Design of UGW SHM Sensor System for L-39NG Aircraft

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Abstract

Several methods for Structural Health Monitoring (SHM) have been designed, but many of them are still under development process. At the present time, Honeywell is developing the SHM system for the next generation of Czech trainer aircraft L-39NG. Developed SHM system is based on piezoelectric sensor (PZT) network. Each PZT sensor in the network acts either as a transducer or a sensor. In contrast to classic ultrasound Non-Destructive Testing (NDT) methods, damage evaluation is based on measured signal comparison with ‘baseline’ signal measured on a healthy structure.

Presented paper introduces the development of SHM sensor system, based on PZT sensors. Honeywell’s SHM system intends to detect change in structural 'health' condition. Change in the structure 'health' may be caused by mechanical damage such as impact, fatigue, corrosion or any other structure damage or degradation.

1 Introduction

Nowadays, up to 50% of airplane structure components are made of composite materials (1). For helicopters, the volume of composite materials reaches up to 90% (2).

Traditional metal materials differ from composites in the type of damage and structure failure mechanisms (3). One of the most challenging defect of composite in aerospace is barely visible impact damage (BVID). By a definition, BVID is a small damage with the typical dent depth of 0.25mm to 0.5mm (4) (dent depth relaxation must be accounted for). Due to small size, it may not be found during general visual inspections under typical lighting conditions from a distance of 1.5m.

In contrast to traditional ‘time-consuming’ Non-Destructive Testing (NDT), the future vision of damage detection and aircraft maintenance lies in the ‘fast’ in-situ evaluation of current condition of the structure (5). Modern Condition-Based Maintenance (CBM) combines the intelligent scheduled maintenance methodologies, procedures and requirements of Air Transport Association Maintenance Steering Group (ATA MSG-3), and expert knowledge, incorporating multiple criteria decision making (6).

One of the possible solutions which support the idea of CBM is Structure Health Monitoring (SHM). Generally, SHM represents technologies which intend to monitor and detect the presence of damage or change in the structural health condition. Honeywell present activity in this area is the development of SHM system for the engine air duct of next generation Czech trainer aircraft L-39NG. The L-39NG is the brand new aircraft of AERO Vodochody Company, which combines the proven aerodynamic concept of L-39 aircraft with the most advanced manufacturing technologies and systems. One of the innovation of L-39 structure is the new innovative...
design of engine air duct made of composite material. A particularly challenging design problem of engine air duct is damage caused by collision with bird, hail or small runway debris during take-off or landing. These impacts may cause considerable damages recognized immediately or BVID damage, which can lead to structural failure in the future.

Impact damage and BVID detection problem is topic of many projects and scientific papers. Feasibility of damage detection by PZT sensors in composite material was proven by many authors. For example, (7) performed impact tests on a composite aircraft wing skin panel utilizing the PZT sensors and passive monitoring approach. Similarly, (8) demonstrated simple detection of impact on carbon composite panel with PZT sensors spacing 20 cm. (9) demonstrated the SHM based on circular PZT discs for the delamination monitoring of woven-glass/phenol composite panel. (10) used PZT sensors for monitoring stiffened carbon-epoxy composite panel.

The presented paper introduces the development of Honeywell SHM system based on PZT sensors and presents performed experiments for BVID detection.

Figure 1 - AERO Vodochody L-39NG aircraft and engine air duct

2  L-39NG Engine Air Duct

Figure 2 shows the monitored structure. It is a newly developed carbon composite engine air duct for L-39NG (11).

Figure 2 – L-39NG engine air duct with highlighted impact zones and basic dimensions
Material of the engine air duct is carbon/Kevlar/epoxy prepreg composite covered by primer and top coat. The inner surface contains lighting protection copper grid (Figure 3). The impact area of air duct is made of 24 prepreg layers and the rest of structure is made of 12 layers.

3 L-39NG SHM System Overview

General requirements for SHM system are to assure practical easy usage and implementation to the aircraft structure, ability to provide well-defined resolution and assure operational reliability (12).

The SHM system under development in Honeywell, sends a predefined pulse (burst) of predefined frequency and voltage to the material using a PZT actuator. Issued ultrasonic pulse generates Ultrasonic Guided Waves (UGW), which are detected by a PZT sensors. The SHM system records resulting wave and compares it with a baseline, i.e. a wave recorded on the healthy’ structure). The difference in recorded signals is expressed by so called ‘Damage Index’ (DI). There exist various approaches to calculate DI. In general, value of DI depends on the wave dispersion, wave modes interaction, reflections, attenuation etc. Due to complex propagation and interaction of UGW with damage, there is no simple relation between damage size and DI value. Thus, in the case of growing damage and periodic SHM measurements, obtained DI running in time does not show continuous increase, yet vary with sharp drops or rises. Since DI is calculated from comparison of currently recorded signal and signal measured on ‘healthy’ structure, any difference between signals indicate change of environment or the increase of damage. If there is no change in structural health, DI value will remain the same. Figure 4 shows simplified schema of the SHM system.

As mentioned above, SHM system based on the network of PZT sensors covers monitored area. The number of necessary PZT sensors depends on sensor’s network density, which is one of the major factors affecting sensitivity of the system to the
damage. Sensors distribution in the network shall assure required performance of the SHM system even if one or more sensors became functionless. Thus, redundancy shall be considered in the design of the sensor network with respect to required detection capabilities of the SHM system and its tolerance to eventual sensor failures.

Figure 5 shows rectangular sensor network layout with sensor to sensor distance 10 cm and 15 cm. In case of 10 cm sensor spacing, the total number of required sensors is 63. In the case of 15 cm spacing, the required number of sensors is only 33. Optimization of the sensor network layout is one of the objectives of SHM system development (13). For purpose of optimal sensor layout design several test were performed supported by FEM modeling of UGW propagation in composite material of L-39NG air duct.

![Figure 5 - L39NG air duct impact area and PZT sensor network density](image)

Real performance of the sensors was tested in cooperation with Czech Aerospace Research Centre in Prague (VZLU). Tests were focused on identification of min. impact energy, which causes BVID damage, BVID detection and the definition of field of view for a one sensor couple. These tests were followed by the tests of environmental condition influence to measured signals (temperature, applied load). Data from mentioned tests are currently evaluated. Presented paper introduces first part of testing – BVID detection tests and field of sensor couple evaluation.

4 Impact damage test

For purpose of impact tests, several test panels of HexPly 8552 material were used (Figure 6). Sensors were bonded to test specimen by glue LH232 and technology developed by 5M company (14). Location of sensors shown in Figure 7.

![Figure 6 - Test specimen](image)

Performed impact tests consist of set of impacts at various energies and two sizes of impact plunger diameter. After each impact, ultrasound NDT A-scan was done to
roughly localize damaged area. At the end of the testing, the ultrasound NDT C-scan was done to delineate exact damage area. Measured data during these tests are shown in Table 1. Based on the results, the impactor size and impact energy were chosen for further tests.

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*Table 1 - Measured Data of Impact energy and SHM test*

The next test was focused on the investigation of effect of the damage size and its position on the acquired signals. The same energies and impactor diameters were used to provide consistent results. The damage growth was linearly simulated in one direction as can be seen in Figure 7. In this test, the sensitivity and field of view of the SHM sensor couple was determined.

The test specimen was impacted by the impactor of size 0.5” and the impact energy of 8J. Distance between impacts was set to 10mm. Figure 7 shows test specimen with impact positions and the indication of assumed field of view by a blue ellipsoids.

Impacts to the test panel started in the middle of path between sensors 2-34 (Figure 7). Performed impacts then proceed towards the flow-line of sensors 1-35 (*impacts denoted by ‘L’ as ‘Left’ side of sensor 2-34 flow-line*). After reaching flow-line 1-35, impacts were performed in the opposite direction, again starting on flow-line 2-34 and proceed towards flow-line of sensors couple 3-33 (*impacts denoted by ‘R’ as ‘Right’ side of sensor 2-34 flow-line*). Test panel and the final damage is shown in Figure 8. The order of performed impacts is shown in Table 2.
4.1 Data Analysis

As already mentioned the DI is evaluated from comparison of two signals. Currently measured signal is compared to a baseline signal. Baseline signal is measured at the beginning of the monitoring. Thus, baseline signal is first measured signal – signal of ‘healthy’ structure.

Precision of the SHM system depends on number of factors. According to definition, precision is the repeatability of the measurement. Resulting precision of the SHM system is influenced by used hardware, used sensors, sensor installation technology, wiring, tested material properties etc. These factors caused difference in repeatedly measured signals. In case of used test panel the precision of measurement was DI_T = 0.005. ‘DI_T’ represents threshold which measured DI have to exceed to trigger alert of damage presence.

DI running of all measured paths of the test panel is shown in Figure 9. The detectability threshold is in Figure 9 expressed by a horizontal dashed black line.
Table 3 presents ‘Damage Index Matrix’ in which the detected impacts are recorded. Rows of Table 3 represent measured paths (sensor couples), and columns represent the comparison of performed measurement to baseline. ‘DI’ in cells of ‘Damage Index Matrix’ (Table 3) indicates that the real values of DI in particular cell was higher than threshold.

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Table 3 - Damage Index Matrix

From Table 3 can be seen loss of DI indication (e.g. in path 2-33 after impact ‘L2’) despite the fact that previous impact ‘L1’ caused DI indication. This is due to DI value variation as explained in section 3 (Increase in damage may cause decrease in DI value). Value of DI after impact ‘L2’ was lower than DI_T.

However, ‘Loss’ of already existing DI after impact ‘L2’ clearly indicates damage growth. If the damage remained unchanged, the DI value would be the same as after impact ‘L1’. For structure health evaluation is important first occurrence of DI (greater the DI_T). Since that time, it is known that the structure is damaged. Any further variation of DI values indicates the damage growth. Special case is damage repair. In this case, further DI evaluation shall be reset to new a baseline measured after repair.

4.2 Result Analysis

Running of DI of all measured paths during impact test is shown in Figure 9. For the sake of lucidity in the further discussion the DI running of chosen sensor paths are presented in separate figures.

As already mentioned, impacts to the test panel started in the middle of sensors 2-34 flow-line (Figure 7) and proceed towards flow-line of sensors 1-35. After reaching the flow-line 1-35, impacts were performed in opposite direction again starting on flow-line 2-34 and proceeded towards the flow-line of sensors couple 3-33 (Figure 7).

Figure 10 shows DI evaluated after first impact in all sensor paths. The first impact was performed in the middle of flow-line of sensor couple 2-34 (see Figure 7). From Figure 10 it is clear that the difference of all measured signals after damage, compared to baseline (‘healthy’ signal), was smaller than signal repeatability (precision of
measurement defined before damage). Hence, all DI lie under defined threshold. Thus, the first impact caused damage, which was too small to be detected.

Figure 11 shows running of DI (all impacts) in paths of sensors couples 3-33, 1-35 and 2-34. These paths are designated as ‘direct’ paths. The first impact [1-0] was already discussed above (Figure 10). From Figure 11, it can be seen that the direct paths were not sensitive to the first two impacts to the left side of sensor 2-34 flow-line.

As expected, impacts performed to the left side of sensor 2-34 flow line were not noticed by sensor couple 3-33 located on right side of sensor 2-34 flow-line. This can be also seen from Figure 11. On the other hand, DI values of sensor couples 1-35 and 2-34 indicates that these sensor couples are more sensitive to the damage located aside of sensor couple flow-line. From Figure 11, it can be concluded the distance from sensor couple 1-35 flow-line in which this sensor couple was able to notice damage is about 20mm. The sensor couple 2-34 detect damage after the 3rd impact. At that time the internal delamination of test panel was of size about 30mm measured perpendicularly from sensor couple 2-34 flow-line to the left side (Figure 8).

![Damage Index - First Impact](image.png)

*Figure 10 - DI of the first impact*
Figure 12 shows DI running (all impacts) in paths of sensors couples 1-33 and 3-35. These paths are longest and are designated as ‘main cross’ paths. These paths cross the area of first impact. From this point of view, they are ‘similar’ to the ‘direct’ path 2-34. Similarly to path 2-34 the path 1-33 was not sensitive to the first two impacts. Path 3-35 shows the best sensitivity of all measured paths. As can be seen from Figure 12, the second impact was already detected by the sensor couple 3-35. However, the DI of sensor couple 3-35 only slightly exceeded the DI_1 after the second impact. This indicates small difference of measured signal to baseline. Running of DI in both paths indicates the same behavior as in the case of ‘direct’ path 2-34 – small sensitivity to the first two impacts.

Figure 13 shows results in remaining ‘cross’ paths: 1-34, 2-35, 2-33 and 3-34. These paths represent measurement from one sensor couple across the damaged area to the sensor of adjacent sensor couple. Figure 13 confirms the result of analysis of Figure 11 that sensor couple is more sensitive to the damage located aside of sensor couple flow-line. Flow-line of sensor couples 2-33 and 3-34 lies aside of damaged area of first impacts and both sensor couples detected first impact to the left. As explained in section 4.1, the consequent drop of their DI indicates further change in tested structure which represents damage growth. Sensor couples 1-34 and 2-35 behave in similar way as ‘direct’ path 2-34. They show low sensitivity to damage in their flow-line.
Figure 12 - DI of All Impacts, Main Cross Paths

Figure 13 - DI of All Impacts, Secondary Cross Paths
5 Conclusion

Presented paper introduces current Honeywell activities in the field of SHM system development. SHM system design represents multidisciplinary problem. Activities in the presented project are focused on the development of sensor network design, sensor installation technology, BVID damage detection, estimation of influence of environmental conditions, and damage evaluation in composite materials.

Section 4.1 discuss the evaluation and meaning of DI. DI value depends on the complex behavior of UGW, their dispersion, wave modes interaction and conversion, reflections, attenuation etc. During the monitoring of growing damage, the DI may not progress monotonously. Thus, it is challenging to correlate value of DI and size of the damage. The challenge must be addressed by further advanced processing, especially in the case when quantification of the damage size is required from the SHM system in addition to the damage indication. However, DI clearly indicates the change of structural health and for structure health evaluation it is important first occurrence of DI (greater the DI). 

From section 4.2 - Result Analysis, several important conclusions for further development of SHM system arise. According to presented analysis, sensor couples were more sensitive to the damage located aside of sensor couple flow-line. Perpendicular distance from middle point of flow-line in which damage was detected was about 20mm. These conclusions are done for test panel material. Damage detection sensitivity needs to be verified for each SHM application and monitored material separately.

The environmental influence (temperature, applied load) on the SHM system measurement was not presented in the paper. This is one of the next step in the SHM system development.

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