



AEROSPACE RECOMMENDED PRACTICE

ARP6821™

Issued

2025-02

Guidance for Assessing the Damage Detection Capability of Structural Health Monitoring Systems

RATIONALE

The goal of this document is to provide guidance for establishing the damage detection capability of Structural Health Monitoring (SHM) systems to assist in the safe adoption of SHM systems for assessing aircraft integrity. The maturity of SHM systems has evolved to the point where some SHM systems have demonstrated sensitivities that meet or exceed current damage detection requirements and are being considered for on-aircraft use. As a result, there is a growing need for well-defined methods to statistically quantify the capabilities of SHM systems. However, while there are many agreed-upon procedures for quantifying the performance of nondestructive inspection (NDI) techniques, there are limited guidelines for assessing SHM systems. While the intended function of the SHM and NDI systems may be very similar, there are distinct differences in the parameters that affect their capability and differences in their implementation that require special consideration. For example, some factors that affect SHM sensitivity include the flaw size, shape, orientation, and location relative to the sensors, equipment hardware and software, structural configuration, variability in the damage, residual strains, stress fields, operational and environmental variables, and issues related to the presence of multiple flaws within a sensor network. The objective is to apply statistical methods to laboratory and flight test data to derive Probability of Detection (POD) values for SHM sensors in a fashion that agrees with current NDI validation requirements. It is anticipated that all people in the aviation industry that are working in the SHM arena will benefit from standardized methods to establish the performance and reliability of SHM systems. They should be able to use the SHM reliability document to clearly define the different types of SHM damage detection approaches and to assess the damage detection capability of each SHM application.

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1. SCOPE

This document contains information and guidance necessary for the development of a representative, repeatable validation program that may be utilized to assess the capability of SHM systems. The nature of SHM data differs from that seen in traditional nondestructive evaluation (NDE) applications in that the position of SHM sensors is fixed and SHM data can be available much more frequently (if not continuously) over time. This document presents methodologies that can be used to arrive at SHM capability while considering the unique nature of SHM deployment. Each SHM system must be considered independently to determine the applicability and limitations of the guidance contained here for each SHM system being assessed.

1.1 Purpose

ARP6821 provides guidelines for SHM technology users to establish the damage detection capability of their SHM system. It provides guidance on the definition and application of the statistical concepts for POD and how these concepts can be applied to the deployment of SHM technologies in aircraft (both fixed and rotary wing). This document addresses how to satisfy the damage detection capability requirements for an SHM system. It defines different types of SHM detection scenarios and describes how to develop assessment methods for each type of scenario to assess the detection capability. This document also addresses the limitations in establishing the SHM damage detection capability and provides related information that is useful in preparing procedures for conducting SHM interrogations.

The nature of SHM data differs from that seen in traditional NDE applications in that the position of SHM sensors is fixed and that SHM data will be available much more frequently (if not continuously) over time. Similarities between NDE and SHM assessments will be highlighted to provide a foundation in traditional damage detection performance measures. In addition, considerations of the controlling factors to be considered when collecting SHM system data will be discussed. The intent is to augment ARP6461 to address specific, unique aspects of quantifying SHM damage detection. As a result, some beneficial overlap with ARP6461 will exist where necessary. However, to avoid redundancy with ARP6461, this document will simply reference ARP6461 when appropriate.

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.
- Quantifying the damage detection capability of SHM systems while considering all factors that may affect SHM performance.
- 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 the 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 will require negotiation and agreement with the appropriate regulatory agency.

1.3 An Overview of This Document

This document provides key definitions, guidelines, and examples that can assist civil and military stakeholders in the development of methods for assessing the damage detection capability of SHM systems. The approach adopted in developing the guidelines was to maintain harmony with applicable regulations, standards, and existing guidelines that have been adopted by original equipment manufacturers (OEMs) for aircraft NDE equipment and to augment them, as necessary, with specific interpretations and extensions pertaining to SHM. Where existing acceptable definitions, methods, and processes were available for specific application, they have been adopted with interpretations specific to SHM added for clarity. Additional definitions, methods, and processes have been collated or developed where their equivalents did not clearly exist. In this way, consistency is maintained with existing regulations, standards, and industry-accepted practices. The approach adopted in developing the guidelines was also to develop a self-contained document that can be easily understood by engineering graduates. Applicable documents from which the SHM key guidelines and definitions were collated are listed in Section 2. This document does not replace any existing regulations or certification requirements currently in existence.

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 exemption 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
AIR6892	Structural Health Monitoring Considerations and Guidance Specific to Rotorcraft
ARP4754	Guidelines for Development of Civil Aircraft and Systems
ARP4761	Guidelines for Conducting the Safety Assessment Process on Civil Aircraft, Systems, and Equipment
ARP6461	Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft

2.1.2 A4A Publications

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

MSG-3	Operator/Manufacturer Scheduled Maintenance Development
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2.1.3 Code of Federal Regulations (CFR) Publications

Available from United States Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

14 CFR Part 25	Airworthiness Standards: Transport Category Airplanes
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2.1.4 FAA Publications

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

AC 25-19 Certification Maintenance Requirements

AC 25-571-1 Damage Tolerance and Fatigue Evaluation of Structure

2.1.5 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO 13372 Condition Monitoring and Diagnostics of Machines - Vocabulary

2.1.6 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-254 Design Assurance Guidance for Airborne Electronic Hardware

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-810 Environmental Engineering Considerations and Laboratory Tests

MIL-STD-1530 Aircraft Structural Integrity Program (ASIP)

2.1.8 Other Publications

JSSG-2006 Department of Defense Joint Service Specification Guide: Aircraft Structures

Aldrin, J.C., Annis, C., Sabbagh, H.A., and Lindgren, E.A. (2016). *Best practices for evaluating the capability of nondestructive evaluation (NDE) and structural health monitoring (SHM) techniques for damage characterization*. (42nd Annual Review of Progress in Quantitative Nondestructive Evaluation). American Institute of Physics.

Aldrin, J.C., Medina, E.A., Lindgren, E.A., Buynak, C.F., Knopp, J.S. (2011). *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). Stanford: DEStech Publications Inc., 2452-2459.

Dotta, F. and Rulli, R. (2022). *Damage Detection Systems Qualification and the Advancement for Fixed Wing Aircraft Maintenance Procedures*. Airlines for America NDT Forum.

Forsyth, D.S. (2016). *Structural Health Monitoring and Probability of Detection Estimation*. (42nd Annual Review of Progress in Quantitative Nondestructive Evaluation). American Institute of Physics.

Giurgiutiu, V., Roach, D., Redmond, J., and Rackow, K. (2003). Active Sensors for Health Monitoring of Aging Aerospace Structures. *International Journal of Condition Monitoring and Diagnostics Engineering*.

Janapati, V., Kopsaftopoulos, F., Li, F., Lee, S.J., Chang, F-K (2016). Damage Detection Sensitivity Characterization of Acousto-Ultrasound-based SHM Techniques. *Structural Health Monitoring*, 15, 143-161.

Kessler, S.S., Thomas, G., Borgen, M., and Dunn, C.T. (2015). *Carbon Nanotube Appliques for Fatigue Crack Diagnostics*. Proceedings of the 10th International Workshop on Structural Health Monitoring, Stanford University.

Kessler S.S. and Dunn, C.T. (2019). *Detection Sensitivity Analysis for a Potential Drop (PD) Structural Health Monitoring (SHM) System*. Proceedings of the 12th International Workshop on Structural Health Monitoring, Stanford University.

Kessler, S.S. and Schubert-Kabban, C.M. (2023). *Covariance of Limit Defining Pairs (CLDP): A Novel Approach to Establishing Detection Sensitivity for Structural Health Monitoring Data*. Proceedings of the 13th International Workshop on Structural Health Monitoring, Stanford University.

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Meeker, W.Q., Escobar, L.A., and Pascual, F.G. (2022), *Statistical Methods for Reliability Data, Second Edition*. John Wiley & Sons.

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Thompson, R.B. (2008). A Unified Approach to the Model-Assisted Determination of Probability of Detection. *Review of Quantitative Nondestructive Evaluation*, 27, 1685-1692.

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.

AIR6168 Landing Gear Structural Health Monitoring

ARP5150 Safety Assessment of Transport Airplanes in Commercial Service

ARP5987 Establishing Software Assurance Levels for Engine Health Management Systems utilized for Maintenance Credit (Work in Progress)

2.2.2 Code of Federal Regulations (CFR) Publications

Available from United States Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.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 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

2.2.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, 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

2.2.4 FAA Publications

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

AC 20-115	Document RTCA DO-178, Software Considerations in Airborne Systems and Equipment Certification
AC 20-152	Document RTCA DO-254, Design Assurance Guidance for Airborne Electronic Hardware
AC 20-156	Aviation Data bus Assurance
AC 29-2C MG 15	Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems
AC 121-22	Maintenance Review Board Report, Maintenance Type Board, and OEM/TCH Inspection EASA Publications
AC 521-004	Changes to the Type Design of an Aeronautical Product
FAA CPI Guide	FAA & Industry Guide to Product Certification, Sept 2004.
Order 8100.8D	Designee Management Handbook
Order 8110.37E	Designated Engineering Representative (DER) Guidance Handbook



Documents

Document Sharing Hub

2.2.5 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

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

2.2.6 RTCA Publications

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

DO-200 Standards for Processing Aeronautical Data

DO-201 Industry Requirements for Aeronautical Information

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

2.2.7 Transport Canada Publications

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)

2.2.8 U.S. Government Publications

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

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

MIL-STD-1472 Design Criteria Standard: Human Engineering

2.2.9 Other Publications

ENV13005 Guide to the expression of uncertainty in measurement

JAA JAR145 Aviation Maintenance Human Factors

Hong et al. (2018). Uncertainty quantification for acoustic nonlinearity parameter in Lamb wave-based prediction of barely visible impact damage in composites. *Mechanical Systems and Signal Processing Journal*.

Kumar, A., Roach, D., Beard, S., Xinlin, Q., and Hannum, R. (2006). *In-situ monitoring of the integrity of bonded repair patches on aircraft and civil infrastructures*. Proc. SPIE 6179, Advanced Sensor Technologies for Nondestructive Evaluation and Structural Health Monitoring II, 61790M. <https://doi.org/10.1117/12.657681>.

Schubert-Kabban, C.M., Greenwell, B.M., DeSimio, M.P., and Derriso, M.M. (2015). The probability of detection for structural health monitoring systems: Repeated measures data. *Structural Health Monitoring*, 14, 252-264.

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2.3 Definitions

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

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

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

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

CAPABILITY: A reproducible detection sensitivity proven by statistically sufficient measurements on test articles that include all possible factors that affect the sensitivity of the measurement technique. It is a measure of the defect size that can be detected by a given health monitoring method.

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 (refer to ARP4754).

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

CONDITION-BASED MAINTENANCE: Maintenance performed as governed by condition monitoring programs (refer to ISO 13372.)

CONDITION MONITORING: The process of observing the state of an asset 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 (refer to ARP4761)

DAMAGE: Damage to aircraft structure is any flaw, defect, crack, corrosion, disbond, delamination, discontinuity, or other type that degrades, or has the potential to degrade, the performance of the affected component. Damage can be inherent in the material, introduced during manufacturing, created during normal and abnormal operations and maintenance, or caused by material degradation.

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

DAMAGE TOLERANCE: The ability of the airframe to resist failure due to the presence of flaws, cracks, or other damage for a specified period of unrepaired usage (refer to JSSG-2006).

DEVELOPMENT ASSURANCE: All of those planned and systematic actions used to substantiate, at an adequate level of confidence, that development errors have been identified and corrected such that the system satisfies the applicable certification basis (refer to ARP4754).

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 (refer to AC 25-19).

FALSE CALL (FALSE POSITIVE): Inspection system response interpreted as having detected a flaw or defect when none is present at the inspection location.

FALSE CALL RATE: The percentage of times a technique will indicate a flaw when no flaw is present in the material.

FUNCTIONAL HAZARD ASSESSMENT: A systematic, comprehensive examination of functions to identify and classify failure conditions of those functions according to their severity (refer to 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) (refer to 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 (refer to AC 25-571-1).

INTEGRITY: Qualitative or quantitative attribute of a system or an item indicating that it can be relied upon to work correctly (refer to ARP4754).

ITEM: A hardware or software element having bounded and well-defined interfaces (refer to ARP4754).

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 (refer to ARP4754).

PROBABILITY OF DETECTION (POD): A metric that quantifies the accuracy of an inspection. It involves a statistical method that identifies how well a health monitoring procedure detects a specific defect type (determines the defect size that can be detected with a given statistical probability and confidence level). Inspections, in practice, have multiple factors that affect the detectability of flaws (e.g., human factors, uncertainty in the geometry of the part under test, sensor/instrument noise). POD assesses the probability of detecting a flaw or defect while considering these factors.

PRODUCT: Hardware, software, item, or system generated in response to a defined set of requirements (refer to ARP4754).

QUALIFICATION: The processes of verifying that a product (system, hardware, and software) complies with a specified set of performance and airworthiness requirements (refer to ARP6461).

RECEIVER OPERATING CHARACTERISTIC (ROC): This analysis is a graphical approach for analyzing the performance of a classifier. It uses a pair of statistics - true positive rate and false positive rate - to characterize an inspection system's performance. The ROC curve, which is defined as a plot of test sensitivity as the Y coordinate versus its false positive rate as the X coordinate, is an effective method of evaluating the performance of diagnostic tests.

RELIABILITY: The degree to which the result of a measurement, calculation, specification, or system performance can be depended on to be accurate.

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

STRUCTURAL HEALTH MONITORING (SHM): The process of acquiring and analyzing data from onboard sensors to determine the health of a structure (refer to ARP6461).

STRUCTURAL HEALTH MONITORING (SHM): A nondestructive inspection process or technique that uses in-situ sensing devices to detect damage (refer to MIL-STD-1530).

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

VALIDATION: The determination that the requirements for a product are correct and complete. Validation must accurately represent the real-world application and ensure that the system output produces the proper performance. Are we building the right aircraft/system/function/item (refer to ARP4754)?

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

2.4 Acronyms

A4A	Airlines for America, formerly known as Air Transport Association of America, Inc. (ATA)
A-SHM	Automated SHM
AC	Advisory Circular (FAA) or Airworthiness Certificate
ACO	Aircraft Certification Office
AD	Accidental Damage
AISC-SHM	Aerospace Industry Steering Committee on Structural Health Monitoring
AL	Assurance Level
AMM	Aircraft Maintenance Manual
ARP	Aerospace Recommended Practice (SAE)
CAR	Canadian Aviation Regulations
CCA	Common Cause Analysis
CFR	Code of Federal Regulations
CNT	Carbon Nanotube
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 Union Aviation Safety Agency
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
G-11 SHM	SAE G-11 Structural Health Monitoring Committee (Aerospace Industry Steering Committee)
GAMA	General Aviation Manufacturers Association
GVI	General Visual Inspection
HUMS	Health and Usage Monitoring System
ICA	Instructions for Continued Airworthiness
IEEE	Institute of Electrical and Electronics Engineers
IP 105	International Maintenance Review Board Policy Board issue paper 105
ISO	International Organization for Standardization
JAR	Joint Aviation Requirements
LOV	Limit of Validity
LRU	Line Replaceable Unit
MAPOD	Model Assisted Probability of Detection
MIL-HDBK	Military Handbook
MRB	Maintenance Review Board
MRBR	Maintenance Review Board Report
MSG-3	Maintenance Steering Group 3
MTBF	Mean Time Between Failures
NDE	Nondestructive Evaluation
NDI	Nondestructive Inspection
NDT	Nondestructive Testing
OEM	Original Equipment Manufacturer
OM	Operational Monitoring
OSTI	One-Sided Tolerance Interval
PFA	Probability of False Alarms
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 (piezoelectric ceramic material)
RPM	Random Parameter Model
ROC	Receiver Operating Characteristic
S-SHM	Scheduled SHM
SDI	Special Detailed Inspection
SHM	Structural Health Monitoring
SODAD	Size of Deterioration at Detection
SSA	System Safety Assessment
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. ASSESSMENT PROCESS FOR DAMAGE DETECTION CAPABILITY

As indicated in ARP6461, damage detection involves finding with predefined quality the existence, type, location, and/or extent of structural damage such as cracks, delamination, disbonds, corrosion, and erosion. The predefined quality can be defined in terms of acceptable levels of quality characteristics. Although the specific requirements for an SHM system to have specified levels of quality characteristics are set by the OEM/Operator, ARP6461 defines the following quality characteristics that are often considered: accuracy, reliability, precision, repeatability, resolution, range, bandwidth, sensitivity, durability, and maintainability. The SHM capability assessment process should not only focus on quantifying the damage detection performance characteristics but also verify that acceptable levels of SHM durability and maintainability are achieved. There is a linkage between the durability and maintainability of an SHM system and its capability that must be considered when assessing capability.

The capability assessment process should start before considering the activities required for the aircraft implementation of SHM. As indicated in ARP6461, these activities 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. These activities conclude with developments of instructions for production, installation, operation, and maintenance. The processes adopted to guide these activities include safety assessment, validation, verification, and configuration management. A successful capability assessment process would provide data essential to support the activities/processes required for the aircraft implementation of SHM at a target development assurance level (DAL).

At each step of the capability assessment process, the OEM/Operator would use the step result to initiate or terminate the following steps. The OEM/Operator would initiate the activities/processes required for the SHM aircraft implementation only after successful capability assessment. The type certificate (TC) holder or the supplemental type certificate (STC) holder in agreement with the OEM/Operator should determine the acceptable levels of quality characteristics. For example, an OEM or an operator may choose to incur the costs of implementing SHM having moderate levels of quality characteristics to generate advisory information that does not generate any maintenance/management actions; reasons for such a choice may include: (a) generating information for future structural upgrades and (b) allocating architectural capacities for expected SHM systems having higher levels of quality characteristics.

The POD and reliability are among the important quality characteristics for which ARP6461 states the following: “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. Reliability can indicate the quality of detecting the occurrence of structural events such as hard landings or detecting the presence of faults by computing three probabilities: the probability of correct identification of faults/events, the probability of missing the faults/events (the probability of false negatives), and the probability of indicating the presence of faults/events that did not exist (the probability of false positives).”

In real-world applications, uncertainties play a major role in the assessment of any SHM function. In that sense, it is important to define characteristics that help us quantify the assessment outcomes of the intended SHM function. These characteristics are defined as:

- The POD evaluates the capability of an SHM system to detect a predefined damage size. ARP6461 states the following: “Tests are performed to establish POD curves that indicate the probabilities and confidence levels associated with detecting different damage sizes. Often, the capability of NDI is measured by the smallest damage size ‘a_s’ found with 90% probability at a 95% confidence level (detecting a_s with 90/95 capability). Having established the capability of NDI applications, procedures are adopted to avoid the use of degraded capability and ensure measurement repeatability to assure reliability. The quality terms used to characterize NDI applications should be used for SHM systems performing the same tasks as the NDI applications.”
- A decision threshold (damage detection threshold) can be established to relate an SHM system response with damage detection. The Damage Detection Threshold, chosen within the entire decision boundary, divides the decision making into four groups (see Figure 1).
 - True Positive (TP). The part of the damaged-condition distribution to the right of the decision boundary, i.e., ① + ③ in Figure 1. This means that the damage is identified truthfully (correct decision).
 - False Positive (FP). The part of the healthy-condition distribution to the right of the decision threshold, i.e., ② + ③. This means that damage, which does not actually exist, is falsely identified (a wrong decision).
 - True Negative (TN). The part of the healthy-condition distribution to the left of the decision threshold, i.e., ④ + ⑤. This means that no damage exists and is hence not identified (correct decision).
 - False Negative (FN). The part of the damaged-condition distribution to the left of the decision threshold, i.e., ⑤. This means that the damage, which indeed exists, is not identified (wrong decision).

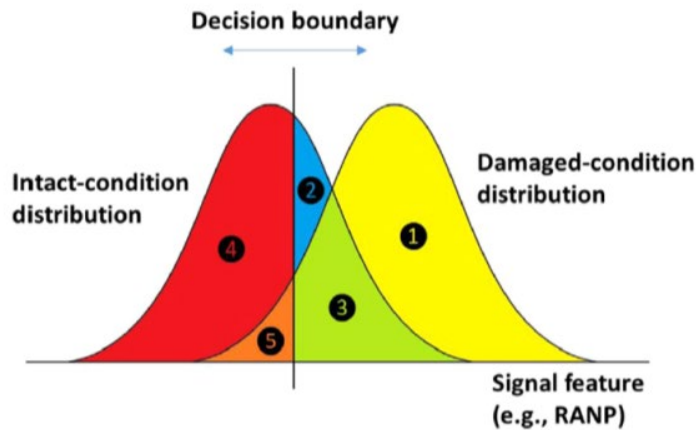


Figure 1 - Outcomes of the intended SHM function

Having classified the possible results scenarios as above, a relationship between TP and FP can be obtained by sliding the decision threshold across the entire decision boundary range of the signal feature's value (the horizontal axis). The resulting curve is referred to as a receiving operating curve. Within the decision boundary, the users of the SHM system will determine a damage detection threshold (decision threshold), which is the SHM signal threshold that is established to produce the necessary damage detection while considering the possibility of producing false calls. The damage detection threshold value is selected to provide the required POD while also meeting the probability of false alarm requirement. See 6.9 for a complete discussion on establishing the damage detection threshold.

NOTE: This ARP is mainly focused on defining design of tests and associated capability analyses methods needed to demonstrate that an SHM capability requirement has been met.

So, ARP6461 distinguishes between a probability noted from one point on the POD curve (one damage size, "as") and the probabilities noted at several points (several damage sizes); in some publications, the former is called "capability." In this document, however, and as stated above, the SHM capability assessment process can involve other quality characteristics. For example, for most of the SHM intended functions, specifying levels of false positives and false negatives would be required. The receiver operating characteristic (ROC) curve is therefore an effective method for evaluating the robustness of an SHM function. For detecting a damage location, the detection quality could be defined in terms of predefined zonal and coordinate accuracies sufficient to guide subsequent repairs; for detecting damage existence, the system would only indicate whether a fault exists or not (hit or miss) with a predefined quality that could be defined in terms of a detection probability; for detecting the extent of damage, the predefined quality could be defined in terms of POD; for detecting a fault/damage type, the SHM system should correctly discriminate between likely fault/damage types. A more thorough discussion of POD can be found in Section 7.

The assessment process of the SHM damage detection capability should involve the following steps:

- Prepare a capability statement. Unlike a research program, the prepared statement should not change after the start of subsequent steps; the capability statement should include sufficient information that enable the OEM to (a) judge the suitability of the SHM technique; (b) justify the costs and plan further assessment and development steps; and (c) tailor/extend the structural coverage not only based on a supplied sensor datasheet but also based on a specified fundamental SHM domain/range configuration. See Section 4.
- Identify the causes of variabilities in SHM measurements. See Section 5.
- Design and conduct assessment tests.
- Apply statistical methods to the test results to quantify the relevant SHM performance characteristics. See Section 7.

4. THE SHM CAPABILITY STATEMENT

The developer should prepare an SHM capability statement specifying the proposed system. The developer should work closely with the OEM to seek any information about the target structures to assist in specifying a capable SHM system. The developer should not only specify the anticipated SHM detection capability but should also provide clear specifications covering hardware, software, and detection coverage. The SHM capability statement should include:

- A datasheet stating the characteristics of the basic sensing technology, which can include applicable information such as weight, dimensions, operating temperature range, maximum/minimum storage temperature, resolution, sensitivity, shock durability, frequency response, input/output voltage, current consumption, etc.
- Clear specifications of the SHM system configuration in terms of: (a) a domain area covered by sensors connected by wires or wirelessly to any airborne or ground-based hardware/software to produce domain signals; and (b) a range area over which damage can be detected from a range vector (response) obtained collectively from the domain signals.
- Clear specifications of detection variables. A detection variable of a given SHM system is a parameter that, when it varies, alters the system response to the same damage in the monitored structure.
- Preliminary estimates of the relevant SHM quality characteristics.
- Evidence of a reasonable level of detection maturity based on, for example, laboratory tests, historical data, R&D programs, and flight tests.

The domain area is the area of the structure that contains a collection of sensors to be used for detecting target structural damage within a predefined range area. In specifying the domain area of a given SHM system, the configuration of the collections of sensors (the sensor locations) over the domain area should be clearly described. The domain area is the area within the perimeters of the collections of sensors: it can be the small area of a global SHM system that reaches a larger range area; it can be the small area of a local SHM system that reaches a hot spot range area below; or it can be in the close vicinity of the domain area. The number of sensors of the domain area is the least optimum number of sensors that can adequately detect damage over the range area with expected quality levels. The assessment results associated with the configuration of one domain and its corresponding range are applicable to the same configuration of any domain/range at similar structural locations. In specifying the domain signals, the technology supplier must describe all the hardware connected to the collection of sensors and the software operating on the sensor signals. The domain signal is a vector that is collectively prepared from the signals of the collection of sensors and used for structural fault detection over the predefined range.

The range area is the area of the structure over which target structural damage, if it exists, can be detected from the range vector with expected detection quality. The range vector is the final response of the system that consists of components derived from the domain signals to directly indicate the extent (size), location, and/or type of target structural damage. In specifying the range vector, the technology supplier must describe the software operating on the domain signals to collectively produce the range vector; the software description should cover any processing techniques, calibration factors, thresholds, noise attenuation algorithms, etc. Thresholds might be introduced to mask benign damage that has no effect on safety and, at the same time, might cause undue concern, trigger unjustifiable maintenance actions, and lead to consequent rise in costs and reduction in aircraft availability. The capability assessment process must determine whether the proposed system can miss damage that can grow to critical size over a planned operational period; in other words, one of the main objectives of the capability evaluation exercise is to determine the largest damage size that the system can miss. Some of the SHM systems may frequently acquire signals and process the frequent signals to, for example, attenuate noise or confirm/magnify diagnostic results. The range vector is a final collective output derived from the signals (or frequent signals) of the collection of sensors.

For SHM systems targeted at detecting the existence of structural damage, the range vector can be a simple binary indication of the presence or absence of the damage (hit or miss). For SHM systems targeted at detecting the extent of structural damage, the range vector is a real calibrated value that indicates the intensity (size) of the damage, noting that the probability of detecting the existence or intensity of faults is expected to increase as the fault extent (size) intensifies.

For SHM systems targeted at detecting both the location and extent of structural damage, the range vector consists of a real value that indicates the fault intensity and a pointer that indicates the damage location. The location pointer can be an integer for a look-up location table or real values indicating the location coordinates. While the accurate detection of the damage extent is required, the precise detection of the damage location is an excessive impractical requirement; a damage location should be judged as successfully detected (a hit) if it is within the area to be accessed for repair or replacement. It will be inaccurately detected (a miss) if it is outside this area or if damage located within the area is not reported as present.

For SHM systems targeted at detecting and discriminating between fault types, the range vector is a pointer indicating the type of the fault; the pointer can be an integer value. For example, zero value can indicate the absence of any fault, and a non-zero value between “1” and “*n*” can indicate a fault type among expected “*n*” fault types.

In summary, the capability statement should clearly specify the domain and range of the SHM system, including the system hardware, software, algorithms, and calibration factors; the algorithms must be developed and applied to produce unambiguous domain signals and range vectors. The capability assessment process focuses on testing the entire system, including its hardware, software, algorithms, and calibration relationships. From the results of the assessment tests and by applying appropriate statistical analysis on the components of the range vectors, the capability of the system can be determined.

5. CAUSES OF VARIABILITIES IN SHM

SHM, like NDE, is subject to variability that may affect the damage response. By “variability sources” we understand the set of parameters potentially influencing the damage response in the application of an SHM system. The object of this section is to provide an overview of typical variability sources occurring in SHM applications that shall be considered when building a design of experiments (DoE) to evaluate detection capability.

The process starts with the understanding and identification of the influent variability sources. This step might also be the opportunity to work on reducing the identified variability sources of the SHM system. Once the SHM setup is fixed and needs to be evaluated quantitatively for its detection capability, then the identified sources of variability shall be taken as input for the DoE of the test campaign. It is to be noted that this process is similar for classical NDE except that, in the case of SHM, sources of variability are partly different, especially linked to the fact that SHM components are installed permanently on the aircraft.

A sample list of SHM sources of variability is described below:

- Damage size, shape, orientation, and initiation site (including changes in these characteristics over time).
- Structural variability:
 - Due to manufacturing tolerances.
 - Due to maintenance, repair, modification, and usage. This is especially true for areas where components are joined as localized stresses in the joints that change over time and frequently have a significant impact on the response of the sensing system.
- Sensor(s) installation and positioning onto the structure:
 - Relative location of the sensor(s) with respect to the potential damage.
 - Sensor(s) bonding - bonding thickness and homogeneity.
 - Other characteristics relating to installation-to-installation variability like cabling and connecting.
 - Installer's level of training, competency, and experience.
- Sensor(s) interrogation: functional test, calibration, and interrogation procedure.
- Sensor-to-sensor manufacturing variability.

- SHM equipment aging and degradation resulting from life cycles (exposure to humidity, temperature, vibrations, loading)
- Interrogation conditions: mechanical state such as strain conditions (e.g., due to variable fuel loading) when doing the interrogation; temperature and humidity when doing the interrogation.
- Changes in sensor performance over time due to events that can be anticipated in the area (e.g., maintenance, usage, repair, modification).

Depending on the application case, this list shall be adapted to properly describe the variables that effectively influence damage detection in the considered application case.

5.1 Typical Sources of Variability In SHM Configurations

5.1.1 Aircraft Structure

The operational loading conditions of the structure when acquiring data by SHM may influence the response of the system. For acquisitions made during different operational conditions, such as climb, descent cruise, and other maneuvers, the influence of the structural loads of these operational conditions must be assessed. Furthermore, the surrounding conditions of the SHM sensors during data acquisitions may influence the system response. Therefore, the ranges of operational loads and environmental parameters (e.g., temperature, pressure, acidity, and humidity) within which the SHM system will operate should be evaluated. Preliminary tests should determine whether each of these parameters is a system variable that influences the SHM response; for example, the system response may (or may not) vary with a rise in temperature from -20 °C to 40 °C. The capability tests should only cover the ranges of the parameters that are found to be variables. Nevertheless, for most of the SHM implementations as NDI alternatives, very narrow ranges would be expected. Furthermore, functional relationships may exist between variables and associated responses. If validated algorithms (models) can be prepared to account/compensate for the influence of these variables, tests over the range of this parameter may not be required. If a model requires measurements of a parameter such as temperature or load, the SHM system itself should provide these measurements; alternatively, the SHM supplier should work closely with the OEM to get these measurements from aircraft sensors or modeled data.

5.1.1.1 Damage

5.1.1.1.1 Damage Size

The damage is often characterized by its “size,” whatever exact dimension it represents. The POD is expressed as a function of this variable, exactly like for NDE.

5.1.1.1.2 Damage Shape

The damage is, in general, much more complex than a simple “size.” For a given size, it can have different shapes that introduce some variability in the signal response. The effect of this variability source is similar to what is encountered in classical NDE.

5.1.1.1.3 Damage Site and Orientation

The damage site and its orientation are of great importance regarding detection, even more in SHM than in NDE. Indeed, if the damage initiates slightly from another location than expected or with a different orientation, the SHM system cannot provide the degree of freedom of a classical NDE to compensate with movement, as the SHM equipment is fixed. It should be well understood by people responsible for specifications and requests for inspection procedures that any underestimation of the importance of this variable might lead to a wrong design of the SHM system, introduce a bias in the detection capability study, and eventually lead to undetected damages on aircraft.

5.1.1.2 Structural Variability

5.1.1.2.1 Manufacturing Variability

The structural component on which the SHM system is deployed might also introduce some variability. Indeed, every structure manufacturing has some tolerances applying to, for instance, thicknesses, assembly positions, and paint and coating thickness. In that sense, many factors potentially influencing the SHM response shall be considered in a damage detection capability study. In classical NDE, the calibration step is usually used to remove most of the variability, but in the case of SHM, the calibration step is different as the sensor is fixed (see 5.1.4.3), so the relative influence of structural variability might be different in this case.

5.1.1.2.2 Structural Variability Over the Life of the Aircraft

Aircraft structure will change over time due to multiple reasons, including variability introduced during manufacture, maintenance, repair, modification, and use. Representative factors that will change include fit-up stresses, addition or removal of structural elements, plus replacement of original components during use of a system. In addition, routine maintenance can have unintended impacts on the structural configuration at the region of interest being evaluated by an SHM system. These factors can influence the performance of an SHM system. Therefore, if such changes are possible, they must be identified through a comprehensive analysis of all possible parameters that could affect the capability of an SHM system. Once identified, these factors need to be evaluated by a sensitivity study to determine if they need to be included in the validation study. The analysis of these factors needs to be fully documented to enable regulators to review the testing processes and the rationale if one or more of these factors are determined to not be included in the evaluation.

5.1.2 SHM Equipment

5.1.2.1 Hardware

5.1.2.1.1 Sensor-to-Sensor Manufacturing Variability

Sensor manufacturing processes may produce variability from sensor to sensor, which leads to variability in the sensor responses (e.g., frequency, bandwidth, noise level, damping, lift-off, sensitivity). We include in this category the sensor-cable connection and the connector at the end of the cable for interrogation. The root causes of this variability are very specific to the particular sensor technologies.

This phenomenon also happens for classical NDE sensors but is in general practically compensated by the calibration process of the inspection procedure so that it becomes a negligible variability source in the overall NDE configuration. However, in the case of SHM, the calibration of the sensor(s) prior to the inspection is affected by the fact that the sensor is permanently installed and cannot be moved on a reference block to adjust a compensation. Even if calibration procedures can also be designed for SHM (see 5.1.4.3), the full compensation of a sensor-to-sensor variability is more difficult for SHM and is therefore usually a variable to be considered in the detection capability assessment approach.

5.1.2.1.2 Cable Length

Depending on the specific location of the sensor on the aircraft with respect to the connecting interface for interrogation of the SHM equipment, sensors can have different cable lengths, ranging from centimeters to several meters. In this case, the influence of the cable length on the noise and especially on the signal-to-noise ratio should be investigated and potentially considered in the damage detection capability study.

5.1.3 Installation

In SHM applications, sensors are installed permanently on the structure. The installation process then becomes a key step and also a major contributor for potential variability. Throughout all future interrogations, a given sensor will always be at the same location, but if the sensor is badly positioned or positioned such that it exhibits high variability or bonded differently, the consequence might be dramatic for the inspection result.

Typically, to fit a system into a fleet of aircraft, a well-defined installation process is developed and specialized technicians are trained to perform the process with assured quality. Furthermore, tools are designed for the installation process to control installation parameters such as pressure, torque, temperature, and adhesive thickness. Quality processes are also developed to operate and maintain the system. Such quality processes should be carefully developed for the target SHM system. Then, during the capability tests of the system, the quality processes for installing, operating, and maintaining the system should be adopted.

5.1.3.1 Sensor(s) Positioning

SHM sensor response is by nature sensitive to sensor positioning as it is fixed on the structure. In some cases, a small error on the sensor positioning can yield a dramatic decrease of the ability to detect the target damage.

Think of a small crack to be detected by a focused UT single-crystal probe. A small tilt in the angle of the probe at installation can lead to a complete miss of the target crack. Respectively, a small variation of the crack initiation site or the crack orientation can also lead to the same effect, as this is the relative positioning of the sensor(s) with respect to the crack which is important (see 5.1.1.1).

SHM configurations should be thought to be, as much as possible, robust with regard to sensors positioning. Robustness can be brought by:

- Robust positioning process (e.g., with tooling).
- Tolerance of the SHM setup with respect to small variations. Wide spectrum configurations or configurations providing electronic degrees of freedom (e.g., phased arrays) can bring tolerance to sensor positioning.

In any case, sensitivity to a positioning variation within a defined range (tolerance) shall be evaluated in a detection capability assessment for SHM.

5.1.3.2 Sensor(s) Bonding

The bonding material, the thickness of the bond line, and the strength of the bond can typically influence the sensor response. By providing a built-in test function that includes a check of the response of the sensor (functional check), one can clear out the “not bonded” possibility. However, variation in bonding quality or bond-line thickness shall be considered in a detection capability assessment for SHM.

5.1.3.3 Installation of Cables and Connectors

Installation of cables and connectors onboard the aircraft is not a source of variability as it is far from the active part of the sensing equipment. It can generally be taken out of the variability sources as such, but it shall be integrated in the durability analysis as it may suffer degradation over time and cycles with a potential influence on the sensor's response.

5.1.3.3.1 Installation Training

The training should include how to install the sensors (including surface preparation, sensor connections, and cabling) and hardware setup, instructions on SHM system operation (data acquisition, data analysis, data interpretation), airworthiness assurance requirements, and any other relevant tasking needed to deploy the system on an aircraft. All required training should be documented and entered into the user's aircraft maintenance files. Training initiatives and installation processes should address the issues described in 5.1.3 to ensure proper SHM system response, minimize installation-to-installation variability, and generate competent installers. Training initiatives should also consider any periodic refresher training that may be needed to ensure that installers are properly utilizing the currently recognized best practices.

5.1.4 Inspection

Depending on the sensor's interrogation process, the type of variability may differ. Basically, three main steps can be identified as possibly responsible for variability: interrogation, calibration, and diagnostic.

5.1.4.1 Functional Test

Many SHM systems feature a functional test procedure to check that the sensor(s) properly answer and can be used to acquire data that will be used to state on the presence or not of damage in the structure. The functional test enables to detect if the sensor(s) has a problem, is disbonded (totally or partially), is damaged, or cannot be used for inspection for any reason.

As any function, this test has a non-null probability to provide a wrong answer - either indicating that the sensor works while it is not or saying the sensor does not work while it does. In the first case, the POD would be directly affected as wrong data would be collected. In the second case, the POD is not affected, but the trust in the SHM system might be affected. If this test is part of the inspection procedure, it shall be integrated in the damage detection capability campaign to take it into account in the capability assessment.

5.1.4.2 Interrogation

Interrogation is the process through which one can get data from the SHM sensor(s). It usually needs to connect an electronic device to the sensor(s), either physically or remotely, pilot the acquisition electronics to excite the sensor(s), and collect the response. In this process, if it is a physical and manual connection to the sensor(s) with an SHM system, then the variability associated to the interrogation is just the same as for a classical NDE.

If it is a remote or automated interrogation, then the interrogation process can introduce some specific variability due to powering, connection, or dataflow variations or problems. In any case, the detection capability campaign shall be realized using the interrogation process targeted for the application on aircraft so that this variable is properly considered in the assessment.

5.1.4.3 Sensitivity Calibration

Calibration in NDE is usually performed by moving a probe on a reference block containing reference damage or a reference area to adjust the acquisition parameters (gains, phase) to the current acquisition conditions. This process enables to calibrate the full acquisition chain and compensates for many variables linked to the probe, the device, the temperature, and other variables.

In the context of SHM, the sensor is fixed on the structure, so calibration cannot happen by moving the sensor over a reference block with a calibrated damage. Yet calibration is necessary to ensure meaningful interrogation results and compensate for the probe variability, the acquisition unit, and the acquisition conditions (e.g., temperature). Specific calibration approaches are developed for SHM using reference data after installation of the equipment for each sensor and/or a specific calibration interrogation executed prior to the inspection interrogation to adjust to the current conditions. These processes are themselves subject to hypotheses (e.g., the sensor has not evolved from one measurement to the next one or evolved following a given behavior) and might introduce some variability while reducing others. Calibration is a key step in the reliability of the SHM system and shall be integrated as part of the detection capability campaign.

5.1.4.4 Software

Software components used to operate the SHM system are also a potential source of variability. Software can be embedded on an electronic device (e.g., FPGA) onboard the aircraft for preprocessing, signal conditioning, analog to digital conversion, signal processing, or can be on the interrogation unit to support the interrogation phase and diagnostic.

Software configuration management shall be put in place so that every change or update is assessed and recorded. However, even with configuration management, the software can contribute to the overall variability. While the software code is fully deterministic and not variable as such, the application of the code can contribute to the chain causing variability in the outcome.

For example, a variation in the signal as input to the code (due to any other variability source) can cause additional variability in the outcome. This is especially true for any software that is using artificial intelligence/machine learning (AI/ML) processes to help produce a decision. As AI/ML methods rely intrinsically on classification and regression, the effect for additional data on the decision-making process of when a signal is outside of acceptable limits needs to be addressed. Also, the use of the software by an inspector, the manipulation, parameterization of the software, or interpretation of the results through the software can be a significant source of variability.

It is recommended that the software is used in the experiments for detection capability assessment, for all measurements, in the exact same process as the one of the real applications, including the functional test process, the calibration, the interrogation process, and diagnostic.

5.1.5 Interrogation Conditions

This section deals with factors external to the SHM equipment potentially introducing variability during the interrogation of the SHM equipment.

5.1.5.1 Operational Loads

The operational loading conditions of the structure when acquiring data by SHM may influence the SHM response if the area and damage to be detected is sensitive to such loading conditions (e.g., crack subject to compression due to fuel loading inspected with an ultrasonic technique). In this type of case, the loading condition should become a part of the variability to account for in the damage detection capability study. Preliminary tests or engineering judgment should be used to assess if any of the variability developed in this section shall be part of the damage detection capability study.

5.1.5.2 Environment During SHM Interrogation

It is necessary to consider the environmental conditions during SHM monitoring. The SHM response may change due to effects of environmental conditions (e.g., temperature, humidity, pressure). If so, the environmental conditions should become a part of the variability to account for in the damage detection study. The goal of such an assessment of environmental effects is not necessarily to prove that the system works in all conditions, but it could be to capture the set or range of acceptable monitoring conditions. For example, the response from an SHM system may change as a function of temperature such that it is necessary to indicate an acceptable monitoring temperature range. In this example, if the aircraft structure is outside of the designated temperature range, then the SHM system cannot be interrogated for damage detection until the structure is determined to be in the allowable temperature range.

5.1.6 Durability and Environmental Factors

Every component of the SHM equipment that is installed onboard the aircraft will be exposed to the aircraft operating environment. Temperature, humidity, altitude, loading, vibration, lightning, shock, or any other physical constraint associated to the aircraft life are variables potentially influencing the response of the SHM system over time and cycles. Therefore, these variables shall be included in the damage detection capability study to assess the detection capability behavior of the system throughout the expected lifetime of the equipment.

Environmental tests consist of the application of environmental conditions representative of what the SHM equipment can see, on ground and in flight, in the area of application on aircraft. They are useful especially to check the SHM equipment ability to survive extreme conditions applicable to the aircraft area. Durability tests consist of the application of environmental conditions representative of aircraft cycles, with a repetition of cycles. They are useful to assess the detection performances of the SHM system over time and cycles. These tests can be performed either on aircraft directly and/or using specific lab test means like climate chambers and/or other mechanical test benches. Durability tests should also consider any other physical environments associated with the aircraft that could affect the durability of the SHM system. These include the range of aerospace chemicals an SHM installation could be exposed to that may affect the response/performance of the SHM system.

The description of durability requirements usually provides, for each variable:

- A range of values (minimum, maximum) that shall be sustained by the equipment.
- A typical cycle (minimum, maximum; variation rate).
- The number of cycles to be sustained by the equipment.

Notice that the specific location of the SHM equipment on the aircraft has an influence on the variables to consider and also on the requirements for each of these variables. The definition of environmental and durability tests can be supported by standard documents like DO-160 or MIL-STD-810 and be specified using engineering judgment. It is important to note that the testing must be for both the anticipated environment of the SHM system and reflect the total time between anticipated maintenance of the SHM system, plus include the number of times the system is activated and/or data is acquired from the system.

A representative, but not complete, sample list of typical environmental factors potentially affecting SHM includes:

- Temperature: temperature variations due to inherent temperature variations on ground and during flight.
- Humidity: humidity variations on ground and during flight.
- Altitude: pressure variations caused by altitude variations due to the aircraft cycles.
- Loads: loads applied on the aircraft structure at the location of installation.
- Vibrations: vibrations spectra in the area of installation on aircraft.
- Lightning: indirect effect of lightning strike on the SHM equipment.
- Operational aviation chemicals that may interact with the SHM equipment.

The full SHM equipment installed onboard the aircraft shall be submitted to environmental and durability tests as not only the sensor can suffer degradation but also the connections, cables, and connectors. In addition, any maintenance, repair, or modification of the structural region of interest must be considered to determine if these actions would affect the durability of the system.

A representative durability test will include repeated interrogation of the SHM equipment during and after environmental and durability tests to record signals and assess the influence of these tests on the detection capability. The periodic interrogation during the cycles can be an additional source of information to characterize a potential degradation of the SHM detection performance of the process of durability.

5.1.7 Human Factors

The human factors potentially affecting an SHM system's detection capability are usually associated with:

- Installation of the SHM components on aircraft.
- The inspection process involving:
 - Hardware manipulations: connecting sensor(s), cable(s), and interrogation unit(s).
 - Software manipulations for functional test, calibration, interrogation, and diagnostic.
 - Interpretation of signals for diagnostic.

In addition, the effect of human factors in these steps may be influenced by the operating conditions, such as:

- The type of access to the area
- Temperature
- Humidity
- Light intensity
- Time factors, especially those that may add pressure to complete a task within a certain time period