Chapter 2
Monitoring Tasks in Aerospace

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Abstract Approximately up to one-fifth of the direct operating cost of a commercial civilian fixed-wing aircraft is projected to be due to inspection and maintenance alone. Managing aircraft health with minimal human intervention and technologies that can perform continuous or on-demand monitoring/evaluation of aircraft components without having to take the aircraft out of service can have a significant impact on increasing availability while reducing maintenance cost. The ambition of these monitoring technologies is to shift aircraft maintenance practice from planned maintenance (PM), where the aircraft is taken out of service for scheduled inspection/maintenance, to condition-based maintenance (CBM), where aircraft is taken out of service only when maintenance is required, while maintaining the required levels of safety. Structural health monitoring (SHM) techniques can play a vital role in progressing towards CBM practice. Therefore, this chapter aims to provide the reader with a brief overview of the different SHM techniques and their use, as well as, challenges in implementing them for aircraft applications.

Aircraft structures are typically designed using safe-life (designed to surpass the required service life through rigorous fatigue testing), fail-safe (having multiple load paths in case one of the components fail) or damage tolerance (discontinuities are assumed to exist from initial manufacturing; thereby, requiring periodic inspections and maintenance to detect and repair such discontinuities before they reach a critical size). These practices in aircraft structural design and long-term performance require a high level of understanding of material performance in both durability and damage

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tolerance. This knowledge and sophisticated structural design tools are enabling newer generations of aircraft to be designed and built using newer and less material to tighter margins, resulting in improved performance in terms of increased operational capability (distance flown and cargo capacity).

Aircraft operators are always seeking ways to improve their existing fleet operation by increasing aircraft availability and reducing overall costs. Keeping the aircraft flying longer, increases the inspection and maintenance requirement. As described in (IATA 2018), the increase in civilian aircraft aging related maintenance cost can be attributed to three main causes: (i) due to increase in routine maintenance driven by scheduled maintenance program; (ii) due to non-routine maintenance, which can be discovered during routine maintenance actions or by unexpected faults and failures; and (iii) due to compliance with the mandatory maintenance actions as called out by airworthiness directives (ADs) and service bulletins (SBs). ADs and SBs can have one-time cost, where the solution is implemented and no addition cost is incurred thereafter or can have an ongoing cost, where permanent fix is not available, thereby requiring repetitive additional inspections (IATA 2018). In the military domain, operators around the world are flying aging aircraft way past their nominal designed life through service life extension programs to fulfill current and future requirements (Maksimović et al. 2015). One of the best example of the service life extension is Boeing B-52 bomber, which first entered in-service in the 1950s and has been continuously upgraded to be flown until 2050s (Collins Aerospace 2020). Extending the life of a component often entails increasing the inspection requirement, which in turn increases the cost and reduces the aircraft availability. There is also a rise in cost due to an increase in periodic inspection to maintain aircraft whose service life has been extended past the optimal designed life. Accurate estimation of overall maintenance cost is challenging as it varies from aircraft to aircraft (narrow-body, wide-body, rotorcraft, etc.) and operator to operator (civilian, military, etc.). As reported by (Heisey 2002), for commercial airline industry, depending on airplane age, type, and range, maintenance costs can represent between 10 and 20% of the overall direct operating cost, which includes cost of ownership, flight crew, fuel, maintenance, and others.

As the number of inspection and maintenance increases so may the number of potential maintenance-related damages such as accidental tool-drops, improper repairs, etc. Some of these maintenance-related damages can be catastrophic at times, such as in the case of China Airlines Flight 611, where fatigue cracks began from a damage due to tail strike incident that was not repaired following the original equipment manufacturer (OEM) suggested procedure. The fatigue cracks grew under the repaired doubler and went undetected, which led to the in-flight breakup of the aircraft killing all on board (IASA 2005). A similar example can be found in Japan Airlines Flight 123, where a poorly repaired rear pressure bulkhead gave way in flight that caused explosive decompression killing 520 passengers (Aircraft Accident Investigation Report 1985). These catastrophic failures due to human errors are very rare; nonetheless, they can still occur. Manual inspection plays a major role in maintaining aircraft safety; however, there are limitations in terms of the detectable size of damage in composite structure with the current non-destructive

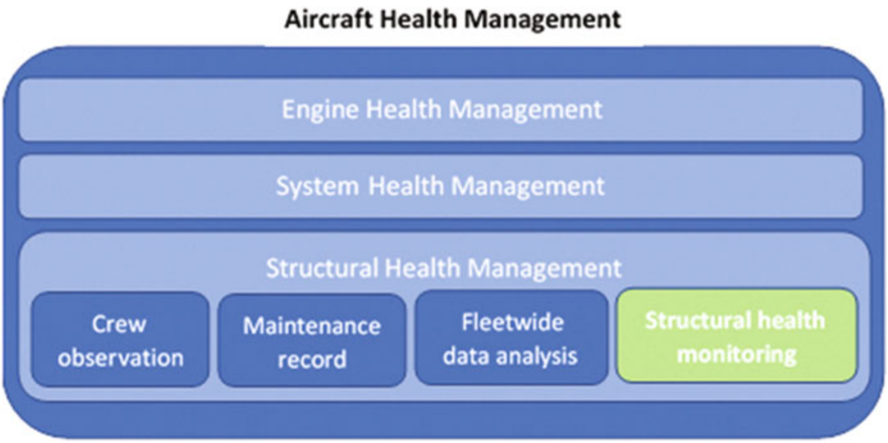

Fig. 2.1 Aircraft health management (SAE ARP6461 2013)

inspection (NDI) techniques. In particular, barely visible impact damage (BVID) if not detected, may cause catastrophic failure and is the main reason for conservative damage tolerant design of composite structure. Therefore, the current scheduled based maintenance have two main disadvantages: (i) the cost of the manual inspection and the loss in aircraft availability/revenue and (ii) the reliability of maintenance which depends on the technician skills; both of which can be reduced by implementing automated inspection techniques. In civilian domain operators are only allowed to use the aircraft within their given type certificate; however, for military aircraft, the actual flown mission profiles oftentimes vary from their initially OEM designed profiles. The actual mission profiles as flown by the military operators are difficult to track and mostly rely on flight crews' input and processing data from the operation load monitoring and flight data recorder (FDR) systems. Therefore, components that are designed using a safe-life approach may not be optimally utilized as they may be retired prematurely due to the difference in actual versus designed flight profiles. Conversely, if the aircraft is flown in severe missions than initially designed, the components may fail prematurely and can be detrimental for flight safety. This also highlights the interest in operation monitoring for an aircraft, where load levels can be recorded to inform the operators about the remaining useful life (RUL) at the aircraft level, as well as, optimization of the maintenance and operation at the fleet level.

Aircraft operators both civil and military are always looking for ways to reduce cost and increase availability by optimizing the use of aircraft components through the aircraft health management (AHM) approach, which is shown in Fig. 2.1.

Managing aircraft health with minimal human intervention and having to take the aircraft out of service for maintenance only when required can have a significant impact on increasing availability and reducing maintenance cost. This can be achieved through structural health monitoring (SHM) technique, which is an element of the structural health management, a subset of the aircraft health management, as shown in Fig. 2.1. SHM aims to shift aircraft maintenance practice from planned maintenance (PM), where the aircraft is taken out of service for scheduled inspection/maintenance to condition-based maintenance (CBM) without compromising safety. However, this decision comes with a cost and higher complexity to the maintenance program.

There are several definitions of SHM. For example, in the military domain (MIL-STD-1530D 2016), United States Air Force (USAF) defines SHM as “a nondestructive inspection process or technique that uses in-situ sensing devices to detect damage”; whereas in the civilian domain (SAE ARP6461 2013), the Society of Automotive Engineers (SAE) (established in 1905 and now covers all types of transport vehicles including aircraft) defines SHM as “the process of acquiring and analyzing data from on-board sensors to determine the health of a structure,” which divides SHM into damage monitoring (DM) and operation monitoring (OM). Conversely, researchers from NASA have defined SHM as “a continuous assessment of structural integrity to increase safety and performance within design constraints to meet operational requirements” (Seshadri et al. 2014). Despite different definitions, common themes among all SHM systems are that they process the acquired data, whether from permanently installed onboard sensors or from other sources such as FDR with advanced data/signal processing techniques.

Currently, there are no certification standards for SHM to be integrated into a maintenance strategy for civil aircraft. There are only guidelines, one of which recommends following the SAE–APR6461 for implementation of SHM onboard civilian aircraft. Depending on how the inspection is carried out, an SHM system can be broken down into scheduled SHM (S-SHM) and automated SHM (A-SHM). The following are the differences between the two: A-SHM system does not have a pre-determined interval and relies on the system to inform the operator when and if any maintenance action is required; whereas, S-SHM system is set to run and acquire data at pre-determined fixed schedule regardless of damage presence (SAE ARP6461 2013).

Application of the SHM system can be widely divided into condition monitoring (CM), OM, and DM.

2.1 Condition Monitoring

Aircraft parts operate under harsh environments and with very strict airworthiness requirements for each part; therefore, their conditions are monitored thoroughly.

The CM system is designed to collect, process, integrate and transmit the information from electro-mechanical systems to avionics systems. The gathered information is then used to monitor the condition of the component.

For example, an aircraft engine constitutes the heart of the aircraft and is expected to work reliably under harsh operational conditions (e.g., high rotation speed, high temperature and pressure). A network of sensors monitors the temperature, pressure, and gas flow within the engine and thus can assess whether the engine parameters are within the operational range in real-time.

Among the available methodologies, one of the promising technologies is prognostics and health management (PHM), which has been successfully applied in avionics and engines. PHM can in general be classified into three classes:

- Model-based method: for a system that can be represented by a mathematical model;
- Experience-based method: building stochastic models, not applicable to complex systems; and
- Data-driven method: based on sensor data and historical operation/test data. This is the only class that requires sensors.

PHM can be applied to different parts of the aircraft such as engines and structures. The data gathered from each system can also serve as input into the scheduled maintenance of the component.

2.2 Operation Monitoring (OM)

Operation monitoring are indirect methods that contribute to the evaluation of a structure's condition or utilization. The usage evaluation can lead to modifying inspection intervals as a function of aircraft use.

Some examples of operational monitoring include:

- Fatigue monitoring: evaluate the structural fatigue response based on related parameters such as flight hours and strain measurement.
- Exceedance monitoring: when the in-service load exceeds the design spectra.
- Environmental monitoring: temperature, humidity, etc. These data can contribute to the increase or decrease in inspection intervals when the environmental conditions vary significantly from the design criteria.

The output of the OM is based on information processed from the recorded data to provide a health assessment of the aircraft structure. The main difference between OM and CM is that operation monitoring records data during flight to assist an operator to identify, quantify, assess and address operational risk but does not provide any diagnosis in terms of the condition of the aircraft and whether a maintenance action is required. In addition, the OM output can be used to support a range of airworthiness and operational safety tasks to the fleet and the process is a subset of safety management system (SMS) of an airline. CM results in diagnosis (whether damage exists and if immediate action needs to be taken) for an aircraft in operation.

Load profiles recorded during operation can be used as an essential parameter to calculate accumulated life and to predict the remaining useful life. They can be monitored either using conventional strain gauges or by calculating the resulting load sequence from recorded flight parameters (e.g., speed, altitude and maneuver).

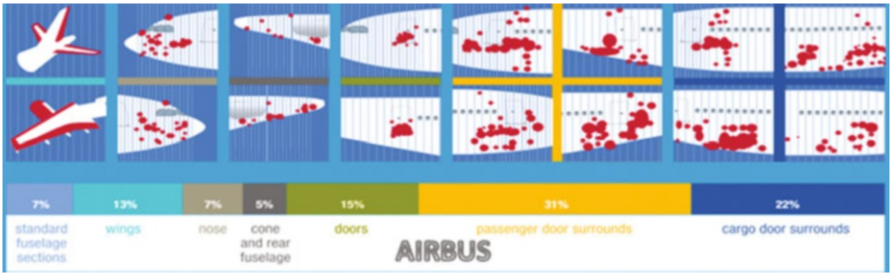

Fig. 2.2 Probable locations of impact damage within an aircraft (Faivre and Morteau 2011)

With the recent developments in SHM techniques, load monitoring has also become an integrated part of the SHM, where the permanently installed sensors can record the load levels during the flight (Nicolas et al. 2016). Fiber optic sensors have gained a lot of interest in load monitoring due to their many advantages such as multiplexing, lightweight, immunity from electro-mechanical interference and high strain sensitivity (García et al. 2015).

Another application of OM is by monitoring and recording impact events (locations that are susceptible to impact damage are shown in Fig. 2.2) during the service-life of the aircraft. The current practice for designing aircraft composite structures is based on probable impacts and their energy levels. For each probable impact (e.g. bird impact at nose, debris impact at lower fuselage), the impact energy levels that is used in the composite structural design is based on metallic structures, where impact events during the service life of an aircraft leaves dents in the structure. By measuring the dents (size and depth), impact energies are estimated. However, this is a conservative approach which is adopted in designing a composite structure. A possible benefit of SHM in the context of OM is to record impact events for each aircraft to estimate the actual impact energy levels. By having a better estimation of the impact energy levels, design of the composite aircraft structures can be optimized, thus resulting in weight savings.

2.3 Damage Monitoring (DM)

In a typical damage monitoring system, permanently attached onboard sensors can be used to monitor aircraft structures continuously or at desired intervals. Processing and evaluation of data acquired from the sensors can be performed onboard or at a ground control station. The evaluation results can be used by the operators to locate and identify damage types, as well as, severity, such that proper maintenance action could be taken. The intent is to reduce the associated cost of performing NDI in areas that are prone to damage and are difficult to access, requiring disassembly of some components. A reliable DM system can also increase the service life of a structure or drive changes to the structural design allowing for a lighter structure.

DM can be classified based on the following sensor technologies:

- Piezoelectric transducers
- Optical fibers
- Micro-electro-mechanical system
- Eddy current foil sensor
- Comparative vacuum monitoring
- Hybrid systems

DM can also be classified based on the following techniques:

- Vacuum or pressure based: monitoring drop in vacuum pressure due to air leakage caused by cracks, defects, etc.
- Ultrasonic guided wave based: analyzing changes in propagation characteristics of guided waves using different algorithms for detecting damage, such as damage index approach, or detecting and localizing based on probability-based approach together with imaging technique such as delay and sum.
- Fiber optics: based on reflectivity shift, spectrum distortion or backscattering.
- Acoustic emission: monitoring release of energy due to impact, crack and damage formation.
- Vibration-based: monitoring change in modal parameters such as natural frequencies, mode shapes and damping due to the presence of damage.
- Conductive medium: measure change in electrical resistance or continuity.
- Data-driven methods: outlier analysis, machine-learning, advanced signal processing, etc., which could be applied to any DM techniques listed above.

Current DM systems span a wide range of technology readiness levels (TRLs), where some are commercially approved for use in United States commercial transport fleet such as comparative vacuum monitoring (CVM) (Swindell et al. 2017). Another example is the use of a conductive medium to detect tail strikes, developed and used by Airbus on its long-haul aircraft. The system consists of two sensors with two conductive mediums (crack wires) on each sensor, which indicates tail strikes to the flight crew. It was also mentioned that the system has "enabled Airbus designers to achieve a significant weight saving by integrating the tail strike system capabilities into the structural design" (Wenk and Bockenheimer 2014). These are two examples of SHM systems that are currently being used in aircraft; however, others are currently being developed and evaluated by OEMs, aircraft operators, research institutes, etc. Table 2.1 shows the examples of some of the most commonly used DM techniques; some of which are discussed in detail in the later chapters of this book.

2.4 Challenges

The use of the SHM system on an aircraft has been envisioned to minimize cost, time and human errors. There has been a significant advancement in research and development of novel sensors, advanced signal processing techniques, signal

Table 2.1 Summary of commonly used DM techniques

Method	Principle of operation	Detectable damage type	Strengths	Weaknesses
Comparative Vacuum Monitoring (CVM)	Cracks on the specimen surface create a leak within the vacuum. This can be tracked via a monitoring device.	Cracks, corrosion, debonding, delamination.	No need for electrical excitation. Can be performed off-line.	Hot-spot/local analysis. Sub-surface crack that do not interact with the vacuum gallery cannot be detected.
Acoustic Ultrasonic (AU)	The propagation properties of an ultrasonic guided wave depend on the state of the medium they travel through.	Cracks, change in thickness (corrosion), composite damage, delamination/debonding, etc.	Covers large distances, lightweight sensors, multi-modal, sensitive to various damage types based on the excitation modes.	Baseline is required (baseline free techniques exist but they have low reliability and cannot be generalized); sensitive to environmental effect (load and temperature) which can be mistaken for damage.
Eddy Current Foil Sensors	Inducing eddy currents in the specimen and observing the interaction to find damage	Cracks, corrosion.	Can be mounted on interfaces between structural parts and can be tailored to work on different shapes. Can be used in locations that are difficult to reach.	Sample material must be conductive. Mainly used for thin materials as thick materials will have penetration constraints.
Acoustic Emission (AE)	Collection and analysis of waves generated by the impact, freeting, rubbing, formation of a new surface, etc.	Impact damage, corrosion formation, crack/damage propagation.	Allows for in-situ monitoring of large areas. Allows for source localization.	Requires active source and real-time monitoring. Prone to background noise.
Fibre Bragg Grating (FBG)	Gratings on the fiber core are subjected to strains. These can be caused by a change in temperature or a local material strain transmitted to the fiber.	Overloads, impacts, and delamination.	Monitors cracks whilst loaded/in-flight (online). Can be embedded in layers of composites during manufacturing. Suitable for networking. The sensor has a	Adds complexity to the manufacturing process. Provides only local damage. Extremely fragile requires extra care during

(continued)

Table 2.1 (continued)

Method	Principle of operation	Detectable damage type	Strengths	Weaknesses
			lifetime close to fiber reinforced polymer composites. Immune to electromagnetic interference.	installation and operation.

transmission, etc. for SHM application. Despite all the advancements, OEMs and aircraft operators are still reluctant in accepting SHM systems for widespread use. Thus, maintenance conducted at a specified number of flight hours and/or calendar days remains the method of choice until the SHM system can meet the same level of damage detectability/reliability as set by the current methods. These challenges include the ability of SHM system manufacturers to minimize/eliminate false calls and to ensure proper operation of these sensors over their useful lifespan. Furthermore, certification authorities may require the SHM system manufacturers to provide the same level of probability of detection (PoD) as is needed for current NDI techniques. Currently, guidelines to develop PoD curve for NDI are provided in (MIL-HDBK-1823A 2009), but may not be generalized in its entirety for SHM application. PoD curves have been developed for SHM application but for specific cases (Roach 2015) (Meeker et al. 2019). Developing a PoD curve for a general SHM sensor setup would likely require a large experimental program with multiple reference samples, with and without damages, in a representative environment translating into a very costly effort. One way to reduce this cost is to implement a robust model-assisted PoD methodology, in which one uses high-fidelity digital models to reduce the number of expensive experimental evaluations. A significant challenge lies in increasing the TRLs of these SHM systems to ensure long-term in-service performance and reliability.

Some of the SHM systems are required to be powered using onboard power supply, as batteries may not be permitted in certain cases. These wired systems may add weight, which in turn may increase fuel consumption. Therefore, energy harvesting, printed circuits and wireless technologies need to be developed to ensure that the benefit of using SHM can be maximized (Chuw et al. 2016).

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