State of Development of Advanced Sensor Systems for Structural Health Monitoring Applications

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ABSTRACT

The advent of advanced development in sensors, microelectronics, adaptive signal processing and predictive technologies have significantly shaped the fundamental approach to dealing with traditional maintenance and repair problems within the aerospace industry. The concept of aircraft Diagnostics, Prognostics and Health Management (DPHM) is increasingly becoming a main stream approach to dealing with aircraft maintenance within an advanced operational autonomic logistics structure. Driven by the requirement for increased safety, reliability, enhanced performance and platform availability at reduced cost, key sensor technologies such as shape memory alloy, piezoelectric materials, magnetostrictive and electrostrictive materials, triboluminescent materials, optical fibres, carbon nanotubes, comparative vacuum monitoring, micro and nano electromechanical systems (MEMS/NEMS) are expected to play a significant role in the development of such DPHM systems. These advanced sensors, often referred to as smart sensors, are further expected to provide functionality that is not matched by current technologies and nondestructive evaluation techniques within in an on-line in-situ environment. Regardless of the extensive number of sensors and sensor systems that could potentially be employed or integrated within a DPHM system, only selected few illustrating near commercial exploitation are introduced in this document.

1.0 INTRODUCTION

The increasing mission complexity, operational constraints and stringent performance requirements of legacy and emerging air platforms have made on-line and in-situ health monitoring and management a critical component of aircraft operational logistics and maintenance programs. From an operator's perspective, the goal of such health management system is to improve operational efficiency and safety, lower life cycle costs, increase maintenance cycle, increase platform operational availability and reliability, and improve asset management. It is estimated [1] that about 60% of the overall ownership cost of an aircraft is attributed to Operation and Support (O&S). Most of this cost is linked to personnel and materials used to support scheduled and unscheduled maintenance actions. Moreover, because it is difficult to diagnose faults in some components, such as engine compressors, more than 40% of compressors replaced on aircraft are not defective resulting in unnecessary false repairs at additional cost. Realizing the significant savings and increased operational availability that could result from the development of on-line in-situ integrated health management systems, the Joint Strike Fighter (JSF) Program Management Office (PMO) has deployed an advanced capability into its new fighter jet program to reduce O&S costs, enhance performance and increase the efficiency the management of the fleet. Such advanced capability, known as Diagnostics, Prognostics and Health Management (DPHM), was initially conceptualized during the introduction of the JSF program for engine diagnostics and prognostics.

Traditionally, real-time operating parameters and damage information are captured and compared against both test and field data to assess the potential damage severity and required maintenance actions. Such global health monitoring approach is well known as Condition-Based Maintenance (CBM). This approach is intended to help manage the frequency and extent of maintenance procedures for various components within a complex integrated system. The incorporation of CBM with predictive tools is expected to increase the level of effectiveness of on-line in-situ health monitoring and management systems' capability and provide advanced life cycle assessment tools. Such capability is known as the DPHM capability and is expected to provide the ability to predict and pinpoint potential damage and problem areas; thus, reducing or perhaps even eliminating the need for periodic inspections. This capability will not only reduce platform's ownership cost, that is considered to be a critical concern for civilian aircraft operators, but also increase air safety, that is mandated by the Federal Aviation Administration (FAA) (e.g. 80% accident reduction by year-end of 2007).

Faas et al. [2] reported that the ultimate results of a DPHM capability are to be able to reliably predict failure with high probability and high confidence. However, they claim that realistically one hopes that such systems provide tools to integrate with existing systems to break the ambiguity groups and then provide some insight into the predictive side. Furthermore, by deploying such capability, they identified that the specific war fighter benefits include reduced maintenance man-hours, restored aircraft to operational status sooner, reduced consumption of spare parts, reduced mission aborts due to system failures, reduced deployment footprint and increased warning time to order spares and invoke proactive repairs. Results reflecting the return on investment (ROI) for the deployment of an on-board monitoring system are illustrated in Table 1 [2].

Table 1: ROI for the deployment of on-board monitoring system.

	100% On-Board	75% On-Board	50% On-Board	25% On-Board
Return On Investment (ROI)	9.2	11.5	16.5	24.5
Time to Break Even (Years)	10	10	9	7

2.0 DIAGNOSTICS, PROGNOSTICS AND HEALTH MANAGEMENT (DPHM)

2.1 A Definition of DPHM

A DPHM system is considered to be the central information system for on-line collaborative environment in aircraft autonomic logistics. DPHM has the capability to determine the state of health of a component to perform its function(s) (Diagnostics). It is also a predictive diagnostics tool that includes determining the remaining life or time span of proper operation of a component (Prognostics). It has the capability to report appropriate decisions making information about component maintenance based on diagnostics/prognostics information, available resources, and operational demand (Health Management) [3]. DPHM evolved from a vision of advanced diagnostics that uses advanced sensors to monitor and manage aircraft health and quite often is referred to as on-line structural health monitoring or advanced on-line nondestructive evaluation capability.

2.2 DPHM Architecture and Structure

Depending on the application and desired outcome, a DPHM system varies in complexity from simple (e.g. detect and alert) to more complex (e.g. detect and advise). Figure 1 illustrates a conceptual implementation approach of a DPHM system having moderate complexity; whereas, Figure 2 [4] illustrates the expected complexity for integrating an aircraft DPHM system within a military operational autonomic logistics structure.

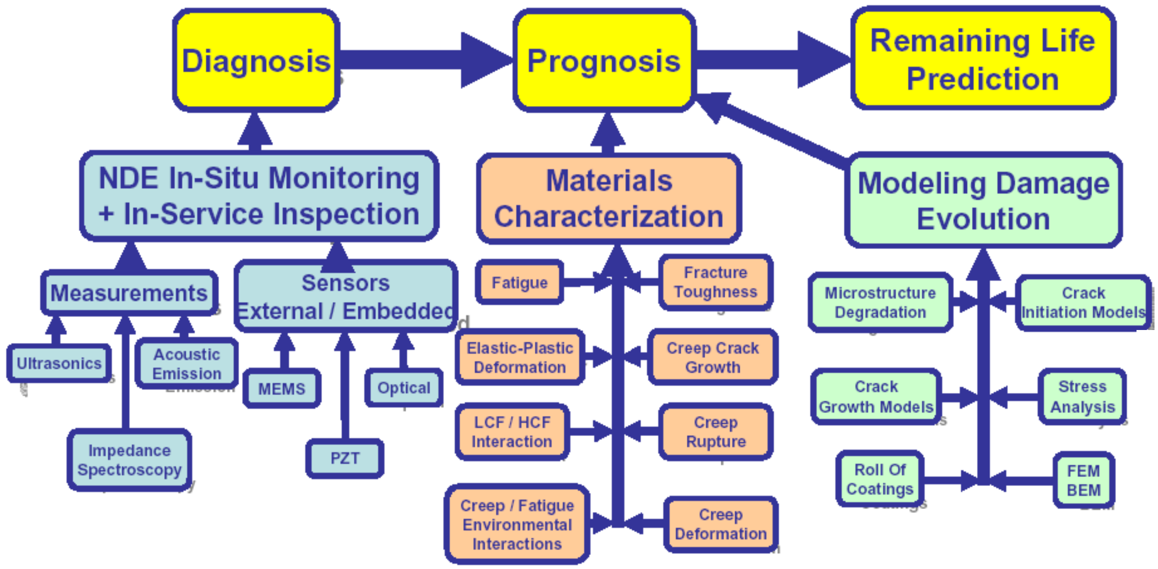


Figure 1: A moderate complexity conceptual structure of a DPHM system.

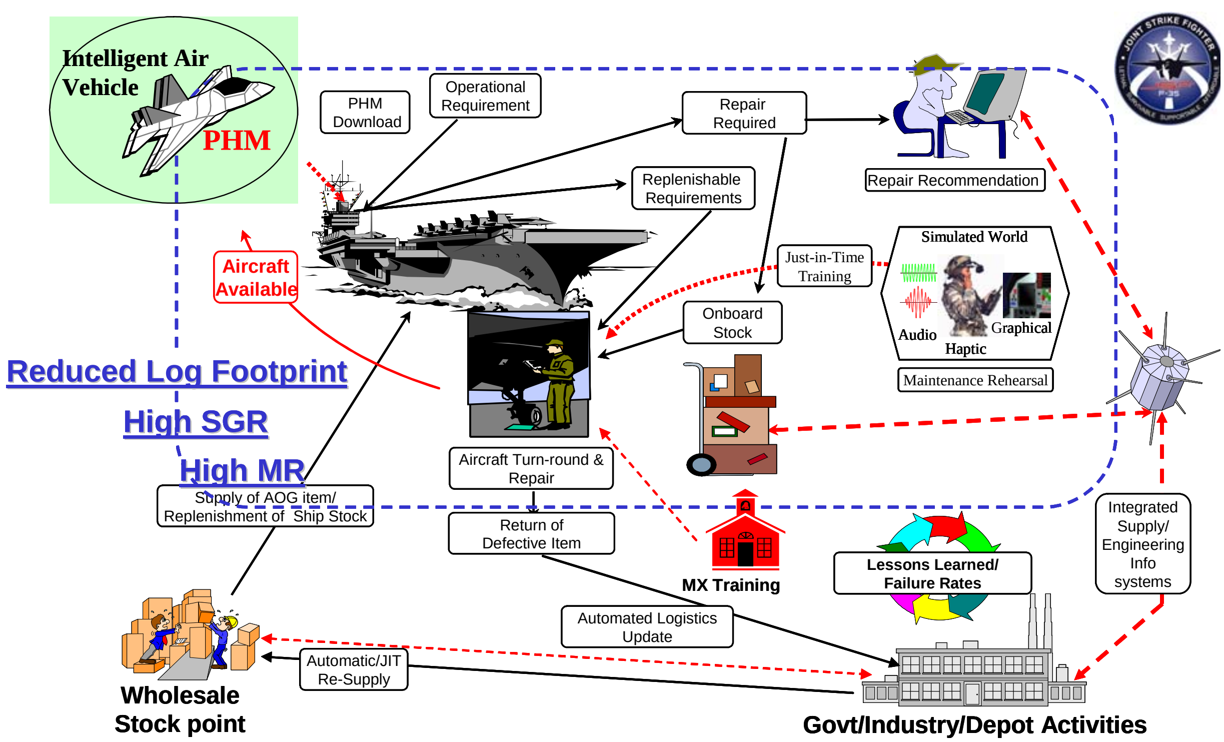


Figure 2: A complex conceptual structure of a military aircraft DPHM system within autonomic logistics structure.

Irrespective of the simplicity or complexity of the system architecture, four major building blocks constitute the core architecture and structure of a DPHM system. These blocks are sensors network, usage and damage monitoring reasoner (diagnostics), life management reasoner (predictive and prognostics), and decisions making support and assets management. One possible approach to describing the functioning of such a system is that usage and damage parameters, acquired via wired and wireless sensors network, are transmitted to an on-board data acquisition and signal processing system. The acquired data is developed into information related to damage, environmental and operational histories as well as aircraft usage employing information processing algorithms embedded into the usage and damage monitoring reasoner. This information, when provided to the life management reasoner and through the use of predictive diagnostic and prognostic models, is converted into knowledge about the state of operation and health of the aircraft. This knowledge is then disseminated and transmitted to the flight crew, operations and maintenance services, regulatory agencies, and/or Original Equipment Manufacturers (OEM) for decision making support and asset management.

It is generally expected that the critical and perhaps the most significant element in the implementation of DPHM systems is the selection of sensors and the proper interpretation of the acquired data (information). Sensors must be energy efficient, accurate, reliable, robust, small size, lightweight, immune to radio frequency and electromagnetic interferences, easily and efficiently networked to on-board preprocessing capability, capable of withstanding operational and environmental conditions, require no or low power for both passive and active technologies and possess self-monitoring and self-calibrating capabilities.

Several sensing technologies and nondestructive evaluation (NDE) techniques are currently in use or under investigation for DPHM system development. NDE techniques refer to the array of nondestructive evaluation techniques and processes that monitor, probe, measure, and assess material response to internal or external stimuli. The measured response, generally conducted off-line, is related to a desired material property and characteristics reflecting the state of its health or its structural integrity. The main NDE techniques are [5]: visual inspection, liquid penetrant inspection, magnetic particle inspection, radiographic inspection (X-ray and gamma ray), eddy current inspection, ultrasonic inspection, and thermographic inspection. Although, each of these methods is dependent on different basic principles in both application and output, repeatability and reproducibility depends significantly on specific understanding and control of several factors, including human factors5. These techniques do not lend themselves as the best candidates for real-time on-line environment; however, due to their maturity, they are significant tools for off-line damage detection and assessment and for validation of emerging and developing techniques and methods.

Advanced sensors often referred to as “smart” sensors, sensor networks, or sensor nodes perform several functions delivered by NDE techniques in a real-time on-line environment with added integrated capabilities such as signal acquisition, processing, analysis and transmission. These highly networked sensors (passive or active) are suitable for large platforms and wide area monitoring and exploit recent development in micro and nano technologies. Some of these sensors include MicroElectroMechanical Systems (MEMS) sensors [6], fibre optic sensors [7], piezoelectric sensors [8], piezoelectric wafer active sensor [9], triboluminescent sensors [10], SMART layer sensor networks [11], nitinol fibre sensors [12], carbon nanotube sensors [13], and comparative vacuum sensors [14]. Regardless of the extensive development of sensor technology, efficient sensor networks, sensor power consumption and conservation, efficient network topologies, data transmission security, miniaturized and fully integrated electronic and signal acquisition and processing (Lab-On-a-Chip), only a handful of emerging sensors present a real potential for integration into a DPHM system. This document presents a selected few sensor technologies that have recently seen significant development or nearing full commercial exploitation. These technologies are identified as advanced non-traditional sensors employing advanced concepts or simply advanced sensing technology.

To put into context the significance of such advanced sensing technology; in the US, the market for industrial sensor technologies in 2004 was $6.1 billion and expected to grow to $7.7 billon by 2009. While an average annual growth (AAGR) of 4.6% is achieved for these sensors, MEMS are expected to observe an AAGR of 7.6% leading to a market value of $2.5 billion by 2009. It is also expected that the semiconductor based world market will reach $21.8 billion in $2008 as opposed to the $12.6 billion of 1998. Fibre optic sensors of several microns in size are no exception. The 1998 world market was $175 million and expected to reach $600 million by 2011 [15].

3.0 MEMS BASED SENSORS

The word smart is defined as “intelligent or able to think and understand quickly in difficult situations” [16]. For example, smart devices are defined as ones that operate using computers (e.g. smart bombs and smart cards.) The same source defines the word intelligence as “the ability to understand and learn well and to form judgments and opinions based on reason.” Furthermore, the definition of advanced is said to be “highly developed or difficult.” According to the IEEE 1451 standard [17], a smart or intelligent sensor is defined as “one chip, without external components, including the sensing, interfacing, signal processing and intelligence (self-testing, self-identification or self-adaptation) functions”. Figures 3 [17], illustrates the smart sensor concept as defined by IEEE 1451.

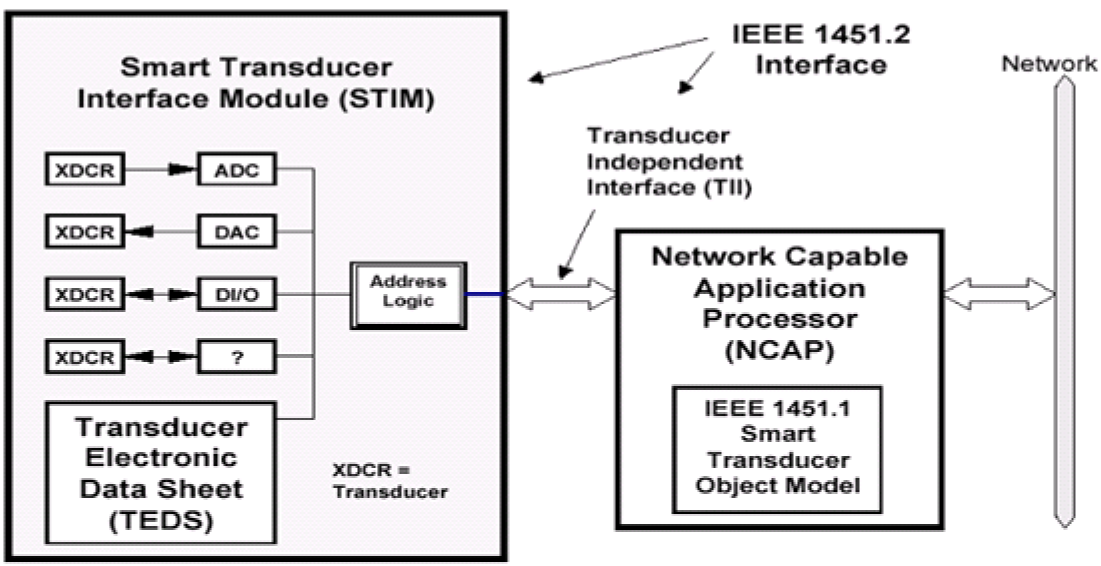


Figure 3: Smart sensor concept defined by IEEE 1451.

Sensors based on this smart sensor concept generally exploit development in MEMS and nano fabrication along with advanced electronics and wireless devices using radio frequency communications technologies. Figure 4 [18] depicts a prototype of a smart sensor, known as sensor node, for multi-parameters sensing. The sensor node contains four major components: a 3M’s MicroflexTM tape carrier, two MEMS strain sensors, a Linear Polarization Resistor (LPR) sensor to detect wetness and corrosion and an electronics module. The electronics module is composed of a Micro Controller Unit (MCU), a signal conditioning unit, a wireless Integrated Circuit (IC) unit, a battery and an antenna. Employing this node design, Niblock et al. [19] developed an Arrayed Multiple Sensor Networks (AMSN) for materials and structural prognostics. Some of the observed benefits employing smart sensors system include the wealth of information that can be gathered from the process leading to reduced downtime and improved quality; increased distributed intelligence leading to complete knowledge of a system, subsystem, or component's state of awareness and health for 'optimal' decision making [20]. Additionally, due to their significant small size and integrated structure, these sensors can easily be embedded into composites structures or sandwiched between metallic components for remote wireless and internet based monitoring. Intelligent signal processing and decision making protocols can also be implemented within the node structure to provide ready to use decisions for reduced downtime and increased maintenance efficiency.

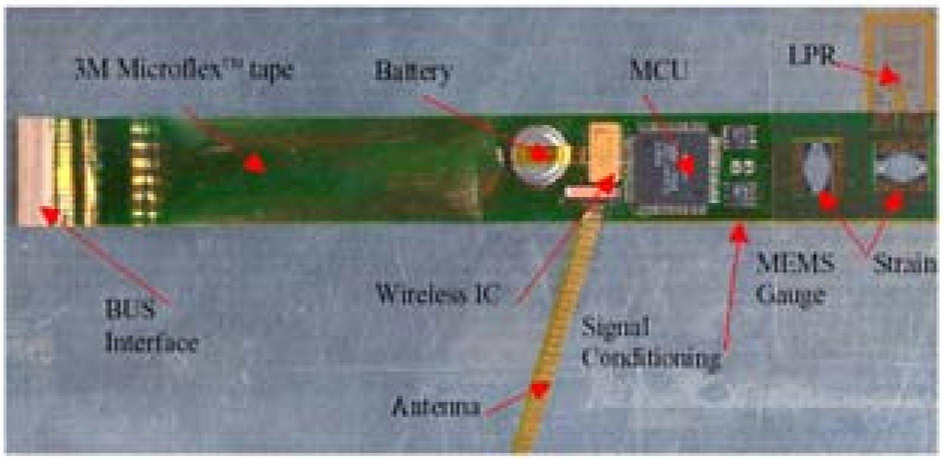


Figure 4: MEMS based smart sensor node.

Recently, Mrad et al. [21] demonstrated, on a commercial Gas Turbine Engine (GTE), the suitability of a MEMS based pressure transducer for fan speed measurement to infer blade health condition. Such MEMS pressure transducer, shown in Figure 5, was placed in front of the fan blades on a spacer as an alternative to directly placing it over the fan blades as necessitated by most engine manufacturers. Figure 6 illustrates the sensor placement and its output for a full engine thrust (take-off thrust condition of 14000 RPM).

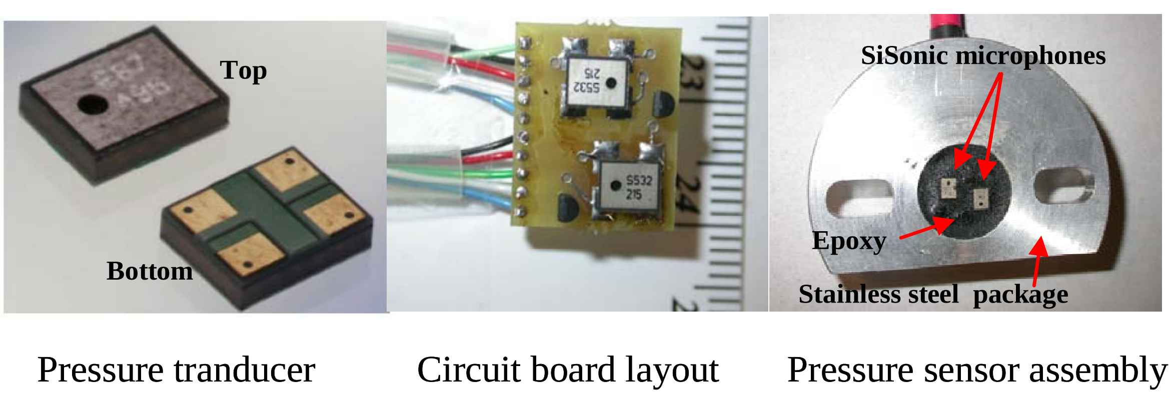


Figure 5: MEMS based pressure sensor for GTE application.

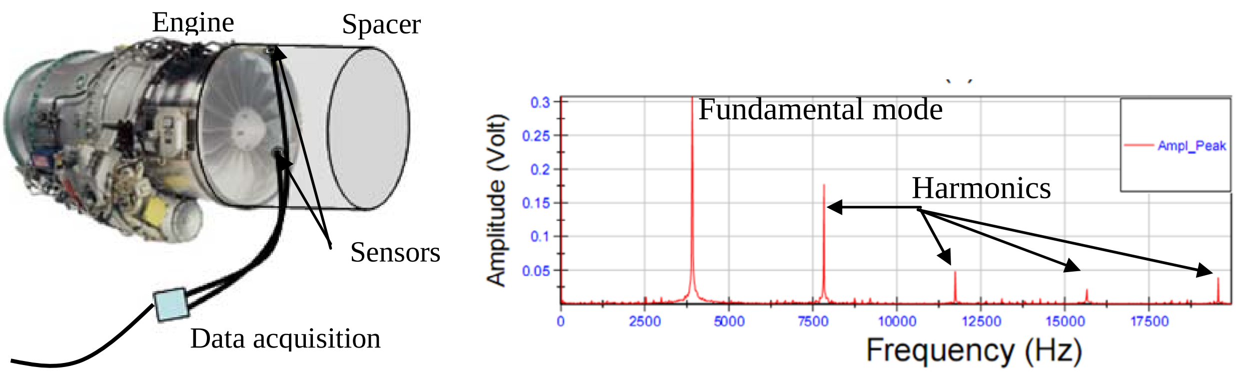


Figure 6: A typical gas turbine engine with the MEMS pressure transducer and a typical frequency response for a full thrust condition.

Even though the promise of this sensor technology is significant, wireless and secure communications particularly in harsh environment applications, power requirements, system miniaturization and integration meeting practical requirements within an economical manufacturing environment require further consideration. For instance, the reliability of the sensor and its associated electronics within a harsh environment and the packaging require further development.

4.0 PIEZOELECTRIC BASED SENSORS

Piezoelectricity dates back to its discovery in 1880 by the Curie brothers. Materials possessing these characteristics are generally referred to as dual function or smart materials and have been used extensively in the development of innovative small size and effective actuators and sensors technologies. Piezoelectric actuators are generally made of ceramics and employ the indirect effect; whereas piezoelectric sensors are made of thin polymers and employ the direct effect. Both materials are exploited in the development of MEMS based sensors and actuators as well as advanced structural health monitoring and prognostic health management systems [22-24].

In recent years, significant research was devoted to the development of structural health monitoring capabilities based on piezoelectric materials. Masson et al. [25] demonstrated a number of modeling tools and damage detection strategies in low and medium frequency ranges. A number of sensing and actuation technologies including arrays of piezoelectric sensors and actuators, shape memory alloys, and micro-accelerometers were also demonstrated for application to structural health monitoring at higher frequencies. Employing piezoelectric transducers' arrays, shown in Figure 7 and a time reversal approach, damage detection and localization were demonstrated. Furthermore, Mrad et al. [26] exploited these smart materials characteristics to detect exfoliation damage in metallic structures through the use of arrayed sensors, as shown in Figure 8. These novel transducers, analogous to nanocoatings, are known as integrated thin film paint-on Ultrasonic Transducers Array (UTA). The fabrication novelty and flexibility in producing UTA with different sizes, thicknesses, for different aerospace applications is documented and demonstrated by Kobayashi et al. [27].

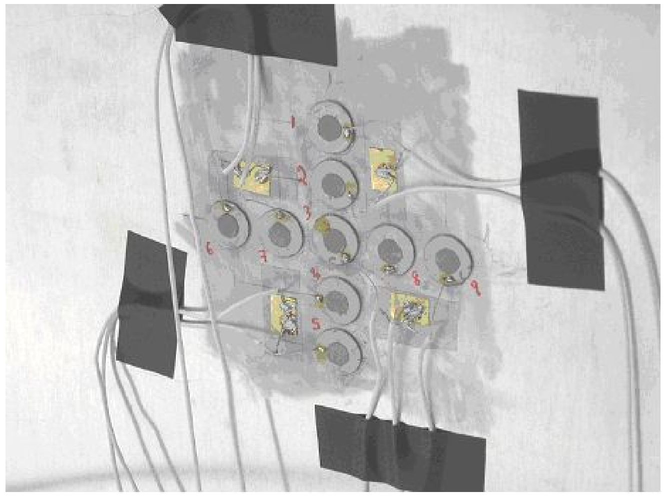


Figure 7: Arrayed piezoelectric sensors used for damage (crack) detection and localization.

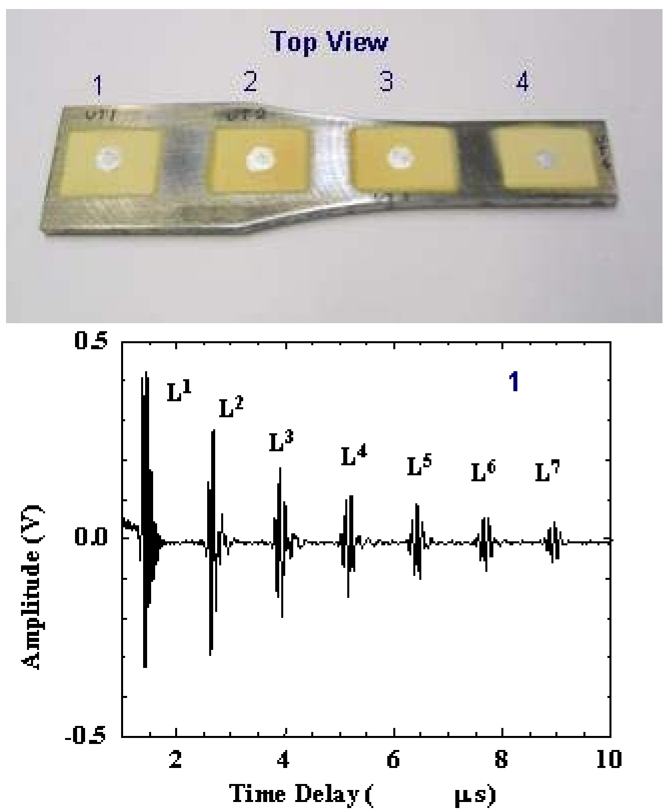


Figure 8: Exfoliated test article with four integrated UTAs and a typical UTA response.

Piezoelectric material can be used both for active and passive defect detection employing network of sensors. As illustrated in Figure 9 [28], in the active mode, an electric pulse is sent to a piezoelectric actuator that produces Lamb waves within the structure under evaluation. The array of piezoelectric sensors will pick up the resultant Lamb waves for processing and analysis. If defects such as cracks, delamination, disbond or corrosion exist within the array of sensors, a change in the signal results, which is distinct from the reference healthy or non-defect component's signature. These systems rely on a reference signal in the structure before they are placed in service. The location and the size of the defect can generally be determined from the degree of signal change. In the passive mode, sensors are used continuously as "listening" devices for any possible damage initiation or propagation. Sensors within the network can detect energy emitted from impact events and defects generation, including crack formation, delamination, disbond, and possibly non-visible impact damage. In this mode, arrays of sensors are used to monitor or detect such events that generally have a particular energy signal associated with them. Cracks of length 0.005 inches from a distance of six inches on flat plate samples [29] were detected using these sensors. The latter mode is generally desired as it requires little or no power for its operation. Systems based on this dual concept of passive and active monitoring have been developed [30,31]. Stanford Multi-Actuator-Receiver Transduction (SMART) Layer based system has been developed and demonstrated for several aerospace structural health applications. The system is designed and built around a set of piezoelectric sensors networked and embedded into desired configurations in a single polyimide layer, known as SMART Layer®. Using dedicated diagnostics software, analysis tools and graphics user interface packaged into a SMART Suitcase™ portable diagnostic hardware, the damage severity and location can be easily identified. Figure 10 [30,31] depict this approach with two applications: composite bonded patch repair health monitoring and integrity assessment and damage detection under fasteners.

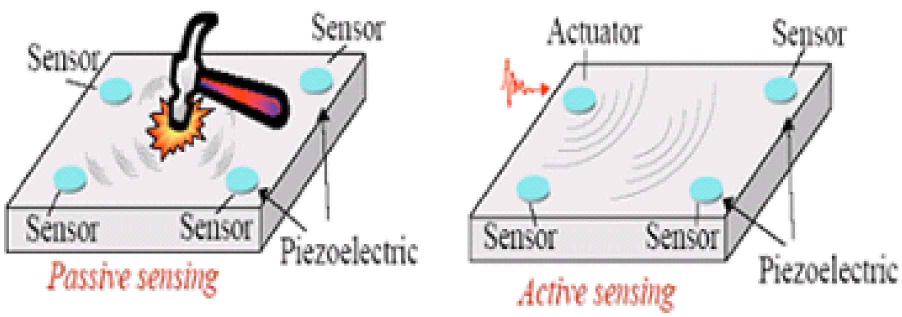


Figure 9: Passive and active sensing mode using piezoelectric material.

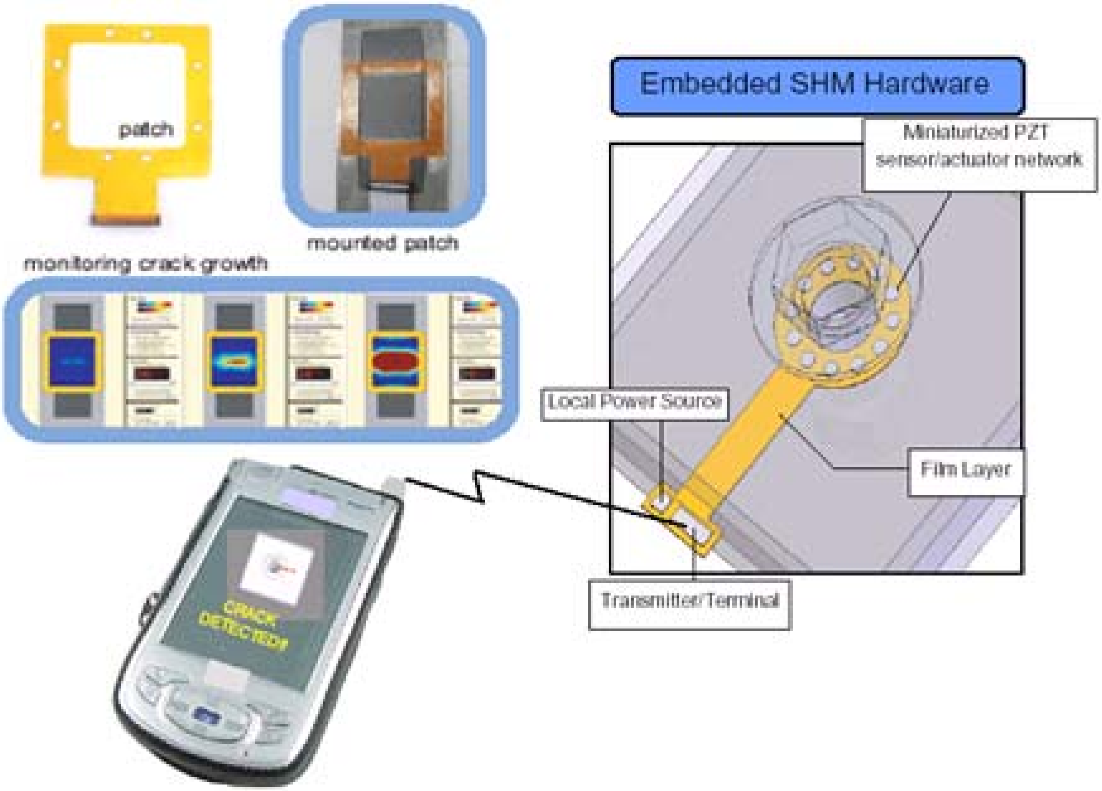


Figure 10: A SMART Layer® technology based structural health monitoring system.

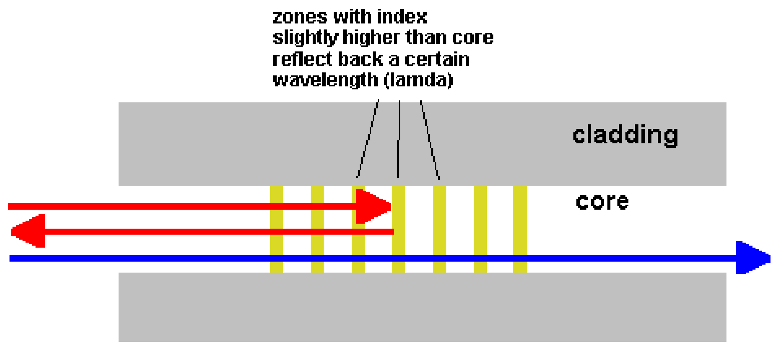
This sensor technology provides significant potential in the development and implementation of DPHM capability due to the high sensor multiplexing capability, the suitability of the sensor array in harsh environment, and its sensitivity to pressure, temperature, vibration, and strain. However, when this technology is used in either mode of operation (passive or active) it presents several challenges that require further research. In the passive mode, background noise (AE from non-defect events) needs to be accommodated for; thus, requiring significant experience and additional expertise to accurately diagnose the presence of damage from the acquired data. In the active mode, sensors/actuators must be spaced properly and excited with certain frequencies at selected energy level to be able to detect damage with certain sizes and region as demonstrated by Pinsonnault [32]. Additionally, from a hardware perspective, the reliability of sensors and actuators wiring, networking and bonding requires validation. Costs associated with added weight, complexity and system certification needs to be weighed against the value added in the integration of this technology as a component of a DPHM system. Tremendous progress was reported in this area; however significant research is needed to bring this technology to practical deployment and to facilitate its qualification and certification on air vehicles.

5.0 FIBRE OPTIC BASED SENSORS

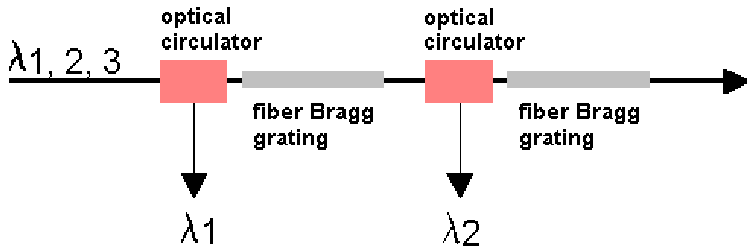
The fibre optic sensor development that capitalized on the 1950's successful discovery of communication optical fibres has been underway since the early 1970's. Only in recent years, accelerated progress was experienced due to the significant development of new, low-cost materials and devices, the emergence of micro and nano technologies for the telecommunications industry and the increased interest in the development and implementation of DPHM systems. The shape and form of optical fibres are similar to those reinforcing fibres used in fibre-reinforced composite materials. However, the diameter of optical fibres is much larger, usually in the order of 40 to 250 microns, compared to glass and carbon fibres used in composites that are typically 10 microns or smaller. Optical fibres consist of a light waveguide inner silica-based core surrounded by an annular doped silica cladding that is protected by a polymer coating. This optical fibre can also be made using other materials, such as plastic [33]. The fibre core refractive index is relatively large compared to that of the cladding index. The change in refractive indices, between the core and the cladding, provides the required mechanics for light propagation within the fibre core. Depending on the wavelength of the light input, waveguide geometry and distribution of its refractive indices, several modes can propagate through the fibre, resulting in the so-called, single and multi-mode optical fibres. Both fibre types are used in the construction of fibre optic sensors. However, single mode fibres are more sensitive to strain variation and are thus the preferred choice for DPHM applications. A summary of the typical properties of various optical fibre types is presented by Krohn [34].

Compared to more traditional measurement techniques, fibre optic sensors offer unique capabilities such as monitoring the manufacturing process of composite and metallic parts, performing non-destructive testing once fabrication is complete, enabling structural and component health monitoring for prognostics health management, and structural control for component life extension. Because of their very low weight, small size, high bandwidth and immunity to electromagnetic and radio frequency interferences, fibre optic sensors have significant performance advantages over traditional sensors. In contrast to classical sensors that are largely based on measurement of electrical parameters such as resistance or capacitance, fibre optic sensors make use of a variety of novel phenomena inherent in the structure of the fibre itself. Some of these phenomena are extensively discussed in the literature [35,36]. In general these sensors can be classified into two classes, the discrete and distributed class. The distributed class of sensors includes Michelson and Mach-Zhender interferometer as well as sensors based on Brillouin scattering. These are generally seen in infrastructure applications where spatial resolution, system's weight and size are not as critical and long range sensing is desired [37].

The discrete class of sensors have cavity or grating based designs and are commonly used for the measurement of strain, deformation, temperature, vibration and pressure, amongst other parameters. Cavity based designs utilize an interferometric cavity in the fibre to create the sensor and define its sensor gauge length. Extrinsic and Intrinsic Fabry-Perot Interferometers (EFPI, IFPI), along with In-Line Fibre Etalon (ILFE) are the most known ones. Grating based designs utilize a photo-induced periodicity in the fibre core refractive index to create a sensor whose reflected or transmitted wavelength is a function of the periodicity that is indicative of the parameter being measured. Fibre Bragg Gratings (FBG) and Long Period Gratings (LPG) are the most commonly used sensors in this class and are the most attractive for integration into advanced diagnostic and prognostic capabilities. Grating based designs, particularly traditional FBG, have emerged as the leading technology in multiplexing and dual parameter sensing. The principle of operation of Bragg gratings based sensors is shown in Figure 11 [38]. Additionally, as shown in Figures 12 [39], these sensors can be used to monitor bondline integrity in bonded joints, acoustic emission resulting from structural damage and corrosion monitoring. When integrated with a centralized monitoring system, as shown in Figure 13, on-line real-time corrosion sensing and health prediction can be performed using very high number (up to 1000) of sensors networked on a single strand fibre.



(a)



(b)

Figure 11: Traditional fibre Bragg gratings principle of operation.

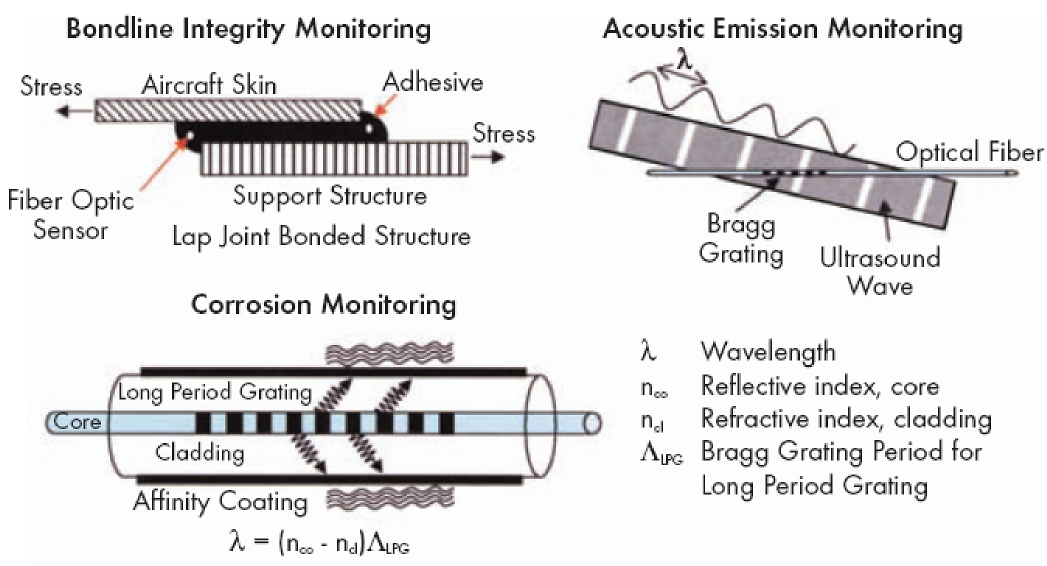


Figure 12: Bragg grating based sensing applications.

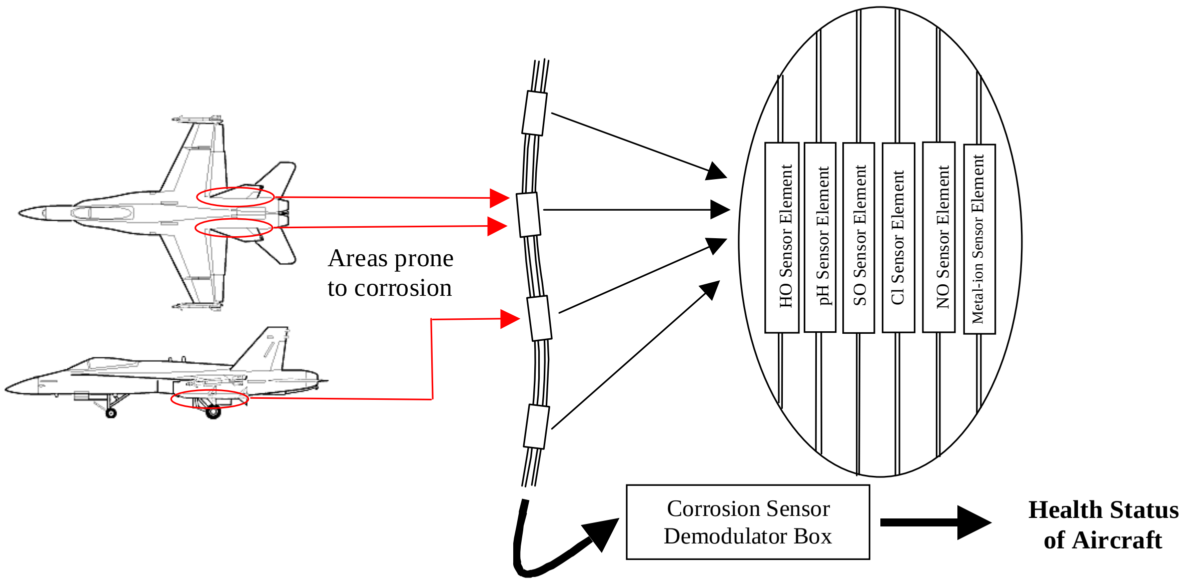


Figure 13: Illustration of a fighter jet health monitoring system.

Several sensor output interrogation techniques and their associated modulation systems have been developed and implemented [40]. These systems are found to be costly and impractical for in-flight applications due to their significant size, weight and power requirements. Recent efforts have focused on developing an increased level of understanding of the issues impeding the implementation of fibre Bragg gratings (single or multiplexed) into aerospace and military air platforms [41,42,43,44] and developing a micro fibre optic interrogation system for increased sensor networks and reduced size and weight. Figure 14 [45,46,47] illustrates the developmental effort in exploiting the enabling area of MEMS technology to develop a micro arrayed highly multiplexed FBG interrogation system providing significant advances in air platforms diagnostics and prognostics.

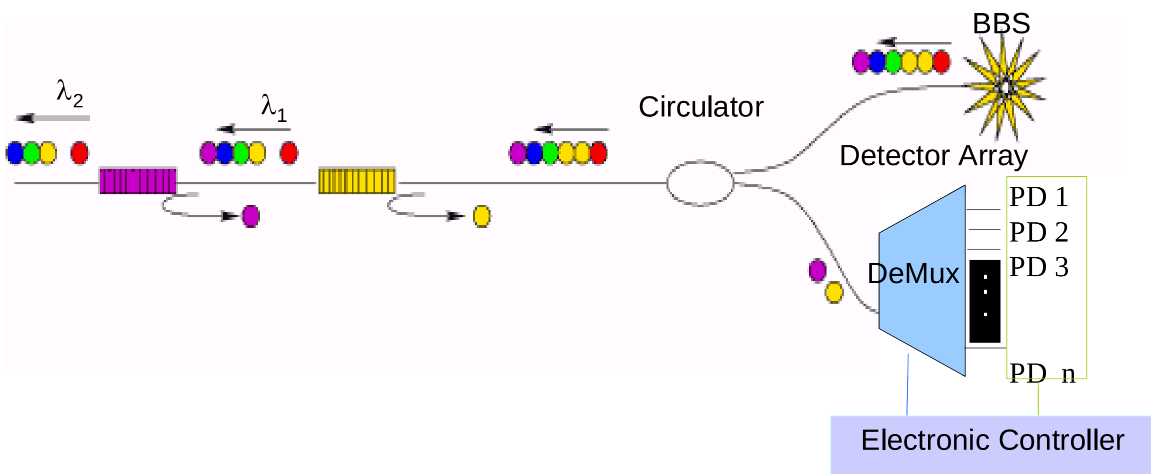


Figure 14: Conceptual illustration of a micro arrayed highly multiplexed FBG interrogation system.

Regardless of the extensive and successful outcome of several investigations supporting aerospace platform DPHM requirements, research effort continue to address the critical issues for practical implementation that include adhesive selection, bonding procedures, quality control processes; optimum selection of sensor configuration, sensor material and host structure for embedded configurations; characterization of embedded fibre optic sensors at elevated and cryogenic temperatures; resolution optimization for desired parameters from multi-gratings as well as sensitivity to transverse and temperature effects; development of an integrity assurance procedure for embedded sensors, particularly sensor protection at egress/ingress points.

6.0 COMPARATIVE VACUUM MONITORING

Amongst the wide range of sensor technologies that have emerged in recent years as damage detection sensors, Comparative Vacuum Monitoring (CVM) technology is assessed to be a mature technology, for both non-destructive testing / inspection (NDT/NDI) and condition monitoring (CM) of structural integrity, that is ready for deployment onto operational platforms. The state of maturity of this technology coupled with the desire of the aerospace industry to deploy an automated inspection method that does not have reduced accuracy and that could take place with personnel remote to the inspection area has triggered a desire to evaluate this technology within an aerospace environment. Recently, Boeing, FAA, Airbus, Northwest Airlines, the United States Navy (USN) and Royal Australian Air Force (RAAF) initiated independent verification trials with this technology. These trials involve laboratory, environmental and on-aircraft tests. A validation trial within the US Navy has successfully demonstrated the detection of a crack [48,49]. Based on these trials, it is expected that the CVM technology be approved as an alternate means of compliance [48]. This CVM technology has been developed for crack initiation and propagation detection. It consists of three primary components; a sensor, a pressure differential flow meter and a stable host reference vacuum source. Figures 15 and 16 [50] illustrate the conceptual model of a typical CVM system and an example of crack detection process on a component, respectively. The sensor is linked to a reference vacuum source through a flow meter, which contains impedance to the flow of air molecules through the system. The flow meter measures the pressure difference across the impedance. The vacuum source provides the flow meter with a continuous stable reference vacuum and power to maintain vacuum at a stable level. The fundamental principle of the CVM operation is the detection of pressure difference caused by a crack in a vacuum channel, known as 'gallery' within the sensor pad. If there is no damage and since the sensor is sealed to the test article there should be no leaks or change in pressure difference and hence a balance is maintained between the sensor and the vacuum source. If there is damage, a leak occurs at the location of the sensor pad and a pressure increase is detected by the flow meter. The rate of growth of the damage (crack) is determined by the rate of pressure change. The increase in pressure is measured as a differential pressure in relation to the reference vacuum level. This is significantly more sensitive to micro fluidic air flow than conventional air flow meters.

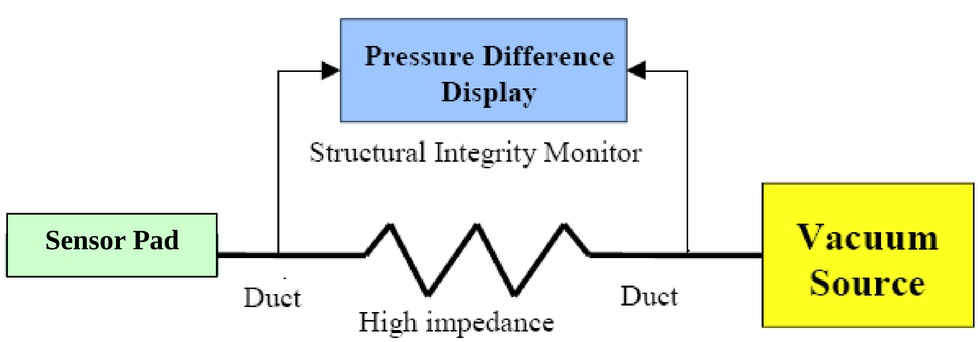


Figure 15: Conceptual model and principle of operation of a typical CVM system.

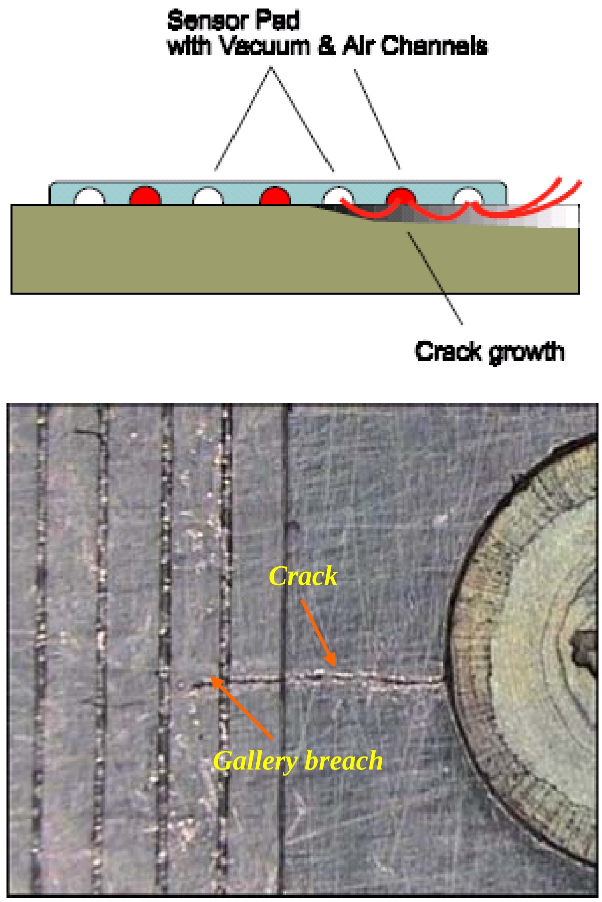


Figure 16: Illustration of crack detection using CVM technology.

An example of the operation of the commercially available system is also shown in Figure 17 [51]. As can be illustrated by the extensive work in the open literature, this technology is experiencing tremendous growth for both military and civilian aircraft [52,53]. This technology, however, is very well suited for localized damage detection but not for global system health monitoring. Sensors employed for this technology are often compared to resistive based crack detection gauges. Even though sensor multiplexing is demonstrated, implementation remains limited to hot spots and applications where false positives and system weight can be tolerated. Other limitations experienced by this technology are common to the sensor discussed in this document and require further consideration. The technology is seen to be commercially more mature than the earlier presented technologies.

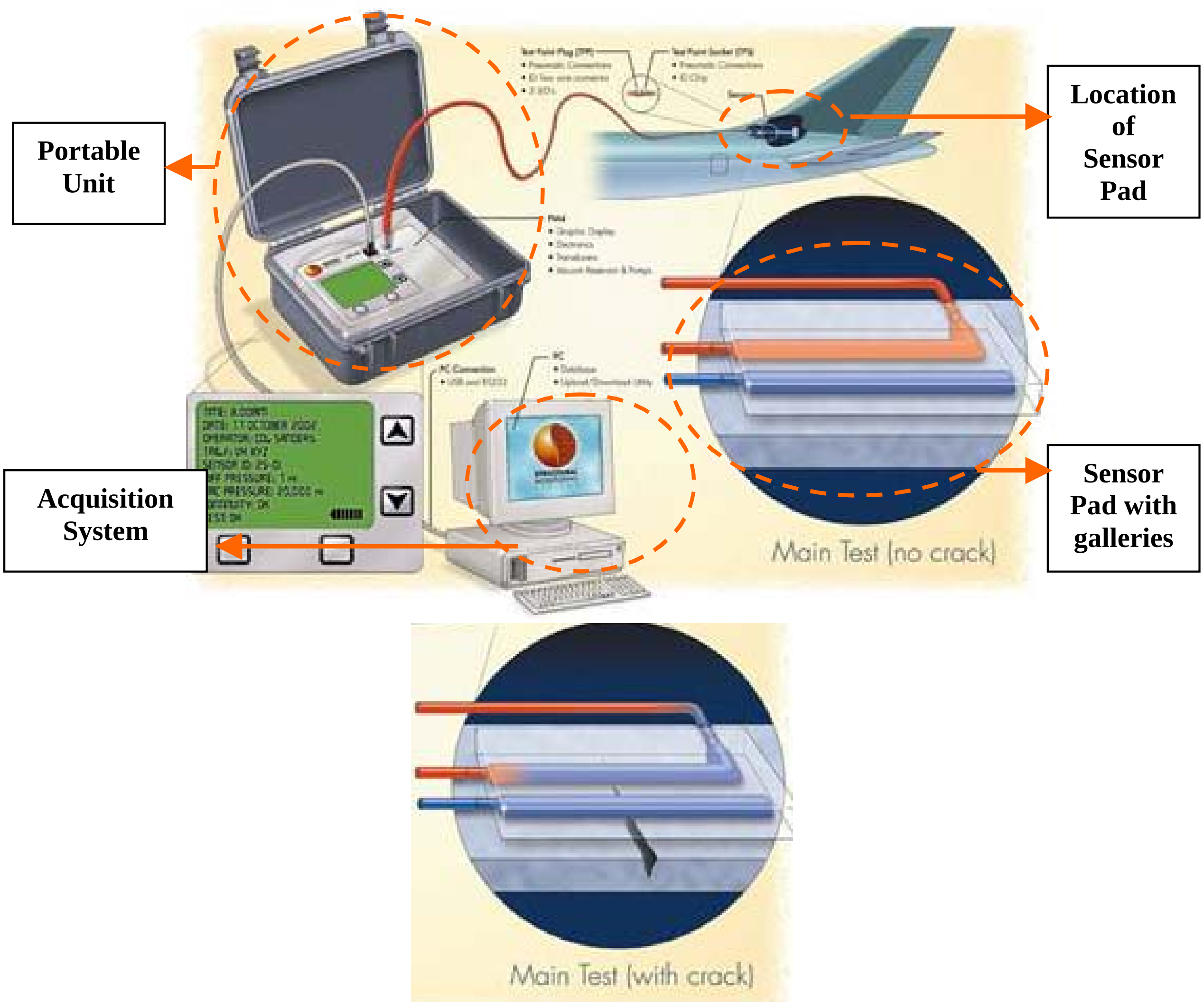


Figure 17: Commercial CVM System – with and without crack.

7.0 CONCLUSIONS

The Diagnostics, Prognostics and Health Management (DPHM) concept has emerged in recent years as the desired approach for aircraft enhanced operational envelope, reduced life cycle costs, increased aircraft availability, enhanced operational logistics and reduced complexity for new acquisition programs and legacy platforms alike. The implication of employing a DPHM system that includes continuous operational monitoring and damage detection, assessment and prediction technologies is significant. However its impact is underestimated as it enables lesser access to aircraft reduces reliance on statistical based scheduled maintenance, increases maintenance efficiency and aircraft availability, and moves from condition based to predictive maintenance approach which can substantially reduce ownership costs. One major challenge in the implementation of the DPHM system is the distribution, networking and communication of sensors providing minimal impact on vehicle operation, maintenance, and repair. The presented sensors and sensory systems based on fibre optic, piezoelectric and comparative vacuum technologies are assessed to be near commercial exploitation and are considered to be advanced in addressing some of the challenges. However, numerous sensing devices (in addition to the ones covered here) are emerging with the introduction of new technologies that are expected to help overcome the technical and operational challenges and to ensure the implementation of high-performance DPHM systems.

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