Fielding a SHM System for an Aged Military Aircraft

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SUMMARY

Aging military aircraft require an increasing amount of structural inspections to safely maintain them. In a case with Norwegian Defence Sea King search and rescue helicopters, required X-ray and Eddy Current inspections on two of the Main Gearbox Attachment Lugs threatened to ground the fleet. The lugs are made of casted aluminum and subsequently have a very short critical crack length. After extending the use of the helicopters beyond its safe life of 10000 flight hours, crack lengths became critical faster than the OEM recommended inspection intervals.

The SMART layer sensor network was installed on the remaining fleet of helicopters while they were in for heavy maintenance. With the help of hardware for data acquisition and analyzing software, the RNoAF technicians have been able to inspect the cracks at short intervals. Acellent have verified the data integrity and reported crack status.

With the Acellent SHM system installed in the remaining active fleet of Sea Kings, the following requirements where adhered to:

- The installation did not need any certification
- The sensors did not cover the damaged area
- Time used for inspection is well beyond 10 minutes
- The installation did not require any design changes
- Applying the sensors did not increase normal depot downtime.

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INTRODUCTION

The Norwegian Defence 330 squadron [10] is a part of the Royal Norwegian Air Force. The squadron is based at six air stations located along the coast of Norway. The unit's primary role is search and rescue (SAR) operations. While scaling up its new AW101 helicopters, the squadron operates twelve aging Westland Sea King helicopters. The Sea King helicopters are now located at Rygge air station, and up to two helicopters are at any given time on long-term maintenance. At all bases at least one AW101 or Sea King helicopter is on stand-by at any time.

The Sea Kings flew a combined 4,500 flight hours last year. Half of these are used for missions, the remainder for training. Because the unit operates under military rules, it has a stricter training regime than civilian operators. It can also operate under more severe weather conditions. The squadron is also a part of the National Ambulance Service for which it carries out about 800 missions per year, or about ten percent of the total helicopter ambulance missions in Norway. The unit's helicopters are used when the ordinary helicopter ambulances are unable to operate due to weather; missions in which a large cabin is needed such as due to the number of patients; and in areas where the Sea Kings are closer than other SAR entities or areas where there is no ordinary air ambulance service.

AIRCRAFT HISTORY

Norway purchased the Westland Mk43B Sea King helicopters for Search and Rescue (SAR) operations in 1972 (Figure 1). In total, over 196,000 flight hours have been flown with the 12 airframes, of which many of them have gathered more than 16,000 flight hours. The original safe life for the Sea King was 10,000 flight hours, but with a regular availability rate of more than 99% and no tempting alternatives, the Air Force was reluctant to ground the aircraft. Instead typical repairs where bundled into extra depot work, inspections where added and intervals where shortened. Due to the age of the aircraft, they require an increased focus on structural issues. Typically, the usage pattern for military aircraft changes over the lifespan and differ from the usage the aircraft was designed for [6]. Subsequently the maintenance organizations have received reports of increased or new cracks and have countered this development with shorter intervals on the inspections. The inspections can, when the aircraft approaches end of life, be resource demanding to such a degree that the cost and decline in availability rates will result in the grounding of the aircraft.

One area with cracking beyond repair is where the four Main Gearbox (MGB) attachment lugs fasten the MGB and rotor to the airframe (Figure 2). The cracking started before end of life, but since the usage pattern had changed, it was hard to determine the cause. When inspected and found with cracks, the lugs were replaced before next flight. On one occasion a lug cracked while the helicopter was in midair causing an alarming change in the vibration pattern in the aircraft. It managed to fly to the nearest airport, but clearly the inspection interval was not short enough.

After replacing failing attachment lugs on all aircraft, neither the maintenance organization nor design organization had enough data to set a new initial inspection flight hours and knew that the interval would be demanding. The current intervals were 50 flight hours for an Eddy Current inspection of assumed crack start areas and 100 flight hours for X-ray inspection of the lugs. Decreasing the intervals would impact availability and it was therefore decided to add a Structural Health Monitoring (SHM) system if it could fulfill the following requirements:

- The installation should not need any certification
- The sensors shall not cover the damaged area
- Time used for inspection shall be less than 10 minutes
- The installation shall not require any major design changes
- Applying the sensors shall not increase normal depot downtime.

Figure 1: The Norwegian Mk43B Sea King SAR helicopter (Source: Dmitriy Pichugin – http://www.airliners.net/)

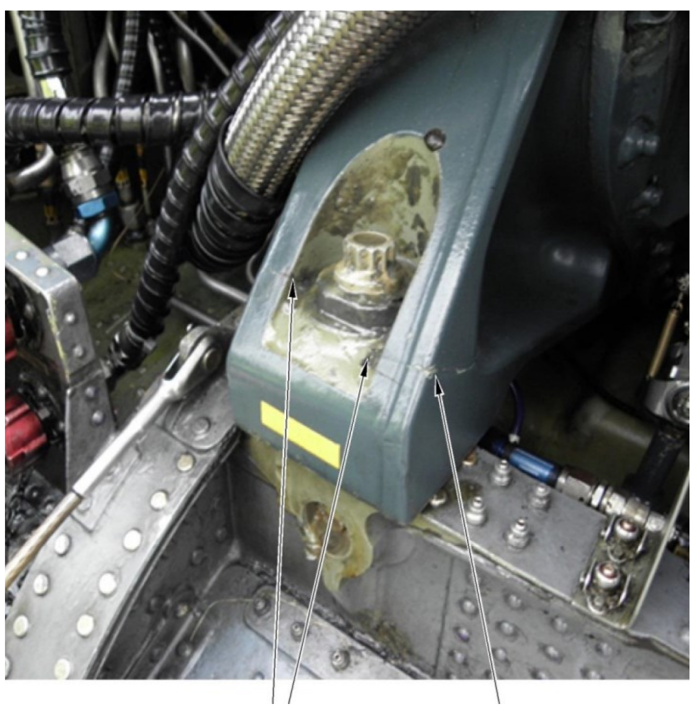

Figure 2: Cracked Main Gearbox attachment lug at R/H FS 290. Crack lines are marked. (Source: RNoAF)

STRUCTURAL HEALTH MONITORING SYSTEM

After a careful study, it was determined that SHM systems have matured to the point where they can be used to evaluate the structural health of engineering structures under operation over the years. For aging infrastructures, an SHM system can provide information on damages in critical areas and immediate maintenance activities can be initiated. Such an SHM system can reduce the total inspection costs for rotorcraft structures and avoid unplanned structural inspection/maintenance and catastrophic failures. It was determined that the SHM system developed by Acellent Technologies, Inc. fulfilled the requirements and was subsequently selected by the Norwegian Defence Material Agency for a flight testing program to evaluate the reliability of the system in an operational environment. Acellent provides complete structural health monitoring solutions including the SMART layer sensor network, hardware for data acquisition as well as software for data analysis. These have been tested and validated previously on many aircraft platforms [8,9].

The Acellent SHM system for aircraft includes three major components integrated together:

1. ***SMART Layer*** is a network of miniature sensors and actuators that can be surface mounted on structures to provide a built-in assessment of the health of the structure. The ***novelty*** of the SMART layer lies in its networking capabilities with any type of sensor enhancing its monitoring capabilities and eliminating the need to place each type of sensor individually on the structure. The layer can incorporate sensors such as piezoelectric, strain, thermal and moisture gages into the embedded network to monitor these properties.
2. ***Diagnostic hardware*** including the ScanGenie series that are all lightweight and portable and have been especially developed to interface with the sensor network of the SMART Layer and provide an easy tool for data acquisition.

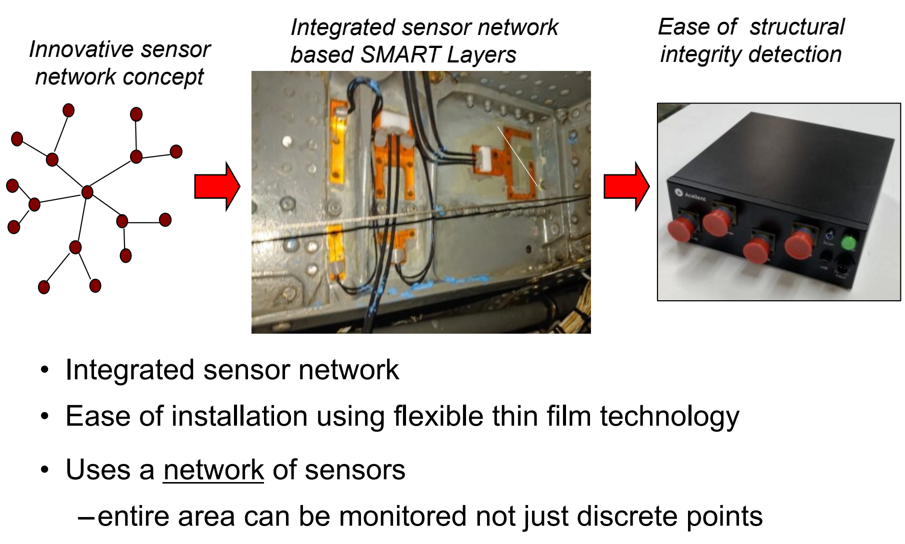

Figure 3: SMART Layer sensors

3. ***Diagnostic Software*** such as *SHM Patch* that come with a variety of data acquisition and user-friendly display functions to simplify the structural monitoring process. With the push of a button, the software can instruct the hardware to actively interrogate the structure (using the SMART Layer), collect the diagnostic data and then display damage information in real time.

Acellent is working closely with the Norwegian armed forces for the evaluation of the SHM system for use on their aging SAR helicopters. Acellent's SMART Layer sensor networks [1-4] and data acquisition hardware shown in Figure 3 were used for ultrasonic inspection of critical areas in the Norwegian Sea Kings.

The SMART Layer sensor signals are received and digitized by the data acquisition system and transferred to the SHM Patch software for further post-processing of the data. The software post-processes the received signals and predicts the damage size and locations.

PROBLEM STATEMENT

A project to develop and flight test the designs and inspection protocols for the application of the Acellent SHM system to the Norwegian Defence (ND) Sea King fleet was undertaken. Six helicopters in the Norwegian Sea King fleet are under inspection in the present project with Norwegian Defense Material Agency (NDMA). These are tail numbers (T/N) 062, 069, 070, 073, 074, and 189. NDMA engineers have identified the locations of possible crack formation in two major areas in the aircraft, left-hand fuselage station (FS) 243.5 (sensor arrays 186, 187) and right-hand FS 290 (sensor arrays 188, 189 and 190_191).

The inspection of ND Sea King helicopters at the critical areas using the SHM system during actual operation of the aircraft needs to be validated. The sensors were installed on hotspot areas of the aircraft. A hot spot area represents a location of possible crack formation. The hot spot areas were identified by Norwegian defense in their aircraft. SMART layer sensors were designed and installed in these areas to record signals and identify the formation of damage.

An example of the inspection areas and sensor installation in this area is presented in Figure 4. The sensor placement and the distance between sensors are determined by the critical damage size to be detected and the sensitivity of stress waves to the damage. The wave speed of stress waves depends on the material properties, thickness of the structure as well as frequency. The optimization of the sensor was performed to design the optimal spacing of the sensors in the layer.

The connection in the test setup includes the circuits between the sensors and terminals, connectors, and the cable from the connector to the diagnostic hardware. A strain relief connector on the layer is necessary to avoid any electric disconnection. Depending on the host structure, the connector can be fastened to the structure or bonded to the structure.

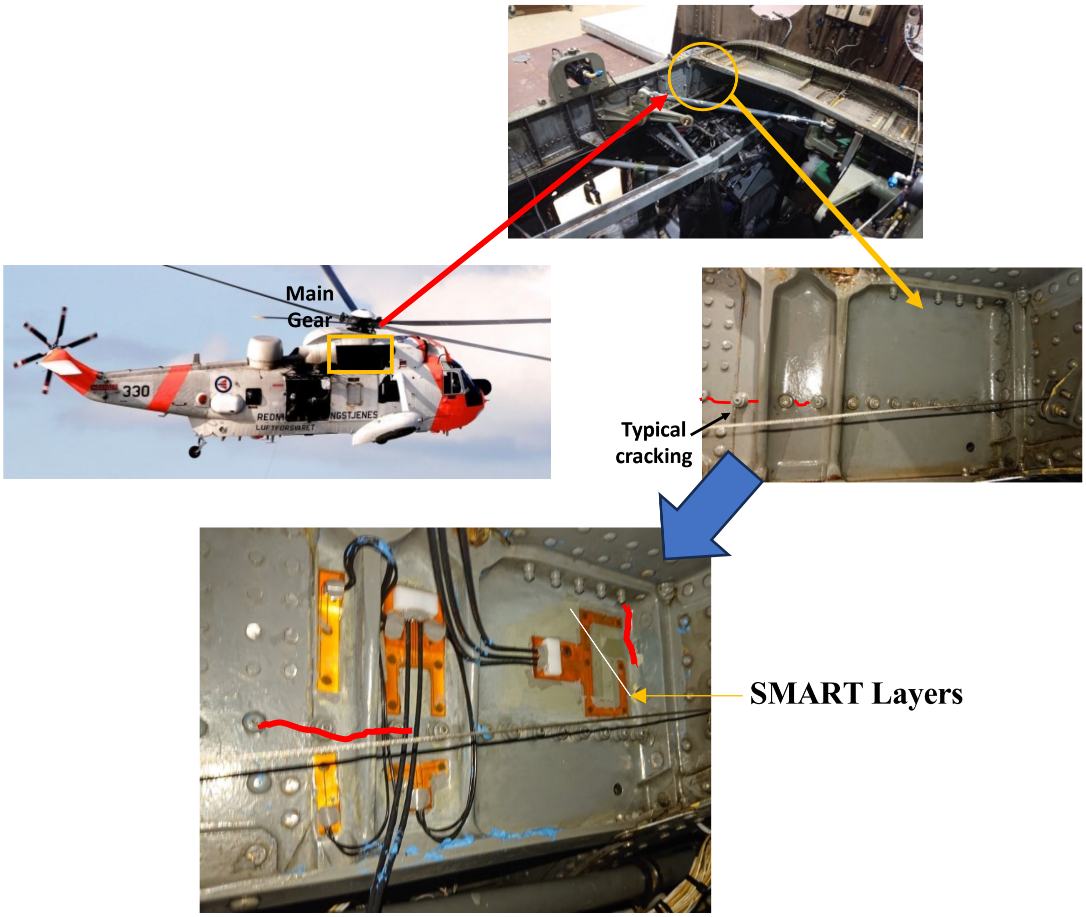

Figure 4: Example of inspection area and SMART layer designed for the area

METHOD OF APPROACH

SENSOR INSTALLATION

The sensor layers were installed on the structure using the following sensor installation method. First, clean the surface of the SMART Layer with Isopropyl Alcohol using a soft paper towel or tissue. Using a wet paper towel, wipe gently over the surface of the SMART Layer to remove any surface oil. Thoroughly clean the bonding surface of the structure, removing oil, dirt, and other contaminants using a suitable solvent such as Acetone. Clean the surface before sanding to avoid sanding the contaminant into the surface. Follow all safety precautions when working with solvents. A slightly roughened surface usually permits the best bond. Use 300~500 grit sandpaper on the bonding surface. Remove any flaking, chalking, blistering, or old coating before sanding. Remove all dust after sanding.

Epoxy adhesives are used to mount the SMART Layers on the surfaces of the structure because a “rigid” interface between the piezoelectric elements and structure is needed. The interface will provide the mechanical coupling needed to transmit strain between the actuator/sensor and the structure.

Though a number of epoxies can be used to mount the SMART Layer on the surface of the structure, two-part Hysol® structure epoxy adhesives or Hysol® epoxy film adhesive is recommended. For the Sea King installation, the Loctite EA 9394 was used. Mix the components (Resin and Hardener) together with a recommended ratio by the epoxy manufacturer. Place the mixed epoxy onto the sensor side of the layer (i.e. the side with the white piezoceramics) and the mounting surface of the structure. Use a squeegee to spread epoxy to a uniform thin layer on the surfaces. Place the SMART Layer on the surface of the structure (the side with epoxy resin face to the surface of the structure). Gently use a rubber roller or equivalent to apply light pressure on the top surface of the layer. Start at the center of the layer and roll to the outer edges to remove entrapped air.

While the epoxy is curing, pressure must be applied to keep the SMART Layer in place and get a good bond. A vacuum or rubber pad is recommended for uniform clamping pressure of which vacuum was used on the Sea Kings. It did require experienced and skilled personnel to adhere the sensors to the airframe to ensure a good bond. After the sensor installation, the sensors integrity check of the sensors was performed to confirm the sensors were installed to the structure without any defect. Although there were some incidents of damaged sensors during installation, the setup allowed for a certain degree of missing sensors without compromising the final results.

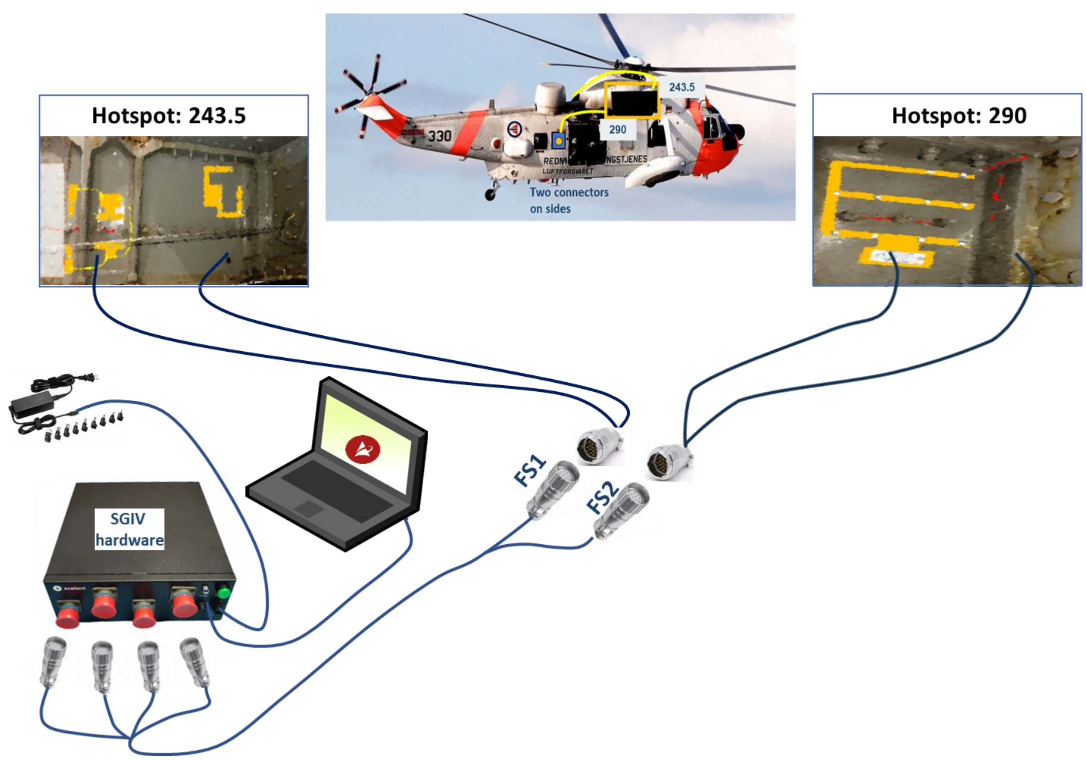

Figure 5: Schematic of the SHM system

SYSTEM SETUP AND CALIBRATION

The schematic of the SHM system for the ND Sea King aircraft is presented in Figure 5. First, connect the charger to the ScanGenie IV (SGIV) hardware. Then, connect the USB cable from the laptop to the SGIV hardware. Connect circular connectors from inspection areas (FS 243.5 and 290) to the cable to the SGIV hardware. Turn on the SGIV hardware. Collect data using the new 'SHM Patch' software for the SGIV hardware.

During the initial setup of the hardware, calibration of the system needs to be performed. Optimization of the sensor gain values was performed using the automatic optimization method in 'SHM Patch' software. During this step, the software identifies the optimum gain values for each sensor for obtaining sufficient strength of the receiving signal.

Before first data acquisition, the baseline signals were recorded. The recorded baseline is used for comparison of the signals recorded later on to identify the signal deviation that is used to perform the damage identification and quantification. If there is any deviation in the signal, the signal deviation in each path is quantified as the damage index (DI) values [1]. The damage index values are used for identifying the location and severity of the damage.

DATA ANALYSIS

As shown in Figure 6, during each data collection, a system integrity check of the sensors was performed to make sure the sensors were functioning. After confirming the integrity of the sensors, the data were recorded. The excitations were applied for 250 and 350 kHz five-count tone burst frequencies. The data collection was performed every 10 flight hours. If any repair or replacement of the areas under investigation is performed, a re-baseline of the data will be performed. In this situation, a new baseline of the data will be recorded. After the re-baseline, flight mode monitoring of the aircraft will be continued by data collection and analysis after specific intervals. The DI values for each path were calculated by the software.

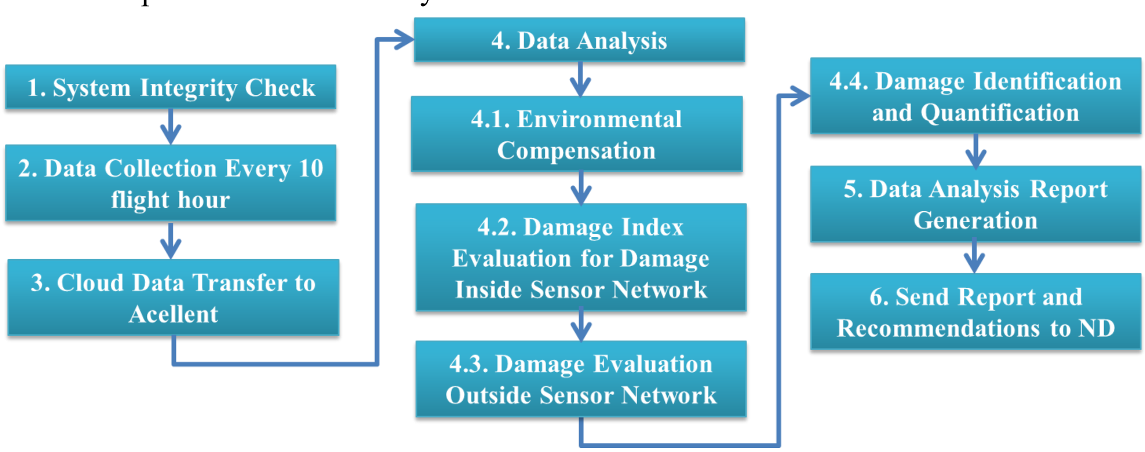

Figure 6. SHM procedure

The software also performs compensation for environmental effects on the signals before damage identification so that the effect of environmental conditions on the signals is eliminated. Using the DI values in each path, the DI values of each sensor array locations are estimated as an average of the values. These DI values are recognized as the representative health index for each sensor array structure area. The history of the DI values of each array is tracked over the historical data and the trend of deviation is estimated for confirming the health monitoring of each hot spot. This procedure determines health status by identifying the cracks inside the sensor network. The sensor network data can also identify the damages outside the sensor network. Using a specialized method for damage identification outside the sensor network, the software also checks if any damage is formed at the near surroundings of the sensor array. Thus the software can identify and quantify cracks inside and outside the sensor network.

RESULTS AND ACCOMPLISHMENTS

The analysis results for T/N 073 based on the data received are presented in Figure 7. The unit cell DI history trend of T/N 073 observed for the past data is presented. Data were recorded on August 30, 2022, September 17, 2022, October 6, 2022, October 16, 2022, November 16, 2022, November 16, 2022 and December 7, 2022. The data recorded on August 18, 2022 was set as baseline. The damage index values were calculated for the rest of the data using the baseline. The DI history trend for the historical data for each unit cell was calculated and plotted as presented in Figure 7.

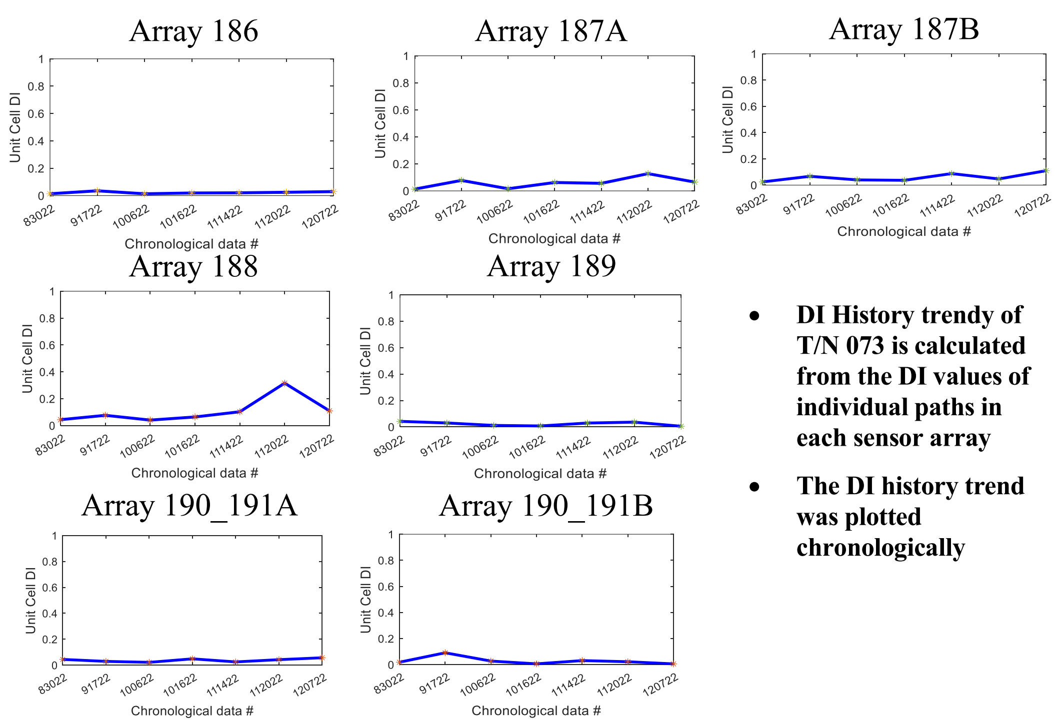

Figure 7: Unit cell Damage Index (DI) history trend for all unit cells of T/N 073

No significant variation in the DI history trend was identified for the aircraft from the data received. An X-ray inspection of the areas was also performed along with the SHM inspection. No damage was identified from the X-ray inspection of the areas. Therefore, the SHM inspection was regarded as validated by the X-ray inspection. Similar plots of the DI trends were generated for all other aircraft under inspection as well and validated the same way using X-ray inspection. In the same timeframe multiple Eddy Current inspections where also performed although covering a smaller area.

During the data collection and interpretation of the Norwegian Sea Kings, it was learned that there are several factors which can affect the ultrasonic signals in field conditions. Typical factors are temperature, load, maintenance activities performed and open hatches or platforms. Identifying and compensating for such factors are necessary to accurately conclude the structural health of the inspection area [7].

Damage index values can be calculated for each path in the sensor network. For each unit cell, the Unit Cell Damage Index (UCDI), derived from the DI values of individual paths is a representative quantity of the health status of the area. In the present data processing approach, the UCDI was calculated for each unit cell and further inspection of paths was performed for anomaly unit cells from the index values. This way, the health status of each unit cells was identified and determined. The health status of the aircraft was evaluated using the SHM system results and independently verified using the conventional NDI methods (ultrasonic or eddy current). An example for the Sea King helicopter with tail number 073 is shown in Figure 8.

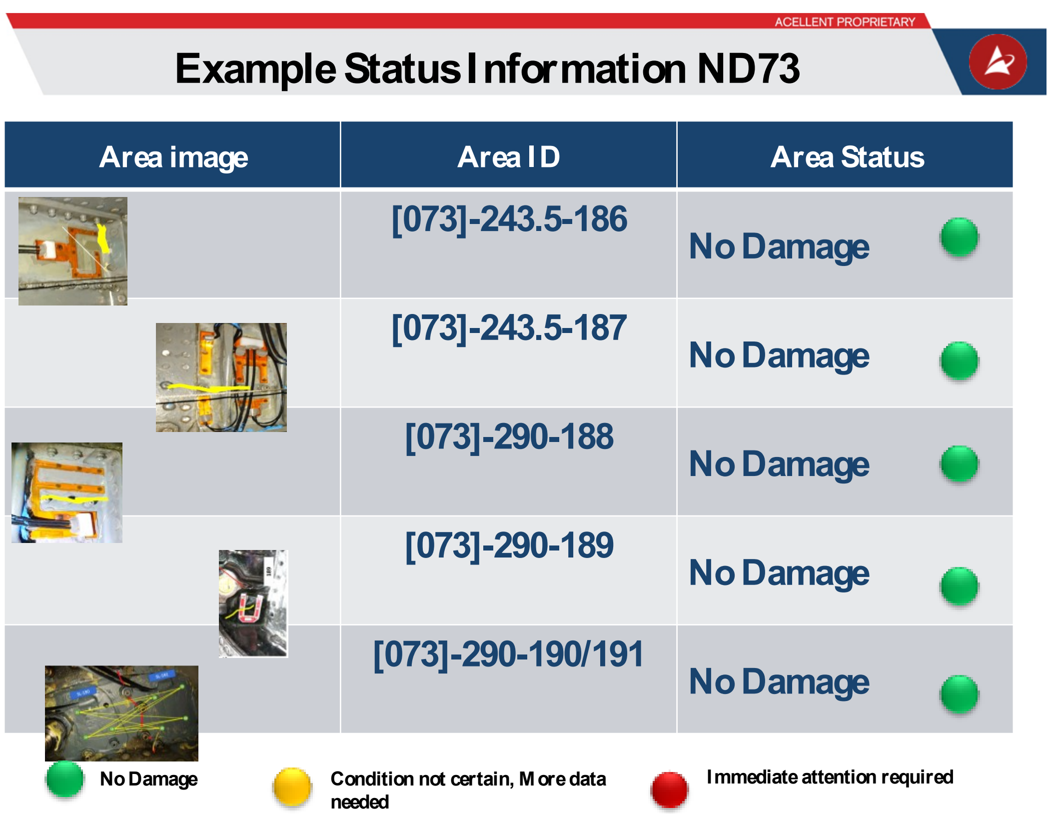

Figure 8: Example Health Status for Helicopter with tail number 073

CONCLUSIONS AND FUTURE WORK

This paper discussed how the requirements for the operative Norwegian Defence Sea King SAR helicopters were met for the structural health monitoring of critical areas in the helicopter. The structural health monitoring system deployed was shown to be able to monitor the helicopter for cracks in less than 10 minutes and without any major design changes in the aircraft. The fleet now has an availability rate of 99,6% on a 15-minute notice, which is remarkable for aged helicopters.

A process for the utilization of the Acellent SHM system to perform inspections of critical areas for the Norwegian Defence Sea King helicopters was developed and validation is in progress. The hotspot areas in the helicopter were identified for sensor installation. Customized smart layer sensors were installed on the aircraft hotspot areas for structural health monitoring. The system integrity check was performed to confirm the quality of the sensor installation. The setup was calibrated to optimize the data recording. At present the structural health monitoring system records ultrasonic data from the aircraft periodically and damage identification at the hot spot areas is being performed using the Acellent in-house developed SHM Patch software algorithms. Being a passive system only used on ground, no electromagnetic compatibility (EMC) testing and certifying was needed.

In the future, the SHM system will continue to record data and inspect the areas at periodic intervals. In the present field system, we have identified many variables affecting the ultrasonic signal variation such as temperature, load, maintenance activities etc. The clustering and grouping of such signals is of much importance for efficient health monitoring of field systems. Automation of the data group segregation will be added so that the system itself can cluster the data files, build the structured data base, and further improve the SHM damage detection.

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