Chapter 4
Aerospace Requirements

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Abstract This chapter covers the overview of requirements arising in the aerospace industry for operating a structural health monitoring (SHM) system. The requirements are based on existing standards and guidelines and include both requirements on the physical components of the system (such as sensors, data acquisition systems and connectors) and their functional requirements (such as reliability, confidence measure and probability of detection). Emphasis has been given to on-board and ground-based components because they have different functionality requirements. An important factor in the reliability of the system is the effect of the environment and operational loads on the reliability of the diagnosis and, consequently, prognosis. The recommended guidelines for testing the reliability of the system under varying operational conditions are presented. This chapter is then finalized by reporting on methodologies for optimal sensor number and placement, based on different sensor technologies and different optimization algorithms.

Presently, there are various international committees comprising industry, government and academia with a mission to develop guidelines, procedures, processes and standards for the implementation and certification of structural health monitoring (SHM) technologies for a variety of application to commercial and military aircraft. This is only achievable through close collaboration between regulators, operators, aircraft manufacturers, system developers and research institutes.

An effective SHM system should not result in any significant negative effects on the performance of the host structure after the integration of its components. The SHM system architecture can be divided into two significant attributes as shown in Fig. 4.1 (SAE International 2013):

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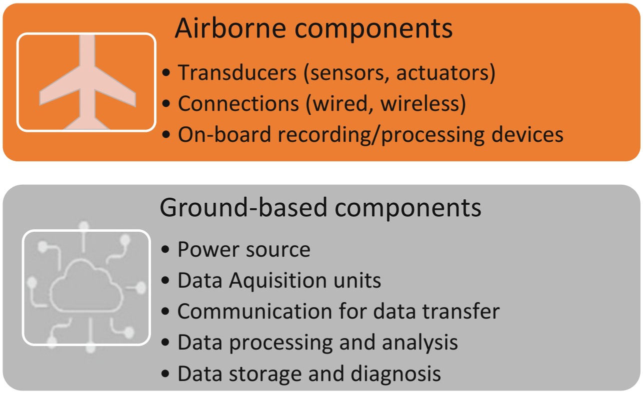

Fig. 4.1 Physical components of SHM systems

- Physical architecture: components and subsystems such as sensors, transducers, data acquisition (DAQ) systems, amplifier, wires, connectors and their interconnections
- Functional architecture: performance requirements such as reliability, probability of detection (POD), intended function (level of diagnosis) and damage size (BVID).

For an SHM system to apply to an aircraft under operational condition, a maintenance strategy should be dependent on factors such as the additional weight, additional cost and the reliability of both diagnosis and prognosis. The benefits of SHM that come from the early damage detection, reduced grounding times and reduced human error need to be evaluated against the additional cost that the system introduces. This can be introduced by evaluating the value of information (VOI) (Straub 2014), which should be integrated with the reliability analysis to compute the probability of failure of the system. The first step in designing and developing the SHM system is for the engineer to define what is the purpose of the diagnostic system, or what is the intended function for the system that defined the level of detailed information the diagnosis will be providing about the integrity of the structure (Sharif Khodaei and Aliabadi 2016). SHM intended that elementary functions can be divided into four levels (SAE International 2013):

- Level 1 (Detecting the presence of damage): This is the most elementary function of the system where it indicates whether damage exists or not with a pre-defined quality and to an acceptable probability (false positive and missed detection).
- Level 2 (Detection of damage location): Damage is not only detected but also localized with a prescribed accuracy (either zonal or exact coordinates depending on the required level of accuracy).
- Level 3 (Detection of damage size): This level of functionality is in addition to detection and localizing results in detecting the damage size to a set POD.

- Level 4 (Detection of damage characteristics and the influence on residual strength): The SHM system may be targeted towards characterizing the type of damage such as debonding, delamination, severity and single and multiple damages.

The level of accuracy of the decision making (intended functions mentioned above) will require a different combination of transducers in terms of number and location. This means that the VOI of the system will increase with the increase of complexity of the decision making. For example, to size damage (Level 4) with an acceptable probability, a lot more transducers are required than just detecting damage (Level 1). Therefore, each different level will require different system requirements. Based on the intended function selected, the system requirements will then be defined. There will be a different set of requirements for airborne SHM and ground-based SHM equipment, and it should cover the following specifications (SAE International 2013).

Functional requirements included the type of features to be monitored, details of the DAQ, handling and storage. By contrast, the operational requirements specify the interfaces between the operator and maintenance crew and between the airborne and on-ground SHM components. This means that the operational requirements will influence the type of actions and decision that will result from the diagnosis (e.g. ground or continuous operation and repair or replace), the type and form of information requirements (e.g. go/no-go) and timing (how often to acquire data, time interval and how long to store the data).

Performance requirements define the attributes of the system that makes it useful for application to a space vehicle. It includes function specifics such as accuracy (flaw size), reliability, reusability, range, resolution, speed and response time.

The system requirement shall include the following specification for both airborne and ground-based equipment:

- *Physical requirements* include system/item attributes such as system weight (mass, size), cooling and power consumption.
- *Environmental requirements* depict the condition in which the SHM system is required to perform and/or survive (temperature, vibration, vacuum, shock and radiation). These requirements will strongly depend on the specific location of the SHM system within the aircraft.
- *Structural requirements* are correlated to specified application scenarios and include the sensor and equipment integration.
- *Installation requirements* consider the permanently integrated SHM equipment such as sensors, wires, connectors and DAQ units. Their protection, calibration and baseline measurement, manufacturing and assembly will be addressed.
- *Re-usability requirements* are self-diagnostic capabilities to define faulty parts during installation and operation, repairability and maintainability of permanent parts.
- *Interface requirements* include the physical system and item interconnections such as data integrity, data availability and communication.

- *Safety and reliability requirements* are related to the redundancy requirements of the system, risk, false alarm and miss-detection rates and functional hazard assessment.

The requirement for ground-based equipment should be the same as those of existing non-destructive inspection (NDI). The standards already used for NDI equipment may include the following:

- MIL-STD-810: Test Method Standard for Environmental Engineering Considerations and Laboratory Tests;
- MIL-STD-461: Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment;
- RTCA DO-278: Guidelines for Communication, Navigation, Surveillance and Air Traffic Management (CNS/STM) Systems Software Integrity Assurance.
- ATA MSG-3: SHM working group recommendations to facilitate the incorporation of SHM in maintenance programme of aircraft.

The requirements for airborne equipment should be met through environmental qualification tests as required by RTCA/DO160C.

4.1 Power Consumption

Power consumption is part of the physical requirements of the SHM system. Traditionally power is supplied to the system through wires; this however does have some significant disadvantages such as the cost associated with installing the wiring. This wiring also adds significant weight to an aircraft, reducing efficiency and increasing the cost of operation. That is the reason why there is a great interest in implementing wireless SHM system (Noel et al. 2017; Lee et al. 2016; Dutta et al. 2005; Rusci et al. 2017; Sutton et al. 2017; Li et al. 2010; Champaigne and Sumners 2007); in fact, it is estimated that in the lifetime of an aircraft, cost savings of 14–70 million dollars could be achieved (Gao et al. 2018). The removal of wires although have weight saving benefits, creates a clear problem: how to power the device in a manageable way? This has led to developments in terms of energy efficiency of the electronic units (DAQs and sensors) (Fu et al. 2018, 2019). In terms of passive SHM system monitoring (e.g. impact events), advancements have been caried out to develop energy efficient event-triggered systems (Fu et al. 2018 Yuan et al. 2016; Qiu et al. 2013; Yuan et al. 2014). Similarly, for active sensing (guided wave excitation and sensing), several wireless monitoring systems have been developed, each with advantages and shortcomings in terms of size and weight of the units, power consumption and the response time (Fu et al. 2019; Aranguren et al. 2013; Zhang 2013; Zhong et al. 2015). Most of the proposed wireless DAQ units are battery operated, with some recent research in terms of energy harvesting capabilities. A unique development which overcomes the wiring and energy challenges of a passive unit was proposed through inductively coupled transducer system (Zhong et al. 2014) where its ideal for ground maintenance but will require access to the embedded sensors. Therefore, not ideal for areas with limited accessibility.

Batteries are common within wireless sensors; however, concerns over their safety and their limited battery life mean that application within aerospace structures is restricted. To remove the need for batteries, or to extend their lives, energy harvesting is being utilized. Available sources of power vary depending on the application and location, typically when available solar power has been used, as it can produce the highest power for its size. Within aviation, however, this is not a reliable single source of power and its integration will interfere with the aerodynamics of the structure, so alternative sources must be considered; for aircraft applications, the most applicable are vibration and thermal (Le et al. 2015).

Vibration harvesters are very effective in areas where consistent vibration exists, such as near engines, or helicopter gearboxes, as available energy is abundant at a known frequency. Elsewhere, vibration may also be high because of airflow; however, this is highly dependent on operating conditions, making it random and difficult to harvest. Although values are very dependent on the aircraft type and operating conditions, studies have shown that the typical frequency is between 100 and 500 Hz, up to 5 g (Thomas 1962). Within helicopters, rotor speeds will also lead to lower frequency vibration (Le et al. 2015). Although advancements had been made into less resonant sensors (Townsend et al. 2019), most vibrational energy harvesters only operate efficiently at resonance, making it possible near consistent sources. Stated values for vibration based-energy harvesters in research vary, as the acceleration that they are exposed to is not uniform. The size of the harvesters is also variable, some being micro-electromechanical systems and others not; this makes direct comparison difficult. It however can be concluded that a vibrational energy harvester suitable for a wireless system is likely to produce at most milliwatts of power (Wei and Jing 2017).

Another option that has the potential to produce higher power values is the thermoelectric generator (TEG), which harvests energy between two faces where a temperature gradient exists. This includes areas near the engine outlets or the outer shell of the aircraft during take-off and landing, where over 50 °C of temperature difference can be temporarily produced. Most TEG utilize the phenomenon called the Seebeck effect, and when operating in the conditions found on-board an aircraft can generate hundreds of milliwatts (Hamid Elsheikh et al. 2014), be it for a limited time period.

Power availability on-board an aircraft is limited, meaning the power consumption of any wireless device must be kept to a minimum, whether it is powered by battery or energy harvesting.

4.2 System Reliability/Durability

A key feature for the certification of the SHM is its reliability compared to existing NDE techniques. It should follow MIL-HDBK-1823 which is the handbook for Nondestructive Evaluation System Reliability Assessment. The reliability requirements should cover the minimum performance constraints. The reliability of the SHM system includes both on-board and on-ground equipment. This means that the SHM installation, wiring, connectors and sensors must survive the harsh environmental and operational conditions of flight and their service life should be comparable to the life of the structure. If their service life does not comply with the service life of the host structure, there should be reliable ways of detecting, repairing or replacing faulty parts (Yue et al. 2018).

Moreover, fault-tolerant design of equipment and installations should be considered in reliability analysis for the chosen intended function, e.g. tolerance in sensor placement, baseline measurements. These requirements can be linked with the design, development and optimization of the SHM system to increase its reliability and redundancy.

The APR 4671 guidelines can be followed for the safety requirements of an SHM system which is acceptable by industry. These include the following:

- The SHM system must follow the airworthiness regulation for systems and equipment which are to be installed on-board of aircraft. These requirements ensure that the integration of the on-board SHM system should not reduce the safety of the structure and hence have any adverse effects on the safety of the passengers, operators and maintenance technicians.
- The installation and operation of the SHM system should not have any noticeable effects on the performance and the reliability of the structure. In addition, the maintenance of the SHM should also be possible.
- The SHM system should not use any chemicals which can harm the environment during its manufacturing process, an application that includes integration and operation or during the repair and replacement stage which could result in the disposal of material.
- Potential conditions that can fail SHM items (hardware) and diagnosis algorithm, (software) should be identified and solutions to solve, repair and replace them should be in place. Each failure should be classified based on its criticality, and the introduction of safety requirements should be carried out to meet the safety requirements of integrated systems and maintenance.

The SHM should remain effective for the expected life duration of the host structure and survive its surrounding environmental and operational conditions of flight.

4.3 Effect of Operational Conditions

The SHM system should function reliably under all foreseeable operation conditions of flight. The operational requirements for an SHM enabled aircraft will specify interfaces between the maintenance crew and on-aircraft and ground SHM components

The on-board requirement of the SHM system should follow RTCA/DO-160C certification guidelines for environmental conditions and test procedures of airborne equipment to ensure the reliability, durability and long life of the installation of on-board equipment as well as their operation.

The on-ground requirements are primarily directed towards condition-based monitoring (CBM).

The ground operational requirements should report on the following:

- Damage detection should be decomposed into its elementary functions i.e. detection of damage presence, localization of damage, detecting the size and severity of the damage. For each of these levels, the reliability and POD under the operational conditions of the flight should be demonstrated.
- A development assurance level (DAL) for each of the elementary functions listed above is based on the negative effects that their failure will have on the airworthiness of the structure as well as on the reliability of the operation.
- The quality characteristic of SHM measurements and functions e.g. accuracy, reliability, precision and durability.
- The operation of the SHM system should not result in any reduced performance of the structure not it should reduce the reliability or the remaining useful life of the host structure.
- The requirement for ground-based equipment should be the same as those of existing or known equivalent from non-destructive testing (NDT).

As part of the reliability assessment of the SHM system, the accuracy of the measured parameter (e.g. strain, guided wave) under operational conditions must be compared with the real value that the structure experiences and the error of the measurement evaluated. The Table 4.1 describes the different test methods and procedures that should be followed for on-board electronics (sensors, connectors, wires) (Salmanpour et al. 2017).

For example for a regional aircraft operating within Europe the operational and environmental test following MIL-STD 180G guidelines requires the on-board SHM equipment to be tested in ‘Basic cold C1’ category, with daily air temperature ranging between −32 and −21 °C, (−33 to −25 °C induced) in the low range with the extremely low temperature in Europe set as −55 °C in Russia.

Depending on the location of the equipment on board of an aircraft, the RTCA DO-160 specifies a specific vibration profile. The functionality and longevity of the SHM components as well as the reliability of the diagnosis should be tested in the presence of the vibration load.

Table 4.1 Integrity test: environmental load cases and references

Test category	Reference test method
Pressure (altitude)	MIL-STD-810G-Method-500.5
Temperature and altitude	RTCA/DO-160F Section 4
Temperature	RTCA/DO-160F Section 5 MIL-STD-810G-501.5 to 503.5
Humidity	RTCA/DO-160F Section 6 MIL-STD-810G-Method-507.5
Acceleration	MIL-STD-810G-Method-513.6
Vibration	RTCA/DO-160F Section 8 MIL-STD-810G-Method-514.6
Fluid susceptibility	RTCA/DO-160F Section 11
Combined loading: temperature and altitude and humidity	MIL-STD-810G-Method-520.3
Combined loading: temperature and vibration	MIL-STD-810G-Method-520.3
Sensor—Fatigue	Defined based on the frequency of acquisition and the life expectancy of each structural part
Mechanical and fatigue for sensor integrity and installation integrity	Following ASTM standards as provided for mechanical tests
Impact tests	The output from calibration tests on each representative coupon

4.4 Size/Weight Restrictions

For aeronautical applications, the decision to have a permanently installed SHM system for structural prognosis will be driven by its reliability, cost and the added weight of the system. The additional weight of the on-board SHM system might be outweighed by the reduction of structure thickness and hence weight which be one of the benefits of the application of SHM. Therefore, the restriction of size and weight of the SHM components is closely related to sensor optimization which is presented in the next section. Some recent innovations have resulted in reducing the weight of the wires and connectors significantly which is specifically beneficial to guided wave-based SHM systems. Considering that each sensor has to be connected from both positive and negative terminals with a wire to the DAQ unit, for a sparse network of sensors, this results in a substantial additional weight. In addition, handling of the wires is an added challenge to have them fixed to the structure. During the operation, they could become projectile and they can break the sensor terminals as well as cause safety concerns. This challenge is not so significant for fibre optic sensors or embedded sensors. However, for piezoceramic sensors, the proposed solutions are in the form of a ready-made layer that can be installed onto the structure either during manufacture or assembly and will include sensors, wires, connectors and the protective layer. Examples of these solutions are the smart layer by Stanford (Qing et al. 2009), Diagnostic film by Imperial College shown in

Fig. 4.2 Example of Diagnostic film by ICL (Bekas et al. 2018)

Fig. 4.2 (Bekas et al. 2018) and the integrated SHM layer (Schmidt et al. 2016), just to name a few.

4.5 Optimal Sensor Placement

As it was emphasized in the previous sections, the performance and reliability of the SHM system is a critical factor in its uptake as a maintenance strategy. The performance of the diagnosis based on the sensor data is directly related to the number and position of the sensors. There is a balance between the cost and the benefit of how many sensors should be added to the host structure without affecting its functionality but still diagnose the structure with high reliability. Therefore, specialized optimization algorithms should be developed which takes into account the specific outcome of the SHM system for composite structures as well as the limitations in terms of placement of sensors and their numbers.

Depending on the application of the SHM, different SHM techniques have been developed which include: vibration-based methods, strain monitoring and ultrasonic guided wave-based techniques. Each class of techniques will have different inputs and outputs, different types of sensors and different operational parameters and hence a different objective function to optimize. There have been many approaches proposed for the optimal sensor placement (OSP) for SHM systems mostly based on an objective function which is the POD of the damage detection algorithm. These techniques include data-driven methods such as an artificial neural network (ANN) in (Staszewski and Worden 2001), genetic algorithm (GA) (Guo et al. 2004) and Bayesian approach (Flynn and Todd 2010a, 2010b), which the objective function for all of them is based on the POD of the damage detection algorithm. The disadvantage of such an approach is that first, it requires a lot of data to be able to build the POD function. Secondly, the POD function for damage detection in composite

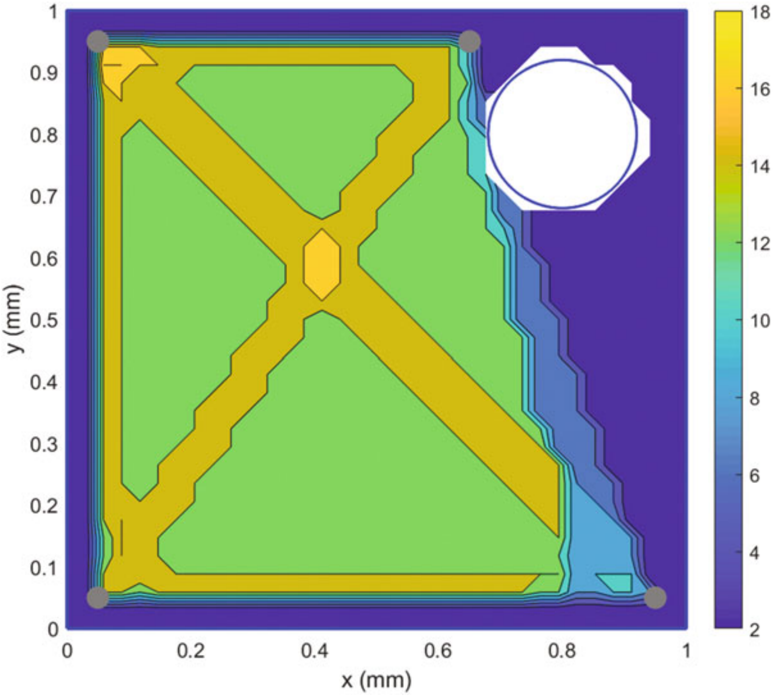

Fig. 4.3 Optimal 4 sensor location for a plate with a corner hole

structures is not well defined because of the complex nature of the damage. Last but not least, if any changes will be made to the damage detection algorithm, the optimum sensor number and location will then no longer be valid. In a different work, Fendzi et al. (2014) proposed an optimization strategy based on GA but one which does not depend on the damage detection algorithm, but it depends on a POD function constructed from scattered energy of guided wave interacting with a damage. This scattering is a theoretical model and does not represent the scatter profile in a complex composite structure. Most of the reported techniques are application-specific and consequently cannot be evaluated in a comparative study. Moreover, their performance depends on tuning factors which makes it impossible to compare for two different techniques. A different approach was proposed in (Thiene et al. 2016) where the optimization is based on maximum area coverage (MAC) within a sensor network and applies to any structure of complex geometry and any damage detection algorithm which is based on guided waves in the pitch-catch configuration. In addition, complex geometries such as plates with openings can also be considered. The objective function (which is to maximize the guided wave coverage) is then optimized using a genetic algorithm (GA) optimization framework. An example of optimal locations for 4 sensors on a rectangular plate with a hole is shown in Fig. 4.3, where the objective was set to maximize the area inside the sensor network (to avoid edge reflected waves).

A comprehensive review is presented in (Ostachowicz et al. 2019) where different OPS algorithms for different SHM techniques are thoroughly investigated. This area of research still requires a lot of attention to propose an optimum method with could be adapted to any structure and any SHM method.

4.6 Summary

In summary, this chapter presented an overview of the requirements that need to be addressed, for any SHM system to be considered for CBM of a real aeronautical structure under real operational and environmental conditions. The most important factor for an SHM to be used in diagnosis and prognosis is for the designer and the maintenance engineer to show that the SHM system can survive the life cycle of the structure, and if not, each component can be identified when malfunctioning, repaired or replaced. The second important factor is to demonstrate that the SHM methodology is capable of diagnosis with the same level of accuracy and reliability (often called 90/95%) of non-destructive techniques that are currently being used by manufacturers and aircraft operators. To this end, the SHM system needs to be considered from the design stage to manufacturing, assembly and finally operational life of the structure.

References

Aranguren G, Monje P, Cokonaj V, Barrera E, Ruiz M (2013) Ultrasonic wave-based structural health monitoring embedded instrument. Rev Sci Instrum 84(12):Art. no. 125106

Bekas DG, Sharif-Khodaei Z, Aliabadi MHF (2018) An innovative diagnostic film for structural health monitoring of metallic and composite structures. Sensors 18:2084. https://doi.org/10.3390/s18072084

Champaigne KD, Sumners J (2007) Low-power electronics for distributed impact detection and piezoelectric sensor applications. In: Proc. Aerosp. Conf, pp 1–8

Dutta P, Grimmer M, Arora A, Bibyk S, Culler D (2005) Design of a wireless sensor network platform for detecting rare, random, and ephemeral events. In: Proc. 4th Int. Symp. Inf. Process. Sensor Netw, pp 497–502

Fendzi C, Morel J, Rebillat M et al (2014) Optimal sensors placement to enhance damage detection in composite plates. In: 7th European workshop on structural health monitoring

Flynn EB, Todd MD (2010a) Optimal placement of piezoelectric actuators and sensors for detecting damage in plate structures. J Intell Mater Syst Struct 21:265–274. https://doi.org/10.1177/1045389X09338080

Flynn EB, Todd MD (2010b) A Bayesian approach to optimal sensor placement for structural health monitoring with application to active sensing. Mech Syst Signal Process 24:891–903. https://doi.org/10.1016/j.ymssp.2009.09.003

Fu H, Sharif Khodaei Z, Aliabadi MHF (2018) An event-triggered energy-efficient wireless structural health monitoring system for impact detection in composite airframes. IEEE Internet Things J 6(1):1183–1192

Fu H, Sharif Khodaei Z, Aliabadi MHF (2019) An energy-efficient cyber-physical system for wireless on-board aircraft structural health monitoring. Mech Syst Signal Processing 128:352–368

Gao S, Dai X, Hang Y et al (2018) Airborne wireless sensor networks for airplane monitoring system. Wirel Commun Mob Comput 2018:1–18. https://doi.org/10.1155/2018/6025825

Guo HY, Zhang L, Zhang LL et al (2004) Optimal placement of sensors for structural health monitoring using improved genetic algorithms. Smart Mater Struct 13:528–534. https://doi.org/10.1088/0964-1726/13/3/011

Hamid Elsheikh M, Shnawah DA, Sabri MFM et al (2014) A review on thermoelectric renewable energy: principle parameters that affect their performance. Renew Sust Energ Rev 30:337–355. https://doi.org/10.1016/j.rser.2013.10.027.

Le MQ, Capsal JF, Lallart M et al (2015) Review on energy harvesting for structural health monitoring in aeronautical applications. Prog Aerosp Sci 79:147–157. https://doi.org/10.1016/j.paerosci.2015.10.001

Lee Y, Blaauw D, Sylvester D (2016) Ultralow power circuit design for wireless sensor nodes for structural health monitoring. Proc IEEE 104(8):1529–1546

Li P, Olmi C, Song G (2010) Energy efficient wireless sensor network for structural health monitoring using distributed embedded piezoelectric transducers. Proc SPIE 7647:7647–7647-11

Noel AB et al (2017) Structural health monitoring using wireless sensor networks: a comprehensive survey. IEEE Commun Surveys Tuts 19(3):1403–1423

Ostachowicz W, Soman R, Malinowski P (2019) Optimization of sensor placement for structural health monitoring: a review. Struct Health Monit 18:963–988. https://doi.org/10.1177/1475921719825601.

Qing XP, Beard SJ, Kumar A, Li I et al (2009) Stanford multiactuator–receiver transduction (SMART) layer technology and its applications. Encyclopedia of Structural Health Monitoring. https://doi.org/10.1002/9780470061626.shm098

Qiu L, Yuan S, Liu P, Qian W (2013) Design of an all-digital impact monitoring system for large-scale composite structures. IEEE Trans Instrum Meas 62(7):1990–2002

Rusci M, Rossi D, Farella E, Benini L (2017) A sub-mW IoT-endnode for always-on visual monitoring and smart triggering. IEEE Internet Things J 4(5):1284–1295

SAE International (2013) Aerospace recommended practice. In: Guidelines for implementation of structural health monitoring on fixed wing aircrafts. SAE International, p 95

Salmanpour MS, Sharif Khodaei ZS, Aliabadi MHF (2017) Impact damage localisation with piezoelectric sensors under operational and environmental conditions. Sensors 17:1178. https://doi.org/10.3390/s17051178.

Schmidt D, Kolbe A, Kaps R et al (2016) Development of a door surround structure with integrated structural health monitoring system. In: Smart intelligent aircraft structures (SARISTU). Springer, Cham, pp 935–945

Sharif Khodaei Z, Aliabadi MH (2016) A multi-level decision fusion strategy for condition based maintenance of composite structures. Materials 9:790. https://doi.org/10.3390/ma9090790

Staszewski WJ, Worden K (2001) Overview of optimal sensor location methods for damage detection. In: SPIE's 8th annual international symposium on smart structures and materials. International Society for Optics and Photonics

Straub D (2014) Value of information analysis with structural reliability methods. Struct Saf 49:75–85. https://doi.org/10.1016/j.strusafe.2013.08.006

Sutton F et al (2017) The design of a responsive and energy-efficient event-triggered wireless sensing system. In: Proc. ACM EWSN, pp 144–155

Thiene M, Khodaei ZS, Aliabadi MH (2016) Optimal sensor placement for maximum area coverage (MAC) for damage localization in composite structures. Smart Mater Struct 25:095037. https://doi.org/10.1088/0964-1726/25/9/095037.

Thomas CE (1962) Flight vibration survey of C-130A aircraft Aeronautical systems. DIV Wright-Patterson AFB OH

Townsend S, Grigg S, Picelli R et al (2019) Topology optimization of vibrational piezoelectric energy harvesters for structural health monitoring applications. J Intell Mater Syst Struct 30:2894–2907. https://doi.org/10.1177/1045389X19873392.

Wei C, Jing X (2017) A comprehensive review on vibration energy harvesting: modelling and realization. Renew Sust Energ Rev 74:1–18. https://doi.org/10.1016/j.rser.2017.01.073

Yuan S, Mei H, Qiu L, Ren Y (2014) On a digital wireless impact monitoring network for large-scale composite structures. Smart Mater Struct 23(8):Art. no. 085007

Yuan S, Ren Y, Qiu L, Mei H (2016) A multi-response-based wireless impact monitoring network for aircraft composite structures. IEEE Trans Ind Electron 63(12):7712–7722

Yue N, Khodaei ZS, Aliabadi M A (2018) Repairable installation procedure for SHM sensors onto composite structures. 9th European workshop on structural health monitoring, July 10-13, 2018, Manchester, United Kingdom

Zhang C (2013) Trigger circuit for low-power structural health monitoring system. U.S. Patent 8 401 804, Mar. 19

Zhong CH, Croxford AJ, Wilcox PD (2014) Passive wireless ultrasonic transducer systems. AIP Conference Proceedings 1581:1896. https://doi.org/10.1063/1.4865055

Zhong CH, Croxford AJ, Wilcox PD (2015) Portable wireless ultrasonic systems for remote inspection. AIP Conf Proc 1650:883. https://doi.org/10.1063/1.4914693