KOREAN AERO-VEHICLE STRUCTURAL HEALTH MONITORING SYSTEM

C. Y. Park[1*], J.-H. Kim[1], S.-M. Jun[1]
[1] The 7th R&D Institute-2, Agency for Defense Development, Daejeon, Korea
* Corresponding author (pcy1216@add.re.kr)

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1 Abstract

KASHMOS refers to Korean Aero-vehicle Structural Health Monitoring (SHM) System that is an applied research program launched by Agency for Defense Development (ADD), Korea. KASHMOS also refers to a special session in ICCM18. This session presents seven papers that introduce studies performed in the KASHMOS program. This paper is the first one that outlines the program overview, operation concepts of the developed system, and SHM tests. In-depth summaries on study results, achievements, fabricated equipment, assembled structures and developed techniques are described in other six papers of this special session.

Through the 3-year-long program, ADD tries to develop an SHM system that will be applicable for composite unmanned-aerial-vehicle (UAV) structures. At the applied research stage, the developed system and its key technologies were evaluated and demonstrated in simulated operation environment.

Operational load monitoring and damage identification are the two main branches of the system architecture. Multiplexed optical fiber sensors were used to monitor load while piezoelectric sensors and laser-induced ultrasonic wave propagation sensors were mainly used to detect damage. After studying the functions and operation concepts of the system, the detailed requirements of hardware and software components were defined. The SHM system consists of an onboard device and ground station with sensor integrated structures. In this program, sensor integrated structures from simple coupon specimens to a full scale composite wing section were manufactured and tested. Various kinds of damage modes that may occur in typical composite aircraft structures were considered and tried to detect. A series of SHM tests such as static loadings, dynamic loadings, temperature variation, low-velocity impact, and bird-strike tests were performed to evaluate the developed system

2 Introduction

The recent study on the UAVs [1] projects that the UAV market is expected to grow dramatically, as military, civil and commercial applications continue to develop. It is because UAVs offer notably ultra-long endurance and high-risk mission acceptance, which cannot be reasonably performed by manned aircraft. From airframe structure point of view, modified design requirements and criteria are demanded. The structural design aspects and criteria for military UAVs [2] describes that health and event monitoring in UAVs can be more important than in manned air systems. In manned air systems, pilots usually observe events that may affect the structural health of aircraft such as bird strikes, lightning strikes, abnormal vibrations, acoustic noise, and dynamic responses due to gusts, buffets, and hard landing impacts. Pilots are also working as a sensor system in manned aircraft. And it is an international trend to utilize multilayered composite materials for such UAVs. The use of advanced composite materials in aircraft applications has been rapidly increased due to their outstanding advantages over conventional metals. However, composite aero-vehicle structures could be susceptible to various kinds of damage which is hidden and hardly detected. To solve the difficulty, there is a demand of developing swift online event monitoring and comprehensive ground nondestructive testing systems for composite unmanned aerial vehicles.

Following this demand, ADD launched an SHM program called KASHMOS in 2008. Seven groups of people have been working together in the

KASHMOS program. In late 2010, the leaders of all the groups agreed to hold a special session called "KASHMOS" in the 18th international conference on composite materials (ICCM18) and to present the summaries of their studies and achievements. Firstly, this paper written by ADD provides an introduction of the program and brief descriptions on the operation concept, developed devices, and evaluation tests. In the second paper, DACC Co. describes how to fabricate sensor-integrated composite structures [3]. The third paper introduces the study on the impact localization for a composite wing box under bending loadings by Aerospace Department of Korea Advanced Institute of Science and Technology (KAIST) [4]. In the fourth paper, the damage detection study using an integrated impedance and guided wave technique is proposed by Civil Department of KAIST [5]. The fifth paper looks into the new non-destructive method using laser-induced ultrasonic propagation imaging (UPI) methods devised by Aerospace Department of Chonbuk National University (CBNU) [6]. In the sixth paper, Engineering Institute (EI) of Los Alamos National Laboratory (LANL) introduces freeware tools called "SHMTOOLS" which were applied to detect damage in an aircraft lug assembly [7]. Finally, a developed onboard SHM instrument which could interrogate optical fiber sensors and piezoelectric sensors is described by FIBERPRO Inc. [8].

3 Project Overview

The goal of the KASHMOS program is to develop the key SHM technologies that are applicable to monitor load in real-time and automatically detect damage in composite UAV wings. The technologies were implemented on virtual composite wings, an onboard SHM device and a ground SHM station which were fabricated. The developed SHM system was evaluated and demonstrated in simulated environment in laboratories.

The KASHMOS is an applied research program with the technology readiness level (TRL) 6. ADD launched the program in 2008 and the duration of the program is three years. There are five domestic organizations referred in Section 2 were selected and got funded. DACC Co. is in charge of fabricating sensor-integrated composite structures and assembling the SHM system. Studying algorithms and building software tools on optical fiber sensors and active piezoelectric sensors are assigned to Aerospace Department and Civil Department of KAIST. Aerospace Department of CBNU works on a new method of detecting damage in composite aircraft structures using ultrasonic waves which are created by laser beams and propagate through the structures. FIBERPRO designs and fabricate the onboard SHM device.

LANL-EI located in New Mexico, United States started to collaborate with ADD through the KASHMOS program in 2009. Both groups cooperate to identify and develop effective active SHM methods that could be applicable to detect probable damage of aircraft components designed by ADD.

4 Operation Concepts & Developed SHM Systems

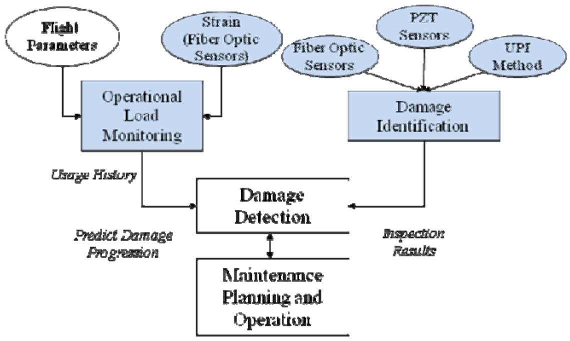


Fig. 1 SHM system architecture

Until now, damage in the structure is indirectly detected and inspections are performed based on operational load monitoring for current in-service aircraft. Flight parameters and a small number of conventional strain gauges are typically used to measure and calculate the operational load. Then, inspection points, methods and intervals are determined based on the cumulative fatigue load. This study took advantage of fiber optic sensors to monitor the operational load instead of conventional strain gauges. Fiber optic sensors have many advantages over conventional strain gauges. Especially, fiber Bragg grating (FBG) sensors can be multiplexed and be widely used for strain sensing. In this study, fiber optics sensors, piezoelectric (PZT) sensors and ultrasonic propagation imaging (UPI) method were used to identify damage directly. Using fiber optic sensors, damage induced events such as low-velocity impact and bird strike could be monitored in this study. PZT sensors were utilized for hot spot monitoring. Finally, surface and sub-surfaces could be scanned to find damage using the UPI method. Fig. 1 shows the SHM system architecture. At this stage, the technologies related to the items shaded in Fig. 1 were studied.

The SHM system of the KASHMOS project consists of three parts – a sensor integrated composite wing, onboard device and ground station. Followings are the operation concept:

(1) The onboard device continuously monitors the composite wing using fiber optic sensors which can measure static and dynamic strain changes of selected points. In case measured strain values are over their threshold sets or any dynamic events are detected, an alarm will go off to the crews and all measured data with flight parameters will be recorded.

(2) Mechanical-electrical impedance changes of preselected hot spots are also continuously measured with PZT sensors by the onboard system. The differences between current impedance values and the baselines are computed. If the discrepancies are unacceptable, another alarm will go off to the crew.

(3) After landing, the recorded data will be downloaded to the ground station. If some areas that may have damage are isolated through data evaluation, more comprehensive inspections will be applied. For the hot spots, more precise impedance can be measured using the ground station by activating PZT sensors. For the subsurface and surface areas, the areas of interest can be scanned by laser beams and damage can be detected using the UPI equipment in the ground station.

Based on the goals of the program and the operation concept, the detail requirements of hardware and software were specified. The specification and performance data of instruments and algorithms are described in other papers in this KASHMOS session.

5 SHM Tests

In order to evaluate the developed hardware and software, a series of tests such as coupon tests, element tests, sub-assembly tests, full scale static and dynamics tests, low-velocity impact tests, fatigue tests, environmental tests, and bird strike tests were performed.

Through static and fatigue tests with coupon specimens, the sensors and their installation methods suggested in this program were proved to have better mechanical characteristics than conventional strain gauges. Through the fatigue tests shown in Fig. 2, FBG sensors endure 10^6 fatigue cycles of 0 to 3,000 $\mu\varepsilon$ without any degradation.

(a) Static test (b) Fatigue test

Fig. 2 Coupon specimen tests

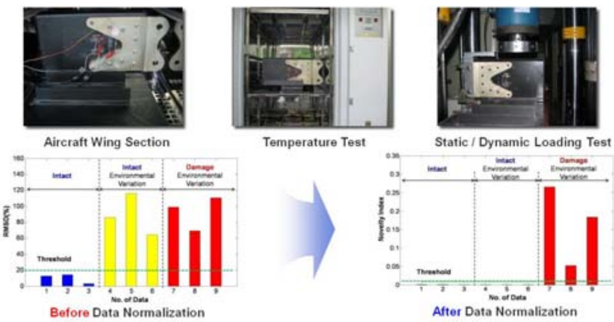


Fig. 3 Sub-assembly tests for the PZT sensors

Each type of sensor required its own computer programs to monitor structures and detect potential damage. Computer simulations, element tests, and sub-assembly tests were involved in designing, writing, testing, and debugging the programs. Environmental effects were also considered to make the computer programs robust under real operating conditions such as temperature changes and vibration. One example for the PZT sensors appears in Fig. 3. In order to detect structural damage under changing loadings and temperature conditions, a data normalization technique was studied and successfully applied to detect loosened bolts.

Fig. 4 shows the composite wing and setup for the full scale tests. More than 60 optical fiber sensors and 40 PZT sensors were installed during manufacturing. There were two hydraulic actuators for loadings, a low-velocity impact tester, and a laser head in the setup. The developed hardware components and damage detection programs had been evaluated and enhanced for more than 6 months. Various damage types such as static strength damage, debonding, delamination, cracks, bolt loosening, etc. had been tested and identified. Through the full scale test, it was noticed that the laser-induced ultrasonic wave imaging method could detect small-sized damage with millimeter precision. The point is that the UPI method is handy to apply to assembled structures on the spot and shows the similar quality of the C-scan. There is one example in Fig. 5 that shows the NDI results of a composite stiffened panel.

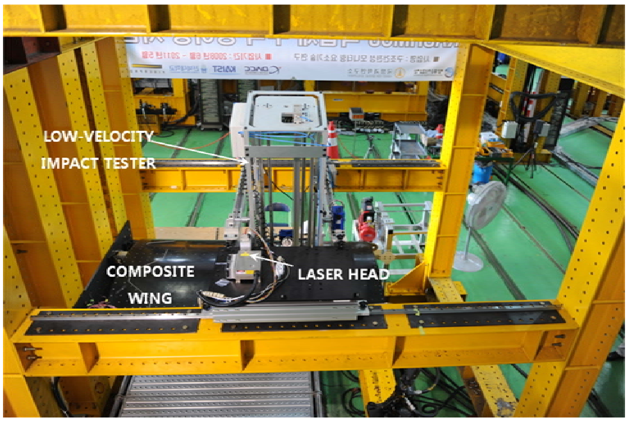
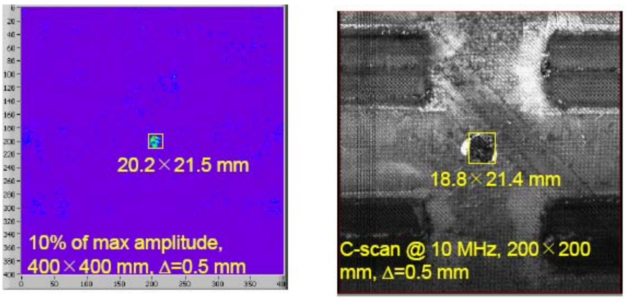


Fig.4 Test setup for full scale composite wing tests.

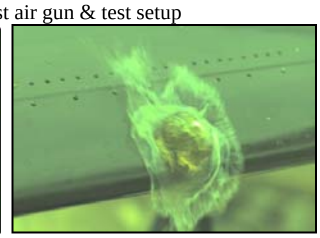


(a)UPI method (b) C-scan method

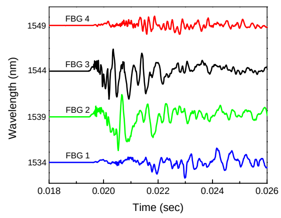
Fig.5 The non-destructive inspection result for a composite stiffened panel using the UPI method

Fig. 6 shows the air gun, composite wing, sensor locations, simulated bird and recorded signals of the bird strike test. There was only one line of optical fiber with four sensor heads bonded on the inner surface of the leading edge. The bird strikes produced high speed structural responses within 10 milli-seconds, but the developed optical fiber sensor interrogator had the capability and stability of capturing the events. The interrogator captured the signals with a 100 kHz sampling rate. Using the computer program for the optical fiber sensors, the impact events were able to be localized.

(a) Bird strike test air gun & test setup



(b) Test specimen & sensor position (c) Simulated bird hitting the wing



(d) Measured signals

Fig.6 Bird strike test machine, test specimen, simulated bird, measured signals

6 Conclusions

Korean Aero-vehicle Structural Health Monitoring System (KASHMOS) is an applied research program launched by ADD. The goal of the program is to develop the key SHM technologies that are applicable to monitor load in real-time and automatically detect damage in composite UAV wings. The program involves seven organizations – ADD, DACC Co., Aerospace Department and Civil Department of KAIST, Aerospace Department of CBNU, FIBERPRO Inc., and LANL-EI. Operational load monitoring and damage identification are two branches of the architecture of the SHM system. Based on the architecture, the operation concept and system functions were defined. The developed system consists of sensor integrated structures, an onboard SHM device and ground SHM station. The developed hardware devices and damage detection algorithms have been evaluated through a series of tests such as coupon tests, sub-assembly tests, environment tests, low-velocity impact tests, full scale structural test and even bird strike tests.

Through the tests, developed technologies to detect possible damage in composite wing structures were tested and upgraded. Brief study results and achievements are introduced by other six papers in the KASHMOS session.

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