Chapter 10
Conclusions

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Abstract The state of the art of structural health monitoring damage detection systems reviewed in this book shows that it is a promising area of technologies. SHM damage detection systems in civil aviation are still mostly limited to lab applications because there are still issues, which need to be solved for such systems to be integrated in an aircraft structure. Therefore, further research is needed to solve the current drawbacks/limitations of the existing SHM approaches such that this technology can be used in aircrafts.

Despite the current limitations, SHM application for damage detection in aircrafts would make the flying safer and the structure lifetime longer and reduce the maintenance time and costs considering that the maintenance could be performed not at the predetermined intervals, but upon the need based on the condition that would be determined by the SHM systems used. We conclude some of the important differences and the common challenges to the methods reviewed in this book and provide an outlook on the next steps to a successful implementation.

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10.1 Overview of the SHM Methods for Aerospace Integration

As outlined in detail throughout Chaps. 5, 6, 7, and 8, various SHM methods are readily used in aerospace research and applications. Recently, an SAE industrial committee presented an International Aerospace Recommended Practices document SAE ARP 6461 “Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft”. With its focus on the integration of SHM methods into aircraft maintenance procedures, generic requirements and advice on validation, verification and airworthiness, it does not have a strong focus on the actual methods as outlined in the previous chapters. Thus, in the following, a quick overview regarding some selected technological aspects with high relevance for practical applications is provided. It is necessary to evaluate/compare, even quantify the capabilities of different SHM methods. Unfortunately, no strict guidelines are yet available for quantitatively assessing and comparing the performance of SHM systems. Table 10.1 lists several technological aspects for the comparison of four primary SHM approaches discussed in this book, namely monitoring using ultrasonic guided waves, vibration, acoustic emission, and strain. Nevertheless, there are certainly more SHM technologies proposed and demonstrated in operational aircraft, such as Comparative Vacuum Monitoring (CVM) for crack detection or leakage monitoring by percolation sensors, but the scope of this chapter is limited to the primary approaches presented throughout Chaps. 5 to 8.

System reliability is understood as the combination of reliability under normal operation mode and susceptibility to external factors of influence, such as arising from climate changes, as well as operation of nearby technical systems. As established in non-destructive testing approaches, reliability can be assessed in terms of the probability of detection (POD), but this is not directly transferable in the same fashion to the SHM methods discussed herein.

Integration readiness considers all aspects of the measurement chain to properly integrate the system inside an aircraft, as well as the ease of sensor and wire integration in the context of production technologies.

As *maturit*y, the overall technological readiness of the method, including the factors of traceability to physical principles and the capability and repeatability of the involved algorithms to retrieve information from the sensing system is considered.

Under *power consumption*, the methods with respect to the electrical power required to operate the system for SHM are compared.

In the category *form factor*, the SHM methods with respect to their size and weight, including the aspects of bulk attachments vs. sensor solutions fully integrated into the aircraft components is compared.

Finally, under *costs*, the SHM methods relative to each other in terms of investment and operation costs of the required measurement chain are compared. The latter may solely provide a first estimate because the overall number of sensors required to

Table 10.1 Overview of the selected technological aspects for SHM integration

SHM method	System reliability	Integration readiness	Maturity	Power consumption	Form factor	Costs
Ultrasonic guided wave monitoring	Limited (For screening applications can be high, for small defect detection low)	Good	Medium	Medium, active pulsing required	Medium	Medium cost, depends on complexity of the system (sensors, instrumentation and applications)
Vibration-based monitoring	Sensitive to environmental conditions and noise in sensors; both can be reduced through bespoke processing, but not eliminated	Good	Good	Medium, sensors can be wired or wireless	Reasonable, but depends on the sensors; MEMS can be very small; piezoelectric have higher dimensions	Depends on the sensors (MEMS can be low cost)
Acoustic emission monitoring	Good for some aspects like detection and localization, but limited for characterization	Medium	Medium	Low	Good	Low
Strain monitoring	Good in case the sensors are protected (coated)	Very good for optical fiber sensors, good for strain gauges	Good (optical fiber sensors) to very good (strain gauges)	Low	Very good, compact and light-weight	Low

cover a certain area strictly depends on the required probability of detection, type of monitoring (e.g., type of defect), and material.

The capabilities of each of the four SHM methods are summarized in Table 10.1 to provide more details.

10.1.1 Ultrasonic Guided Wave Based Monitoring

Ultrasonic guided waves (GW) could serve as a promising tool for the assessment of aerospace components. Guided waves are sensitive to the change in the mechanical properties of the material and possess relatively minor attenuation; thus, different defects can be detected from the single transducer position, which makes them essentially attractive for structural health monitoring applications. However, the development progress of guided wave methods is still limited because many external factors must be suppressed to obtain a response that is not influenced by temperature, loads, geometrical variations, structural boundaries, or coupling of the sensor. Guided waves have emerged as a powerful tool due to their ability to screen large areas and overcome the existing limitations of point-wise bulk wave inspections. GW possess multiple modes and through-thickness distributions, meaning that the defects of different size, type, depth, and orientation can be interrogated. On the contrary, this technique suffers from its own complexity. Many methods are being developed by various research groups to isolate specific modes of interest or extract and visualize weak responses of flaws. The reflections from the defects are usually concealed within the multimodal and quite noisy signals; hence, such developments usually include approaches to minimize the number of modes propagating in the structure and specific processing, such as filtering, summation, and various signal transformations. The scaling of existing methods from the laboratory to in-situ is still quite limited due to the complexity of the signal analysis, which itself becomes even more complicated with multi-layered and anisotropic structures in addition to stiffeners and bolt holes. With the advent of machine learning methods and increasing computational capabilities, GW inspections are expected to overcome some of their existing limitations and used to a larger extent with more confidence.

10.1.2 Vibration-Based Monitoring

Vibration-based monitoring allows the identification of damage due to changes of structural stiffness, mass or energy dissipation capacity. Damages that usually affect aeronautical structures usually cause stiffness variation. Modal frequency variations are features sensitive to this type of damage; thus, their variation can provide useful information for its detection. The advantage of this method is that it enables damage detection at a global level using sensors not necessarily located in the proximity of the damaged location. For this reason, vibration-based damage detection does not require prior knowledge of the so-called ‘hot spot,’ which is a location where damage is likely to develop. Sensors must be installed at locations that enable the most accurate, precise, and complete identification of modal parameters, discarding any consideration about the location where damage will happen. The only exception is damages at locations where one or more modes have a node and are not affected by that damage. Sensor location must be chosen to account for this. A further issue to consider when using modal frequencies as damage features is their sensitivity to the variations of environmental parameters, such as temperature or humidity. This means that changes of modal frequencies may occur due to damage or variation of environmental sources. Therefore, these effects must be accounted for or eliminated to obtain a reliable identification of damage. Alternative or further damage features may be defined in terms of other modal parameters, which are less sensitive to environmental sources and/or more sensitive to the damage location, to address this issue and enrich the description of damage (e.g., through information about its location). Modal shapes are extensively used for this aim. One drawback of vibration-based methods for damage identification is their scarce sensitivity to small damages. This is the reverse side of the advantage related to the global nature of these features: on one side, this enables the identification of damage without any prior knowledge about its location; on the other side, it limits their sensitivity to small localized changes. This issue is worsened by modelling and measurement errors, which increase the uncertainty in the identified modal parameters and the reliability of damage identification in real-world applications.

10.1.3 Acoustic Emission Monitoring

The condition monitoring of aeronautic components is extremely important for flight safety. Due to its sensitivity, AE allows the detection of crack nucleation and propagation earlier than other NDT techniques. The main advantages of AE are the aforementioned sensitivity, ability to localize active sources even without visual contact, inspection of a large area with limited sensors, and the possibility for fracture mode evaluation, which is very useful, especially in composites. It is applied without influencing the object under monitoring while wireless sensor solutions are gaining ground. One of the disadvantages of AE is related to its sensitivity because it makes it prone to noise, either environmental or anyway unrelated to structural health monitoring. This may not be uncommon in real flight conditions and require specialized filtering techniques and sophisticated pattern recognition approaches that are helpful for classification, while compressing data could be an extra burden. Another disadvantage is the influence from experimental conditions like sample geometry, sensor separation distance, and sensitivity. While laboratory studies have greatly advanced in interpretation and accuracy, this is not reflected to in-situ studies due to the aforementioned limitations. Issues that are relatively reliable and mature are detection and localization. An exact characterization (size, orientation, mode of defect) can be achieved mostly in laboratory conditions, while this would facilitate decision on the maintenance action and, possibly, prediction of the remaining life in reality. Nevertheless, the currently faced lack of standardization does not allow engineers and scientists to share more robust conclusions.

10.1.4 Strain-Based Monitoring

Both strain gauges and optical fiber sensors can be used to measure the local strain of aircraft components and systems. Strain gauges are extensively used during the flight testing of new aircraft types to measure loads during a flight operation. In addition to the low frequency strains, strain sensors (strain gauges and optical fiber sensors) can also be used to measure the dynamic vibration response of components. As such, vibration-based monitoring techniques, as described in Sect. 10.1.2, can be used in combination with strain sensors. Moreover, optical fiber sensors like fiber Bragg gratings also allow measurements at very high frequencies of up to several MHz. Therefore, these strain sensors can be used for acoustic emission monitoring (Sect. 10.1.3).

Optical fiber sensors are lightweight and compact (diameter: typically 125 µm). They are easy to integrate in composite materials and metals (by using grooves in which the fibers are laser cladded). One single fiber in a Fibre Bragg Grating can easily contain several tens of sensors. By using adapted interrogation principles, it is even possible to continuously realize distributed sensor systems.

10.2 Defect Detectability

Based on the review of different defect types in Chap. 3, Table 10.2 lists the primary categories of defects encountered in aircrafts distinguished by the top-level categories of metals, composites, coatings, and joints. In this context, the different methods in their capabilities of detecting the defect type are ranked. Focus is given to these defects, which are not due to manufacturing deficiencies (e.g., bad curing, foreign inclusions, etc.), but on those defects that may occur inside a flight-ready qualified aircraft as a result from detrimental operation conditions (e.g., overloading, weather conditions, accidents, etc.) or even as a result from a system malfunction under regular operation conditions.

We use a scale ranging from good to medium to poor to rank the methods in case they are able to detect the defect.

Table 10.2 Comparison of the defect sensitivities of different SHM methods

Defects	Ultrasonic guided waves monitoring	Vibration-based monitoring	Acoustic emission monitoring	Strain-based monitoring
Metals				
Fatigue	Poor	Good	Good	Good
Corrosion	Good	Good	Medium	Poor
Wear	Medium	Poor		
Creep deformation	Poor	Poor	Poor	Good
(Micro-)cracks	Poor	Poor	Good	Good
Composites				
Disbonds (Sandwiches)	Good	Good	Medium	Good
Core crushing/buckling (sandwiches)	Medium	Medium	Medium	Good
Delamination	Good	Good	Good	Good
Matrix cracking	Medium	Medium	Good	Medium
Fibre breakage	Poor	Medium	Good	Good
Moisture absorption	Medium	Poor	Poor	Medium
Temperature induced degradation	Medium	Poor	Poor	Good
Fatigue cracks	Poor	Good	Good	Good
Coatings				
Corrosion	Good	Poor	Medium	Poor
Wear	Good	Poor	Medium	Medium
(Micro-)cracks	Medium	Poor	Medium	Medium
Delamination	Good	Poor	Medium	Medium
Joints				
Wear	Poor	Poor	Medium	Good
Disbond	Good	Medium	Poor	Good
Voids	Medium	Medium	Poor	Medium
(Micro-)cracks	Poor	Medium	Good	Medium
Kissing bond	Poor	Poor	Poor	Medium
Moisture absorption	Poor	Poor	Poor	Poor
Temperature-induced degradation	Poor	Poor	Poor	Poor

10.3 Advantages and Disadvantages of SHM Techniques

In this section, we focus on the distinct advantages and disadvantages that originate from the principles of different methods. We attempt to objectively discuss the strength and the weakness of each SHM approach because this provides some further background to the suitability of a method for a given task. Furthermore, Table 10.3 includes some of the current challenges associated with the use of each method.

Table 10.3 SHM techniques: advantages and disadvantages

SHM method	Advantages	Disadvantages
Ultrasonic guided wave monitoring	Directly sensitive to the change of the structural properties of the material; can be used to screen large areas with a small amount of sensors; sensitive to both surface and internal defects of various kinds; can be used to inspect almost any kind of large components, including metals and composites; can be used to inspect inaccessible parts located under the ground or coatings; and various parameters of the flaws, such as size, position, and depth can be extracted	Requires sophisticated methods to avoid generation of multiple modes; interpretation of the structural responses is usually nontrivial and requires deep understanding about the structure and additional modelling; complicated verification, calibration of the inspection techniques, and scaling from the laboratory to the in-situ environment; and many surrounding factors influence the result of structural response
Vibration-based monitoring	Provides global damage features that do not require prior knowledge and accessibility of the damage location. They can detect damage with a very small number (ideally just one) of sensors. They can be used for any material and enable detection, localization, and quantification of damage	Vibration-based damage features are affected by environmental sources that can hide erroneous damage identification. Modal frequencies are global quantities, scarcely affected by local damages. The noise level in available sensing systems usually decreases with the cost; hence, low-cost sensors have still high noise levels that furtherly reduce the sensitivity to small damages. POD concept was not used for vibration-based tests. Recent studies have investigated the extension of the POD concept for vibration-based monitoring. Currently this is possible only for small laboratory specimens since the definition of the POD requires data measured in the damaged configuration which might not be always possible when working on large structural components
Acoustic emission monitoring	Capacity to detect active damage; localization; high sensitivity; global inspection with necessary access only at specific points on the surface; ability to characterize the type/mode of damage; and passive, not necessary to inject signal	Prone to noise; influenced by sample size and sensor distance and sensitivity; transfer of conclusions from the laboratory to real size and interpretation not straightforward
Strain-based monitoring	Strains allow the measurement of the loads of an aircraft component or system; Optical fibers sensors for strain measurement can be fully integrated in a component, especially in composite materials	Strain sensors (gauges and OFS) are brittle and should be protected (with a coating)

10.4 Roadmap for SHM Integration in Future Aircraft

The modern aircraft manufacturing technology aims to further increase the production rates to the amount of 60–100 planes a month (at least 2 planes a day) with even more serious reduction in weight, cost, waste, environmental impact and assembly time. To achieve this, a composite manufacturing technology is changing rapidly, going from hand layup and automated fibre placement (AFP) technologies to resin transfer molding (RTM), high pressure HP-RTM, thermoplastic composites, hybrid metal-composite structures and 3D printed parts. The more advanced technologies like HP-RTM are already implemented in some parts of an aircraft, i.e. manufacturing of Airbus A330/A340 spoilers, Airbus A350 passenger doors and surrounding frames. Such manufacturing technology allow to achieve approx. 30% cost reduction and increase of the production efficiency by 10–20%. The production efficiency can also be increased with thermoplastic composite technology which allow greater integration of structural elements by using thermoplastic joining technologies like overmolding and welding. This will reduce the amount of assembly steps, eliminate some rivets and fasteners, resulting in reduced overall manufacturing cost. Thermoplastic composite materials are up to 10 times lighter than metals, are temperature, chemical and corrosion resistant, have better design flexibility and fatigue properties. Another example of the automation is the emerging additive manufacturing (AM) technology. The new Boeing 777X aircraft will have GE9X engine which consists of 304 separate additively manufactured parts like low pressure turbine blades, heat exchanger, combustor mixer, fuel nozzle etc. The AM technology allowed to combine multiple parts into single one since the shape of the part is no longer limited like in the conventional manufacturing methods such as stamping and casting. The production of the modern aircraft clearly seeks faster, cheaper production, increased automation, reduced weight and fuel consumption of an aircraft. Inevitably this can be achieved by using composites and modern manufacturing technologies only. This drastically changes the design process, meaning that the NDT technologies will have to adapt.

As a result of the comprehensive assessment of different methods presented in this book, several targets must be achieved that are common to all methods and individually for each method. For all methods, the roadmap to SHM implementation in aircrafts should start at the hotspots, implementing sensors with a minimum of changes to the structure first. One should think about simple, but effective solutions because complex integration solutions will require time and contribute to weight, and the operation of such solutions might be error-prone and not cost-effective, even requiring additional maintenance needs. The first approach could be to use off-line sensor systems, being able to upgrade later to on-line sensor systems and perspectival to fully integrated sensors. Smart structures with integrated sensing capabilities should be developed to reduce weight and cost. SHM approaches must be standardized, including sensors, sensor application, and integration into the systems, as well as subsequent algorithms. Last but not the least, certification costs are an important factor as well.

Guided waves offer many advantages over other existing techniques to be used in SHM. They involve a rather complex technique that requires much a-priori knowledge about the structure and the propagation of guided waves. Consequently, it offers tremendous sensitivity to structural changes and may be used for a huge variety of objects. To simplify the guided wave inspection, additional tools are required, which can monitor environmental factors or adjust inspection parameters dynamically. Hence, the guided wave inspection may be seen as a part of a smart inspection system that uses different sensors and signal processing algorithms that communicate with each other. The creation of an inspection ecosystem with wireless communications, real-time signal processing boards, and regulations for calibration, verification, and reference cases (baselines) are the main development areas for a successful integration of guided wave techniques.

Vibration-based methods provide a tool for damage detection at a global level, which does not require prior knowledge of the damage location. Currently, the uncertainty connected with measurements and modeling errors still hinder their large-scale application under operational environmental conditions. The development of low-cost wireless sensors and procedures for real-time processing is a requirement, as well as standardization, for their further development.

The potential of contribution of AE technique in SHM is high. AE analyses may provide a relatively simple and fast platform for damage detection. However, difficulties with interfering noise, data interpretation, inability to understand the underlying physical mechanism in real applications, and the lack of standardization prevent widespread application. Wireless systems may be a potential direction to reduce the whole system weight, which is a crucial factor for aviation. Recording whole waveforms for an elaborate analysis for source identification may require much memory power and time, but will greatly upgrade the assessment. Basic features like damage detection and localization are more mature because they can go forward only with a representative reduced dataset.

Apart from typical applications, such as load monitoring and low-frequency vibration monitoring, strain-based structural health monitoring can be used for shape sensing and prognosis of damage-based on the fatigue behavior of the component. Some implementations of shape sensing have been performed in the morphing wings of aircrafts using fiber optic strain sensors, where a long length of optical fiber covers the wing area and measures the strain behavior of the wing during flight and disturbances. By monitoring this strain behavior, the fatigue life of the wings can be assessed and used to optimize scheduled maintenances. In this example, the optical fibers were surface mounted on the wing structure. However, the installation of the electrical strain gauges or fiber optics can be improved by embedding them either in the internal layers of the structure or its walls. Furthermore, technological advances in increasing the signal acquisition rates and improving the signal-to-noise ratio of acquired strain values, as well as improvements in big data management can also boost the relevance of these methods.

10.5 Future Research Directions

Finally, we would like to summarize the key items identified for a further development of the SHM methods discussed in this book.

One of the key objectives for all methods are automated data analysis systems, which require advanced signal processing algorithms. As elaborated in Chap. 9, this will enable the diagnosis of problems and the initiation of high-level decisions.

With the advent of machine learning methods, the large amounts of data generated by guided wave SHM systems can be exploited in trying to estimate features and dependencies between the parameters of guided waves and properties of defects that cannot be observed by a human. This will gradually open new horizons for guided wave inspection and data interpretation. The risks of biased predictions will remain high, and the in-situ performance of such models will have to be carefully verified. Another development area is the extraction of more advanced defect features, such as through thickness positions, severity of damage, and remaining lifetime of the structure, which would allow the implementation of a true condition-based inspection of engineering assets in aircrafts.

For vibration-based monitoring, the identification of features more sensitive to damage and less affected by environmental sources is a stringent research need. The development of low-cost wireless sensors systems is another important aspect necessary for their application to inflight monitoring. Standardization is another requirement to pave the way to a larger usage of these techniques.

An interesting research direction for acoustic emission monitoring is the prediction of the type of damage before severe defects actually occur. Past research has shown that the developed strain, even at a low load, leaves its signature to the AE recordings, even before the actual crack manifestation. This demonstrates the huge potential of the method. However, an important point is the compensation of the signal against the distortion caused by the long propagation through heterogeneous, dispersive media like composite or metal plates, as used in aeronautics. This would allow a clearer assessment of the source, the elimination of a large amount of error that is now included in the waveforms, masking the original source content. Technical issues like wireless transmission speed and capacity and power requirements are also open for optimization.

Strain-based structural health monitoring can benefit from in-depth research in several aspects. On the mechanical side, optimizing the sensor placement and concentrating them on the more sensitive areas, along with optimizing the embedment procedure to avoid risking the health of sensors and changing the aerodynamics of the structures, can be among the most relevant research topics. On the data-processing part, the reliability of the prognosis algorithms and big data management, along with improvements in signal processing algorithms, can be investigated. Incorporating machine learning approaches can also be beneficial in this area and is certainly an interesting research topic.

While each method has acquired technological development within many decades, much potential is left for further research. With some current mega-trends out of the field of artificial intelligence, as well as microfabrication of sensor systems and electronics, there is a huge playground to push SHM methods beyond the current limits. Ultimately, these shall provide highly integrated system solutions and a true benefit for the safe operation of aircraft.