HEALTH AND USAGE MONITORING OF AEROSPACE STRUCTURES

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Abstract

Aircraft maintenance involves usage and/or damage detection of structures. Usage is associated with measuring load sequences and a typical application example is Operational Loads Monitoring (OLM) whereby either flight parameters or direct structural strain measurements in aircraft are used to quantify the fatigue life of the structure. Current damage monitoring involves traditional non-destructive techniques such as Eddy Current or Ultrasonics. The paper gives a brief overview of currently used and emerging technologies in maintenance of aerospace structures. Recent developments in this area, related to damage detection techniques based on integrated smart sensor technologies, are also discussed. These techniques are associated with a new design philosophy leading to multifunctional and adaptable structures.

Keywords: Aerospace Structures, Health Monitoring, Usage Monitoring, Smart Sensor Technologies

EKSPLOATACJA I DETEKCJA USZKODZEŃ KONSTRUKCJI LOTNICZYCH

Streszczenie

Eksploatacja samolotów związana jest z monitorowaniem stanu zużycia oraz detekcją uszkodzeń konstrukcji. Monitorowanie stanu zużycia samolotu sprowadza się do analizy obciążeń konstrukcji oraz do szacowania i prognozy wytrzymałości zmęczeniowej. Metoda pośrednia oparta jest na parametrach lotu, podczas gdy metoda bezpośrednia wykorzystuje pomiary odkształceń konstrukcji. Tradycyjne metody detekcji uszkodzeń konstrukcji lotniczych wykorzystują badania nieniszczące oparte na indukcji magnetycznej oraz ultradźwiękach. Praca przedstawia w skrócie tradycyjne oraz nowe metody detekcji uszkodzeń wykorzystywane w eksploatacji samolotów. Nowe metody, oparte na inteligentnych czujnikach pomiarowych zintegrowanych z samolotem, związane są z nową koncepcją projektowania wielofunkcyjnych i adaptacyjnych konstrukcji.

Słowa Kluczowe: Konstrukcje Lotnicze, Detekcja Uszkodzeń, Monitorowanie Stanu, Inteligentne Czujniki

1. INTRODUCTION

Aircraft designers, manufacturers and operators face many technical challenges in the near future. On the one hand, new large capacity civil structures, making greater use of composite materials, are being developed and will be widely used. At the same time, new military structures exhibit improved performance associated with greater structural complexity. Among many other improvements and expectations, the end-users of these new structures demand high rate operational availability and reduced life-cycle costs. On the other hand, the existing aircraft fleet is ageing continually. A number of life extension programmes have been performed and considered in recent years; civil structures are converted from passenger aircraft to freighters whereas military aircraft are redesigned to add extra weapon systems. All these developments are a major challenge to inspection and maintenance of aircraft structures.

Maintenance and inspection of aircraft involves usage and/or damage detection in structures. Usage is associated with measuring load sequences and a typical application example is Operational Loads Monitoring (OLM) whereby either flight parameters or direct structural strain measurements in aircraft are used to quantify the fatigue life of the structure. Usage monitoring is performed in military structures. Current damage monitoring involves traditional non-destructive techniques such as visual inspection, Eddy Cur-

rent or Ultrasonics. All these elements are discussed in [1].
Recent developments in this area are related to Structural Health Monitoring (SHM) techniques utilising new technologies and transducers which are capable of achieving continuous damage monitoring. These developments are associated with a new design philosophy leading to lighter, more reliable and high-performance structures.
The paper gives a brief overview of currently used and emerging technologies related to health and usage monitoring of aerospace structures. The focus here is on airframes, not on engines and avionics. Section 2 briefly discusses the current structural design of aircraft. This is followed by Section 3 describing the ageing aircraft problem. The usage and health monitoring technologies used in aircraft are summarised in Sections 4 and 5, respectively. New SHM developments that have the potential for aircraft inspection and maintenance are discussed in Section 6. Finally, the paper is concluded in Section 7.

2. AIRCRAFT STRUCTURAL DESIGN

Guidelines for aircraft design and operation result from different approaches to fatigue of materials. Current design principles of aircraft structures are based on the *safe-life* concept. Load spectra representative of typical operational conditions are first determined. This requires a significant amount of data related to mission profiles, mass distributions and many other parameters. The load spectra and fracture mechanics are then used to evaluate structural components in terms of their service fatigue life. This is followed by a series of fatigue tests of materials, coupons, elements, subcomponents and components, leading finally to the Major Airframe Fatigue Test (MAFT). In practice, the scatter in design input data (e.g. unknown parameters, change of load conditions, variation of material properties, quality of manufacturing, human errors or structural modifications in service) is quite significant. Thus various safety factors are imposed on the structure to guarantee the safe fatigue life. The structure is designed for a specific number of flight hours and retired from service afterwards even if no failure occurs.

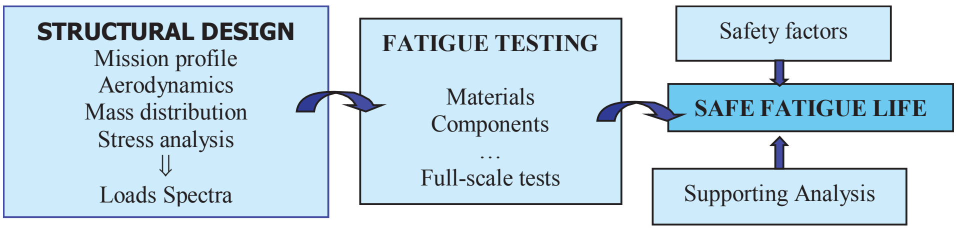

Figure 1. Safe-life aircraft design concept.

The structure is designed for a specific number of flight hours and retired from service afterwards even if no failure occurs. The estimation of operational life of ageing aircraft is even more difficult.The *safe-life* designed concept, illustrated in Figure 1, leads in practice to structures which are safe but over designed This is not desirable if economy and performance are analysed. Non-critical structural components which are exposed to multiple load paths are often design using the *fail-safe* concept. Even if these components develop damage, the structural integrity is not jeopardized since the assumption is that damage can be detected before any catastrophic failure. This requires periodic inspections of components. Monitoring techniques offering reliable detection, location, estimation of severity and prognosis of damage can lead to the *damage-tolerance* design concept. Detected damage is monitored to maintain the safe life of aircraft in this design concept. Although significant inspection effort is required, this concept can lead to lighter structures and better performance. In fact the prevention of crack initiation behind the safe-life concept of design does not prevent catastrophic failures. Therefore maintenance and inspection of aircraft structures is very important whatever the design concept is. More details related to current design concept of aircraft and potential benefits associated with the damage-tolerant approach can be found in [1].
Fatigue of materials in Aerospace Engineering has significantly contributed to structural design. The *safe-life* and *fail-safe* design concepts, introduced in aerospace, are widely used in many areas of engineering.

3. AGEING AIRCRAFT PROBLEM AND STRUCTURAL DAMAGE

Statistics show that a significant number of civil and military aircraft have exceeded their design lives. The number of civil structures older than 25-years has increased from 1900 in 1997 to 2130 in 1999 [2]. The same problem exists in the military area where for example in 2000, 75% of US Air Force aircraft were older than 25 years [3]. Recent years have shown many aircraft being retired. However, it is very likely that these structures will be used in the future. Although, through-life upgraded structures are cheaper than new structures, the costs associated with their maintenance is a serious problem. This is due to the fact that ageing aircraft structures require a significant maintenance effort in order to guarantee the extended safe life. This is why reliable and cheap techniques for damage detection in aircraft are very important. These methods need to detect and monitor various types of structural damage.

It appears that fatigue cracks and corrosion are the major cause of damage in aircraft metallic components whereas Barely Visible Impact Damage (BVID) is the major concern in aircraft composite components [2]. In practice only certain critical areas need to be monitored periodically. The most critical areas in civil structures include: frames, joints, stringer run-outs in fuselage, wing/fuselage attachments, pressure bulkheads and landing gears [2]. Loads and geometry of these components are the major contribution to fatigue.

4. USAGE MONITORING

Aircraft usage can be monitored using structural load sequences. Load sequences are than transformed in order to estimate the accumulated fatigue life. Various analytical tools are required for the transformation. Loads models from the aircraft design process are not used in practice for fatigue life estimation. These models are very expensive to produce and then update if any modifications are required. This section briefly describes major approaches used for usage monitoring in aircraft structures. Usage monitoring systems based on loads are commonly known as Operational Loads Monitoring (OLM) systems and mainly applied in military structures.

Fatigue monitoring, introduced in 1950s, was the first approach used for aircraft usage evaluation. The method uses fatigue meters that count the cumulative number of reached or exceeded values of critical vertical acceleration. This technique not only results in poor accuracy but also leave many areas which are not monitored. A significant improvement can be achieved when loads monitoring is performed using flight parameters such as speed, altitude, acceleration, fuel content, flap position, air temperature and many other parameters offered by sensors already used to monitor aircraft performance. Despite the fact that parametric systems have been significantly improved over the years, their accuracy is still limited.

An alternative approach to loads monitoring can be offered when direct strain measurements are performed.

This approach utilises a small number (10 to 20) of strain gauges bonded in critical locations. Strain signals can be converted to stress histories which can be related to loads. A rainflow cycle counting procedure is used to analyse the loads. The accumulated damage is then estimated using the Fatigue Index (FI) which is based on the fatigue-life (S-N) curve and linear damage accumulation rules. Although the method is sufficiently accurate, it is still very costly to install and support. Also, the assumption of linear accumulation of damage is not always valid. Recent developments in this area include the application of optical fibre sensors for strain and temperature monitoring [4].

The *Eurofighter Typhoon* combat aircraft is equipped in one of the most sophisticated systems that performs real-life fatigue calculations, as described in [5]. The system uses events (e.g. reports on hard landing) and loads (strain gauges or flight parameters) monitoring. This information is combined with the auxiliary data (e.g. flying log data and design/performance parameters) in order to estimate the life consumed by the airframe. The entire system is directly linked to ground-based maintenance.

5. HEALTH MONITORING

Damage detection/monitoring, Non-Destructive Testing/Evaluation (NDT/E) and SHM have the same meaning in many engineering areas. *Damage, health* and *monitoring* of structures can be described using various definitions. In general, *health* is the ability to function/perform and maintain the structural integrity throughout the entire life-time of the structure; *monitoring* is the process of diagnosis and prognosis and *damage* is a material, structural or functional failure.

Also, in this context, structural integrity is the boundary condition between safety and failure of engineering components and structures. Damage detection and direct monitoring of damage accumulation offers and alternative approach to loads monitoring in aircraft maintenance. In fact civil aircraft are inspected using classical NDT techniques developed mostly between 1940s and 1960s.

Various approaches, technologies, techniques and signal processing methods have been proposed for structural damage detection and monitoring. The applicability of these techniques for aircraft damage detection has been discussed in [6]. It appears that only a few techniques are used in practice for aircraft inspection and maintenance. These include: visual inspection, Ultrasonics and Eddy Current.

Visual inspection, which includes examination by eye, optical devices and illumination techniques, is the most commonly used approach in aircraft service. Although the method is effective for detection of surface and sub-surface damage, it is very time consuming and often applicable only in laboratory conditions. Ultrasonic inspection utilise various properties of elastic waves propagating in structures. Various physical phenomena, such as wave attenuation, scattering and reflections, are used for damage detection. Damage detection tests are conducted using either the *pitch-catch* or *pulse-echo* mode. The former utilizes two probes moving in tandem on either one or two sides of the specimen. The latter uses only one probe which works as an actuator and sensor. Conventional ultrasonic inspection requires coupling medium between ultrasonic probes and monitored specimens. In summary, ultrasonic inspection is highly sensitive to surface and deep flaw type damage. The major limitations of these techniques are related to difficulties with coupling, requirement for time-consuming scanning and cost of ultrasonic equipment. Eddy Current is the third most commonly used technique for crack detection in aerospace structures. The method works on the principle of electromagnetic induction; damage is detected by changes in electromagnetic impedance due to strain in the material. The method is relatively inexpensive and offers the ability to detect surface and sub-surface small defects. Unfortunately only conducting materials can be tested with Eddy Current probes. Also poor depth penetration and scanning requirement (time-consuming for large areas) are the major limitation of the technique.

6. EMERGING DAMAGE DETECTION TECHNOLOGIES FOR AIRCRAFT INSPECTION

Recent years have shown a number of new technologies that have the potential for automatic damage detection in aircraft structures. This section summarises the most promising techniques for rapid, reliable and effective damage detection.

Recent developments in SHM area are related either to modifications of well-established techniques, new equipment and sensor technologies or new monitoring principles. Acoustic Emission (AE) is a well-established NDT technique used for damage detection. It is based on rapid release of transient elastic energy in form of short elastic waves that propagates in the monitored specimen. These bursts are produced by microscopic deformations, dislocation movement or crack propagation/fracture under the external loading. The modified AE system has been recently developed jointly by *Airbus UK* and *Lloyds Register of Shipping* and built by *Ultra Electronics*. The system contains phenomenological filters that perform dramatic data reduction resulting in improved detection and location of damage. Application examples to full-scale aircraft fatigue tests can be found in [7]. An application of optical fibre sensors for AE –based damage detection is another promising development in this area, as also discussed in [7].

Although elastic waves and their propagation have been used for many years to analyse structural damage, a number of interesting approaches have been proposed recently for integrated health monitoring systems. Lamb wave inspection is the most widely used damage detection technique based on guided ultrasonic waves (i.e. wave packets propagating in bounded media). The technique is based on guided ultrasonic waves propagating in plate-like structures (Figure 2). These waves are introduced to the monitored plate by one transducer and sensed either by the same transducer or another transducers at a different location. The former involves the analysis of reflected waves whereas the latter utilises transmitted waves. Structural damage is identified by a change of the response signal. Often wave attenuation and/or mode conversion are sufficient to detect defects. The first NDT/E application of Lamb waves goes back to the 1950s. A significant progress has been achieved when low-profile, smart transducers (e.g. piezoceramic, polymer, discs, paints, fibres) were introduced in the early 1990s. One of the most interesting developments in this area is the *Smart Layer*® [8] comprising small piezoceramic transducers on a thin dielectric Kapton layer which can be easily surface mounted on a structure or integrated into a structure/material. A review on guided ultrasonic waves for SHM applications is given in [9]. This review includes recent developments in: transducers, monitoring strategy, modelling, signal processing and application examples.

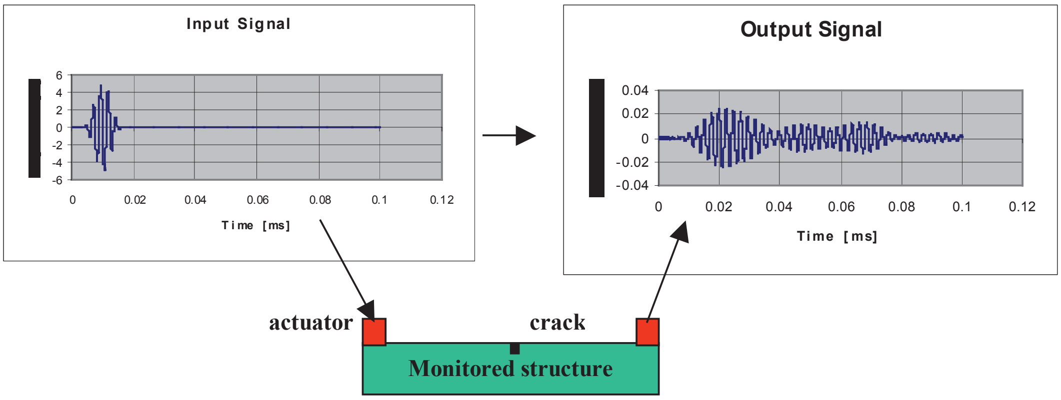

Figure 2. Damage detection using guided ultrasonic waves.

The major progress in the area of guided ultrasonic waves for SHM has been achieved in transducer technologies. Figure 3 gives examples of two recently developed and promising transducers used for guided ultrasonic waves. A phased array transducer [10], shown in Figure 2a, generates Lamb waves propagating in various directions. These directions (angles and focal lengths) are controlled electronically by appropriate delays of the signal emitted by an array of small crystal elements that can work in a combined transmitter/receiver mode. Damage detection systems based on phase array transducers [11] are sensitive to small cracks in metallic structures allowing for a significant reduction of transducers required for monitoring. Figure 2b shows an example of the Micro-Electro-Mechanical System (MEMS) used for generation/sensing of guided ultrasonic waves. This MEMS transducer, introduced in [12], is in fact a vibrating thin silicon nitride membrane supported on the 500μm silicon substrate. The resonance frequency of this transducer is in the vicinity of 1MHz. Recent studies show that optical fibres can also be used for Lamb wave sensing, as demonstrated in [13], where a Bragg grating sensor with a narrow bandwidth laser was used. If the wavelength of the laser matches a certain part of the grating spectrum, any shift of the spectrum will as a concequence modulate the reflected optical power. Thus Bragg gratings can be used as multi-functional sensors measuring strain, temperature, vibration and ultrasound (AE and guided ultrasonic waves). Although, optical/laser based systems are widely used for Lamb wave generation and sensing, only recently scanning laser vibrometry has been used for damage detection in metallic structures, as shown in [14-15]. Figure 3 demonstrates how laser vibrometry can be used for crack detection in metallic structures. Here, a Lamb wave signal is generated in the aluminium plate using a low-profile piezoceramic actuator. The indicated area of the plate is then scanned by a laser vibrometer. The damage detection scan exhibits increased amplitude levels of Lamb wave responses in the vicinity of damage. A new Comparative Vacuum Monitoring (CVM) method was developed in the mid 1990s for crack detection [16]. The CVM techniques utilizes self-adhesive polymer sensor pads which are bonded on monitored specimens. A low vacuum pressure is maintained between sensor pads and monitored surfaces. An increase in pressure indicates cracks. A number of different types of sensor pads have been developed for various geometrical and structural configurations. The method is sensitive to detect 250μm cracks. Microwaves have been considered for surface crack detection since 1970s [17]. A number of different damage detection techniques based on microwaves have been developed since that time under different names such as [18]: microwave imaging, microwave antennas, microwave waveguide sensors or microwave thermography.

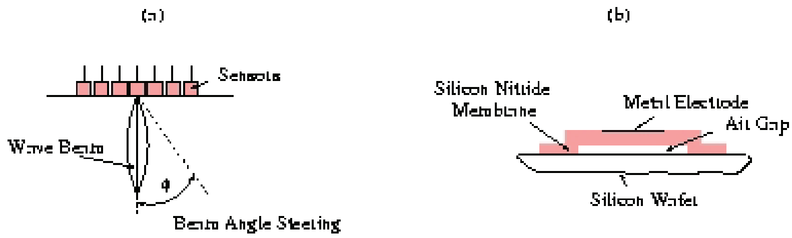

Figure 3. Examples of recent sensor design concepts: (a) phased-array sensor (b) MEMS capacitance transducer.

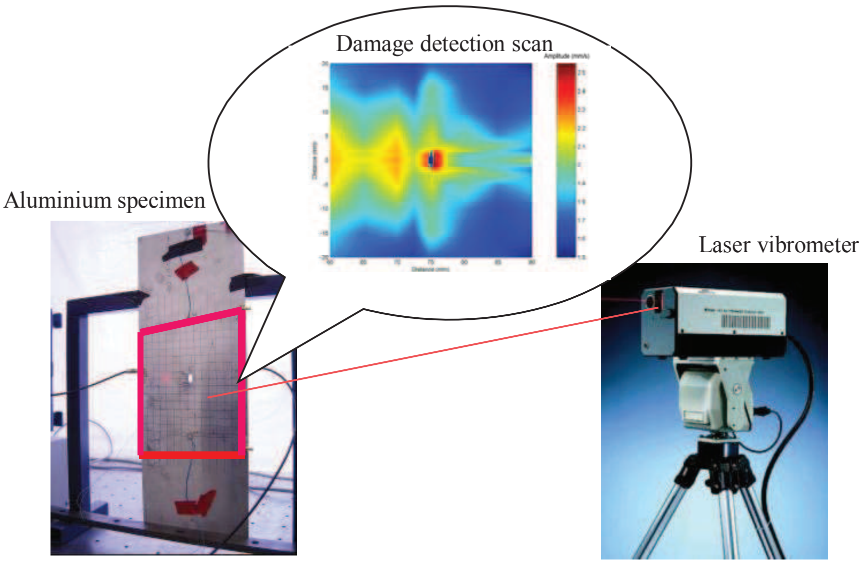

Figure 4. Damage detection using laser vibrometry.

Microwaves are electromagnetic waves having a wavelength of 10 to 300 mm (frequency of 1GHz to 30GHz). They exhibit many properties usually associated with waves in the optical frequency range. Electromagnetic microwaves can penetrate non-metallic materials and, in contrast to ultrasonic waves, they can propagate well in the air. Thus non-contact damage detection is possible without any coupling medium. Microwave wireless systems consist of transmitting and receiving antennas. Receiving transducers detect characteristic signals in standing waves created by short-circuited microwave waveguides due to surface cracks. Microwave-based damage detection systems can be classified into active and passive systems [19]. Active systems analyse reflected waves whereas passive systems utilise information about damage from emitted energy (e.g. temperature change).

Vibration/modal based techniques have also been considered for aircraft damage detection [20]. The assumption of these techniques is that damage results in modifications of structural parameters, i.e. mass, stiffness or damping. This approach utilizes natural frequencies, mode shapes, modal energy curvatures and transfer functions. However, the major problem with vibration/modal-based techniques is the damage sensitivity; global, not local, detection and monitoring of large damage is only possible in practice.

6. CONCLUSIONS

The paper has briefly discussed current approaches used for inspection and maintenance of aircraft structures. Recent developments in this area are related to new monitoring and sensor

technologies based on the integrated system approach. These techniques have the potential to influence current aircraft design concept leading to lighter, high-performance structures which designed using damage-tolerance principles.
Research and development for aerospace applications are at the forefront on engineering achievements. Therefore the applicability of these techniques goes far beyond aircraft damage detection; the methods presented can be used in other areas of transportation, civil and process engineering.

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