level needs not to be TRL 9. In other words, the activities required to achieve a high TRL level (e.g., TRL 6 to TRL 9) may overlap with system development activities.

The guided technology development is performed in a way that the given order to fulfill requirements and to perform the corresponding development work should be maintained and followed from TRL 1 to TRL 9. Further, the guided technology development introduces tasks to foresee implication on the technology design from higher TRL requirements within earlier TRLs in order to anticipate and prevent future issues during the development phase.

In order to reach a certain maturity level (TRL) each requirement has to be completely fulfilled from TRL 1 onwards. For instance, in order to reach TRL 5, all the requirements from TRL 1 up to TRL 5 have to be fulfilled. In this way, the maturity assessment is performed in an objective way, in contrary to the most common subjective maturity assessment, which is performed on the bases of loosely defined TRL, requirements, and criteria.

There exist several TRL definitions, one general and one SHM specific are presented in the following sub-paragraphs. Any of the available TRL definitions to monitor and assess the maturity of SHM technologies can be used. For an effective and guided SHM system development, it is recommended to follow the SHM specific TRL assessment rule.

5.7.2.1 TRL Definitions Originated by the National Aeronautics and Space Administration (NASA)

The National Aeronautics and Space Administration (NASA) TRL definitions are:

***Table 37 - NASA technology readiness levels***

| | |
|---|---|
| TRL 1 | Basic principles observed and reported.<br>This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development. |
| TRL 2 | Technology concept and/or application formulated.<br>Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be "invented" or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture. |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof of concept.<br>At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. |
| TRL 4 | Component and/or breadboard validation in laboratory environment.<br>Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory. |
| TRL 5 | Component and/or breadboard validation in relevant environment.<br>At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a "simulated" or somewhat realistic environment. |
| TRL 6 | System/subsystem model or prototype demonstration in a relevant environment (ground or space).<br>A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system, which would go well beyond ad hoc, "patch-cord" or discrete component level bread boarding, would be tested in a relevant environment. At this level, if the only "relevant environment" is the environment of space, and then the model/prototype must be demonstrated in space. |
| TRL 7 | System prototype demonstration in a space environment.<br>TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system, and the demonstration must take place in space. |
| TRL 8 | Actual system completed and "flight qualified" through test and demonstration (ground or space).<br>In almost all cases, this level is the end of true "system development" for most technology elements. This might include integration of new technology into an existing system. |
| TRL 9 | Actual system "flight proven" through successful mission operations.<br>In almost all cases, the end of last "bug fixing" aspects of true "system development." This might include integration of new technology into an existing system. This TRL does not include planned product improvement of ongoing or reusable systems. |

#### 5.7.2.2 TRL Definitions for SHM

The bases of the guided technology development and maturity assessment are—apart from the requirements—technology readiness levels (TRL) ranging from 1 to 9. These TRL have been adapted for the needs of the SHM system from the TRL definitions of Airbus which in turns have been derived to the NASA assessment scheme. These TRL for the SHM system are defined in the following:

***Table 38 - SHM technology readiness levels***

| | |
|---|---|
| TRL 1 | "On-board NDT system is only an idea on paper."<br>The basic the SHM system principles are described in the literature. It is understood in principle in which way the SHM system interacts with the structure/material information (e.g., damage, stress, strain) to be monitored. Research begins to be translated into applied research and development. |
| TRL 2 | "In depth formulation of how the system should operate. System concept is still on paper."<br>Once basic principles are observed, practical applications are invented or defined in paper, available in the literature. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. It is understood how the SHM system technology applies to monitor structural/material information (e.g., damage, stress, strain). |
| TRL 3 | "The system is partly in a hardware and software stage. Each component is stand alone."<br>Active research and development is initiated. This includes analytical and laboratory studies to physically validate analytical predictions of separate elements of the SHM system technology. Examples include components that are not yet integrated or representative. From this stage on, the development is targeted at an application scenario. |
| TRL 4 | "The system works at a laboratory stage. All components are connected to each other."<br>Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the expected system. Examples include integration of "ad hoc" hardware in the laboratory. |
| TRL 5 | "The system works at a laboratory stage. All components are connected to each other and are compliant to the harshest typical environmental conditions."<br>The fidelity of the SHM system demonstrator technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components. |
| TRL 6 | "The system is at a prototype stage. Both are compliant to relevant aircraft environment conditions."<br>A representative the SHM system prototype equipment is tested under in-flight environment on ground. Examples include testing a prototype in a high fidelity laboratory environment or under in-flight environment simulated on ground. The SHM system has reached "technology readiness" to be offered to the program. |
| TRL 7 | "The system is at a prototype stage and tested in-flight on flight test aircraft."<br>Prototype near or at final form in terms of airworthiness design and manufacturing. This TRL represents a major step up from TRL 6, requiring demonstration of an actual equipment prototype tested in-flight. Examples include testing the prototype in a flight test aircraft. |
| TRL 8 | "The system is in its final form and qualified for use on in-service aircraft."<br>The technology is proven to work in its final form and under expected conditions. In most cases, this TRL represents the end of true equipment development. Examples include developmental test and evaluation of the equipment during in-service utilization to determine if it meets specifications. |
| TRL 9 | "The system is on its final form and proven through extensive in-service use."<br>The actual application of the technology is in its final form and under mission conditions, such as those encountered in operational test evaluation. Examples include using the system under operational mission conditions. |

## 6. VALIDATION AND VERIFICATION

The evolution of an SHM system begins with desirable intended functions (e.g., crack detection, corrosion detection, load monitoring, etc.), Figure 2. When the SHM technologies required to deliver the intended functions are sufficiently matured, the development process starts with a proposed architecture that can deliver the intended functions, Figure 8. The most important aspects of architecture are physical and functional aspects: the physical architecture describes the system by showing how it is broken down into subsystems, components and items (a representation of the system physical items and their interconnections); the functional architecture identifies the functions allocated to each item (a partially ordered list of activities or functions). Based on architectural analyses and safety assessment methods, requirements are allocated to items/functions. The safety assessment process consists of functional hazard assessment (FHA), preliminary system safety assessment (PSSA), common cause analysis (CCA) and system safety assessment (SSA), which have to be considered at the aircraft level and system level, Figure 8. ARP4761 gives detailed guidelines on the SSA process and describes methods for conducting the process. In practice, the development of system architecture and the allocation of requirements are tightly-coupled, iterative processes. Validation encompasses the efforts required to ensure that the allocated requirements are sufficiently correct and complete. Verification encompasses the efforts required to check the correct implementation of the system requirements. As a simple example, a validation task could be checking that a requirement for a specific weight exists; weighing the system is a verification task assuring that the specified weight is not exceeded.

### 6.1 Development Rigor, Use and Approval of SHM Systems

A safety assessment process consisting of FHA, PSSA, and SSA is used to identify and classify the failure conditions of SHM and its items; the consequence of a failure is classified as catastrophic (A), hazardous/severe-major (B), major (C), minor (D), or no safety effect (E); then, safety requirements are established to minimize the probabilities of development errors and system failures to acceptable low values that satisfy applicable airworthiness regulations and operating rules:

- To reduce potential development errors, a development assurance level (DAL) is assigned to each item and function based on the classification of related failure conditions (e.g., A, B, C, D, or E) and based on the intended functions and the intended use of these functions along with the detailed requirements of the item. A DAL defines the rigor of all planned and systematic actions used to substantiate, at an adequate level of confidence, that errors or omissions in requirements, design, and implementation have been identified and corrected to satisfy the applicable certification requirements. The more severe the failure condition classification, the higher the level of development assurance necessary to mitigate the errors that could lead to this failure condition. Thus, the levels of rigor of the development processes of SHM items and functions are established by assigning appropriate DALs to the items and functions.

- The probabilities of failures can be reduced by introducing additional requirements that identify the need for alternative protective strategies; examples are: (a) safety maintenance task intervals, (b) partitioning, (c) functional independence where two sets of different requirements are employed to deliver the same function (e.g., a navigation function delivered by a global position system (GPS) and by an inertial reference system), and (d) development independence where the likelihood of a common development error is minimized through the development of two items using different teams/processes, different technologies such as hydraulic and electrical actuations, different software languages, different operating systems, etc.



Mainly, a DAL is assigned depending on the classification of failure conditions considering the possible independence between items and functions that can limit the consequences of development errors. For example, if a catastrophic failure condition could result from a possible development error of an item, then at least DAL A is assigned to the item. If a catastrophic failure condition could result from a combination of possible development errors between two or more independently developed items then, either at least DAL A is assigned to one item, or at least DAL B is assigned to two items; no lower than DAL C is assigned to the other independently developed items; DAL A is assigned to the process required to establish that the two or more independently developed items are truly independent.

Thus, the DAL assignments to functions and items determine the levels of rigor required for development processes including validation and verification processes. For DAL A and B, all of the validation/verification data and methods described in this document would be required to support certification. For DAL E, all of these data and methods may not be required to support certification; however, the development of a system at DAL E should follow structured validation and verification processes, perhaps at a minimum effort, to support the development of a usable useful SHM product. In other words, the validation, verification, and certification processes described in this document are not necessarily required for each SHM system; they may or may not be fully required depending on the determined development rigor; for comprehensive guidelines on DAL assignments, refer to ARP4754.

The validation, verification, certification, and use of SHM systems would require one or more of distinct development disciplines covering structural items, airborne equipment, and system use; the following paragraphs briefly discuss the development processes and rigor associated with these disciplines.

6.1.1 Modified Structures

The first development discipline covers any structural items that might have been modified by the SHM system or its sensors. Some SHM systems may require "minor" or "major" structural changes in the type design:

- According to the FAA regulation 14 CFR § 21.93, "a minor change is one that has no appreciable effect on the weight, balance, structural strength, reliability, operational characteristics, or other characteristics affecting the airworthiness of the product. All other changes are major changes."

- EASA, EC 748/2012, 21.A.91 defines the minor and major changes as follows: "a minor change is one that has no appreciable effect on the mass, balance, structural strength, reliability, operational characteristics, noise, fuel venting, exhaust emission, or other characteristics affecting the airworthiness of the product, all other changes are major changes."

- The Canadian Aviation Regulations CARs 101.01 define the major changes as follows: "major modification—means an alteration to the type design of an aeronautical product in respect of which a type certificate has been issued that has other than a negligible effect on the weight and center-of-gravity limits, structural strength, performance, power plant operation, flight characteristics, or other qualities affecting its airworthiness or environmental characteristics. A minor change to the type design is a change other than a major change," AC 521-004.

Generally, the major changes can be approved only by the appropriate regulator after witnessing validation, verification, and certification activities conducted at a level of rigor depending on the magnitude of the structural changes. It is anticipated that these activities will be performed by the type designer, mainly as structural development activities, not SHM development activities, because the aircraft structural carrying load functions are primarily performed by the structures not by SHM; this is also the case for structural items with embedded sensors. In other words, structural specialists working for the type designer or his license holder must perform these activities with rigor proportionate to the most severe failure condition of the modified structural items not SHM. For example, according to EASA CS 25.302, aircraft equipped with systems that affect structural performance, either directly or as a result of a failure or malfunction, the influence of these systems and their failure conditions must be taken into account when showing compliance with the requirements of CS 25 Subparts C and D, which are equivalent to Subparts C and D of 14 CFR Part 25; these subparts cover airworthiness requirement for "Structure" and "Design and Construction." In Canada, CARs 521.151 to CARs 521.161 indicate that a change to a type design that has other than a negligible effect can be approved only by the regulator after submitting an appropriate application and performing specified certification steps.

Generally, minor changes do not require regulatory approval. They require approval under procedures agreed with the regulator. Delegates authorized by the regulator can decide whether the changes are minor or not. A delegate can be an organization or an engineer working for the manufacturer. The regulator specifies the qualifications, experiences, and responsibilities of the delegates.

- According to 14 CFR § 21.95, minor changes in a type design may be approved under a method acceptable to the regulator before submitting to the regulator any substantiating or descriptive data. According to FAA Order 8110.37E, the acceptable methods can include approvals given by the manufacturer designated engineering representative (DER) without prior authorization by the aircraft certification office (ACO). The decision as to whether changes and/or modifications are major or minor must be reviewed with the ACO if the decision is controversial or if the DER needs guidance. According to FAA Order 8100.8D, a designated airworthiness representative (DAR) may perform examination, inspection, and testing services necessary to the issuance of certificates for the company.

- In Europe, EASA, EC 748/2012, 21A.95 states that minor changes in a type design shall be classified and approved either (a) by the agency, or (b) by an appropriately approved design organization under a procedure agreed with the Agency. Therefore, minor changes can be approved by the manufacturer under an agreed procedure and, the substantiating data maintained for potential audits; in this case, the certification process described in this document will not be required.

- In Canada, CARs 521.154 indicates that the holder of a design approval document who proposes to make a negligible change to an aeronautical product, other than a major change, shall establish procedures to ensure that the changed aeronautical product continues to conform to its certification basis and make the change after the minister accepts the procedure. AC 521-004 gives details about the procedures required for such minor modifications. Among other requirements, AC 521-004 indicates that these procedures must include a process that the persons authorized to approve these changes must use to assess the proposed change and the means by which the change is classified as minor. Such negligible/minor modifications are deemed to have insignificant effects on airworthiness. Authorized delegates (e.g., design approval designee (DAD) or design approval organization (DAO)) decide whether the modifications are truly negligible. Although minor changes do not require regulatory approval, they require the approval of the manufacturer under controlled procedures.

6.1.2 Airborne Equipment

The second development discipline covers any SHM airborne functions and items including sensors, avionics, and software. The second discipline must include validation, verification, and certification activities for each airborne function/item at a level of rigor depending on the interaction level of the function/item with other aircraft systems.

The SHM airborne item(s) may require airborne resources for power management, data acquisition, data processing, data storage, data transfer, or alert displays. If such resources are taken from, or affect, other aircraft systems, the airborne item(s) must be developed with rigor proportionate to the effect of its most severe failure conditions on the aircraft systems. If the aircraft systems support aircraft-level functions and have failure modes with the potential to affect the safety of the aircraft, the development of the SHM item(s) must strictly follow guidelines such as those of ARP4754, ARP4761, and ARP5150; examples of aircraft-level functions are flight controls, ground operation controls, engine controls, communication, passenger safety, collision avoidance, navigation and guidance, etc.

If the installed equipment does not significantly affect aircraft systems or structures (e.g., DAL E), the validation, verification, and certification processes described in document may not be required; however, an appropriate DAL should be proposed by the aircraft manufacturers to ensure their approval of the installation and use of SHM.

6.1.3 System Use

The third discipline addresses the processes required to issue instructions/manuals on how to use the SHM system. Often, issuing instructions/manuals does not require certification (i.e., the issued instructions do not require the approval of a regulatory authority (FAA, EASA, etc.)). However, they must be approved by the aircraft manufacturers or their license holders. Similar to NDI processes, it is anticipated that the manufacturers will test and calibrate the SHM equipment to ensure compliance with, for example, the approved inspection requirements. In other words, existing processes can be used to issue such SHM instructions including inspection instructions, operational monitoring instructions, etc.

It is worth emphasizing that the rigor of the development processes, and hence, the assignment of DAL to SHM functions and items, does not only depend on the classifications of SHM failure conditions, but also depend on the intended functions and the intended use of functions. SHM can be used to (a) generate advisory information, (b) provide favorable improvements or changes of maintenance practices, (c) provide favorable improvements or changes of operational practices, and (d) enable favorable changes in design methods by underwriting new materials and designs.

An advisory SHM system does not change any existing maintenance tasks, operational processes, structural integrity approaches, or design approaches. The use of an advisory system can generate evidence required to approve favorable improvement or changes to existing tasks and processes; it can also generate requirements for advanced SHM systems and new designs. The development of an advisory SHM system would require the least development efforts. The development rigor and efforts required for SHM systems that change existing practices are expected to be more than those required for SHM systems that improve these practices: an example of the former is a system that defers inspection or alters inspection intervals; an example of the latter is a system that does not change inspection tasks but performs them faster with better quality. SHM systems that would change existing design methods by underwriting new materials and designs would require the highest development rigor and efforts.

6.1.4 Implementation of Determined Rigor and Assurance Levels

The previous sections describe how the rigor of SHM development activities can be determined and how the associated development assurance levels can be assigned to items and functions. In order to implement a required level of rigor, the associated process activities described in industry accepted standards should be applied. For example, ARP4754 regards the activities described in DO-178 and DO-254 as a means to implement the determined development assurance rigor for software and electronic hardware items, including sensors. Furthermore, more extensive qualification and environmental tests would be required to demonstrate a high degree of performance rigor following standards such as DO-160. Existing SHM systems, health and usage monitoring systems (HUMS) and engine monitoring systems (EMS) use sensors such as strain gauges and accelerometers, and sensors that measure parameters such as speed, temperature, engine spool speeds, etc. The design, production, and installation of these systems (hardware, software, and sensors) have been approved and certified after demonstrating that the appropriate degrees of rigor are correctly determined, implemented, and demonstrated using standards such as ARP4754, ARP4761, DO-178, DO-254, DO-160, etc. The previous sections and the following sections highlight the considerations specific to SHM.

The previous sections also indicate that for SHM systems that have no appreciable/negligible effects on aircraft structures and systems, the design, production and installation of the systems may be approved by the holder of the type design documents (often, the aircraft manufacturer) through procedures approved by the regulator; for the other SHM systems, only the regulator can approve the design, production and installation of the systems through projects that must involve the holder. The aircraft manufacturer may approve, under approved procedures, the use of a system to improve existing maintenance and operational practices without changing them; an example of such a system is a system that performs the same existing inspection tasks at the same intervals faster with better quality. Only the regulator can approve the use of a system to change existing maintenance, operational, or design practices; an example is a system that alters inspection intervals or defers maintenance tasks; however, the use of a system to introduce minor changes may be approved by the manufacturer under approved procedures with varying involvement levels from the regulator.



6.2 Validation

Validation is the determination that the requirements for a product are sufficiently correct and complete. The validation process provides answers to the following questions: Do the requirements of the desired product fulfill its function? Are we making the right thing? Will the product, if produced in accordance with the requirements, do what the user needs and requires? Does the product definition correspond to its need and function? So, the validation process ensures and provides evidence that one is building the right thing.

The input to the validation process does not only include the SHM system requirements, but can also include information such as a definition of the system architecture, a description of the system operating environment and the development assurance levels allocated to each subsystem or item. The objective of the validation process is examining these inputs to ensure the following:

- The requirements are correct: The proof of correctness requires checking that each requirement is traceable to a parent or rationales, unambiguous, not redundant and verifiable, has a unique interpretation and can be physically implemented. The proof of correctness also requires ensuring that the requirements reflect safety analyses; e.g., all system failure conditions are correctly identified and classified; the development assurance levels are correctly assigned to functions and items.

- The requirements are complete: A list of all of possible types of requirements can form a basis for performing a completeness check. The proof of completeness requires checking that the requirements fully satisfy parent requirements, fully include functional requirements traceable to system architecture and allocated to system/items, include all of the safety requirements, fully adhere with regulatory and industry standards, cover all potential operational and maintenance scenarios, include all of the interface requirements to other systems/users, and adequately address design assumptions.

- The requirements are sufficient and necessary, and the probability of the presence of unintended functions are significantly reduced.

- The requirements comply with relevant airworthiness regulations and operating rules.

- The requirements address the needs of various SHM stakeholders (e.g., the developer, supplier, integrator, regulator, user (crew and operator), and maintainer). These needs can be addressed by firstly identifying the interfaces with aircraft structures and other systems as well as the interfaces with aircraft maintenance and operational processes. Then, the needs are addressed by identifying the relevant technical disciplines for each interface and the individuals that have the primary interest in the interface along with their development and review responsibilities.

Ideally, the requirements should be validated before the design implementation commences. However, adequate validation of requirements may not be possible until the system is implemented and tested. In other words, validation can be a staged process continuing through the development cycle; at each stage, the validation activity provides increasing confidence in the correctness and completeness of the requirements.

Differences in the format of the validation processes of various organizations are expected. However, each development organization should clearly define and adopt a structured validation process to support certification. The validation activities should be planned, tracked and performed with rigor determined from the DAL assignments to items/functions. Key aspects of a structured validation process are presented in the following paragraphs.

### 6.2.1 Validation Planning

The structured validation process should pivot on a clear plan. The plan should define the methods to be used for requirement validation and describe how any development assumptions will be managed; in other words, the plan should outline how the requirements will be shown to be complete and correct. The plan should state the roles and responsibilities of the individuals required to perform identified validation activities; the plan should estimate the efforts and timescales required to perform these activities. The plan should also identify the required validation data to be generated and collected; it should describe how validation data, information, and results will be managed stored and accessed; it should specify how reviews and investigations will be performed and their results recorded; etc. For additional details, refer to ARP4754.

### 6.2.2 Validation of Assumptions

Assumptions are introduced as a substitute for more explicit knowledge that will be available later or not directly provable at the time the information is needed. The processes used to validate assumptions may include reviews, analyses, and tests.

Some requirements may be based on assumptions about operations, environments, reliabilities, and/or human factors rather than on traceable requirements. Examples of such assumptions are the assumption made about operational flight envelopes, exposure times to various environmental conditions, traffic densities, failure rates, potential failure latency, adequacy of scheduled maintenance tasks and their frequency, completeness of failure modes analyses, adequacy of durability data to demonstrate MTBF predictions, provisions for service and repair that do not degrade safety, response times of crew or maintenance personnel, and interpretation accuracy of system information under various environmental conditions and emergency conditions. These assumptions can be accepted based on reviews against existing industry experience, common practice, historical data, service and maintenance procedures and industry standards.

Some requirements may be based on assumptions arising during the SHM iterative development process as a substitute for precise knowledge from concurrent interfacing systems underdevelopment. The validation process should check the reasonableness of these requirements, track them and ensure that they are eventually adjusted based on the precise knowledge when becomes available. The adjusted requirements may require re-validation.

Installation assumptions such as isolation, environment, sources of contamination, mount integrity, grounding, and shielding should be validated by review against industry standards/practice, selective testing and/or inspections of mockup, prototype, or production drawings/hardware. For additional details, refer to ARP4754.

### 6.2.3 Validation Rigor

The levels of validation rigor are determined by the DAL assignments to system functions and items. Additional details are provided in ARP4754. For a high DAL (A and B) a more rigorous validation process can include independent reviews of requirement data and supporting rationale to determine if there is sufficient evidence to argue the correctness and completeness of requirements; the reviews can include engineering reviews and reviews by customers, users, maintainers, and certification authorities, and can also involve independent organizations.

For DAL A and B, the validation data and methods recommended to support certification usually include the following: PSSA, validation plan, validation tracking data and summary, traceability of requirements, rationale of derived requirements, similarity and engineering reviews/inspections along with modeling, analysis, and/or tests.

For DAL E, all of these data and methods may not be required to support certification; however, the development of a system at DAL E should follow structured validation process, perhaps at a minimum effort, to support the development of usable useful SHM product. For comprehensive guidelines on DAL assignments, refer to ARP4754.

### 6.2.4 Validation Tracking and Summary

The status and data of the requirement validation process should be tracked with a level of detail proportional to the DAL assignments to functions and items associated with the requirements. The tracked status and data should include references to requirements, derived requirements, assumptions, sources of requirements, rationales, environmental and operational considerations, associated functions, hardware/software performance, DAL assignments, references to validation supporting evidence, validation methods, validation results (valid or invalid), etc. The tracked status/data should be updated regularly during the development and included in the validation summary.

The validation summary should provide assurance that the requirements were adequately validated. The summary should include: a reference to the validation plan and a description of any significant deviations from the plan, DAL assignments, validation tracking data, any supporting data, and validation results. For additional details, refer to ARP4754.



## 6.3 Verification

Verification is the evaluation of requirement implementation to determine that they have been met. The verification process provides answers to the following questions: Have we made what we were trying to make? Does the product conform to specifications? Specifications include product specifications, relevant regulations, or any conditions imposed on the implementation processes. The verification process ensures and provides evidence that the product was built correctly. So, the objectives of a successful verification process are:

- Confirm that each level of implementation meets its specified requirements.
- Confirm that the requirements are satisfied.
- Ensure that the safety analysis remains valid for the system as implemented.
- Confirm that the implemented system can correctly deliver the intended functions.

The inputs to the verification process include documented requirements and complete descriptions for each subsystem and items to be verified.

The verification activities do not only ensure correct implementation that delivers the intended functions, but also uncover and report any anomalies or unintended functions so that they can be rectified. The verification activities should be planned tracked and performed with rigor determined from the DAL assignments to items/functions.

### 6.3.1 Verification Planning

A structured verification process should pivot on a clear plan. The plan should identify all system configurations and items including any hardware and software items to be verified. The plan should identify the verification methods required to show compliance with each requirement for each identified item. The plan should identify any special test equipment and facilities required for verification. The plan should clearly define the success criteria required to judge the results of each applied verification method. The plan should organize and sequence key verification activities. The plan should estimate the efforts and timescales required to perform these activities taken into account the timescales of design activities. The plan should also identify the required verification data to be generated and collected; it should describe how verification data, information, and results will be managed stored and accessed; it should specify how reviews and investigations will be performed and their results recorded; etc. For additional details, refer to ARP4754.

6.3.2 Verification Rigor

The levels of verification rigor are determined by the DAL assignments to system functions and items. Minimizing implementation errors can be achieved through rigorous verification methods; minimizing implementation errors can also be achieved through independence. The most common means of achieving independence in verification is independent specification and execution of verification methods such as tests, analysis, and reviews (e.g., teams not involved in the system design independently generate the details of the verification methods).

For DAL A and B, the verification data and methods recommended to support certification usually include the following: SSA, verification plan, verification tracking data, verification procedures, verification summary, service experience, and reviews/inspections along with tests and/or analysis; the verification methods should involve some form of test and should also include tests targeted at minimizing the probability of the presence of unintended functions. The extent to which each method needs to be applied or data developed should be agreed with the certification authority.

For DAL E, all of these data and methods may not be required to support certification; however, the development of a system at DAL E should follow a structured verification process support the development of usable useful SHM product. For comprehensive guidelines on DAL assignments, including the applicable use of DAL C and DAL D, refer to ARP4754.

6.3.3 Verification Tracking and Summary

The status, data, methods, procedures of the verification process should be tracked and documented with a level of detail depending on the DAL of the system or item being verified. The tracked information should include clear references to requirements, associated functions, applied verification methods, verification procedures, and results, verification conclusion (valid or invalid), etc. The tracked status/data should be updated regularly during the development and included in the validation summary.

The verification summary should provide assurance that the implementation of the system/items met the requirements; the summary should include: a reference to the verification plan and a description of any significant deviations from the plan, DAL assignments, verification tracking data, descriptions of any open problems, and safety assessment results of these problems along with any supporting data, verification results, and verification coverage summary. For additional details, refer to ARP4754.

6.4 Validation and Verification Methods

For each requirement, the structured validation process should determine and apply a combination of methods necessary to validate the requirement and establish a required level of validation confidence. The validation methods include traceability, analysis, similarity, service experience, modeling, reviews, inspections, and test.

The main verification methods include analysis, similarity, service experience, modeling, reviews, inspections, and test. The purpose of these methods is to verify satisfactory implementation of requirements in all intended operating environments. More than one verification method may be necessary to substantiate compliance with requirements and assure correct implementation under worst case scenarios.

Thus, the above methods can serve the purposes of both verification and validation; however, the emphasis of a method used for validation should be demonstrating the correctness and completeness of requirements; the emphasis of the same method when used for verification should focus on demonstrating satisfactory implementation of requirements.

6.4.1 Traceability

Each requirement should be traceable to one of the following (a) a parent requirement, (b) a missing parent requirement that should be added to the system requirements, (c) rationale of an architectural choice or a design decision resulting in a derived requirement that may not be uniquely related to a higher-level requirement, or (d) assumptions arising during the SHM iterative development process as a substitute for precise knowledge that will be available later from, for example, concurrent developments of interfacing systems.

6.4.2 Analysis

The analysis of an aspect, such as functionality, performance, and safety, involves an evaluation based on decomposing the aspect into simple elements to provide unambiguous validation and verification results.

Like any aircraft system, safety analysis methods should be used for requirement validation and verification. The safety analysis methods include the methods needed for conducting an accepted safety assessment encompassing FHA, PSSA, and SSA. These methods include fault tree analysis (FTA), dependence diagram (DD), Markov analysis (MA), failure modes and effect analysis (FMEA), failure modes and effects summary (FMES), and common cause analysis (CCA). These safety-related analysis methods are described in ARP4761.

For some SHM systems, analysis may be required to demonstrate that the load carrying characteristics of the structures are not degraded by SHM; more specifically, rigorous development efforts at a high DAL may require analysis involving, for example: stress analysis, finite element analysis, and dynamic analysis that may take into account steady and unsteady aerodynamic characteristics as well as all significant structural degrees of freedom, including rigid body motions and elastic modes.

Coverage analysis can be performed through traceability examination to determine the degree to which the requirements are sufficiently and correctly allocated and implemented. Furthermore, models, simulations, and tests can be implemented for analysis purposes.

Careful analysis efforts do not only check the correctness and completeness of requirements, but also provide compliance evidence of correct implementation capable of delivering target functionality, performance, and safety objectives.

SHM analysis results can influence the required ingredients of the other validation and verification methods. Therefore, analysis details should be carefully considered; 6.5 highlights some of these details.

6.4.3 Similarity/Service Experience

Similarity involves using gained experiences to validate requirements by comparing them to the requirements of similar certificated systems or items, or by comparing them to the requirements of existing acceptable applications. Verification evidence for systems/items may also be derived from satisfactory service experience or verification evidence previously gained from similar systems/items that have been successfully implemented for other aircraft. The relevant service experience and similarity data along with engineering and operational judgment should be well documented to show that all potential implementation and installation failures have been identified, classified, and resolved.

For emerging SHM systems, such service experiences may have not been adequately accumulated. However, for an item of an SHM system, the similarity argument may be used if sufficient previous experience or data are accumulated and used to approve/certify an existing similar item fitted in another system. For example, previous experience or validation/verification data accumulated for a bonded strain gauge, a HUMS accelerometer, or a HUMS software item may be used for a similar SHM item. Validation and verification by similarity may be claimed if the two items have the same function and failure condition classification, and operate in the same environment with similar usage. Existing acceptable applications that may contain items similar to those of some SHM systems are NDI applications and ground-based data management systems. Certified systems such as HUMS contain airborne items such as processors, memories, and data transfer devices, which may be similar to airborne items of some SHM systems.

Service history obtained from samples of a new SHM item or system may be used to support validation, verification, and certification: the samples of the new item or system can be developed and shown to be airworthy; then, the samples can be installed into a number of service aircraft; data collected from the samples can support the validation of specific requirements, such as intended functions and intended use. The similarity argument gains strength as the applicable period of service experience increases.

6.4.4 Modeling

Models provide representations of given aspects of systems or items; the models are used for analysis, simulation, and/or code generation; they should be developed in structured way and should have unambiguous well defined characteristics. A system model can consist of a combination of software and hardware (computation and test article); a model of a deterministic system may be based only on computational software. The models of a desired system/item may be used to validate requirements, evaluate system parameters and generate some of the verification evidence.

A proposed system can be also modeled by hardware and/or software prototypes. Furthermore, development versions of the proposed system can be used as prototypes. Prototypes permit interaction with the modeled system to (a) prove the correctness and completeness of requirements, (b) provide some of the evidence of satisfactory implementation, or (c) highlight missing requirements, undesirable behaviors, and potential problems. A model of system environments can be developed and interfaced to a prototype to validate applicable requirements and provide a high degree of functional coverage. By exercising the prototype, missing requirements may be identified and the prototype updated by introducing the identified requirements. Thus, the prototypes are powerful validation tools that aid demonstrating the completeness of requirements.

Methods such as state diagrams can be used to construct scenarios that model the operational aspect a system. These scenarios can describe, in detailed steps, how a system should function to accomplish a desired goal in response to inputs from users in all possible operational conditions. Exercising these scenarios is a powerful means for identifying any missing requirements and eventually demonstrating the completeness of requirements.

### 6.4.5 Test

Requirements may be validated by testing articles such as structural specimens instrumented with sensors, mock-ups of systems/items, prototypes, simulations, or actual hardware/software of systems/items.

Verification tests may also be used to support validation; in other words, testing may simultaneously serve the purposes of verification as well as validation. The verification tests provide repeatable evidence that verifies satisfactory implementation of requirements. Test readiness reviews establish the applicability of the test cases to system or item requirements.

The validation tests of an article can be conducted at any time during the development phases when the article becomes available. Each article should be developed and tested using procedures documented in sufficient detail so that the article test results can be independently reproduced. Generally, an article is developed and tested to validate a group of requirements or to verify some of the implementation aspects.

By exercising an article, testing provides repeatable evidence of correctness and verifies that the requirements are satisfied. The purposes of testing a system/item are (a) to check that the requirements are met by the implemented system/item, (b) to demonstrate that the system/item implementation performs its intended functions, and (c) to provide adequate confidence that the implemented system/item does not perform unintended functions that impact safety. It should be noted that complete absence of unintended function can never be established by test. Problems uncovered during testing should be reported, tracked, corrected, and the corrected system/item retested.

The specifications of each test should include: the required input variability, the sequence of test actions required, the test rationales, the requirements covered by the test and the expected results/measurements and their qualities. These results should be tagged with the specification version of the test and the design version of tested article; the results should be recorded and concluded with a clear statement about the success or failure in achieving the test objectives.

### 6.4.6 Reviews/Inspections



Reviews or inspections involve applying experiences of engineers through visual examinations of process documents, drawings, hardware or software; they also involve witnessing tests, simulations, and demonstrations. The reviewers and their roles should be identified and their reviews structured and documented (e.g., through check lists). The reviewers should examine whether properly justified rationale or logic was applied and documented through the development phases including, for example: rationale for the allocation of requirements to hardware or software with appropriate safety objectives and development assurance levels, rationale for the classification of each failure condition through FHA, rationale for any assumptions, and rational for each test, simulation, or demonstration. The rigor of a review depends on the review scope and details, the care taken with the review, the degree of independency of the reviewers, and their experience levels.

Reviews/inspections should be structured and performed to support the validation of requirements and the determination of their completeness and correctness. The reviewers should challenge the assumptions and interpretations of captured requirements to ensure that they have not caused deviations from the meanings of the original source of requirements. Prior experiences of reviewers that cover similar systems or items, if available, should be implemented as an effective means of validating derived requirements.

Reviews/inspections could also be structured and performed to verify that requirements are satisfied and to establish that the physical implementation of the requirements of a system or an item are met. Problems uncovered through the review/inspection activities should be reported, tracked, and corrected.

## 6.5 Detailed Validation and Verification Analysis for SHM Systems

As defined in ARP4754, analysis is an evaluation based on decomposition into simple elements. Hence, decomposing the SHM-intended functions into elementary intended functions (simple elements) is an essential analysis step; the evaluation of each elementary intended function is the second important step. Furthermore, by decomposing the SHM-intended functions into elementary functional tasks, these guidelines would cover the wide spectrum of SHM systems and avoid the exclusion of an SHM system that only performs a part of an intended function or that performs SHM tasks across two functions.

Therefore, the SHM-intended functions should be broken down into elementary intended functional tasks. For example, the detection of damage location in a composite structure can be considered as an elementary task; the detection of the damage size can be another elementary task. Furthermore, practical consideration may impose requirements for performing other tasks, such as producing maintenance or management instructions to directly act upon them without the need for consulting other systems; examples are inspection and repair instructions or instructions to change aircraft routes between short and long hauls. Each SHM elementary task, whether offered or imposed, should be clearly identified, its criticality assessed, validated, and verified.



### 6.5.1 Validation and Verification Steps

The validation efforts must check the completeness and correctness of requirements adequate to reliably perform the identified elementary intended functions. The validation and verification efforts should consider the following steps:

- Decompose the SHM-intended functions into elementary intended functions; see 5.2.
- For each elementary intended function, identify from the system architecture, all physical items (and their functions) required to deliver the elementary intended function.
- Scrutinize the safety assessment results to ensure that the failure conditions of these items/functions are adequately and correctly identified and their severity classified.
- Ensure that a complete and correct set of requirement are allocated to each item and function; Section 5 presents, in detail, all potential types of requirements that can be allocated to SHM items and functions.
- Ensure that the DAL assignments to the items/functions are consistent with the severity of failure conditions taken into account the intended use of the elementary intended function and the requirements of the items/functions as well as any mitigation or independence methods used.
- Ensure that sufficient measurement characteristics are specified to achieve the elementary intended function with the rigor required; see 6.5.3.
- Apply an adequate combination of the validation and verification methods described in 6.4 with rigor determined from the DAL assignments.
- If required, extend the methods to include conclusive validation and verification plan and efforts demonstrating that the SHM system when installed into the aircraft can conclusively deliver its elementary intended functions with the specified quality measures; see 6.9.

### 6.5.2 The SHM Elementary Intended Functions

Although SHM is an abbreviation of the words structural health monitoring, these words have been used worldwide to indicate not only a monitoring elementary function but also other elementary functions such as crack detection and structural health assessment and rarely, limited management tasks. Whilst the main elementary functions of SHM are monitoring and detection functions, the following subsections define the three elementary functions of structural health systems, which include the encompassing management system of Figure 4. One SHM system can be targeted at performing one elementary intended function; another system can be targeted at performing a number of elementary intended functions.

6.5.2.1 Detection

Detection involves finding with pre-defined quality the existence, type, location and/or extent of structural faults (FD, ED, or AD) such as crack, delamination, corrosion, erosion, and moisture absorption. The detection tasks require data from dedicated onboard sensors. A detection intended function can involve a number of elementary intended functions:

- Detection of fault existence where the SHM system only indicates whether a fault exists or not with pre-defined quality. The detection quality of this elementary intended function can be defined in terms of a detection probability along with acceptable “false positive”/”false negative” probabilities; “false positive” occurs when the system trigger a false alarm indicating the presence of a damage that does not exist; “false negative” occurs when the system fails to detect a damage that does exist.

- Detection of a fault location where the SHM system is targeted at detecting the damage location with pre-defined quality. The detection quality of this elementary intended function can be defined in terms of a pre-defined zonal and co-ordinates accuracies to guide, for example, subsequent fault repairs.

- Detection of a fault extent where the SHM system is targeted at detecting the fault size with a pre-defined quality. The detection quality of this elementary intended function can be defined in terms of probability of detection (POD).

- Detection of a fault type where the SHM system is targeted at detects more than one fault type and correctly discriminates between them. However, the optimization of an SHM sensor technology is often targeted at detecting a specific fault type.



6.5.2.2 Monitoring

Monitoring involves maintaining regular surveillance over factors that can lead to or indicate structural faults; these factors include, for example, loads, usage, impact events, fatigue, and/or environments. The monitoring functions can be classified as direct and indirect monitoring functions:

- The direct monitoring functions use inputs from sensors that directly measure the factors of interests; for example, the loads can be monitored using data directly acquired from strain gauges or fiber optic sensors.

- The indirect monitoring functions implement algorithms that operate on a set of parameters acquired by onboard sensors to indirectly compute the factors of interest; for example, the loads can be accurately estimated from FDR parameters such as speed, acceleration and temperature.

Monitoring events such as impacts or landings that may be excessive and lead to overloads or damage can include a number of elementary intended functions:

- Event occurrence: The monitoring quality of occurrence can be defined in terms of occurrence probability along with acceptable “false positive”/”false negative” probabilities.

- Event location: The monitoring quality of location can be defined in terms of a pre-defined zonal and co-ordinates accuracies.

- Event magnitude (e.g., impact energy or overload value): The monitoring quality of event magnitude can be defined in terms of accuracy.

The threats of the monitored events to structural integrity are evaluated through assessment tasks.

6.5.2.3 Structural Health Assessment

Structural health monitoring output assessment will be done by algorithms managing data from various sources under the framework of structural health management, as illustrated in Figure 4.

Assessment involves the use of detection and/or monitoring results along with design information and structural properties to determine the current structural status and generate, if required, instructions including inspection, repair, and replacement instructions. The design information and structural properties include, for example: design flight envelopes, fatigue data and algorithms, crack growth algorithms, design usage spectra, strength, toughness, and critical crack sizes.

In other words, the information required for assessment includes information directly generated by structural health monitoring (damage and operation monitoring information) and information held by other stakeholders (design/structural information).

Assessment can also include prognostics where the future condition of the structure are forecasted and/or the remaining life of critical components estimated.

A complete airframe health assessment solution should be combination of a structural health monitoring solution complemented by an assessment solution, as seen in Figure 4.

### 6.5.3 Quality Characteristics of SHM Measurements

Although the specific requirements for an SHM system, to include the requirements for the "quality" of measurements, will be defined by the OEM/user, the sections included in 6.5.3 highlight some of the possible and likely types of quality requirements that might be included.

The measuring capabilities of the majority of SHM systems are unlike those of direct measuring devices that measure quantities such as temperature and acceleration. The SHM measuring capability can involve specialized algorithms operating on data acquired from more than one sensor; the SHM measuring capability should provide reliable results under all foreseeable operational condition. Therefore, the performance of the SHM sensors/algorithms should be evaluated in terms of quality attributes adequate for each associated elementary intended function: the values of these quality attributes should not be too high or too low, they should be values consistent with the elementary intended function, the function intended use and its assigned DAL level; for example, the measurements of an advisory non-critical system may not need to be as accurate as those of a safety critical system. For each SHM elementary intended function, the validation process should check the presence, adequacy of these quantitative quality requirements that characterize the SHM sensor/algorithm measurements.

Therefore, the following subsections present widely used measurement characteristics and discuss their interpretations or extensions for SHM measurements. Requirement allocation and validation activities should identify, from these characteristics those characteristics that are applicable to the SHM application under consideration; not all of the characteristics are necessarily required for each SHM application.

#### 6.5.3.1 Accuracy

The accuracy is the degree of closeness of agreement between a measured quantity value and a true quantity value of a measurement; the true quantity value is obtained by a device that has been widely accepted as being accurate with high degree of confidence. The accuracy may be quantified by the differences between the true value and the two extremes of observed measured values (a maximum and a minimum values). In simple terms, the accuracy of a measured quantity value is the degree to which it is true and free from error; the accuracy can be measured as the difference between the measured quantity value and an accepted quantity value. The accuracy determination for SHM measurements should include sufficient quantitative measures that relate to the intended function; for example, these quantitative measures can indicate: (a) accuracy of a crack length, damage size, or computed load values, and (b) accuracy of an identified zone containing structural damage. The true values of such measurements should be obtained by devices that have been widely accepted as being accurate. For example, known accurate loads or weights can be applied to SHM structures and compared with measurements taken from SHM to determine the system accuracy; X-rays and other measuring device can be used to determine true crack sizes to be compared with the outputs of SHM.

#### 6.5.3.2 Reliability of SHM systems

The reliability is measured by the probability of repeatedly and successfully observing a desirable outcome from an entity under prescribed conditions. The entity can be any observable item such as structure, system, sensor, mission, or event. A common example of a desirable outcome as sited in system engineering literature is the ability of a system or component to perform a required function under stated conditions for a specified period. Therefore, for SHM systems, reliability can involve evaluating the probability of successfully delivering an intended function under specified environmental conditions for a specified period (e.g., the maintenance free period of the system); for example, the reliability of a crack detection system can involve evaluating the probability of successfully detecting cracks having lengths greater than a specified minimum under specified environmental conditions for a specified period.