

White Paper



Structural Health Monitoring (SHM)

Enabling Technology for paradigm shift in next generation Aircraft Design and Maintenance

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Executive Summary

Aircraft industry continuously reinvents itself for reducing acquisition, operational and maintenance costs while meeting stringent performance requirements. The challenge is to design light weight aircraft structures with reduced maintenance cost. It is essential to maintain readiness levels of the aging aircraft fleet to avoid squeezing out recapitalization budgets. This paper discusses a new realm of predictive maintenance known as in-situ Structural Health Monitoring (SHM). SHM helps in realizing slender and light weight structures leading to reduction in fuel costs, provides long-term cost savings in maintenance and also helps in extending fleet life.

Current Aircraft Industry Challenges

Aircraft industry faces many challenges to reduce both operational and maintenance cost. The weight of an aircraft directly impacts the operational (fuel) cost. At present, a pound saving in aircraft weight translates to \$100 savings per year per aircraft. Many innovations have taken place in aircraft industry towards weight reduction. The percentage of composite, hybrid materials and advanced aluminum alloys in airframe have increased substantially over the years realizing significant weight benefits. However, full potential of composites, hybrids and advanced aluminum alloys, as substantial reduction in material allowable, are yet to be realized due to still prevailing conservative design philosophy. It is essential to increase the confidence in assessing fatigue, crack/delamination identification/growth and damage tolerance characteristics of these advanced materials. This will help in reducing conservatism built in current aircraft structural design leading to realization of slender airframe structures.

The second major cost incurred by Aircraft industry is current aircraft Maintenance Repair and Overhaul (MRO). MRO industry was about \$45B in 2007 and is expected to reach \$61B business by 2017. In 2007 about 18,935 commercial aircrafts and 38,970 military aircrafts were in service worldwide. The average age of more than 50% of US commercial airplanes is about 15 years and US military planes is about 23 years [1][2]. Majority of the maintenance costs incurred are due to preventive maintenance schedules and scrapping of expensive parts, owing to the conservative approach, which still hold a good life. It is forecasted that Military aircraft retirements will outpace deliveries in about three years and probably this trend continues in the next decade [3]. Hence, it is essential to extend the life of the existing aging aircrafts so that the required fleet is in place to maintain level of readiness [4]. The importance of controlling sustenance costs is epitomized by the fact that many old U.S. military aircraft are expected to remain in service for another 25 years which will encounter severe aging problems [5].

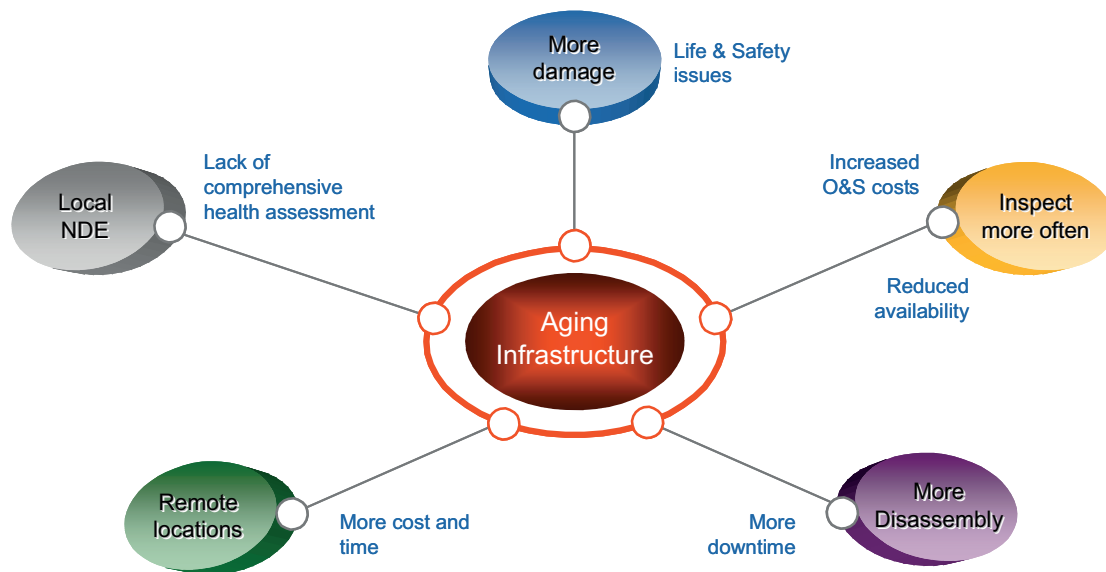


Figure 1: Issues related to the aging infrastructure

As shown in Figure 1, aging infrastructure poses many issues. Inspection requirements become more frequent due to higher risk of damage in the aging fleet, thereby increasing the maintenance costs. Frequent disassembly of the aircraft adds to the increased downtime. As most of the current inspections are limited to local area inspections, it takes a lot of experience and expertise to assess the overall health of aircraft at any given point in the time.

Structural Health Monitoring (SHM)

Aircraft under goes various stress reversals during its ground-air-ground (GAG) cycles due to which fatigue cracks develop, which may grow into critical sizes over a period of time and may lead to catastrophic failure. In addition, many structural damages can occur due to ground handling, bird hit, debris hit, lightning strike, tool drop etc. The critical size of a crack, beyond which repair is required, is termed as damage tolerance which is dependent on many factors like material used, operating and environmental conditions. The nature and growth of these damages varies based on the type of the material used for an aircraft component. Thus structural health in the context of aircrafts refers to retaining the complete structural integrity for the entire GAG cycle. The aircraft's structural integrity is of utmost importance owing to the huge risk of losing life in the event of any mishap.

Structural Health Monitoring (SHM) is an online health monitoring system and enables instantaneous maintenance triggers when the system's health falls below predefined level of confidence. An SHM system's key focus is to monitor aspects related to damages and load conditions which have direct influence on fitness of structure for service. Multi-faceted functionalities of an SHM system include detection of un-anticipated structural damage events, damage location identification, damage characterization through imaging, monitoring damage growth and enabling feedback action / alarm mechanism. SHM system makes embedded non-destructive testing sensors an integral part of the structure and operates with minimal manual intervention.

The three key subsystems of SHM are shown in Figure 2. These include

- Diagnosis
- Prognosis
- Life extension and predictive maintenance

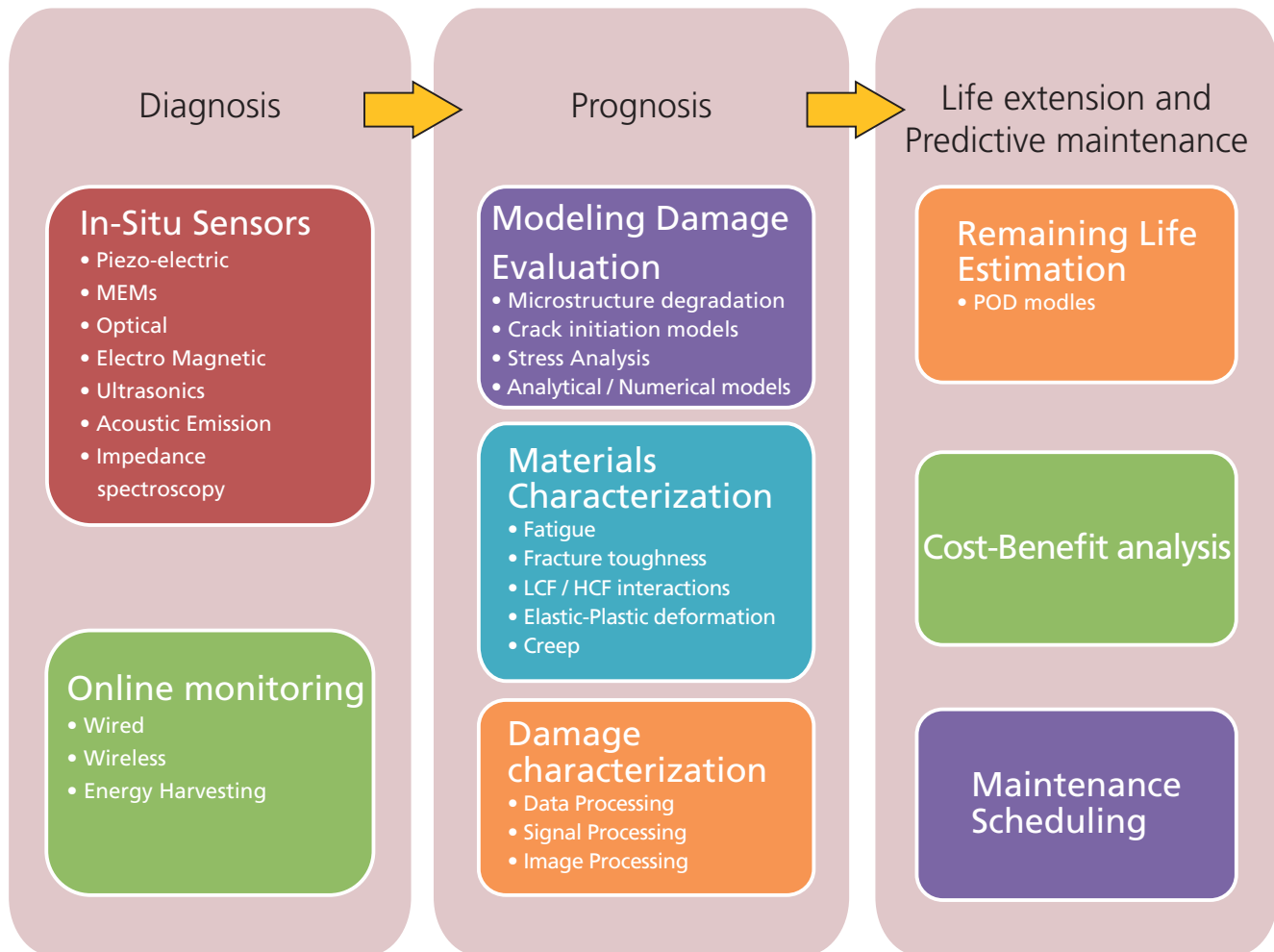


Figure 2: Components/sub-systems of a SHM system

Diagnosis subsystem deals with monitoring of the entire structure under inspection. It has an underlying wired/ wireless network of sensors, which are generally designed to cover large areas of inspection in the structure. As the aircraft structure comprises of various kinds of hybrid material combinations, a variety of sensing mechanisms need to be adopted for different sections of aircraft. Periodic measurements are tapped from these in-situ sensors either through wired or wireless media into a centralized analysis station in the SHM system. Prognosis subsystem takes the periodic inspection data from diagnosis subsystem to analyze and estimate various possible internal and external damages that might have occurred in the structure. The estimated damage characteristics are used in the damage evolution models to estimate the remaining life of the structure as well as to find a necessity to trigger maintenance. The damage evolution models are effectively combined with probability of detection (POD) models for structural integrity assessment and remaining life assessment. Cost-benefit analysis is performed to arrive at a tradeoff between the safety allowance and maintenance costs to be incurred while triggering maintenance in the given conditions.

At present, research and development is focused on evaluating and maturing technologies that can make these subsystems practical for commercial deployment of full-fledged SHM system. More of the ongoing research activity is discussed in the subsequent sections.

SHM in Aircraft Maintenance

Due to various stress conditions during the flight, aircraft structures develop various kinds of defects which include stress corrosion, cracks, accidental damage, impact damage, delaminations, debondings, water ingress, damage due to loads/strain. A thorough inspection schedule is instructed by the aircraft manufacturer, which include various types of checks as shown in Table 1. The current state of the art in the schedule-based inspection and maintenance is to conduct time-based localized inspection of few selected parts of the structure. Hence, at any given point of time, it is difficult to comprehensively understand the structure's health in totality.

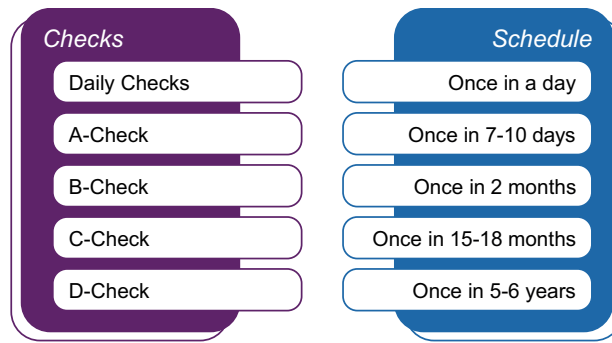


Table 1: Aircraft Maintenance Schedule

Schedule based maintenance works well during designed service life. However, over time, the focus shifts towards life extension i.e. need to use aircraft longer than planned or to use it for different missions than designed. As aging aircrafts continue in service, they result in increased inspection time, increased operations and maintenance costs and decreased availability, due to higher risk of hazard. Such high risk of hazard and maintenance costs can be minimized by employing a continuous online monitoring technique which triggers the maintenance schedule as and when required. SHM enables condition based maintenance with a capability to initiate inspection requirements not only based on the scheduled intervals, but also on actual wear indicators exhibited by the equipment at that given point of time. Advantages of SHM as opposed to the conventional schedule based maintenance are summarized in Figure 3. Continuous in-situ online monitoring of the structure will help having intelligent maintenance scheduling. Thus, the prognostic and predictive maintenance through SHM will significantly reduce the downtime of these critical structures, thereby optimizing operations and maintenance spend and improving fleet availability for the aircraft operators.

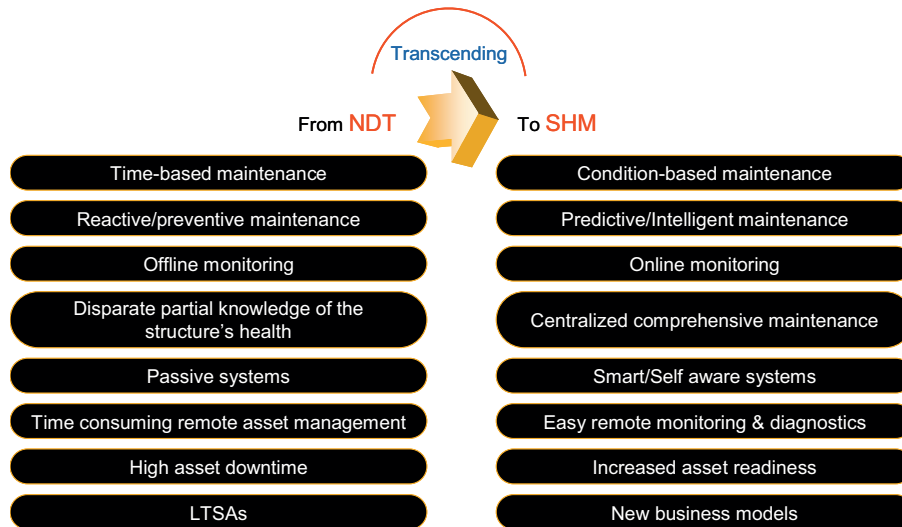


Figure 3: Advantages of SHM over conventional NDT

Theoretically, SHM aims at having the online monitoring of the complete infrastructure analogous to the human sensory nervous system and a centralized tracking, analyzing and decision making system analogous to human brain. It is also envisaged that this online monitoring be wireless to avoid complex wiring systems. The sensors are also expected to be smart self-aware systems so that they can automatically connect or disconnect from the network depending on their health. Such systems also enable remote in-service inspection. SHM technology helps in

- Increased availability of the aircraft [6]
- Effective assessment of actual damage events
- Reduced costs of life-cycle and total ownership
- Reduced logistics
- Increased safety and reliability

Moving beyond preventive maintenance into predictive maintenance, in-situ Structural Health Monitoring (SHM) can provide long-term cost savings and extended fleet life. Thus, SHM will enable new maintenance concepts.

Influence of SHM in Aircraft Structural Design

Composites, hybrids and advanced metal alloys are increasingly being used in the airframe to reduce the overall weight of the aircraft. However, the full potential of these advanced materials are not realized due to less confidence in their fatigue and damage tolerance characteristics. Lot of conservatism is built in the material allowables used by the aircraft design houses. Many degradation factors are used for these allowables taking into account unknown factors like stress concentrations, operating and environmental conditions. SHM can play an important role in increasing confidence in predicting the fatigue and damage tolerance characteristics of these materials. Any increase in material allowables will have a direct impact on the overall structural weight reduction.

However the use of SHM will revolutionize the current structural design practices and processes. The structural design is no longer considered as mechanical product design but a system design in which both mechanical and electronic components (sensors) interact. Both the structure and the health monitoring system have to be designed in parallel. Identifying optimal sensor locations is quite challenging for a structure. This need to be identified based on the overall behavior of the structure and its operating and environmental conditions. The choice of sensors depends on the material used for the structure especially for layered structures like composites and hybrids. Each of these sensor locations should not become sources of delamination. The interaction between the structure and sensor plays an important role in capturing and analyzing the response for effective health monitoring.

Certification clearance of SHM enabled aircraft structures is quite challenging. Many experiments need to be carried out to characterize the interaction between sensors and the structure supported by strong analytical models. This data need to be used for certification clearance before the technology gets into aircraft.

Technology Landscape

In the last few decades, research in all related areas of Structural Health Monitoring has gained momentum with many active players from sponsoring agencies such as NASA, EASA, CRC- ACS, Sandia Labs, Boeing, Airbus and many other government agencies in North America, Europe and Asia. Indian government has also formed National Program for Smart Materials (NPSM) to conduct research on smart materials and SHM for aerospace and defense applications. The collaborative research efforts among these sponsoring agencies, industries and academia has reached a maturity level that enables SHM systems to be tested on experimental flight tests. In order to consolidate and streamline the research efforts, the SHM community felt the need for standards and certification procedures to be brought into place, before their technologies can be fully implemented. In November 2006 a Structural Health Monitoring - Aerospace Industry Steering Committee (SHM-AISC) was formed. This committee includes representatives from original equipment manufacturers (OEMs) (Airbus, BAE-Systems, Boeing, Bombardier, EADS, Embraer, Lockheed - Martin), government organizations (EASA, FAA, Sandia Labs), operators (US Air Force, US Army, NASA, ATA, AEA), academia (Stanford University, University of Tokyo) and industry (Fuji HI, Honeywell). As depicted in Figure 4, research and development is progressing on various segments of SHM such as

- Sensors for next generation materials such as hybrid and composites
- Sensors which can be bonded, embedded or integrated into the structure
- Smart sensors, either wired or wireless, which can collaborate in a networking environment to cover large area of inspection;
- Energy harvesting mechanisms for self-reliable, durable sensors that have longer life time
- Communication architecture and protocols for energy efficient wide area monitoring and diagnostics;
- SHM software that can schedule the repair and maintenance requirements based on life prediction models and the damage detection capability from sensor data;
- In-situ performance testing of these end to end integrated SHM systems in the test flights.

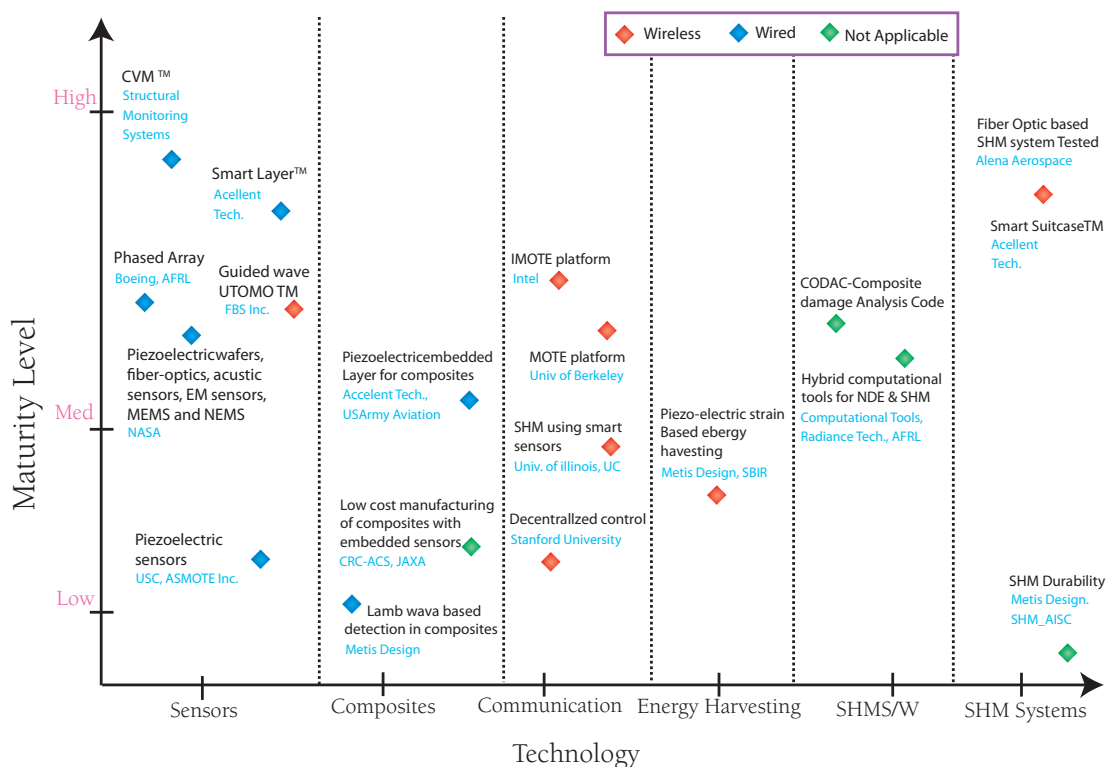


Figure 4: Summary of various state of the art technologies in Structural Health Monitoring domain
Source: Infosys research

Los Alamos National Laboratory has published literature reviews on structural health monitoring [7][8] till 2001. Some of the ongoing research work in SHM is summarized below.

Sensors: Sensor research is progressing towards technologies that can detect multiple damage types of interest such as cracks, corrosion, debonding, delamination, impact damages, etc. in both metallic and composite structures. Following sensing technologies depicted in [9][10] have become prominent due to their low-profile, lightweight, easily mountable or embeddable, durable and reliable features. These include Fibre Bragg Gratings (FBG), Acousto Ultrasonics (AU), Comparative Vacuum Monitoring (CVM), Acoustic Emission (AE), Electro Magnetic (EM) and Microwave.

Sensor Networks: Distributed sensor networks can be deployed in any of the three approaches listed below. More the complexity of the system, less the labor required to monitor the structure.

1. **In-situ sensors:** In this simplest approach, sensors are the only objects permanently installed on the structure. At the desired inspection intervals, the data is collected manually with external data acquisition systems.
2. **Sensor network with in-situ data acquisition:** In this system, miniature packaged electronics is placed in-situ with the sensor network. The gathered data must be downloaded periodically by a technician via manual hook-ups on the ground.
3. **Wireless Sensor network:** As advancement to the second approach, these in-situ networks do real-time data transmission to a remote site. Co-located processing electronics conducts structural health diagnostics in real time. The telemetry system enables continuous, wireless transmission of data - in the air or on the ground - to a remote site. A web site can be programmed to interrogate the data and use preset thresholds to provide continuous information regarding structural health. Further, the web site can be programmed to automatically send an e-mail to maintenance personnel if there is a need for repairs or other maintenance.

Energy Harvesting: Active research is going on by various institutions and funding agencies for energy harvesting methods to enable in-situ self-powered SHM systems. Most likely, solutions are application specific, as they depend upon total power budget, SHM algorithm/sensing duty cycle, power generation capability and storage, and low cost electronics available. Sandia National Labs published a report [11] summarizing various energy harvesting techniques presented in the literature. Some of them include piezoelectric transducers generating power from mechanical vibration, microscale piezoelectric harvester based on resonance, polyvinylidene fluoride (PVDF) films, micro electromagnetic power generator based on mechanical deflection, thermoelectric generators using Seebeck effect and RF energy harvesting to supply energy to the networks using RF radiation

SHM diagnostic software: SHM software forms the backbone for operational execution and communication between various sub-systems at different levels. Some of the critical components at various stages of SHM system are system calibration and setting optimizations, operation and data retrieval from sensor networks, algorithms to process sensor data for damage identification and assessment, integration of damage models from SHM data with probabilistic models of fatigue crack growth to attain product life management models, assessment of probability of failure, repair and maintenance scheduling based on design tradeoff along with optimization goals such as cost, reliability, and system availability, including the maintenance effects to reflect changes in SHM system operating parameters.

Test SHM Systems: Commercial full scale SHM systems are not available at present. But, there are developments by many organizations as shown in Figure 4 which have undergone in-flight testing for their viability. Out of these, FAA has cleared certification process to use CVM™ (Comparative Vacuum Monitoring) technology developed by an Australia based company “Structural Monitoring Systems”. Airbus and Boeing are few of the early adaptors of this CVM™ technology.

Future of SHM in Aircraft Industry

An ideal SHM system for aircraft covers the inspection and integrity of the entire aircraft including various functional segments viz. airframe, structure and power plant and their corresponding subsystems. Such a full fledged SHM system is still far from full scale deployment as many practical challenges remain unsolved [12]. Some of these practical issues faced in implementing smart sensors in SHM systems are given below.

Sensors: The sensor system, unlike the human nervous system, is hybrid and involves a variety of sensors due to the inspection requirements of the aircraft structures. Airbus [12] and Boeing identified few critical aircraft components and inspection techniques that will use the SHM system. Varied sensor inputs need to be simultaneously analyzed to present a holistic state of health. Sensor optimization might vary for the same area under inspection depending on the global health and local health considerations. Every sensing mechanism needs to be accurate, low cost, robust, maintainable, repairable and need to be certified by FAA and other regulatory organizations for the acceptable POD limits, to be qualified for onboard implementation. Further, sensors need to be suitable for wireless transmission to central station.

Wireless Communication: Wireless communication brings in additional complexities related to energy efficiency of communication protocols. Other challenges include data and time synchronizations, dealing with data losses and need for large data management techniques.

Sensor Integration: Sensors and communication mechanism need to be suitable enough either to be bonded or integrated into the structure without causing unacceptable deviations in the structural integrity. Hence, the manufacturing area is also being researched to develop the structures integrated with sensors [14].

Sensor Data Processing: In order to interpret data from various sources, it is required to identify effective data normalization and data fusion techniques. As the data acquisition is continuous, large data storage, retrieval and processing techniques need to be identified. Appropriate data filters need to be put in place to deal with the bad or corrupted sensor data. This is very important to minimize the false calls which may impact aircraft operator.

Energy Harvesting: A variety of sensors in the sensor network might require different types of energy harvesting techniques customized for each sensor type. Research is still needed to identify effective energy harvesting techniques that make sensors self-reliable and having a long-life to meet the service needs.

Damage evolution and Prognosis: Mechanisms need to be evolved to evaluate micro-scale damage up to the system level failure. Probabilistic failure methods need to be integrated into the package to perform an effective evaluate damage evolution. There is also a need for near term damage progression assessment to initiate the maintenance schedules.

Conclusion

SHM as a concept is matured and now identified as one of the key enabling technologies to ensure the integrity of future aircraft structures. SHM along with advanced alloys, composites and hybrid materials will revolutionize both airframe and engine structures of future aircrafts. SHM can help in increasing the structural allowables with higher confidence removing the conservatism in the current designs. This will reduce structural weight leading to reduced acquisition and maintenance costs. SHM enabled structures need to be designed differently using integrated systems approach considering both mechanical aspects of structure and sensor technologies. The sensor integration with structure is very critical and sensor locations should not become damage initiation locations. Use of SHM can translate to over 40% of reduction in the maintenance cost through inspection time and cost savings. Thus SHM is one of the enabling technologies to revolutionize the future aircraft design, development and maintenance.

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