Review of aeronautical fatigue and structural integrity investigations in the UK during the period April 2013 - April 2015

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Executive summary

This review is a summary of the aeronautical fatigue and structural integrity investigations carried out in the United Kingdom during the period April 2013 to April 2015. The review has been compiled for presentation at the 34th Conference of the International Committee on Aeronautical Fatigue (ICAF), to be held in Helsinki, Finland in June 2015.

The contributions generously provided by colleagues from within the aerospace industry and universities are gratefully acknowledged. The names of contributors and their affiliation are shown below the title of each item.

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1 Introduction

This review is a summary of the aeronautical fatigue and structural integrity investigations carried out in the United Kingdom during the period April 2013 to April 2015. The review has been compiled for presentation at the 34th Conference of the International Committee on Aeronautical Fatigue (ICAF), to be held in Helsinki, Finland in June 2015.

The contributions generously provided by colleagues from within the aerospace industry and universities are gratefully acknowledged. The names of contributors and their affiliation are shown below the title of each item.

The format of the paper is similar to that of recent UK ICAF reviews; the topics covered include:

- Whole aircraft structural integrity overviews
- Developments in fatigue design and structural lifing tools
- Fatigue of metallic and non-metallic structural features
- Structural ageing aircraft programmes
- Fatigue testing
- Developments in fatigue, usage and structural health monitoring

References are annotated at the end of each contribution and are self-contained within the contribution. Figure and table numbers are also self-contained within the contribution.

2 Whole Aircraft Structural Integrity Overview

2.1 Hawk the 21st Century Trainer

Robert Young, BAE SYSTEMS Brough

(This is an abstract from the full ICAF 2015 paper)

The prototype Hawk aircraft first flew on 21 August 1974, and entered Service with the RAF in 1976. The Hawk is still in production, and still being developed. The Hawk name is the same but by evolution and development the aircraft is significantly different. The latest variants are state of the art trainers, training 21st Century pilots for the platforms of the 21st Century. These include training for F-16s, F-18s, Mirages, Tornados, Typhoons, and is earmarked to continue doing so for F-35s

The Hawk has had 998 aircraft bought or sold to 18 Air Forces the world over, and as such has been altered continuously for changing training needs, and developed to meet ever evolving and changing sets of requirements. The latest variants are eons away from the initial T Mk 1 for the RAF in 1976, with digital cockpits, emulation and simulation, and total aircraft performance within a training system worthy of training for the aircraft in service and development continues.

Figure 1: RAF Hawk Aircraft

In order to provide a platform worthy of the new total aircraft capability the airframe has been developed in parallel, and continues to be so to match the new requirements.

The full ICAF paper discusses how the operating requirements have evolved over time, and how the Fatigue Spectra has been cleared to ensure that the needs of the new operators are catered for. It shows how the airframe has been developed and upgraded to match the new expanded requirements plus the desire for longer lives, up from the initial 6000 hours to the standard 10000 or 12000 hour lives now required. The inevitable increases in mass because of the extra equipment, and increased capabilities in weapons carriage has also been factored in, as have the increasing desire of Air Forces to fly deeper into buffet whilst carrying out Air Combat Training. The total is a vastly different aircraft and airframe in terms of its capabilities throughout this expanded training, and other operational envelope, not only providing a platform with truly leading training ‘cockpit capabilities’ but also capable of pursuing all types of combinations of punishing manoeuvres / flying /operational usage.

The paper contains details of how the vast In Service usage information is harvested to create real fatigue operational data, starting with the older, fewer, more traditional Operational Load Measurement aircraft though to the current expansive all aircraft fitted Fatigue Monitoring System (FMS), part of a comprehensive Health and Usage Monitoring System (HUMS). Every Hawk since 1999 / 2000 has been fitted with the strain gauge and parameter based FMS / HUMs, equating to around 170+ aircraft all producing detailed information of their flying. This FMS / HUMS not only provides the operators with real information from key structural items and parameters but helps them via a Fatigue Index calculation on the key items to manage their fleets pro-actively and identify any particular types of flying that may impact on their aircraft, so as to be able to respond accordingly to this information. The extensive data is also used to enhance existing information with timeslice-by-timeslice real flying based Fatigue Spectra using the parameters and the strain gauge information from the FMS.

The total Structural Integrity of the Hawk is underwritten by advanced fatigue analysis and testing. The analysis has evolved and incorporates leading technology methods, correlated by test information to provide a sound basis for new design developments with confidence. The underwriting is, of course, supplemented by extensive structural tests, and these are discussed, along with the history of Hawk tests and information on the current tests, the Hawk Tailplane and Rear Fuselage Buffet test, at Brough, and the whole aircraft Full Scale Fatigue Test (FSFT) jointly funded with the Royal Australian Air Force (RAAF) and based in Melbourne, Australia.

Test spectra versus fleet spectra are illustrated. These tests provide many Hawk Marks with vital information in supporting safely and economically the Structural Integrity of these many fleets.

The paper also highlights how all of this extensive In Service data and Testing together with the Test Based Analytical Methods are used to support to the full In Service Hawks safely. It also discusses how some of the existing fleets are being assisted in attaining Life Extensions via upgrade modifications, based on current build standards and supported extensively by the above fleet information, test information, analysis, and ongoing testing.

The name may be the same, but the aircraft is significantly improved by virtue of evolving requirements and designs to meet them plus the fact that ‘we know now what we didn’t know then’.

3 Development in fatigue design and structural lifing tools

3.1 Developments in fatigue design tools – HBM nCode

Andrew Halfpenny and Rob Plaskitt, HBM nCode

HBM nCode continues to increase the fatigue capabilities of its software products. nCode DesignLife, which is used for fatigue assessments based on finite element analysis (FEA), and nCode GlyphWorks, which is used for test-based fatigue analysis have the following new capabilities:

- Composites – static and fatigue assessment from FEA stress results. New methods include: strain energy based damage models for short-fibre composites and multiple static failure criteria for long-fibre and woven-composites.

- Vibration fatigue from FEA stress results - New methods include: closed form solutions for sine-on-random and swept sine-on-random vibration tests along with support for multiple uncorrelated broadband random inputs.

- Strain-life fatigue testing –Table 1 shows a sample of aerospace structural materials tested and included in the nCode Premium Materials Database. The Premium Database is based on a very high volume of test coupons to ensure the most reliable design curves are obtained. (Note that these new data are in addition to, and separate from, any customer confidential strain-life tests).

- Signal processing techniques for analytical loads development – "Aircraft Parametric Structural Load Monitoring Using Gaussian Process Regression", presented at the 7th European Workshop on Structural Health Monitoring (using data from 100 flights of a Short Tucano, RAF military trainer).

The more detailed HBM nCode paper "The Fatigue Damage Spectrum: Explained" is included in the ICAF 2015 proceedings. The fatigue damage spectrum (FDS) is a very useful analysis technique to quantitatively assess the potential for a fatigue failure mode in components or systems operating in a mechanical vibration environment.

The mathematical theory to calculate the FDS is summarised in Mechanical Conditions AECTP-240 Edition 1 (2009) Leaflet 2410/1, part of STANAG 4370 "Environmental Testing Procedures". This AECTP is referred to by the UK DEF STAN 00-35 and the USA MIL-STD-810.

The paper will summarise the FDS method and its use in test tailoring to combine multiple vibration environments into a single accelerated tailored test.

Additionally HBM nCode have acquired ReliaSoft, an industry leader in reliability engineering software and services, through its parent organization, Spectris plc. ReliaSoft will be integrated with HBM nCode, an engineering software business within the Spectris Test and Measurement segment.

For further information see:

- http://www.spectris.com/news-media/acquisition-reliasoft-corporation

- http://www.ncode.com/en/about-hbm-ncode/ncode-newsroom/reliasoftacquisition/
- http://www.reliasoft.com/media/012315_reliasoft_acquired_by_spectris_plc.htm

ReliaSoft are a reliability solutions company that offer a comprehensive range of software and services dedicated to meeting the reliability engineering and quality needs of product manufacturers and maintenance organizations worldwide.

Alloy Family	Material Name	Example Use
Precipitation hardened stainless steel	13-8 PH Stainless Steel	Actuator rods, landing gear components.
Heat treatable high strength aluminium alloy (“Dural”)	AA 2014-T651	Now obsolescent but still used for maintaining aging aircraft.
Heat treatable high strength aluminium alloy	AA 2024	Structural. When clad (“Alclad”) used for skins and some engine areas.
Heat treatable high strength aluminium alloy	AA 2124-T851	Better high temp performance than 2024. Primary use machined bulkheads and wing skins in military aircraft (ref. Alcoa.)
High strength aluminium alloy	AA 6061-T6511	Extrusions. Weldable. Used in fuselage interior applications.
Heat treatable high strength aluminium alloy	AA 7050-T7451	Fuselage frames and bulkheads – also sheet for wing skins. Well suited to thicker applications. Better SCC resistance and excellent exfoliation resistance but lower strength than T7651 temper.
Heat treatable high strength aluminium alloy	AA 7050-T7651	Fuselage frames and bulkheads – also sheet for wing skins. Well suited to thicker applications. T7651 highest strength with good exfoliation corrosion resistance and adequate stress corrosion cracking resistance.
High strength steel	AISI 4330V	Forgings and mountings – e.g. engine mountings, actuator components
High strength steel	300M	Forgings, mountings, actuator shafts, landing gear components.
High strength steel	BS Aerospace 5 S99	Forgings and mountings – e.g. engine mountings, actuator components
Bronze	Al-Bronze Def Std D833	Bushes and bearings
Magnesium alloy	MgAl6Mn	Cabin parts, seat frames
High strength titanium alloy	Ti6Al4V	Engine discs, some stator blades

Table 1: A sample of aerospace structural materials strain-life tested within the HBM nCode fatigue test laboratory and included in the nCode Premium Materials Database

3.2 Fatigue Crack Growth and Corrosion Related Damage with BEASY

Sharon Mellings, C M BEASY

3.2.1 Residual Stress

The BEASY software has for many years been used to solve linear elastic crack growth problems, including cases where the parts have surface treatments to reduce fatigue damage, and cases where parts may be subjected to other manufacturing processes, for example welding, which can introduce additional tensile stresses that accelerate crack growth.

In all of these cases complex residual stress fields are present within areas in which cracks initiate or grow. The characterisation of the crack growth within these types of structures is critical to the understanding of how cracks will propagate and how the residual stress field will affect the fatigue life. For example, this type of evaluation may allow alternative surface treatments to be investigated without the requirement for expensive prototyping.

Experience of using BEASY to model this type of problem has been growing and comparisons have been made to test data. In one such example, an airframe lug is loaded using a dynamic varying traction applied to the lug hole, shown as "Load Case 1" in *Figure 1:* below.

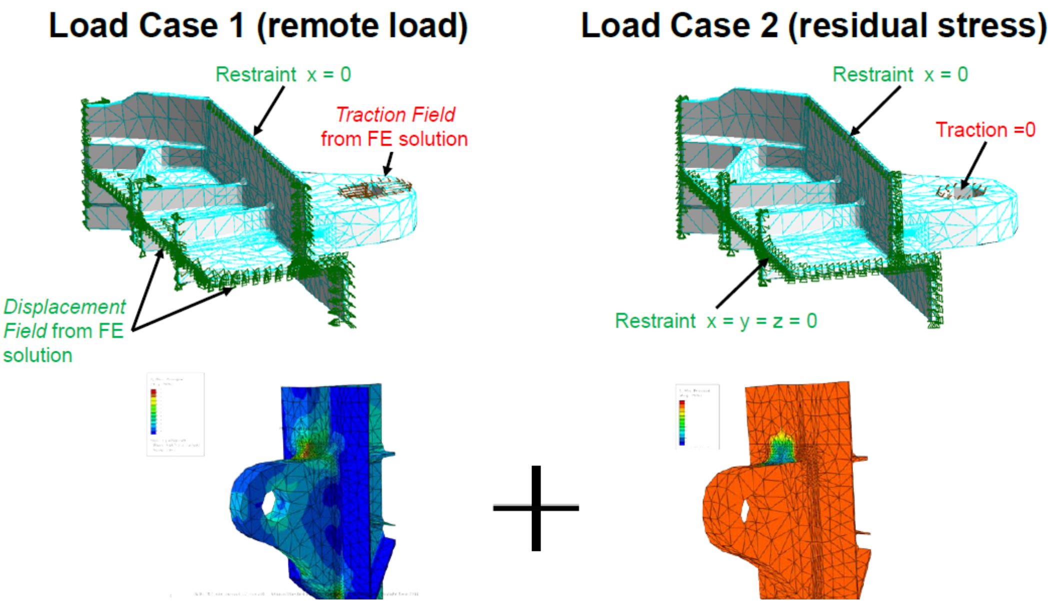


Figure 1: BEASY model showing load cases used to compute stress intensity factors

The part has been subjected to laser shot peening (lsp), with the residual stress field computed using FE analysis (ABAQUS in this case), and shown in *Figure 1:* as "Load Case 2". As shown in *Figure 2*, the residual stresses are applied to the crack faces during the BEASY simulation to find the SIFs. In regions of tensile stress this load opens the crack faces, resulting in positive SIF values whilst in compressive regions, negative SIF values are computed as the crack faces are allowed to interfere.

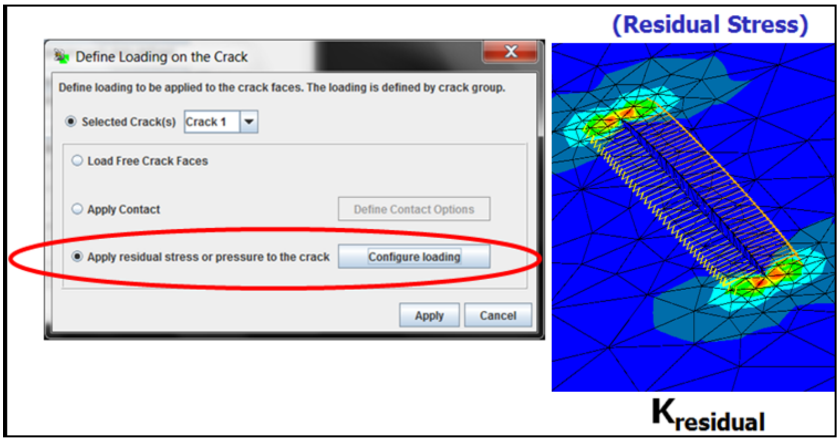


Figure 2: Applying residual stresses to the crack faces

The computed SIF values from the first load case are first scaled to represent the load cycling from the maximum applied load ($K_{\max}$) to the minimum load ($K_{\min}$), then combined with the SIF from the residual stress to give the required values for the fatigue crack growth:

$$\Delta K = K_{\max} - K_{\min} = (K_{\max} + K_{res}) - (K_{\min} + K_{res})$$

$$R = \frac{K_{\min} + K_{res}}{K_{\max} + K_{res}}$$

Two crack growth simulations of the part shown in *Figure 1:* were performed, firstly without residual stress loading (shown with the red lines in *Figure*) and secondly with residual stresses from the laser shot peening (lsp) (shown with the blue growth lines in *Figure*). The residual stress retards crack growth at the surface of the part.

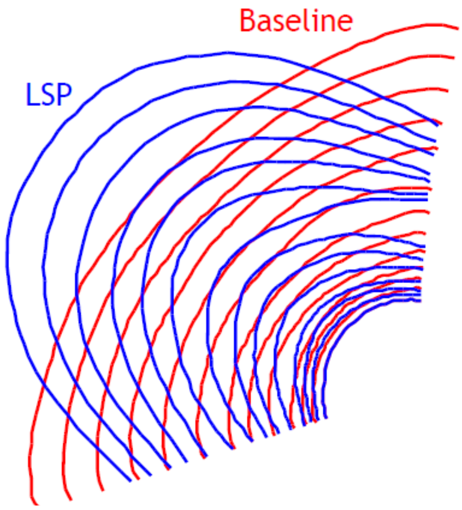


Figure 3: BEASY predicted crack front evolution with and without lsp in a structural frame specimen (courtesy Hill Engineering LLC)

Figure shows a comparison of these fatigue growth profiles with a test specimen confirming that the simulation incorporating the residual stresses from laser shot peening is a more accurate representation of the real crack occurring in the structure.

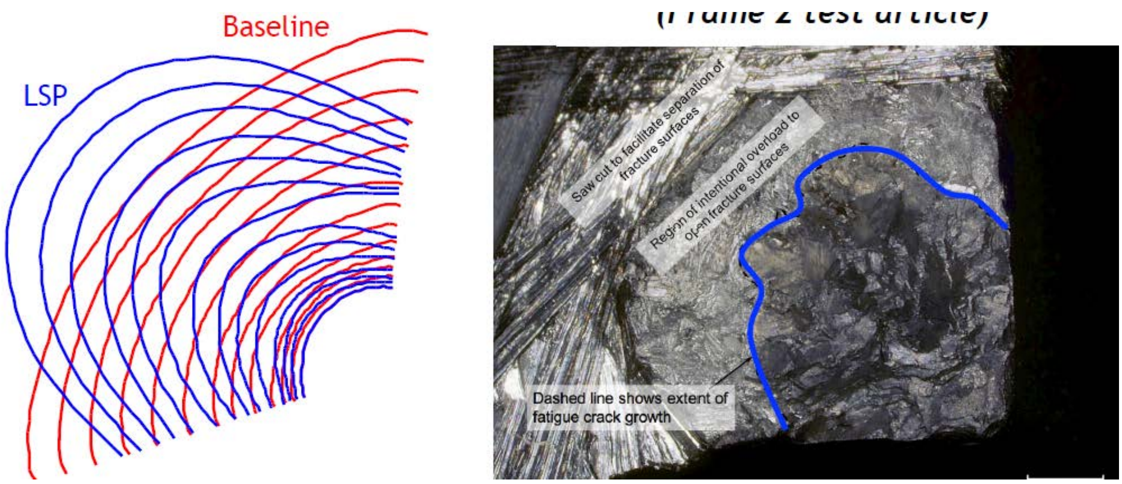


Figure 4: Comparison of BEASY predicted crack front evolution with failed structural frame specimen (courtesy Hill Engineering LLC)

This type of simulation has been repeated with a test specimen including a cold worked hole. *Figure* shows two crack growth profiles: the red (baseline) profile is from a dynamic load with a load ratio of 0.5 whereas the green profile additional incorporates the residual stress from the cold working.

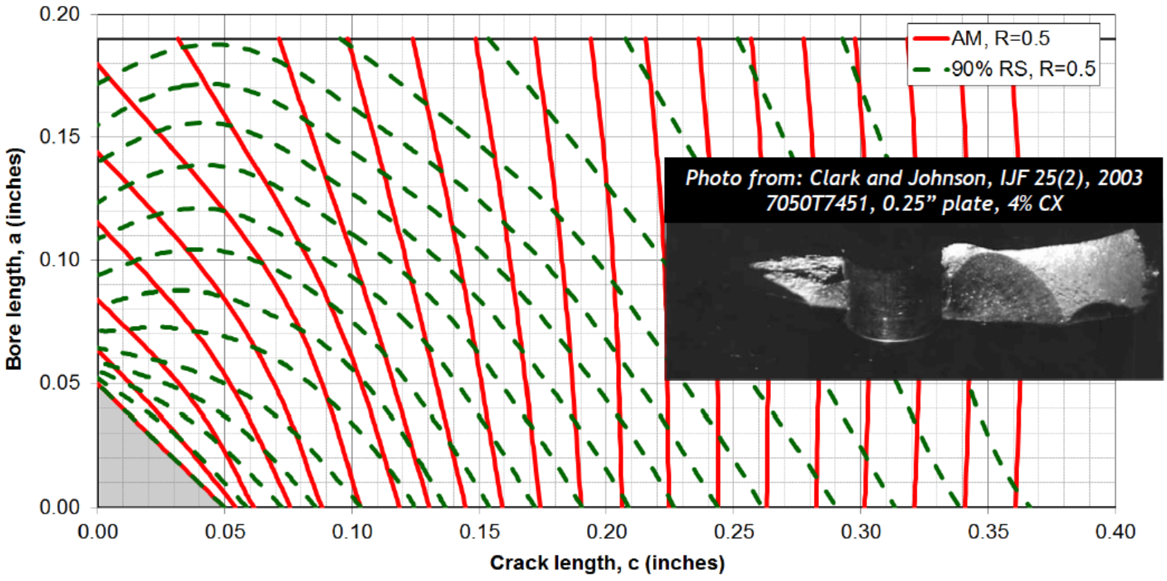


Figure 5: Predicted crack shape evolution for corner crack in a cold worked hole test specimen (red line - baseline, dotted green line - residual stress).

As can be seen from the comparison with the part photograph, the residual stress simulation again agrees well with the way the test specimen failed. This agreement can again be seen in the plots of fatigue life in *Figure 6*. In this figure, results of the BEASY simulation performed without residual stress are shown by the green dotted line, and results obtained with the residual stress are shown by the solid green line. The solid green line compares well with the C190-1NC and C190-5NC test results.

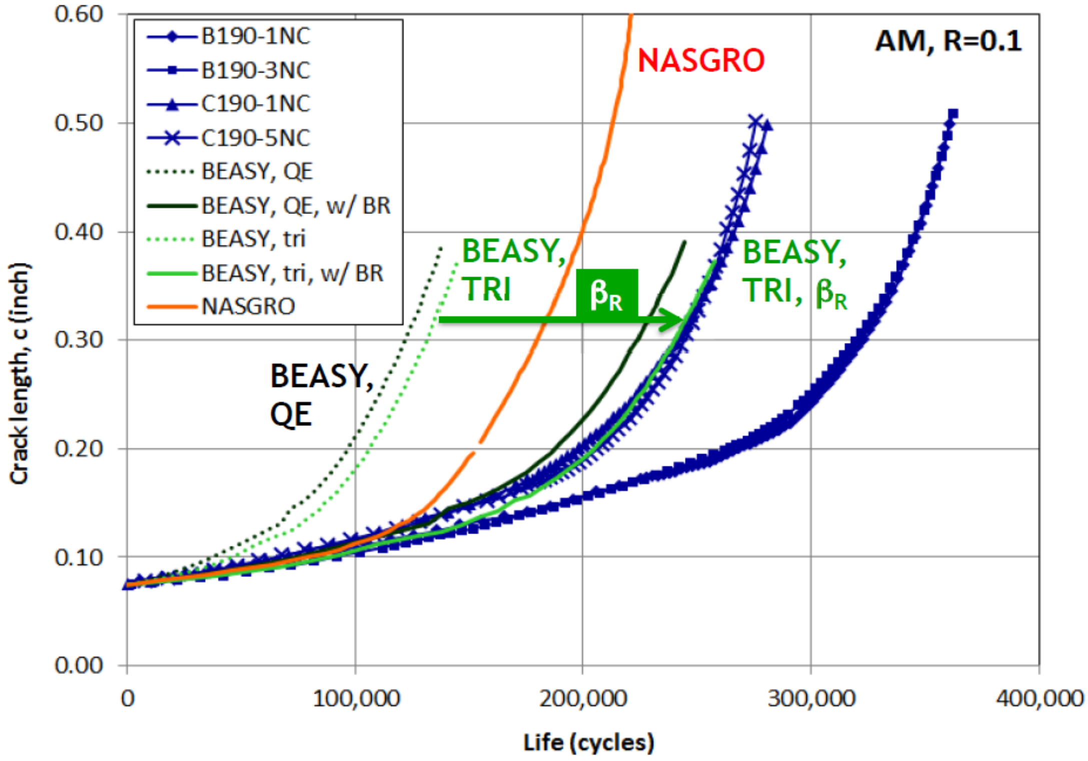


Figure 6: Comparison of experimental and predicted crack growth history for cold worked hole test specimen (courtesy Hill Engineering LLC).

3.2.2 BEASY Corrosion manager

The BEASY Corrosion Manager software (Figures 7-9) solves the galvanic corrosion problem of a complex three-dimensional assembly of different materials exposed to a thin film electrolyte using polarization curves experimentally determined under relevant conditions. The model requires structural geometry and polarization data as inputs and uses a thin film electrolyte solution to determine galvanic behaviour. The BEASY Corrosion Manager software accepts typical CAD file formats to generate a model. The model is divided into surface groups based on material type, and discretized using automatic meshing routines. The computer model presently produces instantaneous (Time = 0) potential and current distribution across the active surfaces of a galvanic couple. The simulated current densities can be converted to corrosion rates and mass loss estimates. Research is ongoing to include time based simulation so that service life analysis can be performed adding a forecasting capability that could be integrated with current structural integrity analysis methodology.

Corrosion modelling will enable aircraft engineers to quickly assess the corrosion risk of a structure and determine the effectiveness of surface protection systems. The geometry of the connections, the characteristics and extent of the electrolyte, and the type of mitigation methods employed affect the extent and rate of corrosion. Corrosion modelling software tools will enable engineers to replace the “find it and fix it” approach with a more fundamental approach based on the accurate simulation of the corrosion process.

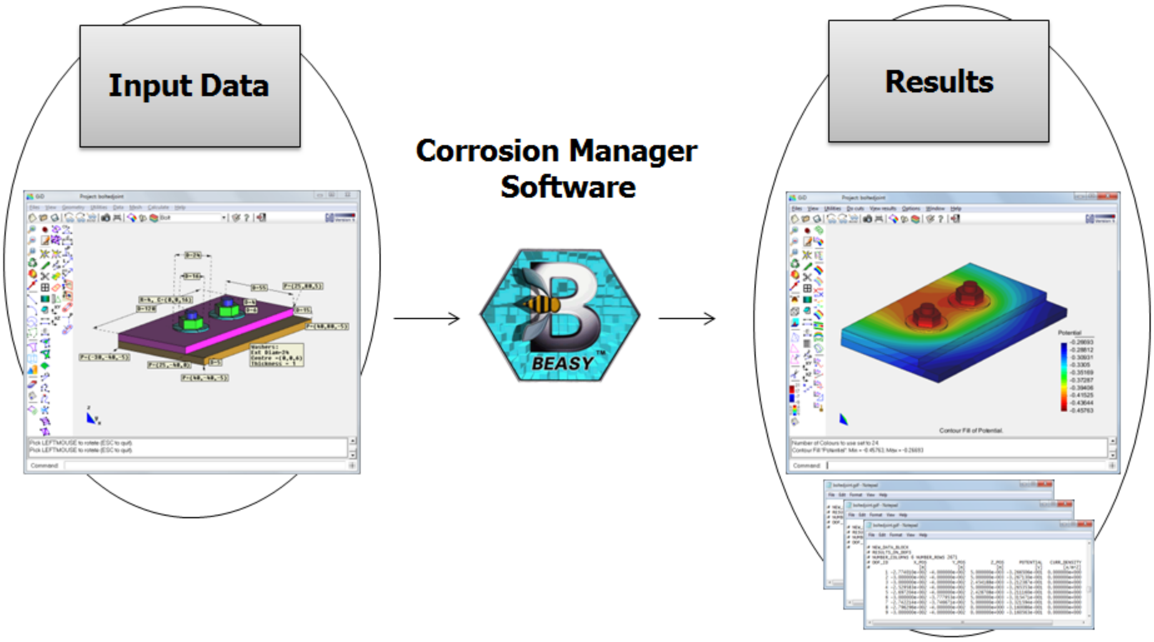


Figure 7: Thin Film Galvanic Modelling System (BEASY Corrosion Manager).

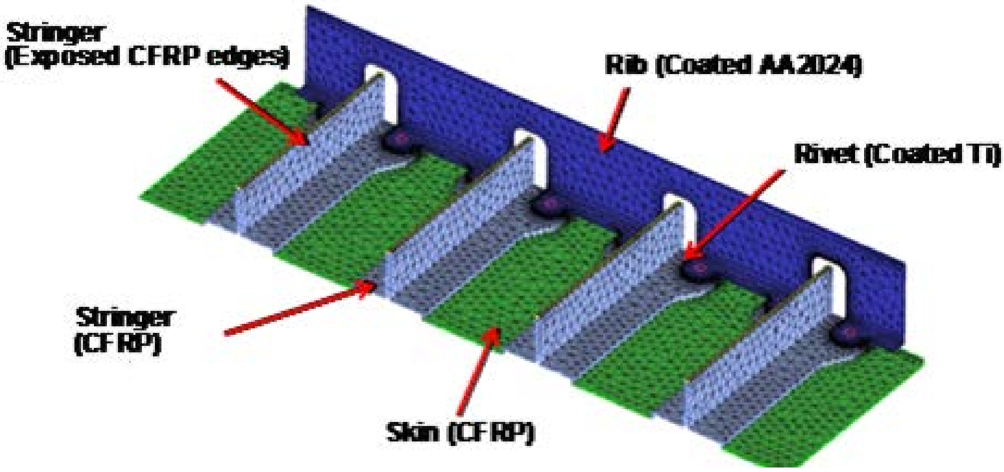


Figure 8: BEASY model with a variety of materials exposed to the thin film of electrolyte

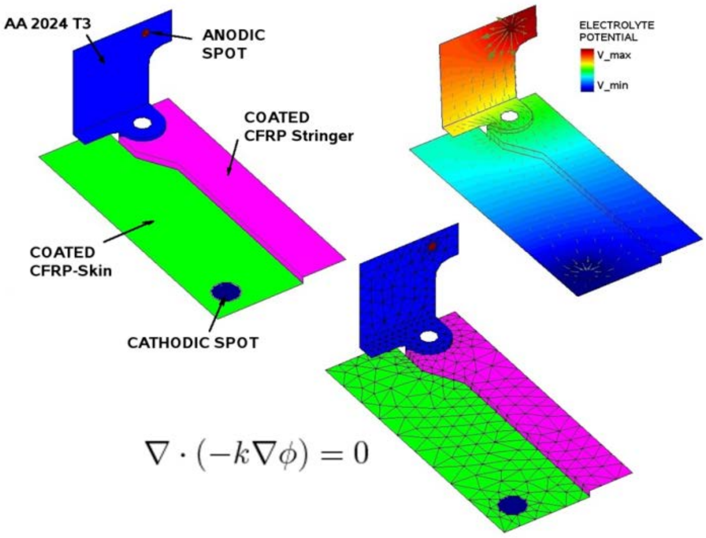


Figure 9: Computed potential results due to the electrolyte

3.2.3 Simulation of corrosion damage with fatigue crack growth

A detailed paper discussing the simulation of corrosion damage with fatigue crack growth, presented by Dr Sharon Mellings, is provided in the ICAF2015 proceedings.

Computation of corrosion related electrical fields can be used to identify areas in the airframe structure that are most susceptible to corrosion damage and which, after possible fatigue crack initiation, may lead to structural failure. Corrosion simulation can be used to take account of the properties of the electrolyte as well as the structural materials, to determine the rate of material loss from the structure. Having removed material from the surface (corresponding to corrosion occurring over a given exposure time) the stress concentrations can be evaluated and, if required, cracks can be initiated in each potential problem area, to identify vulnerability to fatigue failure.

Figure 10 shows a view of the part to be analysed which combines an aluminium stretch part with CFRP clamp parts, resulting in potential contours when covered by an electrolyte.

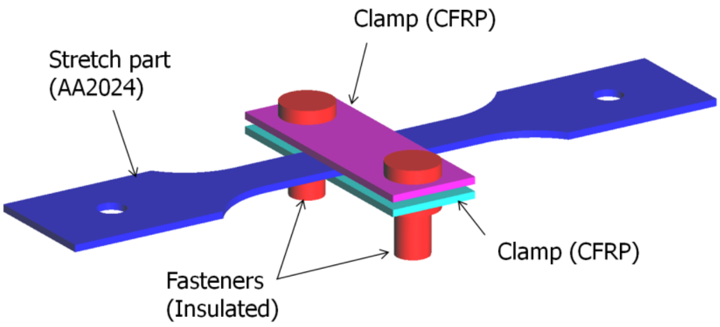


Figure 10: Test specimen used for corrosion modelling.

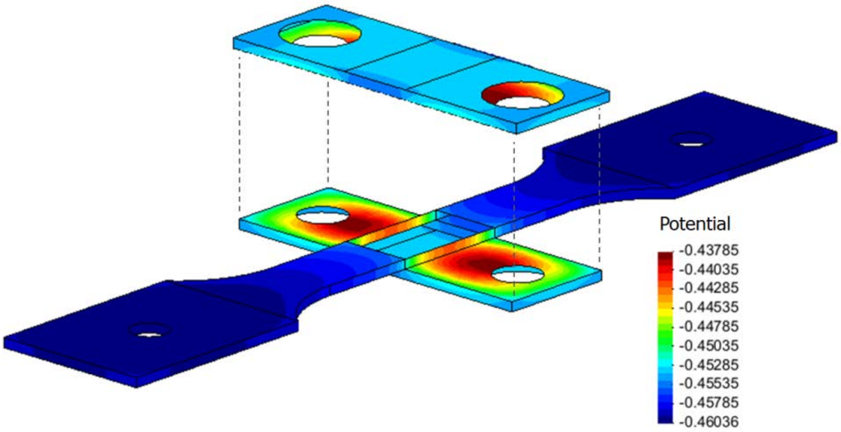


Figure 11: Contours of polarisation potential (u) in Volts on anodic and cathodic surfaces.

This potential distribution results in damage to the structural members, including the stretch part which could then be more susceptible to fatigue damage. After modification of the structural part, introducing stress concentrations, cracks can initiate and grow. Figure 12 shows a fatigue growth simulation of a single edge crack and Figure 13 show a fatigue crack growth of two initial cracks (edge and corner cracks).

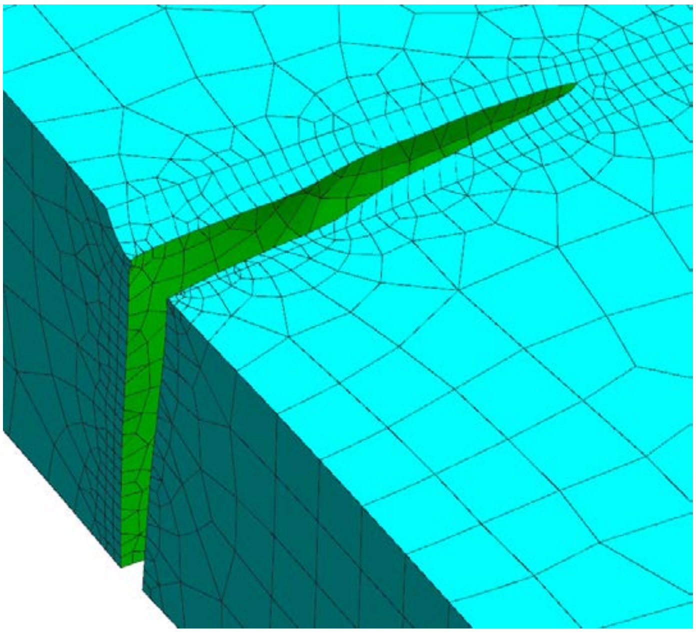


Figure 12: Crack growth simulation of an edge crack (transitioned to a through crack)

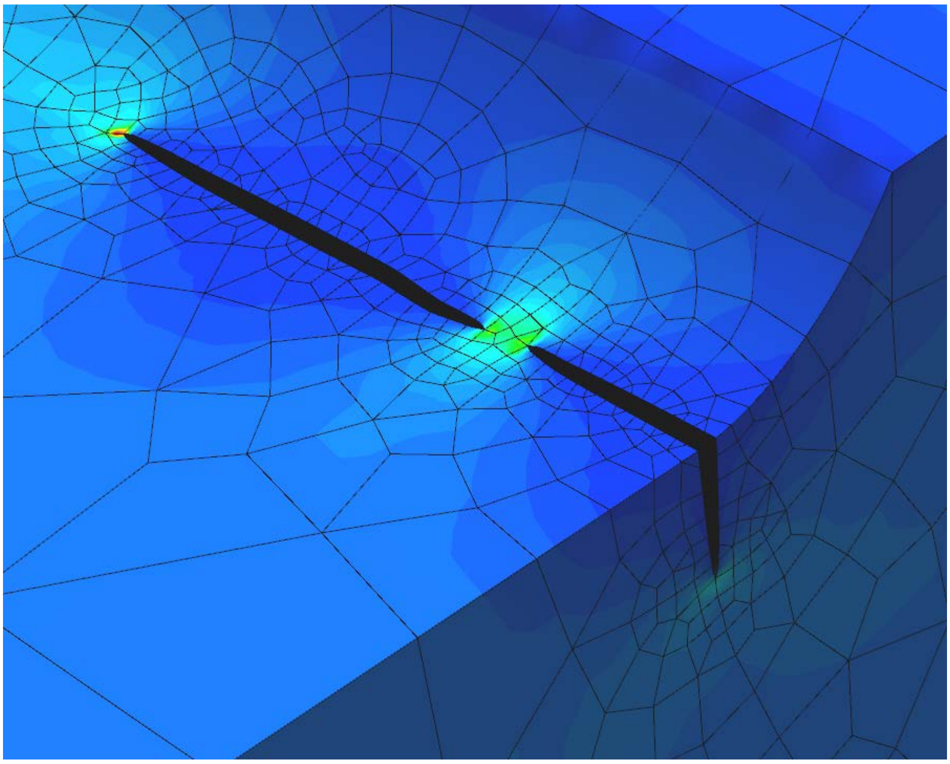


Figure 13: Crack growth simulation of two initial cracks

4 Fatigue of metallic and non-metallic structural features

4.1 Stress Concentration Factors at Reinforced Holes in Flat Plates in Uniaxial Tension

Richard Skelton, Jesmond Engineering

It is well known that the gross stress concentration factor (Kt) around holes in flat plates can be reduced through the addition of a reinforcement typically consisting of an integrally-machined circular boss. The determination of weight-optimised reinforcement dimensions has practical applications for the aerospace industry.
A fine-mesh 3d Finite Element study was commissioned to investigate stress concentrations in a uniaxially-loaded plate with a range of different boss geometries. The dimensions relating to the boss (D,T,r_f) were varied whilst the overall plate dimensions(d,t,W,L) were kept fixed.

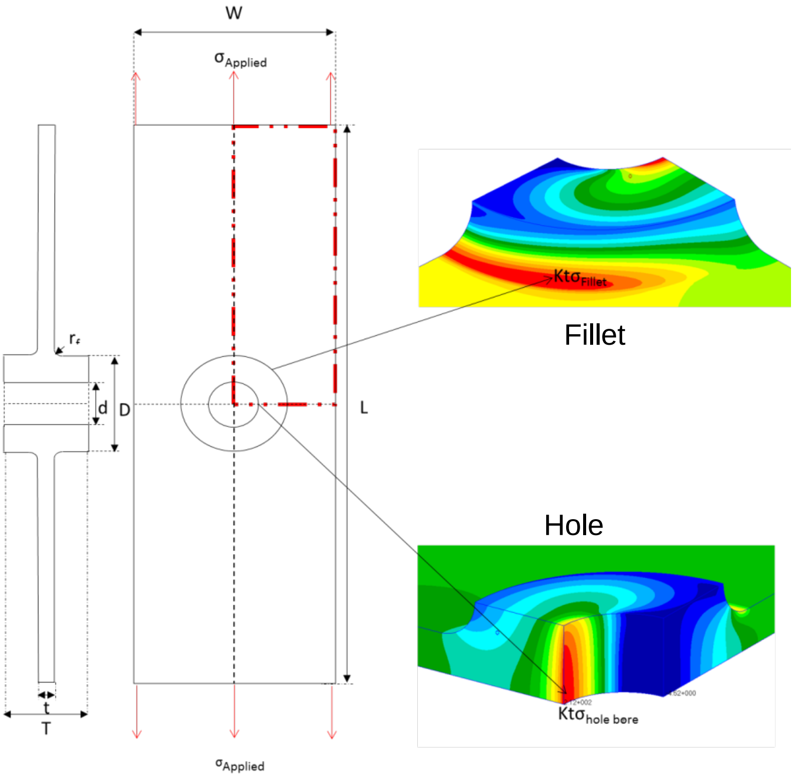


Figure 1: Example specimen geometry (left), typical fringe plots at fillet and hole bore (right)

Two stress concentration features of interest were found, namely the hole bore and the fillet (see Figure 1). Note that the specimen contains three symmetry planes, allowing modelling using one eighth of the overall geometry.

The maximum principal stress was used to derive the gross-section stress concentration factors, Kt, at the two features via: $Kt = \frac{\sigma_{max\_principal}}{\sigma_{Applied}}$.

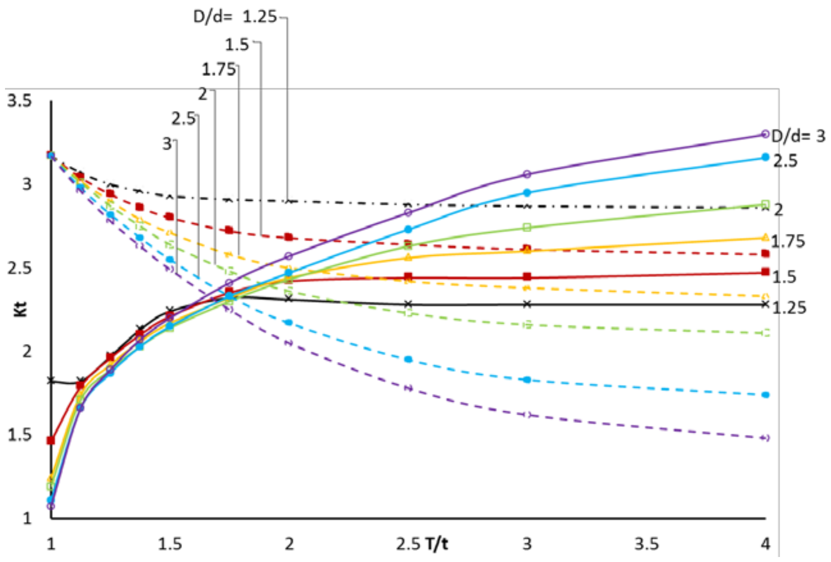


Figure 2: FE analysis results for a range of geometries rf/t=0.1

Figure 2 shows the Kt factors for a range of geometries. One notable conclusion is that in some situations the Kt at the fillet radius, between the reinforcement and plate, exceeds the Kt at the hole bore. This situation can be made less likely through use of a larger fillet radius which reduces the Kt at the fillet; although this is shown to have little effect on the Kt at the hole bore.

For any given boss weight (or volume) it is not immediately obvious how Kt may be minimised via an optimal set of dimensions.

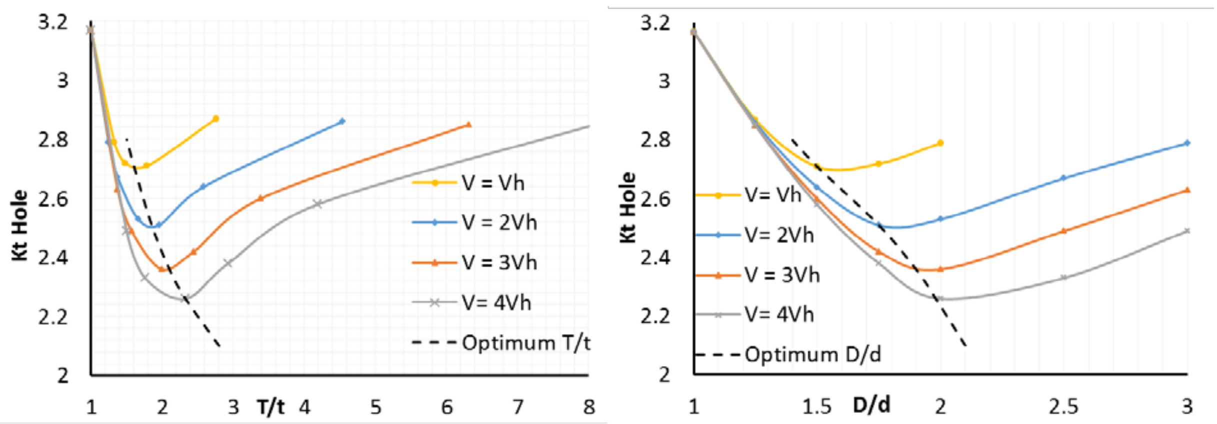


Figure 3: FEM results of constant volume specimens with respect to T/t and D/d (Vh = Unreinforced hole volume)

Figure 3 shows the results of constant volume reinforcement studies in which D & T were varied whilst r_f, was kept constant. From these curves the optimum weight reinforcement can be found for a required Kt. The minimum Kt for each volume is shown in Figure 4.

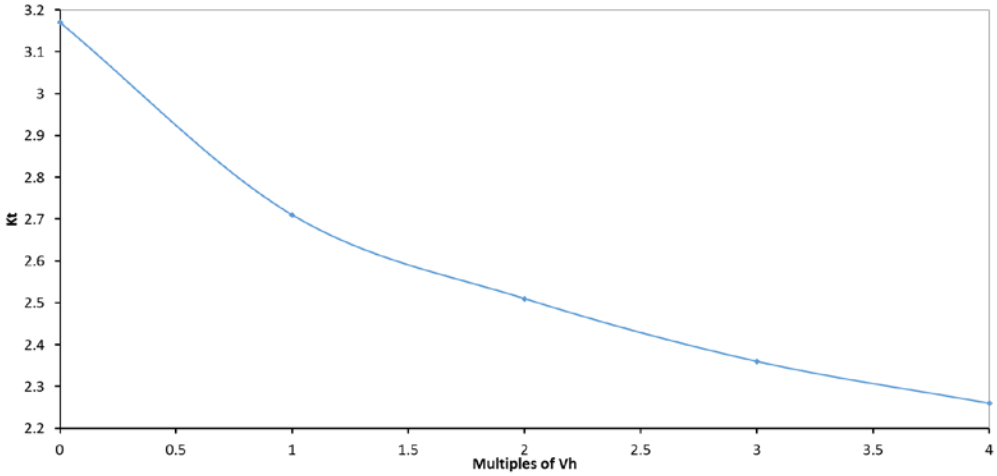


Figure 4: Minimum gross Kt at the hole against volume (W/d=10, Vh = Unreinforced hole volume)

Two common sources of stress concentration data used in industry for analysis of reinforced holes are Peterson's Stress Concentration Factors0 and ESDU Data Item 800270. Comparisons of these data with the results of the current study are ongoing.

References:

[1]. Pilkey, W.D., and Pilkey, D.F., 2008, Petersons stress concentration factors 3rd Edition.

[2]. ESDU, 1995, Elastic stress concentration factors. Single reinforced and unreinforced holes in infinite plates of isotropic materials, ESDU data item 80027.

5 Structural Integrity

5.1 A Framework for Ageing Aircraft Audits

Martin Hepworth, Aviation Support Consultants

The Defence Science and Technology Laboratories (Dstl), with the support of the Military Aviation Authority (MAA) through the Ageing Aircraft Programmes Working Group, have initiated a research and development programme titled “Understanding Ageing Aircraft”. This paper, “A Framework for Ageing Aircraft Audits” contributes to this programme.

The MOD has been carrying out Ageing Aircraft Audits (AAA) for over 15 years initially the audits concerned only the ageing of aircraft structure. However, following the high profile loss of two commercial airliners and perhaps more poignantly the loss of Nimrod XV230 over Afghanistan in 2006, AAA were extended to encompass sub-audits for Systems and Propulsion System. In the intervening period considerable experience has been gathered carrying out AAAs and this paper seeks to expand on selected areas of the current policy laid down in MAA Regulatory Article (RA) 5723. It provides additional guidance and introduces some new suggestions based on best practice from within the MOD and from the wider aviation community. A background is provided to events leading to the current approach to identifying Ageing in Aircraft, both Military and Civilian.

The importance of pre-audit planning is stressed and guidance is provided on the subjects that should be covered in this important phase of the Audit.

The Paper breaks the AAA tasks down into four areas. Experience has shown that there are aspects of the audit that are common to the three sub-audits areas of Structure, Systems and Propulsion System.

RA5723 mandates that the audit include an independent physical examination of representative aircraft, however it does not expressly mandate intrusive forensic sampling. This paper includes details of the types of conditions survey that will satisfy the requirements and provides details of the purpose and management of a condition survey. It also provides an insight into more in depth surveys.

Finally, selection of common forms of material degradation given with a shot description of what an AAA Team should be aware of. The list is not extensive but merely seeks to provide an insight into material ageing.

The Framework for Ageing Aircraft Audits Ageing Aircraft has been endorsed by the MOD/Industry Ageing Aircraft Programme Advisory Group (AAPWG) as Paper 011 and will be published on the Internet presently.

5.2 Corrosion Prevention and Protection

Don Bartlett, QinetiQ

This work programme is being undertaken by the Corrosion Team at QinetiQ Farnborough. The work undertaken during this year covers the following areas:

Corrosion Protection of Landing Gear

Four coating systems have been identified as having potential to improve the corrosion protection of landing gear. The coatings were subject to laboratory testing and initial results were encouraging. This will be reported in June 2015. The QinetiQ team has also engaged with a landing gear supplier and relevant design organisation to ensure exploitation of the work; initial discussions have also been encouraging [1].

Additionally, two protective tapes or polymeric films have been identified from ongoing work on rotor blades protection. Samples of the two candidate tapes have been requested for evaluation purposes and these will be subject to a similar testing protocol as the paint coatings.

Protection of Electrical Bonding Straps

Three candidate protection coating systems were investigated through screening tests to determine application, fluid and abrasion resistance and corrosion protection. On completion of these tests, IP80-109 (from Indestructible Paint) was identified as equivalent in performance to PR-1005, which is likely to be subject to restrictions under REACH. QinetiQ has recommended [2] that IP80-109 should be considered as a replacement for protecting bonding points and straps, with the exception of inside fuel tanks, where sealant is mandated. However, further work is still required to clarify the bonding inspection responsibilities.

References:

[1]. Harris, S. J., Bartlett, D. L., and Patel, J. N., Understanding Ageing Aircraft Progress Report, March 2015, QINETIQ/15/00908, 20 March 2015.

[2]. Bartlett, D. L., Electrical Bonding Straps Corrosion Protection Best Practice, End of Task Report AA1430/2, QINETIQ/15/00510, March 2015.

5.3 Understanding the corrosion threat to military ageing aircraft

Dennis Taylor, Dennis Taylor Associates Ltd

With many military aircraft platforms being required to operate past their original out of service date (OSD) there is an increasing concern that structures and systems may be experiencing an increased airworthiness risk from corrosion. Therefore, a corrosion survey, across all the air platforms looking at arisings and best practice solutions has been undertaken by Dennis Taylor Associates. The findings, with key recommendations for remedial actions and identification of beneficial practice have been reported as Ageing Aircraft Working Group (AAPWG) Paper 012. Paper 012 is currently undergoing peer review and should be published later in 2015.

5.4 Monitoring of surface coatings on aircraft

Jay Patel, QinetiQ Ltd

The surface finish of an aircraft protects the structure from environmental damage; corrosion can lead to other forms of damage such as fatigue. The chromate content of the primer reduces over time and eventually becomes ineffective at preventing corrosion.

The exterior coating system on UK military aircraft is removed and re-finished at intervals which are usually based around the scheduled engineering maintenance requirements for specific aircraft. If the condition of the surface finish is satisfactory, then there may be no need to re-finish the aircraft at these specified periods and hence there may be potential cost savings.

Non-destructive techniques were required to assess the durability of a coating and to determine the chromate content of primer films. These non-destructive techniques were required to provide good correlation with destructive test methods and for 'field use' the equipment would need to be portable.

Research was undertaken to evaluate the durability and performance of a coating system under artificial weathering conditions in the laboratory by adopting non-destructive and destructive test methods. The work evaluated the performance of an aged and un-aged coating system in the laboratory. The colour and gloss determinations, i.e. non-destructive test methods, were correlated with the results from destructive test methods, including flexibility and fluid resistance tests.

On exposure to the accelerated weathering, the gloss level of the top-coat reduces as weathering progresses. The flexibility of the coating was also found to reduce. The colour of the coating remained relatively unchanged throughout the exposure period. Resistance to tri-n-butyl phosphate (synthetic hydraulic fluid) was found to have improved with ageing; resistance to water remained unaffected by the ageing processes. The study indicated that there is a correlation between gloss changes and the flexibility of the coating.

The feasibility of using a X-ray fluorescence (XRF) technique for determining the chromate content of primer paint films was also investigated. The results were checked by Energy Dispersive X-ray (EDX) analysis in a Scanning Electron Microscope (SEM) and the early indications are that XRF has the potential for determining the chromate content of primers.

This work showed that the use of gloss property could be used as one of the non-destructive techniques for determining the state of the exterior coating on the aircraft. Changes in the gloss levels indicate that there could be changes occurring within the paint film that would affect its performance.

Also, the XRF technique could prove to be useful for detecting chromates only within the primer paint films. The presence of a top-coat has a significant influence on the measurements. For this technique to be useful in the field, the top-coat would either need to be removed or absent over the primer film.

Chromate level determination is especially important as there are some areas within the airframe's internal structure that are left in primed condition without any top-coat. These locations, could suffer from corrosion from the localized environment and it is where the presence of an intact chromate containing primer layer is critical. Also, knowing the chromate content of those painted areas which are not maintained as regularly as other areas because of poor accessibility is equally important

Information concerning condition of the coating and the levels of chromate present is useful to the aircraft fleet managers, since it would enable them to decide when to re-prime or re-paint the aluminium structure.

In the latest phase of this task, the aim was to develop the use of hand-held XRF techniques to allow in-service application. The differences identified in initial comparative results in the Cr:Ti ratios (used for life assessment) measured on test panels between the hand-held and laboratory XRF equipment have been larger than expected. Further work is ongoing to understand this variation and once completed, field trials will be undertaken.

<u>Reference:</u>

[1]. QINETIQ/13/00778

5.5 The effect of REACH legislation on surface coatings

Jay Patel, QinetiQ

The European legislation (Regulation (EC) No 1907/2006 dated 18 December 2006) for controlling the manufacture and use of chemicals is known as REACH (Registration, Evaluation, Authorisation and restriction of Chemicals) and became embodied into UK law on 1st June 2007.

REACH affects the availability and use of certain chemicals, some of which are present in the materials used for maintaining aircraft. Aircraft maintenance is vital to ensure its safe operation and is performed at regular intervals to meet this important criterion. One method for preserving and protecting the airframe and systems is by the use of surface coatings.

REACH is being implemented in stages and is due for completion on 1st June 2018. When REACH is fully enforced, the legislation will require the registration of chemical substances that are either manufactured or imported in quantities greater than 1 tonne/year. The deadline for registering chemicals manufactured or imported in quantities greater than:

- 1000 tonnes/year was December 2010
- 100 tonnes/year is by June 2013
- 1 tonne/year is by June 2018

In addition to the registration of chemicals, REACH also addresses 'substances of very high concern' or SVHCs. These SVHCs are classed as hazardous (e.g. carcinogens and bio-accumulatives) and are controlled by regulating their use if more than 1 tonne/year is used or if the substance is present in a paint or other compound with a concentration of more than 0.1% by weight.

A registered substance will be evaluated for its risks to human health or the environment.

Substances identified as SVHC will require authorisation before they can be used or sold. To date, the list of SVHCs (known as Annex XIV (Article 59(10))) comprises 138 chemicals. If an authorisation is not granted, then the use of that SVHC will be prohibited beyond a date (called the sunset date) specified by the Commission.

A substance which poses an unacceptable risk to health or the environment will be restricted in the way it is used. The main consequences from the REACH legislation are:

- Substances may become more expensive to procure due to the cost of registration and associated procedures
- Substances, if classified as hazardous, may not be readily available
- Substances will not be available if not registered or authorised

A systematic assessment that the impact of REACH could have on the supply of products listed is required. It is noteworthy that any potential alternative substances may have to be tested and validated by the appropriate aircraft design organisations before they are adopted for use.

A preliminary check of the current list of 138 SVHCs suggests the following chemicals used for surface finishing activities will need to undergo the authorisation process: Potassium dichromate, Sodium dichromate, Chromium trioxide, Pentazinc chromate octahydroxide, and Strontium chromate.

Over the past year a further 14 additions have been made to the Substances of Very High Concern (SVHC) within REACH and QinetiQ is currently identifying whether these substances have any effect on paints and related products [1]. A REACH database is also being constructed and populated for this purpose.

References:

[1]. Harris, S. J., Bartlett, D. L., and Patel, J. N., Understanding Ageing Aircraft Progress Report, March 2015, QINETIQ/15/00908, 20 March 2015.

5.6 Dehumidification trial for the Puma HC Mk2

Ian Hughes, Musketeer Solutions

The aim of the trial [1] was to demonstrate that dehumidification (DH) be applied to Puma HC Mk2 aircraft, using the Puma Ageing Aircraft Programme Laboratory AAPL(P) as a test facility and that the DH arrangement was capable of significantly reducing the humidity levels within the fuselage. An illustration of the trial installation is at Figure 1.

Figure 1: Puma HC Mk2 dehumidification trials rig

The trial took place during an 8-week period, 8 October to 3 December 2014. During the trial, the DH rig was operating for only part of the time. During the first half of the trial period (15 - 28 October 2014) the rig was off-line more often than not. From 28 October 2014 onwards, the rig performed reliably and was operating relatively continuously.

In general terms, during the period of steady-state DH rig operation (28 October 2014 onwards), the rig maintained the RH level in the fuselage consistently below the 40% target and achieved an average of 20% RH. During periods when the cabin door had to be opened for access, the humidity would rise sharply, but when the aircraft was re-sealed, the DH rig had an immediate beneficial effect. The trial confirmed that it would not matter where within the cabin the humidity was measured, the DH benefit was achieved throughout the aircraft. Confirmation of this would have an impact on Puma Mk2, which has avionic equipment mounted in the tail boom. The trial confirmed that introducing dry air through the sliding window adaptor would have a positive effect throughout the fuselage.

In order to gauge the performance of the DH rig over a shorter timeframe, data recorded during a 9-day window was analysed in more detail (11 – 19 November 2014); this is illustrated at Figure 2, below:

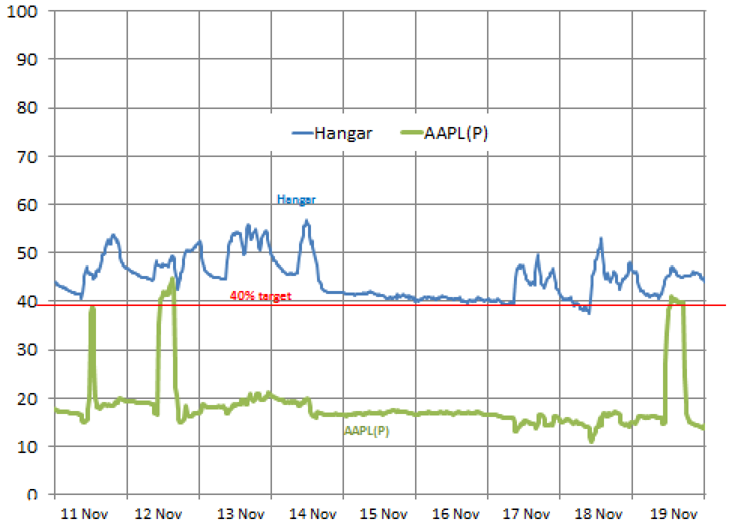


Figure 2: RH in detail: 11–19 November 2014.

The results of the DH trial in the hangar on the AAPL(P) demonstrate that it would be worthwhile applying dehumidified air to the Puma Mk2 aircraft whenever they are parked in the hangar, particularly during the winter months. The trial demonstrated that the aircraft rapidly achieved levels of humidity well below the target, using the equipment available to the Mk1 fleet.

As a result of this trial, DH of the Puma HC Mk2 fleet is currently being introduced into service.

[1]. Hughes, I., Puma Helicopter Dehumidification Study Final Report, Dstl task AA1432/3, Dstl/AAPL(P)/DH/10115, 4 December 2014.

6 Fatigue testing

6.1 Full Scale Wing Test – Test Health Monitoring

Stephen Dosman and Naumaan Hamid, Marshall Aerospace and Defence Group

Introduction

The full paper on this topic can be found in the ICAF 2015 proceedings.

So you've set up a full scale wing test, you have your load spectrum, and you have a rig that can apply the spectrum within your stroke and load limits – are you ready to go? Not quite. Test 'health' is a key concern when carrying out a test programme over several years, and this can cover such things as ensuring that you are applying loads consistently as well as looking after the response of your equipment and the impact the equipment has on test fidelity as it ages.

The RAF/RAAF C-130J Full Scale Wing Fatigue Test currently under way at Marshall Aerospace and Defence Group's Cambridge UK facility is a complex system that must run for many years at a high accuracy level; There is a PID control system that includes airbag loading as well as 40 hydraulic loading actuators, an applied loading spectrum derived directly from on-aircraft measurements rather than constructed from idealised wing states, hundreds of strain gauge measurements to monitor, and a customer requirement to identify and deal with developing damage via trend monitoring as well as via normal maintenance inspections. The test was contracted to meet tight levels of applied loading Accuracy, Repeatability and Dynamic Overshoot, and a means to monitor, assess, and confirm that these requirements continue to be met is a deliverable of the contract.

To meet this challenge a comprehensive Trend Monitoring Process was developed that would confirm metrics achieved against these requirements for every one of over 750,000 Load Lines (LL) applied during every 3,000-Equivalent-Flight-Hour test block. This ongoing process needed to confirm that the applied loads were as intended, identify incipient damage developing based on strain response, and aid in the diagnosis of any misbehaving equipment.

Discussion

The test health monitoring includes here the software monitor, overshoot, component ageing, and damage detection.

Test Monitor and Diagnostics

The test was contracted to meet exacting requirements on actuator absolute accuracy, actuator repeatability from test block to test block, and on actuator dynamic effects; the customer had specified that this monitoring process would need to be actively reviewed and checked and formally reported for every Load Line applied to the test article.

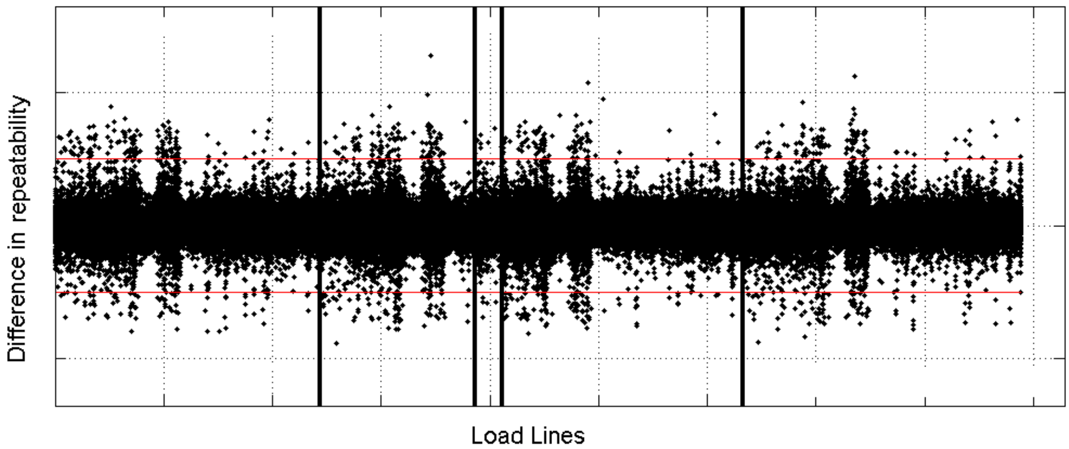
In order to achieve these monitoring goals software and methods were developed that generated automated reports with summary plots on prime metrics going into a regularly issued report; behind these reports soft copy annexes contained thousands of html generated plots covering the detailed response of each actuator and strain gauge that could be queried if a metric summary indicated a possible issue. Also generated is a strain gauge follow-on report where any strain gauges with anomalous behaviour would be assessed and classified in order to identify possible damage development

Overshoot

The ‘a priori’ assumption used when developing the loads for the test is that the test article is in equilibrium for every applied Load Line; however in reality when a Load Line is applied the test article it is motion, and the assumption that Total Force equals Mass times Accelerations equals Zero is therefore not strictly correct. If the control system is well set up and if the test is not run too quickly, then these dynamic effects are negligible; however quantifying the magnitude of various dynamic effects is not easy and there are still misconceptions about what exactly is occurring to the test article during ‘overshoot’. Marshall found that the initially developed methods designed to identify overshoot simply measured repeatability differences from block to block, and as a result needed to come up with a new method of measuring all the dynamic effects that might be affecting test fidelity.

Component ageing and overhaul

Issues such as repeatability (i.e. applying for each load line the exact same load for every test block) errors exceeding acceptable limits would crop up (See Figure 1), and it was found that servo-valve dither to minimise the effect of valve stiction (stick-slip motion) could in some cases dramatically improve performance at the cost of excessive wear on the servo-valve. What this highlighted was that for a long term, multi-actuator test, all components of the loading and control system would need to be monitored, repaired and overhauled on a more regular basis.



A typical load repeatability chart (above), and two charts showing poor repeatability (below left), and then significant improvement after servo valve replacement (below right).

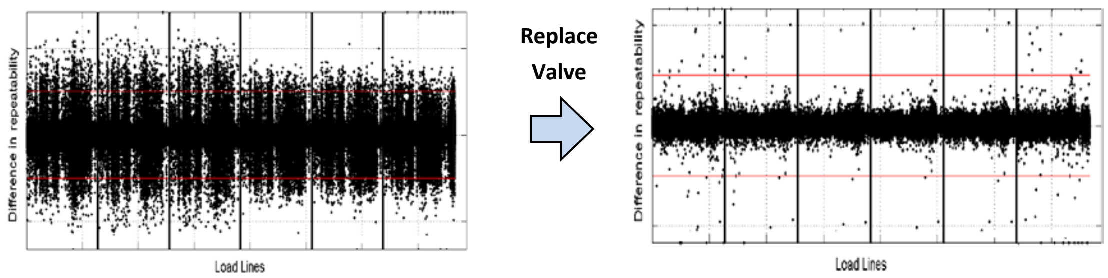


Figure 1: Hydraulic actuator load repeatability plots.

Damage detection through remote monitoring

A strain gauge starting to drift in response (See Figure 2) might signify a failing gauge, but it might also be a sign of a nearby crack in the structure. In the early stages of the test, retrospective assessment of failures showed that detectable changes in strain gauge response were occurring well before failure, and therefore the hundreds of active strain gauges on the test article are monitored and assessed on an ongoing basis. This required a means to separate out the signs of malfunctioning from signs of structural change.

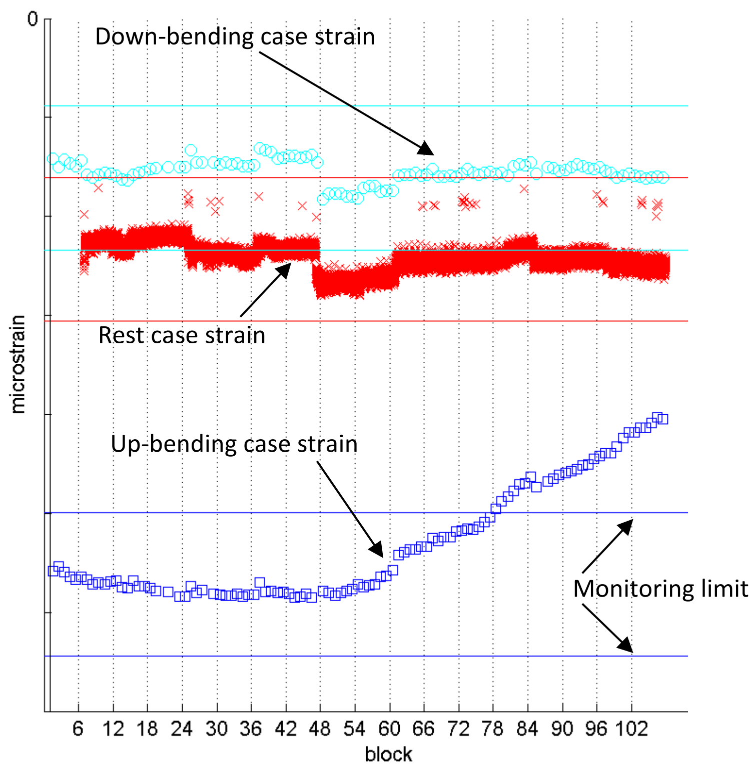


Figure 2: A typical strain response trending plot showing drifting strain in up-bending

The test now being in the latter stages of intended running has a number of natural and introduced flaws in critical locations. In order to ensure that damage can be captured and, if appropriate, repaired prior to failure we use crack detection gauges which are connected into the control system with an auto-shutdown function. This has been proven to halt the test once flaws exceed acceptable limits, and greatly increases the ability to run with extant flaws, which can then provide more crack growth information in the test interpretation phase.

Summary

Marshall have developed a means to monitor performance of the RAF/RAAF C-130J full scale wing fatigue test, which has helped ensure that the test loads are being applied accurately, consistently and has helped to identify incipient damage before it might be detected using other means. Furthermore, component ageing and the impact on test health is also a key concern on multi-year tests, and means to identify and address component degradation is important for overall test health.

7 Developments in integrity and usage monitoring

7.1 Development of Numerical Models to Support Model Assisted Probability of Detection

Alex Ballisat, University of Bristol and David Hallam, Dstl

In 2010 the Military Aircraft Structures Airworthiness Advisory Group (MASAAG) Structural Integrity Strategy [1] highlighted the difficulties in introducing new non-destructive testing (NDT) technologies into the military air domain. In an effort to address this issue, Dstl commissioned Professor Robert Smith at the University of Bristol to identify the issues inhibiting the exploitation of new NDT technologies, which recommended a programme of work be undertaken to draft, demonstrate and introduced a protocol for technique validation of new NDT capabilities using Model Assisted Probability of Detection (MAPOD) [2]. To support this programme, in 2014, a Dstl sponsored 4-year Engineering Doctorate (EngD) was initiated at the University of Bristol to provide the underpinning fundamental modelling research.

It has been proposed that the use of numerical models may allow NDT techniques to be introduced faster by reducing the reliance on the significant weight of empirical evidence from POD trials. The technology that has been identified as most desirable for introduction into the MOD is phased array ultrasound testing (PAUT). The aim of the EngD is therefore to develop a methodology for MAPOD using numerical models to simulate and 'qualify' PAUT inspections and demonstrate its viability on real metallic and composite sample components.

A key criterion to successfully implement MAPOD techniques in the MOD to validate new NDT inspections is the requirement for a short simulation run time that can be undertaken on a standard desktop computer. Progress to date has demonstrated that the use of Finite Element Modelling (FEA) as a modelling tool would be too slow to produce a useful output to aid NDT qualification. Instead Graphical Ray Tracing (GRT) has been identified as a potential method to meet this requirement. Recent efforts have focused on using the ultrasonic ray tracing model to simulate an inspection under variable parameters. This has been achieved by performing a simulation of a simple inspection of a fastener hole with a perpendicular crack. The setup of the inspection, simplified to two dimensions, is shown in Figure 1. To account for possible variations in an inspection, both the crack length and probe position relative to the crack origin were varied. The result of this is a two dimensional parameter space of possible combinations of probe position and crack length. For completeness, this parameter space was fully mapped, running a simulation at every point in the space. The measure of the inspection was chosen to be the maximum amplitude of the response of the signal, with the result of this process shown in Figure 2, where all amplitudes are relative to the initial amplitude. Figure 2 also demonstrates a two dimensional profile which appears to follow a Gaussian – hyperbolic tangent product function, peaking at a certain probe position with increasing response for increasing crack size. This map allows numerical interpolation for intermediary values. From this, based on arbitrarily chosen thresholds, the Probability of Detection (PoD) curves as a function of crack size can be determined which requires an estimation of the probability distribution of each parameter. In this example, this was chosen such that all crack sizes were equally likely, thus following a uniform distribution, whilst the probe position was more likely to be close to the maximal response, thus a fairly narrow Gaussian distribution was used. More detailed investigation is required to accurately determine the appropriate probability distributions for both these parameters and other parameters which will be accounted for in future. The PoD curves are shown in Figure 3. These are promising results for a first mapping as they provide a realistic result.

Given that each model required approximately 140s to run, a key area of research is sampling methods to minimise the number of simulations that have to be performed to achieve an accurate result. Currently the most promising technique is the use of Latin Hypercube Designs (LHDs) in which each value of every parameter is sampled once and only once. This process naturally extrapolates to higher dimensions which will be required for several inspection parameters to be accurately accounted for. At this stage, this is providing promising results for minimising the number of simulations to be performed.

Future EngD work will expand the ray tracing model, optimise it to minimise run time, use Finite Element models to validate the ray tracing model, investigate inspection parameters and their probability distributions, perform further simulations of other inspections, further develop the methodology and optimise sampling methods to minimise the number of simulations required, thus minimising the overall qualification time.

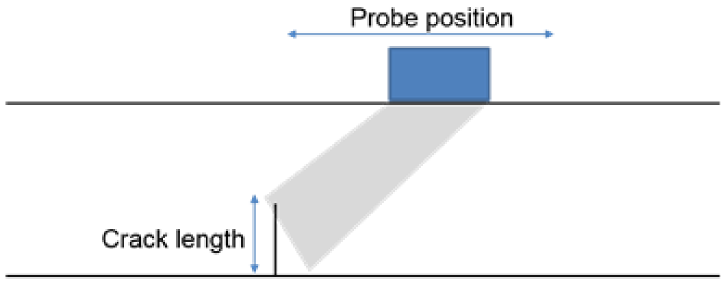


Figure1: Diagram of a simple inspection that has been simulated. The probe is treated as a mono-element ultrasonic probe at an angle which is directed towards the crack. The crack originates in the back wall. The length of the crack and the position of the probe relative to the origin of the crack were varied.

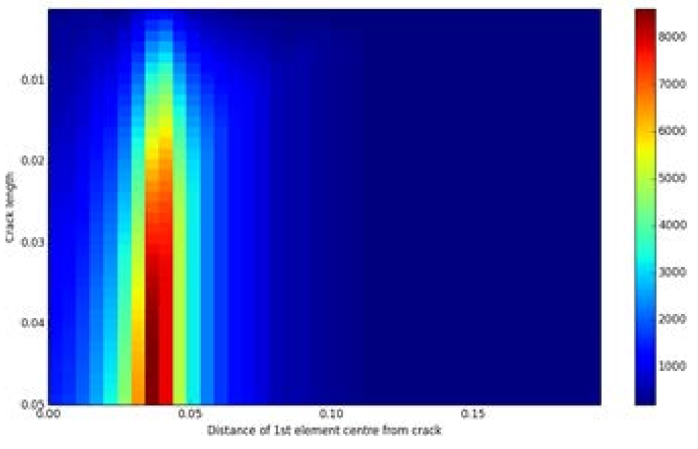


Figure 2: Resulting amplitude map across the parameter space. The values are relative to the initial amplitude. It demonstrates two trends: increasing amplitude with increasing crack size and a peak value at a certain probe position of approximately 0.04. No interpolation between values has been performed leading to the sharp changes in values observed.

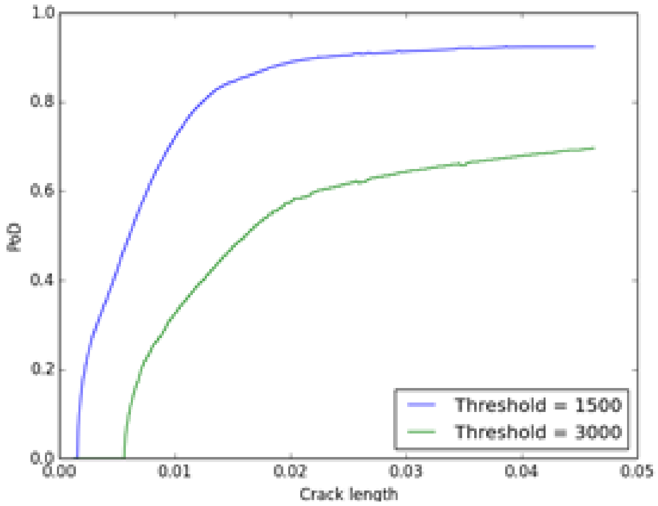


Figure 3: Probability of Detection (PoD) curves based on two arbitrarily chosen thresholds. This demonstrates that a lower threshold gives a higher PoD for a given crack size but does not provide any information about false positive and false negative rates which may be of significance.

References

[1]. Reed, S. C., Airframe Structural Integrity Research and Development Strategy, Military Aircraft Structures Airworthiness Advisory Group (MASAAG), Paper 114, 2010

[2]. Smith, R.A., Birt, E.A., Phang, A.P., Allen, B.P. and Williamson, C. 'Mechanisms for introduction of new non-destructive testing capability' Military Aircraft Structures Airworthiness Advisory Group (MASAAG) Paper 119, 2012.

7.2 Guidance on Integrating Matured SHM Systems into UK Military Aircraft

Hesham Azzam, HAHN Spring Ltd, Jim McFeat, BAE SYSTEMS

The UK Military Aviation Authority became aware of the international efforts of the SAE G-11 SHM technical committee. The Committee's first work was a published Aerospace Recommended Practice paper for civil transport aircraft. Whilst the Committee has planned an international military version of the paper, the progress on the paper is anticipated to be slow because the military regulations and standards required for designing and managing aircraft structures can vary between nations and between the military operators of one nation. Therefore, it was suggested that a paper could take benefit from existing work and include contents covering the UK military perspective to provide a good opportunity for peer reviews. This paper provides an overview of the UK perspective and does not promote or endorse a technology or a system; the paper only provides guidance on best practice processes required to integrate a matured SHM technology/system into UK military aircraft. This paper was produced as Military Aircraft Structures Airworthiness Advisory Group (MASAAG) Paper 123 and has been endorsed following peer review.

7.3 Non-stationary models for predicting strain on aircraft landing gear from flight data measurements

Geoffrey Holmes, Keith Worden and Elizabeth Cross, The University of Sheffield, Valerijan Cokonaj and Paul Southern Messier-Bugatti-Dowty

This paper (full paper can be found in the ICAF2015 proceedings) explores the use of two classes of non-stationary modelling frameworks to model different physical regimes within datasets collected from production aircraft. The aim is to predict strains on specific components of the aircraft main landing gear from in-flight measurements collected at other locations on the aircraft, including the standard measurements taken by the flight data recorder.

Due to physical properties of the system in question, such as full shock absorber closure, the system is highly non-linear. Previously the authors have applied a stationary Gaussian Process model to model these non-linear relationships and achieved a good degree of success in predicting strain at different locations on the gear, especially during the latter stages of landing events. However, whilst a Gaussian Process is known to be a powerful and flexible regression tool for non-linear systems, it was found that the stationary Gaussian Process used lacked the full flexibility to model the different physical regimes which one assumes to be present within these aircraft landing datasets. In particular, if there is an initial bounce event, when the landing gear wheels leave the runway briefly subsequent to initial contact, the predictions of the stationary Gaussian Process models used tend to have a large structural error, when compared to the observed strain outputs, during this early phase.

Treed Gaussian Processes and Bayesian Mixtures of Experts represent two ways in which the input space of a modelled system can be partitioned. In conjunction with this partitioning, appropriate models are estimated and allocated to the distinct regions. This allows the continued use of relatively straightforward, stationary, component models but with the benefit of global non-stationarity of the resulting composite model.

Here, the Treed Gaussian Process and a Bayesian Mixtures of Linear Experts are applied to the aircraft landing data modelling problem and compared, with reference also to the use of a single stationary Gaussian Process. The modelling fidelity, quantification of uncertainty and computational efficiency of the three methods are evaluated. It is found that the two input partitioning methods reduce both the modelling error and associated prediction uncertainty compared to the standard Gaussian Process. Computational efficiency is more variable. The Mixture of Experts, with linear component models has a closed form iterative solution and completes its training over approximately the same timescale as the standard Gaussian Process. The Treed Gaussian Process, however, requires Markov Chain Monte Carlo sampling and requires significantly more computation time. Both partitioning methods find divisions of the input space that are reasonably consistent with one another and which suggests changes in the physics of the system that can be explored further.

It can be concluded that these approaches provide promising ways forward for modelling aspects of the data that have been problematic in the past. As such they will be useful for accessing important factors for structural health of aircraft which are not otherwise easily measured.

7.4 Coating Degradation and Corrosion Sensing

Mark Balmond and Steve Morris, BAE SYSTEMS Advanced Technology Centre

Corrosion in aerospace platforms and vehicles in general is an enormously costly problem, both in terms of part replacement and preventative inspection and maintenance. Accurate, dependable corrosion sensors can allay both these aspects and produce significant running cost benefits.

BAE Systems corrosion sensors use strips of alloy that mimic the corrosion in structural alloys they are monitoring. The sensor measures the electrical resistance of the alloy strips, which is dependant on how much corrosion has taken place, and in turn is a measure of degradation of the protection provided by the paint scheme.

BAE Systems offers different sensor types to monitor three different aspects of degradation and corrosion:

[1]. Corrosion Sensors (CSR)

[2]. Coating degradation (CDR)

[3]. Environmental (including ToW (Time of Wetness) and Commercial-off-the-Shelf (COTS) sensors for variables such as temperature and humidity

<u>Corrosion sensors - resistive (CSR)</u>

In CSR sensor types (Figure 1) the sensor alloy strips line up with deliberately defined gaps in the sensor's paint coating, and as such are intentional defects for the monitoring of corrosion progress in simulated flawed paint schemes. In this sensor type, artificially large defects act as early warnings before any actual corrosion should have taken place on the platform. However the narrowest strip is designed to equate to real platform defects such as cracks around fasteners.

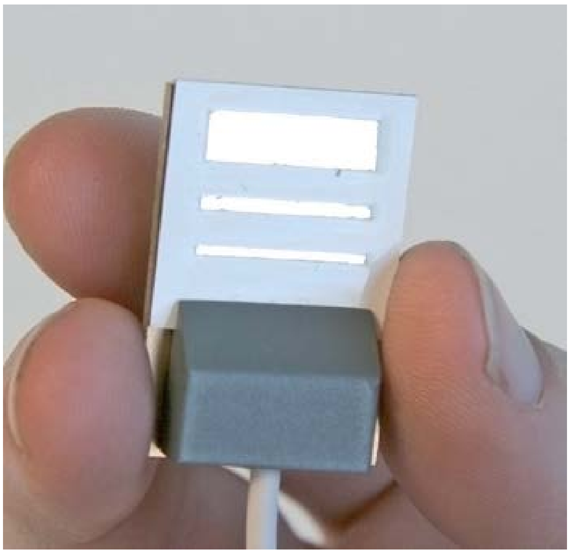


Figure 1: Corrosion sensor - resistive

Type CSR 2V2 has a group of 3 strips, designed to offer a ‘traffic light’ early warning system, as in a corrosive atmosphere the strips will suffer corrosion and ‘burn out’ in sequence, giving a stepped resistance output. This type is read out directly, using constant current interrogation

Type CSR 2V3 has the same corrodible strips as CSR 2V2, but the group is placed in one arm of an on-chip Wheatstone bridge, so that it can be read out as a millivolt change emulating a strain gauge. The Wheatstone additionally offers a good degree of temperature compensation.

All the sensors described above are wired with PTFE cabling and packaged with PR2001 sealant, ready to be fixed to a platform substrate with further sealant.

Type CSR 2V4 is as CSR 2V3, but with modified packaging which offers rugged handling tolerance and reduced need for additional sealing detail when fixing to a platform.

All the above sensors are designed to mimic actual platform alloys and coating systems and as such exhibit realistic cumulative degradation/corrosion status, and do not rely on constant powering or monitoring.

Coating degradation sensors (CDS)

In CDS sensor types (Figure 2) the fundamental ageing of the structure’s protective coating scheme (normally paint) is measured, assuming no flaws, thus the sensors are all-over painted and do not feature any deliberate defects. Whilst coating degradation is the main aim, this is measured indirectly through corrosion of the sensor’s elements beneath the paint and so the sensor also provides information about corrosion once the coating has degraded. The CDS sensor is specifically designed to measure a variety of degradation mechanisms e.g. weather, pin-hole, impact, UV and physical erosion of the coating protection system.

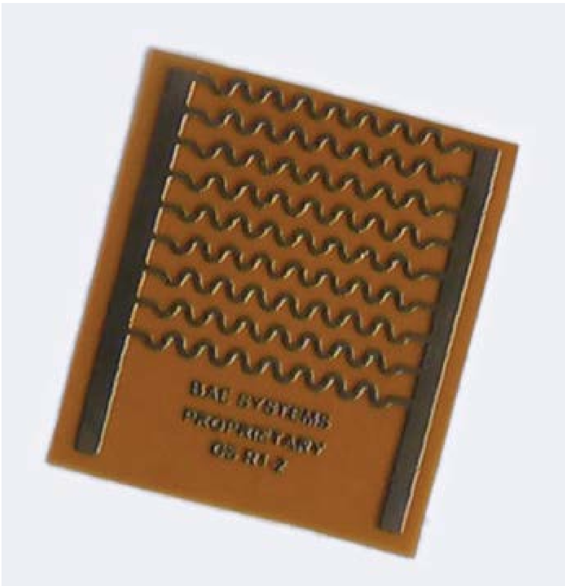


Figure 2: Coating degradation sensor

Type CDS 1VA consists of a serpentine element which will fail in a very marked way when any part of the serpentine is corroded as a result of coating degradation. The element's track width is chosen to suit the application, related to critical spot failure size in the specific coating. This device allows the primer and paint top coat degradation to be independently monitored.

Metal Loss Sensors (MLR) In this sensor type, activity beyond paint degradation is measured resistively for situations where a platform can tolerate significant metal loss e.g in marine applications, the point at which a few hundred microns has been lost can be sensed.

Time of wetness sensor (TOW)

The ToW sensor (Figure 3) is used as an environmental sensor to record periods when the monitored surface experiences wetting. As such these sensors are used in environmental data gathering systems and corrosion prediction systems.

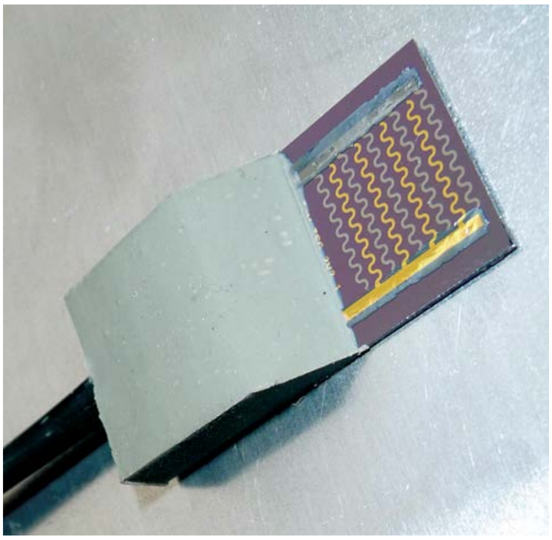


Figure 3: Time of wetness sensor

Two variants of ToW sensors are available, depending upon the severity of the environment:

Type TSG 2V2 is a galvanic sensor consisting of interdigitated gold and tungsten electrodes. This is sensed potentiometrically (Voltage) and is the most sensitive, but electrochemically consumed through life.

Type TSNG 1A is a non-galvanic sensor, which is suited for more severe environments, but requires a constant current to evaluate wetness.

The wetness can be interpreted digitally (wet/not wet) or in an analogue manner (indication of how much of the surface is wet, correlating to humidity in the range 70-100%).

Supplementary commercial-off-the-shelf (COTS) sensors

Systems are often formulated with the addition of COTS sensors for environmental monitoring, and we have chosen examples of Temperature, Humidity and atmospheric pressure/altitude sensors.

Qualification

Type CSR 2 and TSG sensors have achieved interim qualification through customers for flight on JSF, Hawk and Dassault Falcon 50 aircraft.

Applications

The principal application of the corrosion sensor system is in platform locations (Figure 4) that are difficult and time-consuming to inspect manually. A particularly suitable application is nominally-sealed internal bays in aircraft, where unsealing introduces a risk of faulty re-sealing. The corrosion sensor acts as an early warning device for corrosion in such areas which, once confidence is gained with the application, reduces the need and cost of regular manual inspections. In this mode the sensors can be used as stand-alone monitors of cumulative paint degradation/corrosion, and do not need constant reading.

Figure 4: Application example

Corrosion and time-of-wetness sensors can also be used as part of a corrosion prediction system, where supplementary inputs are used, such as temperature, humidity and time-of-wetness.

7.5 The Use of Micro Electro-Mechanical Systems to characterise the Structural Usage of a Multi-Role Military Aircraft

Robin Kamiya and Michael Duffield, QinetiQ

Airworthiness Policy in the UK Military Aviation Authority Regulatory Policy (MRP) mandates an Operational Loads Measurement Programme (OLMP) periodically throughout an aircraft's life. A full aircraft OLM programme can be highly complex as an airframe needs instrumenting with strain gauges and then the measurement system calibrated. Furthermore, from the beginning of such a programme, a clear understanding of how the multitude of recorded parametric and strain gauge data should be used is essential in order to realise the value of the expense and time put into such a programme. The full paper on this subject can be found in the ICAF2015 proceedings.

Under these circumstances such a programme can seem daunting and a step too far too soon for some MoD aircraft operators given the relative complexity/simplicity of the airframe and the role it performs. As such it may be appropriate to seek an exemption from the OLMP requirement by obtaining suitable data by other means that represent an Acceptable Alternative Means of Compliance (AAMC). Therefore a risk reduction programme collecting a single parameter to characterise typical flying can be seen as a good way forward to conducting that first step, e.g. time series normal acceleration (Nz) spectra. Nz spectra can be captured relatively cheaply, quickly and easily given that the pace of modern technology has miniaturised suitable accelerometer devices to the size of something little bigger than a common wrist watch. Various companies now market micro electro-mechanical systems (MEMS) for the sole purpose of being able to fit recording equipment to aircraft or other platforms with minimal interruption to normal operation and precluding any need for extensive design modifications to facilitate the installation. These MEMS type devices can be programmed to automatically start recording and shut down according to set of predefined conditions, thereby needing no operator involvement and resulting in a high capture rate of the required data while operating autonomously and inconspicuously in the background. Furthermore, they can be removed from the aircraft for download of the recorded data and replaced with a fresh unit easily and unobtrusively. Such devices are ideal for investigations on smaller, simple aircraft types operating in utility, surveillance and other non-combat roles.

Notwithstanding the practical simplicity of this type of data collection programme, considerable technical expertise is still required to define the scope of the associated analysis and interpretation of the resulting spectra; however, this is much more manageable than is typically required for a full OLMP and the aims of such a programme are likely to result in a meaningful outcome in a much reduced period of time.

QinetiQ has worked with the UK Defence Science and Technology Laboratory (Dstl) to conduct a fleet wide Nz data capture exercise on the UK MoD fleet of Britten Norman Islander aircraft using MEMS accelerometers. The UK Islander fleet has been in-service since the late 1980s and has a usage history defined in terms of Nz spectra obtained from traditional, electro-mechanical, counting accelerometers - otherwise known as fatigue meters. However, these meters were removed from the fleet approximately 10 years ago and since then, the aircraft operator has had to rely upon non-quantitative means of substantiating structural usage.

Figure 1: Islander aircraft

Hence, the installation of a MEMS type device to capture Nz data from flying for the Islander fleet provides tangible benefits as the resulting spectra can be compared to the past usage to provide corroborative evidence of how typical operational flying has evolved. Furthermore, due to the much greater resolution of the MEMS data compared with the fatigue meter records, there is considerable scope for refining the associated fatigue analysis to assess the actual structural usage of individual aircraft from the perspective of historical, present and future flying.

Taking into account the conventional, robust design of the Islander, the fatigue analysis uses well established methods to calculate nominal fatigue consumption rates. Consequently, the analysis using the Nz spectra captured using MEMS devices has allowed the Islander operator to quickly gain a meaningful insight into their recent aircraft usage for the cost of considerably less than many well-known luxury cars and now has a sizeable repository of evidence to justify an AAMC and apply for exemption from OLMP. Furthermore a baseline assessment of typical usage has been derived such that, should operational roles change and more data need to be captured, a comparison with 'then' and 'now' can be easily and inexpensively achieved by reactivating the data capture and analysis programme. This programme has clearly demonstrated that, under appropriate circumstances, MEMS technology can be used to obtain a valuable assessment of the effects of operational usage on structural fatigue consumption for an aircraft fleet at a fraction of the cost, complexity and timescale of traditional operational loads monitoring practices.

7.6 Challenges and Proposed Methodologies for Structural Health and Usage Monitoring Systems (SHUMS) in the domain of Airborne Complex Weapons

C Lomax and A Whitelaw, MBDA(UK), J Raiker, MJVR, A Groves, Dstl

Structural Health and Usage Monitoring Systems (SHUMS) have existed within aerospace and civil engineering for many years, and although there are many parallelisms in the design, operating environment and support activities there are very few examples of their use in airborne Complex Weapons, i.e. guided missiles and bombs.

This paper (see ICAF 2105 proceedings for full paper) will discuss the unique challenges of developing an autonomous self-contained SHUMS for airborne Complex Weapons with reference to the techniques and strategies for recording and assessing the remaining air carriage life and ensuring the Structural Integrity of the installed Weapon System.

It will detail the difference between Operational Monitoring and Damage Detection approaches for SHUMS and the implications on the current design criteria of airborne Complex Weapons

The relative merits of several analytical techniques including Regime Recognition, Direct Load Measurement and Indirect Load Reconstruction shall be considered, with a review of work which has developed, or is looking to develop, these techniques. A specific focus is drawn on the development of Indirect Load Reconstruction where various computational algorithms such as Inverse Methods and Pattern Recognition may be used to generate a Loads Reconstruction model to derive the real-time flight loads for use in a fatigue assessment of typical structural features.

The paper concludes with a development SHUMS proposal, utilising a combination of the various approaches and analysis techniques discussed within the report, and SHUMS technologies, such as sensors, that are available to meet the specific SHUMS requirements.

7.7 Flight Condition Recognition and Independent Flight Severity Monitoring for the Management of Helicopter Fleets

Brian Perrett, HeliSAC Limited

The work described in this paper (see ICAF 2105 proceedings) has been sponsored as part of the UK, Dstl 'Understanding Ageing Aircraft' R&D programme and evolved from the need to describe flight severity for the UK historic helicopter fleet in order to confirm that the aircraft were being operated within the design performance envelope. Whilst this early stage of the programme concentrated on describing the distribution of Normal accelerations over the range of angular pitch and roll displacements encountered in service, simple Flight Condition Recognition (FCR) algorithms were also developed to identify a restricted range of usage parameters that could be related to the Design Usage Spectrum and also to the manoeuvre activity. These algorithms used data from a low cost instrumentation suite providing only pitch, roll and yaw displacements in addition to three-axis accelerations - all recorded on a common time base.

The programme emphasis changed when data containing a greater number of flight parameters (from a Eurocopter AS350 squirrel of the Defence Helicopter Flying School) became available. By changing the way in which the flight parameters were used to identify both steady state flight conditions and transitions (Figure 1), it became possible to increase the number of flight events that could be identified using a series of deterministic FCR algorithms. In addition, the manoeuvre severity algorithms based on pitch rates, roll rates and acceleration were developed to provide an independent measure of aircraft activity that could be compared in software with the flight profile and usage spectrum described by the FCR algorithms. These capabilities have been developed in parallel with features that provide elements of fleet management, allowing the review of individual tail histories, individual sortie histories and cumulative fleet histories.

The work is currently being expanded to provide an alternative to the Manual Data and Operational Data Recording (ODR) programmes that are a requirement of the UK Military airworthiness regulations. The ODR programme involves an extensive instrumentation fit and is required to provide information describing helicopter usage and usage severity (in the form of strain histories at a limited number of locations) for aircraft that must then be exposed to the full range of fleet usage. Typically this might involve the instrumentation of between three and five aircraft (including slip-ring systems), a data gathering programme lasting three to five years - during which the aircraft must be exposed to the full range of operational flying - followed by an intensive analysis programme. This is an expensive undertaking and very intrusive in terms of engineering support and system reliability. To provide an alternative approach, the Fleet management capability described in this paper, developed using data from the AS350 has been extended to operate with the Health and Usage Monitoring system (HUMs) outputs of the new AgustaWestland Wildcat fleet in order to provide a permanent fleet history that will obviate the need for both Manual Data Recording and the ODR Programme.

This paper describes the current Fleet management capability in terms of the FCR algorithms, the flight severity algorithms and the independent correlation of Flight conditions, flight events and flight severity metrics (Figure 2). It also describes how usage and usage severity will be related to damage by correlation with the original loads database and lifing procedures of the Design Authority.

Figure 1. Change in pitch during a transition from low speed manoeuvring to forward speed

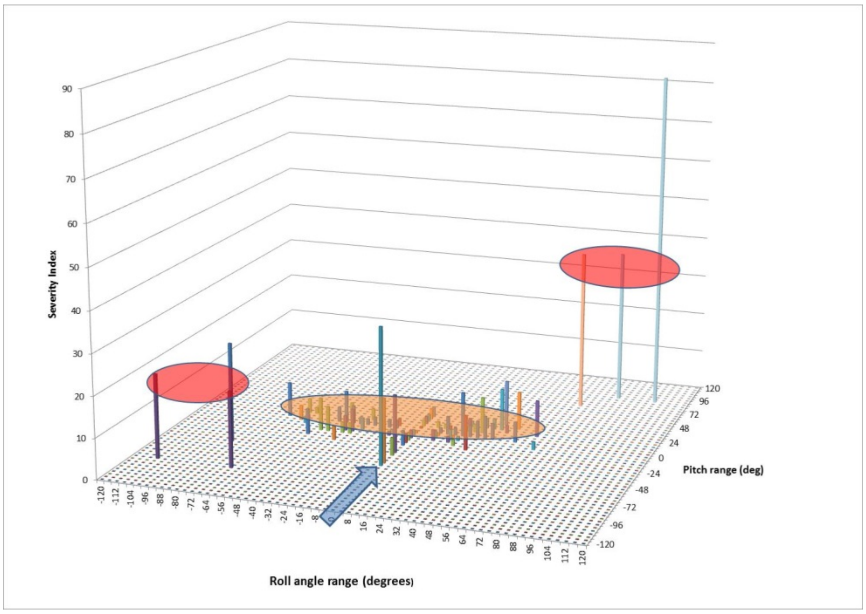


Figure 2: Severity Index distribution for a single display sortie of the AS350 Squirrel

7.8 Sensor location studies for damage detection in Aerospace Structures using 3D Scanning Laser Vibrometry

R. Marks, A. Clarke, C. Featherston and R Pullin, Cardiff University and C. Paget Airbus UK

With the increasing complexity of aircraft structures and materials there is an essential need to continually monitor the structure for damage. This also drives the requirement to optimize the location of sensors for damage detection to ensure full damage detection coverage of the structure whilst minimizing the number of sensors required, hence reducing costs, weight and data processing requirements.

An experimental study using 3D scanning laser vibrometry was carried out to investigate Lamb wave interaction with a disbonded stiffener (see ICAF 2015 proceedings for the full paper). A piezoelectric transducer was coupled to two different stiffened aluminium panels; one healthy and one with a 25.4mm long disbond. Three excitation frequencies were used; 100kHz (Figure 1), 250kHz and 300kHz, to investigate the effects of frequency on wave interaction with the disbond.

A computational study using local interaction simulation approach (LISA) was carried out for comparison with the experimental results. The objective of the simulation was to determine its viability as a tool for simulating wave interaction with disbonds for damage detection sensor network design. The results from the LISA model produced good results that qualitatively compared with the experimental results. This demonstrated that this simulation technique is well suited for performing sensor location studies for active sensor networks and has the potential to serve as a useful tool for damage detection sensor network designers.

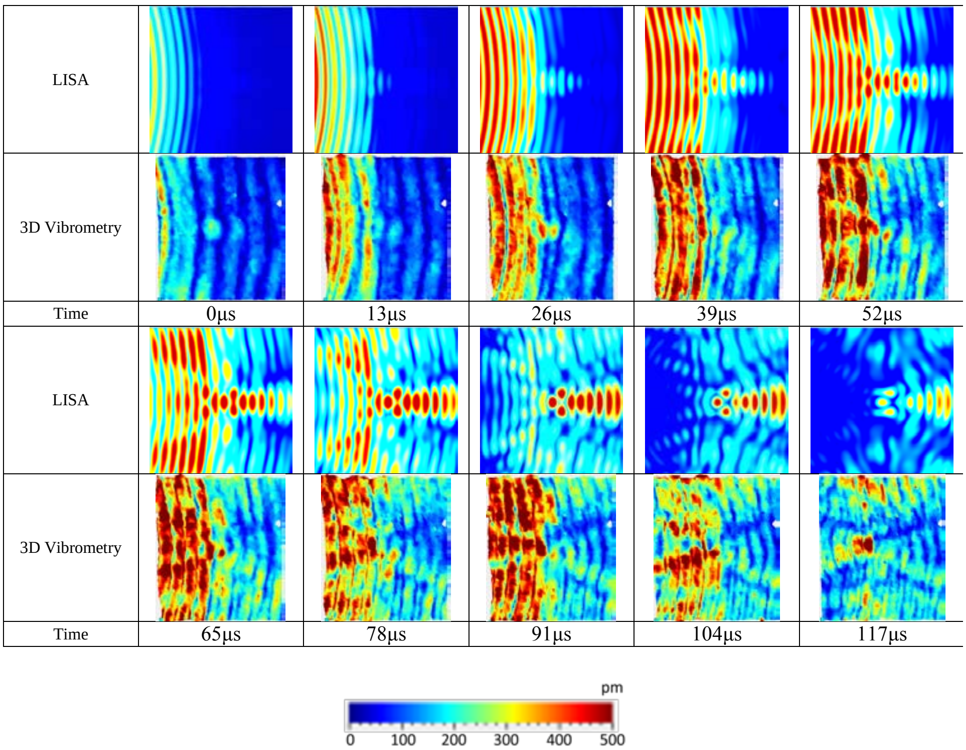


Figure 1: 100kHz disbonded stiffened panel.

7.9 Fixed-wing structural usage monitoring

Steve Reed, Dstl

Dstl has developed a low-cost structural usage monitoring system, based upon commercially-available, Micro Electro Mechanical System (MEMS) technology. The Modular Signal Recorder (MSR) is self-contained and places a very low burden on front-line maintenance crews (see ICAF 2015 proceedings for the full paper).

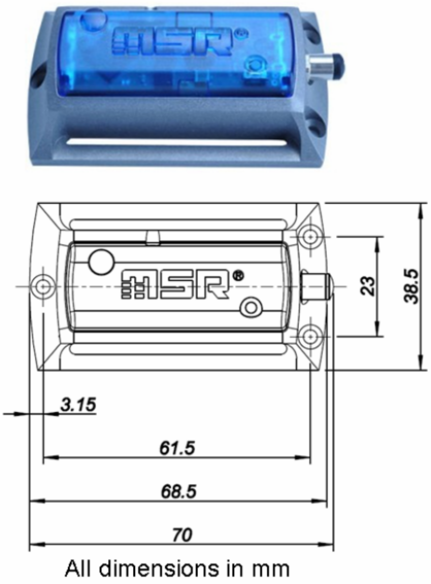


Figure 1: Modular Signal Recorder

In addition, Dstl has developed a universal Aircraft Data Analysis and Monitoring system (ADAM) for analysing flight data from a range of acquisition systems (including the MSR), using a common-core-code approach.

This technology has now been exploited with a fleet-wide fit for Islander and Defender aircraft (Figure 2), from which over 5000 flying hours of data have been captured.

Figure 2: Islander (top) and Defender (bottom) aircraft

The aim is to allow comparison between the current fleet usage with the fatigue test spectrum and historical usage data. The system has also been used to support usage data capture for the Lancaster, Spitfires, Hurricanes, Dakota and Chipmunk from the Battle of Britain memorial Flight, and Shadow, Swordfish, Beaver and Hunter aircraft (Figure 4, typical data Figure 5) as well as road transport monitoring of a Puma fuselage (Figure 6) during transit into the Life Extension Programme.

Figure 4: Lancaster, Swordfish, Beaver and Hunter aircraft

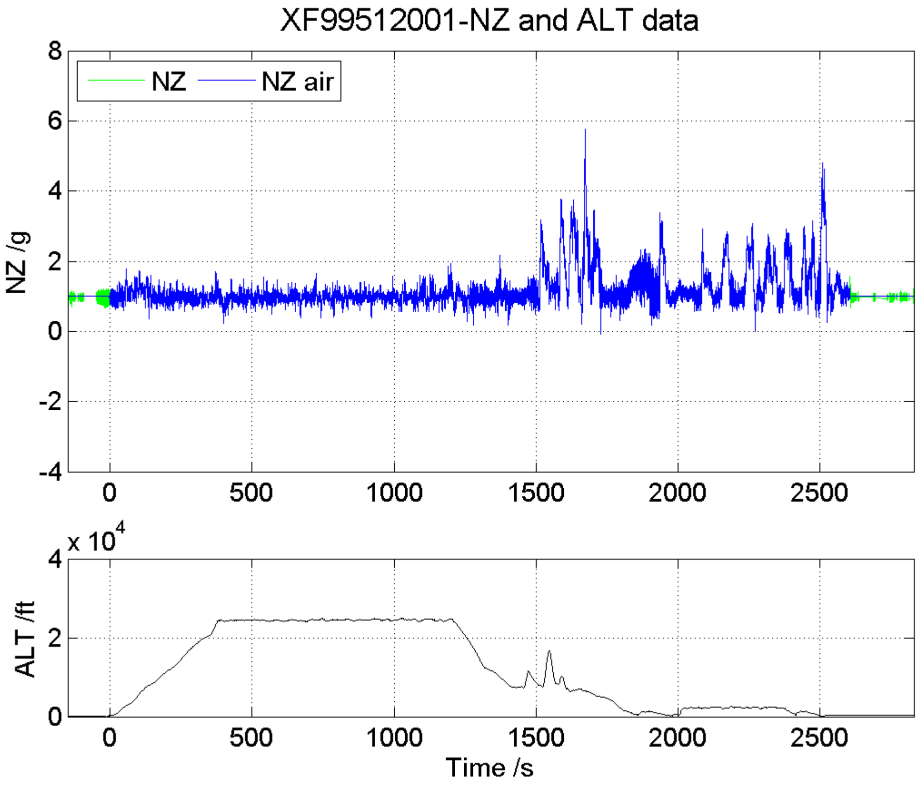


Figure 5: Example Hunter structural usage data

Figure 6: MSR located on Puma fuselage for road transport

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