Full Field Stress Measurement for in Situ Structural Health Monitoring of Airframe Components and Repairs

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FULL FIELD STRESS MEASUREMENT FOR IN SITU STRUCTURAL HEALTH MONITORING OF AIRFRAME COMPONENTS AND REPAIRS

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ABSTRACT

The fatigue usage monitoring systems installed on various military aircraft rely primarily on strain gauges for sensory information, and for good reason. Strain gauges have a well established certification framework, a relatively good track record of reliability and they directly target the parameter that drives fatigue. Extending the role of strain gauges to structural health monitoring however is problematic. The reasons are manifold but a key one is that strain gradients at "fatigue hot spots" are often of a length scale shorter than the gauge. Stress imaging techniques have no such restriction but few have realistic prospects for application to in situ structural health monitoring. Recent developments in miniature low-cost microbolometer technology could make thermoelastic stress analysis an exception. The present paper examines the potential of this class of infrared detector to furnish a basis for in situ structural health monitoring. It first covers some preliminaries starting with a brief comparison of thermoelastic stress analysis to other full-field strain measurement techniques, followed by a discussion of several aircraft related applications illustrating the key properties of the methodology. Finally, it describes a case study in structural health monitoring involving the centre barrel assembly of an F/A-18 A/B fighter aircraft.

KEYWORDS : *thermoelastic stress analysis, structural health monitoring, infrared thermography.*

1. INTRODUCTION

Aircraft are safety critical structures that endure relatively high operational loads over service lives that can stretch to many decades. Fatigue is inevitable but the risk of catastrophic failure is kept low through structural design measures and strict adherence to a prescriptive fatigue management regime. These safeguards generally work well, however on the occasions where unforeseen failures occur the root cause is often an inadequate knowledge of the relevant stresses. Strains of course are routinely measured as part of the fatigue usage monitoring process mandated for military aircraft by regulation [1]. However, the number of strain gauges in on-board monitoring systems are normally quite low, with seven an historical average [2]. With so few sensors available, the scope for direct monitoring of critical or hot spot locations is clearly limited, however sparsity is not the primary inhibiting factor. The ones of fundamental concern are listed in [3] and can be summarised as follows: (i) access to hot spot locations is often restricted so the replacement of a faulty gauge can be potentially expensive, (ii) gauges placed in regions of high strain gradient can be difficult to calibrate with respect to a full-scale fatigue test article, (iii) hot-spots may not be known until after a full-scale fatigue test has been completed, and (iv) since a gauge averages strain over its length a measurement of peak strain is implausible.

Loads monitoring is an alternative approach that ignores hot spot areas entirely. It instead focuses on areas of low strain gradient where the principal damage inducing loads are dominant. Strains in critical areas are subsequently inferred using transfer functions. Although a pragmatic approach loads monitoring does have weaknesses. Some are outlined in [3] and include a problem referred to as 'sensor drift' which is when the gauge response to a particular loading condition varies over time, not because of the sensor itself, but due to structural changes in the airframe caused by effects such as fretting of fasteners and the elongation of fastener holes. The effect can have potentially serious consequences, as illustrated by a prior incident involving the F/A-18 fleet where drift in the wing root gauge, caused by wear in a bushing, led to erroneous calibration values that in turn caused a miscalculation of expended fatigue life [3]. Hot spot measurements would obviously circumvent such issues, but the point might seem moot given the reservations outlined in the previous paragraph. Those however apply not to the principle of hot spot monitoring but to specific deficiencies in electrical resistance strain gauge technology. Other sensor options are emerging. Optical fibres for instance have better static and fatigue strength and are immune to electromagnetic interference so should in principle offer superior reliability. Fibre Bragg gratings (FBG) can be made in lengths at least as short as 0.2 mm, and can be written in relatively dense arrays (1 mm spacing), enabling the measurement of relatively high strain gradients. Like all discrete sensors however they still rely on optimal placement which assumes an a priori knowledge of the stress distribution at the hot spot.

Full-field strain measurement offers an obvious solution to the question of placement, but could also have potential as an in situ monitoring approach in its own right. A basic example of such use was described in [4], where the context was airframe full-scale structural fatigue testing and the technique thermoelastic stress analysis (TSA). Thermoelastic stress analysis is of course an established method, however the circumstances of the application were novel in several respects. The measurement was done using a microbolometer device, which is smaller, more rugged, consumes less power and is far less expensive than the photon detectors conventionally used for TSA. This allowed the device to be installed on the airframe itself which had never been done before. Such monitoring, which is now routine at the Australian Defence Science and Technology Organisation, is prescient of more ambitious in-service and possibly even in-flight monitoring applications. The challenges involved are not to be underestimated, however there is cause for optimism, buoyed in part by the steady stream of innovations in microbolometer technology, particularly with respect to their miniaturisation. Imaging cores smaller than a thumb are already commercially available and further miniaturisation (and cost-reduction) is inevitable given the mass-market opportunities in consumer, remote surveillance, and night-vision applications.

The present article reports on recent work involving the use of compact microbolometers to monitor the structural health of aircraft components. It culminates in a demonstration on an F/A-18 fighter bulkhead undergoing full scale structural fatigue testing, however, to ensure the reader is familiar with some of the key properties of TSA, and with the capabilities of microbolometer detectors for such roles, the first few pages deal with preliminaries, including a comparison of TSA with two other full-field measurement techniques and several case-studies in the application of microbolometers to airframe structural integrity assessment.

2. THERMOELASTIC STRESS ANALYSIS

Thermoelastic stress analysis exploits a coupling between volumetric deformation and a reversible change in temperature known as the thermoelastic effect [5]. It is defined by the linear adiabatic relation,

$$\delta T = -\frac{\alpha_T}{\rho C_p} T \, \delta\sigma, \tag{1}$$

where δT is the change in temperature produced by a change in bulk stress $\delta\sigma$, T is the absolute temperature, α_T is the coefficient of thermal expansion, ρ is the mass density, and C_p is the specific heat at constant pressure. The temperature changes produced by the effect are small (< 1 K) and normally difficult to detect without the aid of signal processing. In practice, measurement sensitivities of well under 1 mK are achievable, however this requires a sustained observation under persistent dynamic loading. Figure 1 illustrates the decline in noise in a thermoelastic response measurement as a function of the number of cycles in a sinusoidal load sequence. The specimen in this case was an aluminium plate with a circular hole, and was loaded in uniaxial cyclic tension at an amplitude corresponding to a far-field bulk-stress variation of $\approx 17\,\text{MPa}$. The photon detector starts with an advantage in image quality, as expected, however the gap declines as the correlation proceeds and the advantage is eventually lost. The accompanying scans to the right illustrate the effect of scan duration on image quality.

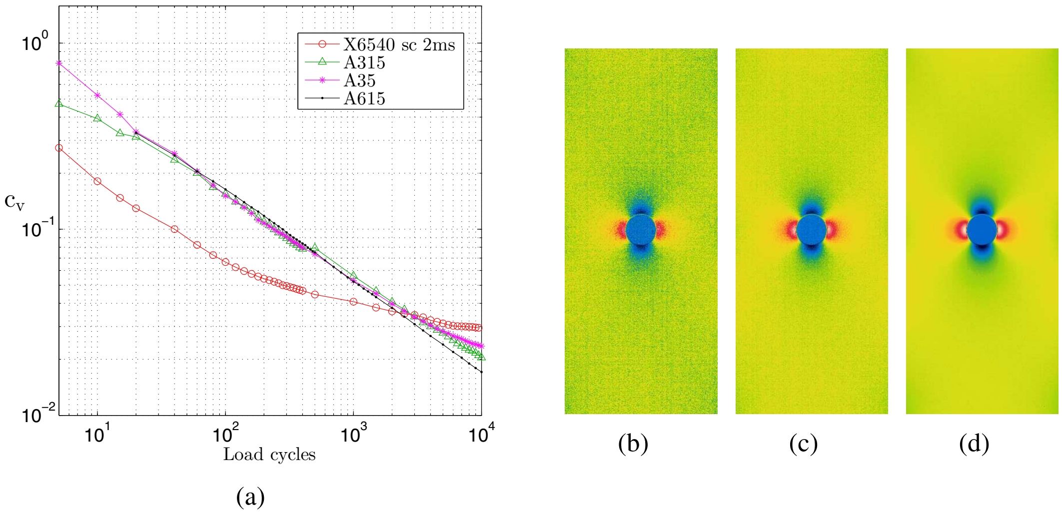
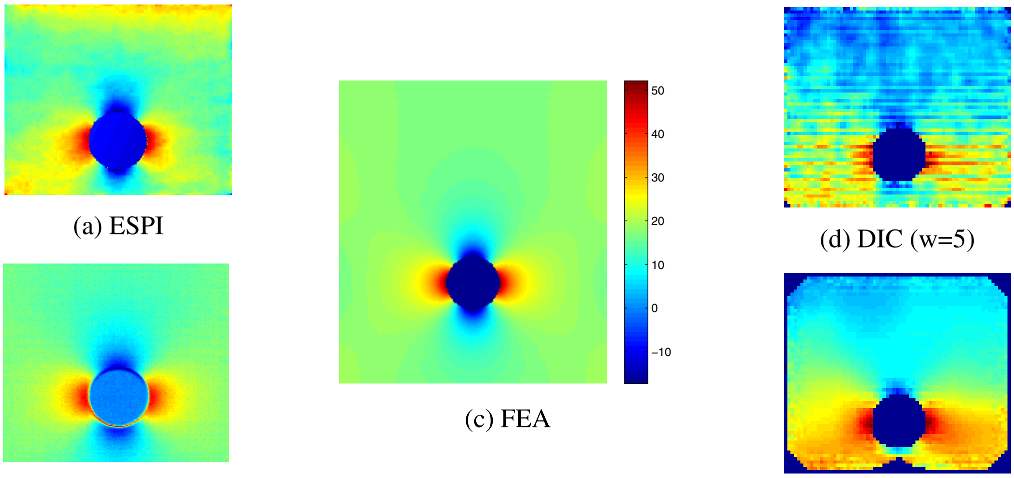


Figure 1: Graph (a) shows signal noise (expressed as the coefficient of variation c_v) as a function of correlation length for a photon detector (FLIR X6540 sc) and 3 microbolometers (FLIR-A35, A315 and A615). Thermoelastic scans (b)-(d) are from an A615 after 100, 1000 and 10000 load cycles respectively.

3. Comparison with Other Full-Field Techniques

Two other techniques commonly applied to full-field stress/strain measurement are digital image correlation [5] and electronic speckle pattern interferometry [5]. It is worthwhile considering some of the key differences between these methods, particularly as most readers are likely to be more familiar with DIC than TSA. One of the primary distinctions is that DIC and ESPI involve measurements of displacements while TSA involves a measurement of bulk stress. Displacements of course are readily translated to components of strain or stress which is an advantage over TSA which yields the sum of the principal stresses; a scalar quantity that in practice is difficult to separate into vector components [6]. Another important difference is that TSA requires a persistent dynamic loading to stem the effects of heat diffusion, while DIC and ESPI can be applied using static loads. There are however serious drawbacks in relying on a measurement of displacement for an estimate of stress. Strains are defined in terms of displacement gradients, so conversions to strain are particularly vulnerable to noise, and are generally difficult to apply to complicated structural geometries. By contrast a thermoelastic response is proportional to stress so the relationship between the measurement and the quantity of interest is more direct.

To compare the noise performance of the three methods, an experimental investigation was performed on a benchmark stress analysis problem. For the three technologies involved, the number of parameters with a potential influence on performance is impractically large to accommodate in a single study. Since the context of the present work is the industrial application of full-field strain measurement the comparison was strictly confined to conventional implementations of each technique. In the



(a) ESPI

(b) TSA

(c) FEA

(d) DIC (w=5)

(e) DIC (w=17)

Figure 2: Various measurements and an FEA prediction of the bulk-stress field in a uniaxially loaded plate containing a hole (scale is in MPa).

case of ESPI and DIC this meant restricting analyses to the software functionality of the commercial systems available to the study; the Aramis 5M and Dantec Q-300 respectively. The TSA system was a custom unit [7] employing a FLIR A315 microbolometer.

The subject under investigation was a straight sided aluminium plate containing a circular hole 20 mm in diameter at its centre. Each technique requires the specimen to have particular surface properties, which are normally achieved with a paint film. TSA requires a surface with a relatively high infrared emissivity. This was achieved by coating the sample with a thin film of fawn-coloured matt paint. For DIC, a black speckle pattern was applied over a matt white base coat, and for ESPI the sample was coated in an optically rough matt white paint. The sample was loaded in uniaxial tension in a servo-hydraulic mechanical test machine. For the thermoelastic response measurement the load waveform was a 5 Hz sinusoid at an amplitude corresponding to a far-field bulk-stress variation of 17 MPa. DIC and ESPI were applied under a static load variation of the same amount.

Figure 2 compares the three measurements to a prediction from finite element analysis (FEA). TSA produces the most consistent result and DIC the least. As others have noted in the literature the performance of DIC can vary considerably with facet size, window length and speckle pattern. Figure 2e is the best result obtained and was achieved at a facet size of 41 pixels and a window length of 17 pixels, settings that correspond to an effective gauge length an order of magnitude larger than the nominal spatial resolution of the TSA and ESPI measurements. Shortening the window length improves spatial resolution but at a significant cost to image quality as witnessed in Figure 2d. The ESPI result in Figure 2a is comparatively better, however it was achieved only after first resolving two experimental issues: (i) a vibration of the detector head excited by the mechanical testing machine, and (ii) a rigid body motion of the specimen. The vibrations of concern were relatively small in amplitude, approximately 3.80 mg rms, but sufficient to render the fringe patterns unstable. Also, initial results were found to contain a spurious gradient in the strain field that was eventually traced to a rigid body rotation of the sample of $\approx 0.014°$ about the longitudinal axis, caused by a very slight twisting of the testing machine hydraulic grips. The artefact disappeared after fitting a mechanical restraint between the coupon and the test machine support columns. TSA was applied for scan durations ranging from $1-2000$ s. Noise in a TSA scan generally declines as a log-linear function of scan duration (see Figure 1a), so the selection of a particular result to compare with ESPI and DIC is somewhat arbitrary. The result in Figure 2b corresponds to a 200 s duration. Figure 1 illustrates the effect on image quality of extending or shortening that duration by one order of magnitude.

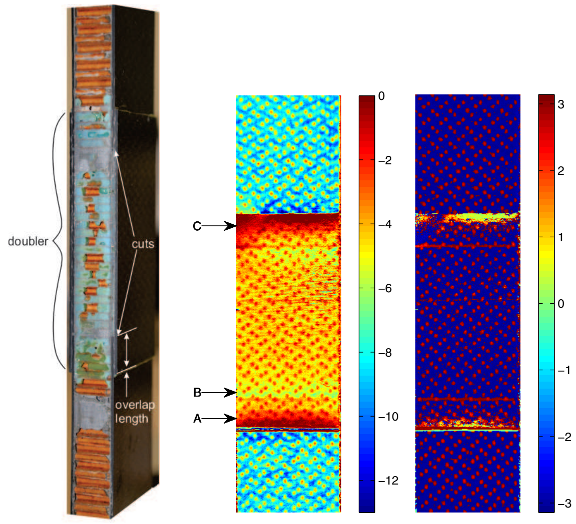
4. Aircraft Component Structural Integrity Testing

Figure 3 shows several aircraft-related examples illustrating some of the key properties of TSA. The results were obtained using FLIR A35 and A615 microbolometers. Figure 3a involves a polymer composite structure representing a prototype battle damage repair for the fuselage structure of Australian Defence Force Tiger and MRH90 helicopters. The key structural element of the repair is an adhesively bonded doubler, which is the main subject of this particular inspection. The thermoelastic response has several points of interest. Firstly, it confirms that the stresses in the doubler are approximately half those in the host, which is consistent with the increase in structural thickness at the doubler. Feature A is an area of low stress in the patch that corresponds to the load transfer length or the distance required for the load to fully develop in the patch which also corresponds to where shear stresses in the adhesive are highest. Feature B is an area of elevated stress corresponding to a butt joint beneath the doubler where the original skin meets the section replaced as part of the repair. This feature is more apparent in the phase map. Feature C is a disbond introduced at the corner of the patch to investigate the damage tolerance of the repair. The mottled pattern reflects the heterogeneous structure of the laminate which is made from a bi-directional satin-weave pre-preg which when consolidated and cured leaves a regular distribution of near-surface resin-rich pockets. The specimen shown in Figure 3b was made from a similar woven pre-preg material for a study into the effects of battle damage. The scan shows the stress distribution in the laminate after impact of a high velocity .50 calibre projectile. The stress field has the familiar clover-leaf shape characteristic of a uniaxially loaded plate containing a hole, and additionally a mottled pattern similar to the one seen in the previous example and other indications of a similarly short length scale around the perforation which relate to delamination, matrix cracking and fibre breakage.

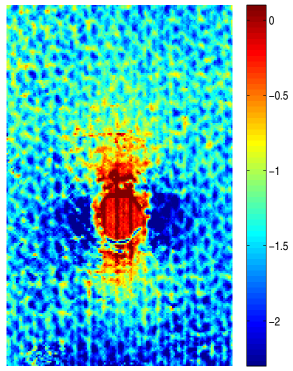
The photograph in Figure 3c shows a rivetted double-cover butt joint where the two cover plates are half the thickness of the host plate and contain two interference fit fasteners. The cover plates were given a standard aircraft primer finish, and to illustrate that no supplementary surface preparation is needed for thermographic inspection, half of the cover plate was overcoated in a matt black heat radiator paint of the type conventionally applied for such inspections. Any emissivity enhancement is marginal at best and the response in fact is weaker overall due to the attenuating effect of the additional coating thickness, a point somewhat better clarified in the phase response which could not be included for lack of space. The other aspect of interest in the result is the breadth of information contained, which spans a range of length scales from the load distribution across the cover plate to short scale features around the rivets. The next example, Figure 3d, gives practical illustration to a point made earlier about the advantage of a direct inference of stress over a calculation based on a displacement measurement. Although straightforward by airframe structural standards, the geometry includes a combination of planar and concave surfaces that make a conversion of displacement to strain difficult. TSA is not immune to geometric effects of course. Perspective distortion and directional emissivity are the main factors however these are relatively benign by comparison. Indeed, both effects are present in Figure 3d. The final example reinforces the same point but in relation to an actual airframe structural component - the centre barrel assembly of an F/A-18. The case brings together a range of complicating factors, including restrictions on available viewpoints, large motions of the assembly under load, a highly complex structural geometry and an equally complex load path. Despite this, the analysis in Figure 3e required no extraordinary measures and took under 10 minutes of effort to complete including system installation and preparation of the surface. The scan is seen to foster the rapid identification of areas likely to be at the highest risk of fatigue, which in the present case are the areas in dark blue corresponding to high tensile stress.

5. In Situ Structural Health Monitoring

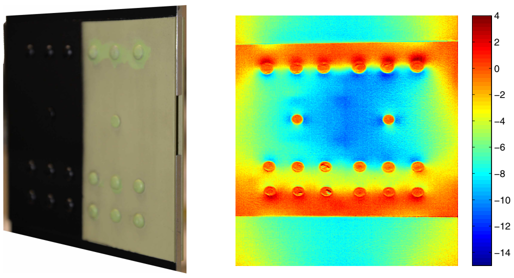
The primary flight and landing loads in the F/A-18 are reacted through a structural assembly called the centre barrel which comprises a set of three bulkheads to which the wings and landing gear are



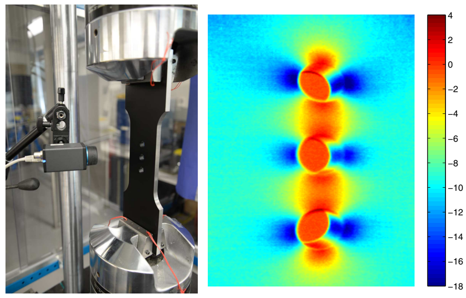
(a) Honeycomb stiffened composite panel with a doubler repair, scanned under uniaxial cyclic loading. Scans are thermoelastic response (left) and phase (right).



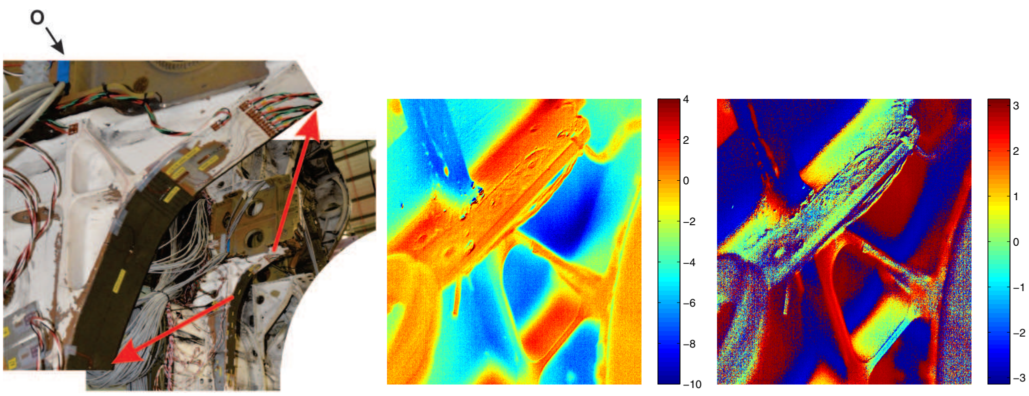
(b) Thermoelastic response of a uniaxially loaded woven carbon-fibre laminate after penetration by a .50 calibre high velocity projectile.



(c) Thermoelastic response of a rivetted connection between Al plates of different thickness. One half of the connection plate has been over-coated in matt black paint.



(d) Stresses inside and around the bore of three 12.5 mm diameter circular holes in a uniaxially loaded plate. Barrel distortion is an artefact of the wide angle (9 mm) lens.



(e) Oblique view (from point O) of the upper kickpoint pockets in the rear bulkhead of an F/A-18 centre-barrel assembly. Scans are thermoelastic response (left) and phase (right).

Figure 3: Aircraft related case studies in TSA applied using microbolometers. Scans show thermoelastic response and phase in the case of (a) and (e). The scales are respectively temperature in arbitrary units and radians.

attached. The assembly is highly stressed and accumulates fatigue at a rate that is life limiting for the aircraft. The Australian Defence Science and Technology Organisation has undertaken an exhaustive full-scale structural fatigue test program involving retired centre barrels to ascertain the scope of replacements required fleet-wide to ensure the planned service-life of the aircraft is reached [8]. Figure 4 shows a centre barrel on its side photographed from the rear. The area painted black below the inlet ducts on both the left and right hand sides is particularly prone to fatigue. Various structural features within this region have been previously examined using thermoelastic stress analyses [8], in some cases to validate finite element models [4]. Such analyses normally involve only several minutes of testing under benign structural loads about an order of magnitude below the peak spectrum load. In the present case the inspection was more ambitious, involving a persistent observation of two specific areas over a duration spanning over 5000 simulated flight hours of testing, which is just short of the design life of the airframe. The monitoring was done using two FLIR-A20V microbolometers attached to the rear bulkhead. The areas inspected are a bonded metallic reinforcement to the left side lower flange and the main landing gear pockets on the same side. Each area was targeted for different reasons. The reinforcement was of interest chiefly to demonstrate the capacity of TSA to continuously monitor the structural efficiency and integrity of a patch in situ, a capability that might aid in certifying bonded repairs for use on primary structure. The other is the pocket region, a common failure site. A preliminary survey of this area revealed two candidate hot-spot locations. In Figure 4 the red hues denote elevated tensile stresses so the areas of interest are obvious; one is near the top right of the scan and the other is adjacent to the left uplock hole toward the bottom of the scan.

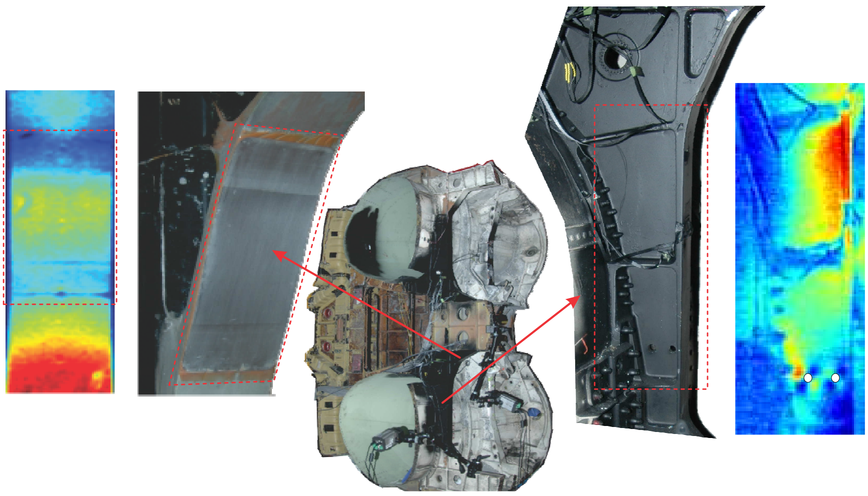


Figure 4: F/A-18 centre barrel on its side with a pair of FLIR A20 microbolometers mounted to the rear bulkhead. The two areas of interest are the main landing gear pocket area (right photo) and an adhesively bonded metallic patch to the kick point flange (left photo). The scans show the thermoelastic response under a $\approx 1\,\text{Hz}$ sinusoidal load at 8% of the peak spectrum load.

The monitoring exercise spanned 5198 airframe hours before the fatigue test was suspended for other activities. No fatigue failure had been recorded to that stage and analysis of the 220 scans taken autonomously during the test revealed no sign of incipient failure, as illustrated in Figure 5 which shows scans at the start, mid and end points of the test. A detailed description of the outcomes will be reported elsewhere. Amongst the main findings are: (i) that such monitoring is feasible for full scale fatigue testing of airframe assemblies, (ii) that the observations were relatively stable throughout the duration of the test, which is despite relatively adverse test conditions involving ambient temperature fluctuations, large structural displacements and vibration of the camera mounts, and (iii) that the mean load-spectrum frequency of 96 mHz was insufficient to resolve the stress concentration at the uplock holes, evident when Figure 5 is compared to Figure 4 which was taken under constant amplitude loading at $\approx 1\,\mathrm{Hz}$. Low frequency under full spectrum loading is an issue likely to hamper the use of TSA in many airframe full-scale fatigue tests, however it can potentially be resolved by adding short blocks of low amplitude loading into the spectrum specifically for TSA. In the present case $1\,\mathrm{Hz}$ is readily achievable and thought to be satisfactory in resolving the structural features of main concern.

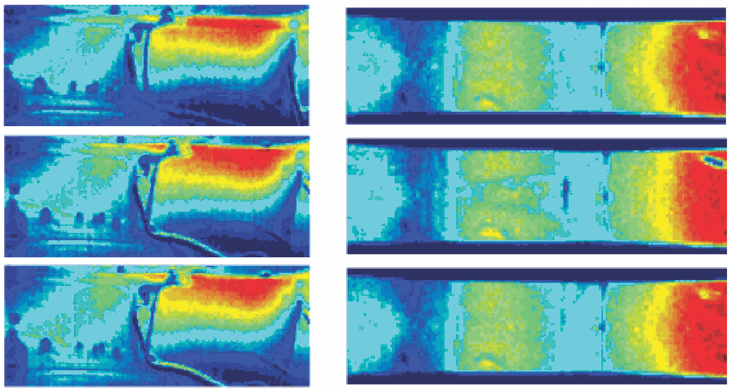


Figure 5: Left shows scans of the main landing gear pockets and right of the bonded metallic repair. Top, middle and bottom rows correspond to 0, 2599 and 5198 airframe hours respectively.

6. Conclusion

It has been shown that compact microbolometer detector technology enables thermoelastic stress analysis, a powerful and robust full-field stress measurement technique, to be applied to continuous structural health monitoring of airframe components under full-scale fatigue testing. The recent emergence of miniature infrared imaging cores suggests that an extension of such an approach to operational structures is a realistic prospect worthy of investigation.

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