An Australian Perspective on the Application of Infrared Thermography to the Inspection of Military Aircraft

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Abstract: This paper provides a summary of the Australian experience with infrared thermography as a nondestructive inspection (NDI) tool for through-life support of aircraft within the Australian Defence Force (ADF). It covers the key variants of active thermography including flash, synchronous (or lock-in), and sonic as well as thermoelastic stress analysis and presents a range of applications to military aircraft including the F/A-18, F-111, and the MRH-90. This work, done by the Australian Defence Science and Technology Organisation over a period of a decade, has helped to clarify some of the key challenges confronting the introduction of infrared thermography as a routine method of inspection within the ADF. It is argued that the importance of infrared thermography is set to grow with the emergence of aircraft like the Tiger and MRH-90 which are assembled from light-weight composite materials that are amenable to thermal forms of inspection.

Introduction

The Australian Defence Force (ADF) has recently acquired a fleet of Tiger Armed Reconnaissance Helicopters (ARH) and MRH-90 Multi Role Helicopters. Both aircraft are typical of an emerging trend in modern military helicopter design where the bulk of the structure including the airframe and key dynamic components like rotor blades are made almost entirely from composite materials. Composite materials offer significant advantages over metals for airframe construction including a higher strength to weight ratio, and superior resistance to corrosion and fatigue which for metallic aircraft are the key forms of degradation and the main drivers for through-life maintenance costs. However, compared to metals composite materials have an inferior resistance to impact damage. This raises an issue for military operations where the likelihood of an impact event is much higher than for normal civilian use. While ballistic impact damage in battle is the most obvious and extreme threat, peace-time operation also includes a range of hazards. For example, helicopter rotor wash can cause ground debris to impact various parts of the aircraft. Also, since a primary role of the MRH-90 is troop-lift there is an expectation that equipment normally carried by troops will impact various parts of the airframe, with the risk particularly high on entry to and exit from the aircraft. Other impacts might occur in the course of normal maintenance where bumps, knocks and dropped tools are inevitable. Impact by hail is another potential source of damage and there will be many others.

The ADF has little experience in managing aircraft with a large proportion of thin-skinned composite material in the airframe. The combination of a relatively high vulnerability to damage, and the expected high frequency of potentially damaging events...
suggests that nondestructive inspection (NDI) could play a vital role in the long-term sustainment of these aircraft. Although a number of NDI techniques are known to be effective for thin composite structure, infrared thermography holds particular appeal because it offers a substantial speed advantage over most other techniques. The Australian Defence Science and Technology Organisation (DSTO) is currently in the process of evaluating the potential of infrared flash thermography as a primary form of inspection for various types of in-service damage in the MRH-90 airframe.

The evaluation continues a longstanding research effort within DSTO on the application of thermographic techniques to the characterisation and diagnostic evaluation of aircraft materials and structural components. This effort began at DSTO in the 1980's with fundamental research on the thermoelastic effect [1], which led ultimately to the development of a focal-plane array based thermoelastic stress analysis system in 1992, a significant achievement at the time. While some work continues on thermoelasticity, current efforts are largely focused on NDI applications on military aircraft using flash, sonic and optically excited lock-in thermography. This paper provides a brief summary of the Australian experience in the application of these techniques to structural integrity problems in military aircraft and also covers the application of a low-cost thermoelastic stress analysis facility, developed by DSTO, in support of full-scale structural fatigue tests on airframe components.

**Active Infrared Thermography**

Like most other forms of NDI, flash, lock-in and sonic thermography all involve a process of active stimulation where a structural flaw is revealed by its influence on the transport of energy injected into the structure. The three techniques differ mainly in the form of the excitation applied. It is helpful to outline briefly the key differences between the techniques, since these largely determine their relative advantages and disadvantages in practice. Flash and lock-in thermography are similar techniques and differ only in the temporal form of the illumination applied to the structure under investigation. In flash thermography (FT) the excitation is applied in the form of a short pulse. For many structural components and materials (especially composites) this elicits, in effect, an impulse response and provides in a single inspection the most comprehensive description of the thermal characteristics of a structure - that is, it interrogates the component across the widest possible range of inspection frequencies. In optically excited lock-in thermography (OLT) [2] the illumination is modulated harmonically at a single fixed frequency. Each frequency is associated with a thermal diffusion length which needs to be tailored for each application to ensure an optimal inspection outcome, ideally using a priori knowledge of the flaw depth. In this respect OLT requires more careful calibration than FT, however it offers the potential advantage of better sensitivity since it involves a process of synchronous averaging which can lead to a vastly improved signal-to-noise ratio. The averaging process takes time however so OLT inspections are typically much slower than equivalent FT inspections. Sonic thermography (ST) [3] involves a mechanical excitation, normally applied using an acoustic horn resonating at a frequency of 20 kHz or 40 kHz. It notionally relies on vibrations produced in the structure to induce relative motion across the interface of defects such as cracks, delaminations and kissing bonds. In the presence of a contact stress across an interface the lateral motion produces frictional heating and in turn a thermal signature. For kissing bonds and closed cracks, where closure stresses are an impediment to detection for most other forms of NDI, this mode of interrogation can be highly effective.
Applications Within the ADF

**FT - Entrapped Water in F/A-18 Control Surfaces**

The in-flight disintegration of a rudder on a Canadian CF-18 in 1999, and similar experiences with the United States Navy F-18 fleet prompted concerns within the Royal Australian Air Force (RAAF) that its own F/A-18 aircraft may be vulnerable to rudder failure due to the effects of entrapped moisture within the aluminium honeycomb. This concern led to a survey in 2002 of aircraft within the RAAF F/A-18 fleet using infrared flash thermography [4]. Conventionally, the ADF applies a radiographic procedure to inspect for entrapped moisture in honeycomb components. Although an effective method the procedure requires the component to be removed from the aircraft which is labour intensive and, moreover, renders the aircraft operationally unavailable. There was consequently a strong interest in evaluating a technique like flash thermography that can be quickly and easily applied to structural components on aircraft in situ.

![Figure 1](image.png)

**Figure 1** Schematic (left) showing layout of entrapped water in a honeycomb panel, and a processed thermographic image (right).

The survey was carried out using an FT system developed by DSTO [4]. That system employed four linear xenon flash tubes driven by a 6 kJ capacitor to illuminate the subject and the temperature response was imaged using a 256x256 array Indium Antimonide (InSb) detector with a noise equivalent temperature difference (NETD) of approximately 25 mK. No evidence of entrapped moisture was found in the surveyed rudders, however the presence of moisture could not be ruled out without doing supplementary laboratory work to determine the threshold of detectibility for entrapped moisture in rudder structure using the applied FT procedure. Using the relevant structural repair manual as a guide a representative test sample was manufactured by bonding a 3 mm thick carbon-epoxy laminate to aluminium honeycomb core with a 3/16" (4.76 mm) cell size. Varying amounts of water were injected into clusters of cells arranged as shown in Figure 1. The sample was inspected using FT and the raw data processed using principal component analysis [5]. Indications are visible (Figure 1) for all of the considered cases, including the 5% fill volume in a single cell, suggesting a detection threshold near that level. The rudder survey results were reviewed, and on the basis of this threshold, all of the rudders were cleared of any moisture ingress problem. Attention then turned to an F/A-18 horizontal stabilator that had a poorly formed repair to its top skin. An FT inspection of the bottom skin directly beneath the suspect repair revealed an extensive zone of entrapped moisture (see Figure 2). The result proved that moisture could be detected in a real component, bolstering confidence in the conclusions drawn for the inspected rudders. The case also suggested that relative to the conventional radiographic procedure an FT
inspection for moisture ingress would result in a quicker turnaround for an affected aircraft, improving its operational availability. A comparison of the two results in Figure 2 also suggests an advantage to FT in terms of the probability of detection for this particular application.

![Figure 2](image)

**Figure 2** Comparison of moisture indications in an F/A-18 horizontal stabilator furnished by FT (top) and a standard radiographic procedures (bottom).

It was hoped that the example would provide an argument to introduce an FT capability within the ADF. Unfortunately, the case was not sufficiently strong, largely based on the fact that moisture ingress was not a serious problem for the Australian fleet and therefore could not justify the investment in resources required to introduce an entirely new NDI method into the ADF inventory.

*FT - Applications to the MRH-90 Airframe*

The MRH-90 and Tiger ARH are arguably the ADF aircraft most amenable to thermal methods of NDI. Both aircraft are yet to reach full operational capability within the ADF however work has already commenced on assessing the NDI requirements for both aircraft, on the expectation that the composite airframes will be exposed to a relatively high frequency of in-service impact events, as outlined previously. DSTO undertook a field trial of FT on an MRH-90 aircraft at RAAF Base Townsville in 2009. The primary aim of the trial was to complete a basic feasibility assessment looking at fundamental issues affecting the inspectibility of the airframe such as infrared emissivity, electromagnetic shielding mesh, panel curvature, and access. The evaluation focused on one particular aircraft which had known small structural flaws that had previously been subject to inspection using tape test and ultrasonic testing (UT) techniques. This enabled the performance of FT to be systematically compared to those conventional methods in terms of both performance and cost. The results of the survey are described in detail elsewhere [6]. It suffices here to outline just a few key findings.
Rear Fuselage

The surveyed aircraft is one of several ADF MRH-90's known to contain voids in the external skin of the airframe. Work by the Original Equipment Manufacturer (OEM) has shown that these voids do not affect the structural integrity of the airframe. Figure 3 shows one of the affected areas along a radius in the rear fuselage side panel. The chalked area in the photograph corresponds to a defect indication revealed in a prior manual UT inspection done by an ADF technician. The FT inspection was centred on the marked area and covered a square region of approximately 400 mm x 400 mm. A large format InSb detector was employed for the inspection. It represents a marginal improvement in capability over the system used in the F/A-18 rudder inspection trial (conducted 7 years earlier), with both a larger detector array (640x512) and a slightly lower NETD (17 mK). Inspection of the centre panel yielded ample thermal contrast in the raw data to easily define the void, as seen in Figure 3, without the need for image processing. The elapsed time from placement of the inspection head on the airframe panel to the identification of the defect was approximately 10 seconds.

![Figure 3](image)

Figure 3  Photograph (left) of ADF MRH-90 right hand rear fuselage side panel showing a suspect region, revealed by UT, marked in white chalk. Thermograph (right) confirms the presence of a void.

Floor Panel

The floor panels in the MRH-90 comprise a thin aluminium skin bonded to aluminium honeycomb core, and are currently inspected by the ADF using the tap test (TT) method, a relatively slow and labour-intensive process. A previous TT inspection of the floor of the surveyed aircraft conducted by an ADF technician identified seven indications all clustered near the cockpit, as shown in Figure 4.
An FT inspection applied to the same section of floor confirmed the presence of structural anomalies - see Figure 4. Two thermographs are shown. The first (left) is a raw frame taken four seconds after application of the flash, and records the peak thermal contrast achieved within the observation period. On the right is a processed image obtained from a principal component analysis, which previous work [5] has shown to provide a useful improvement in defect contrast. The indications are broadly consistent with the TT result. However, the processed image is noticeably cleaner and yields a more reliable basis for the identification of flaws. Image processing affords a useful improvement in contrast in this case because the aluminium skin has a high thermal diffusivity which leads, in general, to weaker and less sharply defined thermal contrasts than are produced in composite materials of similar thickness. Significantly, two flaws were detected by FT (arrowed in the right image) that were not picked up in the tap test.

The case highlights two of the key advantages of FT over TT for this type of problem: a much higher speed of inspection and a higher probability of flaw detection. The latter point does not imply any inherent technical advantage to FT but simply reflects the reality that maintaining a high level of concentration in a large TT survey is difficult. A business case is currently being developed for the introduction of an FT capability into the ADF, based in part on this example. One of the main points is that the technique will enable a reduction in the recurrent labour costs associated with NDI and this should lead to lower overall through-life maintenance support costs for the platform. Although these savings alone are thought sufficient to merit the introduction of the technique, the reduced loss in aircraft operational availability stemming from a more rapid method of inspection is potentially an even stronger argument, but a more difficult one to frame in precise economic terms.

**Electromagnetic Shielding Mesh (EMS)**

Although the thin composite skins used in the MRH-90 airframe are in principle highly amenable to rapid inspection using thermographic techniques, much of the external skin contains a thin metallic (copper or high copper content bronze) mesh beneath a protective surface layer of fibreglass. The purpose of the mesh is two-fold: (i) to provide a conductive path for the electrical energy of a lightning strike, and (ii) to afford protection for helicopter electrical systems from electromagnetic interference. Both functions require a low-electrical resistance in the mesh, which implies high thermal conductivity. A high conductivity increases lateral heat flow within the mesh layer which diminishes the temperature gradients (or thermal contrasts) caused by a defect. Enough evidence is...
available from inspections done on aircraft so far to suggest that EMS mesh does not entirely obscure defects from thermographic inspection, however it is clear that the mesh does noticeably degrade detectibility. Laboratory experiments were carried out on representative test panels at DSTO to determine the effect of EMS mesh in the MRH-90 skin on the detectibility of defects. Three panels were prepared for the exercise. All three had a carbon-epoxy laminate as the base structure - this comprised a 9 ply quasi-isotropic layup of M18/1/43%/G939 prepreg. One of the samples was cured under vacuum in accordance with the manufacturer’s instructions in this basic configuration. The remaining two samples were co-cured with, respectively, a thin layer of a fibreglass reinforced polymer (FRP) prepreg, and an FRP/EMS mesh layer; the latter configuration represents a close approximation to the actual skin laminate structure in the MRH-90 airframe. To provide defect targets for NDI, disc-shaped sections of Teflon film were included at various depths and locations in the layup of each panel. Additionally, a set of blind holes were milled into each of the panels, matching the diameter, layout and depth of the Teflon inserts.

![Figure 5](image_url)

**Figure 5** Raw thermographs corresponding to peak thermal contrast obtained from FT inspections of a reference panel (a), a panel with a FRP layer (b) and a panel with a FG/EMS layer (c). The defects in the two left columns are blind holes of 5, 10 and 20 mm diameter, with those in the left column corresponding to a subsurface depth of approximately 1mm and those in the adjacent column to a depth of 1.5 mm. The third and fourth columns correspond to Teflon inserts in an arrangement matching that of the blind holes. Subfigure (d) traces the temperature distribution across the middle row of defects.

Figure 5 compares the response of the three panels. The thermographs are raw frames taken at a three second delay relative to the flash trigger, and correspond approximately to the maximum thermal contrast recorded for the deepest Teflon inserts. As expected the effect of the EMS mesh is most pronounced for the deepest inserts, rendering these largely undetectible (see subfigure (c)). By comparison the thin FRP layer has a less noticeable impact on thermal contrast. Figure 5d traces the temperature distribution across the (middle) row of 10 mm sized defects and clarifies more precisely the effect of the FRP and EMS mesh layers. Even for the shallowest blind hole, which is easily detected in all three panels, the effect of the EMS mesh is profound, amounting to a 40% reduction in thermal contrast relative to the reference case. It is to be noted that because each panel has a
slightly different thickness the defect depth (measured relative to the inspected surface) is not precisely consistent across the 3 panels. The largest discrepancy in thickness is between the reference and FRP/EMS panels, where the defect depth differs by 100μm. Although this small increase in depth will account for some of the observed loss in thermal contrast the amount is negligible compared to the effect of the EMS mesh. Another notable feature in Figure 5d is the difference in apparent effect of the FRP layer on the thermal contrast produced by the Teflon and blind hole defects, with the former showing a larger relative decline. In considering this it is important to bear in mind that the behaviour of a Teflon insert will depend to some extent on the conditions of the laminate layup and curing process, so some variation in thermal response between nominally identical inserts is to be expected. Blind holes in comparison are machined into a cured laminate and are consequently far more likely to be consistent.

**ST - Detection of Kissing Bonds in Composite Bonded Repairs on the F-111**

Composite bonded repair technology has played an important role in helping the Royal Australian Air Force (RAAF) sustain its fleet of aging F-111's. Its efficacy is perhaps best exemplified by a successful application to a serious cracking problem in the F-111 lower wing skin [7]. The repair in this case was made with a 14 ply Boron-Epoxy patch, approximately 500 mm x 350 mm in size, bonded to the external surface of the wing skin. A principal concern with this type of repair is the possibility of bondline failure precipitated by for example the undetected growth of a disbond. Kissing bonds or tightly closed disbands pose the greatest challenge to NDI since they often produce only a small mismatch in impedance to energy flow relative to the surrounding structure. This applies irrespective of the form of interrogation, whether FT or ultrasonic testing (UT). Sonic thermography offers in principle a more effective basis for the detection of this type of flaw as the faying surfaces of a disbond are a potential source of frictional heating when forced to vibrate through the high frequency mechanical excitation supplied in the ST process. An F-111 wing fragment containing a boron patch and known to have small sub-critical disbands adjacent to the edge of the patch was used to assess the relative performance of ST against FT and UT techniques in detecting this type of flaw. Figure 6 compares the results for one of the detected disbands. Although evidence of a disband is found in all three results, ST is seen to provide by far the clearest resolution of the flaw. The stark contrast with the weak FT result is noteworthy as it provides evidence of the presence of closure across the disband. As the patch is tapered at the edge, a lack of penetration depth was not considered a significant factor in the FT result.

![Figure 6](image_url) Comparison of ST (left), FT (middle) and UT (right) inspection results for a disband in a Boron composite patch repair to an F-111 wing skin.
Although not formally considered an NDI technique Thermoelastic Stress Analysis (TSA) can be applied to detect structural flaws. It is however more conventionally used to predict likely locations of incipient failure by revealing areas of high relative stress. DSTO considers full-field stress measurement an important technical capability that helps underpin its role in providing advice and support to the ADF on aircraft structural integrity matters. The capability can play an especially important role in full-scale structural fatigue tests on military aircraft. As already outlined it provides a reliable basis for the identification of stress concentrations within a structural component, and it also offers an excellent means of experimentally validating finite element models. A compact low-cost TSA system developed by DSTO [8] was recently applied in support of a full-scale fatigue test program on the F/A-18 centre barrel, which is a large structure consisting of three bulkheads that transfer wing loads into the aircraft fuselage. The photograph on the left in Figure 7 shows a centre barrel undergoing a fatigue test at DSTO-Melbourne. Large hydraulic holes on the outboard side of the bulkhead posed some concern for aircraft structural integrity managers prompting a finite element (FE) analysis of the stresses around the hole. This analysis produced a prediction, however its accuracy was unknown and the result needed to be experimentally validated. TSA was applied to the article to provide an independent measurement. When dynamically loaded the centre-barrel undergoes large deformations which make the article virtually impossible to image from a fixed reference without using some form of motion compensation. However, the diminutive size and low cost of the IR camera meant that it could be fixed to the article itself, eliminating the problem. The TSA result shown in Figure 7 is seen to corroborate the FE prediction.

**Figure 7** Clockwise from left is F/A-18 centre-barrel undergoing structural testing at DSTO, TSA IR camera mounted to test article, close-up of hydraulic hole, bulk stress distribution in the region surrounding the hole as measured by TSA and equivalent FE prediction.

**Conclusions**

This paper has given a brief overview of some of the work done by DSTO in applying active infrared thermography for through-life support of military aircraft. Although active thermography is yet to be applied as a standard NDI technique within the ADF, the
argument for its introduction is steadily growing particularly with the recent acquisition of aircraft like the MRH-90 and Tiger ARH, and the increasing use of composite materials in aircraft construction. As a broad field imaging technique it has a large advantage over most other techniques in its relatively high speed of inspection. It consequently has the potential to reduce the labour costs associated with current NDI procedures, and should in some cases foster improvements in aircraft operational availability. While these are important factors in assessing the case for a new inspection capability, the associated training burden is also a vital consideration. This burden is likely to be modest however, as infrared thermography is a visual technique and likely to be more intuitive for technicians than many other forms of NDI.

References