Current Aerospace Applications of Structural Health Monitoring in China

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ABSTRACT

Structural Health Monitoring (SHM) technology is a revolutionary method of determining the integrity of aircraft structures, and is increasingly being evaluated by the aerospace industry as a possible method to improve the safety and reliability of aircrafts and thereby reduce their operational cost. Researchers in China have been studying SHM technologies for aerospace applications since the beginning of 1990s. This paper presents some typical research and development activities in SHM technologies and their applications in aerospace industry of China during the last two decades, especially the SHM technologies based on piezoelectric sensors. In addition, the paper briefly introduces general perspectives of commercial aircraft company on SHM systems so that they can be applied on commercial aircrafts in real world and play significant roles in commercial aviation maintenance programs. Major challenges for implementing a SHM system in the real world are also discussed, including airworthiness compliance, miniaturized lightweight hardware, self-diagnostics and an adaptive algorithm to compensate for damaged sensors, reliable damage detection under different environmental conditions.

INTRODUCTION

With the rapid development of aeronautic science and technology, the aerospace structures confront some rigorous challenges, including the requirements for light weight, high reliability, high mobility, high maintainability, excellent viability, supersonic cruise, stealth performance, long range and STOL (short takeoff and landing). To guarantee the security of advanced aerospace structures, the concept of Structural Health Monitoring (SHM) has been proposed. SHM technology is a revolutionary method of determining the integrity of structures. Using distributed network sensors permanently placed either on surface or within an aerospace

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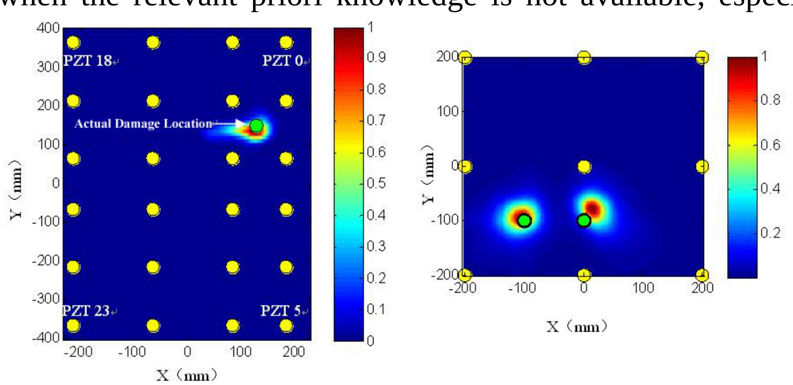
structure to monitor external impacts, measure strains and detect possible damages of composite structure are the major research tasks of SHM [1, 2].

Researchers in China have been studying SHM technologies for aerospace applications for two decades. In the beginning of 1990s, Nanjing University of Aeronautics and Astronautics (NUAA) started to engage the researches in the field of SHM under the support of Chinese governmental research funds. Since then, many achievements in the field of SHM have been obtained by the universities and research institutes in China. This paper presents some typical developments of SHM technology in China during past years. In addition, this paper briefly introduces general perspectives of a commercial aircraft company on SHM systems so that they can be applied on commercial aircrafts in real world and play significant roles in commercial aviation maintenance programs.

WAVE THEORY BASED SHM FOR COMPLEX STRUCTURES

Wave theory based SHM has shown its growing value in practical engineering application. However, there exist some difficulties which constrain its application on aircraft structures. The SHM methods based on the combination of Lamb wave theory and signal processing methods, including Time Reversal, Spatial Filter, Phased Array and Multiple Signal Classification methods, were investigated. These methods have been successfully applied on the complex structures with stiffeners, bolts or variable thickness for monitoring multiple damages, such as crack propagation in metallic structures, delamination and impact damages in composite structures.

As shown in Figure 1, PZT sensor network and Time Reversal focusing based damage imaging method was developed at NUAA to address the multi-reflected signal aliasing problem existing in complex structures. The damage imaging was obtained by enhancing the damage scattering signals. On the other hand, in terms of the PZT sensor placement, a dual-PZT sensor placement strategy to take advantage of the time window function was also developed to solve the multi-reflected signal aliasing problem [3]. In order to address the multi-mode dispersion problem, a complex Shannon wavelet transform was adopted to extract frequency narrow-band signals from the original signals at a special time–frequency scale so that the damage location error caused by the group velocity difference in different frequencies can be avoided. Meanwhile, PZT sensor network phase synthetic based damage imaging method with no requirement for the structural transfer functions was proposed [4]. This method eliminates the obstacle that appears when the relevant priori knowledge is not available, especially for



(a) (b)

Figure 1. The imaging results for (a) single damage, (b) dual damages on composite structures.

complex structures. Furthermore, a virtual Time Reversal based damage imaging method was proposed to use a changing-element excitation and reception mechanism for conserving time information and compensating the multi-mode dispersion simultaneously [5].

DEVELOPMENT OF SHM SYSTEMS

A series of PZT sensor network based structural health monitoring systems were developed for aerospace applications. As shown in Figure 2, electromagnetic shielding PZT sensor layers for reducing spatial electromagnetic noise and crosstalk were proposed and the corresponding layers were developed as well, which is similar to the SMART Layer [6]. The design difficulties in the small-size power amplifier module were also solved, and the concept of multi-path scanning strategy was proposed as well. Furthermore, on the basis of these achievements, a series of PZT sensor network based active structural health monitoring systems, with a maximum of 574 scanning paths, were developed by using a system bus based integration method [7, 8], and shown in Figure 3.

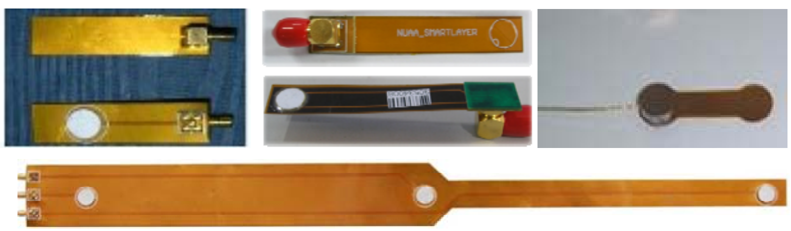
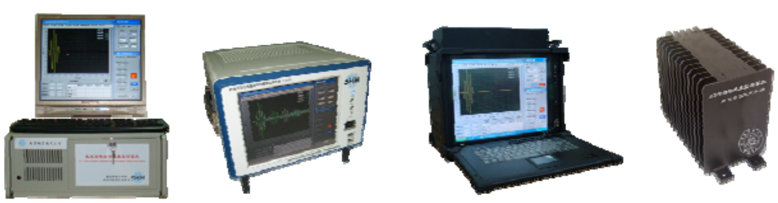


Figure 2. A series of PZT sensor layers with electromagnetic shielding.



For laboratory   For off-board application   For on-board

Figure 3. A series of PZT sensor network based active structural health monitoring systems.

As a part of some National Science & Technology Specific Projects, a passive SHM system has been developed for impact monitoring on aircraft composite structure at Dalian University of Technology (DUT). Meanwhile, a digital acoustic signal processing method for impact monitoring was developed at NUAA, aiming at meeting the requests for both on-line and large-scale structure applications. Based on the proposed method, a series of PZT sensor network based digital impact monitors for sub-region impact location on-line monitoring were developed with advantages of small size (45mm×45mm×20mm), light weight (80g) and low power consumption (less than 0.1W) [9], as shown in Figure 4.

Taking advantages of the wireless communication and distributed signal processing characteristics in wireless sensor network, light-weight SHM systems have been developed to meet the multi-site, multi-parameter, multi-system distributed monitoring requirements of the aircraft structural health monitoring. A series of the low-power wireless sensor nodes for the structural strain and vibration monitoring have been developed at NUAA [10]. For the need of high-speed multi-site continuous monitoring, a networking method, different from standard ZigBee protocol and the throughput improvement method based on fixed time delay design, are proposed, by introducing two new kinds of nodes to the network, namely the multi-channel sink node and the data-relay node. In this way, the difficulty in guaranteeing the real-time health monitoring in large-scale wireless sensor network can be overcome. At the same time, considering the high reliability requirement in a distributed SHM system, a bio-inspired wireless sensor node self-repairing method, which is realized on the basis of FPGA and FPAA, was proposed.

Figure 4. A series of PZT sensor network based digital impact monitors.

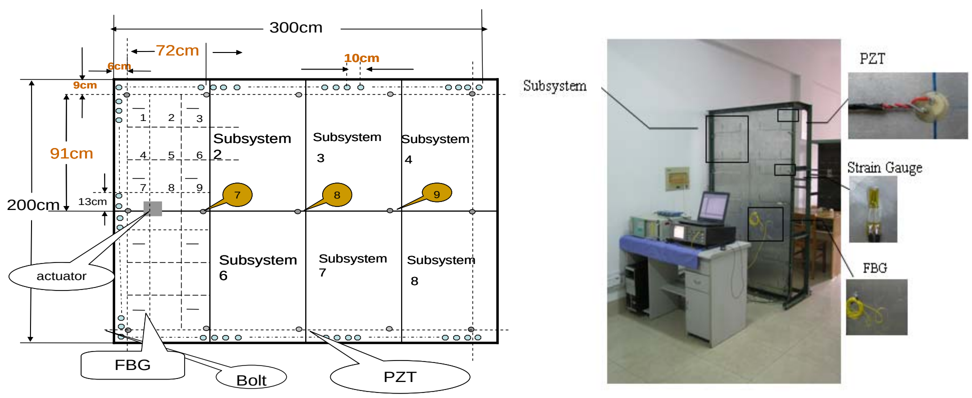


Figure 6.The multi-agent based structural health monitoring evaluation system.

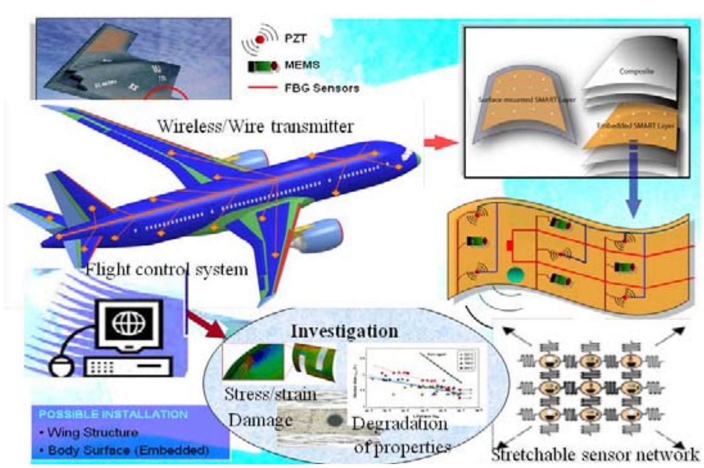


Figure 7. Concept of distributed multi-modal sensor network.

In addition, a multi-agent based distributed collaborative SHM system was developed at NUAA, as shown in Figure 6. In the distributed collaborative SHM system, different information subsystems are treated as different health monitoring agents [11]. Furthermore, the concept of multifunctional sensor network integrated with a composite structure, similar to the human nervous system, is being developed. Different types of network sensors are permanently integrated within a composite structure to sense structural strain, temperature, moisture, aerodynamic pressure, monitor external impact on the structure, and detect structural damages. Utilizing this revolutionary concept, future composite structures can be designed and manufactured to provide multiple modes of information, so that the structures have the capabilities for intelligent sensing, environmental adaptation and multi-functionality, as shown in Figure 7 [12].

DEMONSTRATIONS OF SHM SYSTEMS

Some typical SHM systems described above have been demonstrated, including the systems for impact monitoring and damage detection in composite structures. As shown in Figure 8, the developed passive SHM system for impact monitoring was verified by a series test on a stiffened composite structure at DUT [13]. Figure 9 shows the demonstration system monitoring impact and delamination on the composite wing box. The PZT sensors layers, developed at NUAA, were placed on the inner side of the wing box. This demonstration system estimated the impact location and delamination size well.

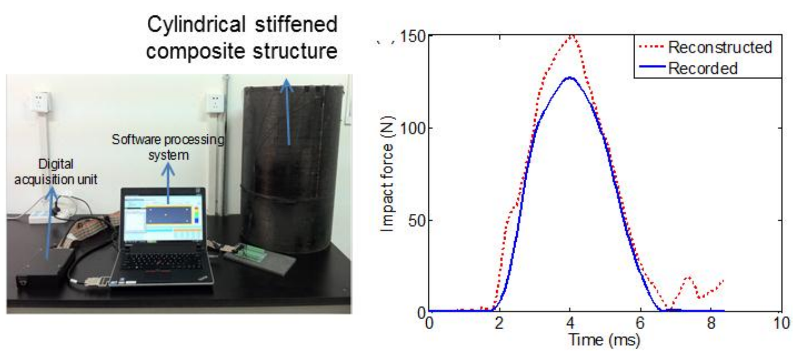


Figure 8. Photograph of impact monitoring system and reconstruction of impact force.

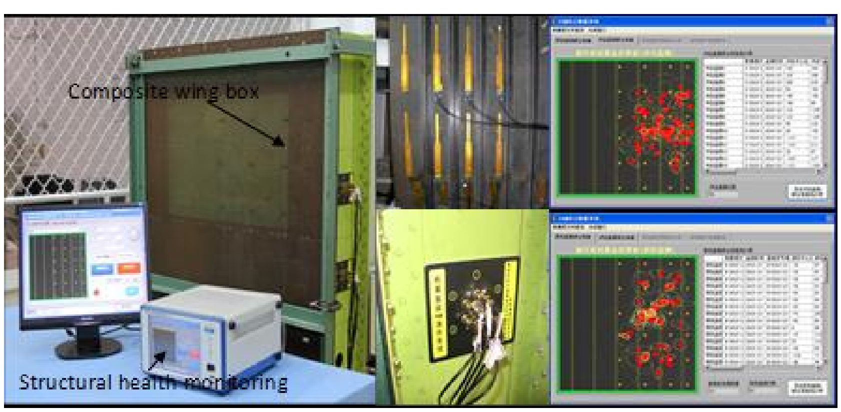


Figure 9. Demonstration system monitoring impact and delamination on the composite wing box.

The effectiveness of piezoelectric sensor network based active SHM system for the disbond detection in the thermal insulation system at room temperature was verified. Then the detection of predefined delaminations in the metal tank specimen under a load-temperature environment was conducted. The results indicated that Lamb wave would be effective and reliable for structural health monitoring on complex tiled structures in space vehicles, as shown in Figure 10 [14].

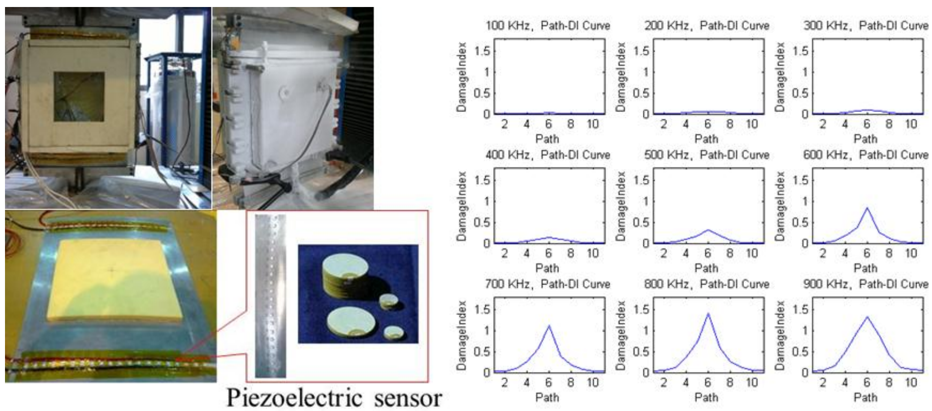
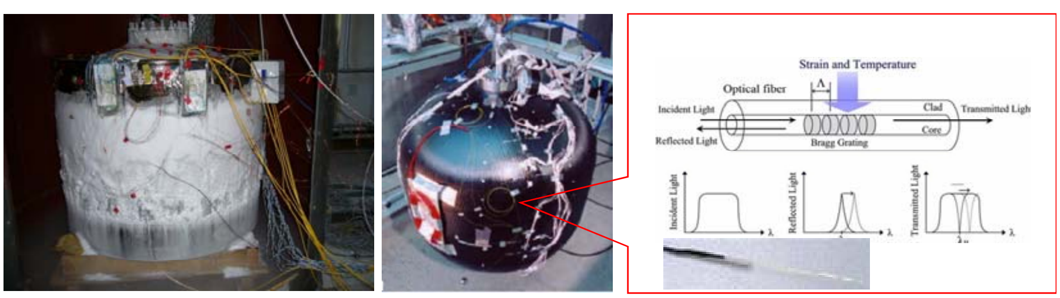


Figure 10. Photograph of the active SHM system for disbond detection in the thermal insulation system, and the damage index curves with different frequency.

DEVELOPMENT OF FBG SENSORS BASED SHM

Fiber Bragg Grating (FBG) sensors as well as FBG demodulators have been developed and extensively applied in aerospace field of China. The Center for Composite Materials in Harbin Institute of Technology firstly used FBG to monitor the health and state of aerospace materials and structures in 2001 [15]. Since then, the FBG sensors have been widely used to monitor the strain and temperature of aerospace structures [16-18]. Figure 11 shows an example.



Fiber Bragg grating sensor

Figure 11. Strain and temperature monitoring using FBG sensors.

DISCUSSION AND CONCLUSION

SHM technology using a built-in sensor network is a revolutionary method of determining the integrity of aircraft structures involving the use of multidisciplinary fields including sensors, materials, signal processing, system integration, and signal interpretation. SHM technology is of paramount importance to structure design, in-service and maintenance of commercial aircraft. SHM technology has many advantages over conventional NDT. For example, one advantage of SHM is that SHM offers the promise of a paradigm shift from schedule-driven maintenance to condition-based maintenance (CBM) of assets. Diagnostic information from sensor data can be used for prognosis of the health of the structure and facilitate decision processes with respect to inspection and repair. Asset management can be performed based on the actual health and performance of the structure, thereby minimizing failures and maintenance costs, while maximizing reliability and safety.

Although the advantages of SHM over conventional NDT are obvious, there are some obstacles needed to overcome in order to have SHM system widely applied on commercial aircrafts. The ultimate application goal of SHM on commercial aircraft is to have a large sensor network with multi-modal sensing capabilities integrated with the aircraft, analogous to the human nervous system, to allow the aircraft structure to "feel" and "think" its structural state. Building such a multifunctional large sensor network for aircraft structure is very difficult. There are many challenges and issues that need to be solved, including:

(1) What kinds of sensors are needed for multi-modal sensing?
(2) How to build a large sensor network and integrate a variety of sensors together?
(3) How to establish the communication link between the sensor networks and processing center?
(4) How all the information from a variety of sensors will be processed?
(5) How the sensing results of aircraft structure can be used to determine the integrity of structure?

Some sensors have been applied on commercial aircrafts to monitor the strain, temperature, etc. of the structure. However, the damage detection SHM technology, which can bring direct benefit to the maintenance of aircraft, is still in laboratory and flight testing, and only focuses on small local area. Most of SHM systems for local area monitoring still face some challenges when they are applied on the commercial aircrafts in the real world. Some major challenges are as follows:

(1) Damage quantification, including the well-defined probability of detection (POD);
(2) Robust and reliable system, including the survivability of sensors and miniaturized lightweight hardware;
(3) Environment compensation, including the practical procedures for obtaining baseline signals;
(4) Airworthiness compliance, including the integration SHM system with aircrafts.
(5) Self-diagnostics, including adaptive algorithms to compensate for damaged sensors

With the Technology Readiness Level (TRL) of some SHM systems improved, it is expected that they will be gradually applied on commercial aircrafts, from local hot spot off-board monitoring (as a short-term goal), small area on-board monitoring (as a medium-term goal), to health monitoring of the whole aircraft structure (as a long-term goal).

Overall, some typical research and development activities in SHM technologies and their applications in aerospace industry of China were presented in this paper. In addition, major challenges for implementing a SHM system in the real world were also discussed.

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