# Flight Demonstrator of a Self-Powered SHM System on a Composite Bonded Patch attached to an F/A-18 Aileron Hinge

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## ABSTRACT:

The use of bonded composite patches to repair or reinforce defective aircraft structures is recognised as a very cost-effective repair procedure for many types of structural problems, such as metallic cracking, repairing corrosion damage and reducing fatigue strain at structural hot spots. However, certification concerns limit the application of bonded repairs to critical components. For certification and management of repairs to critical structure, the "Smart Patch" approach may be a useful approach from the airworthiness perspective in facilitating certification. The "Smart Patch" consists of in-situ sensors used to monitor the structural condition (health or well-being) of the patch system and the status of the remaining damage in the parent structure. Two such in-situ health monitoring systems are being trialed on a composite bonded patch applied to an F/A-18. One system uses a Lithium ion-based battery as the power source, to monitor patch health, based on data measured from conventional strain gauges. The patch health data is up-loaded by the operator using an infrared (IR) link. The other concept, considered a higher-risk approach, had no battery and was powered instead by energy harvested from the environment. It was wirelessly-interrogated and employed piezoelectric elements for both powering and health monitoring functions. In this system the patch health data is up-loaded by the operator using a magnetic transceiver. This paper describes the development, evaluation and implementation of the self-powered system, including issues such as system design, patch health monitoring techniques, system functional testing and system installation. Flight data from the SHM system and lessons learned during the program will also be presented.

## INTRODUCTION

The application of bonded composite patches or doublers to repair or reinforce defective (secondary) metallic structures is becoming recognised as an effective and versatile repair procedure for many types of problems [1]. However, the application of bonded composite repairs to cracked aircraft primary structure is generally acceptable only on the basis that a margin on design limit-load (DLL) capability is retained in the loss (total absence) of the repair [2]. However, assuming that the static requirements and quality assurance processes are satisfied, one approach to certify full credit for the patch in slowing crack growth could be justified by a *continuous safety by inspection approach.* This approach is based on the

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continuous self-assessment of the patch system integrity using a "smart patch" approach [2,3], that is by incorporating in-situ sensors to continuously monitor the structural condition of the patch system and associated remaining damage in the parent structure. The need to follow approved patch design, fabrication and quality assurance procedures is unchanged; this approach simply allows a relaxation of the probability of failure requirements, particularly in relation to environmental degradation. However, the viability of any "smart patch" or in-situ structural health monitoring (ISHM) approach now depends on establishing its reliability or probability of damage detection which is similar to the problem of probability of detection in NDI, and should include system self-checking and redundancy to provide the required level of confidence.

In order to demonstrate and evaluate the feasibility of the *smart patch* concept the Australian Defence Science and Technology Organisation (DSTO) has developed two in-situ structural health monitoring (SHM) systems to interrogate the structural health of a boron/epoxy doubler (or reinforcement) on an F/A-18 inboard aileron hinge, as shown in Figure 1a. The instrumented aileron was installed on a Royal Australian Air Force (RAAF), Aircraft Operation Support Group (AOSG) F/A-18 in early 2006. A low-risk approach for the smart patch uses a Lithium ion-based battery as the power source, to monitor patch health data measured from conventional strain gauges. The patch health data is up-loaded by the operator using an infrared (IR) link. The other involves more technical risk and consists of a self-powered piezoelement-based sensing system powered by an array of piezotransducers, which converts structural dynamic strain to electrical energy, and monitors damage in the repair via piezoelectric film strain sensors. This system is referred to here as the Smart Patch System Demonstrator based on Piezoelectric elements (SPSD-P). In this system the patch health data is up-loaded by the operator using a magnetic transceiver.

This paper describes some of the critical issues associated with the development, evaluation and implementation of the self-powered system of the smart patch concept, including issues such as system design, patch health monitoring techniques, system functional testing and system installation.

## GENERAL SPECIFICATIONS

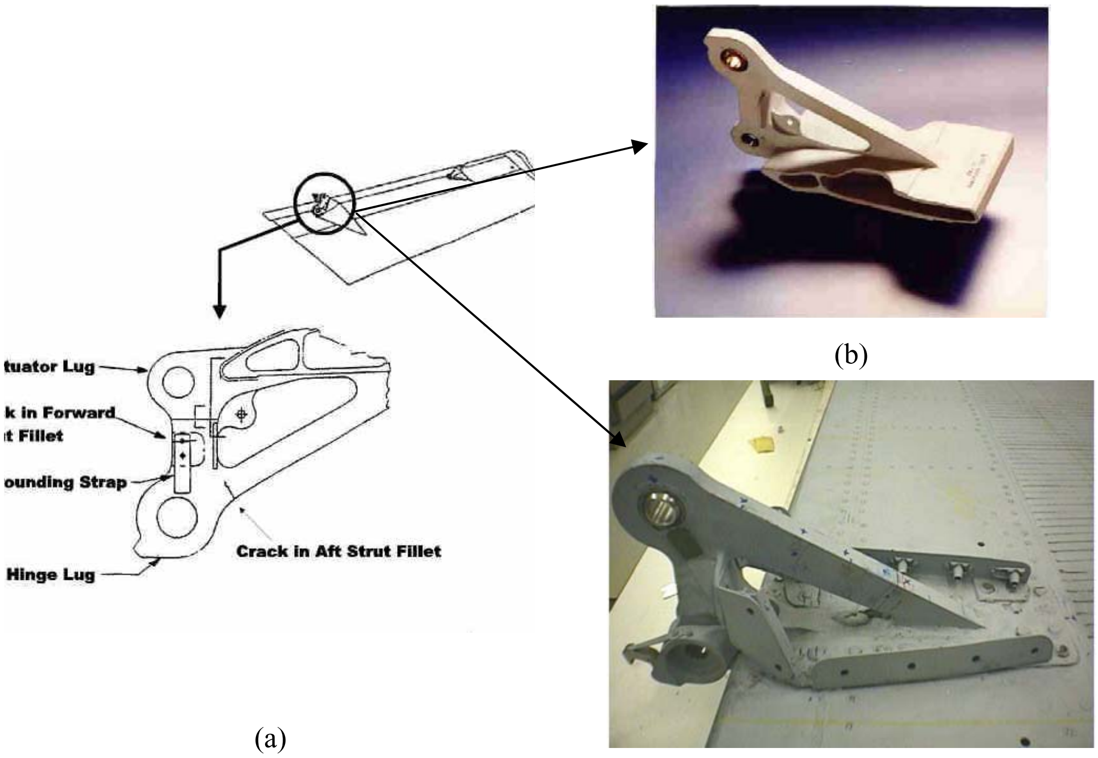
The first phase of the project was to establish the operating envelope of the system, including temperature, strain and vibration at the aileron hinge, flying time and elapsed time between system installation and removal from the aircraft. All these issues are critical when designing and implementing such a system. In summary these specifications are listed below [4]:

- Operational temperature range: -40°C to 70°C
- No strain time history data was available for the hinge; however, from flight loads data and design data, operational peak strains of the order of 1500 microstrain at an excitation frequency of between 8 to 42 Hz was assumed.
- Flight times of the order of 40 to 60 minutes per sortie.
- System was expected to be operational for an elapsed time of one year which would entail between 100 – 200 sorties.

## CONCEPT DEVELOPMENT AND HIGH LEVEL SYSTEM DESIGN

There are several methods of deriving an indication of structural health. A common way is to inject a known excitation and measure a response at "interrogation" time. An alternative is to use some form "in-service" excitation. In this case, in-flight loading is used as the excitation mechanism and strain distribution as the damage indicator.

The initial idea was to evaluate the smart patch concept on a bonded composite patch/reinforcement designed for an F/A-18 aluminium aileron hinge with a propensity to cracking [5], see Figure 1a. During the initial system design phase the RAAF decided to refurbish the ailerons and, in so doing, replaced the aluminium hinges (see Figure 1b) with redesigned titanium hinges (see Figure 1c); thus eliminating the cracking problem. However, in consultation with senior RAAF Engineering Managers, it was decided to proceed with the smart patch demonstrator on a titanium aileron hinge. In general, the 'smart patch' concept needs to continuously inspect regions of the reinforcement likely to suffer disbond damage [2]. A finite element (FE) analysis of the hinge was undertaken to check the design of the boron/epoxy (b/ep) reinforcement and to determine the most likely regions of damage [4]. Figure 2a shows the FE model of the titanium aileron hinge with the reinforcement. Two load cases were considered in the FE analysis, viz., load case WO39 a tensile design ultimate load condition and WO42 a compressive design ultimate load condition [5]. Figure 2b shows the peel and shear stress distribution in the adhesive of the reinforcement, respectively, for load case WO39, and indicates that two critical regions exist, viz., the tapered region at the end of the repair on the hinge strut (x ~ 200 mm) and the region of high adhesive peel stresses in the concave portion of the reinforcement (x ~70 mm). In both cases damage is detected by monitoring the change in ratio of critical region strains to far-field strains (referred to as the patch health indicator in this paper) [6].



(b)

(a)

(c)

Figure 1: (a) Schematic of the aileron, hinge lug and hinge aft strut with likely crack locations (taken from reference [7]). Photograph of F/A-18 (b) aluminium and (c) titanium aileron hinge.

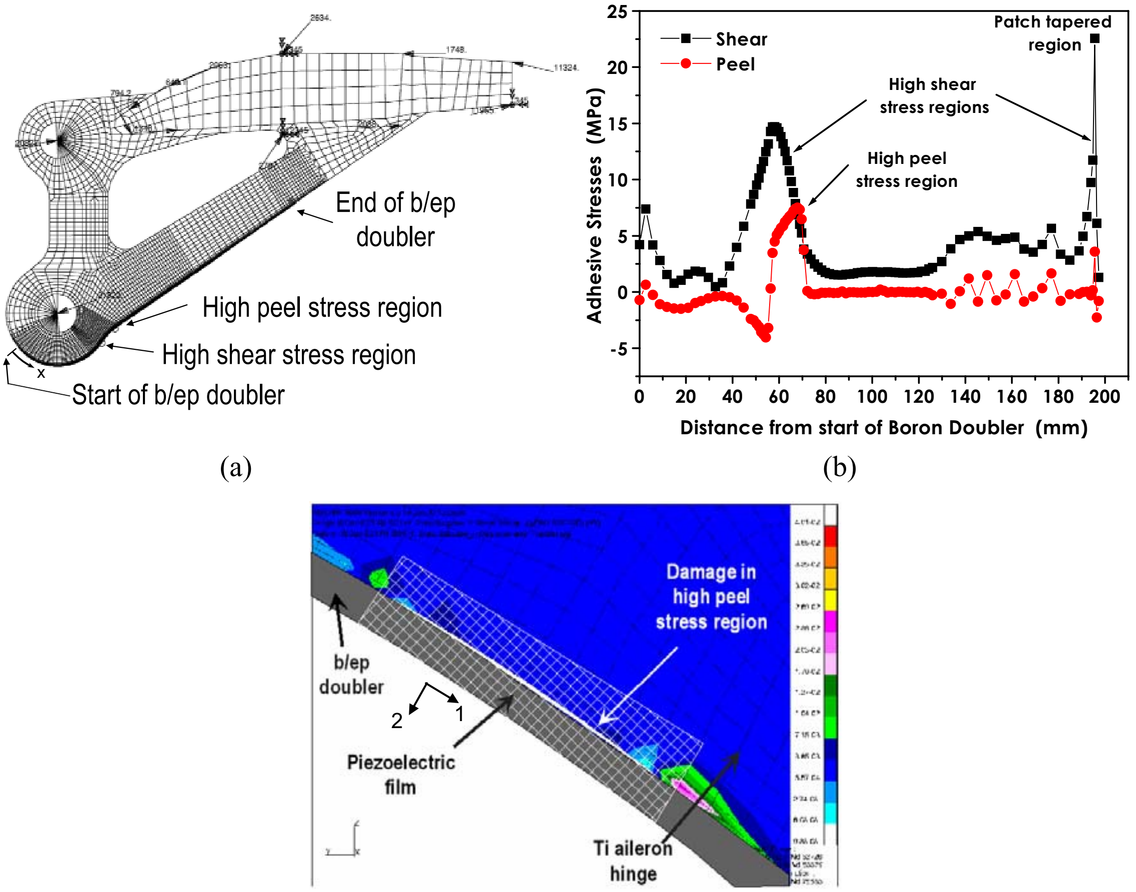
To encourage acceptance by operators and maintainers a fully autonomous system design was chosen with no batteries. The basic information flow being;

- When in flight a combination of piezoelectric film (chosen for its durability) and piezoelectric ceramic (chosen for its higher output) elements are used to power up the system

- When power is available, the temperature is within the selected range and the strain is at a threshold level, a patch health measurement is taken by the piezoelectric film sensors. As damage growth is slow the relatively sparse sampling is considered adequate.
- The reading is used to refine the current health estimate stored in FRAM (chosen for its low write energy requirements (~90 nC).
- Once a week or so a hand held interrogator is brought near the hinge, which powers the circuitry of the SPSD-P system via inductive coupling and allows readings to be downloaded via the same inductive link. Inductive coupling was chosen as it is able to carry power and information through a thin barrier (in this case the plastic cowl, although transmission through thin aluminium is also possible).

## FINITE-ELEMENT ANALYSIS OF DAMAGE DETECTION SCHEME

Finite element (FE) analysis was employed to determine the most appropriate position and geometry for the sensors. The results showed that a 2 mm and 4 mm wide (by 15 mm long) PVDF sensor would have a 2 to 4 and 1.5 to 2.5 fold increase, respectively, in response to a 10 mm disbond compared with the undamaged case [4].



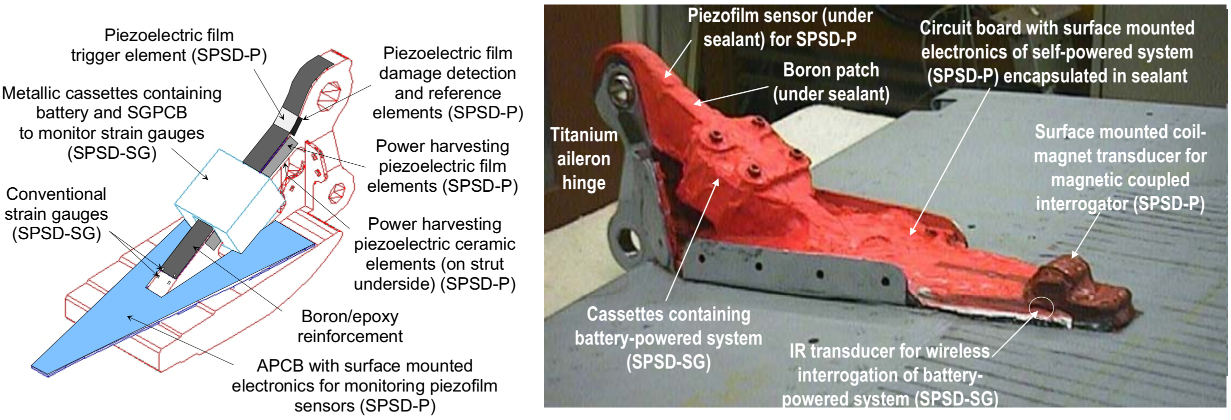
(a) (b)

(c)

Figure 2: (a) Finite element model of titanium aileron hinge. (b) Predicted adhesive stresses in the reinforcement system with no damage present (load case WO39). (c) FEM displacement plot and damage detection scheme for damage in the high peel stress region.

## DETAILED DESIGN

Geometric constraints and limitations in strain level and frequency response, limit the amount of power available using piezoelectric elements to fractions of a milliWatt in the SPSD-P system. Since it is difficult to get a reasonable amount of signal processing done on this kind of power budget, the harvested power was stored in a capacitor. Consequently, a reading was taken only once the following conditions was met: (i) sufficient energy was available for a complete reading cycle, (ii) the structure was experiencing significant strain, and (iii) the temperature was within a given window. Figure 3 shows the mounting arrangement of the smart patch, including the SPSD-P system, and the location of the transducers on the aileron hinge. Budget and time constraints have necessitated a fairly large A-shaped printed circuit board (APCB) footprint with surface mounted commercial off the shelf (COTS) electronic components, schematically-illustrated in Figure 3. However the design is such that it should be a relatively straightforward process to reduce the unit to very small proportions using standard complimentary metal oxide semiconductor (CMOS) technology.



(a) (b)

Figure 3: (a) Schematic and (b) photograph of the installed of the Smart Patch system on an F/A-18 aileron hinge.

The piezoelectric film sensors require no excitation power, have modest signal conditioning requirements, and a good fatigue life, however these virtues come at a cost, in the form of poor low frequency response. As there is a high probability of a substantial amount of strain at low frequencies it was considered important to ensure that the frequency roll-off characteristics were fairly accurately matched. Considerable care was taken to reduce the risk of moisture ingress creating a shunting effect that would adversely affect this matching.

In the most elementary case the only value needed would be the last worst patch health indicator reading. However this was considered not to be sufficiently robust, since a single noise "spike" could cause a misleading reading. This led to the conclusion that filtering and some other confidence building indicators were required. A time stamp was considered but thought to be a little too challenging to implement using the technologies readily available, therefore a reading counter was chosen as a compromise. Unfortunately the only place to maintain the count is in the nonvolatile memory, thus necessitating a "measurement cycle" to consist of (1) reading the memory, (2) taking the measurement and (3) writing the updated information back into memory. In an attempt to reduce the effects of spurious spikes, a simple slew rate filter algorithm was employed. This was thought to be appropriate as the damage is expected to grow relatively slowly with respect to the reading rate, and even if the patch suddenly failed this would be indicated after only 10 reading cycles at most. A temperature dependant lockout was fitted to the supply circuit to prevent any operations being attempted if the operating temperature was outside specified temperature limits of the 'industrial grade' off-the-shelf electronics used in this device, and an actual reading was made when the temperature was in the window range of 10°C to 40°C. This was considered an acceptable option in this application as the data required was a very small number of samples and not considered to be particularly dependant on temperature.

During the information up-loading operation the circuit is both powered and clocked by an alternating magnetic field provided by the interrogator. The prototype design is capable of reading two ratios, with respect to a common reference (to 10%), and maintaining a latest reading number (that wraps back to zero at approx. 16.7 million readings). Measurements indicated the prototype consumed about 210nJ of energy to perform the digitizing and dividing function, 60nJ to perform the storage and retrieval function and 10nJ for clocking.

On the supply side, the PVDF element appear to be rated at about 0.37 $nJ/m^2/\mu\varepsilon$ and PZT elements at about $30nJ/\mu\varepsilon$ (when using basic harvesting techniques, and before accounting for losses). The power harvesting was achieved by a combination of (1) two stacks of three 28 μm thick 155 mm long by 20 mm wide PVDF elements located on both sides of the strut and (2) PZT power harvesting elements consisting of two 32 mm long by 12.5 mm wide two layered 0.66 mm thick PZT wafers on the lower side of the hinge strut, in the location indicated in Figure 3. Power issues are discussed in more detail in reference [8].

Sections of computational, storage and the majority of the interrogation function were chosen to be implemented in digital technology. A programmable logic device (PLD) was originally chosen on the grounds it provided low operating power with maximum flexibility. However further investigation revealed a large and potentially problematic start-up energy requirement. As standard cell and custom integrated circuits (IC) were beyond our budget it was decided to use medium scale integration (MSI) CMOS as the most appropriate option. Information stored is 2 by 4 bit ratio values and one 24 bit count indicating the number of reading cycles.

The antenna on the SPSD-P consists of a coil of copper wire wound on a ferrite core. The SPSD-P is energized by the current produced in the coil in response to a low frequency magnetic field produced by the interrogator. The data is modulated on this carrier by changing the reflected impedance. The data rate is derived as a sub-multiple of the carrier frequency.

## SAFETY OF FLIGHT AND FUNCTIONAL TESTING AND SYSTEM INSTALLATION

A number of testing activities were undertaken, during the development of the smart patch system, to cover two main aspects:

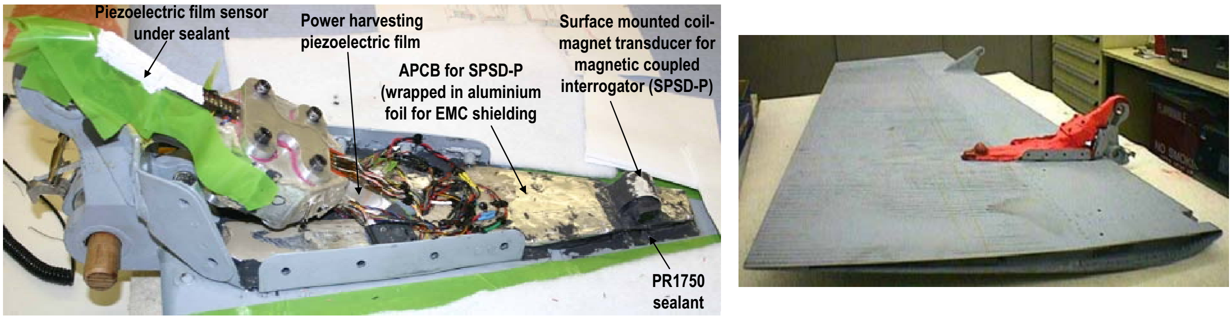
(1) Safety of flight issues which required testing on a prototype smart patch system to characterise the system response from specified mechanical vibration/shock, electro magnetic and pressure/temperature environments.

(2) System functional testing consisting of both bench-top testing of the electronic components (especially the APCB and interrogator) and a prototype smart patch system installed on an ‘original’ aluminium aileron hinge component (removed from an F/A-18 aileron).

Electronic components (such as APCB and handheld interrogator) were bench tested using simulated voltage inputs for the PVDF sensor and power harvesting elements. Then a trial installation was performed on a sub-component ‘original’ aluminium aileron hinge taken from an F/A-18 aileron, similar to the component shown in Figure 1b and then subjected to functional and environmental testing. That was undertaken to ‘fine tune’ and validate the installation procedure and evaluate the performance of the smart patch after adverse environmental (i.e. hot/wet/cold) loading. The environmental testing involved placing the sub-component in an environmental chamber and subjecting the specimen to several moderate thermal cycles of -30°C to 40°C and severe thermal cycles of -40°C to 70°C. All thermal cycling was undertaken at maximum % relative humidity of the chamber and each temperature extreme was maintained for at least 30 minutes, to ensure condensation would occur on the sub-component during the environmental cycling; the aim was to ensure that the environmental cycling would comprehensively test the protective coating process. The specimen was then installed in the testing machine to perform a number of functional tests. This testing program was extremely useful and outlined several installation and electronic deficiencies. The main issues were problems in the FRAM used in the SPSD-P, as well as problems associated with the protective coating process, shielding layer bonding to the protective polysulfide PR1750 sealant and wiring procedures. A mitigation strategy was developed for all these issues.

## SYSTEM IMPLEMENTATION AND FLIGHT TEST RESULTS

A comprehensive installation procedure was written and approved by the appropriate airworthiness authorities [4]. The system was then installed, by DSTO personnel, on the aileron supplied by ARDU, over about a two week period in November 2005, under RAAF supervision. The aileron with the installed smart patch is shown in Figure 3b and Figure 4.

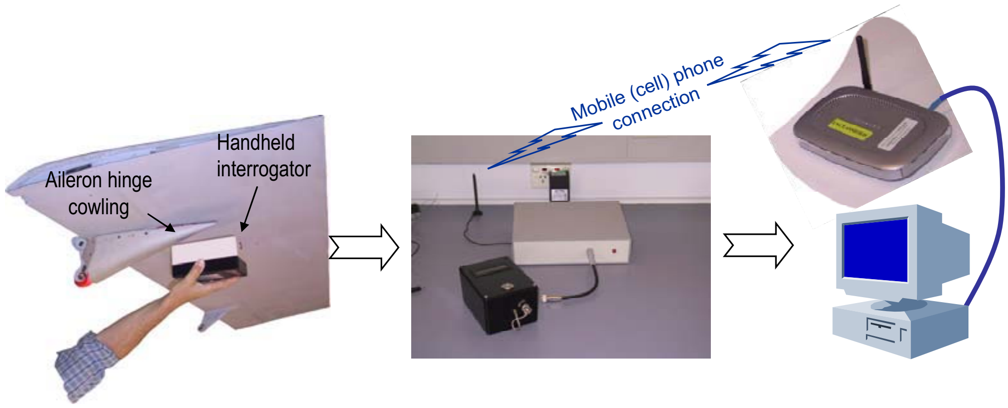


(a) (b)

Figure 4: (a) Smart patch, without protective coating and emc shielding, installed on aileron hinge; (b) Photograph of SPSD on the F/A-18 aileron hinge.

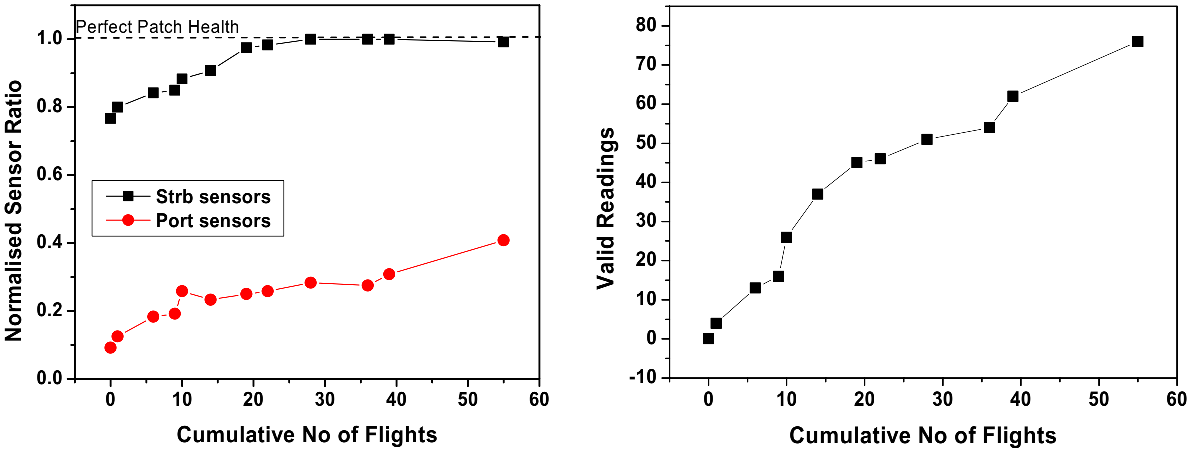
The instrumented aileron hinge was installed on Hornet A21-101 in February 2006. Current arrangements with the maintenance personnel is that patch health information is downloaded from the instrumented aileron using a handheld unit, as shown in Figure 5, at the end of every week (if the aircraft has flown during the week). After each download the handheld unit is connected to a nearby docking station, which ensures that the handheld device is fully charged and allows the patch health data, from the hand held unit, to be downloaded via a GSM mobile phone link for analysis at DSTO-Melbourne, a plot of this data is shown in Figure 6.

Currently 55 flights have been undertaken and during this time the self-powered unit has registered 76 valid readings. The patch health indicator readings from PVDF sensor A (starboard) and B (port), monitored by the self-powered device, were initially set to an arbitrary low health value (sensor B was initialised to a substantially lower health value). Figure 6a shows that both patch health readings are showing similar trends. In fact, the starboard sensor has converged to a unity ratio (indicating perfect patch health) and the port sensor should converge to a unity ratio if patch bonding remains intact. After 55 flights, readings from sensor A have reached the good health value and readings for sensor B are approaching the good health value. As already mentioned, 76 valid readings have been obtained after 55 flights, as shown in Figure 6b. The steady increase in valid readings is another indication that the device is working correctly.



(a) (b) (c)

Figure 5: Patch health data download from smart patch (a) using handheld interrogator, (b) connecting handheld interrogator to docking station and (c) download data to base station via GSM mobile phone link.



(a) (b)

Figure 6: (a) Variation of smart patch normalized sensor ratios (patch health indicator readings) with increasing number of flights (from Mar 06 – Aug 06). (b) Plot shows the number of valid readings for the self-powered system with increasing number of flights

## CONCLUSIONS

The “smart patch” approach which is based on self-monitoring would considerably alleviate the certification concerns for implementing bonded composite repairs to primary aircraft structures. This approach relies on the ability to autonomously detect disbonding in the patch, i.e., the ‘smart patch’ approach is basically a continuous safety-by-inspection approach for the bonded repair. The main aspects of a self-powered in-situ patch health monitoring system, to be applied to a composite bonded reinforcement on an operational F/A-18 aircraft, were outlined in this paper. The system consists of piezoelectric film PVDF sensors and is designed to operate using the electrical power generated by an array of PVDF and PZT power harvesting piezoelements, which convert structural dynamic strain to electrical energy. The system has been successfully installed on an operational RAAF F/A-18 aircraft. Patch health information downloaded to-date from the smart patch system, after about 6 months of operational flying, has indicated that the device is performing as expected and that the patch has ‘good’ health.

## ACKNOWLEDGEMENTS

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