A validation study for a new SHM technology (ICM) under operational environment

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Abstract A new invented SHM technology, named as Intelligent Coating Monitoring (ICM), was verified by various lab-scale experiments as along with full-scale fatigue tests to inspect ICM capability for monitoring crack initiation and propagation in metal substance. In order to apply the technology to fighter aircrafts, ICM system was validated at real service condition. Firstly, ICM is briefly introduced, including the principle of sensor, the make-up of the system and various lab-scale experiments as well as full-scale fatigue tests for verification and application. Then the installation of ICM system on an operational aircraft structure was given which includes the determination of critical locations that needs monitoring, the selection of sensors corresponding to each monitoring point with certain geometry, the method of sensors splicing and main-/sub-interrogation units fixing and the connection of the above hardware through wires laying to form a ICM system. Finally, the operating situation and the effectiveness of the ICM system under operational environment were validated and summarized.

Keywords Crack monitoring, Aircraft Structure Health, Intelligent coating, Fracture

1. Introduction

At present, the safety of aircraft structures in most of countries is generally maintained by periodic inspection utilizing traditional nondestructive testing (NDT) techniques such as eddy-current, ultrasound, radiography, thermograph etc. However, these inspections often require the disassembly of the structure, which is a difficult and time-consuming procedure. As many locations of fighter aircraft in which cracks are prone to generate or form during full-scale fatigue in aging airframes are hidden in the structure, it is impossible to access for some certain areas. It is reported that recent aircraft crashes such as C-130A and F-15C in USA were resulted from catastrophic structural failure [1], suggesting that the current NDT is not reliable and is not adequate for aircraft safety. Moreover, the catastrophic risk of critical components also increases with the continued operation of aging fighter aircraft beyond its initial design life and in more severe service environments. Consequently, a desired solution is to implant a structural health monitoring (SHM) system on fighter aircraft which have the huge potentials to improve aircraft safety and reduce operational and maintenance cost.

Currently, several candidates of sensors suitable for SHM application have been widely investigated through lab-scale experiments, which include piezoelectric, fiber-optic, MEMS, strain-gages, CVM etc. To validate the effectiveness, some technologies based on different sensors have already installed in the service civil airplanes. For example, Bragg Fibre Gratings, impact and crack monitoring facilities, such as acoustic emission, eddy current and CVM sensors have installed in an AIRBUS A320 and an AIRBUS A340-600. In addition, diverse SHM technology such as crack wires, CVM or acoustic emission sensors were used during the full-scale fatigue test of the fuselage of the Airbus A380 [2]. Moreover, some structural health monitoring (SHM) systems have matured in recent years, allowing SHM systems to be tested on experimental flight tests [3-6]. However, there is a huge gap for SHM technology to translate these laboratory outcomes to practical application on the fighter aircrafts.

Although the effectiveness of detecting crack, the reliability and the durability for many sensors /actuators of SHM have been valiated in the lab-scale experimental condition, it should overcome many barriers in the practical applications, for instance, how to integrate the sensors /actuators to an already "overcrowded" aircraft structures effectively, how to connect them by wires to form a SHM net system which do not conflict with current systems in aircraft, how to optimize the number and location of sensors and how to enhance the reliability of the sensors in order to survive in the severe environments. It is no doubt that the gulf may exist between what has been demonstrated in the laboratory and what has been rigorously validated for operational use, since most of sensors are tested by a limited number of components with simple geometric shape such as plates, shells or shafts with possible some notches. But the real aircraft components usually are heavy-loaded and light weight with more complex geometric and shape. Moreover, it is inevitable to increase the costs and complexity when a prototype concept translates into service.

It is an indispensable step to carry out validating tests for any type of SHM systems under operational environments before they become the application-ready products. Canada Institute for Aerospace Research (IAR) developed a novel National Research Council (NRC)-developed crack detection system called the "Surface Mountable Crack Sensor (SMCS)" which had shown promising results as a means of detecting cracks proved by lab-experiments. In order to put SMCS into real application, a prototype installation of the SMCS was carried out on an operational aircraft [7] which showed that was a very important step in verifying its operation effectiveness.

A new SHM technology called ICM (Intelligent Coating Monitoring) which is mainly based on the intelligent coating sensors has been invented in China [8, 9]. ICM has shown the capability of monitoring crack initiation and propagation verified by a series of coupons with different material and dimensions under fatigue loading. Furthermore various experiments under environmental loading (temperature extremes, thermal shock, high humidity, fluid susceptibility, altitude/pressure) were carried out to test the durability and reliability of ICM system. It should be noted that ICM technology has been applied on several full scale fatigue tests [10]. Besides the achievements mentioned above, the sensors and interrogation units of the ICM system added on an aircraft have very small size and light weigh. Those superiorities make it easier to implant ICM instruments on aircraft structure on the active service as a part of an SHM system than most of other available SHM technologies which usually require heavy instruments.

The goal of the present study is to validate the durability, reliability, longevity and crack detecting capability of the ICM system under real flight conditions and improve various properties. An active service fighter aircraft which was in the overhauling was selected for the study. Total 78 sensors monitoring 42 sites were distributed in different areas of the aircraft such as wing, landing gear, horizontal tail and airframe etc, 12 sub-interrogators connecting all sensors and 2 main-interrogators connecting all sub-interrogators were installed on the aircraft. The aircraft returned to service after installing all the instruments of ICM system on the aircraft. So far, the aircraft with ICM system has been on active service more than 2 years, the data recorded by the system during the period were collected and analyzed once per month. ICM system provides more valuable information in the future applications.

This paper briefly introduce ICM system including the principle of sensor, the make-up of the system and various lab-experiments as well as full-scale fatigue tests for verification, give information about the installation of ICM system on an operational aircraft structure including the determination of critical locations that needs monitoring, the selection of sensors corresponding to each monitoring point with certain geometry, the method of sensors splicing and main-/sub-interrogation units fixing and the connection of the above hardware through wires laying to form a

ICM system, valiate the effectiveness of the ICM system under operational environment and summarize on the experiences and lessons from the study.

2. Description of ICM Technology

2.1. Principle of sensor

The core of ICM technology is intelligent coating sensor which comprises of three layers: the driving layer, the sensing layer and the protective layer， as shown in Figure 1. The driving layer is made of bifunctional nonconductive materials: one function is that crack will also form on the driving layer once cracks generate on the substrate, and further makes the sensing layer split at the same time; secondly the driving layer spaces out the substrate and the sensing layer with good insulating efficiency in conformity to the design requirement. The sensing layer is made up of conductive materials such as Cu, Ag, C, etc and can detect the crack length in the substrate by the variation of electric resistance. As the ICM sensor is about several tens of micrometers, a small surface crack will cause the sensor cracking and the electric resistance rise accordingly, as shown in Figure 2. The increase of electric resistance of the sensor corresponds to the crack growth. The method of ICM is very simple and stable measurement system, which consists of a DC power source, an electric resistor and a data recorder.

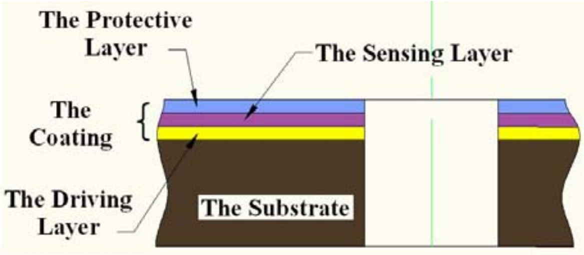


Figure 1 A formation of the intelligent coating sensor

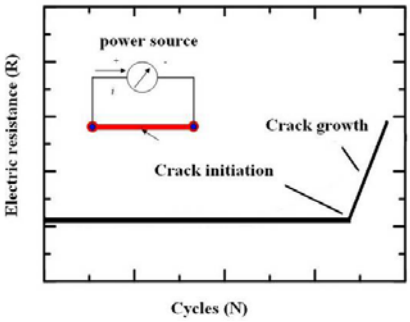


Figure 2 The relationship of eletricc resistance and crack length

2.2. ICM system construction

A typical ICM system consists of hardware and software. The on-board hardware parts include virus sensors, sub-interrogators and main-interrogators, see figure 3. Each sub-interrogator, a chip microcomputer system, consists of switches for signal channel of multi path sensors, conversion circuits for A/D modulus, central process units, digital communication circuits and power circuit and other auxiliary circuits. The sub-interrogators can realize the online measuring and processing of the electric resistance value detected by each cable-connected sensor and transmit the digital signals to the main interrogator by cables. One sub-interrogator can connect with as many as 8 sensors. A main interrogator comprises of following units: 1) communication unit for sending and receiving the message from each sub-interrogator; 2) storage unit for saving all working parameters and data; 3) date-time unit for recording the date and the time as the resistance value changes of each sensor; 4) man-machine interaction for monitoring working conditions of all sensors through the lights in the main-interrogator and downloading the message to a ground–portable computer through the USB interface for further processing; 5) central process unit for managing all the above units and 6) DC power converting module with wide inputting voltage.

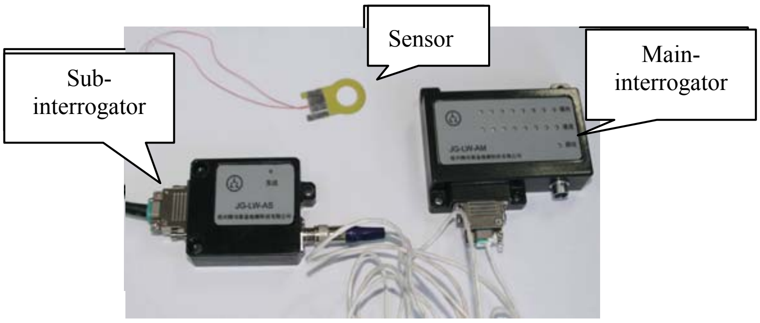


Figure 3 The construction of ICM system hardware

The weight of sensor can be ignored and the weights for a typical sub-interrogator and main interrogator are less than 180g and 80g, respectively. The dimensions of a normal sub-interrogator are 67mmx50mmx16.5mm and the dimensions of a normal main interrogator are 110mmx50mmx 20mm.

The software component is a special developed program for managing the ICM system which can be installed on a portable computer. The program can download and process all the data recorded and saved by the ICM system. Since the system has a huge internal memory, it can store up all recorded data by existing sensors during their lifetime, the intervals for off-board downloading and processing the data can be conducted by users according to their own needs. The possessed data can help users determine whether the ICM integrity has been compromised or real damage like cracks has been appeared on the monitored locations. In addition, the program can also realize real-time monitoring.

2.3. Verification tests

2.3.1. Coupon tests

Figure 4a Five types of specimens

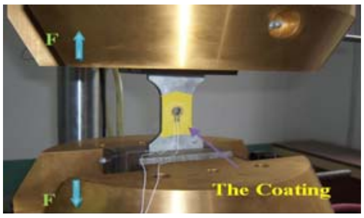


Figure 4b The picture of coupon testing

Fatigue tests were carried out on five types of specimens including riveted lap joint and screwed connection made of 4340M steel, 7074 aluminum alloy and TC4 titanium alloy, as shown in Figures. 4 and 5. All specimens were fatigue loaded with 15 Hz, load ratio R=0.2 and the maximum tension load P=18KN. As one example, Figure 5 is the relationship between resistance variations measured by sensor spliced on one 7074Al specimen and test load cycles. As the set alarm value was ΔR = 0.05Ω in the test, the crack was detected at approximate 5.8×10^4 cycles. The crack length was about 0.3mm corresponding to ΔR=0.05Ω which was measured on the fracture surface by stereoscope analysis.

ICM under different loading ways, such as tension-tension, tension-push and three point bending, has the similar results for crack detection, as depicted in Figure 6. Particularly, ICM sensors are able to monitor the riveted lap and butt joints where fatigue cracks likely commence at holes edges. From above coupon results, it is thought that ICM is suitable to detect small fatigue cracks and monitor their growth.

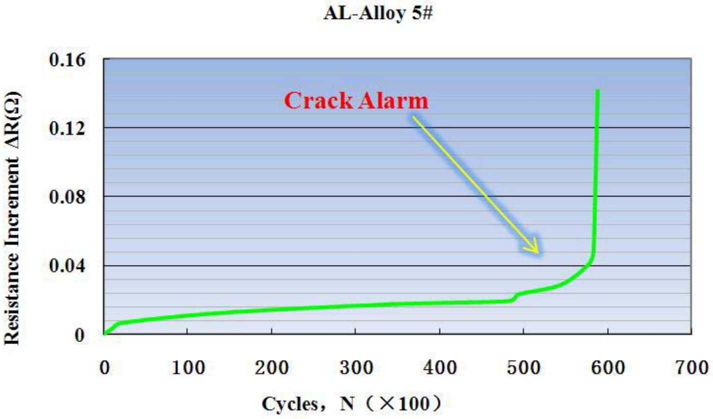
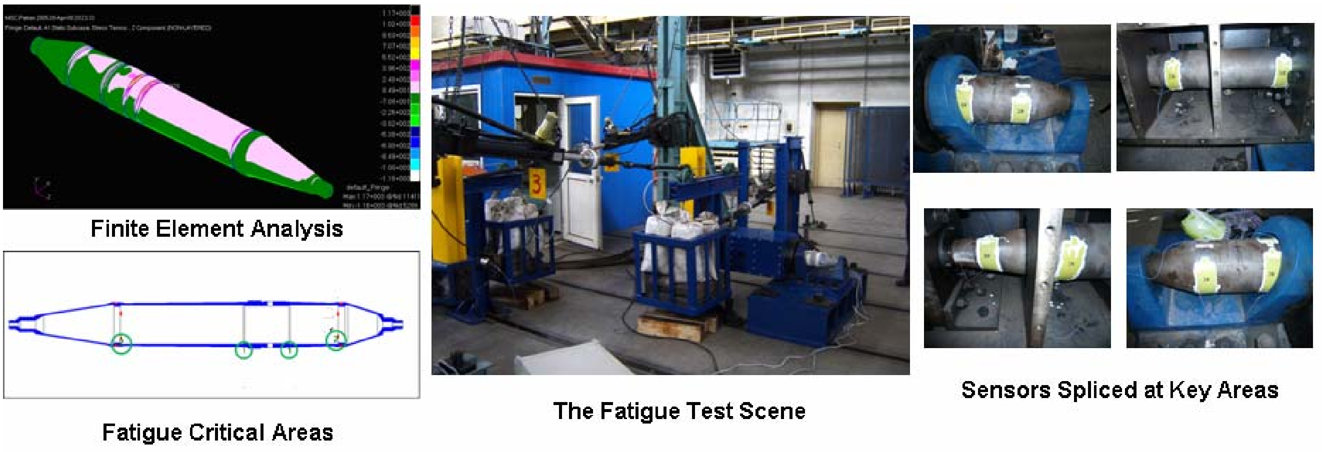


Figure 5 The curve of resistance and load cycle from 7074Al specimen test results

2.3.2. Component tests

Full-scale fatigue tests were carried out using real horizontal tail shafts as specimens. Taking this advantage, ICM system with 5 special sensors spliced on the fatigue critical areas of the shaft determined by finite element analysis has been used during the test, as shown in figure 6. The histories of cracks from initiation, growth till fracture in the shafts were monitored by ICM system during tests. Figure 7 is a resistance-hour curve recorded by ICM system for one of shafts which can verify the effectiveness of crack detection for ICM system in real component.



Finite Element Analysis

Fatigue Critical Areas

The Fatigue Test Scene

Sensors Spliced at Key Areas

Figure 6 Some works done for extending the fatigue life of the shaft in a type of fighter aircraft

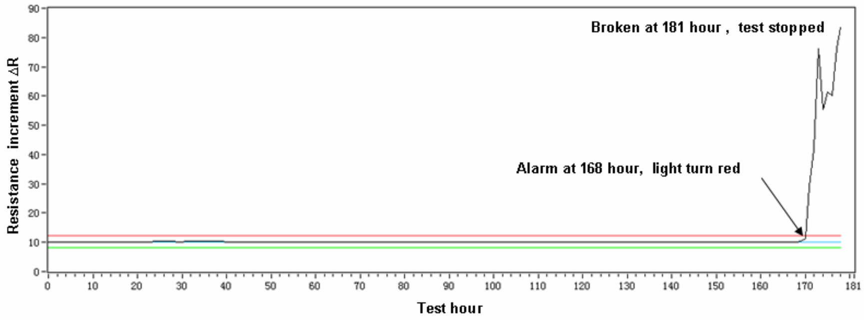


Figure 7 The history of crack length increasing with test time

2.3.3. Full-scale aircraft structure tests

Based on the above coupon and component verification experiments, ICM system has been verified in several full-scale aircraft structure fatigue tests with most sensors spliced at fatigue critical locations where are hidden in the structure and hard to access by the conventional non-destruction inspection methods. For example, ICM sensors were mounted on a full scale central wing fatigue testing aircraft. Figure 8 shows the sensor splicing between two repaired Al-alloy parts with a piece region of rivets which can give alarm signals when the cracks appear at this location. The other example is a full-scale fatigue test for a fighter structure. Total 110 sensors were fixed in 80 key locations inside structures including fuselage frames, wings, empennages and landing gears which formed a net after connected with interrogators for monitoring all locations prone to crack. With the aid of ICM system, some cracks were detected in time. Figure 9a shows sensors distributed in one frame and figure 9b gives the history of crack length increasing with test time in the fractured locations of the frame.

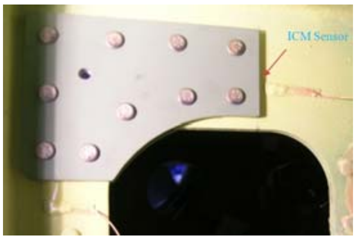


Fig.8. ICM Sensors Monitoring on Central Wing

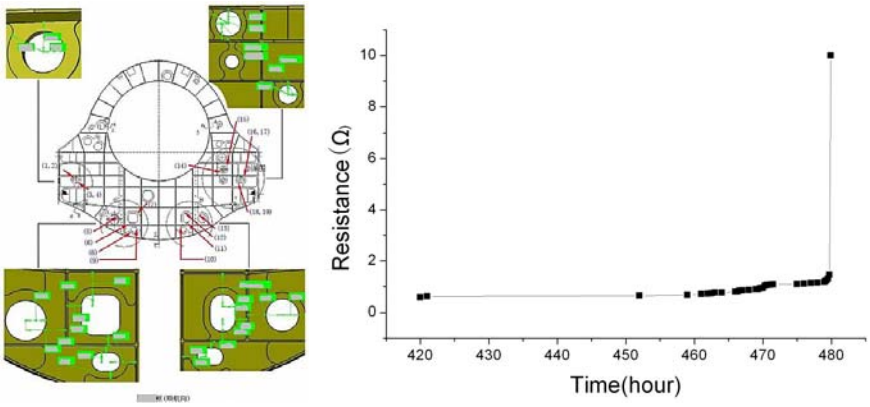


Figure 9 Sensors distributed in one frame (a) and the history of crack length increasing with test time in the fractured location of the frame (b)

At present, ICM system has become an indispensable measure for monitoring damage in most full scale aircraft fatigue tests carried out in China.

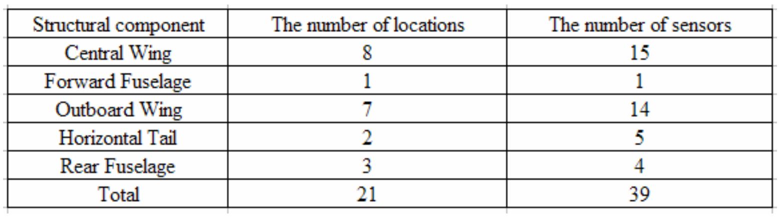
3. Validation study on ICM system under operational environment

From various levels tests mentioned above, it can verify that ICM system can detect damage in the aircraft structure. Furthermore, ICM product have excellent electromagnetic compatibility and environmental adaptability, which were tested by various harsh environmental loading experiments such as high/low temperature extremes, thermal shock, high humidity, fluid susceptibility, altitude/pressure etc. Hence, it is believed that that ICM system is reliable, robust, immune to radio frequency and electromagnetic interferences, easily networked to on-board preprocessing, capable of withstanding environmental conditions and low power which make it easier to obtain approve for installation of ICM hardware on aircraft structure in service. In order to put ICM into the oncoming real application, a study was carried to validate durability, reliability, longevity and crack detecting capability of the ICM system under actual flight condition and improve various properties accordingly.

3.1. Installation of ICM hardware

One of overhauling fighter aircrafts was selected as the subject for the study.Total 78 sensors monitoring 42 fatigue critical sites distributed in different locations of the aircraft including wing, fuselage, horizontal tail and landing gear which were distributed symmetrically along the yaw axes of the aircraft, as listed in Table 1. All those sites determined by full-scale fatigue test and finite element analysis were impossible to access by conventional NDT methods. Each side of sensors was connected by 6 sub-interrogators which were connected by one main-interrogator. Actually two independent ICM systems are responsible for two sides of the aircraft. Figure 10 shows the distribution of ICM hardware in a whole aircraft.

Table 1 Sensors and locations in different structural components (one side of aircraft)



Structural component	The number of locations	The number of sensors
Central Wing	8	15
Forward Fuselage	1	1
Outboard Wing	7	14
Horizontal Tail	2	5
Rear Fuselage	3	4
Total	21	39

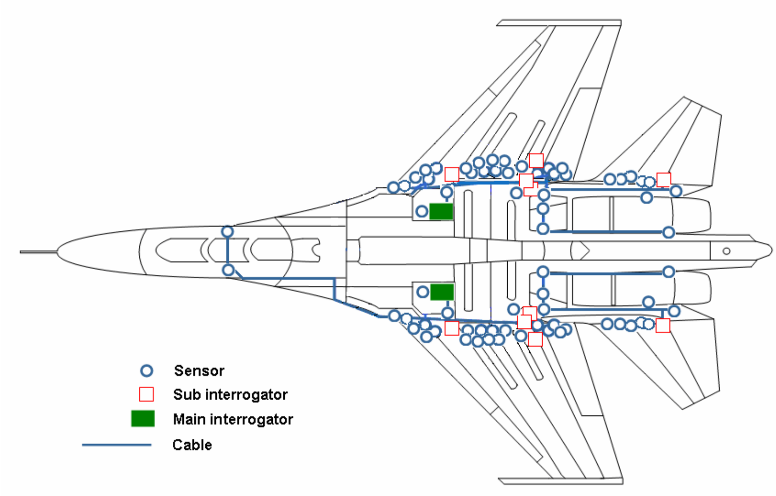
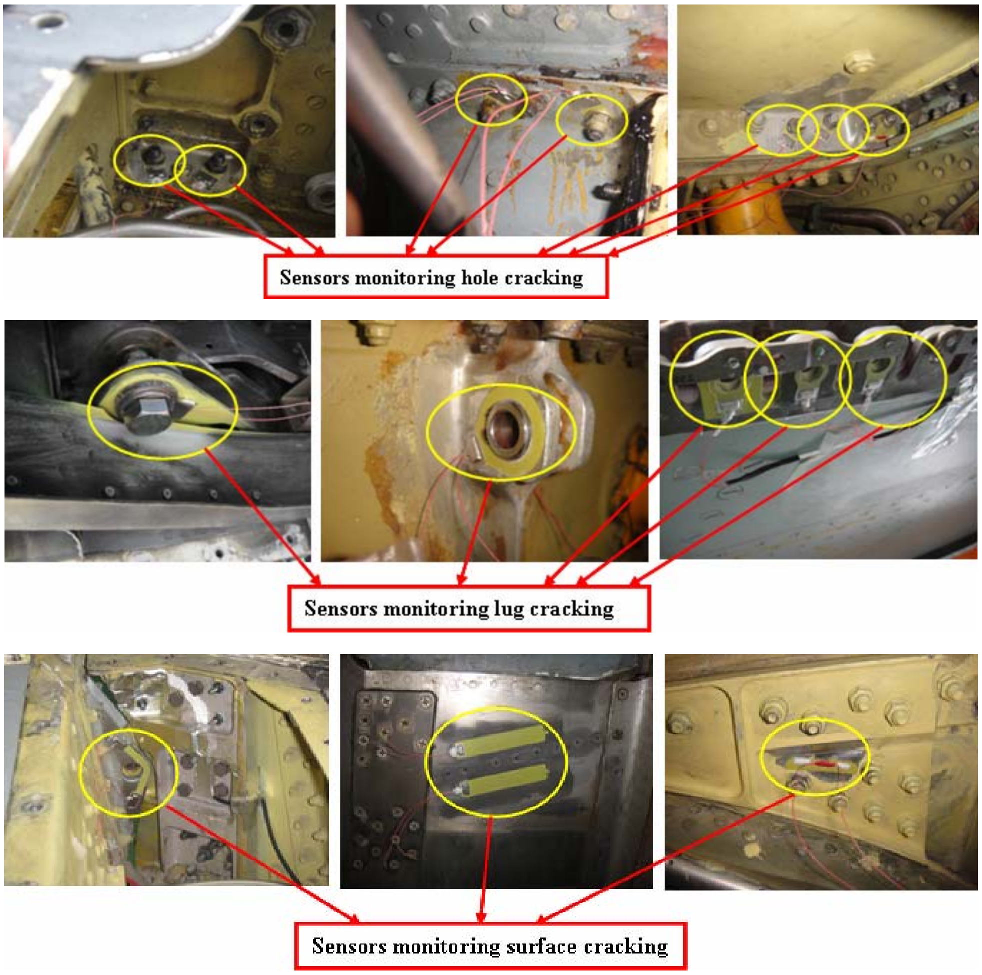


Figure 10 Laying-out of ICM hardware

Different shapes of sensors were designed according to their geometries of monitored sites. Figure 11 gives 3 kinds of sensors for monitoring hole, lug and surface cracking which were spliced in different sites on the aircraft. Figure 12 are main interrogator and 6 subinterrogators fixed at the different locations.



Figures 11 Typical sensors spliced in different sites

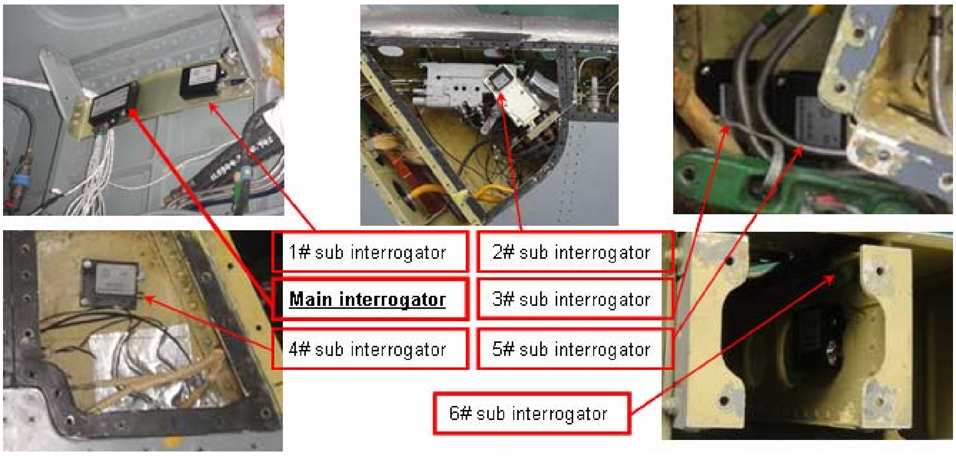


Figure 12 Main interrogator and 6 subinterrogators fixed at the different locations.

3.2. Working situation of ICM system under operational environment

There are two rows of lights on one main interrogator, with each row of 8 lights as shown in figure 13. Therefore one main interrogator can connect with as many as 8 sub interrogators and 64 sensors accordingly. When the ICM system is in working condition, the main interrogator continually checks its sub interrogators one by one with each taking 2~3 seconds for checking its subordinating sensors. During the process, only one light in the first row is on at each turn, which indicates the state of the sub interrogator being checked. If the light is “green”, then the lights in the second row will be “green”, which indicates that all sensors subordinated to this sub interrogator are in good conditions. If the light is “red”, there must be one or more “red” lights in the second row, which indicates that the corresponding sensors are in bad conditions, suggesting that either cracks appear or sensors including wires are broken.

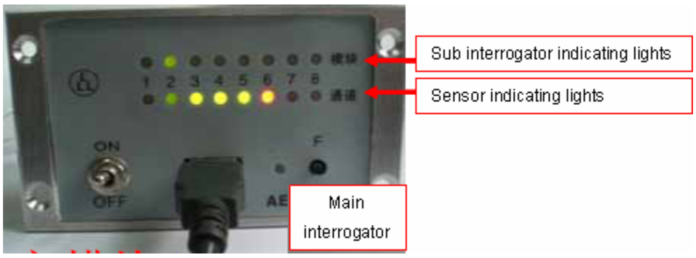


Figure 13 The front view of main interrogator

After installating ICM system, the aircraft returned to the service. In comparison with other same type aircrafts, the only additional thing for the mechanician of the aircraft is to check the lights on the main interrogators fixed in the landing gear cabin shown in Figure 12 before and after every flight. The mechanician can obtain the message immediately once he finds any “red” light based on the data analysis from the system. Besides the data recorded by the ICM system were collected and analyzed once per month. Up to now the aircraft with ICM system has been used more than 2 years, during this period, the working situations for both the aircraft and the ICM system run well as expected except some broken sensors transmit false signals.

4. Summaries

It can prove by the present investigation that ICM system installed on the aircraft structure can monitor cracks which might occur at any specified location, and most sensors along with other hardware can operate normally and effectively under actual condition.

Meanwhile, it is regrettable that some sensors located in the areas of high strain failed in short-time running, thus resulting in false signals. Therefore, more research is needed to design special sensors and corresponding splicing process for those high strain areas. Fortunately, a large progress has been made on this field which will be verified soon.

In a word, ICM prototype installation is a significant first step in validating its effectiveness in operations and putting it into practical applications. Field data including false signals collected from operations provides useful results of the environmental effects on the ICM system and valuable information for ICM improvements.

Acknowledgments

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