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Guidance for Aircraft Operational Loads Measurement Programmes

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EXECUTIVE SUMMARY

Aircraft Operational Loads Measurement (OLM) programmes are now firmly mandated in MoD policy and there is general acceptance within the military aviation community that these programmes need to be undertaken. However, OLM is technically complex, costly and often takes many years to complete. This means that, certainly from the MoD's side, it is highly unlikely that an OLM programme will be completed on any one person's tour of duty. From experience, it is not uncommon to deal with 6 or 7 MoD desk officers in the time scale of an OLM programme. This brings great inefficiency where a fundamental review and bringing-up-to-speed exercise is invoked every 2 years or so. Furthermore, with the MoD increasingly moving from a 'provider' to a 'decider' organisation, the technical knowledge within the MoD will only decrease further, making the challenge of conducting successful OLM programmes even greater.

From an industry perspective, much hard won experience is frequently concentrated in a few key personnel. Furthermore, where programmes are cyclic rather than continuous, knowledge gained in industry is often lost in the intervening period between programmes. Additionally, in-depth technical and management problems have occurred in many OLM programmes; these have incurred additional cost, time delays and, in some cases, undesirable compromises have had to be made to make progress. Furthermore, with the dominance of commercial issues in today's engineering environment it is easy to forget or fail to appreciate the technical complexity of these programmes. Therefore, there is a very real need for more detailed guidance to be made available for those involved in OLM programmes.

The aim of this paper is to provide a basis for guiding those involved in an OLM programme through the planning, installation, data capture and analysis, and reporting phases of the programme. The reasons behind each of the steps in each phase are explained in generic terms and the key activities are captured in OLM Actions, which have been concatenated into a generic Statement of Requirement (Appendix B) for use as a starting point in OLM planning. Detailed technical data have also been included in Appendices where possible.

A draft of this paper was circulated to MASAAG members and OLM practitioners for their consideration and comments. This draft provided the basis for an OLM Workshop held at QinetiQ Farnborough on 22 Mar 07, attended by OLM Practitioners. Invaluable comments and contributions were provided during the course of the workshop and these comments have been included within the version of this paper presented here. It is hoped to retain this paper as a 'live' document and readers are asked to forward their comments and experiences from ongoing and future OLM programmes to the MASAAG.

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ABBREVIATIONS

ACS	Active Control System
ADD	Analysis Definition Document
ADR	Accident Data Recorder
AEDIT	Aircraft Engineering Development and Investigation Team
AP	Air Publication
ARINC	Aeronautical Radio Incorporated
ASTM	American Society for Testing and Materials
BCD	Binary Coded Decimal
BNR	Binary Encoding
COTS	Commercial Off the Shelf (procurement)
CSMU	Crash Survivable Memory Unit
da/dn vs ΔK	Crack Growth Curve (Fracture Mechanics)
DAU	Data Acquisition Unit
DAT	Digital Audio Tape
Def Stan	Defence Standard
DERA	Defence Evaluation and Research Agency (UK)
EMC	Electromagnetic Compatibility
ENOB	Effective Number of Bits
ESVRE	Establish Sustain Validate Recover Exploit
F725	MoD Form 725 – Flight and Fatigue Data Sheet
F/A	Fighter/Attack Variant
FFT	Fast Fourier Transform
FI	Fatigue Index
FLM	Flight Loads Measurement

FLS	Flight Loads Survey
FOOM	Frequency of Occurrence Matrix
FTI	Flight Test Instrumentation
FTR	Fatigue Type Record
GAG	Ground-Air-Ground Cycle
GB	Gigabites
GPS	Global Positioning System
IAT	Individual Aircraft Tracking
IPT	Integrated Project Team
IPTL	Integrated Project Team Leader
JSP	Joint Service Publication
LITS	Logistics Information Technology System
MDRE	Manual Data Recording Exercise
Mil Std	US Military Standard
MoD	Ministry of Defence (UK)
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
Nz	Normal Acceleration
ODR	Operational Data Recording (Rotary Wing)
OEM	Original Equipment Manufacturer
OLM	Operational Loads Measurement (Fixed Wing)
PC	Personal Computer
PCM	Pulse Coded Modulation
PITS	Point in the Sky
PMG	Programme Management Group
POG	Point on Ground
PSD	Power Spectral Density
R	Pearson’s Correlation Coefficient

R^2	Coefficient of Determination
RTC	Real Time Clock
RTW	Return to Works
SHM	Structural Health Monitoring
SINAD	Signal Including Noise and Distortion
SIWG	Structural Integrity Working Group
S-N	Stress – Endurance Curve
SPC	Sortie Profile Code
SFID	Sub-Frame Identification
SI	Structural Integrity
SOI	Statement of Operating Intent
SOIU	Statement of Operating Intent and Usage
SOO	Special Order Only (Modification)
SOR	Statement of Requirement
STF	Special Trial Fit
STR	Static Type Record or Structural Type Record
SYNCH	Synchronised
TAM	Type Airworthiness Meeting
UAV	Unmanned Aerial Vehicle
V-g	Airspeed – Normal Acceleration
ε-N	Strain-Life

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1 INTRODUCTION

Aircraft Operational Loads Measurement (OLM) programmes are now firmly mandated in MoD policy (JSP553 and JAP100A-01) and there is general acceptance within the military aviation community that these programmes need to be undertaken. Nevertheless, the potential risks of failing to understand military aircraft usage should not be underestimated. This position is reinforced by the example of the Tornado IDS aircraft where analysis of OLM data identified that the fatigue meter formula was underestimating fatigue damage by a factor of around 3.

OLM is technically complex, costly and often takes many years to complete (in some cases over a decade). This means that, certainly from the MoD's side, it is highly unlikely that an OLM programme will be completed on any one person's tour of duty. From experience, it is not uncommon to deal with 6 or 7 MoD desk officers in the time scale of an OLM programme. This brings great inefficiency where a fundamental review and bringing-up-to-speed exercise is invoked every 2 years or so. Furthermore, with the MoD increasingly moving from a 'provider' to a 'decider' organisation, the technical knowledge within the MoD will only decrease further, making the challenge of conducting successful OLM programmes even greater.

From an industry perspective, much hard won experience is frequently concentrated in a few key personnel. Furthermore, where programmes are cyclic rather than continuous, knowledge gained in industry is often lost in the intervening period between programmes. Additionally, in-depth technical and management problems have occurred in some OLM programmes, incurring additional cost, time delays and, in some cases, undesirable compromises have had to be made to make progress. With the dominance of commercial issues in today's environment it is easy to forget or not appreciate the technical complexity of these programmes.

There is a very real need for more detailed guidance to be made available for those involved in OLM programmes. JSP553 and JAP100A-01 may mandate the OLM requirement but there is no source of information available which details what is really meant by an OLM programme and what needs to be undertaken to meet the policy requirements. Therefore, QinetiQ has obtained tasking from CASD-ASI to:

- Produce a guidance document to detail appropriate technical information needed by desk officers involved in OLM programmes
- To identify best practice where applicable
- To define the processes needed for OLM and produce a generic statement of requirement for an OLM programme

Readers are first provided with an historical perspective of OLM. The evolution of OLM requirements and practice has been based upon experience and it is imperative that this experience is not lost over time.

The potential aims of OLM programmes are detailed. From these aims the requirements for data capture, equipment and analysis will flow and specific OLM Actions have been identified. In order to provide a logical framework for this information, a generic OLM programme has been considered from inception to final reporting, picking up the OLM Actions accordingly. Supporting information has been provided covering what needs to be done to ensure that the programme is successful. Generic instrumentation, calibration methods and data analysis requirements have been identified; in-depth information has been included in appendices, as appropriate. It is accepted that one size does not fit all for OLM but a generic approach will provide a foundation for future programmes which can be modified to suit the particular circumstances of each programme.

A draft of this paper was circulated to MASAAG members and OLM practitioners for their consideration and comments. This draft provided the basis for an OLM Workshop held at QinetiQ Farnborough on 22 Mar 07, attended by OLM Practitioners from across the industry. Excellent comments and contributions were provided by the OLM Practitioners during the course of the workshop and these comments have been included within the issued version of this paper.

Much of the content of this paper is equally applicable to helicopter Operational Data Recording (ODR). However, there are rotary-wing specific issues associated with ODR programmes and these have not been addressed within this paper. The way ahead agreed at the 61st MASAAG was to complete the OLM guidance paper and then develop an ODR deltas paper subsequently, as required.

2 HISTORICAL PERSPECTIVE

2.1 RELEVANCE OF HISTORICAL PERSPECTIVE

In practice even if an activity, such as OLM, is clearly mandated in MoD policy it still does not provide guarantees that this activity will be undertaken in a timely manner or, in some cases, at all. Fortunately, structural failures of military aircraft are rare events nowadays. However, the lessons of recent history are quickly forgotten in times of ever-decreasing budgets and in the face of fierce competition between equipment capability enhancements and support costs. Not surprisingly, experience has shown that the most successful OLM programmes have been undertaken when all parties involved have been convinced of the need to undertake this activity, rather than merely complying with policy. Therefore, to improve the chances of success, those involved in an OLM programme must be convinced of the need to undertake the work.

A brief historical overview of the development of aircraft fatigue monitoring and the role played by OLM is presented in the following sections. The aim of this section is to put the development of OLM in context as part of the fatigue usage validation process. However, those reading this paper who do not want to cover this historical information can move forward to Section 3 without losing the continuity of the paper.

2.2 EARLY MEASUREMENT OF SERVICE LOADS IN AVIATION

Although Wöhler (1870) had understood from his investigations into fatigue failures on the railways that the sizing and design of a component for fatigue was not possible if the service loads and stresses were not known, it was not until the 1930s that significant efforts were made to measure in-service loads in aviation. As has so often been the case, these efforts were often a ‘Newton’s 3rd Law’ response to a series of fatal accidents. Foremost among these was a Dornier Merkur which crashed in 1927 following the fatigue failure of a wing spar attachment. In the same year a Handley Page W10 crashed into the English Channel following the fatigue failure of a connecting rod and in 1934 a Curtis Condor crashed after the wing strut failed in fatigue (Schütz 1996).

Although the electrical resistance strain gauge, still the mainstay of in-service aircraft loads measurement today, was not invented until the late 1930s (de Forrest 1936; Simmons 1942), in-service loads were measured from the early 1930s on a range of military and civil aircraft, using induction strain gauges and glass-scratch strain gauges. The relationship between acceleration at the centre of gravity and wing deflection or strains was highlighted in these studies. Incredibly, these ground breaking in-service loads measurements included over 300 sorties of data captured by the Germans from Junkers Ju-87 and Ju-88 aircraft during air raids on Malta in

1941. Additionally, load or strain measurements were carried out on a range of British military aircraft during combat operations (Pugsley 1946). Furthermore, the link between measuring in-service loads and generating loads spectra for variable amplitude testing was forged during this period (Kaul 1938; Filzek 1942).

Although losses from structural failures due to fatigue were dwarfed by combat losses during World War II some fatal crashes due to fatigue failures did occur. No less than 20 Vickers Wellington bombers were recorded as lost due to fatigue failures (Mann 1983) and 10 German Messerschmitt Bf110 bombers were lost following fatigue failures of the ribs in the tailplane, leading to flutter (Gassner 1956).

2.3 POST-WAR YEARS

In the post-war years, the focus on fatigue switched to civil aviation. The civil aircraft of the era were originally safe life designs and hence it was vital to quantify the environment in which they flew. Thereafter, the de Havilland Comet 1 losses (Williams 1969) forced a review of fatigue testing techniques used, in particular the implications of using a fatigue test article that had already been used as a static strength test article. The subsequent changes in fatigue testing included the introduction of flight-by-flight tests of complete aircraft structures. Additionally, a series of further civil aircraft fatigue-related accidents and incidents occurred in this period (Figure 1 (from Williams (1969)). A contributory factor in many of these accidents was a lack of understanding of the structural loads experienced by aircraft.

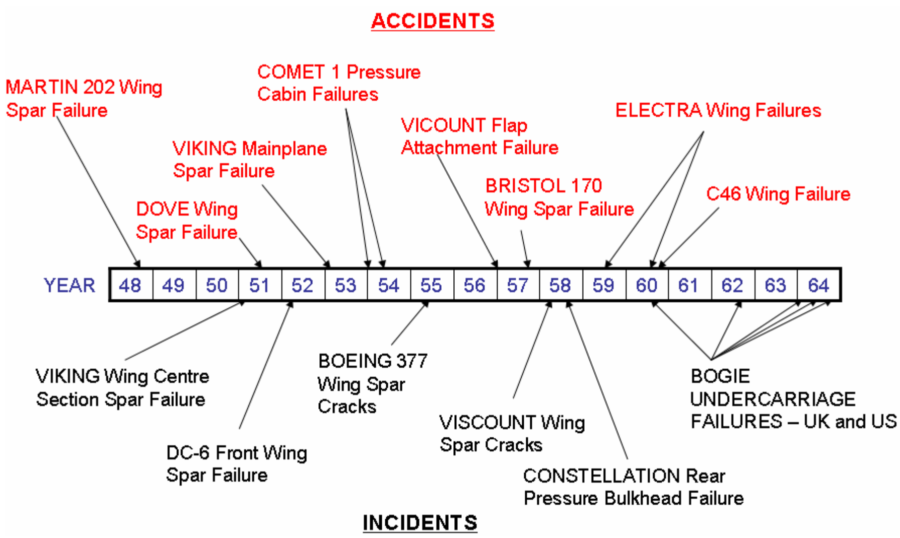

Figure 1 - Fatigue Accidents and Incidents to US and UK Civil Aircraft (Williams 1969)

Flight through turbulence was known to generate repeated loading and much effort was concentrated on defining these environmental loads. Consequently, the late 1940s, 1950s and 1960s saw enormous data gathering exercises, primarily in the UK (Bullen 1959) and the US (Coleman and Copp 1954), largely aimed at capturing gust data, finally reported through AGARD by Peckham (1971) and Kaynes (1972). Generally, civil aircraft were instrumented with either V-g recorders (airspeed and normal acceleration) (Figure 2(a)), developed by the NACA (forerunner of NASA), strain range counters (Vickers-Lambie) or counting accelerometers.

Recovery and analysis of the recorded V-g data was a highly skilled manual task and the data captured were primarily used to generate design information for next generation aircraft. Generally, extreme load conditions were identified as a frequency of occurrence envelope (Holford 1988). The Vickers-Lambie strain range counter (Lambie 1955) was essentially a recording extensometer. The unit was about 10 inches long and there were 4 preset levels of strain range that could be counted. The absolute level of strain was not recorded and so the mean had to be supplied from other data sources. Williams (1969) reported the capture of 300,000 flights of gust data with the strain range counter by the British Aircraft Corporation from 150 Viscount aircraft, operated all over the world. Counting accelerometers were also used extensively during the period. The RAE counting accelerometer used mechanical counting of acceleration levels, later replaced by electro-mechanical counting. All versions of the RAE instrument used photographic recording. A picture was taken every 2 to 10 minutes showing the counters, altimeter, airspeed and clock. These accelerometers were fitted to 17 different types of aircraft and data were acquired from a total flight distance of 8 million nautical miles. These data were used to generate gust statistics for test and design purposes, their use in defining gust requirements being extended later by the addition of data acquired by CAA from Boeing 747 aircraft (CAA 1990). The data were also used to assess operational fatigue life against that demonstrated by test.

As an exception to the concentration on civil aircraft, counting accelerometers were also used for a study of low level flying with Canberra aircraft (Bullen 1960). Under "Operation Swifter" almost 2000 hours of low altitude flying were recorded over North Africa, aimed at refining the gust statistics and understanding physiological factors for future low level aircraft against the requirement which lead to the development of the TSR2.

2.4 EARLY FATIGUE MONITORING OF MILITARY AIRCRAFT

During World War II and in the period immediately following, the gargantuan technological developments being made in aviation meant that military aircraft were designed to meet ever increasing performance goals. Consequently longevity was not a significant design constraint as aircraft were quickly replaced by ones of superior performance (Holford 1988). In the UK, overall assessment of the loads experienced by military aircraft was gained largely from V-g data (Figure 2(a)) (Jones 1947). From these V-g data, it was known that different types of flying produced different g-Exceedance rates and the first fatigue usage monitoring was based on this premise. Different mission types or operational usage incurred different fatigue damage rates and the time spent in each role was logged and used with fatigue damage rates deduced from the available normal acceleration data to calculate the fatigue life consumed.

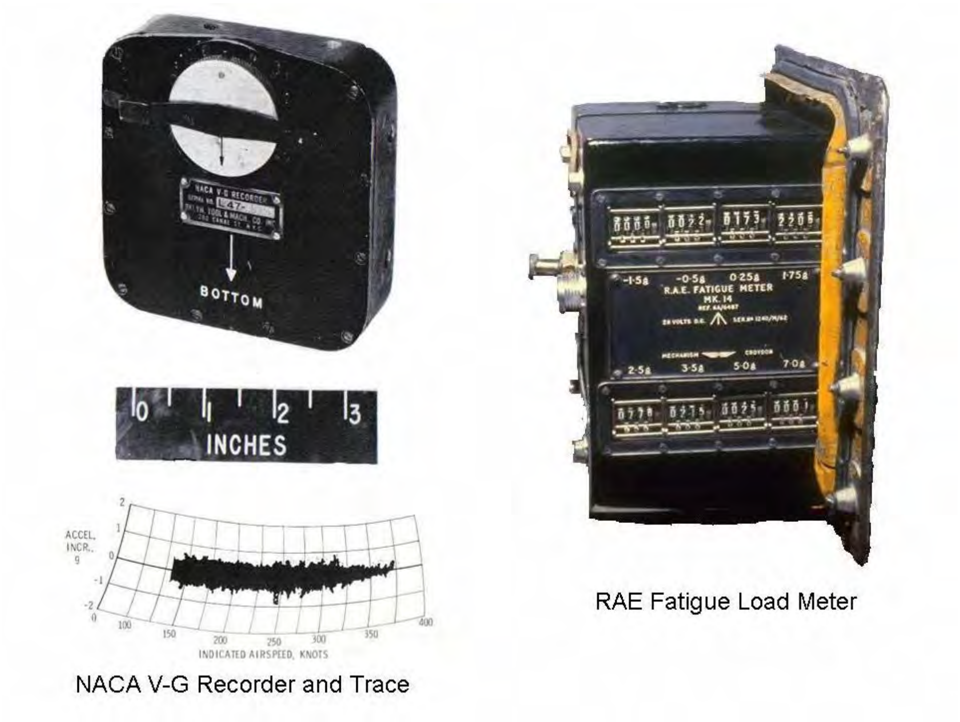

Figure 2 - Loads Monitoring Equipment (a) NACA V-G Recorder (b) RAE Fatigue Load Meter

Military aircraft fatigue problems in the period were primarily associated with the wing centre section. The structural loads in this region of the aircraft were known to be highly correlated with the normal acceleration of the aircraft and therefore efforts were focused on the automatic collection of accelerometer data to identify actual usage. Furthermore, the early recorded data had revealed a large scatter in the normal acceleration spectra from different aircraft nominally performing the same task; this had cast doubt on the continued use of mission damage rates. Additionally, because the mission damage rates included no quantification of the actual loading on the individual aircraft, an additional safety factor was applied to the test result to cover variability in loading compared with that expected. Therefore, logically, if the loading could be quantified reliably on an individual aircraft basis then the additional safety factor would not be necessary and the usable life of the aircraft could be extended.

A parallel monitoring activity was underway in the US (Ward 1991). The Service Loads Recording Programme which had commenced in 1936 with the objective of collecting design information had its bias changed in 1958 towards the collection of fatigue usage data. Additionally, Skopinski *et al*. (1954) published their report on the calibration of strain gauge installations for use in load measurement programmes. This represented a significant step forward for techniques in loads monitoring and Skopinski-type calibration methods are still in use today; this method is explained later in this paper.

It should be noted that rotary-wing aircraft were used by the military from the late 1940s and early 1950s; however, individual aircraft fatigue monitoring for helicopters was extremely limited and is therefore not addressed here.

2.5 THE INTRODUCTION OF THE FATIGUE LOAD METER

In the UK, from 1954 onwards most military aircraft were fitted with a counting accelerometer called the fatigue load meter (Figure 2(b)) (Taylor 1965). The fatigue load meter was positioned close to the centre of gravity of the aircraft and utilised an electromechanical arrangement to log the number of times the normal acceleration exceeded a given level (the lock level) and subsequently fell to a lower level (the release level). The basic instrument was simple and robust and the results were readily logged for each flight and thereafter segregated into sortie type if required.

However, the fatigue load meter only provided statistical information on a component of the structural loading. The datum load conditions had to be supplied from alternate sources. These datum conditions would be influenced by weight and configuration. Conversion factors to translate the incremental g readings to stress levels in the wing were also required and these were often a function of flight condition. Assumptions had to be made about the flight condition and configuration at the time of the count before the associated fatigue damage could be calculated from a knowledge of the structural endurance. Thus, to calculate the fatigue life consumed, an average operating condition had to be assumed. The development of these fatigue formulae as they became termed was largely based upon the work of Raithby (1961) and Phillips (1960). If the fatigue critical area was not related to normal accelerations then other techniques had to be employed.

In the UK throughout the 1960s, fatigue load meter data were used to generate design data and to provide fatigue life data for most military aircraft. Recording programmes comparable to those in the civil field were very limited due at least in part to the reduced space available in combat aircraft for recording equipment. Various other strain-based mechanical systems were developed but failed to better the fatigue meter for ease of installation, simplicity of data recovery and usage and were not used in the UK to any great extent (Holford 1988). Strain gauge technology, data recording equipments and computing facilities all improved but the study of structural loads through direct load measurement was confined to the flight test environment. This situation prevailed despite military aircraft becoming far more complex and it becoming more difficult to interpret the fatigue implications of fatigue meter readings with confidence. Furthermore, although generally major components of the aircraft were subject to fatigue test, components where loads were uncorrelated with normal acceleration could only be tracked in service against an assumed damage rate by logging flight hours. An impetus for progress was provided when unexpected fatigue failures occurred in service.

Structural failures on USAF aircraft, particularly the 1969 failure of an F-111 aircraft after only 100 flying hours (Lincoln 1991), caused the USAF to embark upon a damage tolerant approach to fatigue life management. However, the investigations following the structural failures seen in the UK in the late 1960s and early 1970s, including losses of a Vulcan, Phantom, Harrier and a Gnat from the RAF Aerobatic Team (Adams and Cansdale 1992), concluded that, once again, it was the understanding of loads on the aircraft which was lacking, not the underlying safe life policy adopted by the UK.

2.6 THE ADVENT OF OPERATIONAL LOAD MEASUREMENT PROGRAMMES

UK OLM programmes (Holford and Sturgeon 1984) began in the mid 1970s but progress was initially slow until the fatal loss of a Buccaneer aircraft during a ‘Red Flag’ exercise in 1983. This aircraft had been designed and tested for maritime operations as a naval aircraft. However, it had been operated by the RAF in a terrain-hugging overland role and a failure unpredicted by the fatigue test had occurred. In the aftermath of the subsequent investigation the UK MoD was heavily criticised for failing to exploit available technology in fatigue monitoring systems (Davies 1991). Thereafter, OLM programmes proceeded apace and are now a mandated element of UK Ministry of Defence structural integrity policy for all aircraft (JSP 553).

The objective of these OLM programmes was to validate the fatigue substantiation process in the light of service usage. These programmes aimed to quantify the structural fatigue loading through direct load measurement using electrical resistance strain gauge installations on all major components. In addition, the causes of high fatigue damage rates were identified and the effectiveness of monitoring procedures was assessed. Where required, data from these programmes were used to generate full-scale fatigue test spectra. Where full-scale fatigue tests were underway or had been completed, comparisons between OLM data and test spectra were made. Typically, for each OLM programme, several aircraft within the subject fleet were instrumented and operated as normal squadron aircraft for 1 to 2 years. Data were collected in time-history format for subsequent analysis on the ground.

The direct strain measurements captured during OLM programmes have generally been interpreted in one of 3 ways. A fatigue or feature calibration has involved installing the OLM strain gauge array on the fatigue test specimen and recording data during the test. Appropriate structural endurance (S-N) curves for monitored areas have then been fitted to the test results and hence are a function of the feature considered and the loading sustained during the test. Alternatively, load calibration has involved obtaining a calibration of the strain gauge installation in terms of overall applied load, using Skopinski-based methods (Skopinski 1954). Structural endurance has then been related to the loads input to the test, rather than strains or stresses. Finally, data have been interpreted from direct strain measurements captured from the aircraft. In addition to strain data, comprehensive parametric data have been captured primarily to assist in the identification of the causes of structurally significant occurrences.

Early OLM programmes were limited by the technology available at the time. Data sample rates were restricted, often to a total of 512 or 1024 samples per second of 10-bit data for all data streams. However, the systems in place by the mid 1990s allowed near unrestricted data capture with 16-bit data. Nearly all OLM programmes run to date have highlighted significant shortfalls in either test loading or monitoring systems (Holford 1988) and have resulted in significant changes in the understanding and implementation of aircraft structural integrity measures.

2.7 DEVELOPMENT OF STRUCTURAL MONITORING SYSTEMS

Fatigue load meter systems backed up by OLM have been the mainstay of UK military structural monitoring for over 30 years but there are still significant limitations with this method. Fleet wide decisions are made based upon a relatively small sample of data as rarely does OLM data capture represent more the 1 or 2% of flying. Increasingly, partial fleet capability enhancement of military aircraft has generated mini-fleets within fleets, where the usage is often significantly different from the average for the fleet and can call into question the validity of the OLM data for these aircraft and measures need to be taken to ensure that fleet-within-fleet data are captured. Furthermore, the need to maximise the service life of aircraft means that structural monitoring of the whole aircraft is often required to remove the additional safety factors in place for unmonitored structure. Even with the fatigue load meter system backed up with OLM these systems are only reasonably accurate when considered on average over a large data set. Performance on a flight-by-flight basis can be poor. Fundamentally, fatigue load meter data are only applicable to loading environments which are proportional to normal acceleration. A strain-based system for each aircraft in the fleet would address these issues and such systems have been introduced with the UK Eurofighter-Typhoon fleet (Hunt and Hebden 1998) and will be fitted to the Hawk Mk128 variant and Sentinel R Mk1.

However, OLM still retains an essential role for these aircraft. It is impractical for aircraft to be fitted with an array of sensors that will monitor every structural component on the aircraft. The Eurofighter-Typhoon SHM for example has 16 strain gauge monitor locations and an array of parametric sensors; the Hawk Mk128 Health and Usage Monitoring System (HUMS) has 7 strain channels for a fleet-fit aircraft (and 21 channels for the OLM aircraft) and a wide range of parametric sensors. Additional foreseen and unforeseen strain and parametric monitoring requirements will inevitably occur during the life of the aircraft. Undercarriage OLM is an excellent example of a 'foreseen' requirement which is a highly likely requirement in the life of a modern military aircraft.

2.8 The Role of OLM in Future Structural Monitoring Systems

Future military aircraft procurements are likely to consist primarily of multi-national projects, off-the-shelf purchases and 'power-by-the-hour' contracts. The role of OLM in the continued airworthiness assurance of such fleets is likely to grow rather than reduce. Additionally, advanced parametric, non-adaptive, predictive fatigue monitoring systems, often using artificial intelligence, will require large volumes of OLM data to train the prediction systems.

Off-the-shelf purchases, particularly from equipment suppliers less familiar with UK Defence Standards than traditional suppliers, are still governed by the same airworthiness and duty of care requirements. Consequently, particularly where traditional levels of fatigue and static testing have not been undertaken to support the clearances and where flight loads validation activity has been limited, OLM data are likely to have an even greater role in the assurance of continued airworthiness.

Finally, 'power-by-the-hour' contractors for civil aircraft types are likely to insist that aircraft can pass back and forward between civil and military registers to meet demand. Therefore, military usage will need to be well defined for these aircraft and hence combinations of OLM and individual aircraft tracking (IAT) are likely to be introduced as part of these contract arrangements.

3 OLM DEFINITION

It is always a minefield trying to pin a definition onto such a wide ranging activity as OLM. However, with an increasing reliance upon multinational programmes, use of civil designed aircraft and procurement of new breeds of air vehicles, such as UAVs, often from non-traditional suppliers, it is extremely useful to identify what the UK MoD means by an OLM programme. It is noteworthy that there are some very different perceptions of what constitutes an OLM programme in the literature, particularly from the civil arena where the distinction between flight loads measurement and OLM appears to be less clear than in the military environment. Therefore, the following definition of an OLM programme is tabled for discussion:

OLM Definition: *Operational Loads Measurement is a structural usage substantiation*[1] *activity involving the capture, analysis and reporting of representative, directly measured strain data or derived loads and associated flight parameters from a sample of suitably instrumented in-service aircraft within a fleet.*

[1] Substantiation in this context refers to the assessment of structural usage in service in relation to the assumptions and methods used in design and qualification.

4 REGULATORY AND GUIDANCE MATERIAL

The current regulatory material governing OLM programmes is contained in the Military Airworthiness Regulations (JSP 553), Defence Standard 00-970 (Def Stan 00-970) and Joint Airworthiness Publication 100A-01 (JAP 100A-01). These regulations will undoubtedly be updated in future years and hence readers are advised to refer to the most up-to-date sources. The relevant extracts from JSP553, Def Stan 00-970 and JAP100A-01 at the time of writing this paper are included in Appendix A for completeness.

The extracts in Appendix A provide a wealth of information on what should be attempted in a programme which seeks to capture operational loads; a number of these extracts make direct reference to OLM programmes. In the following sections a generic OLM programme is described through the planning (Section 6), installation (Section 7), data capture and analysis (Section 8) and reporting phases (Section 9).

5 GENERIC OLM PROGRAMME

5.1 BACKGROUND

The top-level aims of an OLM programme are described in this section. Thereafter, the OLM activity required to meet these aims is described in the subsequent sections. This activity has been divided into Planning phase, Installation phase, Data Capture and Analysis phase and Reporting phase as a convenient method of subdividing the tasks. In reality, there will inevitably be an element of overlap between the different phases of the programme. Furthermore, to aid readers through the remainder of this section, a diagrammatical representation of the OLM phases and activities described is presented in Figure 3.

Within each section, the work required and reasons behind this work are described; furthermore, key OLM actions are identified at the outset of each section and these are collated into a generic statement of requirement (SoR) in Appendix B.

There is considerable detail contained within this section and no apology is made for that; OLM programmes are technically complex and while not everybody involved in the programme needs to have full cognisance of all the detail, a basic understanding of what has to be done and why is necessary to manage such a programme successfully. However, where deeper technical information can be omitted from the body of this paper, thereby improving the flow of the text, that information has been decanted into Appendices.

The conduct of future OLM programmes will be affected by the sweeping changes introduced to the way the MoD supports aircraft. The traditional roles within organisations are likely to change dramatically but these are not yet fully defined or necessarily consistent from project to project and hence the responsibilities here are defined by function rather than organisation. Nevertheless, throughout this paper the term ‘Designer’ is used to describe the organisation undertaking the historic Design Authority role and IPT is used to define traditional MoD Project Office or Integrated Project Team roles.

OLM Planning Phase (Section 6)
- Aim: Substantiation of Design and Qualification Fatigue Usage Spectra and Fatigue Clearances
- Aim: Identification of local stresses in a structural feature
- Aim: Substantiation of Fatigue Monitoring System
- Aim: Capture of Fatigue Test Spectra
- Aim: Identification of Highly Damaging Activity or Manoeuvres
- Aim: Review of the Statement of Operating Intent and Usage
- Identification of Measurement and Data Requirements
- Number of OLM-Instrumented Aircraft
- Review of Fatigue Analysis Methods
- OLM System Design
- Ground Station
- Data Analysis Process Design
- Calibration Requirements
- In-service Maintenance and Through-Life Support
- Planning Phase Review
- Reporting Summary

Installation Phase (Section 7)
- OLM System Installation
- Calibration Procedure
- Confidence Checks
- Air Test Requirements
- Installation Phase Review
- Reporting Summary

Data Capture (Section 8)
- Data Capture Programme
- Service Involvement
- Data Capture Phase Review
- Reporting Summary

Analysis and Reporting (Section 9)
- Post Air Test / Initial Analysis and Report
- Progress Reporting Against Programme Aims
- Interim Reporting Against Programme Aims
- Final Reporting
- Follow-up Actions
- Reporting Summary

Figure 3 - OLM Activities Schematic

5.2 ESTABLISHMENT OF OLM MANAGEMENT AND SPECIALIST GROUPS

***<u>OLM Action 1</u>**: An OLM Programme Management Group, chaired by the IPT and including representation from the Designer, IPT, MoD Structures Specialist and Independent SI/OLM Advisors should be established at the inception of an OLM Programme. For new aircraft types this Group should be formed during the design phase as OLM has implications for design and production. Additionally, an OLM Specialists' Group, reporting to the OLM Programme Management Group, should be formed to determine, agree and manage the in-depth technical aspects of the OLM Programme and should include core representatives from the Designer's OLM Specialists and Independent SI/OLM Advisors.*

Successful OLM programmes require the involvement of a wide range of organisations and specialists within the MoD and industry. Ultimately, OLM is required to underpin the continued airworthiness of the fleet. Therefore, even in a 'decider' rather than 'provider' role, the MoD should retain sufficient involvement in an OLM programme to be satisfied that the airworthiness of the fleet is being suitably protected. Establishing an OLM Programme Management Group and Specialist Group from the various disciplines and organisations and ensuring this OLM Team has 'ownership' of the programme is a tried and tested method for keeping such programmes on track.

A management structure along the lines illustrated in Figure 4 below is suggested.

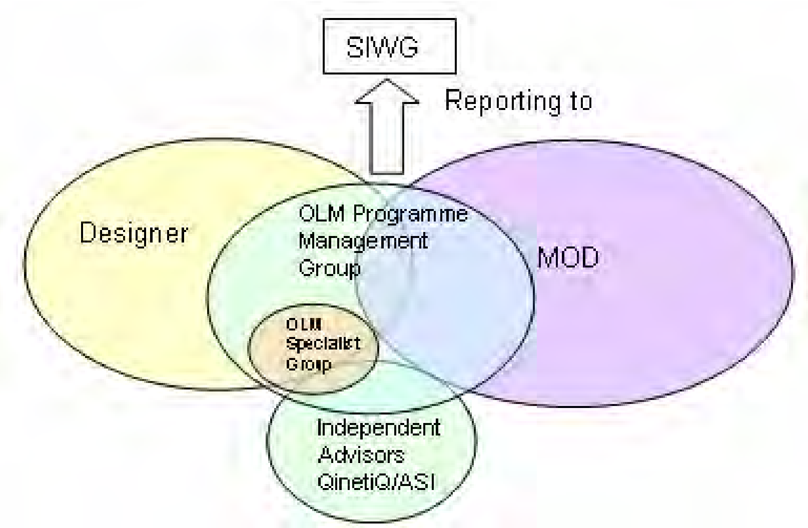

Figure 4 – OLM Programme Management Organisation

The OLM Programme Management Group (PMG) should be chaired by the MoD Aircraft Project Office / Integrated Project Team (referred to as IPT henceforth) and report to the Structural Integrity Working Group (SIWG). With changes in organisational arrangements it is quite conceivable that the Chairman and other IPT members could be industry employees but acting on behalf of the MoD organisation. For an aircraft entering service the OLM Programme Management Group should be formed in the initial aircraft project development phase, as the conduct of OLM has significant implications for design and production. The OLM Programme Management Group should also contain core members from the IPT, Designer, MoD Structures Specialists and MoD's Independent SI/OLM Advisors with other members co-opted at appropriate times during the development of the project. As well as chairing this group, the IPT should appoint an OLM Project Officer who has 'ownership' of the day-to-day running of the project. Designer representation should include a Technical Project Manager and OLM Technical Specialists. The Designer's Technical Project Manager needs to be able to coordinate the diverse disciplines within the Designer's organisation. This is a particularly challenging role and requires the Technical Project Manager to have a good level of understanding of the technical issues within the project. Additionally, successful OLM programmes have generally had dedicated OLM Specialists from the Designer organisation allocated to the project. This allows continuity across the programme and fosters the essential 'ownership' needed for success. Even Designer organisation OLM Specialists will rarely have sufficiently deep knowledge in all the disciplines associated with an OLM programme including loads, aerodynamics, flight loads measurement, instrumentation, installation, integration, structures, fatigue and data analysis. Hence, other discipline specialists will have to be called upon periodically throughout the programme. The MoD Structures Specialists and Independent SI/OLM Advisors bring highly-valuable and relevant experience from previous and ongoing OLM projects on other platforms to the Management Team.

Experience has shown that as well as an OLM Programme Management Group there is a need for smaller OLM Specialists' Group, reporting to the OLM Programme Management Group, to allow a forum in which in-depth technical detail can be discussed and agreed. Therefore, an OLM Specialists' Group with core membership of the Designer's OLM Specialists and Independent SI/OLM Advisors should be formed.

In essence, these 2 Groups will be required to determine, agree and manage all aspects of the programme, as described in the following sections.

5.3 OLM PROGRAMME AIMS

OLM Action 2*: The structural integrity aims of the OLM programme should be clearly defined. These aims should be agreed by the OLM Programme Management and Specialist Group, documented and endorsed by the SIWG (or forerunner where the SIWG has yet to be established). These aims may include but are not restricted to:*

- *To substantiate the fatigue spectra used in design and qualification and review fatigue clearances*
- *To identify local stresses in a structural feature*
- *To substantiate the monitoring systems (including identification of further monitoring requirements)*
- *To capture fatigue test spectra data*
- *To identify particularly damaging activity or manoeuvres*
- *To provide data to support investigations of structural issues or as life extension programmes*
- *To provide data for use in a review of the Statement of Operating Intent and Usage*

The aims of the programme will, necessarily, dictate the conduct of the programme from planning, installation through data capture, analysis and reporting. The success of the programme will be highly dependent upon clearly defining these aims at the outset and monitoring progress towards achieving these aims during the conduct of the programme.

A detailed explanation of the background of each of these aims is presented in Section 6. The intent is to provide the reader with sufficient knowledge to understand what they mean, why they are important and how they fit into the overall structural integrity assurance or continued airworthiness processes.

5.4 TIMING OF AN OLM PROGRAMME

OLM Action 3*: Timing of the initial OLM programme after introduction to service of a new aircraft type will largely be governed by the aims of the programme. Generation of fatigue test spectra will generally require data capture early in service; however, care needs to be taken to ensure data are sufficiently representative of usage.*

Permanent installation of an OLM system is mandated in JSP553 Annex K.4 (Appendix A) and the facility to record OLM data should be enabled for a new aircraft type within 2 years of entering service. Timing of initial data capture will be influenced by the aims of the OLM programme and these are discussed in detail in the following paragraphs. However, data capture may be required early into service, particularly if OLM data are required to support one or more of the following activities:

- Generate fatigue test spectra
- Supplement FLM activity
- Support extension of restrictive interim fatigue clearances

However, care should also be taken to ensure that major fatigue life decisions are made using OLM data representative of service usage. History has shown that the usage of an aircraft on initial introduction to service is not generally representative of longer-term usage.

6 OLM PLANNING PHASE

Adequate planning is essential to the success of any technically complex programme. However, it is all too common for the commercial issues surrounding an engineering project to take centre stage and consequently insufficient emphasis is placed upon the technically complex issues of deciding what has to be done, how it has do be done, by whom and when. Therefore, the planning elements of a generic OLM programme are described in the following sections in a near-chronological order.

6.1 AIM: SUBSTANTIATION OF DESIGN AND QUALIFICATION FATIGUE USAGE SPECTRA AND REVIEW OF FATIGUE CLEARANCES

6.1.1 MOD SI 'ESVRE' POLICY

OLM primarily fits within the Validation of SI measures activity of the current MoD's ESVRE-based SI Policy (JAP100A-01 Chap 1.11). The principal function of these programmes is to substantiate the fatigue usage spectra used in design and qualification of the aircraft.

6.1.2 DESIGN ASSUMPTIONS

<u>OLM Action 4:</u> *Identify and collate fatigue spectra used in the design or qualification of the structure, structural components and stores carried by the aircraft (source fatigue type record or equivalent documentation).*

During development of an aircraft the Designer must make a great many assumptions about the eventual usage of the aircraft. The data supporting these assumptions are drawn from a variety of sources. These may include usage data captured from a previous in-service aircraft type performing a similar role, with adjustments made for changes in capability of the latest design. Additionally, MoD Air Staff will have been requested to identify intended usage, role and stores carriage etc for the new type. These data will be collated into a Statement of Operating Intent (SOI). Designers will then use all these sources of data to develop assumed usage spectra for design and qualification purposes and agree these spectra with the customer.

Nowadays, the vast majority of major military aircraft programmes are multinational projects and one of the consequences of this is a plethora of expected roles for the new aircraft from different nations and services within these nations. In practice, compromise design and qualification spectra are often developed based upon a combination of intended usages. Experience has shown that in general UK usage of military aircraft is likely to be more severe in fatigue damage accrual terms than that of European or US partners. Therefore, from the outset of a new multinational project it is likely that intended UK usage will be more severe than that assumed in design and qualification. That said, historically even for UK single nation projects, in-service usage has generally deviated significantly from design assumptions and this has been highlighted during OLM programmes over the years. Furthermore, in response to rapidly changing military threats it is highly unlikely that an aircraft will be used solely within its originally intended role throughout its life. The change in role and configuration of the Buccaneer[2] in relation to the demonstrated life on test was a classic and fatal illustration of a failure to appreciate the implications of such changes (Davies 1991).

The different fatigue spectra used in the design and qualification of the total aircraft are far more numerous and diverse than one might initially think. For a combat aircraft, initial fatigue spectra might be concentrated on the normal acceleration (Nz) spectrum while for a large transport one might consider the ground-air-ground spectrum and time-at-flight-level gust spectrum. While these spectra may dominate the loading for many of the key structural components of the aircraft, different features in the structure will be driven by different elements and combination of loading actions. A structural component may for example, be subject to symmetric and asymmetric manoeuvre loads, gust loading, buffet loads, landing impact loads, ground handling loads, thermal loading and engine thrust or propeller torque loading.

The increased use of modified civil aircraft adds further issues to consider. Usage in a military environment may be considerably different to that assumed in design. Also, the modifications made to the aircraft (e.g. conversion to a tanker aircraft) may introduce significant changes in local loads within the structure.

Therefore, one of the essential initial elements of the OLM programme is to capture all fatigue design and qualification spectra and identify appropriate methods of assessing these spectra against in-service usage. For an aircraft designed and qualified to Def Stan 00-970 these fatigue spectra should be identified in the Fatigue Type Record (FTR) for the aircraft. In this instance, one of the outputs of the OLM programme, together with flight record data and the Statement of Operating Intent and Usage (SOIU) may then be a transition from a design-spectra based fatigue clearance to an in-service usage based fatigue clearance and this may well lead to the generation of a Part 2 FTR. Where fleets do not have a FTR or where only a partial FTR exists, data may be dispersed around various documents and possibly held by various suppliers within the aircraft programme. To date spectra substantiation has generally concentrated on the

[2] The Buccaneer's role changed from maritime to low-level overland operations; additionally the wing tip region was extended and ejection seat sides were modified to allow the pilot to achieve a greater roll capability.

aircraft aspects; however, with significant changes in the carriage of stores on combat aircraft in recent years, validation of stores, pylon and attachment spectra should also be considered within the OLM programme aims.

6.1.3 SPECTRA SUBSTANTIATION METHODS

OLM Action 5: *Identify appropriate methods for OLM substantiation of each of the design or qualification fatigue spectra. Where practicable direct measurement (e.g. strain gauges) should be used but where this is impractical, parametric-based measurements should be considered as an alternative.*

Once all relevant fatigue design and substantiation spectra have been identified and collated it is necessary to identify which of these spectra can / will be validated by the OLM programme and how this will be done. Direct measurement of loads or strains using strain gauges has been the preferred method of validating fatigue spectra within OLM programmes. (The subject of strain gauge locations is discussed in later sections in this report.) However, there are circumstances where measuring strains may not be practicable and validation of spectra using parametric methods may be preferable.

Despite significant advances in aircraft design capability and the increased fidelity of design tools leading to a greater understanding of the expected loads in aircraft structure, aircraft design is still a largely iterative process. In reality, it is too time consuming and hence costly to optimise fully the fatigue design of every structural component or feature within the aircraft. Many structural components or features are primarily designed statically, often including the use of fatigue design allowables, which permit a quasi-static approach to fatigue design using a design spectrum and peak stress or strain value in the spectrum compared with a maximum fatigue allowable stress or strain in the material or feature. The initial approach to the fatigue analysis of a feature will generally be to make conservative assumptions about the fatigue spectra and function of the feature, such as the load transfer through a joint. If the feature meets the fatigue life requirements and is within the mass allocation, then further refinement and removal of conservatism from the fatigue analysis process may not necessarily be undertaken.

Furthermore, where the fatigue qualification of a feature is supported by fatigue test, the applied test spectra (effectively the qualification spectra) can often be a simplification of the spectra likely to be seen by the feature, concentrating on the prime loading actions and often applying equivalent fatigue damage methods to accelerate testing[3], particularly if features are subject to higher-frequency load cycles in service. Also, even for full scale fatigue tests, compromises in how loads can be applied to the test to generate balanced load cases, due to testing constraints and to focus on representative loading of the key features in the structure (such as the wing-to-fuselage joints) have to be made.

6.1.4 PLANNED REVIEW OF FATIGUE CLEARANCES

OLM Action 6*: A review of the Release to Service and Fatigue Type Record (or alternative fatigue documentation) and identification of remedial actions should be planned to follow the OLM programme. Traditionally, these activities have not been included within the OLM programme itself and have been funded as follow-on actions. These aspects are discussed further in the Analysis and Reporting Section (Section 9).*

Once an aircraft enters service and its usage becomes relatively stable it is essential that the effect of all these assumptions in design and qualification are understood. Firstly, from a safety perspective it is essential that any usage spectra more severe than assumed in design are identified and remedial action put in place. Secondly, usage more benign than assumed has the potential for life extension or to accommodate increases in usage severity in the future. This is illustrated well for a feature underwritten by test in Figure 5, from Cronkite and Gill (1998).

[3] Equivalent fatigue damage methods are used to replace large numbers of small cycles with fewer larger cycles but summating to the same fatigue damage. Care should be taken when using this method to ensure that sufficient cycles remain to replicate any fretting action for example and to ensure that the critical features are not altered by the application of damage equivalence.

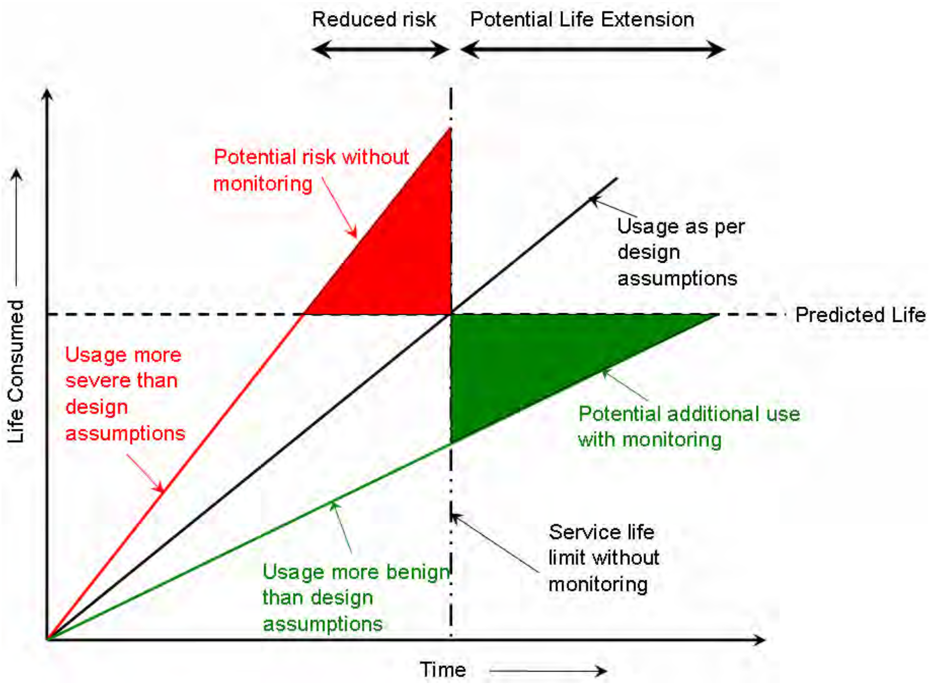

Figure 5 - Benefits of Monitoring (from Cronkite and Gill (1998))

6.2 AIM: IDENTIFICATION OF LOCAL STRESSES IN A STRUCTURAL FEATURE

***OLM Action 7**: Identify all structural features where direct local stress determination is required.*

In addition to the substantiation of fatigue spectra, there may be a requirement to determine the local stresses in a structural feature from overall forces and moments. This scenario might occur when a feature cannot be exercised adequately on a fatigue test for example and hence comparison with test loading would not be appropriate. Although the aim would be to measure strains as local to the feature as possible, this may not be practicable on an in-service aircraft. In these cases load calibration to overall forces and moments and use of structural modelling (such as finite element modelling) may be required to generate an understanding of local stresses in the feature.

6.3 AIM: SUBSTANTIATION OF FATIGUE MONITORING SYSTEM

***OLM Action 8**: Where possible, identify and substantiate all assumptions made within the aircraft fatigue monitoring systems.*

Where the Designer is also the Original Equipment Manufacturer (OEM) then these data should be readily available. However, where the Designer is not the OEM, full access to all assumptions within the aircraft fatigue monitoring system may not be available. In such circumstances the appropriate level of substantiation should be agreed by the OLM Specialist Group and endorsed by the SIWG. An independent assessment of life consumption may be required to provide the necessary confidence in the monitoring system.

6.3.1 INDIVIDUAL AIRCRAFT TRACKING

The usage of all military aircraft is tracked in some way. This ranges from counting take off / landing cycles (flight cycles) or flying hours for the most simple of aircraft in the inventory to full aircraft monitoring using strain-gauge fits installed on every aircraft in a fleet. All of these tracking methods contain assumptions about the usage of the aircraft and even a system as sophisticated as the Typhoon Structural Health Monitoring (SHM) system cannot measure usage in all structural components of the aircraft and therefore some assumptions have to be made.

6.3.2 INDIVIDUAL AIRCRAFT MONITORING

Practicality dictates that a monitoring system should be fit for purpose and accord with the principles of Occam's Razor[4] (i.e. be no more complex than necessary). However, the simpler the monitoring system the greater the extent of assumptions likely to have been made and needed to be substantiated by OLM. The significance of substantiation of the usage monitor is reinforced in a proposed amendment to the monitoring section of Def Stan 00-970, as discussed in Section 4 and included in Appendix C, in which safety factors appropriate for monitored structure can only be invoked once the monitor has been substantiated by comparison with data captured during an OLM programme. To qualify as an effective monitor the system must not, on average, underestimate fatigue damage by more that 10%, when compared with the OLM data. This method of substantiation preserves the safety aspects of monitoring and allows the economic aspects to be developed on a case-by-case basis. Therefore, less sophisticated and consequently less costly monitoring methods can be used as long as they protect the structural integrity of the fleet. This proposed change to Def Stan 00-970 is built upon hard-won

[4] OCCAM, W., (c.1349), Occam's Razor (also spelled Ockham's Razor), is a principle attributed to the 14th Century English logician and Franciscan friar, William of Ockham. It forms the basis of methodological reductionism, also called the principle of parsimony or law of economy. In its simplest form, Occam's Razor states that given two equally predictive theories, choose the simpler.

experience of substantiating a wide range of monitoring systems and this is discussed further at the end of this section.

The basis of the individual aircraft tracking (IAT) or monitoring system for the majority of the current in-service fleets[5] is the fatigue loads meter (or fatigue meter) or a synthesised equivalent of it. As discussed in the historical section, this instrument is a counting accelerometer with lock and release levels set according to the likely operational environment of the aircraft. For a combat and associated trainer aircraft these lock and release levels will be set to capture normal acceleration exceedances associated with manoeuvres; a typical installation would have 8 'g' windows between +8g and -1.5g with the first positive g window set at +2.5g. Alternatively, for a transport aircraft, where the usage spectrum will be dominated by the ground-air-ground (GAG) cycle and the gust environment, typically, the 8 exceedance windows will be set to a range of plus 2.65g to minus 0.35g with the first positive window at +1.25g. The captured g exceedance values and additional recorded data, usually from the Flight and Fatigue Data Sheet (MoD Form 725), detailing masses, role fit, stores, sortie profile code etc, are combined within a fatigue meter formula to provide a measure of fatigue damage accrued during the flight. This is usually in terms of fatigue index (FI), where 100FI corresponds to the safe life of the aircraft. The fatigue computation process, or fatigue meter formula, in its simplest form is a linear function of the counts at each meter window. Fatigue meter formulae, by necessity, contain a great many assumptions. For example, the fatigue meter has no time base and hence assumptions have to be made as to the flight conditions associated with the manoeuvres or gust loading. This is usually defined at the fatigue point in the sky (PITS), with assumed airspeed and altitude and fuel mass distribution. Also, the effect of mass variation from the assumed fatigue PITS will be governed by assumptions which require validation.

The triggering methods for fatigue meter data capture also differ for various aircraft types. Except for a few specific installations, ground loads are not to be captured because the relationship between normal acceleration and say wing load is different on the ground and in the air. For combat and associated trainer aircraft the fatigue meter is usually triggered by a weight-off-wheels or undercarriage door closure switch; for transport aircraft, an airspeed switch is generally used to trigger the fatigue meter. This is to avoid recording of the normal acceleration associated with the landing impact. The complete GAG cycle therefore cannot be captured by the fatigue meter and is covered by ground, take-off and landing loads assumptions in the fatigue meter formulae.

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[5] A detailed review of the fatigue monitoring systems in place across the MoD fleets was undertaken by the DERA in the late 1990s and reported under Jones *et al*. (1998).

Monitoring systems are not restricted to normal acceleration measurements; for example, cabin pressurisation cycles can be monitored using differential pressure recorders. These systems use a similar process to the fatigue meter formula with a predetermined relationship between pressure differential exceedances and fatigue damage being incorporated into a formula with associated assumptions, all of which require substantiation.

In recent years, more sophisticated parametric and strain-based monitoring systems have been introduced and future acquisitions are likely to feature artificial intelligence-based parametric monitoring systems. All these systems require substantiation as they include assumptions, predictions or processes within the monitoring system. Failure to substantiate the system for the current utilisation causes a structural risk in the longer-term and potentially significant economic and operational implications even in the shorter term if for example a modification embodiment point is missed.

6.3.3 RELATIONSHIP WITH LOADS MODEL SUBSTANTIATION

As discussed briefly in Section 4, substantiation of the loads models should be undertaken during qualification as part of the flight loads measurement or survey. Although on occasion OLM substantiation of a structural monitor can expose lack of understanding of the loading actions, generally it is the usage assumptions that prove to be in greater error. For example, considering a relatively simple g-based parametric monitor, if the fatigue PITS for a combat aircraft was assumed in design to be Mach 0.8 but in reality the aircraft is generally operated closer to Mach 0.6 then the centre[6] of pressure would be further forward than assumed. This in turn would affect the loading distribution between the wing attachments with the forward attachment taking a greater proportion of the load. Therefore, if the forward wing attachment represented the critical feature then a parametric fatigue monitoring system based upon design assumptions and established to monitor assumed usage would significantly underestimate damage accrual in service.

Historically, OLM programmes have frequently highlighted major shortfalls in monitoring system assumptions, often resulting in large-scale corrections to fatigue meter formulae. It has not been uncommon for the original fatigue meter formula to under predict fatigue damage by a factor of 2 or more.

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[6] Broadly speaking the Centre of Pressure would lie near the 25% wing chord line at low Mach numbers and moves aft towards 50% wing chord approaching Mach 1.0.

6.3.4 IDENTIFICATION OF ADDITIONAL MONITORING REQUIREMENTS

OLM Action 9: *Identify any additional monitoring requirements and adjustments required to component tracking methods where there are insufficient margins of safety or unacceptable levels of risk, using current tracking measurands.*

The functionality of the structural monitoring systems introduced with an aircraft type will generally be based upon a combination of factors, including:

- Previous experience of similar types and roles
- Safe fatigue life requirements
- Technological development at the time
- Uncertainly in the intended usage of the aircraft
- Likely deviation in usage from that assumed in design

As well as validating this monitoring system, one of the aims of the OLM programme is to identify whether the coverage provided by the monitoring system is adequate to ensure aircraft are operated within acceptable levels of risk. Structural features not protected by a monitor are generally tracked in terms of flying hours, flight cycles, landings, or some appropriate and simply (often manually) recorded measurand. For these items the spectra used in design or qualification should have been compared with measured usage spectra, as described in the previous section. Where the tracking of these unmonitored structural components using these simple measurands does not correlate sufficiently with fatigue damage accrual or where sufficient conservatism to provide a safe relationship between the simple measurand and fatigue damage accrual of the feature would result in unacceptably short lives, then alternative measurands and monitoring options should be considered. For example, the Hawk TMk1/1A OLM programme (Gelder *et al*. (2000)) identified that flying hour accrual was an inadequate method of tracking the fin structure for the Hawk. Evidence from the OLM identified that fins with high flying hours were not necessarily those likely to have accrued the highest fatigue damage and hence there was a high risk of fatigue inspections being incorrectly targeted. Individual aircraft monitoring for the fin structure was considered prohibitively expensive and hence a modified tracking system, rather than monitoring system (hence unmonitored safety factors retained), was introduced whereby OLM data were used to identify a fin damage rate for each sortie profile code. Historical data were assessed to apply these damage rates retrospectively for each fin in service, effectively using role factors. This method has been used to target inspection thresholds and repeat inspection periodicities. Furthermore, the continued applicability of such systems should be checked using OLM data.

Novel aircraft types where there are no historical data (such as UAVs) are likely to have a significant level of uncertainty in their design usage data. Also, projects that use civil-designed aircraft in military roles are most likely to face uncertainty in usage or deviation in usage from that assumed in design. Challenging fatigue life requirements or targets, limited fatigue testing and an aim to reduce inspection burdens may drive the Designer down the avenue of introducing additional monitoring to invoke the reduced safety factors associated with monitored structure. Furthermore, technological development, such as flight control, weapons management and fuel system data readily available on the aircraft data bus systems, for example, may make monitoring systems more attractive and relatively low-cost, compared with modification or inspection costs.

6.4 AIM: CAPTURE OF FATIGUE TEST SPECTRA

OLM Action 10*: If one of the output requirements for an OLM programme is the generation of fatigue test spectra and additional data to validate these spectra (e.g. detailed stresses, accelerations, pressurisation cycles), then this will be a significant design driver for the OLM programme. The OLM aircraft will have to be subject to Skopinski-type calibration in a loads rig. This will allow the OLM data to be described in global loading terms of shear, bending moment and torque for fatigue test load spectra generation.*

One of the additional aims of an OLM programme may be to capture fatigue spectra for use in a full scale fatigue test. This is most likely to fit into one of 2 scenarios. If the fatigue clearance for the aircraft is being conducted along the lines prescribed in Def Stan 00-970, then a pre-production fatigue test will have been undertaken. This test will have provided an initial fatigue clearance for the aircraft using design spectra and will have identified vulnerable features in the fatigue design of the aircraft. Thereafter, a second production fatigue test will be initiated using a production-standard aircraft and tested to a spectra compiled from in-service OLM data. OLM local strain and flight parameter data will also be used to validate the test spectra. Such an approach was taken with the Tucano TMk1 aircraft. A 2-test approach is being taken with Typhoon, although the production fatigue test does not include OLM-derived loads.

The second likely scenario is to support a life extension programme, where a second or extended fatigue test is required to provide the necessary evidence of fatigue durability needed to meet the life extension requirement.

If the planned OLM programme is required to generate fatigue test spectra this will have significant implications for how the OLM programme is conducted. In particular, the capture of load spectra for a full scale fatigue test will require the OLM installation to be subject to Skopinski-type (Skopinski *et al*. 1954) loads calibration in an appropriate rig. This will allow the

OLM data to be described in global loading terms of shear, bending moment and torque for fatigue test load spectra generation. The issues surrounding loads calibration are discussed further in Section 7 of this paper.

6.5 AIM: IDENTIFICATION OF HIGHLY DAMAGING ACTIVITY OR MANOEUVRES

OLM Action 11: *Identify loading conditions likely to generate high load levels for critical features.*

OLM Action 12: *Identify particularly damaging activities or manoeuvres in fatigue damage terms and apportion structural costs to these activities.*

As well as substantiating usage assumptions, monitoring systems and possibly generating fatigue test spectra, one of the aims of an OLM programme is to identify highly damaging activities or manoeuvres. This is an aspect of the programme that can easily be misunderstood and there are several strands to this task. Firstly, comparisons between maximum and minimum load/stress or strain conditions should be made with limit-load and maximum fatigue allowable conditions. For major structural components, such comparisons will identify whether an in-service manoeuvre is likely to generate greater than expected loading conditions. If such risks are identified then either additional evidence should be required to support an increase in the loads envelope or appropriate limitations may need to be introduced into the Release to Service.

Secondly, the aim is to identify the structural cost, in fatigue damage terms, of activities or manoeuvres. This information can then be used by Air Staff to make informed decisions as to the need to undertake such manoeuvres or activities, particularly for fatigue life restricted fleets and potentially to illustrate how education of aircrews can reduce fatigue consumption without significantly affecting mission effectiveness.

Air display is an ideal example of a structural cost that can be clearly quantified. OLM data across various fleets has indicated that air display sorties are generally highly costly in fatigue damage terms. Being able to apportion a structural cost to air display sorties, compared directly to operational or essential training sorties can allow Air Staff to balance usage for fatigue limited fleets. This concept was expanded further for the RAF Aerobatic Team (RAFAT) (Gelder *et al.* (2000)). Here the relative structural importance of elements of the display and break-to-land manoeuvres were identified. This led directly to changes in standard operating procedures of the RAFAT and subsequent reductions in tailplane fatigue consumption with minimal effects on operations.

6.6 AIM: PROVIDE DATA FOR STRUCTURAL ISSUES INVESTIGATIONS

OLM Action 13: *To provide data to support investigation of structural issues or as a life extension programme.*

OLM programmes have frequently been used to provide data to support structural investigations and to exploit potential fleet life extension. In reality, structural issues or exploitation of life extension potential have often been the catalyst needed to initiate an OLM programme for a fleet. Designing additional capacity into the OLM system to meet unknown requirements is challenging. However, these requirements can sometimes met by modifying one or more of the OLM aircraft within a fleet for a relatively short period of time to capture the necessary data for a structural investigation.

6.7 AIM: PROVIDE DATA TO SUPPORT SOIU REVIEW

OLM Action 14: *To provide data for use in a review the Statement of Operating Intent and Usage and associated sortie profile codes from representative OLM data.*

The Statement of Operating Intent, generated during the design process, evolves into the Statement of Operating Intent and Usage (SOIU) (Topic 15S) with the introduction to service of the aircraft. All MoD aircraft have a SOIU and it details the usage and future intended usage of the aircraft. The original intention of these documents was to make the Designer aware of how the military used the aircraft and intended to use the aircraft in the future. The SOIU is also the source document for the various sortie profile codes (SPCs) in use for each aircraft fleet. SPCs provide a manageable method of subdividing the flight data into alike sortie types for trending and further analysis. Initially, on entry to service SPCs will be based upon usage of previous aircraft in the role, with amendments provided by Air Staff as to the likely usage of the aircraft and changes to account for the different capabilities of the new type.

Prior to undertaking the OLM programme, the SOIU and the flight and fatigue data sheets are the prime sources of information on usage of the aircraft. SOIU SPCs represent best estimates of typical usage of the aircraft and hence one of the functions of the OLM programme is to review the data contained within the SOIU.

In reality, the function of the SOIU changes fundamentally once OLM data are available. Representative OLM data provides more definitive information on typical profiles and usage of the aircraft than the SOIU; hence the principal role of the SOIU becomes identifying future usage of the aircraft and identification of usage for stores and pylons for example where OLM data may not be available.

6.8 IDENTIFICATION OF MEASUREMENT REQUIREMENTS

Having identified the OLM programme aims, the next stage in the programme planning phase is to identify the measurements needed to meet these aims.

6.8.1 RELATIONSHIP BETWEEN OLM AIMS AND INSTRUMENTATION REQUIREMENTS

OLM Action 15*: All OLM instrumentation requirements should be reviewed and justified on the basis of meeting the programme aims. However, this justification should include consideration of contingency for expansion of data capture requirements. This review should be undertaken by the OLM Specialist Group and endorsed by the OLM Programme Management Group.*

The OLM instrumentation requirements should be driven by the programme aims. Therefore, there should be a clear review of the use that measured data will be put to before it is included within the OLM system design. Installation of instrumentation that does not contribute to achievement of the aims of the programme has far reaching cost and time implications from design and installation, through data capture, analysis and reporting. However, experience has also shown that additional data capture requirements, unforeseen at the time of systems design, are highly likely and consideration for expansion requirements should be considered. These might include the laying of additional cabling or Ethernet connections while systems are disturbed or ensuring additional capacity within the data acquisition system can be accommodated. Retrospective additions and modifications to OLM systems can often prove extremely costly and can generate significant time delays in programmes. The OLM Specialist Group is best placed to undertake this review and the review report should be endorsed by the OLM Programme Management Group. Where full support of the OEM or the Designer is not available this may have implications for the design of the OLM instrumentation. It is highly likely that a more extensive instrumentation fit will be required to compensate for a reduced understanding of the design and substantiation of the aircraft, including access to flight loads measurement data.

6.8.2 OLM INSTRUMENTATION FIT

In the following sections issues that should be considered when defining instrumentation requirements are discussed. Brief descriptions of specific instrumentation such as strain gauges are discussed.

6.8.3 REVIEW OF FLIGHT LOADS MEASUREMENT AND PREVIOUS OLM INSTALLATIONS

OLM Action 16*: Where flight loads measurement or flight loads survey has been undertaken, a review of the data captured and instrumentation fit should be undertaken to identify the most appropriate sub-set of the FLM instrumentation for inclusion in the OLM fit and to identify any potential weaknesses in the instrumentation fit .*

OLM Action 17*: Where previous OLM programmes have been undertaken on the aircraft type a review of the previous OLM programme should be undertaken to identify relevant design issues, such as: strain ranges, difficulty in interpreting strain outputs or adequacy of data sample rates.*

As previously discussed, OLM is to a certain extent a natural progression from Flight Loads Measurement (FLM) or Flight Loads Survey (FLS), although the external pressure transducers traditionally used for FLM/FLS would not be suitable for use within the in-service environment of an OLM. The FLM instrumentation fitted to an aircraft during the design, development and substantiation process will have been designed to capture the primary loading actions in the main structural components in order to validate the loads models. Therefore, at first glance the FLM instrumentation fit would appear to offer an OLM solution. However, generally, FLM instrumentation will be far more extensive than can be justified for an OLM programme and FLM installations are often not sufficiently robust to be used in-service. However, FLM experience should be invaluable in establishing the most suitable elements of the instrumentation for inclusion in the OLM fit and the FLM data should be reviewed with this aim in mind. FLM experience should be invaluable in providing strain-range information and in assisting with the definition of strain gauge sample rates. Additionally, areas of weakness in the FLM fit, such as sensor vulnerability or unreliability, difficulty in interpretation of strain gauge outputs, EMC issues etc should be identified during this review and suitable changes incorporated within the OLM system design. A similar activity should be undertaken if a previous OLM programme has been conducted on the aircraft type. Also consideration should be given to legacy instrumentation on fatigue test articles for example, where these data to be used within the OLM programme.

6.8.4 STRAIN GAUGE INSTALLATIONS

OLM Action 18: *Where the aims of the OLM programme include fatigue spectra substantiation, the strain gauge installation should be configured to allow direct comparison with fatigue design spectra.*

OLM Action 19: *Where the aims of the programme include comparison of in-service usage against a fatigue test, the fatigue critical sites should be fitted with strain gauges on both the*

OLM installation and the fatigue test. A thorough review of the test loading should be undertaken to ensure the loading on the test at the chosen location is as representative of in-service loading as is practicable.

OLM Action 20: *Where the aims of the OLM programme include provision of data for fatigue test load spectra generation then the OLM installation should include strain gauging located, configured and loads calibrated to allow the calculation of bending moment, shear force and torque values in the structural components from the recorded data.*

OLM Action 21: *Where the programme aims include the generation of local stresses in a feature from overall forces and moments using load calibration methods, the strain gauge location, configuration and structural modelling should be designed to meet this aim.*

OLM Action 22: *Where the OLM programme aims include substantiation of fatigue monitoring systems, strain gauge installation should be located and configured to capture the loading in the critical features protected by the monitor.*

OLM Action 23: *In addition to measurement requirements to meet programme aims, the following factors should be considered in determining the location of strain gauges and strain gauge installations:*

- *Capture of primary loading actions in critical features*
- *Location in low strain gradient position*
- *Vulnerability to in-service damage and maintenance traffic*
- *Access for installation and repair*
- *Ability to undertake surface preparation for strain gauge bonding*
- *Heat sinks in surrounding structure for gauge bonding*
- *Minimise length of strain gauge wiring runs*
- *Cable shielding and grounding*
- *Location of potential sources of interference (e.g. electric motors)*
- *Calibration methods required*
- *Ability to incorporate secondary (back-up) strain gauges and cabling*

Although electrical resistance strain gauges have been in use for over 50 years (de Forrest 1936; Simmons 1942) they are still the mainstay of instrumentation used in OLM data capture. Strain gauge systems rely upon the Wheatstone bridge principle whereby a strain change in the structure to which the measuring arms of the bridge are attached causes an imbalance of resistance across the bridge and generates a small output voltage (mV). This voltage is measured, conditioned and converted to a measure of the strain/stress/load in the structure, using appropriate calibration equations. Strain gauge bridges can be arranged in several different configurations, such as a ¼ bridge, a ½ bridge, a full bridge or rosette depending on the measurement requirement.

Where the aims of the programme include fatigue spectra substantiation then strain gauges will have to be located and configured to meet this aim. For example, if a full scale fatigue test has been carried out or is underway, substantiation of the in-service usage, compared with the test would most likely be achieved by installing a sub-set of the fatigue test strain gauge suite within the OLM installation. This would allow direct comparison, often using un-calibrated[7] strain gauges, between in-service and fatigue test spectra. Knowledge from analysis of the loads paths and strain responses of the test article should be used to identify the most appropriate fatigue test strain gauge subset to include in the OLM installation. Care should also be taken to ensure that chosen locations on the test are subject to representative loading actions. Fatigue tests invariably contain compromises in the way loads have to be applied and how the test article is constrained. Therefore, if for example a relatively minor loading action seen by a feature is not represented on the test but is present on the in-service aircraft (such as a drag loading action) and the strain gauge bridge is sensitive to this loading action, this may cause significant difficulty in generating a test-based clearance for this feature.

If the test does not exercise a feature thoroughly, which will often be the case, the probability of that feature failing at the end of test is extremely small. However, the methodology used to compare OLM data directly with the fatigue test loading assumes that failure occurs at the end of testing, if it does not occur during testing. Hence, for un-failed features, when in-service data are captured and if the OLM spectra are more severe than the test spectra, low fatigue lives will be identified. In the assessment of such cases Def Stan 00-970 recommends the use of supplementary evidence and this would include the fitting factor[8] that had to be applied to the spectra to simulate a failure at the end of test (referred to as setting to the end of test).

[7] Un-calibrated in this context means not subject to loads calibration in a rig.

[8] Factor by which the stress levels have to be amplified to predict a fatigue failure at the end of the application of the fatigue test spectrum.

Also, although assessment in terms of fatigue damage (or crack growth rate) is the ultimate fatigue life currency, this can often be quite a blunt tool. Damage comparison is only really valid when the stress or strain spectra are similar shapes. Therefore, if the strain range seen on the fatigue test is highly dissimilar to that seen on the in-service aircraft, a direct damage comparison may not be appropriate and the feature may not be substantiated by the test. Therefore, once data are available, test and in-service spectra comparison, in addition to fatigue damage comparisons should be undertaken.

Therefore, before embarking upon a comparison of in-service loading with a fatigue test, a thorough review of the fatigue test arrangement should be undertaken. This review should consider the applied test loading, response of strain gauges, in-service issues (such as equipment fitted on in-service aircraft but not on the test and their effect on local response and access to installed gauges). The output of this review should be a recommendation of the most appropriate sub-set of test strain gauge bridges to be installed upon the OLM aircraft.

Alternatively, if the aims of the OLM programme were to include provision of data for assembly of fatigue test load spectra then OLM strain gauging would have to be located and configured so that the outputs from the strain gauge bridges can be combined to produce bending moment, shear force and torque values in the structural components required to be tested and suitable loads calibration methods would be required (Section 7).

Where programme aims include validation of fatigue monitoring systems, strain gauge installation would have to be located to capture the prime loading in the critical features protected by the monitor. For wing fatigue monitoring this has generally been wing-to-fuselage or wing centre-line joint features but the critical features will be aircraft specific.

In practice, as discussed, most OLM programmes will have several of the aims described in the preceding sections to meet and a combination of configurations will often be required. Where there is some leeway or options to be considered for locating strain gauge installations there are a number of factors that should be considered when weighing up the most appropriate gauge locations. Firstly, the aim is to capture the primary loading actions in critical features. Thereafter, strain gauges should be located in regions of low strain gradient to ensure that small errors in gauge positioning are not significant. Locations should be chosen to avoid vulnerability to in-service damage from maintenance traffic and general use. Access for installation and any subsequent repair should be considered. Poor access for installing gauges does increase the risk of a poor-quality bonding and the associated risk of repair being required. Most strain gauge bridges are bonded to the structure with epoxy-based adhesives. Surface preparation is essential to obtaining a high-quality bond with this process and hence access to install the gauge and recover the protective coatings for the structure is essential. For many applications the in-service temperature range will require elevated temperature cure for gauge epoxy-based (or similar) adhesives. A temperature survey will be required to identify heat sinks in the structure to ensure accurate curing temperatures for the strain gauge adhesive. Additionally, as a general rule, wiring lengths from the strain gauge to the signal conditioning unit (which converts the analogue strain gauge signal into digital data) should be kept as short as possible to minimise the effects of cable resistance. However, there are methods of compensating for cable lengths by using sense wires from the data acquisition unit (DAU) to the strain gauge bridge; however this increases loom size by going from a 4-wire to a 6-wire arrangement. For large aircraft in particular lengths of cable runs can be a significant issue. Additionally, that path of strain gauge and instrumentation cables should be considered from an interference perspective and where possible avoidance of interference sources such as high-power electric motors should be avoided. Finally, the method of calibrating the strain gauge arrangement should be considered. For example, for easily removable components, loads calibrations undertaken on static test machines represent an attractive and cost-effective option although consideration has to be given to end constraints and stiffness (Section 7).

The majority of these considerations are common sense but there are inevitably compromises that have to be made between these criteria as some of the considerations can often counter each other. Capturing the primary loading actions in or around the critical features is an obvious requirement. However, where large strain gradients are present in the feature or where access to bond gauges is particularly poor, or where these locations are highly vulnerable to in-service damage or maintenance traffic, then consideration should be given to locating strain gauges in alternative positions and using local structural models, such as Finite Element Models or Boundary Element Models to generate stress transfer functions from the gauge location to the critical feature.

6.8.5 STRAIN GAUGE INSTALLATION RELIABILITY

OLM Action 24: *A reliability review of the proposed strain gauge installation should be undertaken. The scope of this review should include:*

- *Gauge and wiring installations located in vulnerable locations*
- *Gauge specification*
- *Surface preparation and bonding methods*
- *Gauge protection from damage and water ingress and gauge markings*
- *Vulnerability to maintenance or usage*

- *Competency and currency of strain gauge installation technicians*
- *Clear marking of strain gauge installations*
- *Provision of additional strain gauged removable components*

Historically, the reliability of strain gauge installations across OLM and direct strain-based fatigue monitoring systems has been mixed. Combating poor reliability must begin in the planning phases of the programme. Where it is imperative that a strain gauge installation is located in a relatively vulnerable location then the maximum protection and marking should be afforded to the installation and a programme of education of maintenance staff undertaken. Gauge locations should also be carefully reviewed against routine maintenance procedures to ensure that vulnerable installations are avoided. Furthermore, experience has shown that surface preparation is the key to successful bonding of gauges to the structure and detailed processes are defined by the British Society of Strain Measurement (BSSM 1992) and in relevant Industry Processes.

6.8.6 BACK-UP STRAIN GAUGE INSTALLATIONS

<u>OLM Action 25:</u> *Secondary or back-up strain gauges and wiring should be introduced where practicable.*

It is efficient practice to install secondary or back-up gauges during installation, where a similar response from primary and secondary systems is expected. Additionally, channels should either be recorded simultaneously, if capacity allows, or a relatively simple, but controllable switch-over system should be installed. Hence, if gauge failures do occur, secondary systems can be used until gauge repair can be undertaken during scheduled maintenance. The alternative is either repair outside of scheduled maintenance down time or lost data. Symmetric gauge installations can also provide a level of back up from read across, once the asymmetric effects have been identified.

6.8.7 PARAMETRIC AND DISCRETE MEASURANDS

<u>OLM Action 26:</u> *Parametric data capture requirements should be justified in meeting programme aims. Uses for parametric data may include:*

- *Provide confidence in strain data*
- *Identify flight conditions for airborne calibration or cross checks*

- *Generate fatigue spectra for substantiation of design assumptions where strain measurements are impracticable*

- *Substantiation of monitoring system or development of a monitoring system (e.g. training data for advanced parametric monitoring system)*

- *Review of the SOIU SPCs*

- *Triggers for data recording*

- *Provide data for improvements in parametric structural monitoring systems*

Non-strain gauge parametric data are defined here as continuous measurements within a pre-defined range. Discrete measurands are Boolean in nature and occupy one of 2 states, on/off or 1/0. Within the remainder of this section parametric data should be interpreted as meaning both parametric and discrete data. The instrumentation most commonly used in OLM programmes to obtain parametric data include accelerometers, synchros, potentiometers, tacho generators, gyroscopes, flow meters, switches, thermometers and pressure transducers.

As with strain gauge instrumentation, the requirements for parametric data captured within an OLM programme should be driven by programme aims. Uses to which parametric data are put can be quite varied. Traditionally, the prime role of the parametric data has been to provide a basis for understanding the strain/stress/loads (referred to as strains hereafter in this section). A simple example of this would be comparing an inner wing bending moment plot with the normal acceleration parameter. A peak bending moment would be expected to have a corresponding peak in the normal acceleration (Nz) parameter. The occurrence of a peak in either the wing bending moment or Nz time history without a corresponding peak in the other should spark further investigation. Additionally, combinations of parameters, such as airspeed, altitude, accelerations, roll and pitch rates etc can be used to identify a flight condition or particular manoeuvres. This may be essential in cases where airborne calibration or check calibration of strain gauges is required (airborne calibration is discussed further in Section 7). Also parametric data are used to understand the strain response, for example, when the deployment of a flight control surface induces buffet loading in the structure.

Furthermore, where strain monitoring of a feature is impractical it may be necessary to use parametric data to substantiate the fatigue spectra. Substantiation of the performance of an aspect of the parametric monitoring systems, such as the lock and release levels in the fatigue meter, is also generally undertaken using a flight test instrumentation standard normal accelerometers. Parametric data will also be the prime source of information used to review the SOIU. Sortie Profile Codes (SPC) are described using an altitude profile with airspeed together with typical Nz exceedance values. Data recording can be triggered using parameter thresholds or combinations of parameter thresholds.

Where a parametric structural monitoring system is shown to be inadequate then additional (i.e. not used by the monitor) parameters captured during the OLM programme could provide the basis for developing an adequate structural monitor.

6.8.8 CAPTURING PARAMETRIC DATA FROM DATA BUS SYSTEMS

OLM Action 27: *Capturing parametric and discrete data from aircraft data bus systems is an attractive and potentially highly cost-effective option but the data should be confirmed as fit for its intended purpose within OLM. An understanding of the origins of the data, any manipulation undertaken on the data and the effects of data management systems used by the data bus controllers should be obtained to ensure that fitness for purpose can be assured.*

The majority of modern aircraft used in military roles are fitted with data bus systems. Military aircraft generally use Mil Std 1553 or similar data bus systems and civil-derived aircraft tend to use ARINC 429 or similar systems. A brief explanation of the workings of these data bus systems is provided in Appendix E. Many of the parameters needed to support an OLM programme may well be available on these data bus systems as they are required by flight control systems, fuel management and stores management systems. Additionally, most modern data acquisition systems will have acquisition cards for interpreting data from these buses. Furthermore, if these data are used by mission-critical and possibly flight-critical systems then they will be maintained and repaired quickly should faults arise. Therefore, capturing the data stream from a data bus appears a highly attractive option for many of the required parameters. However, care should be taken to ensure the parameter provided on the data bus is fit for the purposes of OLM.

Refresh rates onto the data bus are often quite low (e.g. 5 times per second). Also, data on the bus can often be stale (i.e. it has not been refreshed and is merely a repeat of the previous data). Furthermore, data refresh rates quoted as 5Hz may not necessarily be sampled every 0.2 seconds; rather it may be data sampled at 5 times within each second, depending upon the mission computer work load and priorities. Additionally, it is imperative that the original source of the data and any corrections applied to these data are understood. For example, one of the prime parameters used in an OLM programme would be normal acceleration (Nz). The normal accelerometer should be positioned as close to the centre of gravity of the aircraft as possible. However, a signal on a data bus described as Nz could equally originate from a cockpit mounted inertial navigation platform; this parameter may or may not have a pitch and roll rate correction applied to simulate Nz at the centre of gravity. Also the accuracy, resolution and bandwidth[9] of the original source should be considered. Time synchronisation of signals from the data bus with data from other sources should also be considered and this is discussed further later in this section. These factors do not preclude the use of data from the aircraft data buses but they must be addressed.

6.8.9 CAPTURING PARAMETRIC DATA FROM AIRCRAFT INSTRUMENTATION

<u>OLM Action 28:</u> *Tapping into existing aircraft systems should be considered where essential parameters cannot be captured from data bus systems or where the data available on the bus are not suitable for the OLM aims. Generally, tapping into primary flight instrumentation systems should be avoided due to the increased risk posed to these systems. However, modern ADR/CSMU systems are often fitted with data ports and accessing these data should be considered.*

Where an aircraft is not fitted with a data bus or essential parameters cannot be captured from data bus systems or where the data available on the bus are not suitable for the OLM aims, tapping into existing aircraft instrumentation or the installation of OLM-specific instrumentation will be required. From a design, qualification and through-life support perspective, use of existing aircraft instrumentation represents a far more cost effective approach. However, tapping into primary flight instrumentation systems, such as pilot's altimeter, should generally be avoided due to the increased risk to these systems. Additionally, as with data bus systems, an understanding of the specification of the instrumentation is essential. Furthermore, the form of the output signal produced by the instrument should be identified as the data acquisition unit will be required to condition this signal. Generally, taking a tapping from existing aircraft instrumentation is likely to be a more costly option than extracting the data from a data bus due to cable runs, signal conditioning and the implications of breaking into aircraft systems. Moreover, consideration has to be made as to whether the tapping loads up the signal.

Where aircraft are fitted with Accident Data Recorders (ADR) or Crash Survivable Memory Units (CSMU) tapping into input or output ports for these systems can also be considered for OLM data capture. Interfacing with ADR systems has generally been discouraged due to the risk of interfering with these systems; however, modern systems in particular are often fitted with output data ports and these options should be considered.

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[9] The bandwidth is the frequency range containing useful information

6.8.10 INTRODUCING OLM-SPECIFIC INSTRUMENTATION

OLM Action 29: *It is most likely that OLM-specific instrumentation will be required (such as accelerometers). As well as fitness for purpose, consideration should be given to equipment reliability, vulnerability in the operational environment, long-term support and additional data acquisition signal conditioning requirements.*

Experience has shown that even short–term OLM programmes last considerably longer than ever envisaged at the outset and long-term support of the installation should be considered within the system design.

6.9 NUMBER OF OLM-INSTRUMENTED AIRCRAFT

OLM Action 30: *Historically, instrumentation of around 10% of the fleet fit, ideally with a minimum OLM fit of 2 aircraft, has proven a reasonable proportion for planning OLM installations, However, each programme should be judged on a case-by-case basis and the factors considered should include:*

- *Programme aims*
- *Fleet size and disposition*
- *Roles within the fleet*
- *Fleet-within-fleet issues (including structural build standard)*
- *OLM installation capability and reliability*
- *Cost*
- *Attrition*
- *Volume of data required against collection time*

One of the most vexing questions posed within the planning phase of an OLM programme is how many aircraft within the fleet should be instrumented. In practice there is no definitive answer to this question but there are a range of factors that should be considered when making this decision and these are discussed in the following sections. Historically, installing OLM installations on around 10% of the fleet has proven to be a reasonable starting point for planning the extent of the fleet fit to achieve an adequate data capture rate across a spread of aircraft.

6.9.1 Programme Aims

As with everything else in an OLM programme, one of the key criteria in deciding the number of instrumented aircraft required is the OLM programme aims, time scales required to meet these aims and cost. For example, in a scenario where one of the aims of the programme is to develop full scale fatigue test spectra then the number of OLM instrumented aircraft will be partially driven by the need to obtain a test-based fatigue clearance in a timely and cost-effective fashion. Time scales for achieving this clearance may dictate a larger number of instrumented aircraft to allow more rapid data capture but this will have cost implications.

6.9.2 Fleet Size and Disposition

The size and disposition of a fleet will also affect the number of OLM aircraft instrumented. Practically, where fleets are widely dispersed or frequently deployed, capturing representative OLM data will either take longer or will require more instrumented aircraft.

6.9.3 Roles Within the Fleet

The range of roles undertaken by the aircraft will affect the number of instrumented aircraft required. Where roles are clearly defined and well bounded, such as a basic flying trainer aircraft, fewer OLM aircraft would be required to capture usage in reasonable time scales. However, for a combat aircraft fleet with, for example, an air-to-air role, air-to-ground role and training role, capture of sufficient quantities of representative data will inevitably require more instrumented aircraft or longer data collection periods with aircraft rotation.

6.9.4 Fleet-Within-Fleet Issues (including Structural Build Standard)

Fleet-within-fleet issues are particularly relevant to combat aircraft where avionic upgrades, partial fleet weapons capability, software standards, engine upgrades and partial fleet structural modifications can significantly affect the usage and loading of different aircraft within the fleet; hence requiring OLM aircraft representative of the mini-fleet configuration. However, as well as the more obvious avionic capability issues, the structural build standard, particularly of large fleets which may have various Tranches or Blocks need to be considered. Fleet-within-fleet coverage by OLM should be addressed either by rotation or dedicated aircraft. Non-coverage of mini-fleets should be justified and endorsed by the SIWG. Furthermore, this issue should be considered carefully in the selection of aircraft to be modified to the OLM role to ensure essential coverage can be achieved.

6.9.5 OLM INSTALLATION CAPABILITY AND RELIABILITY

The capacity of the OLM acquisition system in terms of the number of measurements that can be taken and the reliability of the system will significantly affect either the time scales of data capture or the number of aircraft that have to be instrumented. Where an extant OLM system is in place but its capacity is insufficient to undertake the entire OLM data capture requirement on a single aircraft it may be necessary to split the task over a number of aircraft, thereby increasing the instrumentation requirement. Acquisition capacity is less of an issue with modern data acquisition units. However, where older equipment is in use or where a large number of gauges are sampled at high rates, such as undercarriage OLM or buffet monitoring exercises, capacity may become an issue. Reliability of the OLM system as a whole from the strain gauge bridges to the data download process will obviously affect data capture rates.

6.9.6 COSTS

Cost will always be a key issue in any decision over the number and extent of instrumented aircraft. It is impossible to identify generic costs reliably for an OLM programme as there are too many variables to consider. However, a frequently made error in driving out costs from OLM programmes is to concentrate on data acquisition equipment costs. In reality, the cost of any OLM-specific hardware will be small compared with the rest of the programme costs and great care should be taken to avoid false economies in acquisition equipment procurement and costly knock on issues throughout the programme.

6.9.7 ATTRITION

Likely attrition losses, dependent upon the type of aircraft and its role should be considered in determining the number of instrumented aircraft.

6.9.8 VOLUME OF DATA AGAINST COLLECTION TIME

Careful consideration needs to be taken of the trade off between data capture rates and the number of instrumented aircraft in the fleet. Data capture rate estimates have invariably proved optimistic in most programmes. Historically, even in fleets with relatively large numbers of instrumented aircraft, maintenance, repair and operational requirements can often conspire to produce pitiful OLM data capture rates. Therefore optimistic planning should be avoided.

6.10 REVIEW OF FATIGUE ANALYSIS METHODS

OLM Action 31: *A review (or development) of the fatigue analysis process in the context of OLM should be undertaken and should include:*

- *An investigation into the suitability of design 'fatigue-life' curves used for OLM analysis (e.g. S-N, ε-N or or da/dn - ΔK curves)*
- *Implications of differences between design and usage spectra content*
- *Likely effects of fatigue analysis fitting procedures including situations where excessively large fitting factors occur (e.g. above 1.5-2.0) or factors below 1.0 are produced.*
- *Development of an appropriate fatigue analysis process for use within the OLM programme if required*.

As OLM is primarily a substantiation exercise and the fatigue analysis processes established for the aircraft type should be used within the OLM data analysis process, where possible. This process will be fundamentally a stress-life, strain-life or damage-tolerance approach but within these methodologies there are significant variations in the implementation of the fatigue analysis process between designers. A detailed explanation of the various methodologies is outside of the scope of this paper. In addition, the term 'fatigue-life curve' is used in this paper to describe stress-life (S-N), strain life (ε-N) or crack growth (da/dN - ΔK) curves.

Although the fatigue process for the aircraft type should be well established, the process will have been focussed on the design and qualification of the aircraft type. Substantiation of this design and qualification process using OLM data can highlight issues not previously exposed; therefore a review of the fatigue analysis process should be undertaken in the context of OLM. The need for this can be illustrated well with a relatively simple example which is shown in Figure 6. Figure 6 portrays a stress-life methodology but this is equally applicable where analysis methods are fitted to test results irrespective of the underlying lifing methodology.

Design spectra themselves often include simplifications of the assumed loading and when these design spectra are converted to test spectra often further simplification are made to increase the test speed or reduce the cost of the test. If a particular design spectrum were to contain large numbers of small high-frequency cycles then these small cycles might be replaced in the test spectrum with fewer larger cycles using an 'equivalent damage' or similar method. At the end of the test, a fatigue performance algorithm would be 'fitted' to a test failure point or end of test if no failure occurred. This 'fitting' process involves factoring the stresses in the test spectrum until a failure corresponding to the test failure point or end of test can be predicted using the feature design fatigue-life curves. Thereafter, a usage spectrum would be assembled from OLM data and the fatigue life validated using this in-service spectrum with the test ‘fitting’ factor applied to the spectrum. However, if as per the example in Figure 6, the test spectrum occupied a different region of the fatigue-life curve than the OLM data then the fatigue life obtained from this validation process would be very dependent upon the shape of the fatigue-life curve in the region of cycles in the OLM spectra but not in the test spectrum. If the fatigue-life curve in the OLM region was steep, a short life will be calculated. Conversely a shallow curve in this region would produce a longer life. However, both curves would produce the same life under the test spectra and the same fitting factor. In such cases, comparison of exceedance plots for test and OLM data would expose the stress or strain ranges in the spectra and a review of the shape of the fatigue design curve in the OLM-only data range region should be undertaken.

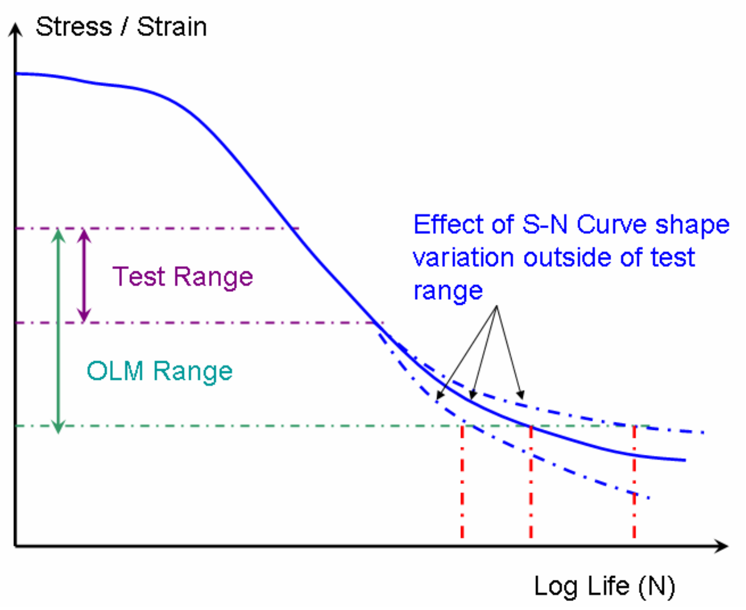

Figure 6 – Example Illustrating Potential Fatigue Analysis Process Issues

If a fatigue test does not exercise well a particular feature (i.e. the strain levels in this feature under test are significantly below the level likely to cause failure) the fatigue analysis fitting procedure will generate large fitting factors. This means that the test spectrum would have to be amplified by a large amount (e.g. over 1.5 – 2 or above) to predict a failure under test. Therefore, if the OLM spectra are more severe than the test spectra, when OLM strain data are amplified by the same fitting factor it is likely that particularly short fatigue lives will ensue. However, this can often be a function of the test not sufficiently exercising the feature rather than a real risk of fatigue failure in service. In such circumstances Def Stan 00-970 recommends the use of supplementary evidence to support a fatigue clearance.

Conversely, fitting factors below 1.0 (i.e. where failure is predicted before the end of the test) should be investigated further to ensure that appropriate fatigue curves and spectra have been used.

Furthermore, if the Designer is not the OEM, or where neither Designer nor OEM are providing support, a fatigue analysis process to support the OLM programme may have to be developed. Lack of visibility of key data from the Designer potentially adds a significant additional complexity and risk to the programme. The approach taken will have to be considered on a case-by-case basis and will depend upon the extent of fatigue design and substantiation data available. However, in such circumstances, simple, understandable processes should be used where possible. For example, although an aircraft may have been designed using damage tolerance principles, the lack of information on the fracture mechanics methodology used within the design process may mean that a stress-life approach[10] may be a more useful tool for understanding the UK military usage of the aircraft than attempting to reverse engineer the fracture mechanics approach. Where such issues exist, the fatigue analysis methodology should be agreed by the OLM Specialist Group and endorsed by the SIWG.

6.11 OLM SYSTEM DESIGN

<u>OLM Action 32:</u> *An up-to-date review of available OLM equipment technology should be undertaken to ensure that appropriate capability and best value for money can be obtained. This should include a review of recent experience on other projects and, where possible, use of common equipment.*

This section of the paper is focussed upon aspects that should be considered when planning the OLM system design. The aim is not to identify particular equipments but rather to provide the reader with sufficient information to make informed decisions in equipment and design selections. Technology in the field of data acquisition and recording equipment is advancing rapidly Hence many of the constraints on signal conditioning capacity prevalent 10 years ago are no longer issues. Further rapid development, particularly in affordable digital memory, largely driven by video technology, looks likely to continue apace and hence up-to-date market research at the time of planning an OLM is essential to obtain appropriate capability and best

[10] Linear elastic fracture mechanics methods assume that the crack elongation is a function of its original length as well as the incremental applied stress/load spectrum, whereas the stress-life approach considers the incremental damage contribution from the spectrum to be independent of the *a priori* damage accumulation.

value for money. Recent cross-project information is highly relevant and full advantage of this hard-won experience should be taken.

6.11.1 INTEGRATED OLM SYSTEMS

OLM Action 33: *Where OLM functionality is integrated into other system architectures, care should be taken to ensure that OLM-specific requirements, such as data integrity rates, are respected within the overall system design requirements. It is essential that sufficient bandwidth is allocated to OLM functions within the integrated system.*

The Future Fatigue Monitoring Systems report (Jones *et al*. 1998) provided a strong recommendation for OLM systems to be integrated into the fleet wide fatigue monitoring or IAT system. With rapid advances in modern avionics equipment and the development of common backplane systems[11], for example, this approach is extremely attractive for new aircraft types, although retrospective installation of such systems to meet OLM requirements could be prohibitively costly. The issues discussed in the following sections are valid, irrespective of whether the OLM system is integrated into other avionic systems or is stand alone.

For integrated systems however there are several additional issues to consider. OLM requirements for issues such as data integrity can be far higher than other systems, even if these systems are mission critical. For example, a digital video data stream will require memory capacity far in excess of an OLM system, even with video-data compression. Therefore, video capture may well drive memory requirements for common data systems. However, the effects of intermittent loss of short time periods of video data is unlikely to affect significantly the functionality of this system but similar data loss for an OLM system can undermine confidence in the OLM data. This simple example illustrates the importance of ensuring common system architectures still preserve the OLM requirements.

6.11.2 DATA ACQUISITION

As discussed previously, the aims of the OLM programme will determine the measurements required and this will in turn define the instrumentation required to capture these measurements. The purpose of the instrumentation system is to take measurements of the parameters (e.g. acceleration, velocity or displacement) and provide data which are used for analysis. The basic

[11] Common backplane avionic systems use, as their name suggests, a common backplane along which data and electrical power lines travel. This system allows various cards undertaking different signal and data processing tasks to be included in the same avionics box.

block diagram, as illustrated in Figure 7 below, illustrates the essential elements of an instrumentation system.

The parameter is sensed by a transducer, which in turn produces data, often in the form of an analogue voltage. These raw data are passed to the signal conditioning unit to be processed into a suitable form having been scaled, filtered and usually converted into digital data. Thereafter the data are transmitted to a data recorder unit.

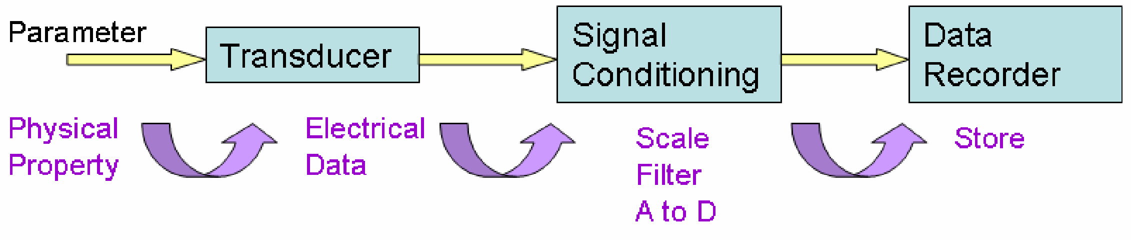

Figure 7 – Data Acquisition

6.11.3 TRANSDUCERS

OLM Action 6.34: *When considering transducer fits for OLM installations, conditioning of the transducer output and its reliability, robustness and support for long-term use within an operational environment should be considered.*

Most transducers used in OLM applications are relatively standard flight test instrumentation (FTI) units that have been widely used in similar applications. However, flight test instrumentation requirements are generally short term and flying rates for FTI aircraft are generally fairly low. Therefore, when considering transducer fits for OLM installations account should also be taken of transducer reliability, robustness and support issues for long-term use within an operational environment.

Additionally, the output from transducers can vary significantly from simple linear voltage outputs (e.g. 0.25V per 'g' for an accelerometer) to a synchro' (often used for angular measurements) in which the ratio of 3 ac phase voltages provides a means of data transmission. Therefore, the transducer output and facilities to condition this output with the data acquisition system should also be considered

6.11.4 STRAIN GAUGE EXCITATION

OLM Action 35: *Consideration should be given to recording the strain gauge excitation voltages generated from the DAU to ensure that these remain within acceptable limits. .*

Most OLM transducers are powered remotely. However, excitation (powering) of the strain gauges is usually undertaken by the data acquisition unit (DAU), using the strain gauge conditioning card. Generally, strain gauges are excited with a +/-5V supply and using a twisted shielded pair cable to reduce common mode effects (i.e. the use of a +/- voltage and twisted cables means noise effects cancel out rather than distort the signal).

6.11.5 SIGNAL CONDITIONING AND AIRBORNE DATA STORAGE

OLM Action 36*: Where data acquisition units and data recording systems are being procured or designed to support OLM programmes then the following issues should be considered in the selection process including:*

- *DAU and recording system capability to meet OLM signal conditioning and recording requirements*
- *Method of establishing reliable common time base*
- *Availability of environmental qualification data*
- *System flexibility in reconfiguration and expansion (50% memory and data capture capability recommended)*
- *Procurement and support costs but avoiding significant long-term implications from short-term procurement economies.*
- *DAU manufacturer's support provision*
- *Obsolescence risks*
- *Configuration control*

The function of signal conditioning is generally carried out within a DAU. The function of the unit is to capture input signals from various sensors or data buses. Where the signals are analogue they are conditioned and converted to digital data by sampling and quantization. When they are already digital data, such as from a data bus, signals are converted into a format compatible with the rest of the data set. Thereafter, the data are sent to either an integral (to the DAU) or external recording device. The function of signal conditioning can be housed in a single unit or can be distributed around an aircraft over several units. Signal conditioning is required because analogue data, such as mV output from a strain gauge are vulnerable to interference, resistance changes, temperature effects or moisture effects. The conversion of these analogue signals into digital data (termed analogue-to-digital (A-to-D) conversion) as close to source as possible reduces the likelihood of data corruption and allows the transfer and process of information within a digital system.

The rapid advance in data acquisition and recording unit technology over the past 10 years or so has had a marked effect on the conduct of OLM programmes. It is not the aim of this paper to specify particular technology or equipment. However, an acquisition system should have the capability of conditioning and recording all the required transducer and data bus signals required for the OLM programme and should provide transient suppression. As previously discussed, the output from different transducer types can occur in many forms and each of these must be recognised and conditioned or often excited (in the case of strain gauges for example) by the DAU. Modern systems tend to be modular and acquisition modules or cards, such as strain gauge conditioning, acquisition cards or Mil-Std1553 data bus cards are fitted into the system as required. Most DAU manufacturers have a range of standard catalogue acquisition cards. However, a proactive manufacturer will be increasing and developing its range continually. Additionally the manufacturer may have developed bespoke acquisition cards for previous applications, or may be prepared to develop bespoke cards for a particular application. Hence, if the equipment catalogue range does not meet all the OLM signal conditioning requirements then the manufacturer should be approached to discuss options. This will also give an indication of the likely support forthcoming from the DAU manufacturer and this is an extremely important aspect of equipment selection.

Modern systems generally include 16bit A-to-D conversion and hence a signal can be converted into digital data in a range of 0-65535 and hence a high degree of resolution can be obtained (previous generation DAUs were often 10-bit systems (0-1024 digits). Functionality such as one A-to-D converter per channel allows all channels to be sampled at the same time (isochronous sampling). Furthermore, far greater flexibility in choice of sample rates is now common due to over-sampling and digital filter with decimation capability. This means that although the user may define a sample rate of for example 256 samples/s, the analogue data will actually be sampled at many times that rate and conditioned, using filters to provide a high quality 256 samples/s signal. Selection of sample rates and filters are described further later in this section.

Establishing a common time base for OLM data is essential to ensure that data are synchronised and that periods of missing data can be identified. There are currently various methods of achieving this, such as dedicated time clock data acquisition cards or tapping into a Global Positioning Signal. Failure to invest in a reliable method of determining the time base is a false economy and is highly likely to generate significant additional costs in analysis or loss of large quantities of data were synchronisation cannot be achieved reliably.

If a COTS OLM system is being procured, rather than an integrated and possibly bespoke monitoring and OLM system, then the equipment should be offered with appropriate environmental qualification evidence. This should cover aspects such as temperature, electromagnetic compatibility, vibration and shock loading (examples of qualification standards include Mil-Std-810F and BS 3G 100). Comparison between the equipment qualification and the environment for the proposed location for the DAU in the aircraft (location is discussed further later in this section) should be made. When comparing DAU equipment options, any additional qualification work and the costs associated with it should be included within the comparison.

Investment in high quality transducers will be wasted if the performance of the signal conditioning unit is poor. There are several quality measures used for assessing performance. The DC accuracy of an analogue channel is the most common indicator of quality. Typically modern systems quote around 0.5% to 0.25% of full scale with future systems likely to be quoted in the region of accuracies of 0.1% over the operating temperature range. Alternative performance indicators used are signal-to-noise and distortion (SINAD) and effective number of bits (ENOB).

DAU flexibility is an essential element of an OLM programme and should be considered from several perspectives. The DAU should be easily reconfigurable without return to the equipment manufacturer. For example, changes in sampling rates (discussed later in this section), sampling plan or measurands (what is measured), recording trigger etc should be user definable changes. It is expected that undertaking these changes would generally need specialist training and knowledge but should not require return to works of the DAU. Flexibility should also be considered in terms of capacity in both the number and type of measurands, sample rates and memory capacity. Experience suggests that an allowance for expansion of around 50% should be made in the system design to cater for additional requirements yet to be identified. This expansion capacity is more likely to be required in strain gauge channel acquisition requirements than in a significant increase in parametric or data bus requirements.

Modern distributed systems have great potential for adding flexibility to OLM equipment architecture and this may well be a convenient and cost effective method of building in expansion capability. For example, if 15 aircraft in a fleet of 150 aircraft are fitted with a baseline OLM installation, several of those aircraft could be fitted with additional ‘slave’ units to provide facilities as required for OLM expansion. Furthermore, a master-slave arrangement with connection between the units utilising network systems such as Ethernet, FireWire or FibreChannel would allow minimal cable runs between master and slave units. In such cases it is likely to be cost-effective to install master-slave network cabling during the initial OLM installation for the later addition of slave units. Network cabling, rather than analogue strain gauge twisted pairs would require several cables rather than a full wiring loom. An undercarriage OLM would be an excellent example of a requirement that could be met by such an arrangement. An undercarriage OLM programme would not warrant all 15 OLM aircraft being modified to meet the data capture requirements. For many aircraft continuous monitoring of undercarriage data for the life of the aircraft is not required. Therefore, by using a slave DAU fitted to several aircraft in the fleet for a data capture period and linking the slave to the DAU master, a cost effective undercarriage OLM installation could be added to the core OLM function.

Historically, one of the major limitations in DAU and recording systems has been data storage capacity or memory. Until relatively recently, tape systems, such as DAT tapes were the only viable and cost effective method of recording reasonable quantities of OLM data. Rugged tape systems have provided good service over the years but they brought with them problems with data loss, tape failures, obsolescence, recorder and playback failures and an often quite significant maintenance burden. Solid state memory has always been an attractive option technically but until recently, cost-effective memory capacity limited its application. Furthermore, the development of DAU systems themselves has significantly increased the memory capacity requirements. In recent years the advancements in commercial electronics equipment has driven down the cost of solid state memory and this now presents an attractive and feasible option for OLM systems. For removable memory modules, current PC flash card format and Compact Flash technologies offer many GB of data storage at reasonable costs.

To put this into context, a 6GB Compact Flash card would allow for 75 parameters at 256 samples per second to be recorded for around 2 days continuously without download. PC flash card technology offers many times higher memory capacity options. The key advantage of using such removable memory technology is that once the hardware recording technology is in place the memory cards can be upgraded as affordable capacity increases or as memory requirements change during a programme.

Cost will always be a large driver in any technical programme. However, it is most probable for any OLM programme that the DAU and recording system costs will be relatively small compared with design, installation, analysis, reporting, support and project management costs. Also false economies in the procurement of DAU equipment are easily made and can have costly repercussions throughout the programme. Capture of time information is a classic example that reinforces this point well. Even in the simplest of OLM installations time stamping is essential to allow the analyst to identify any missing data in the time histories and to correlate the OLM data with manual records. When systems become more complex and data are collated from various sources including data buses and often from several different recording systems, time stamping to ensure data are in phase, becomes even more critical. Where a common time parameter is not available on the aircraft then a real-time clock (RTC) or equivalent time source (such as GPS time) is required within the DAU. Removal of this RTC card from the DAU requirements would be a target for cost savings. However, the potential risk of significant follow–on costs in data analysis due to mismatch of data from several sources and in trying to correlate data with manual records can be enormous and can lead ultimately to the rejection of large quantities of otherwise fit-for-purpose data.

Support for the DAU and data recording system is an essential element within the OLM planning phase. For all but the largest military fleets, the size of an order for stand alone OLM equipment is going to be relatively modest to most DAU manufacturers. Alternatively, where systems are integrated into a fleet-wide monitoring system then the production run can be quite significant. Nevertheless, generally order size will provide only limited leverage and hence the typical level of support provided by the DAU manufacturer will be extremely important to the success of the programme. OLM installations are not 'plug and play' therefore the aircraft designer will require support during the design, installation and through life of the system. Therefore the likely support provided by the DAU manufacturer in design, installation, software, spares and expertise should be assessed as part of the procurement selection process. Undertakings from the DAU manufacturer for support of the DAU and acquisition cards should be sought and risks of obsolescence should be highlighted. That said, in a rapidly changing electronics industry it is unrealistic to expect a manufacturer to support a DAU for the life of the aircraft type and more realistic undertakings should be sought. Spares holdings are discussed later in this report.

Mechanisms for maintaining configuration control of the DAU, acquisition cards and programming software should also be considered within the system design process. Also aircraft interfaces, such as data buses, where modifications and upgrades can generate changes to data items or their characteristics should be considered.

6.11.6 ADDITIONAL RECORDING REQUIREMENTS

OLM Action 37: *Appropriate internally generated DAU data health reports should be recorded and incorporated into the data analysis process. Where several OLM aircraft are in the fleet, tagging the data with a correct tail number identifier should be instigated.*

6.11.7 DATA SAMPLING RATE AND ANTI-ALIAS FILTERS

OLM Action 38*: Strain gauge data should be sampled at a rate at least 10 times the frequency of the highest significant structural mode and have adequate bandwidth to ensure values sufficiently close to the maximum and minimum values in the time history are captured. Where* *insufficient evidence is available to identify the highest significant structural modes sample rates should be initially set to higher than expected rates and reduced when evidence is presented that the loss in fatigue damage and strain range at a lower sample rate is acceptably small.*

OLM Action 39: *In addition to being sampled at a rate at least 10 times the maximum significant frequency, the sample rate for parametric data should be consistent with its intended OLM use. This sample rate should be set with cognisance of the bandwidth of the original transducer output or data bus refresh rate. However, with the increased capacity of modern acquisition and recording systems the use of common sample rates across a range or all parameters, set at the highest sample rate, can be considered. This option reduces or eliminates delay differences due to filtering.*

OLM Action 40*: DAU anti-aliasing filters should be used to prevent the inclusion of unwanted frequencies and the consequent aliasing of the data signals. Where data are sampled at different rates or have differing frequency contents, it is essential that any time delay or phase effect introduced by the anti-aliasing filters is understood and accounted for.*

Data sampling rates are generally a key design driver for the OLM system and in particular for the data recording memory requirements. Data output from analogue transducers is generally continuous in nature; however, to capture these data periodic measurements, or samples, must be taken. Ensuring that the rate at which these data are sampled and that the associated anti-alias filtering applied to these data are suitable to meet the programme aims are essential undertakings. An example of data sampling in which the underlying time history is well captured is illustrated in Figure 8.

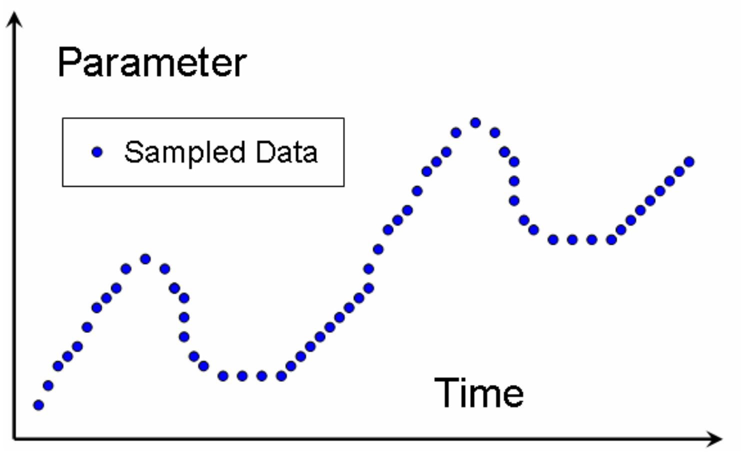

Figure 8 - Data Sampling Illustration

Until relatively recently, airborne data acquisition recording capacities were often severely restricted by the affordable technology available. Therefore, sampling data at higher rates would be at the expense of recording duration or number of channels sampled and often significant compromise was necessary. However, with modern digital systems, the capacity of DAUs to condition data has improved significantly and the cost of memory has reduced. Consequently, restrictions on data sampling rates are not as significant as they once were. However, sampling data at too high a rate is wasteful and often generates costly additional data storage requirements. Also further work may be required in sub-sampling data during post-processing to reduce the file sizes to manageable levels.

The requirement for data sampling rates is intrinsically linked to the aims of the OLM programme and the structural characteristics or response of the aircraft. The majority of data captured within an OLM programme is presented in the form of time histories. A time history is simply data values captured periodically over time. The significance of the accuracy and resolution needed in the capture of these data will depend upon its use. For strain gauge data mV outputs from the strain gauge bridge are converted into engineering units of strain/stress or loads (referred to as strains henceforth) using calibration equations. Ultimately, these strains will be analysed in 2 major ways. Firstly, the maximum and minimum values will be compared with static considerations for the aircraft and the fatigue damage or crack growth calculated from these strains will be compared with design assumptions and qualification data. The sensitivity of this fatigue damage to changes in strain can be illustrated using a heuristic stress-life method in which the relationship between stress range and fatigue damage is assumed to be between a third and fifth power law (i.e. doubling the strain multiplies the fatigue damage by between 8 and 32 times). Therefore, capturing the full extent of the strain cycles seen in the structure is imperative. However, as well as the relatively slow quasi-static strain changes (e.g due to fuel burn or changes in dynamic pressure), aircraft are subject to dynamic effect from a variety of sources including gust, buffet, landing impact etc. The effect of these dynamic loads will depend upon the energy in the excitation and the structural response of the aircraft. Furthermore, the dynamic strains are often superimposed upon the quasi-static strains. This is illustrated in Figure 9 where a 30 second tailplane bending response (sampled at 128 samples/s) is shown with the low-frequency (8Hz low-pass filter) content superimposed upon the time history plot. In general for OLM the filter characteristics should generate a zero phase shift otherwise the use of the resulting signals will be compromised.

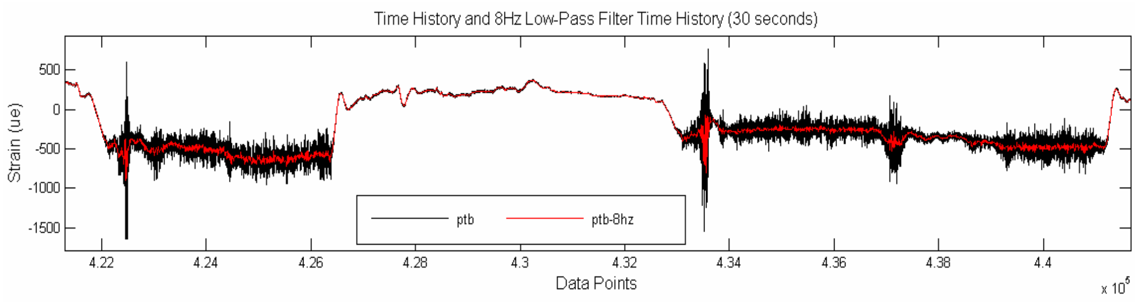

Figure 9 – Illustration of dynamic event superimposed upon low-frequency strain changes.

During the design process, the structural response of the aircraft will be estimated from analysis and will generally be validated by ground resonance testing (GRT), structural coupling tests and flight test. However, accurate modal modelling, analysis and testing is a very exacting science and although this process should identify the various vibration modes in the structure, accurately identifying their contribution to the fatigue damage accrual analytically is extremely complex. A detailed discussion of the dynamic response of aircraft is outside of the scope of this paper. Notwithstanding the limitations of analysis and testing, identification of the maximum structurally significant vibration modes in the monitored components of the OLM is essential. Regions particularly vulnerable to higher-frequency dynamic loading may include:

- Tailplane / Foreplane
- Fin
- Rear fuselage
- Outer wing
- Flying controls and lift devices e.g. rudder, airbrake, slats, flaps, ailerons leading edges devices and leading edge root extensions
- External stores and pylons
- Undercarriage and support structure

To put the frequency of structural modes into context, Gelder *et al.* (2000) reported significant structural modes in the Hawk TMk1/1A tailplane up to around 90Hz and Graham *et al*. (1995) reported significant modes up to around 45Hz in the F/A18 fin and 50Hz in the stabilator (horizontal tail). Higher frequency modes do occur but these are generally not considered significant in structural fatigue terms.

For undercarriages and support structure, the landing impact and associated spin up and spring back are generally highly dynamic events within which the strain values need to be accurately captured.

Experience has shown that data should be sampled at a minimum of 10 times the highest frequency of the structurally significant modes to have confidence in capturing a close approximation to the strain peaks and troughs in the time history. Where there is insufficient data to identify the highest significant structural mode with confidence, an initial data sampling plan should be introduced with significantly higher rates than are likely to be needed and only reduced when analysis of the time histories shows that the sample rate can be reduced safely. Methods such as sub-sampling and repeat damage sums as well as identification of maximum and minimum values of sub-sampled data will identify when the sample rate reduction is significantly affecting the data capture. This is illustrated in Figure 10. Some may argue that to capture the frequency content in a signal it only needs to be sampled at twice that frequency. While it is correct that the frequency content will be identified, the magnitude of the peak and trough of a cycle cannot be reliably captured by only 2 points in the cycle.

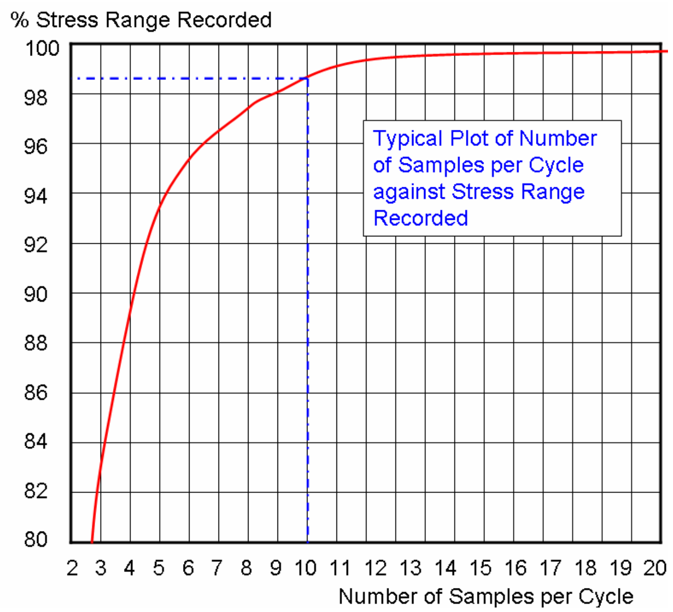

Figure 10 – Identification of sample rate effects

For parametric data, including data captured from data buses, the sample rate should again be determined by the intended use of the data. However, the properties of the original instrumentation, such as its bandwidth, and its refresh rate on the data bus should also be considered. Where parametric data are to be used to validate spectra, particularly if they are to be combined with strain data, the sample rate and anti-aliasing filter settings (see next section) should be consistent or at least the differences and implications should be understood.

Within the analogue-to-digital conversion process it is necessary to filter the data to remove unwanted higher frequency content and to prevent the signal being aliased. Aliasing is, as its name suggests, an effect when a signal appears to be something it is not. Wagon wheels appearing to go backwards in western films is an excellent example of aliasing. An example aliased signal is presented in Figure 11.

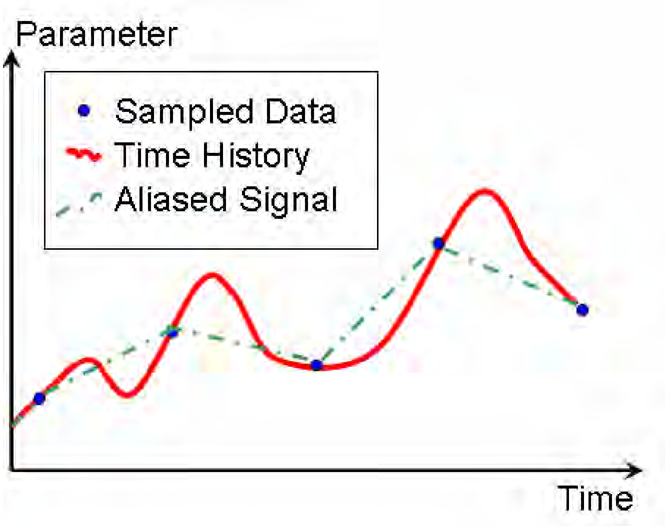

Figure 11 – Example aliased signal

Anti-aliasing filters are required to remove the unwanted high-frequency (structurally insignificant) components of the signal while preserving the portion of interest with minimum distortion. A detailed discussion of filter design and characteristics is again beyond the scope of this paper. Filtering is not a perfect operation and inevitably requires some compromises. Modern signal conditioning systems often use over-sampling with digital filtering and then decimation. Digital filters are seen as offering greater consistency in performance and superior pass-band and roll-off characteristics and can be arranged to ensure that the time delays introduced by filtering are constant across the range of frequencies, rather than being frequency dependent. The trade-off for a constant delay is a significantly greater delay than in an analogue filter. Whatever filter architecture is chosen the filters used should be designed to ensure that the attenuation characteristics (reduction in amplitude) of the filter that removes the unwanted portion of the signal has the least possible effect on the signal of interest. Secondly the quantization noise introduced during the analogue-to-digital conversion should be kept to a minimum; this is achieved using over sampling and down sampling. Finally, the effect of delays in the signal introduced by the filtering must be either fully understood or compensated for. For a COTS DAU it is highly likely that the anti-aliasing filter architecture is predefined and the user-definable aspect will be the cut-off frequency of the filter. General convention is to set the filter cut-off to approximately ¼ of the sample rate and at least 1.25 times the maximum frequency of interest and this coincides with the recommendation outlined in AGARDograph 160 (Veatch 1994).

In early OLM programmes where sample rates where severely restricted by the available technology, it was common practice to use 40Hz in the amplifier bandwidth but sample the data at 16 or 32 samples per second. This allowed capture of sharp transients in the data and gave warning of significant high frequency content.

6.11.8 AIRBORNE OR ON-GROUND PROCESSING

OLM Action 41: *Airborne processing of data should be restricted to signal conditioning and processing of the data should be undertaken off-board. This allows maximum flexibility in the analysis process and prevents unnecessary and costly airborne software changes.*

Generally experience has shown that for OLM data, where immediate actions are not required upon capture of the data, it is more efficient to undertake the majority of the data processing on the ground rather than in the air. Inevitably changes will be made to how data are analysed during the course of an OLM programme and the time scales and costs associated with instigating a change to software on ground-based systems is far less than airborne systems. Additionally, it is essential to capture the data in the rawest possible form and thereby allowing the facility to return to the raw data in future analysis scenarios.

6.11.9 OLM INSTALLATION

Generally, an OLM installation will follow the methods used for avionic and electrical installations fitted to an aircraft. However, there are several OLM-specific issues, certainly for in-service aircraft that should be addressed in the design phase. These include:

- Poor previous performance on EMC issues
- System power up
- System recording trigger

6.11.9.1 Electromagnetic Compatibility

OLM Action 42: *EMC considerations should be included throughout the system design (such as shielded cables) and a full EMC assessment of the completed design should be undertaken. Radio transmission interference in particular has occurred on several programmes, despite detailed design measures being taken to eliminate the problem. Therefore, recording of the Press-To-Transmit (PTT) line should be considered in system design.*

Electromagnetic compatibility (EMC) issues have occurred on several OLM programmes. These issues can either be where the OLM system affects other aircraft systems or where the existing or subsequently introduced aircraft systems affect the OLM system. The first of these has potential safety issues and the second can, in the worst case, render the OLM data next to useless. Problems with radio transmission break through onto data channels and OLM system power cables causing side tones on particular radio frequencies have occurred. In some cases it has proven impractical to eliminate this interference, even using ferrite rings, and measures within the analysis process have had to be introduced to filter interference from the data. The design of the strain gauge cabling should always be twisted shielded pairs and all other OLM wiring, particularly OLM DAU power cables should be shielded where practicable. The recording of PTT lines would allow this interference to be filtered out within the analysis process, should design measures fail to address the problem fully. Additionally, a thorough EMC assessment of the design and installation should be undertaken by EMC specialists.

6.11.9.2 OLM Power Cycles

OLM Action 43: *Where possible the OLM system should be designed to power up only when the system is required to be operative, rather than at every aircraft power cycle. Also, power surge protection of the OLM system should be included within the design.*

Great care should be taken in designing the OLM system power-up architecture. During routine aircraft maintenance power is applied and removed from the aircraft a significant number of times. Some OLM system designs have powered up the OLM DAU at every aircraft power cycle. Although in some cases this may be unavoidable, system reliability is likely to be increased if unnecessary power cycles are avoided. Modern DAUs are likely to have power surge protection facilities; however, particularly when OLM systems are retro-fitted to aircraft, older power supply systems are often less stable. Hence, the surge protection required for the OLM system should be reviewed.

6.11.9.3 OLM System Automatic Recording Trigger

OLM Action 44: *It is essential that the triggering architecture or logic in the DAU/recorder and the requirement to capture structural events (such as take off and landing or taxi loads) are fully understood before the trigger parameters are defined.*

The OLM automatic recording trigger design is an aspect that requires particular attention and has not always been successful in the past. Before designing the trigger the aircraft power-up and flight cycle should be considered and those events requiring capture identified. For example, triggering recording from a weight-off-wheels micro switch for a large transport aircraft, where the wing bending spectrum will be dominated by the ground-air-ground cycle, would be highly inappropriate but may be acceptable for a combat aircraft or trainer. Thereafter it is essential that the triggering architecture or logic in the DAU/recorder is fully understood before the trigger parameters are defined.

6.11.9.4 Ground Testing Mode

OLM Action 45: *A ground testing mode for checks on installation and fault diagnosis in service should be included in the system design*.

It is unlikely that an OLM system would be designed to record data in normal operating mode when the engines were not running. Therefore, a ground-testing mode is required to 'make' the recording triggers to allow system fault diagnosis.

6.12 UNIT-BASED GROUND STATION

OLM Action 46: *The unit-based OLM ground station should be designed to reduce the burden on the operational units to a minimum. However, the role and functionality of the ground station will depend upon the data collection medium, the system maintenance requirements and the method of operation of the aircraft fleet.*

OLM Action 47: *At the time of writing this paper the MoD had recently introduced regulations forcing the memory encryption for IT devices that extract data from aircraft. It is understood that at least one OLM programme has experienced difficulties as a result of switching to encrypted hard drives. Designers should be made aware of this regulation.*

The functionality needed in a unit-based ground station will be dependent upon the design of the data acquisition and recording system. One of the design aims for the OLM system should be to reduce the burden imposed on operational units by OLM to an absolute minimum. This aim is not entirely altruistic. Data capture rates where operational personnel have a heavy burden placed upon them by the design of the OLM system have often been woefully low and have dramatically extended the length and cost of the OLM programmes as a result.

Therefore, a low unit burden concept of operations using memory cards being removed approximately once per week, for example, and despatched to a data analysis centre is a practical implementation of such an aim. In this context the ground station would have no day-to-day role, with the possible exception of backing up data chips before dispatch, if this were considered essential. In this scenario the ground station functionality would most likely be in uploading any user defined data, such as programming plans for the DAU and in routine maintenance and fault finding for use by trained personnel and the ground station could be configured accordingly.

In an operations concept requiring data to be downloaded from fixed memory within the DAU or recorder media then greater ground station functionality will be required. Where possible automated download functions should be used to ensure flight-line personnel can undertake downloads with minimum training. In these scenarios, the ground station or data extraction units will need to be more robust than a system only used for fault finding. Additionally download times should be carefully matched to download frequency. For example, if data download are required at the end of each flight then a one-hour download time will not be acceptable in an operational environment. Also potential operational usage or deployment of aircraft needs to be considered with the Ground Station design. The operations conducted “on the flight line” need to be considered within the system design process. It is essential that the system designers are familiar with how operations are conducted in reality.

6.13 Data Analysis Process Design

6.13.1 Background

As with all other aspects of OLM, having a clear understanding of the aims of the programme is essential before planning the data analysis process. In Section 6.6 the need to review the fatigue analysis process was explained and the data analysis process outlined in this section provides the link between extracting the captured OLM data and the fatigue analysis process.

6.13.2 Analysis Definition Document

OLM Action 48*: An Analysis Definition Document (ADD) should be produced. This document shall describe the requirements to be met by the analysis process in detail and any interface* *requirements to existing software packages, such as in-house fatigue analysis programmes. This ADD should be reviewed and agreed by the OLM Specialist Group and formally endorsed by the OLM Programme Management Group.*

One of the prime aims of this section is to describe the functionality that should be considered in developing the OLM data analysis process. It is accepted that there will be significant differences between OLM programmes, depending on their aims; however, irrespective of differences there will be many common requirements. Necessarily, OLM data represent a relatively small percentage of flying, rarely more than a few percent and wide ranging safety-related decisions are made based upon these data. Therefore, it is essential that there is a high degree of confidence in the integrity of the OLM data and the processes applied to that data within the analysis suite.

There are several approaches that can be taken to developing a data analysis suite for OLM programmes, from in-house development to 3rd party or COTS products and the approach taken will often be dependent upon the programme requirements, skills and time scales available to the designer. Irrespective of the approach taken it is essential that an Analysis Definition Document (ADD) is produced. This document should describe the requirements to be met by the data analysis process in detail and any interface requirements to existing software packages, such as in-house fatigue analysis programmes. This ADD should be reviewed and agreed by the OLM Specialist Group and formally endorsed by the OLM Programme Management Group. Details of the expected content of this ADD are described in the following sections.

6.13.3 ANALYSIS AIMS

OLM Action 49: *The high-level steps in the data analysis process from data extraction to analysis output and the key input and output requirements for each step should be clearly identified in the ADD.*

As with so many aspects of an OLM programme, processing of the OLM data is a technically complex function. Therefore this process should be described clearly to ensure that the aims of the programme are understood and can be met. A useful method of developing the ADD is to identify the steps in the analysis process from a top level, identifying the key interfaces and then to break the process down into further layers of detail. This will ultimately produce a series of elementary functions that can be coded if required or linked by their input and output or interface requirements. An example of a simplified top-level process is provided in Figure 12. In this example the process assumes that the OLM data are recorded onto a Compact Flash memory card and removed periodically for dispatch to a remote data analysis centre.

Alternatively, data may be extracted from the DAU via a link to the ground station or, in the case of many legacy systems a data tape may be extracted and dispatched.

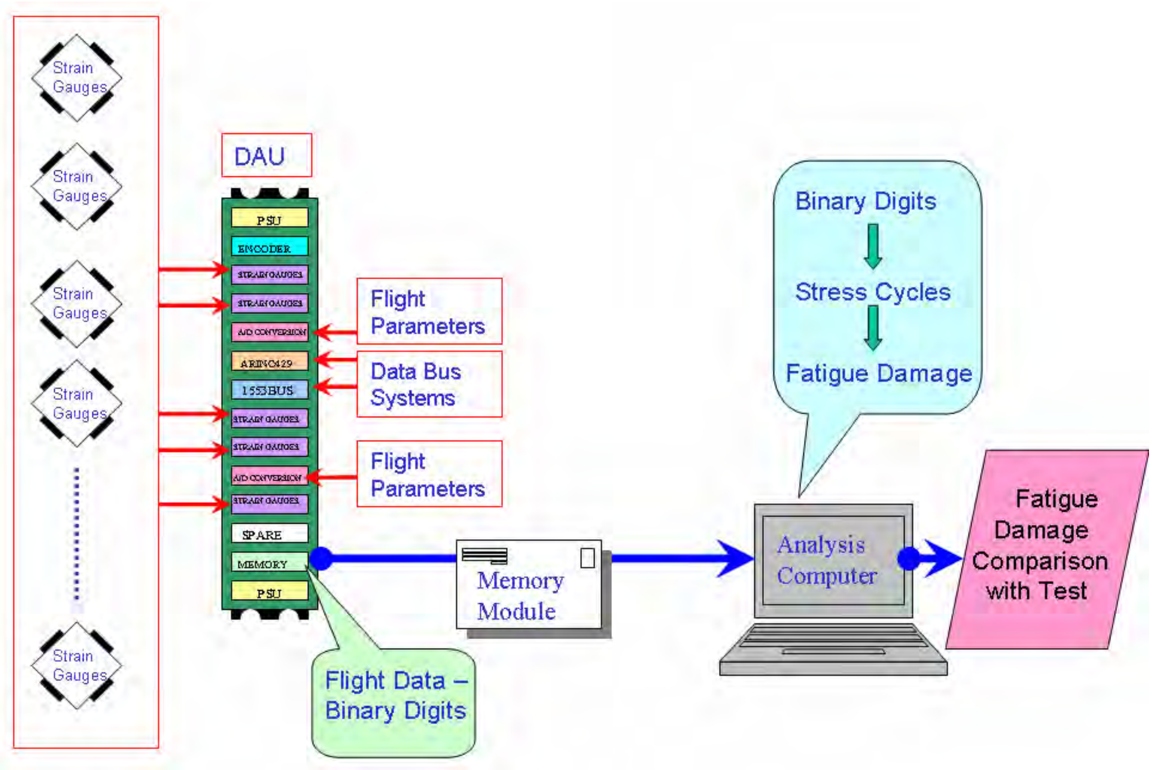

Figure 12 – Example Top-Level Analysis Process

6.13.4 ANALYSIS PROCESS SCHEMATIC

Having established the top-level aims, the next step is to define the data analysis process in more detail. An example data analysis process is illustrated in Figure 13.

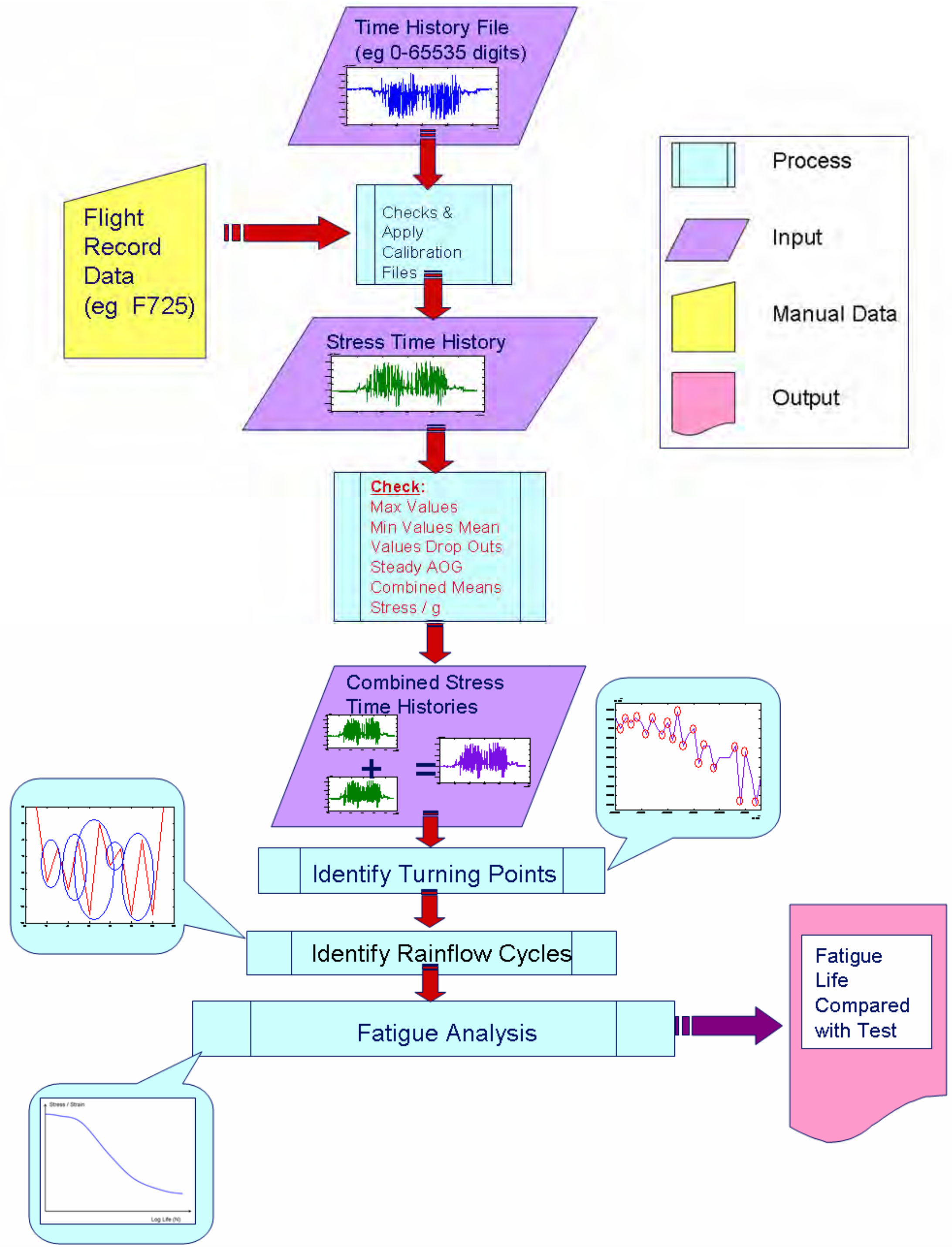

Figure 13 - Example Data Analysis Process Schematic

Within the following sections detailed typical OLM analysis functions are described.

6.13.5 DATA EXTRACTION AND INITIAL INTEGRITY CHECKS

OLM Action 50: *The process for extracting data from the recording media should be carefully planned. Where extraction software has to be written or third-party code used, care should be taken to ensure that support for the programme and configuration control are in place.*

OLM Action 51*: The data extraction process should also include:*

- *Identification of any regions of lost data*
- *Identification of bit failures*
- *Identification of error flags*
- *Collation and reporting of DAU produced data health reports*
- *Identification of provisional data status against established criteria (e.g. data loss<2%)*
- *Check to ensure data loss does not coincide with highly damaging events (e.g. high-g)*
- *Data replacement and identification process for minor losses (e.g. last known good value)*

The function of the data extraction process is to get the OLM data from the recording media and recording format onto media and into a format that can be used within the analysis process. For a modern data acquisition system the data may be stored as a 16-bit unsigned integer (i.e. an integer in the range 0-65535); however, many other formats may be used with fewer or more bits representing a data word. Several examples of these data representation methods such as binary coded decimal (BCD) are described in Appendix F. However, in addition, the data are often recorded onto media using a method that requires bespoke decoding processes. The details of this process and the extraction method will be highly dependent upon the hardware and software used to record the data in the first place. For tape-based systems for example, a ground replay unit is usually required which reads the data tape and converts the data from the recorded format (sometimes proprietary) into a format suitable for further analysis. For example, data may be recorded onto a tape system in Pulse Coded Modulation (PCM) format. For PCM streams, for example, the ground replay unit would be linked to a computer with a PCM decommutation card and appropriate software, which would be used to decode the data stream to reproduce the data in its raw form for further analysis. A PCM data structure would need to be described for the software to identify the appropriate data in the stream and the description might include the number of bits per word, the number of words per frame, the bit rate, synchronisation pattern and the parameter position within the data frame. Irrespective of the specific recorded format and media, a data frame format is commonly used for recording of OLM data. A simplified example of a frame format is illustrated in Figure 14.

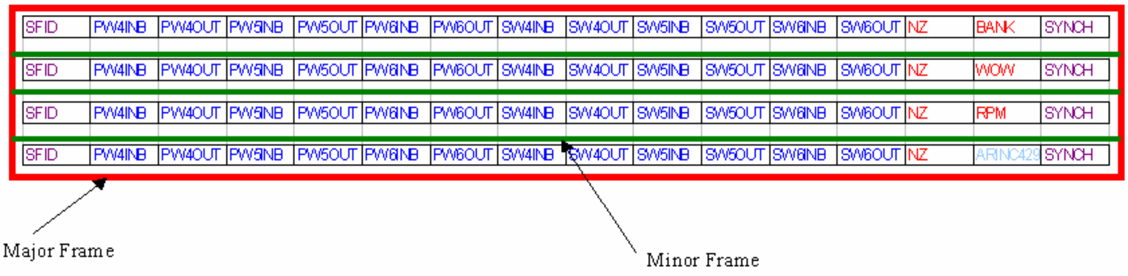

Figure 14 – Example data frame

A major frame will represent a particular time period (e.g. 1/16 of a second) and would comprise a number of minor frames (4 in the illustration in Figure 14). The data within a minor frame is accepted on condition that the synchronising identifiers, preceding and following the frame (sub frame identification (SFID)) and synch word (SYNCH) in this illustration contain expected values. Data sampled at higher rates than the major frame rate (16 samples per second in this case) are repeated within the major or minor frames. Therefore, data sampled at 64 samples per second may well appear once in each minor frame (e.g. PW4INB etc).

For data extracted from the DAU or recorder to a ground station via a cable link[12] or memory modules such as Compact Flash, data would still require conversion from the recording format to a format suitable for further analysis and appropriate software to undertake this conversion process.

Historically, several OLM programmes have had some data extraction problems. Many of these were physical issues with tape systems but data extraction software failures and software configuration control problems have also occurred. Furthermore, even at the planning phase, support for the data extraction hardware and software should be considered within the design process.

Irrespective of the media or data format, the data extraction process should also include identification of any regions of lost data, such as where a synchronisation word cannot be found, and bit failures or error flags within the data. This should also include capturing any DAU produced data health reports and error flags (discussed previously). The extraction process should include production of a summary of these events and a process should be established to

[12] It is assumed that wireless download is unlikely to be undertaken for obvious EMC safety reasons.

identify the provisional status of the data, as to whether the extracted data are considered good, bad or require further investigation. Provisional limits for data rejection criteria should be set and a process for data replacement for small data losses should be identified. The general convention used is that small quantities of lost data are replaced with the last-known good value. Where data are replaced this should be recorded along with the data. Additionally, data losses should be investigated to ensure they do not coincide with damaging events, such as whenever high-g is pulled.

6.13.6 Raw Data Storage

OLM Action 52: *The extracted raw data and associated extraction report should be stored and backed up, ideally automatically. If the initial recording media are to be reused, reformatting should not be undertaken until the data quality has been assured, where practicable, and the data backed-up in its rawest possible form.*

6.13.7 Identification of Flight Record Data Requirements

OLM Action 53: *Requirements should be identified for the capture of manual or electronic data from alternative sources, such as Flight Records (e.g. MoD Form 725 or electronic equivalents).*

The programme aims will determine the OLM data capture requirements and measurement requirements. However, depending on the extent of instrumentation (e.g. whether fuel mass is recorded by the OLM) and the extent of data routinely recorded on the Flight and Fatigue Data Sheet (MoD Form 725 or electronic equivalent) there will most likely be a requirement to capture flight data from either manual records or electronic data from other sources (such as LITS or alternative logistics systems). As a minimum, the sortie profile code (SPC) and flight record number are likely to be extracted from other sources as these are unlikely to be automatically written to the data within the onboard OLM system.

6.13.8 Input and Reconciliation of Flight Data

OLM Action 54: *The analysis process should be designed to accept external source flight record data (e.g. MoD Form 725 or electronic equivalent) and a process of reconciling OLM and flight record data should be specified. The use of real-time stamp and unique tail number tags on the data are strongly recommended as a method of reconciling OLM data with flight records.*

OLM Action 55: *Consideration should be given to methods of handling truncated data, data divided over several OLM flight files or where several sorties are combined into one OLM flight file (e.g. running crew change[13].).*

Where there is a requirement to input either manual flight data records or data from other electronic systems, the OLM data analysis software should be designed to accept these data and a process of reconciling the OLM data with other data sources should be established. The complexity of this process will depend on the data recorded within the OLM programme and the mechanism to align data undertaken on the Operating Units. Where the triggering system for data recording means that OLM data will include engine ground runs for example this alignment process should differentiate between ground runs and sorties. It is noteworthy that an inability to align flight records with OLM data has resulted in the loss of significant quantities of otherwise acceptable data in previous OLM programmes. Time stamping of data, ideally in a real-time format, is probably the most reliable method for alignment with flight record data and for programmes with more than one aircraft, data marking with a tail number or a unique identifier for each aircraft should allow reliable reconciliation. If these data are not available, the process becomes far more labour intensive and the risk of data loss increases.

6.13.9 GENERIC DATA ANALYSIS PROCESS

Figure 15 has been produced to illustrate a generic process as a vehicle for explaining the various aspects of the OLM data analysis. The following sections contain explanations and recommended OLM actions for each phase of this generic analysis process.

[13] A running crew change occurs when part or all of the crew are changed and a second sortie is flown but without the engines being shut down.

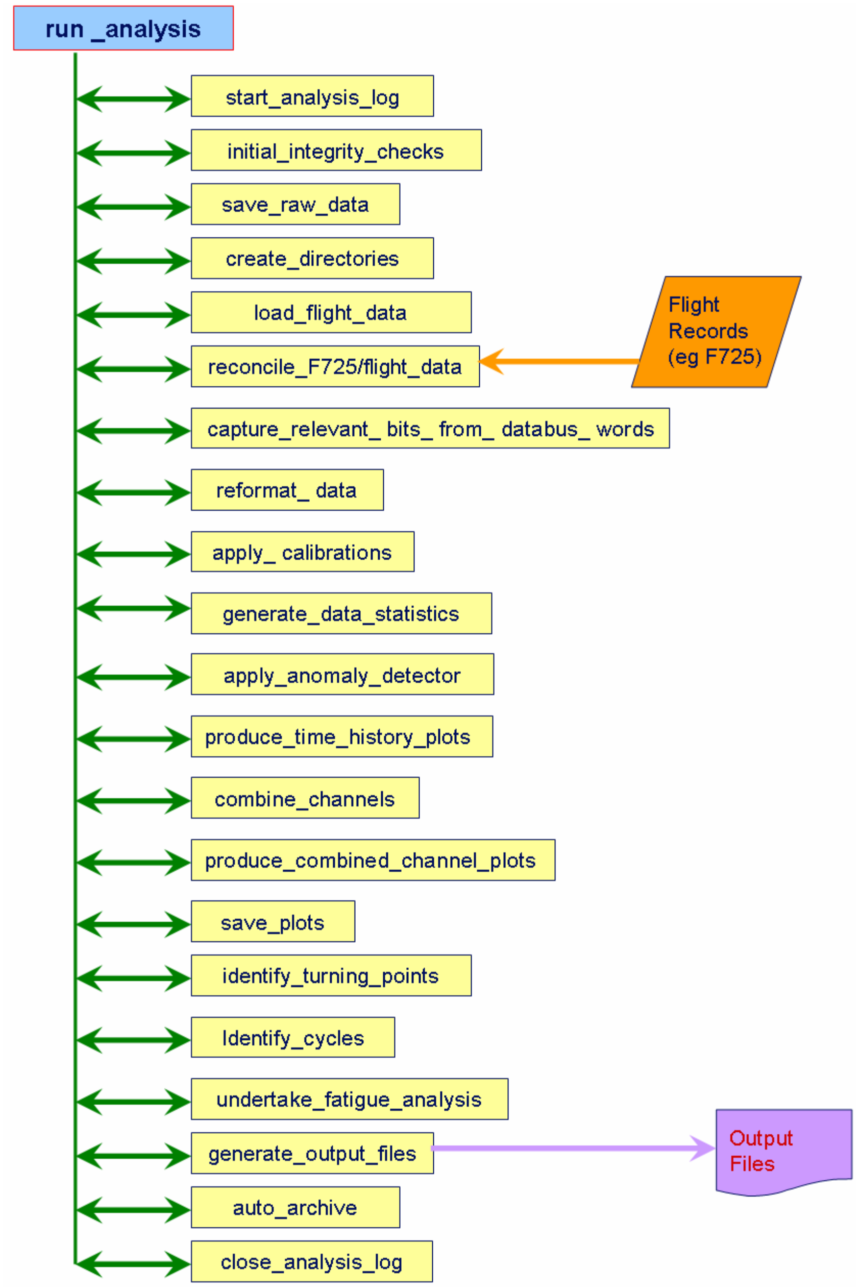

Figure 15 – Example Generic OLM Data Analysis Process

6.13.10 RE-FORMATTING DATA FILES

OLM Action 56: *OLM data are generally stored in the recording media as unsigned binary integer values (e.g. 0-65535 (16-bit)). However, these data should then be copied and may require conversion into formats (e.g. double precision real numbers) appropriate for the* *subsequent operations, such as the application of calibration values to generate data in engineering units.*

6.13.11 DATA BUS STATUS FLAGS

OLM Action 57*: Data from aircraft data bus systems (e.g. ARINC 429 or Mil-Std 1553) will have accompanying status flags in the data bus words. These flags should be captured and processed along with the engineering data.*

It is highly likely that data extracted from data buses (e.g. ARINC 429 or Mil-Std 1553 (Appendix E)) will also require further format changes before it can be used in the analysis process. Data can be extracted from a data bus by either parsing the data stream (taking the words required) or snarfing the data stream (taking all data words). Due to the large volume of data on aircraft buses it is assumed that data will be parsed rather than snarfed and therefore only the required data will be recorded. Although the data available from the data bus will be in engineering units (e.g. Knots for airspeed), a variety of different data types such as, binary, binary coded decimal (BCD), 2's complement binary notation (BNR), discrete, or data status flags are used on the data bus. Examples of these methods are reproduced in Appendix F.

6.13.12 DATA FILE SIZES

OLM Action 58*: An assessment of likely data file sizes should be undertaken and the analysis process architecture, software and hardware should be designed to cater for these file sizes.*

The significant advancements in data acquisition and recording systems in recent years have allowed far greater flexibility and capacity in OLM systems. The result of this is that OLM data files can become extremely large. For example, one strain channel sampled at 2048 samples per second will generate nearly 7.5 million data points per hour. Therefore, it is essential that an assessment of typical file sizes is undertaken and that the analysis process architecture (such as how many files are retained in memory etc), software and hardware are designed to cater for these file sizes. Increases in storage requirements from integers to double precision real numbers for example should also be taken into account in this calculation.

6.13.13 APPLICATION OF CALIBRATION EQUATIONS

OLM Action 59*: The analysis process should be designed to cater for all intended calibration file formats and for changes to calibration coefficients (including primary to secondary strain gauge bridges) without having to initiate software changes (using methods such as look-up* *tables). Configuration control and tagging of data with traceable calibration equation identifiers is essential.*

As previously discussed, most of the OLM data captured will require conversion from binary data units or digits into engineering units. This is achieved by the application of calibration equations. The methods used to obtain these calibration values is discussed in Section 7. From an analysis perspective the issues to address are ensuring that all the calibration file formats necessary can be applied to the data and that a system for configuration control of calibration values is introduced.

Generally, calibration values are simple linear equations ($y = mx+c$). However, linear calibrations may not necessarily be appropriate and the analysis process needs to be designed to cater for all applicable calibration equation formats. Additionally, calibration equations (including changes from primary to secondary strain gauge bridges) are likely to change during the course of an OLM programme, due to recalibration or equipment unserviceability. Therefore, the analysis process should be designed to cater for calibration coefficient changes without having to initiate software changes. Hence, flexible methods, such as the use of look-up tables for calibration coefficients should be used.

6.13.14 DATA ANOMALY DETECTION

OLM Action 60: *Anomaly detection routines should be developed, with limits set with reference to structural capability and aircraft performance. As a minimum these routines should detect the following:*

- *Exceedances of channel maximum and minimum expected strain/stress or load values*
- *Excessive rate of change values (where practicable) compared with performance data*
- *Review performance data*
- *Failure of correlation between measurands expected to have a high degree of correlation*
- *Mismatch between flight record and OLM data*

Limits should be held in configuration controlled look-up tables to allow relatively simple amendment rather than as fixed values within the software.

OLM Action 61: *Automatic correction of anomalies should only be undertaken once sufficient confidence in the performance of the detection and correction algorithms has been gained using the OLM data, rather than test data sets. All detection and correction actions should be logged and a record retained with the data.*

It is essential that there is a high degree of confidence in the integrity of the OLM data throughout the analysis process and therefore basic checks for data integrity and anomaly detection should be undertaken. Integrity checks might include the use of data parity checks and file length consistency checks for example. Data anomaly detection methods include using limits defined from domain knowledge and in engineering units should be undertaken. Maximum and minimum limits and, where practicable, rate of change limits, which are particularly useful for identifying single point drop outs[14], should be identified. These should be compared to credible limit conditions such as the stress/strain or load values corresponding to limit load conditions or rate of change limits set with respect to aircraft performance data. It is recommended that the limits used for anomaly detection are read from configuration controlled look-up tables rather than fixed values within software. This allows changes to be made without software re-qualification. With modern DAU 16-bit (0-65535) systems there is sufficient resolution for reasonable margins to be allowed between expected maximum and minimum values and data ranges.

The performance data should also be reviewed to ensure that real data are not identified as anomalies. There are many examples of stress ranges or limits set from design or test spectra that were subsequently found to be significantly below the range of stresses seen in service.

Furthermore, where correlations are known to exist between measurands then these relationships should be incorporated into anomaly detection methods. For example, if a high rate of change is detected in a wing root bending moment channel then a corresponding high rate of change should be seen in the normal acceleration channel and visa versa. Data recorded from flight records (e.g. MoD F725) can also provide useful anomaly detection information. For example, recorded flight duration and the number of roller landings should broadly match the OLM data. Care should be taken with such comparisons to allow for errors in flight records, particularly when a large number of roller landings were logged.

Manual detection of anomalies can be time-consuming, require high skill levels and consequently costly. Therefore, there is an ever-increasing drive towards automation of anomaly detection routines. While automatic detection of anomalies should be initiated at the outset of an OLM programme, automatic correction of anomalies should only be undertaken once sufficient confidence in the performance of the detection and correction algorithms has

[14] However, longer-period drop outs are more challenging to detect with automated systems.

been gained using the OLM data, rather than test data sets. While experience and confidence is being gained, the detection system should recommend data correction and the final decision should be taken by an experienced analyst. This process is illustrated in Figure 16 in which suspect anomalies are identified in a time history and recommended replacement data identified. In this example, the wing strain response during the suspect periods was automatically cross checked and if below a threshold strain value the normal acceleration was reset to 1g and tagged accordingly. The anomaly software requests an approval or rejection from the analyst of the proposed data replacement. Data replacement should be logged in a manner that can be accessed by analysis routines if required.

For reference and to assist in defining anomaly detection algorithms, examples of various types of anomalies identified in OLM data are reproduced in Appendix G.

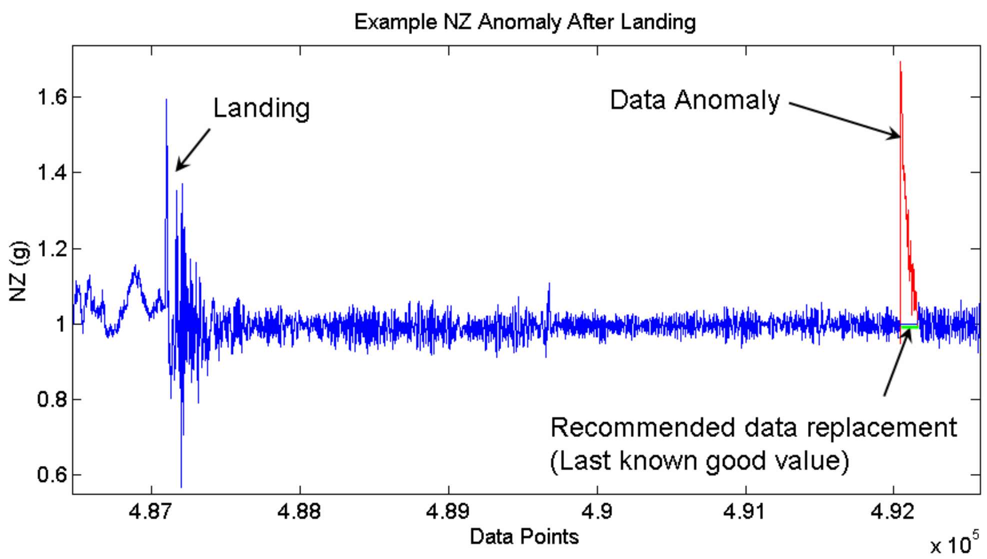

Figure 16 - Example Data Anomaly Detection and Recommended Data Replacement

6.13.15 DATA VISUALISATION

OLM Action 62: *The OLM analysis process should include the facility to visualise all data. Furthermore, initially at least all the data should be viewed by an analyst and this should only be reduced if confidence allows.*

OLM Action 63: *Primary data graphical outputs should be developed for automatic, or semi-automatic production and flexible graphical facilities should be available to the analyst to allow plotting of data to screen, zoom in on areas of interest and call-up a number of parameters on the same plot with cross plotting and time history plotting facilities.*

Even with the best planning and design of an OLM system, anomalous data will occur at some time during the programme. Additionally, it is highly unlikely that even the most detailed anomaly detection routines designed *a priori* will identify all anomalies in the data. Furthermore, deterministic anomaly detection methods cannot compete with an experienced analyst who will be able to identify that the character of the data is not as expected.

In addition, to assist the reader to gain an appreciation of the expected character of OLM data, a series of plots have been re-produced in Appendix H from OLM data for various aircraft types and sortie profiles.

Although visualisation of all data might appear an onerous task, thumb-nail time history plots, similar to those illustrated in Figure 17 can be used to undertake a rapid first pass through the data and to highlight plots requiring further investigation.

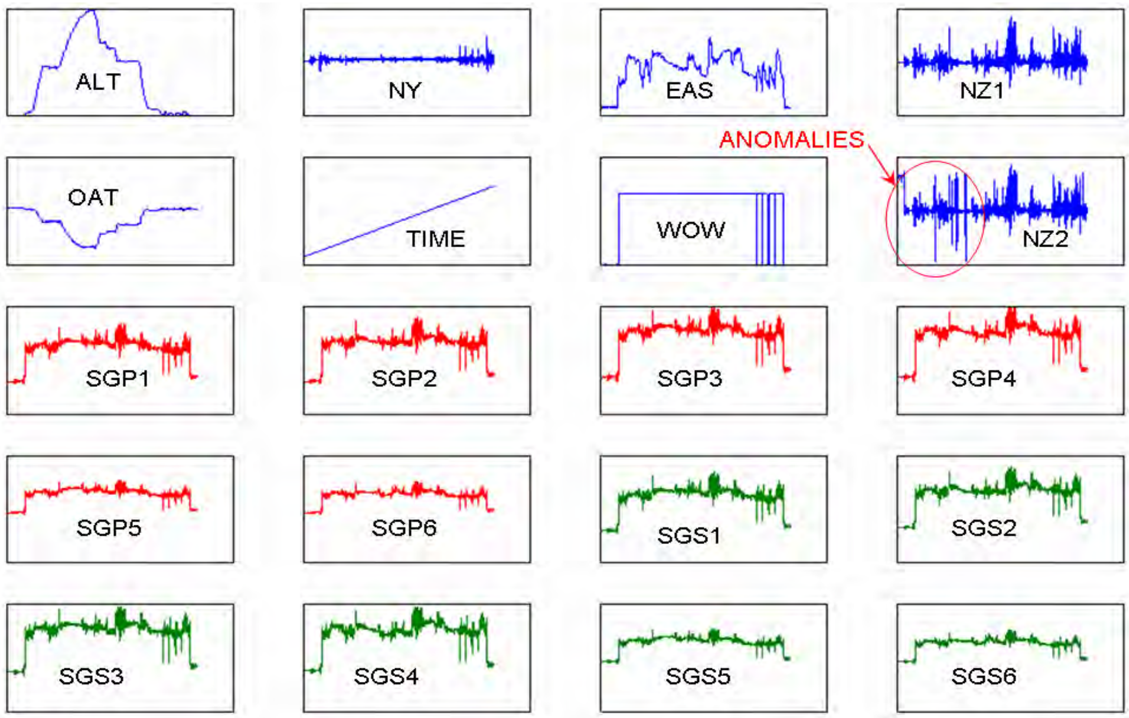

Figure 17 - Example thumb-nail OLM data time history plots (illustrating anomalous data)

Graphical outputs of primary data should be developed for automatic, or semi-automatic production. Experience has shown that production of hardcopies of the prime time history data, rather than just a print-to-screen facility is extremely useful for identifying issues for further investigation and gaining confidence in the data set. Also, flexible graphical facilities should be available to the analyst to allow plotting of data to screen, zoom in on areas of interest and call-up a number of parameters on the same plot with cross plotting and time history plotting facilities.

6.13.16 DATA TRENDING

OLM Action 64: *The OLM analysis package should have the facilities to calculate statistics of the data which might include maximum, minimum, mean and standard deviation. The capability should be available to trend these data by sortie profile code (SPC), squadron, role etc.*

One of the difficult issues with an OLM programme is to identify how much data needs to be collected. This is discussed in detail in Section 8. However, trending provides a tool that can be used to ascertain when sufficient quantities of data have been collected and can also be used to provide estimates of how much data will be needed. To allow trending the analysis package should calculate statistics of the data. Additionally, where fatigue damage calculations have been undertaken (discussed later in this section) damage accruals or crack growth increment[15] for the sortie can be identified. Collating these data by sortie profile code (SPC), or squadron or role etc can provide a valuable insight into the variability in the data and highlight data with significant deviation from the norm. Broadly speaking, where data within a particular SPC show a large variability then a greater quantity of data will be required to capture this usage representatively.

6.13.17 COMBINING DATA CHANNELS

OLM Action 65: *The OLM analysis package should have the facility to combine automatically the required data streams. Where data streams are combined care should be taken to ensure sample rates and filter settings are compatible to ensure that aliased data are not created in error.*

In most OLM applications data channels will need to be combined to produce the required output data. For example, to obtain the shear force, bending moment and torque at the wing root would require different combinations of a range of strain gauge bridge outputs on the various spars in the wing determined during the loads calibration exercise (Section 7).

[15] In fracture mechanics, crack growth increment is a function of initial crack length and hence trending of crack growth increment data will only be valid if the crack increment is calculated from a standard or constant initial crack length.

6.13.18 DATA CONFIDENCE CHECKS

OLM Action 66*: Confidence checks, in addition to data anomaly checks, should be incorporated into the data analysis process. These checks should consist of continuous checks and 'one-off' or infrequent checks conducted to gain confidence in the installation or calibration. Continuous checks should include plotting start-up values, steady-state conditions or producing plots of known or expected relationships, such as stress/g or wing load distributions and should wherever possible be generated automatically. One-off or infrequent checks might include comparing spanwise loading distributions with theory for example. These may not necessarily be automatic and may be procedural in nature. Aircraft operations, performance, FLM, SOIU or previous OLM data can provide useful information for establishing confidence criteria for comparison with captured OLM data.*

The importance of ensuring confidence in the OLM data throughout the analysis process cannot be over-emphasised. Therefore, a series of confidence checks, in addition to data anomaly checks, should be built into the analysis process. In truth the division between anomaly detection and confidence checks is a fine line. Experience has shown that knowledge of the expected operations, performance of the aircraft or data from FLM or previous OLM programmes, or SOIU data can provide useful data for setting criteria for confidence checks. For example, wing stress/ strain or load levels at steady-state cruise or in particular manoeuvres or during start-up and shut-down at particular mass distributions can all provide further confidence in captured data. Furthermore, trending of these data can build continued confidence in the integrity of the data. This is illustrated in a simple example in Figure 18. Here the wing stress level at start-up for sorties flown with a full fuel load (the aircraft in question did not carry stores) is plotted. Outliers were identified and further analysis undertaken.

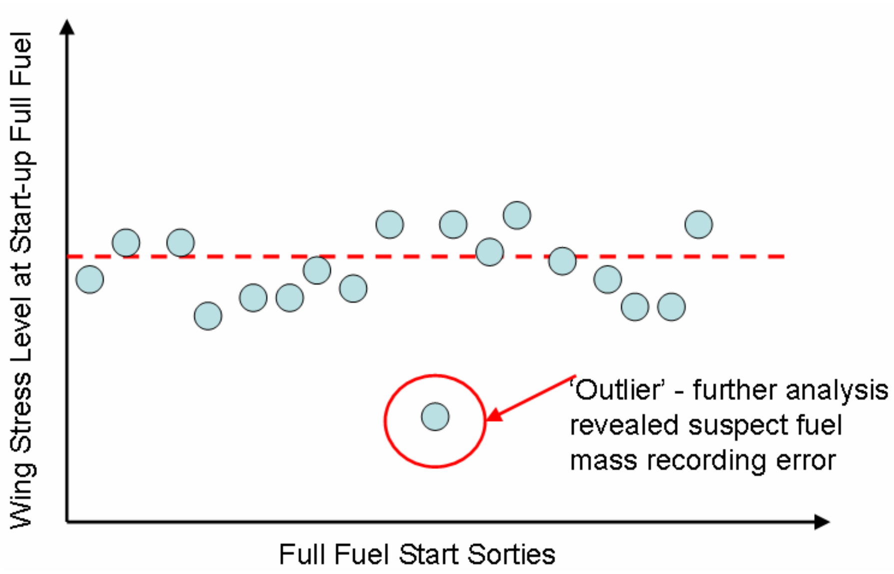

Figure 18 – Illustration of Trending of Wing Stress during start-up

For loads calibrated aircraft where a number of strain gauge bridges are located along the span of the wing for example, confidence in the data can be gained by plotting a load distribution across the wing and comparing this with the expected load distribution shapes (Figure 19).

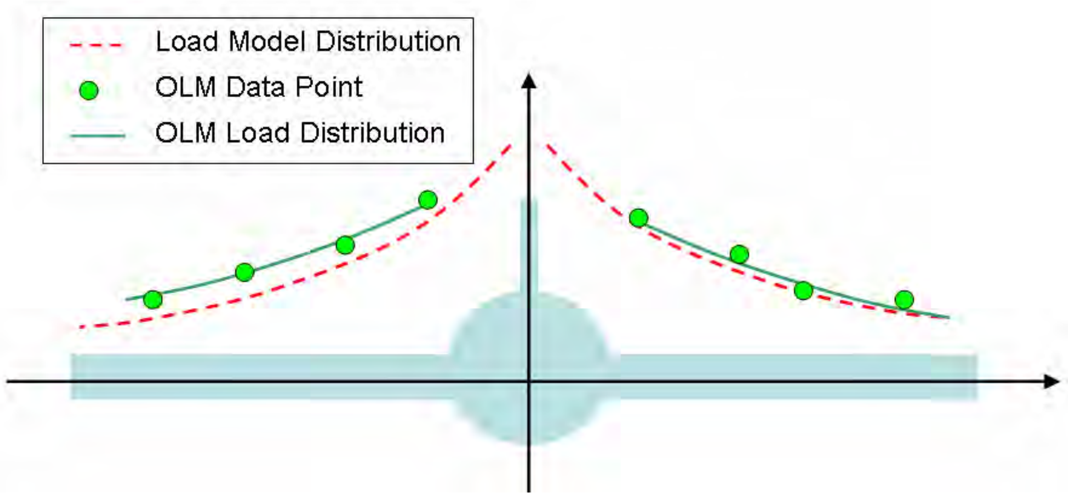

Figure 19 – Example Spanwise Load Distribution Plot

6.13.19 DATA REDUCTION

6.13.19.1 Identification of Turning Points

<u>OLM Action 67:</u> *The data analysis process should include the ability to identify turning points (relative maximum and minimum values or peaks and troughs) in data time histories (generally used for stress/strain or load channels). It is recommended that the time associated with each turning point is retained to allow the facility for later reordering and progressive damage calculations. A gate is generally included in this process whereby small cycles, considered structurally insignificant are removed. However, care must be taken to ensure the gating algorithm is consistent with a fatigue analysis process and captures the significant local maxima or minima values as turning points.*

In-service time history data are analysed in various ways to undertake a comparison with design and qualification spectra. The different methods are too numerous to describe within this paper. The method used should be consistent with the fatigue design process and a typical process is described here for illustration purposes.

Where data are to be subject to cycle counting and fatigue analysis the first step in this process is often to identify turning points. This process effectively captures the local maximum and minimum points (peaks and troughs) in the time history and removes intermediate points. Identification of turning-points is illustrated in Figure 20 below.

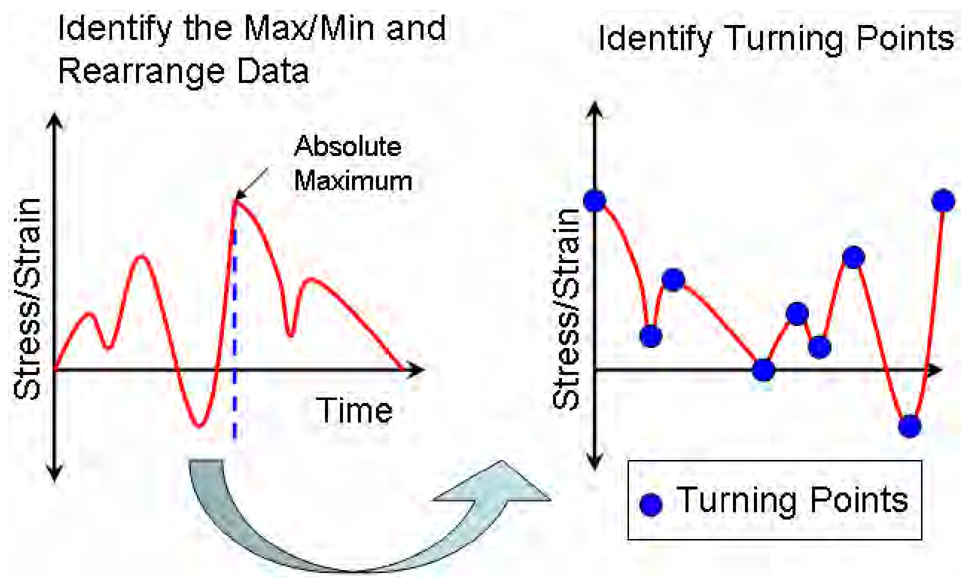

Figure 20 - Identification of Turning Points

There are a number of methods of undertaking this process and in the method illustrated in Figure 20 the time history has been reordered to commence with the maximum value in the time history, as this was greater in magnitude than the minimum value. This reordering is to allow the range-mean-pair rainflow analysis process (next Section) to process the data in a single pass.

6.13.19.2 Cycle Extraction

OLM Action 68: *The data analysis process should include the ability to extract cycles from turning points or peak / troughs using a method consistent with that used in design and qualification.*

OLM Action 69: *A frequency of occurrence matrix (FOOM) in which cycle files are represented by their range and mean or amplitude and mean provides a useful method of visualising large quantities of data. Changes in the FOOM population regions can illustrate anomalous but credible data, changes in usage or incorrectly identified data. Therefore, the ability to represent data in a FOOM should be considered as a function within the analysis process.*

The method used to pair peak and troughs should be appropriate for the method used for fatigue damage evaluation. There are many published variations in the methods used to extract cycles from a turning point or peak/trough file. ASTM 1049-85[16] (1985) and Ellis (1981) describe several well known methods. An illustration of the simplified 3-point range-mean-pair rainflow analysis algorithm method described by Downing and Socie's (1982) and referred to in ASTM 1049-85 is illustrated in Figure 21, alongside a diagram of the associated hysteresis loop.

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[16] American Society for Testing and Materials ASTM 1049-85 contains many of the well known cycle counting methods.

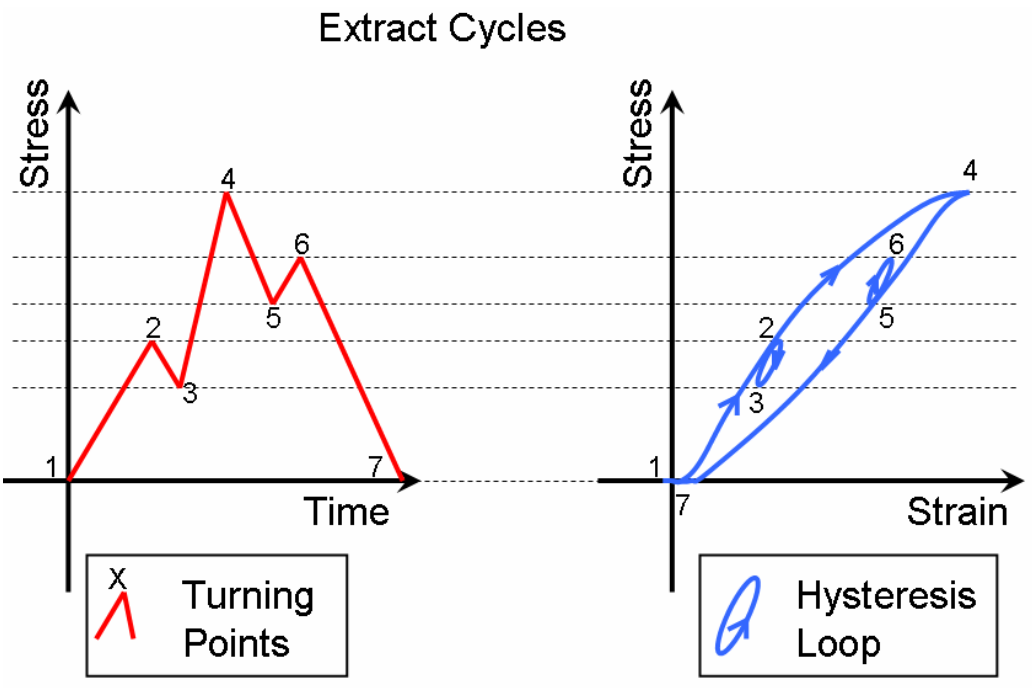

Figure 21 - Illustration of Cycle Extraction

If the data time history were reordered to commence with the absolute maximum or minimum value, then this process illustrated above will extract cycles in one pass of the data. A useful cross check during software testing is to ensure the major peak / trough extracted cycle matches the maximum / minimum values in the original time history. The cycle data are then available for use in the fatigue damage process. Traditionally, cycle data have often been presented in a frequency of occurrence matrix or FOOM, usually by cycle range and mean or amplitude and mean. An example FOOM data representation is presented in Figure 22.

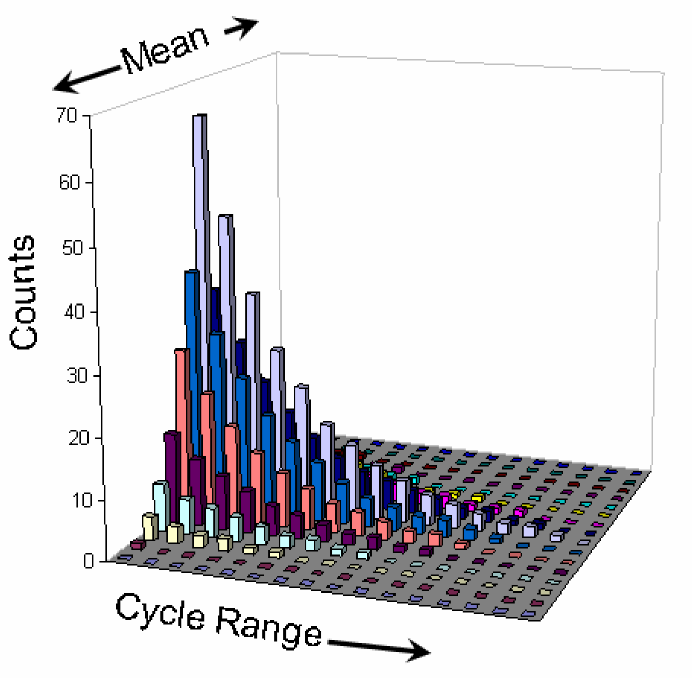

Figure 22 - Example FOOM representation (16x16 FOOM illustrated for simplicity – generally larger)

6.13.19.3 Exceedance Data

***OLM Action 70**: The OLM data analysis process should include the capability to represent data as exceedance plots. Additionally, where exceedance plots are going to be used to compare OLM data with design or qualification spectra then a consistent approach to determining exceedance levels should be used.*

Exceedance diagrams are a frequently used method of data reduction and permit comparison between data sets e.g. test and usage spectra. An example exceedance diagram is reproduced in Figure 23.

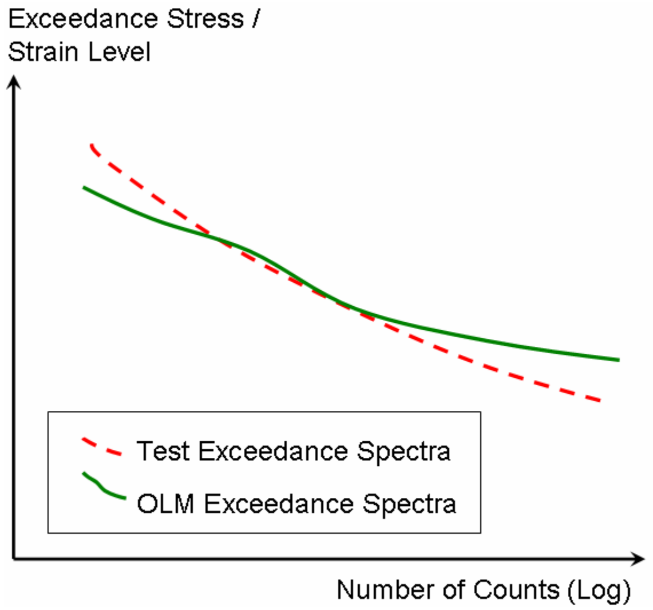

Figure 23 – Example Exceedance Diagram comparing test and OLM spectra

In the example presented in Figure 23 the number of exceedances of a particular stress level represented on the test and from usage data can be clearly identified. This analysis coupled with a fatigue damage comparison would provide a comparison between test and in-service usage and identify areas for further investigation. There are however a number of different methods of obtaining exceedance diagrams and the method chosen to reduce each data set should be consistent with the method used to produce the comparison data initially. For example, the exceedance method used in the fatigue meter uses a 'lock' and 'release' method and different release levels will produce different exceedance spectra.

6.13.20 FATIGUE ANALYSIS

OLM Action 71: *The OLM data analysis process should include the capability to represent fatigue damage or crack growth increment (depending on fatigue analysis methodology) through the flight to identify particularly damaging manoeuvres or regimes.*

The need to undertake a review of the fatigue analysis process (stress-life, strain-life or crack growth) was discussed earlier in this paper. Having reviewed the fatigue analysis process, it should then be either contained within the OLM analysis or 'called' by the analysis software. However there is fatigue analysis functionality that should be considered for inclusion in the OLM analysis process, if it is not contained within the extant fatigue analysis process. Identification of particularly damaging manoeuvres or flight regimes requires a method of apportioning damage (Holford 1982) or crack growth increment through the flight. This is illustrated in Figure 24 for a combat/trainer wing feature and a large aircraft wing feature.

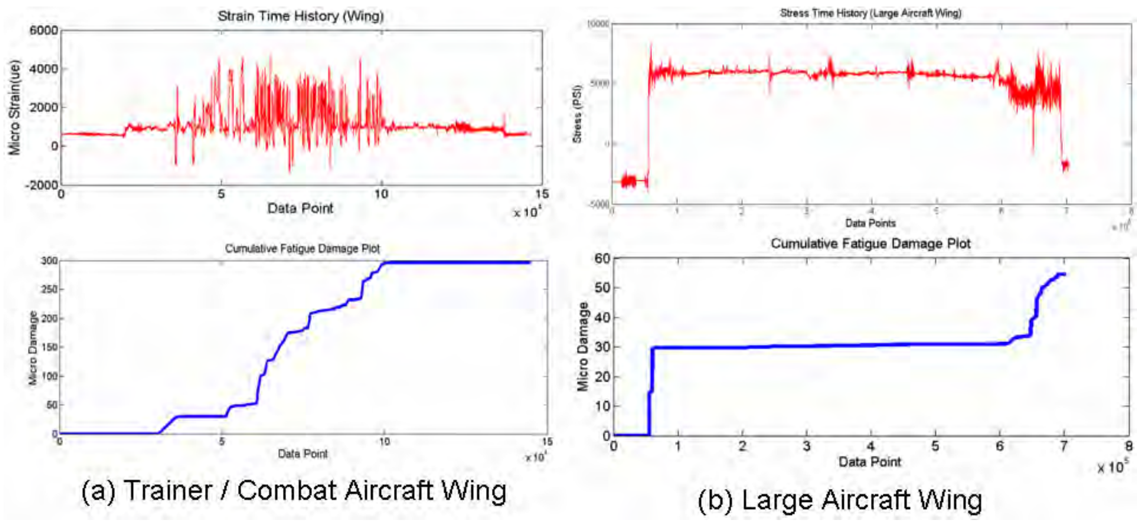

Figure 24 – Example Strain/Stress Time History and Fatigue Damage Accumulation Plots

In the example illustrated here the fatigue damage calculated from each cycle was apportioned equally between the cycle peak and trough and accrued based upon the time occurrence of the peak or trough within the time history (hence the need for retaining time data alongside the peak and trough magnitudes).

6.13.21 SAMPLE RATE CHECKS AND FREQUENCY ANALYSIS

OLM Action 72: *The ability to undertake frequency content analysis and sub-sampling of data and repeat fatigue analysis for sample rate investigations should be considered as a useful analysis tool.*

It is essential that the data captured within the OLM programme is sampled at sufficiently high rates to capture the significant structural modes for strain gauge channels, for example. One of the tools that can be used to substantiate the assumptions behind identification of sample rates is to investigate the frequency content within the time histories. The frequency content in a time signal can be identified by transforming the data into the frequency domain using a Fast Fourier Transform (FFT) algorithm (Cooley and Tukey 1965). From this process, the power spectral density (PSD) in a particular frequency range can be identified. An example PSD plot for signal with frequency content up to around 28Hz (and a tiny blip at 33Hz) is illustrated in Figure 25.

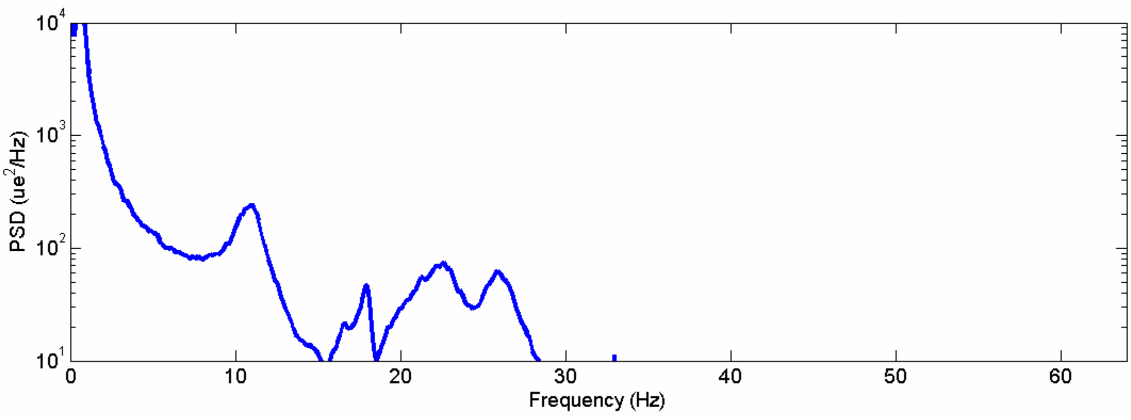

Figure 25 - Example Power Spectral Density Plot

If the frequency content in the signal is significantly different (e.g. higher) than expected from analysis and ground resonance testing, then further investigation may be required. Sample rates and associated filter settings may have to be increased to ascertain the actual structurally significant modes present. Such analysis relies upon flight conditions being achieved where these modes will be excited.

6.13.22 Fatigue Monitor Substantiation

OLM Action 73: *Where substantiation of a fatigue monitoring systems is required, functionality to allow direct comparison between the fatigue monitoring system output and the OLM data used to substantiate the monitor will be required. For the fatigue loads meter this functionality would emulate the exceedance counting mechanism. Care should be taken to ensure that the monitor triggering logic is fully understood. For parametric monitors using non-adaptive prediction methods, substantiation will include identification of limits of validity and identification of retraining requirements.*

6.13.23 Data Back up and Archive

OLM Action 74*: OLM data should be backed up and archived with one copy of the data stored in a fire safe and a further copy stored in a remote location. The data back-up should include the following:*

- *Data in its rawest form possible (e.g. binary digit files)*
- *Intermediate results*
- *Output files*

- *Setting values (e.g. calibration files)*
- *Analysis error codes and remedial action reports*
- *Associated Flight and Fatigue Data (e.g. F725 data)*
- *All source code (specific to OLM analysis) and software configuration control data*

6.13.24 SOFTWARE CONTROL

OLM Action 75*: OLM software should generally be considered as safety related and appropriate standards for software control should be applied.*

The current requirements for software control are well documented in standards such as Def Stan 00-56, ISO9001:2000/TickIT. Designer in-house processes should be assessed for suitability for use in the OLM programme. Failure of the OLM software would not cause catastrophic failure of an aircraft in the next flight. However, in the longer term, credible but underestimated values could have safety implications for the fleet.

6.13.25 VALIDATION AND VERIFICATION

OLM Action 76*: A validation and verification plan should be developed in which function, module and end-to-end tests of the analysis process should be planned with appropriate test cases. This plan should be reviewed by the OLM Specialist Group.*

6.14 CALIBRATION FACILITIES

OLM Action 77*: System calibration has been included in this paper as an Installation Task (Section 7). However, where programme aims dictate, considerable planning activity may be associated with the calibration requirements, particularly if significant loads calibration work is required. Therefore, development of a Calibration Plan should be included within the planning phase of an OLM programme.*

6.15 IN-SERVICE MAINTENANCE AND THROUGH-LIFE SUPPORT

6.15.1 OLM SYSTEM MAINTENANCE

OLM Action 78*: OLM maintenance requirements such as periodic datum checks or electrical shunt calibration requirements should be identified. These should be promulgated either by* *formal aircraft and ground equipment documentation amendment or by less formal means, such as the production of a Topic 2(R)1 leaflet.*

6.15.2 EFFECTS ON AIRCRAFT MAINTENANCE

OLM Action 79: *The effects on aircraft maintenance, including modification requirements to ground equipment should be identified and promulgated either by formal aircraft and ground equipment documentation amendment or by less formal means, such as the production of a Topic 2(R)1 leaflet.*

Where a number of aircraft in the fleet are OLM modified, or where OLM installations have been incorporated into build programmes then the production of appropriate maintenance publications should be considered. However, for a small number of modified aircraft or for periodic programmes this option is unlikely to be cost effective. However, it is essential that maintenance implications are documented and promulgated and that Unit personnel are made aware of these issues. Historically, Aircraft Engineering Development and Investigation Teams (AEDITs) have been well placed to identify the maintenance implications, including the need for OLM specific ground equipment (e.g. Figure 26) and have produced Topic 2(R)1 Leaflets accordingly. Usually the development of the leaflet has been undertaken while the installation of the OLM modification was underway. Historically, avoidable maintenance damage to OLM aircraft has been widespread on some OLM programmes. Furthermore, unnecessary damage to OLM installations has occurred because essential modifications to ground equipment had not been identified.

Figure 26 – Example OLM specific ground equipment ('OLM' wing trestles over strain gauges)

6.15.3 OLM Support Policy, Spares, Support and Test Equipment

OLM Action 80: *The support policy for the OLM installation should be defined. This will affect the requirement for OLM spares, support and test equipment, including instrumentation and strain gauge recalibration and repair.*

Some aspects of maintenance, such as strain gauge repair, will definitely require specialist skills outside of general trade boundaries.

6.15.4 Repeat Calibration Plan

OLM Action 81: *A repeat calibration plan for the life of the OLM programme, for each element of the OLM installation, including strain gauge bridges and parametric instrumentation should be produced.*

For most FTI-type transducers (e.g. accelerometers) the recommended equipment recalibration periodicity is generally annual. For loads calibrated strain gauge bridge installations recalibration in a loads rig should be undertaken if the component is changed and periodically to retain confidence in the loads data. This is a significant undertaking and realistically should ideally be carried out during major maintenance or major modification programmes. For other calibration methods, such as airborne calibration and consistency checks with flight parameters, checks should be carried out relatively frequently initially and as confidence in the data grows the frequency of recheck can be reduced.

6.15.5 Obsolescence reviews

OLM Action 82: *A schedule of obsolescence reviews of all OLM equipment including continued support statements from OEMs and a review of media and data storage facilities should be scheduled (a 3-yearly review is probably adequate).*

Developments in OLM equipment are proceeding apace. While this provides ever-increasing capability it also accelerates obsolescence and generates associated support issues. Therefore, consideration to obsolescence should be built into the OLM design. However, all too often in service crisis management is required to deal with obsolescence issues. These reviews should consider the obsolescence of all OLM equipment including continued support statements from original equipment manufacturers (OEMs) and a review of media and data storage facilities. In practice, it would be useful to link this review with spares holding reviews, dependent upon the support policy chosen.

6.16 PLANNING PHASE REVIEW

OLM Action 83: *A review/reviews should be undertaken by the OLM Programme Management Group or Specialists Group to ensure that all aspects of planning the OLM programme have been addressed. The reviews should include the following aspects:*

- *Timing of an OLM programme*
- *OLM programme aims*
- *Identification of measurement requirements*
- *Number of OLM-instrumented aircraft*
- *Review of fatigue analysis methods*
- *OLM system design*
- *Ground station*
- *Data analysis process design*
- *Calibration requirements (discussed further in Section7)*
- *In-service maintenance and through-life support*
- *Interface control requirements*

6.17 REPORTING SUMMARY

OLM Action 84: *Reporting of the following actions or topics should be included within the OLM programme planning phase (some of the following aspects may well be documented in meeting minutes rather than formal reports):*

- *Programme aims (OLM Action 2)*
- *Collation of fatigue damage spectra used in design or qualification (OLM Action 3)*
- *Fatigue spectra validation plan (OLM Action 5)*
- *Fatigue monitoring system assumption review (OLM Action 8)*
- *OLM instrumentation requirements (OLM Action 15)*
- *OLM instrumentation solutions (OLM Actions 16 – 29)*
- *Fatigue analysis methodology review (OLM Action 31)*
- *OLM equipment market research report (OLM Action 32)*

- *Analysis definition document (OLM Action 48)*
- *Analysis validation and verification plan (OLM Action 76)*
- *Calibration plan (OLM Action 77)*
- *OLM system support policy (OLM Action 78, 79)*
- *Repeat calibration plan (OLM Action 81)*
- *Obsolescence review plan (OLM Action 82)*

7 INSTALLATION PHASE

7.1 OLM SYSTEM INSTALLATION

7.1.1 INSTALLATION DURING AIRCRAFT BUILD

OLM Action 85: *Where possible, installation of an OLM system or making provision for an OLM system should be undertaken during aircraft build. Potentially large cost savings can be made using this approach and modern distributed DAU systems with data links between units can remove the risk of insufficient wiring for analogue signal being incorporated into looms during build due to immature design.*

The installation phase of an OLM programme entails fitting transducers, wiring, acquisition hardware and ensuring the OLM equipment functions as intended. The most efficient method of achieving this is to install the systems during aircraft build. Lengthy major wiring looms running to one central DAU can be avoided nowadays as remote systems can be connected by Ethernet, FireWire etc. These distributed linked systems greatly reduce the risk of major rework due to design changes as local wiring for strain gauges and sensors with data links between remote DAUs is required rather than aircraft-wide wiring for analogue signals. These options make OLM installation during build an even more attractive option. Additionally, surface preparation, bonding and protection of strain gauges at a structural component level during manufacturing will usually be subject to a higher degree of control than retrospective fit. There is also an existing and well-used link between production and design during manufacture with the process of works query notes or design change control to address issues found during installation is already in place. Installation of an OLM fit will undoubtedly have an adverse effect on the production process and this would need to be accounted for in programme scheduling.

7.1.2 RETROSPECTIVE INSTALLATION

OLM Action 86: *Where retrospective OLM installation is required, the most preferable technical solution for the OLM programme is a return-to-works (RTW) programme undertaken by the aircraft designer. Although this can have detrimental effects for aircraft production, from an OLM-programme perspective, return-to-works allows free access by the designer for the installation and calibration of the OLM fit. Long-term serviceability of OLM installations, particularly strain gauge channels has varied significantly across programmes. Furthermore, recovery of failed strain gauge installations can prove difficult in service. Therefore, efforts should be concentrated on ensuring sufficient access and time is allocated for the installation,* *calibration and functional testing of the OLM system and that highly controlled procedures are introduced and followed.*

<u>OLM Action 87:</u> *Where the aircraft designer does not have the skills or will or where the proposed costs are unaffordable, the use of 3rd party design approved organisations can offer a potential installation solution. Where possible, the use of 3rd party organisations should be undertaken with the cooperation of the designer. The use of 3rd parties complicates further the interfaces within the programme and would require clearly defined roles for the various organisations.*

To date most OLM installations have been installed retrospectively and various methods of managing the installation have been used from designer led return-to-works programmes to on-unit 3rd party installations with Service or contractor maintenance personnel. However, an OLM programme is intrinsically linked to the substantiation of the fatigue lives of the fleet and requires underwriting by the Designer. Hence, the installation of an OLM system should ideally be undertaken with the full involvement of the Designer. Assuming the Designer[17] has suitable facilities, skills and desires to fulfil such a role, a return-to-works OLM installation programme allows free access by the designer for the installation and undertaking of calibration of the OLM fit. Where this is not the case, Designer support for 3rd party installation should be sought.

Although some aspects of the installation of an OLM fit are similar to routine avionic modifications or upgrades, strain gauge installation and calibration (particularly loads calibration, discussed later in this section) are highly specialised tasks. Recovery of failed strain gauge installations can become extremely protracted as not surprisingly commanders are highly reluctant to release otherwise serviceable, scarce assets for repair of OLM installations. Also, physical access to repair gauges without relatively deep strip of the aircraft is often limited, causing an increased risk of subsequent failure of the repair. Surface preparation and adherence to bonding processes is essential and while a taut installation programme with minimum aircraft downtime is paramount, corner cutting on preparation, bonding, protection, EMC shielding etc will be regretted later in the programme. Furthermore, the aircraft should be sufficiently stripped to allow the best possible access for temperature surveys, surface preparation and gauge installation. The installation phase of the programme is one aspect that has great potential risk from false economies that will manifest themselves later in the programme.

[17] With changes in the way aircraft are procured it would be an error to assume that the traditional levels of facilities, skills and support offered by UK design organisations will be available for future manned or unmanned aircraft irrespective of supplier.

Where the aircraft designer does not have the skills or the will or where the proposed costs are unaffordable, the use of 3rd party design approved organisations can offer a potential installation solution. Where possible, the use of 3rd party organisations should be undertaken with the cooperation of the designer. Undertaking an OLM programme without the designer's cooperation would be extremely challenging and potentially very inefficient, particularly if critical design and qualification data were not made available, such as access to the workings of the fatigue qualification process. The use of 3rd parties complicates further the interfaces within the programme and would require clearly defined roles for the various organisations.

7.1.3 MODIFICATION PROCESS

OLM Action 88: *An OLM system will have a multitude of interfaces with existing aircraft systems, such as power supplies, data buses, instruments, wiring runs, effects on mass and centre of gravity and hence the use of formal designer-approved modification processes is appropriate. Additionally, where only a handful of aircraft will be modified the special order only (SOO) modification processes may be applicable.*

OLM Action 89: *Service Modifications (SM) (formerly termed Special Trial Fits or Service Engineered Modifications) have been used successfully to introduce short-term OLM installations or to facilitate small changes to existing designer approved modifications, for expedience (although this should be 'covered' by the Designer later to prevent a loss of configuration control). Special consideration should be taken to ensure that safety of flight and fitness for purpose aspects of the installation are thoroughly addressed.*

OLM Action 90*: Irrespective of installation route, detailed drawings, photographs and sketches of the strain gauge bridge locations, arrangements, wiring, with unique identifiers on the structure to ensure correct identification should be produced. Photographs should be taken before protective coatings are applied.*

Where Service Modifications (SM) (formerly Special Trial Fits or Service Engineered Modifications) are used to introduce short-term OLM installations or to facilitate small changes to existing designer approved modifications, for expedience, special consideration should be taken to ensure that safety of flight and fitness for purpose aspects of the installation are thoroughly addressed. This is a significant undertaking and should not be underestimated. To illustrate this, the environmental design considerations alone should include assessment for vibration, acceleration (i.e. crash requirements), temperature, altitude (pressure), rapid or explosive decompression, sand and dust, driving rain, salt fog and contamination by fluids. Certificates of design would be required for bought-out installed equipments and particular care over EMC design, assessment and testing would be required.

Detailed drawings, photographs and sketches of the strain gauge bridge locations, arrangements, wiring, with unique identifiers on the structure to illustrate identification and orientation are essential to support any fault finding work post installation. Photographs of bridge arrangements should be taken before protective coatings are applied (Figure 27). This information will be invaluable if there are discrepancies later in the programme as to bridge configurations or gauge identification.

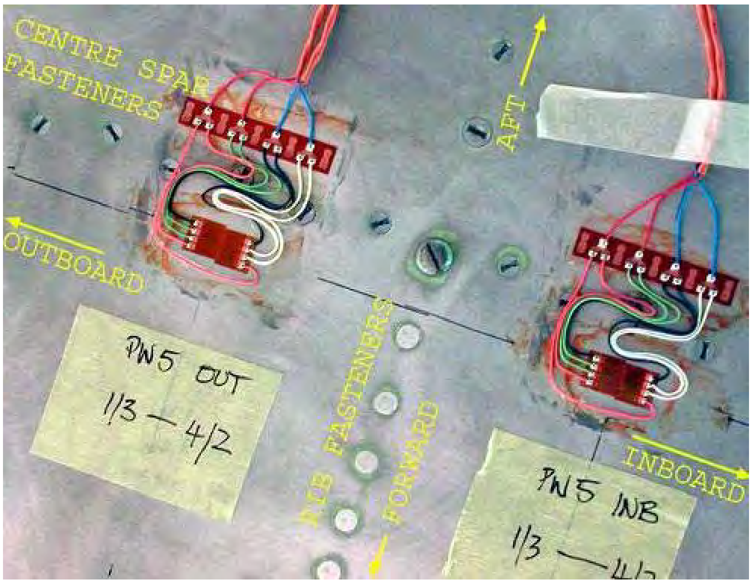

Figure 27 – Example photograph of strain gauge bridges with identification

7.2 CALIBRATION PROCEDURE

Calibration refers to the process of determining the relation between the output (or response) of a measuring instrument and the value of the input quantity or attribute. In non-specialised use, calibration is often regarded as including the process of adjusting the output or indication on a measurement instrument to agree with value of the applied standard, within a specified accuracy. For example, a thermometer could be calibrated so the error of indication or the correction is determined, and adjusted (e.g. via calibration constants) so that it shows the true temperature in Celsius at specific points on the scale.

Calibration can be undertaken using various methods with different aims and it is imperative that the calibration tests performed are relevant to the programme aims and will produce data consistent with these aims. Some of the more commonly used calibration methods, primarily for loads to fatigue test or loads input to a stress model are discussed in the following sections.

7.2.1 SETTING OF PHYSICAL DATUM VALUES

OLM Action 91: *Consideration should be given to the mechanism of setting the physical datum values appropriate to the outputs of a strain gauge installation.*

Irrespective of the method of calibration used, there will be a need to establish the appropriate physical loading condition that corresponds to the zero output from the strain gauge installation. Strain gauge bridges are frequently balanced to give zero output in the calibration state with no external load applied. Bridge balancing can sometimes be achieved with the instrumented component in a zero load state but in general the ‘zero position’ of a gauge installation output has to be set to a physical known output or datum before analysis can proceed. Frequently ground conditions are used in this exercise since mass information is likely to be readily obtainable and an expected output can be derived from suitable models.

7.2.2 ON-AIRCRAFT STRAIN GAUGE LOAD CALIBRATION

OLM Action 92*: Load calibration involves the application of a series of point loads to the aircraft structure and load equations are derived using the strain gauge response to these point loads. Where practicable, representative check cases can be applied using distributed loads (often to a higher proportion of limit load than can be applied using point loads e.g. a 2/3 limit load wing up-bending case). The following aspects should be considered when applying loads calibration to a whole or significant part of an aircraft:*

- *Review any static test data available to identify any possible non-linearity in the response of the structure, such as local buckling at higher loads.*
- *The calibration range should be to the maximum proportion of limit load possible, subject to the methods used to constrain the aircraft, the magnitude of the reaction loads and the local stresses in the structure at the load application points.*
- *The effects of deflection of the structure under load and the introduction of unwanted moments should also be considered.*
- *Shut down protection devices or warning systems should be incorporated into the rig design.*
- *Loads should be applied incrementally up to the maximum calibration load and removed similarly back to the original loading condition.*

- *Where possible, 2 or more initial loading runs should be applied to the aircraft to exercise or settle the aircraft within the loads calibration rig, before the calibration load application proper.*

- *Where possible, load cases should by applied several times to investigate any lag or hysteresis in the system and to identify any spurious runs.*

- *The configuration and location of the aircraft in the calibration rig should be carefully documented (i.e. location of aircraft relative to rig datum points and location of loading points on the aircraft). This information can prove particularly useful when repeat calibrations of the aircraft are required.*

- *Primary and secondary strain gauge bridge configurations should be calibrated. Where possible, primary and secondary bridges should be calibrated at the same time and the best response should be identified as the primary bridges.*

- *Different load conditions, such as ‘full fuel’ and ‘empty fuel’ should also be included in the loading cases. The effects of fuel distribution and wing sweep (if applicable) and 1g offset should be considered.*

- *Where possible, loads calibration should be undertaken with the aircraft in as close to a flight configuration as possible.*

- *Achieved loads (using load cells for example) as well as demanded loads should be recorded, with achieved loads being used for the calibration.*

- *Load reaction points should be monitored and recorded to protect local structure and to identify any excessive losses from friction or fouling.*

- *Periodic load balances should also be undertaken during calibration runs to re-baseline the calibration.*

- *The bridge-to-load calibration equations are usually obtained by using a form of linear regression analysis. Some compromises between resolution and the number of bridge inputs may be required to obtain optimum and practical solutions.*

- *Influence coefficients can be a useful tool in identifying the response of individual bridges to changes in the applied load location.*

- *Carry over effects (e.g. from the opposite wing) should be considered when unexpected bridges are identified as having a high effect on the output. However, caution should be* *exercised in the inclusion of carry over effects that the overall solution is not compromised. The influence of carry over effects on the final solution should reflect the contribution to the expected flight loads.*

- *R values of 0.995 or R^2 values of 0.990 are realistic aims for shear and bending moment load calibrations.*

- *Once the bridge-to-load equation has been optimised, where practicable, this may be cross checked by predicting the distributed load cases and determining the percentage accuracy.*

- *Where possible loads calibration of strain gauges should be undertaken after an aircraft has flown to allow for the settling of the structure, particularly for installations fitted at build. Where this is not possible, additional datum checks should be carried out after first flight and several flights later to identify any shifts in the data.*

Where the aims of the OLM programme require the identification of loads, such as in the determination of fatigue test spectra, a more complex approach is required. The first step, as with direct measurement, is to identify the strain gauge location and this was discussed in the Planning Section. Gauges should be located where strain levels will be adequate to obtain good sensitivity but away from local stress concentrations.

The methods used for loads calibration are generally developed from the work undertaken at NACA (forerunner of NASA) in the early 1950s and published by Skopinski *et al.* (1954). Load calibration is a method that permits the measurement in flight of the shear, bending moment and the torque on the principal lifting or control surfaces of an aircraft. Although it is accepted that the stress in a structural member may not be a simple function of the three loads of interest, processes have been developed for numerically combining the outputs of several strain gauge bridges in a way that the loads may be obtained.

A simple typical installation for a 2 spar structure, using four-active-arm strain gauge bridges is presented in Figure 28.

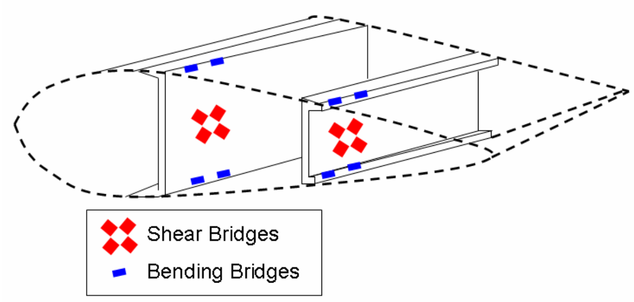

Figure 28 – Example strain gauge bridges for loads calibration (from Skopinski 1954)

Ideally gauges would be placed so that a bending moment bridge would respond only to bending and a shear bridge would respond only to shear and so on. However, this is only true for an elementary truss type beam arrangement and in practical structures more complex interactions between loading mechanisms exist. With care, gauge locations can be chosen and configured so that the bending bridge output should contain predominantly bending moment effects and so on.

The loads on the surface of a wing for example, can be specified by 3 orthogonal forces, normal forces, longitudinal forces and lateral forces (Figure 29) and by 3 orthogonal moments, bending moment, torque and in-plane bending. Thereafter, loads models are used to transfer these overall loads to local loads within the structure.

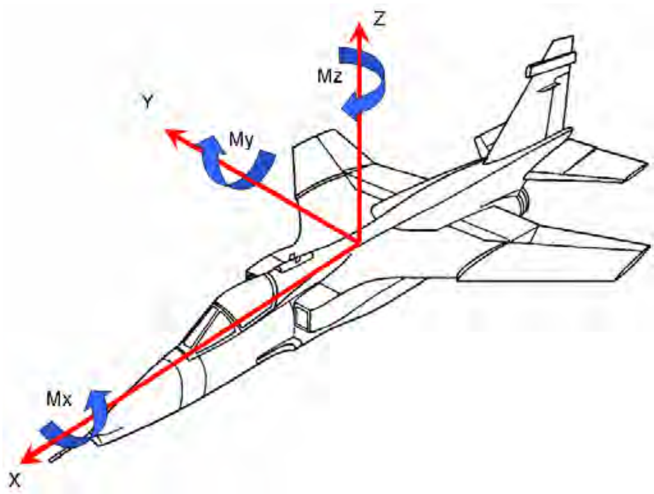

Figure 29 – Forces and Moments

The strain in a structural member or component can therefore be expected to be some function of these 6 quantities and this strain response must be taken into account in any method of relating strain gauge bridge output to load. In real structures these relationships can be complicated further as the strain in a wing root for example may be affected not only by the loads outboard of the measurement station but also by loads on the opposite wing or inboard of the measurement station. This carry over effect, as it is termed, can be particularly significant for unsymmetrical loading actions (Skopinski *et al*. 1954). Certain simplifications to these 6 quantities can be made. For a wing structure the stress in the structural member and hence the output from the strain gauges mounted upon that structure may be taken to be a function of the 3 principal terms of aerodynamic load investigation, shear, bending moment and torque. Additional loading actions may need to be considered for other structural features; for example, drag loads are generally highly significant for external stores and hence may need to be considered.

For major lifting surfaces, the method of obtaining the relationship between the output of the strain gauge bridges and the shear, bending moment and torque loads is by applying a series of point loads and employing the principle of superposition. This assumes that the strain at a particular location due to loads applied simultaneously at several points on the structure is the algebraic sum of the strains due to the same loads applied individually. This is the fundamental basis of Skopinski-type calibrations[18]. Developments from Skopinski's methods have included the application of distributed load to produce check cases.

How loads are applied, using either a single rig or combinations of smaller local rigs will depend on the extent of calibration required and the physical size of the aircraft. A typical loading calibration rig for a light trainer aircraft is illustrated in Figure 30.

[18] A useful review of the application of loads calibration undertaken on 13 aircraft (including the Space Shuttle wing) at NASA's Dryden Flight Research Facility was produced by Jenkins and DeAngelis (1987).

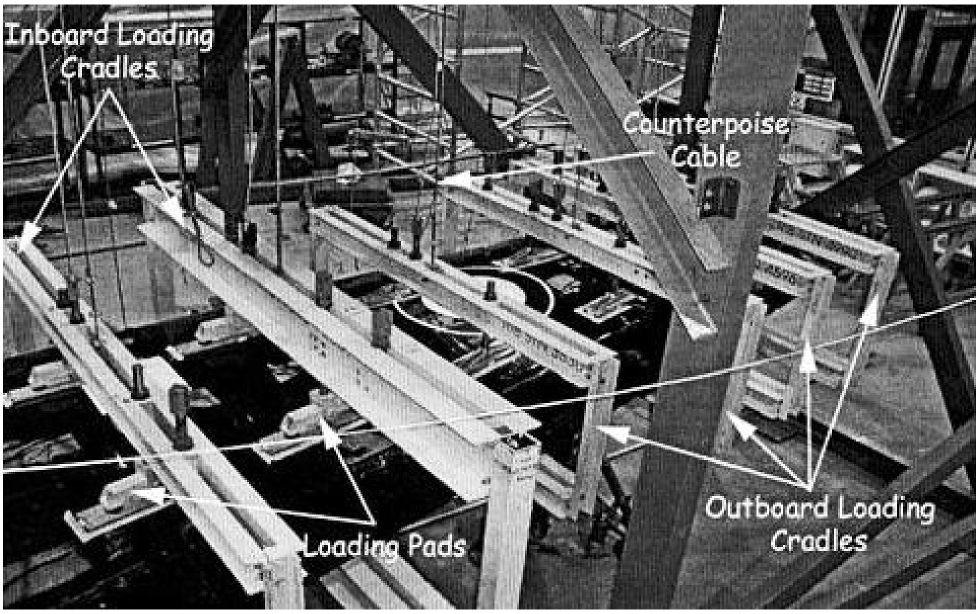

Figure 30 - Example OLM calibration rig (Courtesy of Bombardier Aerospace)

There will undoubtedly be variations in standard practice for load calibration for OLM aircraft across the industry. There are no hard and fast rules as to what proportion of limit load condition should be exercised by the calibration, largely because of practical and conflicting considerations. For example, from a true calibration perspective the structure should be exercised throughout the range (i.e. to limit load). However, in practice application of a point load anywhere near limit load condition is likely to case significant local damage to the structure. Furthermore, the extent of loading achievable is often determined by how an aircraft can be constrained within the loads rig and how these constraint loads can be reacted within the structure. Therefore, detailed design and analysis to ascertain achievable load ranges is required. Loads should generally be applied at regions with local reinforcement such as spar and rib intersections or at external load application points, such as aileron or rudder hinges to prevent local damage.

As discussed above, restraint of the OLM aircraft will be required to react loads applied by the calibration rig. Major attachment locations, such as wing, fin and tailplane mounts, engine mounts, slinging points, undercarriage attachments etc are generally used as reaction points. Loads are usually applied using hydraulic actuators mounted upon substantial rig arrangements or simple pan weight arrangements, where appropriate.

Methods, such as influence coefficients can be used to identify the response of individual bridges to changes in the applied load location. If the normalised bridge output (bridge output /

applied load) remains relatively constant with change in location of applied load then the bridge is more sensitive to shear. If the normalised bridge output varies linearly with variation in the spanwise location of the applied load then the bridge is sensitive to bending moment. However, if the output varies with chordwise location of the load then the bridge is responsive to torque.

Once the bridge-to-load equation has been optimised, where practicable, this may be cross checked by predicting the distributed load cases and determining the percentage accuracy. R values of 0.995 or R^2 values of 0.990 are realistic aims for shear and bending moment load calibrations. Torque values are, in practice, often more difficult to obtain similar levels of correlation. This is partly because the torque value can often be a relatively small number but driven by the difference between 2 big numbers (e.g front and rear spar shears).

Loads calibration is a complex and potentially costly exercise. There are many potential pitfalls and experience has shown that the more checks that can be introduced into the process the more likelihood there is of retaining a high level of confidence in the results of the exercise.

7.2.3 OFF-AIRCRAFT LOADS CALIBRATION

OLM Action 93: *Many components, such as wing links and actuator eye ends, can often be calibrated off aircraft in standard test machines. This allows significant flexibility, potentially greater calibration load range and potential to reduce aircraft down time and therefore consideration of off-aircraft calibration methods should be considered. However, care has to be taken to ensure that the calibration loading is applied representatively and the effects of any pre-load applied to the component when installed on the aircraft are understood.*

Although programme aims may dictate that a particular strain gauge bridge arrangement should be loads calibrated, it may not be necessary to calibrate the component or structure on the aircraft. Wing attachment links are a good example of such a component. Great care has to be taken with off-aircraft calibration methods to ensure that the loading applied to the component during the calibration exercise can be related directly to the loading seen by the component in service.

7.2.4 STRAIN GAUGE CORRELATION TO FATIGUE TEST DAMAGE

OLM Action 94: *Where is in the intention for fatigue damage calculated from OLM strain gauge channels to be compared with fatigue test damage, a review of the loading mechanisms and gauge response should be undertaken. This review should include:*

- *Whether the applied test loading is representative at the gauge locations. For a wing for example identification of load cases where the strain outputs from the fatigue test* *can be compared to the strain outputs seen in the OLM aircraft flown to these cases (e.g. 6g symmetric manoeuvre). However, care should be taken for a fuselage for example where test restraints and balance support may affect the loading.*

- *Whether the response of strain gauges is affected by in-service issues (such as equipment fitted on in-service aircraft but not on the test and their effect on local response and access to install gauges).*

- *A check of the fitting factors needed to set the test spectrum to predict failure at the end of the test running. Where large fitting factors are produced (>1.5-2.0) or factors less than 1.0 then further investigation should be undertaken (see Section 6.10, OLM Action 31)*

Where programme aims are to compare in-service usage directly with fatigue test spectra then a method of calibrating the strain outputs from the OLM aircraft to the damage introduced into the fatigue test can be used. In this method, strain gauge bridge arrangements on the fatigue test are replicated on the OLM aircraft and the fatigue analysis is fitted to either test failure points or the end of test, with appropriate safety factors applied. The fitting factor (stress factor applied to the test spectra to predict a failure criterion at the end of test) is then applied to strain gauge bridge output from the OLM aircraft. Thereby, in-service flying can be compared directly to that replicated on the fatigue test. This process and the issues associated with it were described in detail earlier in this paper (Section 6.10) and hence only a summary OLM Action is reproduced here.

7.2.5 Strain Gauge Airborne and On-Ground Calibration

OLM Action 95: *Successful airborne calibration of strain gauge bridges requires:*

- *The identification of well defined and repeatable flight conditions or manoeuvres and having confidence in the stress or strain conditions that should exist at the monitor location for these manoeuvres or conditions.*

- *Airborne calibration of wing locations and possibly fuselage locations is considered feasible with sufficient data.*

- *However, application of this method to a tailplane and in particularly a fin is considered highly challenging and a potentially high-risk strategy.*

- *The OLM system should be designed to accommodate additional data capture requirements (e.g. detailed fuel distribution).*

- *Ground conditions can provide useful additional calibration points. However, considerable scatter for nominally identical aircraft masses can be apparent in ground condition calibrations due to undercarriage oleo settling, aircraft attitude changes or different mass distributions due to fuel load distribution etc.*

- *Airborne calibration data are likely to suffer greater scatter than would be seen in the controlled environment of a Skopinski-type loads calibration.*

- *If airborne and/or ground-based calibration options are being considered as the sole method of calibrating for an OLM there is a significant risk posed to the programme. Therefore a feasibility study should be undertaken to reduce the risk. This study report should be reviewed and endorsed by the OLM Specialist Group.*

Airborne and on-ground calibration methods have been used in several programmes as either prime calibration or back-up or confidence checks in support of loads calibration or calibration to test damage methods. Airborne calibration is most likely to be chosen as an alternative method where Skopinski-type loads calibration is deemed prohibitively costly. The principles of this method are relatively simple but the application in practice can be highly problematic and the method is considered unlikely to be successful for all applications.

The method requires the aircraft to be flown in several pre-determined flight conditions or manoeuvres or data corresponding to these conditions being extracted from OLM data. For example, for an airborne calibration of a wing root bending bridge on a combat aircraft, a range of symmetric pull-up and push-over manoeuvres over a range of normal acceleration values and a series of wind-up turns[19] could be used to develop slope and offset correction (i.e. $y=mx+c$) for the bridge in question.

Flight loads measurement data or any previous OLM data would be a useful source of information to identify the flight conditions suitable for airborne calibration. With sufficient data and a good knowledge of the global and local loads or stress distributions within the aircraft, airborne calibration is feasible for wing locations and possibly fuselage locations driven by bending loads for example. However, having confidence in the application of this method to a tailplane and in particularly a fin, where relationships between flight conditions and stresses in the component are more complex is considered highly challenging and a high-risk strategy.

[19] In a wind-up turn the aircraft is rolled into a turn at each test condition and, keeping the speed and power constant through the manoeuvre by allowing the height to vary around the nominal test altitude, the normal acceleration is increased progressively until a defined limiting condition is reached.

As discussed in the programme aims section, if airborne calibration is to be used, the OLM system should be designed to accommodate this requirement. For example, fuel mass distribution, particularly on a large aircraft can have an enormous effect on the strain levels in the wing and hence detailed data on fuel mass distribution would be required before an accurate airborne calibration could be undertaken. Manual data recording may be required to supplement instrumentation to allow airborne calibration (such as identification of fuel mass distribution at calibration points in the sky in greater detail than the OLM instrumentation) but significant regular additional workload for operational units is highly undesirable as part of an OLM programme.

7.2.6 OTHER INSTRUMENTATION CALIBRATIONS

OLM Action 96: *OLM instrumentation (other than strain gauges) should be subject to manufacturers' recommended calibration procedures.*

7.2.7 CALIBRATION REPORTING

OLM Action 97: *On completion of all calibration activity a complete calibration report should be produced identifying performance of the calibration against the calibration plan.*

7.3 CONFIDENCE CHECKS

OLM Action 98*: A series of confidence checks should be undertaken and reported during the installation, calibration phases of the programme and before air test. These checks should ensure that all instrumentation is correctly identified, wired, responds in the correct sense and outputs are reasonable. Where practicable, these checks should include comparison between theoretical and measured ground loading cases.*

These checks can be very simple actions such as recording gauge outputs for full fuel and zero fuel conditions, flexing of the wings, moving the flaps or turning an accelerometer up-side down and their aim is to provide further confidence that the channels match their identifications and that they all respond in the correct sense. Turning a normal accelerometer up-side down and checking the output provides a good confidence in the correct wiring and the calibration equations. Such simple checks for all instrumentation should be planned into the installation and calibration process so that confidence in the system can be demonstrated before a confirmation air test. Incorrect gauge wiring ideally should ideally be identified before the aircraft flies not when looking at the air test time histories post installation flight test.

7.4 Air Test Requirements

OLM Action 99: *Specific manoeuvres or flight conditions should be specified for inclusion in the post-installation air test to gain confidence in the OLM data.*

The degree of strip and rebuild required for all but the simplest OLM installation is such that an air test should be undertaken before release of the aircraft to the operating units. The air test schedule is prescriptive and therefore, where necessary, additional specific flight conditions or manoeuvres should to be flown to establish confidence in OLM data.

7.5 Installation Phase Review

OLM Action 100: *A review/reviews should be undertaken by the OLM Programme Management Group and Specialists Group to ensure that all installation aspects of the OLM programme have been addressed. The reviews should include the following aspects:*

- *OLM System Installation*
- *Calibration Procedure*
- *Confidence Checks*
- *Air Test Requirements*

7.6 Reporting Summary

OLM Action 101: *Reporting of the following actions or topics should be included within the OLM programme installation phase:*

- *Installation report (OLM Action 88, 89 and 90)*
- *Calibration report including confidence and sense checks (OLM Action 97 and 98)*
- *Air test requirement (OLM Action 99)*

8 DATA CAPTURE

8.1 DATA CAPTURE PROGRAMME

8.1.1 CRITERIA AFFECTING DATA CAPTURE

Even for fleets well provided with OLM aircraft, OLM data will rarely account for more than 2% of flying. For many fleets with few OLM aircraft and only periodic recording, OLM will represent significantly lower percentages of overall flight data. Therefore, the aim of detailing a data capture programme is to ensure that the programme aims are met with representative data, as efficiently as possible.

Although the aims of some specific OLM programmes may affect the data capture programme, generally the capture of representative data across the various roles flown by the fleet is a requirement irrespective of the fundamental aims of the programme. The analysis undertaken during the planning phase to determine the required size of OLM fleet will also provide a basis for identifying the data capture programme. The need to manage data capture should also be balanced by the desire to make OLM as invisible to operational units as possible. Too lax an approach can result in vital data not being recorded purely because tasking of OLM aircraft to particular missions has not been carried out.

Irrespective of whether an OLM programme is intended to be continuous or periodic in nature, the initial phase of the OLM data capture will most likely be used to establish the baseline usage and subsequent capture will be focussed upon identifying changes or deviation from the baseline and following up observations raised during the baseline establishment process.

8.1.2 IDENTIFICATION OF DATA CAPTURE REQUIREMENTS

<u>OLM Action 102</u>*: Data capture requirements should be specified for the initial OLM programme. A review of available SPC usage data (or data from previous aircraft in the role) should be undertaken as the basis for the data capture requirements and the factors that should be considered in determining the programme should include:*

- *Programme aims (i.e. need for test spectra for example may be first priority)*
- *SPC distribution flown by the fleet*

- *Likely variance within SPC (e.g. air test – low variance, air combat – high variance), based upon cumulative average data from monitoring system if available.*
- *A priori fatigue damage distribution across SPCs (e.g. from monitoring system)*
- *Fleets-within-fleets and matching OLM capability*
- *Fleet distribution, deployments, maintenance and modification programmes*
- *Initial simplification or stores and role equipment variations*
- *Seasonal and syllabus variations (at least 1 year's data should be captured)*
- *Impact of scheduled maintenance*

Once data capture commences, the assumptions made in identifying the initial data capture programme should be reviewed to ensure they remain valid and to identify factors not considered a priori.

Segregating flight data by sortie profile code (SPC) has proven a useful method of identifying the various roles and usage seen by the fleet and a first-cut method for setting data capture requirements. Usage data or statement of operating intent and usage (SOIU) data will provide an indication of the likely usage in each SPC across the fleet. A review of each profile will also provide an initial indication of the likely variance in usage within that SPC. For example, many aircraft types have a SPC code for air test. This is also a rarely flown SPC and hence this SPC contributes little to the fatigue damage accrual for the fleet. Also, air tests are generally highly prescribed sorties with little variance in the flight profile and hence adequate OLM representation of air test data can usually be obtained from a handful of sorties. Conversely for combat aircraft for example, air-to-air combat sorties are usually highly damaging individually, represent a significant proportion of the usage and exhibit a high degree of variance in the severity of sortie. Therefore, a larger number of air-to-air combat sorties would need to be captured to have confidence that the OLM data were representative of usage.

Where usage data are available for a fleet and the fleet is fitted with even a rudimentary monitoring system (such as a fatigue meter), these data can be used to provide an estimate of the number of sorties required within each SPC. A simple time ordered cumulative average fatigue damage or fatigue index plot (Figure 31) can provide an indication of the minimum number of sorties needed in each SPC to gain a reasonable representation of that sortie type *a priori*. (It is accepted that this heuristic method depends upon the monitor being reasonably accurate or at least relatively consistent.) Where no usage data exist, first-cut estimates can be developed from previous aircraft types in similar roles.

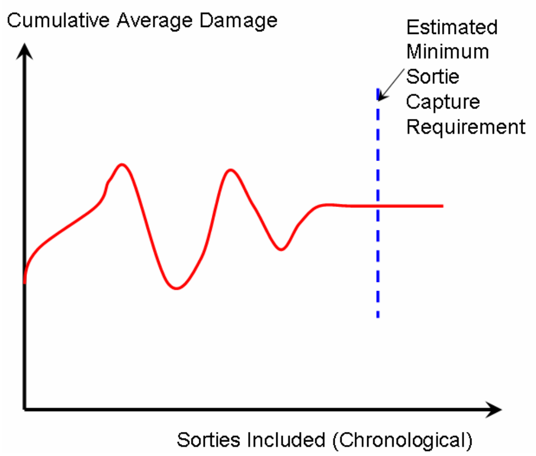

Figure 31 – Example cumulative average plot

Once data capture commences and damage or crack growth[20] data are available, these initial estimates of the minimum data capture requirements should be refined using OLM-derived damage or crack growth rates by sortie profile code and by major structural component (e.g wing, fin, tailplane etc), as applicable. This is because the variance in severity for the same sortie types can be very dissimilar across different structural components. For example, there will be little correlation between fin damage (where dominated by lateral gusts) and wing damage (where dominated by manoeuvre).

In addition where scatter is found to be larger in a particular SPC than expected, particularly where that SPC contributes highly to fatigue damage accrual, a greater number of sorties will be needed.

Also, fleet-within-fleet issues and the requirement to match the configuration of OLM aircraft to particular roles can add significant further complications to the data capture requirement. In establishing these requirements, those issues considered likely to affect usage of the aircraft, such as physical difference between aircraft within the fleet (e.g. engine standard, avionics and weapons capability) should be identified and OLM aircraft matching these capabilities deployed to appropriate units or squadrons. Weapons carriage adds a further additional complication to the data capture requirements. Initially, it can be useful to divide weapons fits into groups of

[20] Linear elastic fracture mechanics methods assume that the crack elongation is a function of its original length as well as the incremental applied stress/load spectrum, whereas the stress-life approach considers the incremental damage contribution from the spectrum to be independent of the *a priori* damage accumulation. Meaningful comparison of crack growth increments on a flight-by-flight basis will require calculation from a standard initial (beginning of sortie) crack length .

similar mass, aerodynamic loading and inertia loading stores. Thereafter, the requirements can be evolved as data are captured and when differing stores carriage effects are found (e.g. stress/g changes).

Fleet disposition across squadrons, units, deployments, maintenance and modification programmes need to be taken into account within the data capture programme. Where there are larger numbers of OLM aircraft across the fleet, aircraft transfers to capture essential data are generally less frequent. However, for programmes where there are few OLM assets and a widely dispersed fleet, careful management and programming of the OLM aircraft is essential. Where assets allow, providing an OLM aircraft to units or squadrons as an additional aircraft can often offset the burden of involvement in an OLM programme.

Additionally, possible seasonal variations and training syllabus variations should be considered and at least one year's data should be captured; weather, temperature, external tasking (e.g. support to scheduled exercises) etc can all have an effect on the ability to capture representative data and hence these issues should be investigated.

8.2 UNIT INVOLVEMENT

8.2.1 UNIT OLM PROJECT OFFICERS

OLM Action 103: *Unit OLM Project Officers should be appointed to act as the focal point for OLM activity on the unit or station. The Unit Project Officer should be responsible for:*

- *Monitoring data capture against requirements*
- *Allocating the aircraft within the unit*
- *Data transfer from units*
- *Control of maintenance ensuring the necessary flight and fatigue data for OLM flights is obtained from the Unit*
- *Act as a focal point on the Unit for OLM issues*

Terms of reference should be issued to the Unit OLM Project Officers by the OLM Programme Management Team. They should be made aware of the overall project aims and the importance of their role within these aims. Once appointed OLM Project Officers should be included within the OLM Programme Management Team.

A successful OLM programme is entirely reliant upon support from the operational units. Despite efforts to minimise the burden placed upon units, in an attempt to improve data capture performance, there will be a need for unit staff to have some involvement with the OLM programme. At the very least this will be extracting a memory module periodically, sending it to an analysis centre, undertaking periodic system checks and often providing flight and fatigue data for OLM sorties.

Experience has shown that by getting Project Officers involved in the programme towards the end of the OLM installation phase pays dividends throughout the programme. Although projects are invariably focussed nowadays on Gantt charts and ‘systems’, this all falls down if people do not do what is required. Therefore, choosing a Unit Project Officer with the right organisational skills and ensuring they are aware of their importance in this role is essential.

8.2.2 TRAINING

OLM Action 104: *OLM training courses covering all tasks required to be undertaken by unit personnel should be developed and provided to the operating units, ideally coincident with the arrival of OLM capable aircraft.*

The training requirements should cascade from the support policy for the OLM installation. Training is an essential element of ensuring the OLM programme runs to plan. As previously discussed, the aim is to reduce unit involvement to a minimum. However, it is essential that unit personnel are adequately trained to undertake the tasks required of them. The OLM system designer is generally best placed to provide training information. Experience has shown that short training courses run by the designer and held at the operating units in conjunction with the arrival of OLM aircraft is an efficient way of ensuring data capture gets off to a good start.

8.2.3 UNIT PRESENTATIONS (PRE AND POST OLM)

OLM Action 105: *Unit presentations to engineering staff and aircrew should be undertaken to explain the OLM requirements and the importance of the unit’s role. Additionally, findings should be fed back to unit staff to ensure their continued support for the programme. For long-term programmes, unit briefings should be periodic to ensure continued focus on the programme and to account for personnel turn over.*

As already discussed, data capture is highly dependent upon unit support within an environment where engineering organisations are increasingly stretched. However, face-to-face presentation to unit engineering staff and aircrew to explain the reasons behind the OLM programme, its importance and their essential role in the programme has proven a wise investment in previous programmes. Aircrew acceptance is almost as important as that of the engineering staff. Allaying aircrew fears of 'the spy in the cockpit' is essential. Ideally the OLM system should be invisible to aircrew but this is not always possible. However, it is essential the OLM aircraft are not flown in a different manner to the rest of the fleet. Making aircrew aware that ultimately this programme is about ensuring their safety usually helps win them around. Furthermore, their assistance in gaining an understanding of what is being done with the aircraft can be invaluable in analysing the data.

In addition to presentations at the beginning of an OLM programme, feedback of findings to units is essential to keep the focus on the programme and ensure that unit personnel are made aware that their efforts have resulted in something tangible.

8.2.4 TRIALS DIRECTIVE

OLM Action 106*: A Trials Directive (TD) (often published in the aircraft Topic 2(R)1) should be produced. The TD provides an overview of the OLM programme aims and the OLM system; it is used to promulgate data capture and reporting requirements, dispatch and fault reporting processes and to identify points of contact within the programme. A template for a TD is provided in Appendix I.*

8.3 DATA CAPTURE PHASE REVIEW

OLM Action 107*: A review/reviews should be undertaken by the OLM Programme Management Group and Specialists Group to ensure that all data capture aspects of the OLM programme have been addressed. The reviews should address:*

- *Data capture programme*
- *Performance against programme requirements*
- *Definition of unit involvement requirements and support provided*

8.4 REPORTING SUMMARY

OLM Action 108*: Reporting of the following actions or topics should be included within the OLM programme data capture phase:*

- *Data capture requirements (OLM Action 102)*
- *Training requirements (OLM Action 103)*

- *Trials Directive (OLM Action 106)*

9 ANALYSIS AND REPORTING

In Section 6 of this paper the design aspects to be considered in the data analysis process were explained alongside details of expected analysis functions required within an OLM analysis package. In this section the initial output, post processing and reporting of OLM data and findings are discussed.

9.1 POST AIR TEST / INITIAL ANALYSIS AND REPORT

OLM Action 109*: Following the air test or initial flying after the installation of the OLM system on each OLM aircraft post-flight analysis should be undertaken promptly. This analysis should include the following:*

- *Identify the serviceability status of all data channels*
- *Identify any data losses or anomalies*
- *Compare channel values with expected values*
- *Compare character of data with that expected for channel*
- *Check of channel ranging values in engineering units*
- *Check frequency content for channels susceptible to high-frequency loading*
- *Review channel sample rates*
- *Recommend remedial action as required*
- *Check analysis software*

The OLM Specialist Group should review the analysis of the initial flight/s and confirm any recommendations for remedial action.

Having confidence in the data provided from an OLM programme is essential in ultimately achieving the aims of the programme. Where confidence in the data is lost, remedial action to recover the situation can be extremely costly and wasteful. Therefore, rapid initial analysis and reporting following initial sorties is required.

9.2 PROGRESS REPORTING AGAINST PROGRAMME AIMS

OLM Action 110: *Regular (e.g. monthly) reporting of data received, analysed and status against programme requirements should be undertaken with remedial action recommended as required.*

It is essential for any OLM programme for data capture against programme requirements and the status of the data to be monitored closely and regularly. Analysis (or at the very least validation) of the data must keep pace with capture otherwise there is a serious risk of recording large quantities of unserviceable data when repairs should have been initiated. Experience has shown that the most successful OLM programmes have had a dedicated OLM team undertaking analysis of the data. If a temporary data backlog should occur, the more recent data should be analysed first to ensure that unserviceable channels are identified soonest. Regular (e.g. monthly) reporting of data received, analysed and status against programme requirements should be undertaken with remedial action recommended as required.

9.3 INTERIM REPORTING AGAINST PROGRAMME AIMS

OLM Action 111: *Interim reporting should be initiated when a reasonable body of data have been or are scheduled to have been received (e.g.100 sorties for 1st interim). The interim reports should include the following:*

- *Identify the serviceability status of all data channels*
- *Identify any data losses or anomalies*
- *Identify any sorties flown but not captured*
- *Compare channel values with expected values*
- *Compare character of data with that expected for channel*
- *Check of channel ranging values in engineering units*
- *Identify any suspect calibration values*
- *Check frequency content for channels susceptible to high-frequency loading*
- *Review channel sample rates*
- *Review of limits set for limits and anomaly detection*

- *Compare captured data with programme requirements*
- *Assess progress against programme aims*
- *Develop provisional observations / conclusions based upon data received against programme aims.*
- *Update estimate of data requirements to meet programme aims, based upon data received (e.g. variance in damage in SPC X is far greater than expected hence data requirements increased etc)*
- *Recommend remedial action as required (e.g. changes to data capture programme, changes to OLM configuration or installation repairs)*

The OLM Specialist Group and/or Programme Management Group should review the analysis of the interim report and confirm any recommendations for remedial action.

9.4 FINAL REPORTING

OLM Action 112: *At a point determined by the programme aims, a final report should be raised. This report should form a natural progression from the interim reports but should be considered as the definitive historical record for the programme and hence should be a stand alone document but with references out to lower-level detailed reports generated during the course of the programme. The final report should include details of:*

- *Programme aims*
- *OLM Installation*
- *Calibration process*
- *Data analysis process*
- *Data Capture Programme*
- *Data Capture Achievement*
- *Data Quality*
- *Data Analysis*
- *Conclusions by Programme Aims*

- *Recommendations for remedial airworthiness action or further work*
- *OLM report references*
- *MASAAG Paper 109 directory entry (see Appendix J)*
- *Lessons identified*
- *Future OLM recommendations, including data capture, system enhancements or care and maintenance requirements*

The OLM Specialist Group should review a draft of the final report before publishing and the agreed final report should be reviewed by the OLM Programme Management Group. Recommendations should be presented to the SIWG for endorsement and for the identification of implementation target dates.

9.5 FOLLOW-UP ACTIONS

OLM Action 113: *Progress against endorsed OLM recommendation implementation target dates should be monitored at SIWG including where required:*

- *Production of revised fatigue life clearances based upon OLM-derived spectra and produce Fatigue Type Record (Part 2) or equivalent document, if appropriate (See OLM Action 6)*
- *Identification of remedial airworthiness actions required for revised fatigue lives below aircraft fatigue life requirement*
- *Review of the Release to Service and identification of amendments required following revision to fatigue lives*
- *Follow-up actions from lessons identified and future OLM requirements*

9.6 REPORTING SUMMARY

OLM Action 114*: Reporting of the following actions or topics should be included within the OLM programme data analysis and reporting phase:*

- *Post Initial Flight Report (OLM Action 109)*
- *Regular (e.g. monthly) data received, analysed and status reports (OLM Action 110)*
- *Interim Reports (OLM Action 111)*

- *Final Report (OLM Action 112)*
- *SIWG Update (OLM Action 113)*

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Appendix A: Extracts from Regulatory and Guidance Material

This appendix contains the regulatory material governing OLM programmes at the time of writing this paper. Extracts from the Military Airworthiness Regulations (JSP 553), Defence Standard 00-970 (Def Stan 00-970) and Joint Airworthiness Publication 100A-01 (JAP 100A-01) have been reproduced here. These regulations will undoubtedly be updated in future years and hence readers are advised to refer to the most up-to-date sources.

A.1 Joint Service Publication 553

A1.1 Appendix K.4 and K.5

The requirements mandating OLM and the process for seeking a 2* exemptions from undertaking OLM is described clearly in JSP 553 Annex K.4 and K.5, detailed below:

MANDATORY REQUIREMENTS

Mandatory Requirements for Operational Loads Measurement/Operational Data Recording

K.4 IPTLs are to arrange for the installation of a permanent Operational Loads Measurement (OLM) system, for helicopters a temporary Operational Data Recording (ODR) capability, in a representative sample of each type fleet, to undertake the scheduled recording of data, or to enable an ad-hoc OLM/ODR programme to be carried out as follows:

K.4.1 Within 2 years of a new type aircraft's entry into Service.

K.4.2 Subsequent OLM/ODR is either be carried out on a continuous basis or at a periodicity defined by the IPTL; the requirement to carry out OLM/ODR is to be reviewed at no less than every 2 years by the IPTL, in consultation with ►PMSD – ASI◄

K.4.3 Following any major change in aircraft operational usage, irrespective of which regime is being applied.

K.4.4 Prior to any planned airframe, and for helicopters any operational load critical component, life extension.

Exceptions to Mandatory Requirements for OLM/ODR

K.5 Exceptions to the policies for the mandatory OLM/ODR recording detailed above may only be granted by the 2*, or equivalent, post in the ►DPA/DLO◄ responsible for the engineering aspects of the MA Release/RTS of the aircraft. If OLM/ODR is not undertaken at 5 years from the last programme, the IPTL's decision is to be endorsed by the 2*, or equivalent, post responsible for the engineering aspects of the MA Release/RTS, and thereafter at 2 yearly intervals.

A.2 Defence Standard 00-970

A.2.1 Part 1 Section 3.2.21 – Structures - Fatigue – Service Monitoring

The prime OLM-related regulation within Def Stan 00-970 is contained within Part 1 Section 3.2.21 – Service Monitoring. The requirement states:

> 3.1.21 Every aircraft in the fleet shall be provided with instrumentation for the purpose of estimating the fatigue life consumption of fatigue-critical structure and validating the assumptions made during substantiation. Provision shall be made for this instrumentation during production.

Compliance with this requirement is identified as:

> For those components that are not individually monitored by an advanced direct strain measuring technique, a continuous or periodic Operational Loads Measurement programme is a condition of compliance with these requirements and shall be agreed with the relevant Service Policy Authority.

A.2.2 Part 1 Section 3 Leaflet 38 – Structures – Service Monitoring

For guidance, readers are referred to Leaflet 38 – Service Monitoring:

At the time of drafting this paper, revisions to the Service Monitoring sections of Def Stan 00-970 (Section 3.1.21 *et al*. and Leaflet 38) had been proposed but these revisions had not yet been endorsed by the relevant authorities for inclusion in the Standard. However, for completeness, the proposed revisions are included in this paper at Appendix C.

Leaflet 38 currently provides the following guidance relevant to OLM:

> 1.2 Comparison of in-service usage with design assumptions is fundamental to airworthiness in determining equivalent safe lives and inspection criteria. Fleetwide structural monitoring, including monitoring by simple usage parameters is underwritten by Operational Loads Measurement (OLM) on fixed-wing aircraft or by Operational Data Recording (ODR) programmes on helicopters. Continuous or periodic OLM/ODR programmes are mandatory to comply with MoD airworthiness policy.
>
> 1.3 Although this leaflet is primarily concerned with fatigue damage arising from manoeuvres and gusts, it is equally important to make provision for recording other usage data which will impact on airframe and component fatigue lives; for example, pressurisations, landings, undercarriage cycles and engine acoustics in flight and during ground runs can all affect lives. Therefore, all parameters necessary to monitor in-service usage are to be identified by the Design Authority to the Project Authority during the design process.

Additionally, although detailed under the Statement of Operating Intent and Usage section, the following paragraph is highly relevant to OLM programmes:

> 2.1 The Design Spectrum is the best estimate of the typical loading that an aircraft is expected to experience when it enters service. In collaborative projects, this spectrum may represent an agreed compromise between the various national authorities. Since in-service or national usage can vary from the Design Spectrum and long-term changes may occur to national flying patterns, it is essential to monitor the operation of most types of military aircraft throughout their service life. This monitoring enables the changes in operating pattern to be assessed by the aircraft Design Authority for their impact on structural component lives and inspection intervals.

Direct reference is made to OLM under the Fixed-Wing Structural Monitoring section of Leaflet 38, as follows:

> 3.1 ….it is preferable to have a single range of equipment to undertake both fleetwide monitoring and OLM programmes, configured to suit specific type requirements …
>
> 3.2 An OLM capability is an essential requirement for all military fleets because of the demanding and diverse nature of military operations; the only exception is civilian aircraft derivatives for which the use is the same as civilian operations. A selected number of aircraft in the fleet are to be permanently modified for loads measurement and, when required, comprehensive instrumentation is to be fitted to record the loads on the major structural components of the airframe, together with other relevant parameters. The number of aircraft requiring this modification will depend on the range of fleet flying patterns, the number of roles and theatres of operation; the requirement for back-up aircraft must be considered.
>
> 3.3 OLM recording must be undertaken on a permanent basis for combat aircraft and, for non-combat aircraft, at a periodicity defined by the Project Authority. The requirement to carry out a periodic OLM must be reviewed every 2 years, taking account of usage changes, but the interval between OLM programmes must not normally exceed 5 years. The benchmark for any OLM programme is to capture a sufficient proportion of the fleet's usage across all types and roles to enable an accurate assessment to be made of total usage. The Project Authority has the overall responsibility for running the OLM programme but the specific requirements of the OLM system, the equipment interfaces and analysis routines should be agreed between the Design Authority, the Service specialists and their advisors.

A.2.3 Part 1 Section 3.1.23 – Structures – Static Strength and Deformation - Measurement

Regulation and guidance directly applicable to Flight Loads Measurement (FLM), but equally relevant to OLM, is contained within Part 1 Section 3.1.23 – Measurement - of Def Stan 00-970.

> 3.1.23 Measurement shall be made at sufficient stations to establish loads in the relevant parts of the structure with reasonable accuracy.

FLM (or flight loads survey as it is termed on some projects) is generally aimed at validation of models in respect of static loads and to clear the aircraft for service flying. FLM involves flying an instrumented aircraft to certain points within the flight envelope and comparing the loads measured with those derived from the loads modelling for these cases. Therefore, FLM has many similarities with OLM but also significant differences, particularly as FLM is not intended to provide data representative of in-service usage. The relationship between OLM and FLM is discussed further in the next Section.

Guidance associated with the above requirement states:

> The following quantities should be considered for measurement:
>
> (a) shear, bending moment and torque at the wing roots and at one or more other stations in the wing,
>
> (b) shear, bending moment and torque at the roots of the fin and tailplane,
>
> (c) shear, and bending moment at one or more fuselage sections,
>
> (d) hinge moments of control surfaces,
>
> (e) load distributions over particular surfaces where special investigation (e.g., or buffet loads) is required,
>
> (f) undercarriage loads, and
>
> (g) loads on external stores.

A.2.4 Part 1 Section 3.1.26 – Structures – Static Strength and Deformation - Measurement

Further regulation and guidance applicable to Flight Loads Measurement, but equally relevant to some aspects of OLM can be found in Part 1 Section 3.1.26:

> 3.1.26 A continuous record shall be made of the relevant flight parameters necessary to define the particular manoeuvres in which the load measurements are being made.

Within an OLM programme the parameters are frequently used to identify the operations behind high ‘fatigue loading’ rather than for defining the manoeuvre being carried out.

Compliance associated with this FLM requirement states:

> The following quantities shall be considered for measurement:
>
> (a) airspeed and Mach Number,
>
> (b) altitude,
>
> (c) normal acceleration,
>
> (d) pilot's force on elevator, aileron and rudder controls,
>
> (e) position of elevator, aileron, rudder and other relevant controls,
>
> (f) rates of roll, pitch and yaw,
>
> (g) angles of incidence, sideslip and roll,
>
> (h) aeroplane weight and its distribution, and
>
> (i) thrust conditions.

A.2.5 Part 1 Section 3.10.61 – Active Controls – Loads Measurement

Section 3.10.61 contains loads measurement requirements for in-service aircraft fitted with active control systems (ACS). Within Section 3.10.61 reference is made to Section 3.10.60 – which contains similar regulations for Prototype, Development and Preproduction aircraft. Section 3.10.61 states:

> In-service aeroplanes incorporating ACS shall, as required by the IPTL, be fitted with instrumentation to enable defined critical fatigue loads (as defined by actions taken to comply with 3.10.60) to be measured and assessed, so that consumption of structural life can be quantified. In addition, a representative sample of in-service aeroplanes shall be fitted with a comprehensive load measurement system, which although not necessarily as comprehensive as that fitted to prototype and development aeroplanes, shall be sufficient to enable defined critical static and fatigue loads to be monitored and to allow new critical loading actions (caused for example by differences between actual aeroplane usage and that assumed during design and development flying) to be identified.

A.2.6 Part 1 Section 3 Leaflet 6 – Structures – General Information

Leaflet 6 in Section 3 is primarily associated with testing; however, paragraph 6 of the leaflet describes methods of load measurement, as follows:

> 6.1 Two current methods of measuring loads in flight, which may be combined if required, are:
>
> (a) strain gauging. A technique of flight loads measurement using this method has been developed in the United States and is described in Ref 1 (see note below). This

technique requires the interpretation of the gauge responses in flight in terms of a static calibration on the ground.

Note: The second method was pressure plotting, which is not an OLM function and has hence been removed. Ref 1 is Skopinski, T. H., Huston W. B. and Aiken, Jr. W. S., Calibration of strain gauge installation in aircraft structures for the measurement of flight loads NACA Report 1178, August 1954 (see Report References).

A.2.7 Part 1 Section 2 Leaflet 6 – Flight – General Requirements and Definitions

Although Def Stan 00-970 Part 1 Section 2 – Flight – is generally less familiar to structures engineers than Part 3 of the Standard, it contains valuable requirements, guidance and information on test and instrumentation, much of which is highly relevant to OLM programmes.

Section 5.2 of Leaflet 6 - General Requirements and Definitions contains the following information:

> 5.2 The Contractor should therefore consider the instrumentation requirements in relation to the methods proposed for demonstrating compliance and should ensure that the instrumentation and the methods of recording are appropriate to the standard of accuracy required. In particular, the response characteristics of the transducers and recording system should be such that they give sensibly correct readings under the dynamic conditions required by the test methods used. If a digital recording system is used, the sampling frequency should be appropriate to the aeroplane frequencies of interest and should be such that it is possible to interpolate with reasonable accuracy between the recorded points to give a good estimate of the maxima achieved and the shape of the aeroplane response. In addition, it should be sufficiently high for spurious indications (e.g. by aliasing) to be avoided. The Contractor should avoid the use of instrumentation systems that are sensitive to the effects of temperature, electrical system voltage, applied accelerations, vibration and other external effects.

A.2.8 Part 1 Section 2 Leaflet 63 – Flight – Requirements for Structural and Equipment Exposure to Noise and Vibration – Data Analysis and Assessment

Leaflet 63 of Def Stan 00-970 Part 1 Section 2 – Flight – provides useful guidance on data processing in the context of exposure to noise and vibration. However, much of the guidance is equally applicable to OLM programmes; for example, para 1.3 states:

> 1.3 The tasks of data gathering, data processing and assessment are strongly dependent upon one another for success. Poor quality or irrelevant data cannot generally be compensated for during processing or assessment. Similarly, good data can lead to erroneous conclusions if processed or assessed in an inappropriate manner.

A.2.9 Part 1 Section 2 Leaflet 10 – 32 – Flight – Various Flight Test Requirements

Leaflets 10-32 of Def Stan 00-970 Part 1 Section 2 – Flight – provide a series of recommended test instrumentation and parameters associated with particular flight regimes or conditions. In addition, recommended ranges, accuracy values, resolution and sample rates are provided, considered appropriate for flight test data. Although these data are orientated towards handling and performance assessment they are nonetheless useful as an indication of likely OLM requirements and elements of these leaflets have been extracted and collated in Appendix D of this paper.

A.3 Joint Airworthiness Publication 100A-01 Chapter 11.1.3

The prime reference to OLM within JAP100A-01 is in section 7 of Chapter 11.1.3 under the validation requirements. This section is detailed as follows:

7 Operational Load Measurement (OLM)/Operational Data Recording (ODR) and Manual Data Recording Exercise (MDRE)

7.1 Background

Fatigue and usage monitoring systems for IAT programmes rely on a number of assumptions. These assumptions may either have been based on incomplete knowledge at the design stage or may subsequently be invalidated due to changes in operating intent and usage. Although gross changes to operating intent and usage will be communicated to the Designer via the SOIU, detailed usage parameters and loading conditions need to be captured in service to validate the assumptions inherent in fatigue and usage monitoring systems and associated fatigue and damage tolerance clearances. As aircraft operating patterns, configuration and inertia properties change, the relationships between flight parameters and local structural stresses will also change, significantly affecting fatigue usage. However, indirect usage monitoring systems that rely simply on flying hours or ‘g’ counts will be insensitive to such changes and therefore must be supported by OLM, ODR or MDRE programmes.

7.2 Principles

Simple, fleet-wide fatigue and usage monitoring systems rely on assumptions for the fatigue and usage parameters that cannot routinely be captured. For fixed-wing aircraft, basic fatigue and usage data is captured by means of simple methods such as the fatigue meter and MOD Form 725. For helicopters, basic flying hour data captured by MOD Form 724 is supplemented by more extensive data gathering by MDRE. In both cases, however, more detailed data is required to validate assumptions and to provide a detailed understanding of aircraft motion parameters, manoeuvre Points-In-The-Sky, asymmetric manoeuvre usage, miscellaneous usage (such as flying control surface usage) and local stresses. This data is normally gathered by OLM (for fixed-wing aircraft) or ODR (for helicopters). Both OLM and ODR involve the instrumentation of a representative sample of the in-service fleet to gather strain gauge, motion parameter and discrete data for normal service flying. JSP 553 details the mandatory requirements for the frequency of OLM/ODR, which may have to be undertaken several times during the life of a type. The OLM/ODR requirement may therefore most effectively be met by permanent installation of equipment on a representative sample of aircraft, for activation of the OLM/ODR system either continuously or as and when required.

The responsibilities of the IPT (detailed in Section 9.2) make clear reference to several OLM activities, reproduced as follows:

Responsibilities

9.2 Integrated Project Team (IPT)

The IPT is responsible for ensuring that:

…

…

4 It seeks SSG guidance:

4.1 On the management of teardown and the selection of a suitable specimen.

4.2 When formulating plans for the structural elements of a schedule review and, following any schedule review, ensures that proposals to amend the structural elements of scheduled maintenance, including structural examination intervals, are ratified by the SIWG/TAM before implementation; see paragraph 6.

4.3 When scoping OLM programmes and if contemplating seeking 2-star OLM exemption as mandated by JSP 553; see paragraph 7.2.

5 JSP 553 OLM/ODR requirements are satisfied. In doing so, the IPT is to ensure that OLM/ODR programmes and associated follow-up actions are incorporated in the SI Plan and guided by the SIWG/TAM; see paragraph 7.2.

6 STR and FTR reviews are undertaken by the Designer following significant changes to the SOIU and on completion of each OLM/ODR programme; see paragraph 8.2.

7 Effective liaison is maintained with the Designer, or in some cases SSG, on those other occasions when an STR or FTR review may be appropriate.

Appendix B: Generic Statement of Requirement for OLM

Note to Readers:

This appendix contains a generic statement of requirement of an OLM programme. The OLM Actions identified in preceding sections have been collated in this Appendix to allow a clear view of the OLM requirements without the background explanation.

GENERIC OLM PROGRAMME (Section 5)

Management - OLM Action 1: An OLM Programme Management Group, chaired by the IPT and including representation from the Designer, IPT, MoD Structures Specialist and Independent SI/OLM Advisors should be established at the inception of an OLM Programme. For new aircraft types this Group should be formed during the design phase as OLM has implications for design and production. Additionally, an OLM Specialists' Group, reporting to the OLM Programme Management Group, should be formed to determine, agree and manage the in-depth technical aspects of the OLM Programme and should include core representatives from the Designer's OLM Specialists and Independent SI/OLM Advisors.

Aims - OLM Action 2: The structural integrity aims of the OLM programme should be clearly defined. These aims should be agreed by the OLM Programme Management and Specialist Group, documented and endorsed by the SIWG (or forerunner where the SIWG has yet to be established). These aims may include but are not restricted to:

- To substantiate the fatigue spectra used in design and qualification and review fatigue clearances
- To identify local stresses in a structural feature
- To substantiate the monitoring systems (including identification of further monitoring requirements)
- To capture fatigue test spectra data
- To identify particularly damaging activity or manoeuvres
- To provide data to support investigations of structural issues or as life extension programmes
- To provide data for use in a review of the Statement of Operating Intent and Usage

Timing - OLM Action 3: Timing of the initial OLM programme after introduction to service of a new aircraft type will largely be governed by the aims of the programme. Generation of fatigue test spectra will generally require data capture early in service; however, care needs to be taken to ensure data are sufficiently representative of usage.

OLM PLANNING PHASE (Section 6)

PROGRAMME AIMS (Section 6.1 – 6.7)

Design Assumptions - OLM Action 4: Identify and collate fatigue spectra used in the design or qualification of the structure, structural components and stores carried by the aircraft (source fatigue type record or equivalent documentation).

Spectra Substantiation Methods - OLM Action 5: Identify appropriate methods for OLM substantiation of each of the design or qualification fatigue spectra. Where practicable direct measurement (e.g. strain gauges) should be used but where this is impractical, parametric-based measurements should be considered as an alternative.

Planned Review of Fatigue Clearances - OLM Action 6: A review of the Release to Service and Fatigue Type Record (or alternative fatigue documentation) and identification of remedial actions should be planned to follow the OLM programme. Traditionally, these activities have not been included within the OLM programme itself and have been funded as follow-on actions. These aspects are discussed further in the Analysis and Reporting Section (Section 9).

Identification of local stresses in a structural feature - OLM Action 7: Identify all structural features where direct local stress determination is required.

Substantiation of Fatigue Monitoring System - OLM Action 8: Where possible, identify and substantiate all assumptions made within the aircraft fatigue monitoring systems.

Identification of Additional Monitoring Requirements - OLM Action 9: Identify any additional monitoring requirements and adjustments required to component tracking methods where there are insufficient margins of safety or unacceptable levels of risk, using current tracking measurands.

Capture of Fatigue Test Spectra - OLM Action 10: If one of the output requirements for an OLM programme is the generation of fatigue test spectra and additional data to validate these spectra (e.g. detailed stresses, accelerations, pressurisation cycles), then this will be a significant design driver for the OLM programme. The OLM aircraft will have to be subject to Skopinski-type calibration in a loads rig. This will allow the OLM data to be described in global loading terms of shear, bending moment and torque for fatigue test load spectra generation.

Identification of Highly Damaging Activity or Manoeuvres (1) - OLM Action 11: Identify loading conditions likely to generate high load levels for critical features.

Identification of Highly Damaging Activity or Manoeuvres (2) OLM Action 12: Identify particularly damaging activities or manoeuvres in fatigue damage terms and apportion structural costs to these activities.

To Provide Data to Support Investigation of Structural Issues or as a Life Extension Programme - OLM Action 13: To provide data to support investigation of structural issues or as a life extension programme.

To Provide Data for use in a Review of the Statement of Operating Intent and Usage - OLM Action 14: To provide data for use in a review the Statement of Operating Intent and Usage and associated sortie profile codes from representative OLM data.

MEASUREMENT REQUIREMENTS (Section 6.8)

Relationship between OLM Aims and Instrumentation Requirements - OLM Action 15: All OLM instrumentation requirements should be reviewed and justified on the basis of meeting the programme aims. However, this justification should include consideration of contingency for expansion of data capture requirements. This review should be undertaken by the OLM Specialist Group and endorsed by the OLM Programme Management Group.

Review of Flight Loads Measurement and Previous OLM Installations (1) - OLM Action 16: Where flight loads measurement or flight loads survey has been undertaken, a review of the data captured and instrumentation fit should be undertaken to identify the most appropriate sub-set of the FLM instrumentation for inclusion in the OLM fit and to identify any potential weaknesses in the instrumentation fit.

Review of Flight Loads Measurement and Previous OLM Installations (2) OLM Action 17: Where previous OLM programmes have been undertaken on the aircraft type a review of the previous OLM programme should be undertaken to identify relevant design issues, such as: strain ranges, difficulty in interpreting strain outputs or adequacy of data sample rates.

Strain Gauge Installations (1) - OLM Action 18: Where the aims of the OLM programme include fatigue spectra substantiation, the strain gauge installation should be configured to allow direct comparison with fatigue design spectra.

Strain Gauge Installations (2) - OLM Action 19: Where the aims of the programme include comparison of in-service usage against a fatigue test, the fatigue critical sites should be fitted with strain gauges on both the OLM installation and the fatigue test. A thorough review of the test loading should be undertaken to ensure the loading on the test at the chosen location is as representative of in-service loading as is practicable.

Strain Gauge Installations (3) - OLM Action 20: Where the aims of the OLM programme include provision of data for fatigue test load spectra generation then the OLM installation should include strain gauging located, configured and loads calibrated to allow the calculation of bending moment, shear force and torque values in the structural components from the recorded data.

Strain Gauge Installations (4) - OLM Action 21: Where the programme aims include the generation of local stresses in a feature from overall forces and moments using load calibration methods, the strain gauge location, configuration and structural modelling should be designed to meet this aim.

Strain Gauge Installations (5) - OLM Action 22: Where the OLM programme aims include substantiation of fatigue monitoring systems, strain gauge installation should be located and configured to capture the loading in the critical features protected by the monitor.

Strain Gauge Installations (6) - OLM Action 23: In addition to measurement requirements to meet programme aims, the following factors should be considered in determining the location of strain gauges and strain gauge installations:

- Capture of primary loading actions in critical features
- Location in low strain gradient position
- Vulnerability to in-service damage and maintenance traffic
- Access for installation and repair
- Ability to undertake surface preparation for strain gauge bonding
- Heat sinks in surrounding structure for gauge bonding

- Minimise length of strain gauge wiring runs
- Cable shielding and grounding
- Location of potential sources of interference (e.g. electric motors)
- Calibration methods required
- Ability to incorporate secondary (back-up) strain gauges and cabling

Strain Gauge Installation Reliability - OLM Action 24: A reliability review of the proposed strain gauge installation should be undertaken. The scope of this review should include:

- Gauge and wiring installations located in vulnerable locations
- Gauge specification
- Surface preparation and bonding methods
- Gauge protection from damage and water ingress and gauge markings
- Vulnerability to maintenance or usage
- Competency and currency of strain gauge installation technicians
- Clear marking of strain gauge installations
- Provision of additional strain gauged removable components

Back-up Strain Gauge Installations - OLM Action 25: Secondary or back-up strain gauges and wiring should be introduced where practicable.

Parametric and Discrete Measurands - OLM Action 26: Parametric data capture requirements should be justified in meeting programme aims. Uses for parametric data may include:

- Provide confidence in strain data
- Identify flight conditions for airborne calibration or cross checks
- Generate fatigue spectra for substantiation of design assumptions where strain measurements are impracticable
- Substantiation of monitoring system or development of a monitoring system (e.g. training data for advanced parametric monitoring system)
- Review of the SOIU SPCs
- Triggers for data recording
- Provide data for improvements in parametric structural monitoring systems

Capturing Parametric Data from Data Bus Systems - OLM Action 27: Capturing parametric and discrete data from aircraft data bus systems is an attractive and potentially highly cost-effective option but the data should be confirmed as fit for its intended purpose within OLM. An understanding of the origins of the data, any manipulation undertaken on the data and the effects of data management systems used by the data bus controllers should be obtained to ensure that fitness for purpose can be assured.

Capturing Parametric Data from Aircraft Instrumentation - OLM Action 28: Tapping into existing aircraft systems should be considered where essential parameters cannot be captured from data bus systems or where the data available on the bus are not suitable for the OLM aims. Generally, tapping into primary flight instrumentation systems should be avoided due to the increased risk posed to these systems. However, modern ADR/CSMU systems are often fitted with data ports and accessing these data should be considered.

Introducing OLM-Specific Instrumentation - OLM Action 29: It is most likely that OLM-specific instrumentation will be required (such as accelerometers). As well as fitness for purpose, consideration should be given to equipment reliability, vulnerability in the operational environment, long-term support and additional data acquisition signal conditioning requirements.

NUMBER OF INSTRUMENTED AIRCRAFT (Section 6.9)

Number of OLM-Instrumented Aircraft - OLM Action 30: Historically, instrumentation of around 10% of the fleet fit, ideally with a minimum OLM fit of 2 aircraft, has proven a reasonable proportion for planning OLM installations, However, each programme should be judged on a case-by-case basis and the factors considered should include:

- Programme aims
- Fleet size and disposition
- Roles within the fleet
- Fleet-within-fleet issues (including structural build standard)
- OLM installation capability and reliability
- Cost
- Attrition
- Volume of data required against collection time

REVIEW OF FATIGUE ANALYSIS METHODS (Section 6.10)

Review of Fatigue Analysis Methods - OLM Action 31: A review (or development) of the fatigue analysis process in the context of OLM should be undertaken and should include:

- An investigation into the suitability of design ‘fatigue-life’ curves used for OLM analysis (e.g. S-N, ε-N or or da/dn - ΔK curves)
- Implications of differences between design and usage spectra content
- Likely effects of fatigue analysis fitting procedures including situations where excessively large fitting factors occur (e.g. above 1.5-2.0) or factors below 1.0 are produced.
- Development of an appropriate fatigue analysis process for use within the OLM programme if required.

OLM SYSTEM DESIGN (Section 6.11)

OLM System Design - OLM Action 32: An up-to-date review of available OLM equipment technology should be undertaken to ensure that appropriate capability and best value for money can be obtained. This should include a review of recent experience on other projects and, where possible, use of common equipment.

Integrated OLM Systems - OLM Action 33: Where OLM functionality is integrated into other system architectures, care should be taken to ensure that OLM-specific requirements, such as data integrity rates, are respected within the overall system design requirements. It is essential that sufficient bandwidth is allocated to OLM functions within the integrated system.

Transducers - OLM Action 34: When considering transducer fits for OLM installations, conditioning of the transducer output and its reliability, robustness and support for long-term use within an operational environment should be considered.

Strain Gauge Excitation - OLM Action 35: Consideration should be given to recording the strain gauge excitation voltages generated from the DAU to ensure that these remain within acceptable limits.

Signal Conditioning and Airborne Data Storage - OLM Action 36: Where data acquisition units and data recording systems are being procured or designed to support OLM programmes then the following issues should be considered in the selection process including:

- DAU and recording system capability to meet OLM signal conditioning and recording requirements
- Method of establishing reliable common time base
- Availability of environmental qualification data
- System flexibility in reconfiguration and expansion (50% memory and data capture capability recommended)
- Procurement and support costs but avoiding significant long-term implications from short-term procurement economies.
- DAU manufacturer's support provision
- Obsolescence risks
- Configuration control

Additional Recording Requirements - OLM Action 37: Appropriate internally generated DAU data health reports should be recorded and incorporated into the data analysis process. Where several OLM aircraft are in the fleet, tagging the data with a correct tail number identifier should be instigated.

Data Sampling Rate and Anti-Alias Filters (1) - OLM Action 38: Strain gauge data should be sampled at a rate at least 10 times the frequency of the highest significant structural mode and have adequate bandwidth to ensure values sufficiently close to the maximum and minimum values in the time history are captured. Where insufficient evidence is available to identify the highest significant structural modes sample rates should be initially set to higher than expected rates and reduced when evidence is presented that the loss in fatigue damage and strain range at a lower sample rate is acceptably small.

Data Sampling Rate and Anti-Alias Filters (2) - OLM Action 39: In addition to being sampled at a rate at least 10 times the maximum significant frequency, the sample rate for parametric data should be consistent with its intended OLM use. This sample rate should be set with cognisance of the bandwidth of the original transducer output or data bus refresh rate. However, with the increased capacity of modern acquisition and recording systems the use of common sample rates across a range or all parameters, set at the highest sample rate, can be considered. This option reduces or eliminates delay differences due to filtering.

Data Sampling Rate and Anti-Alias Filters (3) - OLM Action 40: DAU anti-aliasing filters should be used to prevent the inclusion of unwanted frequencies and the consequent aliasing of the data signals. Where data are sampled at different rates or have differing frequency contents, it is essential that any time delay or phase effect introduced by the anti-aliasing filters is understood and accounted for.

Airborne or On-Ground Processing - OLM Action 41: Airborne processing of data should be restricted to signal conditioning and processing of the data should be undertaken off-board. This allows maximum flexibility in the analysis process and prevents unnecessary and costly airborne software changes.

OLM Installation – EMC - OLM Action 42: EMC considerations should be included throughout the system design (such as shielded cables) and a full EMC assessment of the completed design should be undertaken. Radio transmission interference in particular has occurred on several programmes, despite detailed design measures being taken to eliminate the problem. Therefore, recording of the Press-To-Transmit (PTT) line should be considered in system design.

OLM Installation - Power Cycles - OLM Action 43: Where possible the OLM system should be designed to power up only when the system is required to be operative, rather than at every aircraft power cycle. Additionally, power surge protection of the OLM system should be included within the design.

OLM Installation - Automatic Recording Trigger - OLM Action 44: It is essential that the triggering architecture or logic in the DAU/recorder and the requirement to capture structural events (such as take off and landing or taxi loads) are fully understood before the trigger parameters are defined.

OLM Installation - Ground Testing Mode - OLM Action 45: A ground testing mode for checks on installation and fault diagnosis in service should be included in the system design.

UNIT-BASED GROUND STATION (Section 6.12)

Unit-Based Ground Station (1) - OLM Action 46: The unit-based OLM ground station should be designed to reduce the burden on the operational units to a minimum. However, the role and functionality of the ground station will depend upon the data collection medium, the system maintenance requirements and the method of operation of the aircraft fleet.

Unit-Based Ground Station (2) - OLM Action 47: At the time of writing this paper the MoD had recently introduced regulations forcing the memory encryption for IT devices that extract data from aircraft. It is understood that at least one OLM programme has experienced difficulties as a result of switching to encrypted hard drives. Designers should be made aware of this regulation.

DATA ANALYSIS PROCESS (Section 6.13)

Analysis Definition Document - OLM Action 48: An Analysis Definition Document (ADD) should be produced. This document shall describe the requirements to be met by the analysis process in detail and any interface requirements to existing software packages, such as in-house fatigue analysis programmes. This ADD should be reviewed and agreed by the OLM Specialist Group and formally endorsed by the OLM Programme Management Group.

Analysis Aims - OLM Action 49: The high-level steps in the data analysis process from data extraction to analysis output and the key input and output requirements for each step should be clearly identified in the ADD.

Data Extraction and Initial Integrity Checks (1) - OLM Action 50: The process for extracting data from the recording media should be carefully planned. Where extraction software has to be written or third-party code used, care should be taken to ensure that support for the programme and configuration control are in place.

Data Extraction and Initial Integrity Checks (2) - OLM Action 51: The data extraction process should also include:

- Identification of any regions of lost data
- Identification of bit failures
- Identification of error flags
- Collation and reporting of DAU produced data health reports
- Identification of provisional data status against established criteria (e.g. data loss<2%)
- Check to ensure data loss does not coincide with highly damaging events (e.g. high-g)

- Data replacement and identification process for minor losses (e.g. last known good value)

<u>Raw Data Storage - OLM Action 52</u>: The extracted raw data and associated extraction report should be stored and backed up, ideally automatically. If the initial recording media are to be reused, reformatting should not be undertaken until the data quality has been assured, where practicable, and the data backed-up in its rawest possible form.

<u>Identification of Flight Record Data Requirements - OLM Action 53</u>: Requirements should be identified for the capture of manual or electronic data from alternative sources, such as Flight Records (e.g. MoD Form 725 or electronic equivalents).

<u>Input and Reconciliation of Flight Data (1) - OLM Action 54</u>: The analysis process should be designed to accept external source flight record data (e.g. MoD Form 725 or electronic equivalent) and a process of reconciling OLM and flight record data should be specified. The use of real-time stamp and unique tail number tags on the data are strongly recommended as a method of reconciling OLM data with flight records.

<u>Input and Reconciliation of Flight Data (2) - OLM Action 55</u>: Consideration should be given to methods of handling truncated data, data divided over several OLM flight files or where several sorties are combined into one OLM flight file (e.g. running crew change.).

<u>Re-Formatting Data Files - OLM Action 56</u>: OLM data are generally stored in the recording media as unsigned binary integer values (e.g. 0-65535 (16-bit)). However, these data should then be copied and may require conversion into formats (e.g. double precision real numbers) appropriate for the subsequent operations, such as the application of calibration values to generate data in engineering units.

<u>Databus Status Flags - OLM Action 57</u>: Data from aircraft data bus systems (e.g. ARINC 429 or Mil-Std 1553) will have accompanying status flags in the data bus words. These flags should be captured and processed along with the engineering data.

<u>Data File Sizes - OLM Action 58</u>: An assessment of likely data file sizes should be undertaken and the analysis process architecture, software and hardware should be designed to cater for these file sizes.

<u>Application of Calibration Equations - OLM Action 59</u>: The analysis process should be designed to cater for all intended calibration file formats and for changes to calibration coefficients (including primary to secondary strain gauge bridges) without having to initiate software changes (using methods such as look-up tables). Configuration control and tagging of data with traceable calibration equation identifiers is essential.

<u>Data Anomaly Detection (1) - OLM Action 60</u>: Anomaly detection routines should be developed, with limits set with reference to structural capability and aircraft performance. As a minimum these routines should detect the following:

- Exceedances of channel maximum and minimum expected strain/stress or load values
- Excessive rate of change values (where practicable) compared with performance data
- Review performance data
- Failure of correlation between measurands expected to have a high degree of correlation
- Mismatch between flight record and OLM data

Limits should be held in configuration controlled look-up tables to allow relatively simple amendment rather than as fixed values within the software.

Data Anomaly Detection (2) - OLM Action 61: Automatic correction of anomalies should only be undertaken once sufficient confidence in the performance of the detection and correction algorithms has been gained using the OLM data, rather than test data sets. All detection and correction actions should be logged and a record retained with the data.

Data Visualisation (1) - OLM Action 62: The OLM analysis process should include the facility to visualise all data. Furthermore, initially at least all the data should be viewed by an analyst and this should only be reduced if confidence allows.

Data Visualisation (2) - OLM Action 63: Primary data graphical outputs should be developed for automatic, or semi-automatic production and flexible graphical facilities should be available to the analyst to allow plotting of data to screen, zoom in on areas of interest and call-up a number of parameters on the same plot with cross plotting and time history plotting facilities.

Data Trending - OLM Action 64: The OLM analysis package should have the facilities to calculate statistics of the data which might include maximum, minimum, mean and standard deviation. The capability should be available to trend these data by sortie profile code (SPC), squadron, role etc.

Combining Data Channels - OLM Action 65: The OLM analysis package should have the facility to combine automatically the required data streams. Where data streams are combined care should be taken to ensure sample rates and filter settings are compatible to ensure that aliased data are not created in error.

Data Confidence Checks - OLM Action 66: Confidence checks, in addition to data anomaly checks, should be incorporated into the data analysis process. These checks should consist of continuous checks and 'one-off' or infrequent checks conducted to gain confidence in the installation or calibration. Continuous checks should include plotting start-up values, steady-state conditions or producing plots of known or expected relationships, such as stress/g or wing load distributions and should wherever possible be generated automatically. One-off or infrequent checks might include comparing spanwise loading distributions with theory for example. These may not necessarily be automatic and may be procedural in nature. Aircraft operations, performance, FLM, SOIU or previous OLM data can provide useful information for establishing confidence criteria for comparison with captured OLM data.

Data Reduction - Turning Points - OLM Action 67: The data analysis process should include the ability to identify turning points (relative maximum and minimum values or peaks and troughs) in data time histories (generally used for stress/strain or load channels). It is recommended that the time associated with each turning point retained to allow the facility for later reordering and progressive damage calculations. A gate is generally included in this process whereby small cycles, considered structurally insignificant are removed. However, care must be taken to ensure the gating algorithm is consistent with a fatigue analysis process and captures the significant local maxima or minima values as turning points.

Data Reduction - Cycle Extraction (1) - OLM Action 68: The data analysis process should include the ability to extract cycles from turning points or peak / troughs using a method consistent with that used in design and qualification.

Data Reduction - Cycle Extraction (2) - OLM Action 69: A frequency of occurrence matrix (FOOM) in which cycle files are represented by their range and mean or amplitude and mean provides a useful method of visualising large quantities of data. Changes in the FOOM population regions can illustrate anomalous but credible data, changes in usage or incorrectly identified data. Therefore, the ability to represent data in a FOOM should be considered as a function within the analysis process.

Exceedance Data - OLM Action 70: The OLM data analysis process should include the capability to represent data as exceedance plots. Where exceedance plots are going to be used to compare OLM data with design or qualification spectra then a consistent approach to determining exceedance levels should be used.

Fatigue Analysis - OLM Action 71: The OLM data analysis process should include the capability to represent fatigue damage or crack growth increment (depending on fatigue analysis methodology) through the flight to identify particularly damaging manoeuvres or regimes.

Sample Rate Checks and Frequency Analysis - OLM Action 72: The ability to undertake frequency content analysis and sub-sampling of data and repeat fatigue analysis for sample rate investigations should be considered as a useful analysis tool.

Fatigue Monitor Substantiation - OLM Action 73: Where substantiation of a fatigue monitoring systems is required, functionality to allow direct comparison between the fatigue monitoring system output and the OLM data used to substantiate the monitor will be required. For the fatigue loads meter this functionality would emulate the exceedance counting mechanism. Care should be taken to ensure that the monitor triggering logic is fully understood. For parametric monitors using non-adaptive prediction methods, substantiation will include identification of limits of validity and identification of retraining requirements.

Data Back up and Archive - OLM Action 74: OLM data should be backed up and archived with one copy of the data stored in a fire safe and a further copy stored in a remote location. The data back-up should include the following:

- Data in its rawest form possible (e.g. binary digit files)
- Intermediate results
- Output files
- Setting values (e.g. calibration files)
- Analysis error codes and remedial action reports
- Associated Flight and Fatigue Data (e.g. F725 data)
- All source code (specific to OLM analysis) and software configuration control data

Software Control - OLM Action 75: OLM software should generally be considered as safety related and appropriate standards for software control should be applied.

Validation and Verification - OLM Action 76: A validation and verification plan should be developed in which function, module and end-to-end tests of the analysis process should be planned with appropriate test cases. This plan should be reviewed by the OLM Specialist Group.

CALIBRATION FACILITIES (Section 6.14)

Calibration Facilities - OLM Action 77: System calibration has been included in this paper as an Installation Task (Section 7). However, where programme aims dictate, considerable planning activity may be associated with the calibration requirements, particularly if significant loads calibration work is required. Therefore, development of a Calibration Plan should be included within the planning phase of an OLM programme.

IN-SERVICE MAINTENANCE AND THROUGH-LIFE SUPPORT (Section 6.15)

OLM System Maintenance - OLM Action 78: OLM maintenance requirements such as periodic datum checks or electrical shunt calibration requirements should be identified. These should be promulgated either by formal aircraft and ground equipment documentation amendment or by less formal means, such as the production of a Topic 2(R)1 leaflet.

Effects on Aircraft Maintenance - OLM Action 79: The effects on aircraft maintenance, including modification requirements to ground equipment should be identified and promulgated either by formal aircraft and ground equipment documentation amendment or by less formal means, such as the production of a Topic 2(R)1 leaflet.

OLM Support Policy, Spares, Support and Test Equipment - OLM Action 80: The support policy for the OLM installation should be defined. This will affect the requirement for OLM spares, support and test equipment, including instrumentation and strain gauge recalibration and repair.

Repeat Calibration Plan - OLM Action 81: A repeat calibration plan for the life of the OLM programme, for each element of the OLM installation, including strain gauge bridges and parametric instrumentation should be produced.

Obsolescence Reviews - OLM Action 82: A schedule of obsolescence reviews of all OLM equipment including continued support statements from OEMs and a review of media and data storage facilities should be scheduled (a 3-yearly review is probably adequate).

PLANNING PHASE REVIEW (Section 6.16)

Planning Phase Review - OLM Action 83: A review/reviews should be undertaken by the OLM Programme Management Group or Specialists Group to ensure that all aspects of planning the OLM programme have been addressed. The reviews should include the following aspects:

- Timing of an OLM programme
- OLM programme aims
- Identification of measurement requirements
- Number of OLM-instrumented aircraft
- Review of fatigue analysis methods
- OLM system design
- Ground station
- Data analysis process design
- Calibration requirements (discussed further in Section7)
- In-service maintenance and through-life support
- Interface control requirements

REPORTING SUMMARY (Section 6.17)

Reporting Summary - OLM Action 84: Reporting of the following actions or topics should be included within the OLM programme planning phase (some of the following aspects may well be documented in meeting minutes rather than formal reports):

- Programme aims (OLM Action 2)
- Collation of fatigue damage spectra used in design or qualification (OLM Action 3)
- Fatigue spectra validation plan (OLM Action 5)
- Fatigue monitoring system assumption review (OLM Action 8)
- OLM instrumentation requirements (OLM Action 15)

- OLM instrumentation solutions (OLM Actions 16 - 29)
- Fatigue analysis methodology review (OLM Action 31)
- OLM equipment market research report (OLM Action 32)
- Analysis definition document (OLM Action 48)
- Analysis validation and verification plan (OLM Action 76)
- Calibration plan (OLM Action 77)
- OLM system support policy (OLM Action 78, 79)
- Repeat calibration plan (OLM Action 81)
- Obsolescence review plan (OLM Action 82)

INSTALLATION PHASE (Section 7)

OLM SYSTEM INSTALLATION (Section 7.1)

Installation During Aircraft Build - OLM Action 85: Where possible, installation of an OLM system or making provision for an OLM system should be undertaken during aircraft build. Potentially large cost savings can be made using this approach and modern distributed DAU systems with data links between units can remove the risk of insufficient wiring for analogue signal being incorporated into looms during build due to immature design.

Retrospective Installation - OLM Action 86: Where retrospective OLM installation is required, the most preferable technical solution for the OLM programme is a return-to-works (RTW) programme undertaken by the aircraft designer. Although this can have detrimental effects for aircraft production, from an OLM-programme perspective, return-to-works allows free access by the designer for the installation and calibration of the OLM fit. Long-term serviceability of OLM installations, particularly strain gauge channels has varied significantly across programmes. Furthermore, recovery of failed strain gauge installations can prove difficult in service. Therefore, efforts should be concentrated on ensuring sufficient access and time is allocated for the installation, calibration and functional testing of the OLM system and that highly controlled procedures are introduced and followed.

3rd Party Involvement - OLM Action 87: Where the aircraft designer does not have the skills or will or where the proposed costs are unaffordable, the use of 3rd party design approved organisations can offer a potential installation solution. Where possible, the use of 3rd party organisations should be undertaken with the cooperation of the designer. The use of 3rd parties complicates further the interfaces within the programme and would require clearly defined roles for the various organisations.

Modification Process(1) - OLM Action 88: An OLM system will have a multitude of interfaces with existing aircraft systems, such as power supplies, data buses, instruments, wiring runs, effects on mass and centre of gravity and hence the use of formal designer-approved modification processes is appropriate. Additionally, where only a handful of aircraft will be modified the special order only (SOO) modification processes may be applicable.

Modification Process(2) - OLM Action 89: Service Modifications (SM) (formerly termed Special Trial Fits or Service Engineered Modifications) have been used successfully to introduce short-term OLM installations or to facilitate small changes to existing designer approved modifications, for expedience (although this should be 'covered' by the Designer later to prevent a loss of configuration control). Special consideration should be taken to ensure that safety of flight and fitness for purpose aspects of the installation are thoroughly addressed.

Modification Process(3) - OLM Action 90: Irrespective of installation route, detailed drawings, photographs and sketches of the strain gauge bridge locations, arrangements, wiring, with unique identifiers on the structure to ensure correct identification should be produced. Photographs should be taken before protective coatings are applied.

CALIBRATION PROCEDURE (Section 7.2)

Setting Datum Values - OLM Action 91: Consideration should be given to the mechanism of setting the physical datum values appropriate to the outputs of a strain gauge installation.

On-Aircraft Strain Gauge Load Calibration - OLM Action 92: Load calibration involves the application of a series of point loads to the aircraft structure and load equations are derived using the strain gauge response to these point loads. Where practicable, representative check cases can be applied using distributed loads (often to a higher proportion of limit load than can be applied using point loads e.g. a 2/3 limit load wing up-bending case). The following aspects should be considered when applying loads calibration to a whole or significant part of an aircraft:

- Review any static test data available to identify any possible non-linearity in the response of the structure, such as local buckling at higher loads.
- The calibration range should be to the maximum proportion of limit load possible, subject to the methods used to constrain the aircraft, the magnitude of the reaction loads and the local stresses in the structure at the load application points.
- The effects of deflection of the structure under load and the introduction of unwanted moments should also be considered.
- Shut down protection devices or warning systems should be incorporated into the rig design.
- Loads should be applied incrementally up to the maximum calibration load and removed similarly back to the original loading condition.
- Where possible, 2 or more initial loading runs should be applied to the aircraft to exercise or settle the aircraft within the loads calibration rig, before the calibration load application proper.
- Where possible, load cases should by applied several times to investigate any lag or hysteresis in the system and to identify any spurious runs.
- The configuration and location of the aircraft in the calibration rig should be carefully documented (i.e. location of aircraft relative to rig datum points and location of loading points on the aircraft). This information can prove particularly useful when repeat calibrations of the aircraft are required.
- Primary and secondary strain gauge bridge configurations should be calibrated. Where possible, primary and secondary bridges should be calibrated at the same time and the best response should be identified as the primary bridges.
- Different load conditions, such as ‘full fuel’ and ‘empty fuel’ should also be included in the loading cases. The effects of fuel distribution and wing sweep (if applicable) and 1g offset should be considered.
- Where possible, loads calibration should be undertaken with the aircraft in as close to a flight configuration as possible.
- Achieved loads (using load cells for example) as well as demanded loads should be recorded, with achieved loads being used for the calibration.
- Load reaction points should be monitored and recorded to protect local structure and to identify any excessive losses from friction or fouling.
- Periodic load balances should also be undertaken during calibration runs to re-baseline the calibration.
- The bridge-to-load calibration equations are usually obtained by using a form of linear regression analysis. Some compromises between resolution and the number of bridge inputs may be required to obtain optimum and practical solutions.
- Influence coefficients can be a useful tool in identifying the response of individual bridges to changes in the applied load location.

- Carry over effects (e.g. from the opposite wing) should be considered when unexpected bridges are identified as having a high effect on the output. However, caution should be exercised in the inclusion of carry over effects that the overall solution is not compromised. The influence of carry over effects on the final solution should reflect the contribution to the expected flight loads.
- R values of 0.995 or R2 values of 0.990 are realistic aims for shear and bending moment load calibrations.
- Once the bridge-to-load equation has been optimised, where practicable, this may be cross checked by predicting the distributed load cases and determining the percentage accuracy.
- Where possible loads calibration of strain gauges should be undertaken after an aircraft has flown to allow for the settling of the structure, particularly for installations fitted at build. Where this is not possible, additional datum checks should be carried out after first flight and several flights later to identify any shifts in the data.

Off-Aircraft Loads Calibration - OLM Action 93: Many components, such as wing links and actuator eye ends, can often be calibrated off aircraft in standard test machines. This allows significant flexibility, potentially greater calibration load range and potential to reduce aircraft down time and therefore consideration of off-aircraft calibration methods should be considered. However, care has to be taken to ensure that the calibration loading is applied representatively and the effects of any pre-load applied to the component when installed on the aircraft are understood.

Strain Gauge Correlation to Fatigue Test Damage - OLM Action 94: Where is in the intention for fatigue damage calculated from OLM strain gauge channels to be compared with fatigue test damage, a review of the loading mechanisms and gauge response should be undertaken. This review should include:

- Whether the applied test loading is representative at the gauge locations. For a wing for example identification of load cases where the strain outputs from the fatigue test can be compared to the strain outputs seen in the OLM aircraft flown to these cases (e.g. 6g symmetric manoeuvre). However, care should be taken for a fuselage for example where test restraints and balance support may affect the loading.
- Whether the response of strain gauges is affected by in-service issues (such as equipment fitted on in-service aircraft but not on the test and their effect on local response and access to install gauges).
- A check of the fitting factors needed to set the test spectrum to predict failure at the end of the test running. Where large fitting factors are produced (>1.5-2.0) or factors less than 1.0 then further investigation should be undertaken (see Section 6.10, OLM Action 31).

Strain Gauge Airborne and On-Ground Calibration - OLM Action 95: Successful airborne calibration of strain gauge bridges requires:

- The identification of well defined and repeatable flight conditions or manoeuvres and having confidence in the stress or strain conditions that should exist at the monitor location for these manoeuvres or conditions.
- Airborne calibration of wing locations and possibly fuselage locations is considered feasible with sufficient data.
- However, application of this method to a tailplane and in particularly a fin is considered highly challenging and a potentially high-risk strategy.
- The OLM system should be designed to accommodate additional data capture requirements (e.g. detailed fuel distribution).
- Ground conditions can provide useful additional calibration points. However, considerable scatter for nominally identical aircraft masses can be apparent in ground condition calibrations due to undercarriage oleo settling, aircraft attitude changes or different mass distributions due to fuel load distribution etc.

- Airborne calibration data are likely to suffer greater scatter than would be seen in the controlled environment of a Skopinski-type loads calibration.
- If airborne and/or ground-based calibration options are being considered as the sole method of calibrating for an OLM there is a significant risk posed to the programme. Therefore a feasibility study should be undertaken to reduce the risk. This study report should be reviewed and endorsed by the OLM Specialist Group.

Other Instrumentation Calibrations - OLM Action 96: OLM instrumentation (other than strain gauges) should be subject to manufacturers' recommended calibration procedures.

Calibration Reporting - OLM Action 97: On completion of all calibration activity a complete calibration report should be produced identifying performance of the calibration against the calibration plan.

CONFIDENCE CHECKS (Section 7.3)

Confidence Checks - OLM Action 98: A series of confidence checks should be undertaken and reported during the installation, calibration phases of the programme and before air test. These checks should ensure that all instrumentation is correctly identified, wired, responds in the correct sense and outputs are reasonable. Where practicable, these checks should include comparison between theoretical and measured ground loading cases.

AIR TEST REQUIREMENTS (Section 7.4)

Air Test Requirements - OLM Action 99: Specific manoeuvres or flight conditions should be specified for inclusion in the post-installation air test to gain confidence in the OLM data.

INSTALLATION PHASE REVIEW (Section 7.5)

Installation Phase Review - OLM Action 100: A review/reviews should be undertaken by the OLM Programme Management Group and Specialists Group to ensure that all installation aspects of the OLM programme have been addressed. The reviews should include the following aspects:

- OLM System Installation
- Calibration Procedure
- Confidence Checks
- Air Test Requirements

REPORTING SUMMARY (Section 7.6)

Reporting Summary - OLM Action 101: Reporting of the following actions or topics should be included within the OLM programme installation phase:

- Installation report (OLM Action 88, 89, and 90)
- Calibration report including confidence and sense checks (OLM Action 97 and 98)
- Air test requirement (OLM Action 99)

DATA CAPTURE PHASE (Section 8)

DATA CAPTURE PROGRAMME (Section 8.1)

Identification of Data Capture Requirements - OLM Action 102: Data capture requirements should be specified for the initial OLM programme. A review of available SPC usage data (or data from previous aircraft in the role) should be undertaken as the basis for the data capture requirements and the factors that should be considered in determining the programme should include:

- Programme aims (i.e. need for test spectra for example may be first priority)
- SPC distribution flown by the fleet
- Likely variance within SPC (e.g. air test – low variance, air combat – high variance), based upon cumulative average data from monitoring system if available.
- A priori fatigue damage distribution across SPCs (e.g. from monitoring system)
- Fleets-within-fleets and matching OLM capability
- Fleet distribution, deployments, maintenance and modification programmes
- Initial simplification or stores and role equipment variations
- Seasonal and syllabus variations (at least 1 year's data should be captured)
- Impact of scheduled maintenance

Once data capture commences, the assumptions made in identifying the initial data capture programme should be reviewed to ensure they remain valid and to identify factors not considered a priori.

UNIT INVOLVEMENT (Section 8.2)

Unit OLM Project Officers - OLM Action 103: Unit OLM Project Officers should be appointed to act as the focal point for OLM activity on the unit or station. The Unit Project Officer should be responsible for:

- Monitoring data capture against requirements
- Allocating the aircraft within the unit
- Data transfer from units
- Control of maintenance ensuring the necessary flight and fatigue data for OLM flights is obtained from the Unit
- Act as a focal point on the Unit for OLM issues

Terms of reference should be issued to the Unit OLM Project Officers by the OLM Programme Management Team. They should be made aware of the overall project aims and the importance of their role within these aims. Once appointed OLM Project Officers should be included within the OLM Programme Management Team.

Training - OLM Action 104: OLM training courses covering all tasks required to be undertaken by unit personnel should be developed and provided to the operating units, ideally coincident with the arrival of OLM capable aircraft.

Unit Presentations (Pre and Post OLM) - OLM Action 105: Unit presentations to engineering staff and aircrew should be undertaken to explain the OLM requirements and the importance of the unit's role. Additionally, findings should be fed back to unit staff to ensure their continued support for the programme. For long-term programmes, unit briefings should be periodic to ensure continued focus on the programme and to account for personnel turn over.

Trials Directive - OLM Action 106: A Trials Directive (TD) (often published in the aircraft Topic 2(R)1 should be produced. The TD provides an overview of the OLM programme aims and the OLM system; it is used to promulgate data capture and reporting requirements, dispatch and fault reporting processes and to identify points of contact within the programme. A template for a TD is provided in Appendix I.

DATA CAPTURE PHASE REVIEW (Section 8.3)

Data Capture Phase Review - OLM Action 107: A review/reviews should be undertaken by the OLM Programme Management Group and Specialists Group to ensure that all data capture aspects of the OLM programme have been addressed. The reviews should address:

- Data capture programme
- Performance against programme requirements
- Definition of unit involvement requirements and support provided

REPORTING SUMMARY (Section 8.4)

Reporting Summary - OLM Action 108: Reporting of the following actions or topics should be included within the OLM programme data capture phase:

- Data capture requirements (OLM Action 102)
- Training requirements (OLM Action 103)
- Trials Directive (OLM Action 106)

ANALYSIS AND REPORTING PHASE (Section 9)

POST AIR TEST / INITIAL ANALYSIS AND REPORT (Section 9.1)

Initial Analysis and Report - OLM Action 109: Following the air test or initial flying after the installation of the OLM system on each OLM aircraft post-flight analysis should be undertaken promptly. This analysis should include the following:

- Identify the serviceability status of all data channels
- Identify any data losses or anomalies
- Compare channel values with expected values
- Compare character of data with that expected for channel
- Check of channel ranging values in engineering units
- Check frequency content for channels susceptible to high-frequency loading
- Review channel sample rates
- Recommend remedial action as required
- Check analysis software

The OLM Specialist Group should review the analysis of the initial flight/s and confirm any recommendations for remedial action.

PROGRESS REPORTING AGAINST PROGRAMME AIMS (Section 9.2)

Progress Reporting Against Programme Aims - OLM Action 110: Regular (e.g. monthly) reporting of data received, analysed and status against programme requirements should be undertaken with remedial action recommended as required.

INTERIM REPORTING AGAINST PROGRAMME AIMS (Section 9.3)

Interim Reporting Against Programme Aims - OLM Action 111: Interim reporting should be initiated when a reasonable body of data have been or are scheduled to have been received (e.g.100 sorties for 1st interim). The interim reports should include the following:

- Identify the serviceability status of all data channels
- Identify any data losses or anomalies
- Identify any sorties flown but not captured
- Compare channel values with expected values
- Compare character of data with that expected for channel
- Check of channel ranging values in engineering units
- Identify any suspect calibration values
- Check frequency content for channels susceptible to high-frequency loading
- Review channel sample rates
- Review of limits set for limits and anomaly detection
- Compare captured data with programme requirements
- Assess progress against programme aims
- Develop provisional observations / conclusions based upon data received against programme aims.
- Update estimate of data requirements to meet programme aims, based upon data received (e.g. variance in damage in SPC X is far greater than expected hence data requirements increased etc)
- Recommend remedial action as required (e.g. changes to data capture programme, changes to OLM configuration or installation repairs)

The OLM Specialist Group and/or Programme Management Group should review the analysis of the interim report and confirm any recommendations for remedial action.

FINAL REPORTING (Section 9.4)

Final Reporting - OLM Action 112: At a point determined by the programme aims, a final report should be raised. This report should form a natural progression from the interim reports but should be considered as the definitive historical record for the programme and hence should be a stand alone document but with references out to lower-level detailed reports generated during the course of the programme. The final report should include details of:

- Programme aims
- OLM Installation
- Calibration process
- Data analysis process

- Data Capture Programme
- Data Capture Achievement
- Data Quality
- Data Analysis
- Conclusions by Programme Aims
- Recommendations for remedial airworthiness action or further work
- OLM report references
- MASAAG Paper 109 directory entry (see Appendix J)
- Lessons identified
- Future OLM recommendations, including data capture, system enhancements or care and maintenance requirements

The OLM Specialist Group should review a draft of the final report before publishing and the agreed final report should be reviewed by the OLM Programme Management Group. Recommendations should be presented to the SIWG for endorsement and for the identification of implementation target dates.

FOLLOW-UP ACTIONS (Section 9.5)

Follow-up Actions - OLM Action 113: Progress against endorsed OLM recommendation implementation target dates should be monitored at SIWG including where required:

- Production of revised fatigue life clearances based upon OLM-derived spectra and produce Fatigue Type Record (Part 2) or equivalent document, if appropriate (See OLM Action 6)
- Identification of remedial airworthiness actions required for revised fatigue lives below aircraft fatigue life requirement
- Review of the Release to Service and identification of amendments required following revision to fatigue lives (See OLM Action 6)
- Follow-up actions from lessons identified and future OLM requirements

REPORTING SUMMARY (Section 9.6)

Report Summary - OLM Action 114: Reporting of the following actions or topics should be included within the OLM programme data analysis and reporting phase:

- Post Initial Flight Report (OLM Action 109)
- Regular (e.g. monthly) data received, analysed and status reports (OLM Action 110)
- Interim Reports (OLM Action 111)
- Final Report (OLM Action 112)
- SIWG Update (OLM Action 113)

Appendix C: Proposed Revision to Def Stan 00-970 – Fatigue Monitoring

This appendix contains the proposed revision to the Def Stan 00-970 fatigue monitoring section.

REQUIREMENT	COMPLIANCE	GUIDANCE
SERVICE MONITORING		
GENERAL REQUIREMENTS		
3.2.21 In order to attract the 'monitored' factors in fatigue design, it shall be demonstrated during the design process that the fleet monitor covers all critical features. In service, the effectiveness of the fleet-wide monitor shall also be demonstrated.	For those components/areas that are not individually monitored by an advanced direct strain measuring technique, a continuous or periodic Operational Loads Measurement programme is a condition of compliance with these requirements and shall be agreed with the relevant Service Policy Authority.	
3.2.22 Every aircraft in the fleet shall be provided with instrumentation, for the purpose of estimating the fatigue damage accumulation for the maintenance of structural integrity. Provision shall be made for any required instrumentation during production.	The type of instrumentation to be installed will be stated in the Aeroplane Specification.	See Leaflet 38, Section 4.
3.2.23 Where the fleet-wide instrumentation referred to in 3.2.22 is insufficient to monitor all fatigue-critical components, a representative sample of aircraft shall be fitted with instrumentation that is more extensive for in-service loads assessment. Provision shall be made for this during production.	Operational Loads Measurement programmes for fixed wing aircraft or Operational Data Recording for Helicopters shall be used to demonstrate the effectiveness of the monitor and underpin any simple 'unmonitored' lifing metrics adopted, e.g. hours and number of landings.	See Leaflet 38, Section 5.
3.2.24 Where there is a risk of critical structure design limit exceedance during normal service flying, such events and their magnitude shall be identified before the next flight and made available for post flight activities.		See Leaflet 38, Section 6.12.
3.2.25 The monitoring system should be active for the entire period of significant fatigue loading.		See Leaflet 38, Section 6.6

REQUIREMENT	COMPLIANCE	GUIDANCE
ACCURACY		
3.2.26 The monitor shall not underestimate the fatigue damage accumulation of a representative service usage spectrum by greater than 10%.	System accuracy shall be judged against an OLM/ODR.	See Leaflet 38, Section 6.10.
DATA INTEGRITY		
3.2.27 Data loss for any reason within individual flights shall not be load dependent.		See Leaflet 38, Section 6.11
3.2.28 Interference, such as spikes, must either be prevented or removed prior to analysis.		See Leaflet 38, Section 6.12.
RELIABILITY		
3.2.29 The fleet-wide monitoring system will be classified as flight safety related. As such, the system shall be operational from first flight and the entire system failure-rate shall not exceed two in one hundred flights.		See Leaflet 38, Sections 4 and 6
3.2.30 System drift must be kept within limits to achieve the overall system accuracy requirements as per Section 3.2.26.	Checks for drift are to be done at regular intervals – frequency to be agreed with Project Authority.	

LEAFLET 38
FATIGUE
SERVICE MONITORING

1 INTRODUCTION

1.1 This leaflet describes the scope of in-service monitoring, and an acceptable means of compliance with the requirements of Section 3.2 Service Monitoring. It covers:

(i) Statements of Operating Intent and Usage (SOIU);

(ii) Continuous Fleet-wide Monitoring;

(iii) Operational Data/Loads Recording and

(iv) System Installation and Analysis Considerations.

1.2 In order to meet the requirements of Section 3.2, the Design Authority will have demonstrated the adequacy of the proposed in-service monitors together with their appropriate factors when used with the specified design spectrum and usage.

1.3 Comparison of in-service usage with design assumptions is fundamental to airworthiness, in determining equivalent safe lives and inspection criteria. Fleet-wide structural monitoring, including the use of simple usage parameters, is underwritten by Operational Loads Measurement (OLM) on fixed-wing aircraft or by Operational Data Recording (ODR) programmes on helicopters. Monitoring of service usage links the intrinsic fatigue performance of the structure, as achieved by design and proven by test, with the damage to which the structure is actually exposed. The capability to operate OLM/ODR programmes should be permanent, to enable periodic recording to be done on an as-required basis with the minimum of recovery work.

1.4 Although this leaflet is primarily concerned with fatigue damage arising from manoeuvres and gusts, it is equally important to make provision for recording other usage data which will impact on airframe and component fatigue lives. For example, pressurisations, landings, undercarriage cycles, engine acoustics in flight and during ground test and maintenance can all affect lives. Therefore, all parameters necessary to monitor in-service usage are to be identified by the Design Authority to the Project Authority during the design process.

2 DEFINITIONS

2.1 Flight Safety Related

Incorrect functioning of a flight safety related system does not affect the immediate mission capability of an aircraft. It could however, affect future mission capability and availability. Failure to identify structural limit exceedances correctly could lead to avoidable structural failure during a subsequent sortie. Misidentification of fatigue consumption could lead to premature retirement of expensive military assets or catastrophic fatigue failure of the airframe in flight.

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2.2 Ground Support Station (GSS)

Ground based computer or network, with interface to accept data from airborne data acquisition system. Also included under the generic GSS heading is analysis software, archiving and printing facilities

2.3 Rotary Wing Health and Usage Monitoring System (HUMS) and Fixed Wing Structural Health Monitoring System (SHMS)

HUMS/SHMS are integral instrumentation systems used to acquire pertinent monitoring data from aircraft response parameters, flight condition and configuration data together with top-level usage data (e.g. flight time, rotor start/stops, landings and Ground-Air-Ground cycles). Additionally for rotary wing aircraft, vibration-signatures from rotating parts are collected. Data are downloaded from the airborne system at the end of each sortie and used in a GSS for the purposes of usage monitoring, fault detection, failure prevention and limit exceedance identification/verification.

2.4 Manual Data Recording Exercise (MDRE) (generally a rotary wing practice)

An MDRE provides usage data that can be analysed in a format compatible with that used by the Design Authority to life the components and structure of the aircraft. Ultimately, this requires a list of steady state flight conditions, plus the time for which they apply; a list of transitions between steady conditions, plus their frequency of occurrence; and a list of low frequency event rates such as Ground-Air-Ground cycle, rotor spin-up cycles and aircraft mass changes. A manual observer currently gathers this information using a printed form or a laptop.

2.5 Monitored Structure

Structure is considered monitored, if all critical loading histories are rigorously assessed for life usage over the entire period of significant fatigue loading. The loading history can be obtained via direct monitoring, e.g. by strain gauges, or by inference from monitored flight parameters. The effectiveness of the monitor is to be validated by ODR/OLM. Simple counters of events, such as landings and usage metrics such as hours, cannot be used to support the use of monitored factors, since they do not provide any quantification of the severity of the loading environment.

2.6 Operational Data Recording (ODR) – Rotary Wing and Operational Load Monitoring (OLM) – Fixed Wing

ODR and OLM, in concept are the same; one or more aircraft from a fleet are instrumented with strain gauges, conditioning and recording equipment. The recorder also captures data from a wide range of flight parameters such as control positions, airspeed, altitude, etc. These systems are carefully calibrated and the aircraft are then flown in normal service, in order to confirm the Design Authority understanding of how loads and usage are related and to substantiate the performance of the fleet-wide monitoring system. The principal difference for rotary wing aircraft is the need to monitor rotating components; hence ODRs include equipment such as slip-rings or rf transmitters.

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2.7 Statement of Operating Intent and Usage (SOIU)

The SOIU is a formal document that describes how the operator uses the aircraft, in terms of roles, configurations and flight condition spectrum. The document contains a refined (low resolution) analysis of the latest MDRE or HUMS/SHMS data, supplemented by operator input.

2.8 System

Unless specified in more detail, the System is assumed to encompass all aspects of the airborne monitoring equipment, any required ground-based post processing facility and associated data transfer method.

3 STATEMENTS OF OPERATING INTENT AND USAGE (SOIU)

3.1 The Design Spectrum is the best estimate of the typical loading that an aircraft is expected to experience when it enters service. In collaborative projects, this spectrum may represent an agreed compromise between the various national authorities.

3.2 Since in-service or national usage will vary from the Design Spectrum and long-term changes may occur to national flying patterns, it is essential to monitor the operation of most types of military aircraft throughout their service life. This monitoring enables the changes in operating patterns to be assessed by the aircraft Design Authority for their impact on structural component lives and inspection intervals.

3.3 An overview of the way in which an aircraft is being operated is recorded in a Statement of Operating Intent and Usage (SOIU). This document contains information and assumptions relating to both the current usage and the operating intent. For fixed wing aircraft, Sortie Profile Codes (SPC) are used to describe the characteristic flying patterns in the fleet. Estimated % SPC utilisation is also stated.

3.4 The usage, declared in the SOIU, is based on feedback from the operator, combined with available MDRE or HUMS/SHMS data.

3.5 SOIUs are published and periodically reviewed by the Service Authorities. After each review, the aircraft Design Authority should be tasked to assess the significance of any changes highlighted in the latest operational usage data in relation to published lives and/or inspection criteria. To support this task, the Design Authority should utilise available MDRE or HUMS/SHMS usage information.

4 CONTINUOUS FLEET-WIDE MONITORING

4.1 For fixed-wing fleets, every aircraft must be provided with basic instrumentation to enable the fatigue life consumption to be tracked. The most commonly used acronym to describe this system is SHMS. Furthermore, it is preferable to have a single range of equipment to undertake both fleet-wide structural health monitoring and OLM programmes, configured to suit specific type requirements.

4.2 For fleet-wide monitoring, the scope of the sensor fit will depend on the type of aircraft, ranging from a comprehensive suite on highly manoeuvrable combat types to a more simplistic approach on aircraft being used exclusively in a passenger role. These latter aircraft may rely on a civil aircraft approach, i.e. flying hour accumulation against an assumed usage spectrum. This assumed spectrum however, must be confirmed as being representative.

4.3 Faults within the airborne monitoring system requiring maintenance activity should be identified automatically at aircraft turn-round. However, the detailed fatigue and crack growth assessments can be done in a longer timeframe. Therefore, consideration should be given to the relative merits of on-board computation of fatigue metrics versus ground processing of recorded time histories, to generate the required metrics.

4.4 The airborne hardware should use configurable data acquisition systems, which can be downloaded to the appropriate Ground Support Station (GSS) for processing and analysis. This will also assist the investigation of in-service engineering problems. The ground station used to maintain aircraft lifing data must embody appropriate cross checks and trending analyses to establish the short and long term integrity of the data. Flight by flight loading information must be retained for subsequent reappraisal should the need arise.

4.5 The complexity of rotary wing loading makes it difficult to identify and monitor the fatigue damage using basic instrumentation. Although helicopter Health and Usage Monitoring Systems (HUMS) may eventually provide comprehensive operational usage data for most fleets, many fleets still rely on the civil aircraft approach to damage accumulation, which is merely to log flying hours.

4.6 For helicopters lacking an adequate HUMS fit, Manual Data Recording Exercises (MDREs) are conducted to provide data to update the SOIUs.

5 OPERATIONAL DATA/LOADS RECORDING

5.1 A primary aim of an OLM/ODR programme is to substantiate the process used to monitor the fatigue life consumption under the in-service loading environment. For those components not covered by the fleet-wide monitor, ODR/OLM programmes are required to confirm that simple lifing metrics are adequate and that any read across to the fleet-wide monitor is valid. The only exception is civilian derivatives for which the usage has been shown to be the same as civilian operations and confirmed by the Design Authority as within their design assumptions.

5.2 A selected number of aircraft in a fleet are to be permanently modified for loads measurement, i.e. provision is made for the instrumentation and recording equipment fit. When required, comprehensive instrumentation is then fitted to record the loads on the major structural components of the airframe, together with other relevant parameters. For a helicopter, additional instrumentation to measure signatures of rotating components may also be required. The number of aircraft requiring this modification will depend on the range of fleet flying patterns, the number of roles and theatres of operation. The requirement for back-up aircraft must also be considered.

5.3 An ODR/OLM programme is required, generally within 5 years of introduction into service, commensurate with a need to allow the aircraft's full operational capability to be established. This is aimed at allowing the usage profiles to stabilise before data are gathered. The programme duration is dependent on the variability of flight profiles and the number of instrumented aircraft. The benchmark for any ODR/OLM programme is to capture a sufficient proportion of the fleet's usage across all types and roles to enable an accurate assessment to be made of the total usage.

5.4 For agile fixed wing combat aircraft an OLM recording capability should be available on a permanent basis, although not necessarily always recording. In practice, a permanent recording capability is often utilised to gather samples of data from each sub-fleet by rotation of the instrumented aircraft through the different roles.

5.5 Even the most comprehensive ODR/OLM systems will not directly measure the loading on every single fatigue critical component. In practice, only the most fatigue critical components are likely to be instrumented and less critical structure will be covered by analysis, confirmed by test.

5.6 Design proving information and fleet statistics are used in conjunction with ODR/OLM results to substantiate the fleet-wide monitoring process. The following should be considered:

(i) Flight Loads Measurement data acquired by the Design Authority during development of the type, in conjunction with structural modelling, are used to confirm that the ODR/OLM monitor points cover the remaining fatigue critical structure.

(ii) Results from the continuous monitor, including usage statistics, are required to align the ODR/OLM sample to match overall fleet usage. Where the continuous monitor does not provide adequate usage statistics, periodic MDRE should be used.

(iii) Fatigue test spectra are compared with the normalised ODR/OLM results, to confirm that test loading is representative. Test results also help to confirm fatigue critical feature selection and set a hard life for the continuous monitor points.

(iv) The performance of the fleet-wide monitor is compared with the normalised sample of ODR/OLM data. The monitor process can thus be validated or revised to improve correlation.

5.7 The Project Authority defines the periodicity of ODR/OLMs for non-combat and rotary wing aircraft. The requirement to carry out a periodic ODR/OLM is reviewed every 2 years but the interval between programmes should not normally exceed 5 years. The review should take into account any change in usage of the aircraft and whether it is likely to degrade the continuous monitor. Maintaining a permanent recording capability can be less onerous than trying to reinstate the system whenever it is deemed further data are required.

5.8 The Project Authority has the overall responsibility for running the ODR/OLM programme, however, the specific requirements of the system; the equipment interfaces and analysis routines should be agreed between the Design Authority, the Service specialists and their advisors. This includes selection and positioning of sensors. This process can be formalised as a Project Definition Study, which can also define the objectives and scope of the programme.

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6 System Installation and Analysis Considerations

6.1 The guidance in the following paragraphs applies equally to OLM/ODR and fleet-wide monitoring installations.

6.2 The complexity of the instrumentation fit is normally related to the number of different loading actions that have an influence on the life of the structure and the potential variability of flight profiles. Selection and positioning of sensors and associated wiring should be optimised to minimise risk of damage during aircraft service operations and maintenance.

6.3 Sensor positioning and orientation should be optimised to minimise errors. Examples of this are the attachment of accelerometers to substantial structure and positioning them to minimise errors due to secondary motion effects. Where this is unavoidable, analysis should be done to identify correction factors and/or potential error. Filtering should be utilised to minimise interference from unwanted frequencies, such as local panel vibration when a sensor is attempting to measure rigid body loads.

6.4 Strain sensors should be located away from high strain gradients and configured to minimise output variation due to temperature changes. Strain sensor location and orientation should be defined in a manner that supports accurate repeatable installation.

6.5 Strain sensors should in general be calibrated, usually by applying known load distributions to the associated structure. The sensitivity to all potential loading actions should be identified. Where cross-coupling of loading actions cannot be avoided, multiple sensors will be required to solve the resulting simultaneous equations. The magnitude of calibration loads need to be high enough to confirm the relationship between the sensor output and applied load. Un-calibrated (i.e. non-load calibrated) sensors can be utilised when replicating sensor locations on fatigue test articles, or, when positioned close to a critical feature and the local stress field is well understood. It is necessary to ensure that any un-calibrated strain gauges perform as expected both as individuals and between like installations on other aircraft. This can be done by response testing during build for a fleet-wide fit and/or dedicated flight tests post build.

6.6 If loads are not measured directly, and the transfer function changes for different flight states, e.g. in air and on the ground, the flight state will also need to be monitored to ensure that loads are predicted correctly.

6.7 Sensor installations and wiring should be designed to minimise the risk of interference from other systems and external sources. Consideration should be given to amplification of low amplitude signals at, or close to, the sensor locations. Repairability should also be considered. Where access for repair is difficult, sensor installations and wiring should be duplicated.

6.8 Sensor power supplies should have high reliability and be very stable. Voltage levels should be monitored for variation. The monitoring system should be tolerant of any power spikes, which might occur at power on, power off, or during flight. Examples of events that can cause spikes are; switching from batteries to a generator or during engine flame-out/re-light.

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6.9 Sensor processing and recording should not be affected by other systems. Where a common processor is used to support multiple systems, consideration should be given to processor capacity. The total system requirement should not exceed 50% of the processor's storage and processing power. Where processing is required post engine shutdown, power should be automatically maintained for the required duration.

6.10 All aspects of the System need to be assessed when meeting the overall system accuracy requirement. This includes, but is not limited to, sensor accuracy, bandwidth, sampling rate and digitisation resolution. The level of accuracy required for a fleet-wide monitoring system is dependent on available structural margins. Where margins are considered to be large, a less accurate system would be considered acceptable, provided that overall damage predictions are not overly optimistic and any conservatism does not compromise the design life, or cause an unacceptable inspection burden.

6.11 Data loss can occur for a number of reasons (e.g. processor conflicts, media jams, lost media, or even media not fitted). Gaps during recording should be kept to a minimum, should be logged and should not be load dependent. A significant source of lost data is usually data transfer between the aircraft and the GSS. Rigorous procedures need to be in place to minimise the risk of excessive unmonitored flying.

6.12 Both analysis of operational flight data and limit load exceedance identification should utilise validated time histories, i.e. these should not contain interference spikes or voids. Aircraft, that require fast turn-around between sorties, will have real time limit exceedance monitoring with post flight indication. This is to prevent continued operation when there is a risk of permanent structural deformation. Ideally all aircraft should have an on-board indication of a loads limit exceedance but in some cases, where time history data are transmitted to the GSS, it may be possible to utilise the GSS to report limit exceedances. Ground analysis of OLM/ODR data is considered essential to establish the quality of the data and that the expected relationships between the recorded parameters are realised.

Appendix D: Recommended Flight Test Instrumentation

This section contains an extract from Def Stan 00-970 Part 1/4 Section 2 Leaflet 10 covering recommended Flight Test Instrumentation measurands, range, accuracy, resolution and sampling rates. Although OLM requirements will differ significantly from FTI requirements and many of the parameters indicated below are highly unlikely to be included in an OLM fit, this provides a useful starting point to work from.

DEF STAN 00-970 PART 1/4
SECTION 2

LEAFLET 10
GENERAL HANDLING FLIGHT TEST REQUIREMENTS
TEST INSTRUMENTATION AND TELEMETRY PARAMETERS

This leaflet was previously issued as leaflet 900/2 of DEF STAN 00-970 Issue 1

1 RECOMMENDED TEST INSTRUMENTATION

1.1 General procedures for determining the instrumentation requirements for both contractors and official flight tests are given in DEF STAN 05-123 Chapter 240. This table provides typical requirements for handling and performance trials. The values quoted are recommendations only and, depending upon the instrumentation specified and the nature of the trial, adjustments may be made at the discretion of the Integrated Project Team Leader to the values quoted. Care should be taken not to specify more accuracy and resolution than is essential for the trial.

TABLE 1

ITEM NO.	PARAMETER	UNITS	RANGE	ACCURACY VALUES	RESOLUTION	SAMPLING RATE PER SEC	REMARKS
	GENERAL						
1	Time Base	Sec	Duration of flight + ½ hr				
2	Manual Event Marker	-	-	-	-	16	With external transmission facility
3	Crew Speech	-	Duration of flight + ½ hr				
	FLIGHT CONDITIONS						
4	Indicated Airspeed	kt	50 to (V_D+50)	Greater of 1 kt or 0.5%	0.5 kt	8	
4A	Ground Speed	kt	0 to max required	Greater of 1 kt or 0.5%	0.5 kt	1	
5	Altitude (pressure)	ft	-1000 to ceiling + 3000 ft	Greater of 20 ft or 0.5 mb	1 mb	8	Ceiling is highest altitude anticipated during test
6	Altitude (radio-altimeter)	ft	0 to 5000 ft	Greater of 2 ft of 1%	0.5	8	
7	Total Temperature	°C	-60 to +150	1	0.5°	8	Lower maximum acceptable (as appropriate) for low speed aeroplanes

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SECTION 2

TABLE 1 (contd)

ITEM NO.	PARAMETER	UNITS	RANGE	ACCURACY VALUES	RESOLUTION	SAMPLING RATE PER SEC	REMARKS
8	Angle of Attack	Deg	-10 to +30	0.25	0.1	16	Larger range (50°) may be required for spinning trials
9	Pitch Attitude	Deg	90/10	1/0.1	0.5/ 0.05	16	
10	Bank Angle	Deg	80/10	1/0.1	0.5/ 0.05	16	
11	Sideslip Angle	Deg	30	0.25	0.1	16	
12	Heading	Deg	0 to 360 & 10	1 0.1	0.5 0.05	16	
13	Pitch Rate	Deg/ Sec	±100/±10	1/0.1	0.5 0.05	16	
14	Roll Rate	Deg/ Sec	±300/±10	3/0.1	1.5/ 0.05	16	±300 range may be reduced (as appropriate) for less manoeuvrable aeroplanes
15	Yaw Rate	Deg/ Sec	±150/±10	1.5/ 0.1	0.8 0.05	16	
16	Longitudinal Acceleration	g	±1	0.01	0.001	16	All accelerometers mounted as close as possible to the cg of the aeroplane. Smaller range (as appropriate) accept-able for less man-oeuvrable aeroplanes. See Note 1.
17	Lateral Acceleration	g	-4 to +10	0.05	0.005	16	
18	Normal Acceleration	g	-4 to +10	0.05	0.005	16	
	AIRFRAME CONFIGURATION AND STATE						
19	Flap/Slat Setting	Event	Each Setting	-	-	4	See Notes 2 & 3.
20	Main Undercarriage Position	Event	Up/down	-	-	4	
20A	Wing Sweep Position	Deg	Full	To be determined		8	See Note 1
21	Airbrake Position	Deg	Full	1	0.1	8	
22	Failure State	Event	-	-	-	-	See Note 4.
23	Brake Parachute	Event	Stowed Deployed	-	-	8	

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SECTION 2

TABLE 1 (contd)

ITEM NO.	PARAMETER	UNITS	RANGE	ACCURACY VALUES	RESOLUTION	SAMPLING RATE PER SEC	REMARKS
24	Fuel Contents	Kg	Full	20	10	1	See Note 5.
	CONTROLS						
25	Pitch Inceptor Position	Deg	Full	To be determined		16	
26	Roll Inceptor Position	Deg	Full	" "	"	16	
27	Yaw Inceptor Position	Deg	Full	" "	"	16	
28	Pitch Inceptor Force	N	±600	" "	"	16	
29	Roll Inceptor Force	N	±300	" "	"	16	
30	Yaw Inceptor Force	N	±1000	" "	"	16	
31	Pitch Trim Position	Deg	Full	" "	"	16	
32	Roll Trim Position	Deg	Full	" "	"	8	
33	Yaw Trim Position	Deg	Full	" "	"	8	
34	Pitch Motivator Position	Deg	Full	" "	"	16	
35	Roll Motivator Position	Deg	Full	" "	"	16	Each surface - see Note 6.
36	Yaw Motivator Position	Deg	Full	" "	"	16	
37	Brake Pressure (Port)	N/m^2	Full	To be determined		16	
38	Brake Pressure (Stbd)	N/m^2	Full	" "	"	16	
	SIGNAL SENSORS						
39	FCS state/mode	Event	-	-	-	16	
40	ILS deviation (elevation and azimuth)	A	200	2	0.5	8	
41	Flight director demand (elevation and azimuth)	A	200	2	0.5	8	
42A	Stall/spin recovery device actuation	Event	-	-	-	16	

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SECTION 2

TABLE 1 (contd)

ITEM NO.	PARAMETER	UNITS	RANGE	ACCURACY VALUES	RESOLUTION	SAMPLING RATE PER SEC	REMARKS
42B	Spin recovery device shackle or gantry load	N	-	To be determined		16	Or similar parameter to confirm satis-factory operation
43A	Stall Prevention	Event	-	-	-	16	
43B	Stall Warning	Event	-	-	-	16	
	ENGINE (EACH)						
44	Throttle Position(s)	Deg	Full	To be determined		16	As applicable to engine under consideration
45	Rotational Speed(s)	% or rpm	Full	" "	"	32	
46	JPT/TGT or CHT	K	Full	" "	"	32	Sample 8 for CHT
47	Reserved						
48	Intake Position(s)	Deg	Full	" "	"	32	
49	Intake Door Position(s)	Deg	Full	" "	"	32	
50	Thrust Reverser Position	Event	Normal/ Reverse	" "	"	16	
51	Fuel Flow	Kg/hr	Full	" "	"	16	Engine & reheat where applicable.
52	Fuel Temp at Flowmeter	K	Full	" "	"	1	If required to obtain fuel flow.
53 to 55	Reserved						
56	Inlet Guide Vane Position	Deg	Full	To be determined		32	
57	Variable Stator Vane Position	Deg	Full	" "	"	32	
58 to 60	Reserved						
61	Nozzle Angle	Deg	Full	" "	"	16	Vectored thrust engines only
62	Auxiliary Intake Door Position	Event	-	-	-	16	

DEF STAN 00-970 PART 1/4
SECTION 2

TABLE 1 (contd)

ITEM NO.	PARAMETER	UNITS	RANGE	ACCURACY VALUES	RESOLUTION	SAMPLING RATE PER SEC	REMARKS
63 to 67	Reserved						
68	Relight Event Position	Event	-	-	-	16	
	MISCELLANEOUS SYSTEMS						
69	Brake Temperature (Port and starboard)	K	0-1000	10	1	1	
70	Tyre Temperature	K	0-150	10	1	1	Suitable on-board instrumentation may be difficult to provide and it may be necessary to resort to measuring tyre temperature after the manoeuvre using a portable temperature probe inserted into pre-drilled tyres.
71	Nosewheel angle	Deg	Full Travel	To be determined		16	

NOTES

1 Wing sweep will also be required on swing wing aeroplanes, specification should read: deg/full range/-/-/8.

2 For flaps designed for phases of flight other than take-off and landing, (e.g., manoeuvre flaps), specification should read: deg/each setting/-/-/16.

3 Similar instrumentation is required for each type of analogous control surface provided (e.g., leading edge slats and flaps).

4 Indication of each discrete failure state of primary control and/or stability augmentation systems incorporating reversionary modes is desirable. For auto-pilot/autostabiliser runaway trial the magnitude of the signal from the runaway box should also be recorded to ensure that this is appropriate to the failure under consideration.

5 Data on the disposition of fuel contents is also required: it is acceptable for such data to be derived from fuel usage combined with measurements of total fuel contents.

6 Similar instrumentation is required for each analogous type of control surface - e.g., spoilers.

Appendix E: Data Bus Systems

Mil Std 1553 Data Bus

MIL-STD-1553 is military standard published by the US Department of Defense that defines the mechanical, electrical and functional characteristics of a serial data bus. It was originally designed for use with military avionics but has also become commonly used in spacecraft on-board data handling subsystems, both military and civil. It features a dual redundant balanced line physical layer, a (differential) network interface, time division multiplexing, half-duplex command/response protocol and up to 31 remote terminals (devices). It was first published as a US Air Force standard in 1973, and was first used on the F-16 fighter aircraft. It is widely used now by all branches of the US military and has been adopted by NATO as STANAG 3838 AVS.

MIL-STD-1553B, which superseded the earlier 1975 specification MIL-STD-1553A, was published in 1978. The basic difference between the 1553A and 1553B revisions is that in the latter the options are defined rather than being left for the user to define as required. It was found that when the standard did not define an item, there was no coordination in its use. Hardware and software had to be redesigned for each new application. The primary goal of the 1553B was to provide flexibility without creating new designs for each new user. This was accomplished by specifying the electrical interfaces explicitly so that compatibility between designs by different manufacturers could be electrically interchangeable.

A single bus consists of a wire pair with 70–85 Ω impedance at 1 MHz. Where a circular connector is used its centre pin is used for the high (positive) Manchester bi-phase signal. Transmitters and receivers couple to the bus via isolation transformers and stub connections branch off using a pair of isolation resistors and a coupling transformer. This reduces the impact of a short circuit and assures that the bus does not conduct current through the aircraft. A Manchester code is used to present both clock and data on the same wire pair and to eliminate any DC component in the signal (which cannot pass the transformers). The bit rate is 1.0 megabit per second (1 bit/μs). The combined accuracy and long-term stability of the bit rate is only specified to be within ±0.1%; the short-term clock stability must be within ±0.01%. The peak-to-peak output voltage of a transmitter is 18–27 V.

The bus can be made dual or triply-redundant by using several independent wire pairs, and then all devices are connected to all buses. There is provision to designate a new bus control computer in the event of a failure by the current master controller. Usually, the auxiliary flight control computer(s) monitor the master computer and aircraft sensors via the main data bus. A different version of the bus uses optical fiber which weighs less, and better resists electromagnetic interference, including EMP. This is known as MIL-STD-1773.

Messages consist of one or more 16-bit words (command, data or status). Each word is preceded by a 3 µs sync pulse (1.5 µs low plus 1.5 high, which cannot occur in the Manchester code) and followed by an odd parity bit. The words within a message are transmitted contiguously and there is a 4 µs gap between messages. Devices have to start transmitting their response to a valid command within 4–12 µs and are considered to not have received a message if no response has started within 14 µs. All communication on the bus is under the control of the master bus controller and is on the basis of a command from the master controller to a terminal to receive or transmit.

ARINC 429

Aeronautical Radio Incorporated (ARINC 429) (Condor 2002) is a data format used for civil aircraft avionics systems. It provides the basic description of the functions and the supporting physical and electrical interfaces for the onboard digital information systems. ARINC 429 is a two-wire data bus that is application-specific for commercial and transport aircraft. The connection wires are twisted pairs. Words are 32 bits in length and most messages consist of a single data word and the specification defines the electrical and data characteristics and protocols. ARINC 429 uses a unidirectional data bus standard (transmit and receive are on separate ports) known as the Mark 33 Digital Information Transfer System (DITS). Messages are transmitted at either 12.5 or 100 kbit/s to other system elements that are monitoring the bus messages. The transmitter is always transmitting either 32-bit data words or the NULL state. No more than 20 receivers can be connected to a single bus (wire pair) and no less than one receiver, though there will normally be more.

Each ARINC word is a 32-bit value that contains five fields. The first, bit 32 is the parity bit and is used to verify that the word was not damaged or garbled during transmission. The second field (bits 30 and 31) is the Sign/Status Matrix, or SSM, and often indicates whether the data in the word is valid. The SSM can also indicates the Sign (+/-) of the data or some information related to it like an orientation (North/South/East/West). The third field covers bits 11 to 29 and contains the data. Bit-field, Binary Coded Decimal (BCD), and binary encoding (BNR) are common ARINC 429 data formats. Data formats can also be mixed. The fourth field is bits 9 and 10 are these are the Source/Destination Identifiers (SDI) and indicate for which receiver the data are intended or more frequently which subsystem transmitted the data. Finally, bits 1 to 8 contain a label (label words), expressed in octal, identifying the data type.

Label guidelines are provided as part of the ARINC 429 specification for various equipment types. Each aircraft will contain a number of different systems, such as Flight Management Computers, Inertial Reference Systems, Air Data Computers, Radio Altimeters, Radios, and GPS Sensors. For each type of equipment, a set of standard parameters is defined, which is common across all manufacturers and models. For example, any Air Data Computer will provide the barometric altitude of the aircraft as label 204. This allows some degree of interchangeability of parts as all Air Data Computers behave for the most part, in the same way. There are only a limited number of labels, though, and so label 204 may not be unique and may have a completely different meaning if sent by a GPS sensor, for example. However, many very commonly-needed aircraft parameters use the same label regardless of source.

Appendix F: Number Systems

Airborne data bus systems, OLM data acquisition systems and data analysis processes use numerical data in a number of different forms. It is essential that those involved in developing the processes understand these data numerical data forms and the issues that can arise if inappropriate actions are undertaken using a particular data type or number form (such as rounding errors caused by mixed real and integer division). In addition, OLM specialists will, on occasion, dive into the complexities of number systems and it is useful for those involved in the management of these programmes to have an appreciation of the technical discussion. Therefore, this appendix contains a list of number system and arithmetic data type terms and a brief explanation of their meaning.

Binary

Binary systems use powers of 2 (as apposed to powers of 10 for decimal). Binary numbers are expressed in bits. Modern DAU systems will generally use a 16bit system and hence the representation of decimal numbers in 16bit binary would be as follows:

Decimal	Binary
0	**0**00000000000000**0**
3	**0**00000000000001**1**
21	**0**00000000001010**1**
213	**0**00000001101010**1**
65535	**1**11111111111111**1**
	MSB **LSB**

Table E-1 – Binary Representation

Hence in an unsigned 16bit system, whole numbers (integers see later in Appendix) between 0 and 65535 can be represented. Attempts to represent larger input values in a DAU generally produce full-scale values of 65535 (i.e. topping out). The first (highest number) of the bits is referred to as the most significant bit (MSB) and the last bit is referred to as the least significant bit (value 1).

Signed Binary

In signed binary applications the MSB is used to indicate the sign of the number, where ‘0’ denotes a positive number and ‘1’ denotes a negative number. The number zero can have 2 possible states. The range of signed binary for a given number of bits is one less than unsigned binary but this is insignificant for 16bit systems and is offset by being able to represent negative numbers.

Decimal	Signed Binary
0	0000000000000000
0	1000000000000000
3	0000000000000011
-3	1000000000000011
21	0000000000010101
-21	1000000000010101

Table E-2 – Signed Binary Representation

One's Complement

In One's complement all positive integers are represented by the normal binary form. However, negative values are represented changing each '0' to a '1' and each '1' to a '0'. Again zero has 2 possible states.

Decimal	1's Complement
3	0000000000000011
0	0000000000000000
0	1111111111111111
-3	1111111111111100

Table E-3 – One's Complement

Two's Complement

For Two's complement all positive integers are represented by the normal binary form. However, negative values are represented by the ones' complement plus one. This method is used to describe some of the parameters on an ARINC 429 data bus system for example.

Decimal	2's Complement
3	0000000000000011
0	0000000000000000
-3	1111111111111101

Table E-4 – Two's Complement

Octal. Powers of 8 (rather than powers of 10 for decimal).

Decimal	Octal
3	3
21	25
62	76

Table E-5 – Octal

Hexadecimal

Hexadecimal uses powers of 16 (rather than powers of 10 for decimal), where the alphabet is used after 9, i.e….7, 8, 9, A, B, C, D, E, F. This system is used because of the convenience of using 4 bits in the binary system and 4 bits has 16 combinations.

Decimal	Hexadecimal
3	3
15	F
16	10
21	15
44	2C
255	FF

Table E-6 – Hexadecimal

Binary Coded Decimal

In binary coded decimal each individual numerical of a decimal number is represented by the equivalent 4bit binary word. This system is used extensively for transmitting data from instruments such as digital voltmeters or counters and is used on the ARINC 429 data bus.

Decimal	2	3	0	8
BCD	0010	0011	0000	1000

Table E-7 – Binary Coded Decimal

Integer Data Type

The integer data type can only represent whole numbers but they are stored exactly in all circumstances. The range of numbers covered by the integer type is system-dependent. The majority of modern computer systems use 32 bits for their integer arithmetic (1 bit for the sign and 31 bits for the magnitude) giving a number in the range -2 147 483 648 to +2 147 483 647. The rise of 64-bit computing will obviously increase this. However, as mentioned earlier, 16 bit (e.g. 0-65535) is currently the norm for DAU systems. However, this should provide sufficient resolution if data are scaled with care.

Real Data Type

Real values are stored in computer systems using a floating-point representation which gives a larger range than the integer type but the values are not, in general, stored exactly. Both the range and the precision are machine dependent. In practice most machines use at least 32 bits to store real numbers. Many systems use the IEEE Standard representation: for 32-bit numbers this gives a precision of just over 7 decimal digits and allows the number range from around 10^{-38} to just over 10^{+38} and obviously 64bit systems provide far greater range.

Double Precision Data Type

Double precision is an alternative floating-point type. Generally double precision is at least double that provided by real values. However, storage requirements are twice that of real numbers. Computation is also slower than real number or integer values.

Appendix G: Data Anomalies

Experience has shown that OLM data will contain anomalies within it. Many of these anomalies should be detected by a combination of automated anomaly routines such as max/min values, rate of change, correlation between known related parameters and visualisation of data, converted into engineering units by an experienced analyst. Several examples of more subtle anomalies identified in OLM data are reproduced in this Appendix to illustrate the importance of visualising the data and to provide useful examples for testing anomaly detection algorithms. Normal acceleration anomalies have been used because they require no particular knowledge of the aircraft type in question. Most of the anomalies are also plotted alongside a wing strain gauge response to highlight the presence of the anomaly.

NON-CONSTANT OFFSET VALUE

This non-constant offset value anomaly illustrated in Figure G-1 is easily identifiable when illustrated in engineering units (g) and with an expectation of seeing 1g values during most of the flight. Such an anomaly could be easily missed if the expected value from the transducer was less well defined.

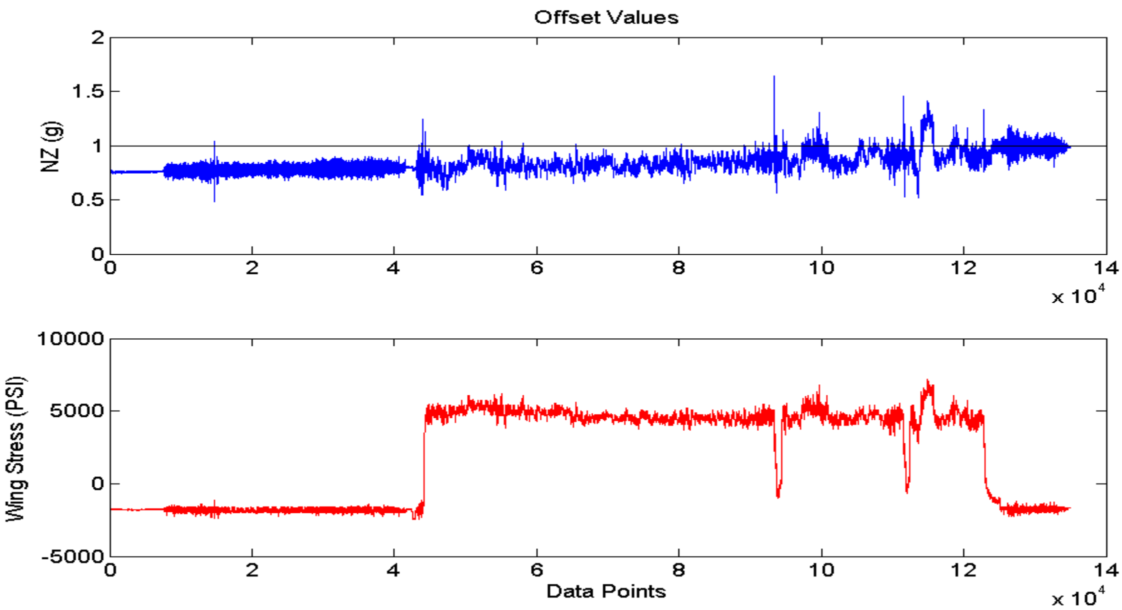

Figure G-1 Offset Values

STEP CHANGE IN RESPONSE

Figure G-2 illustrates a step change in response at around 2.5E5 data points and a return to the expected response just before the end of the flight.

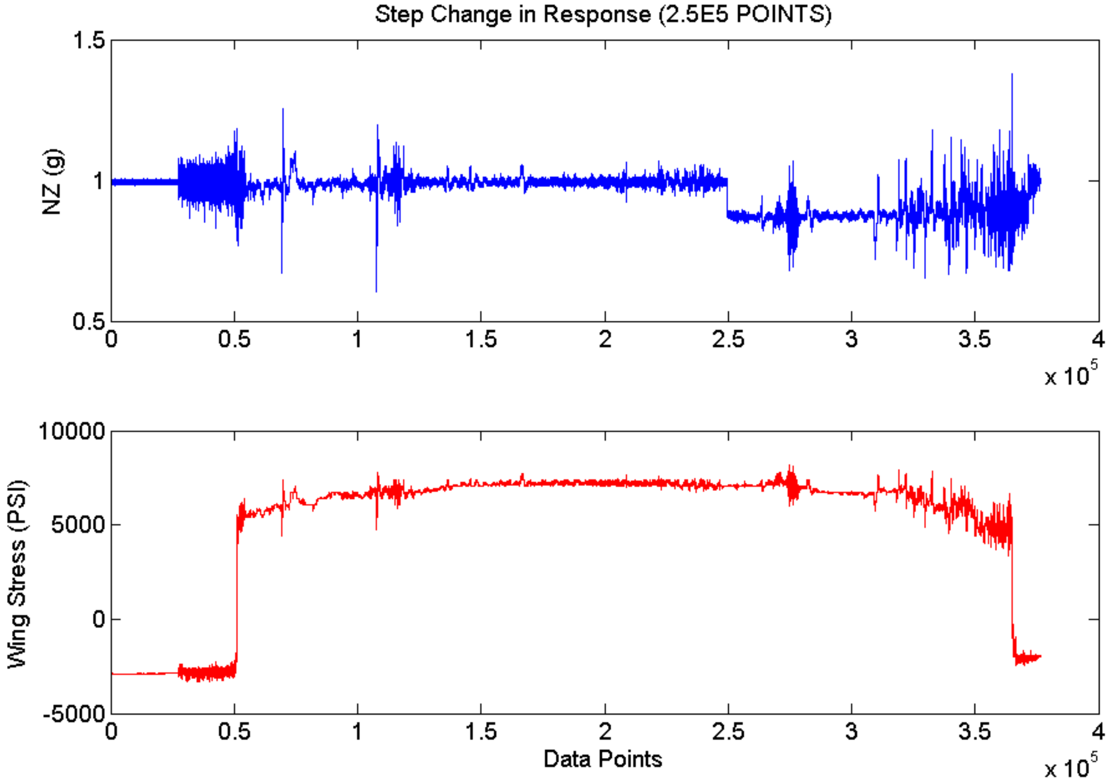

Figure G-2 Step Change in Response

LONG PERIOD ANOMALY

Figure G-3 illustrates a long period anomaly beginning around 1.75E5 data points.

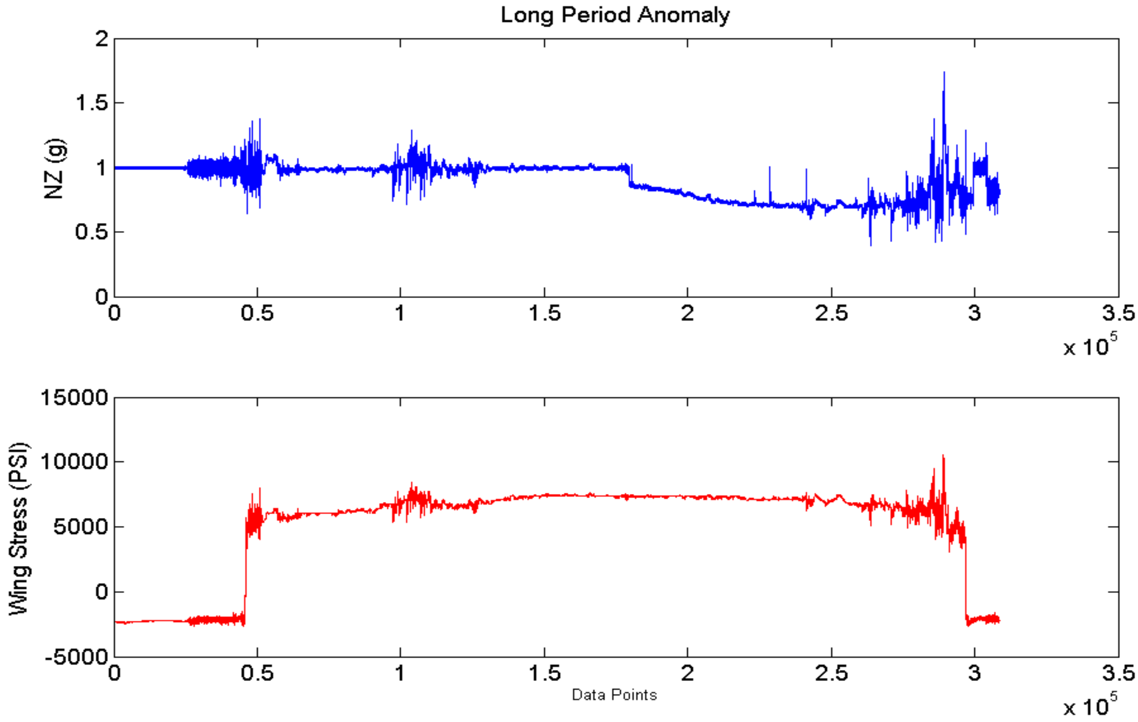

Figure G-3 Long Period Anomaly

NOISY TRACE

Figure G-4 illustrates a 'noisy' trace identified as a faulty installation.

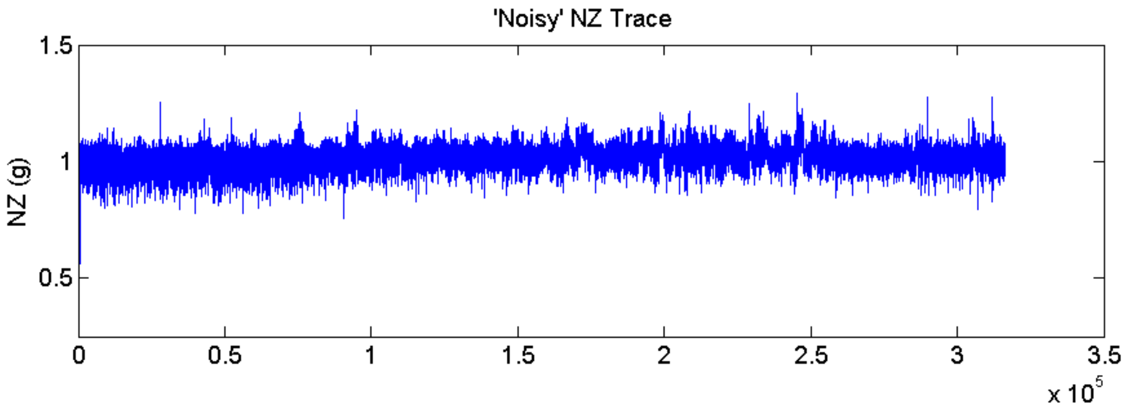

Figure G-4 Noisy Trace

POWER-UP SPIKE

Figure G-5 is a power-up spike seen on several accelerometer installations.

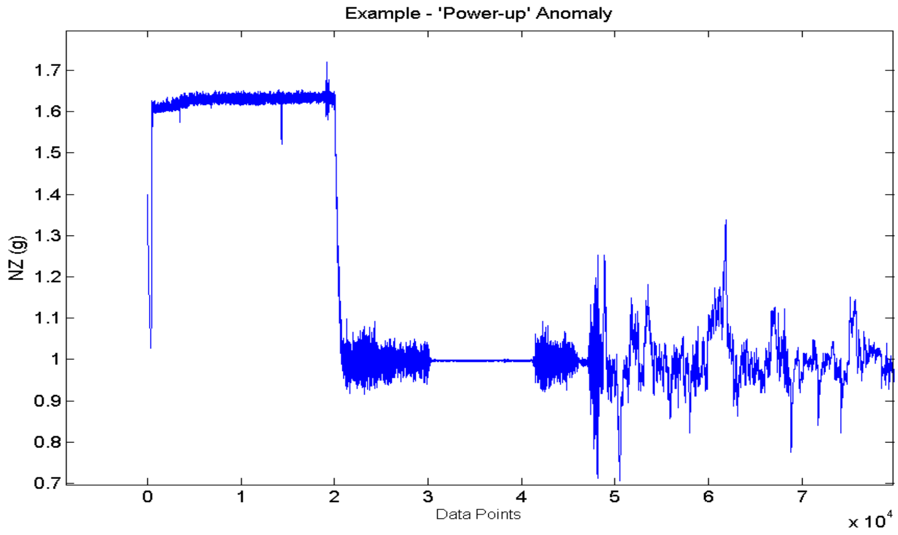

Figure G-5 Power-Up Spike

ANOMALIES SIMILAR TO REAL EVENTS

Figure G-6 illustrates several anomalies which had a similar characteristic to a real event (landing). This is illustrated in Figure G-7.

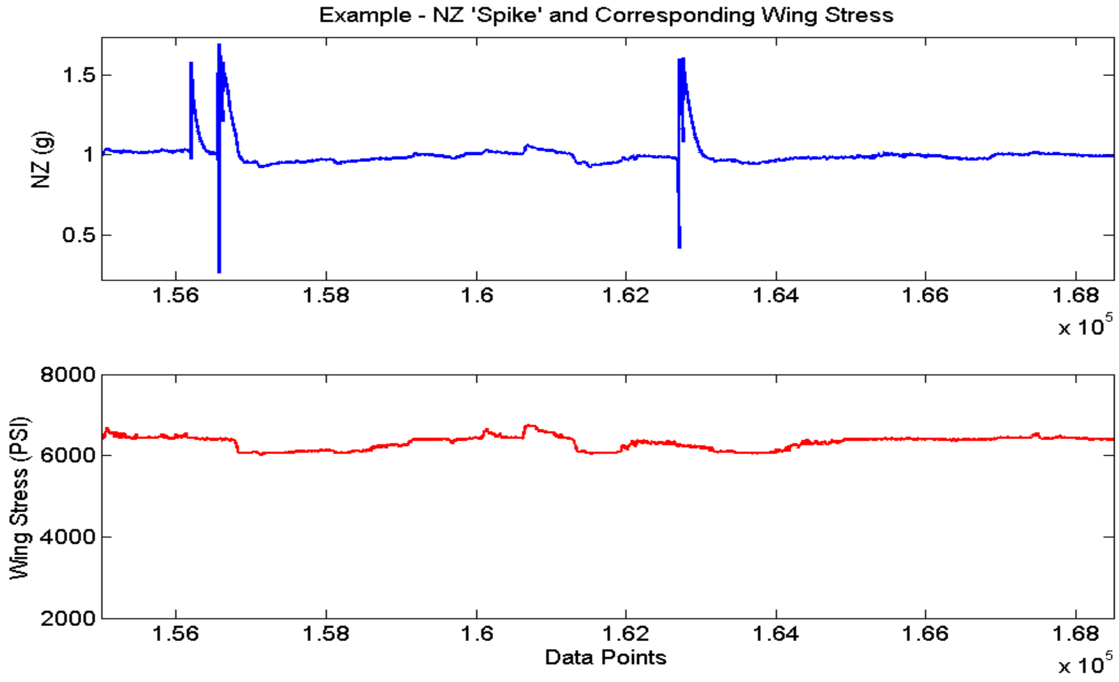

Figure G-6 Anomalies Similar to Real Events

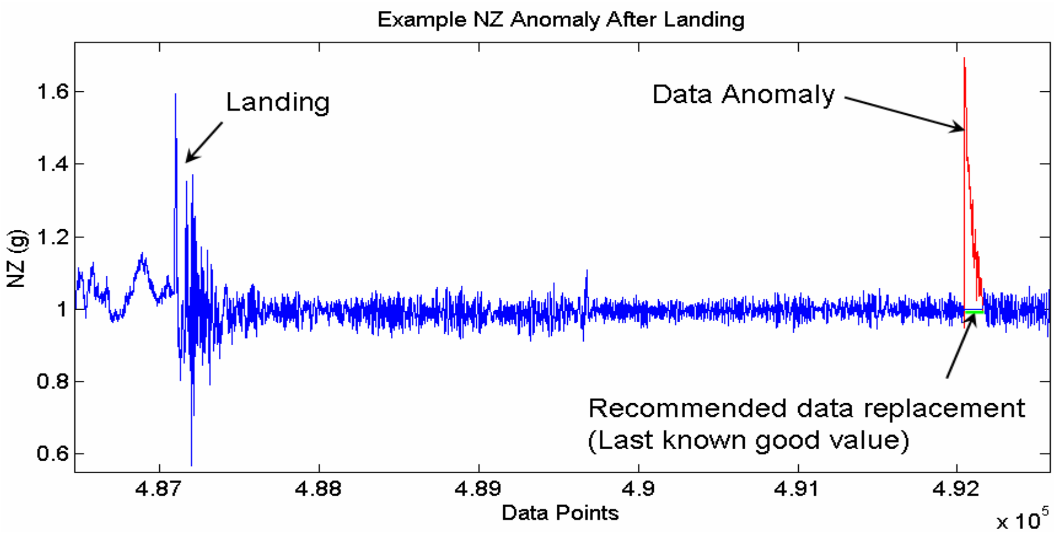

Figure G-7 Anomaly Compared Similar to Landing Event

Appendix H: Typical OLM Strain and Parameter Time Histories

This Appendix contains examples of typical strain/stress/load and key flight parameter time histories for major structural components such as the wing, tailplane and fin for combat, trainer and transport / tanker aircraft types. These plots have been included to illustrate the character of time histories for different components and aircraft types. The wing stress time histories for the latter are used to illustrate the effects of different operations, such as low-level and civil or logistics type sorties.

In the first 2 plots, Figures G-1 and G-2 wing stress or strain time histories for manoeuvre dominated (military trainer) aircraft and gust (transport) aircraft are presented with the key phases of flight marked upon the plots. Figure G-1 is a 30 min aerobatic sortie where the display routine (approximately 11 mins) is carried out twice during the sortie. This is clearly evident in the plot. The change in strain level at take-off and landing is relatively small compared to the large manoeuvre strains seen during the display.

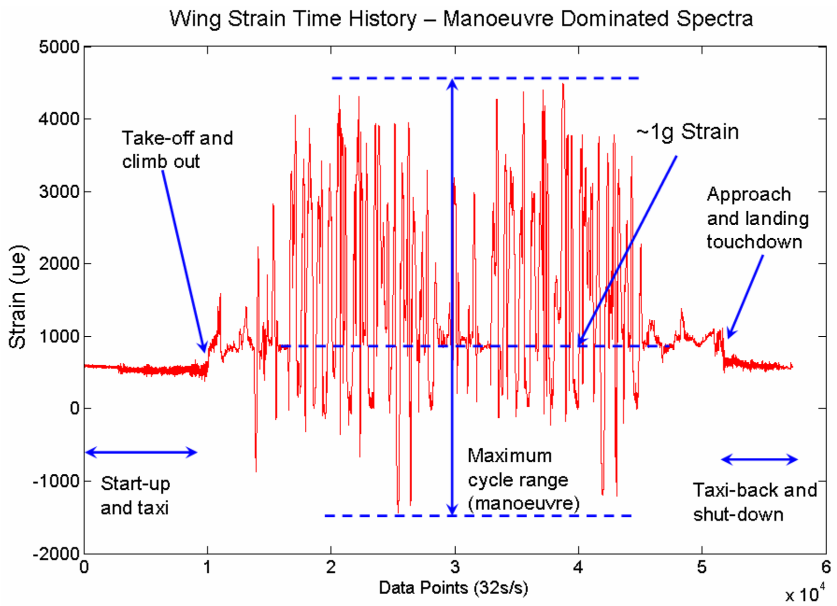

Figure G-1 - Manoeuvre Dominated Aircraft Strain Time History

Figure G-2 is a plot of a civil or logistics type mission for a transport type aircraft. In this plot the GAG cycle is clearly evident with a significant change in stress level being seen at take off and landing.

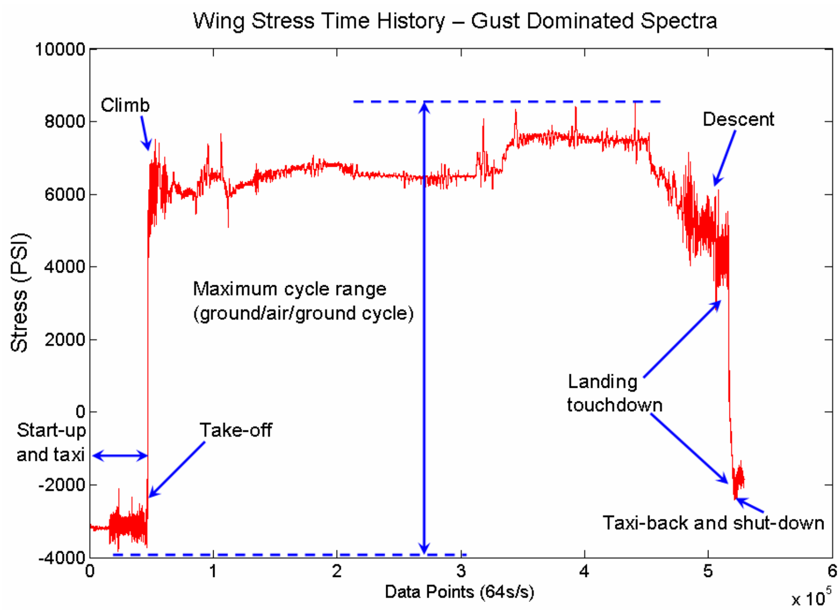

Figure G-2 - Gust Dominated Aircraft – Transport, Tanker and Large Trainers

COMBAT AIRCRAFT PLOTS

Figure G-3 to G-5 are plots of wing, tailplane and fin stresses and associated flight parameters for a combat aircraft.

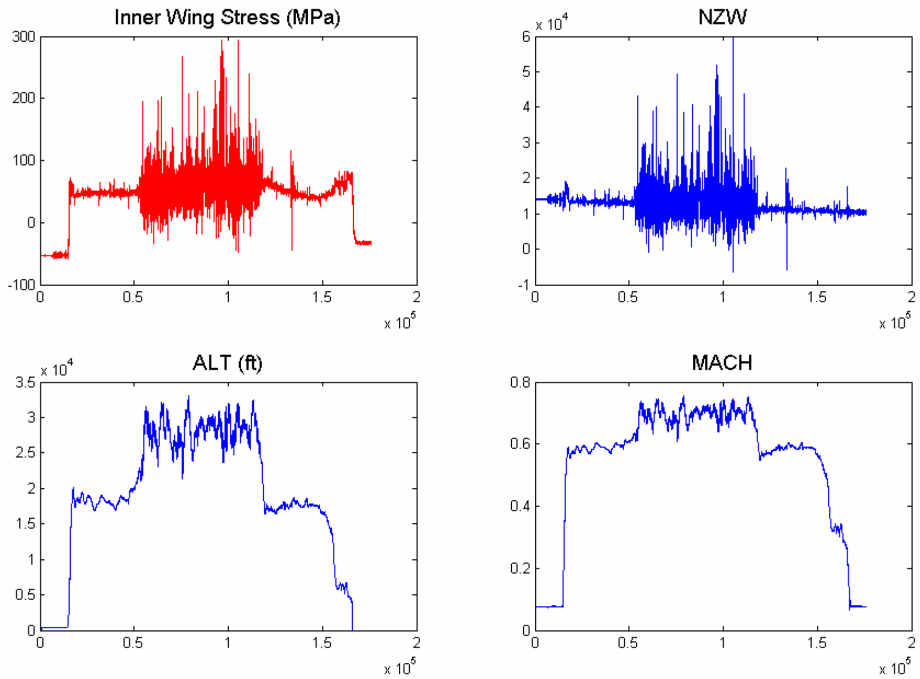

Figure G-3 - Combat Aircraft Wing Stress, NzW, ALT and MACH Plot

The manoeuvre content in the time history is clearly evident in the far greater exceedances of positive stress and normal acceleration.

Figure G-4 is a plot for the same sortie illustrating the tailplane stress time history and mass normalised normal acceleration, tailplane position (conditioned by dynamic pressure), angle of attack, altitude and Mach number.

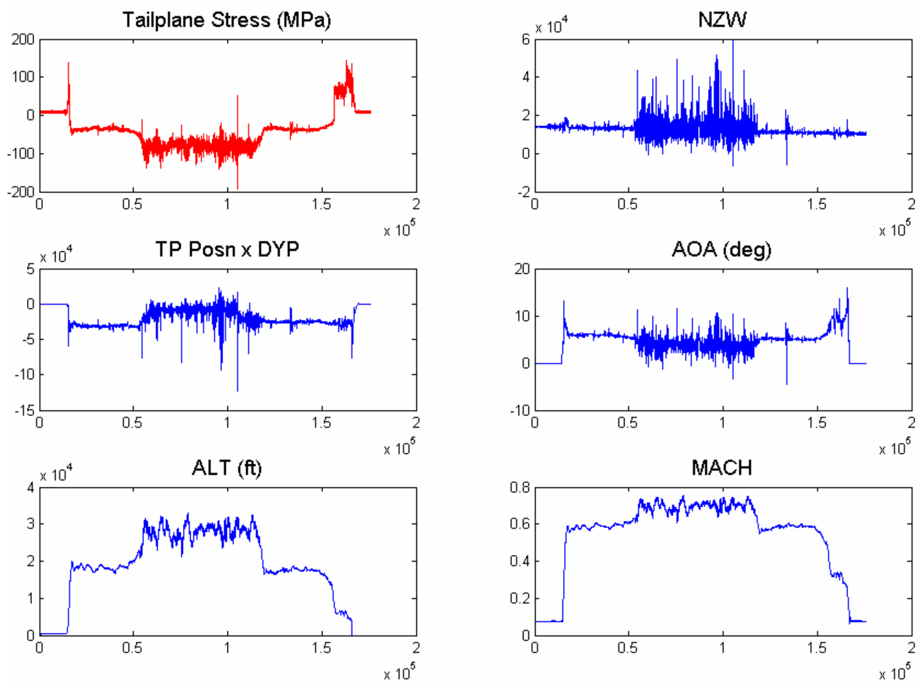

Figure G-4 - Combat Aircraft Tailplane Stress, NzW, Tailplane Position (x Dynamic Pressure), AOA, ALT and MACH Plot

Interestingly, the rapid change in stress at about 1.05E5 data points could easily have been identified as suspect data. A zoomed plot of the stress time history confirmed that these data were not spurious (Figure G-5).

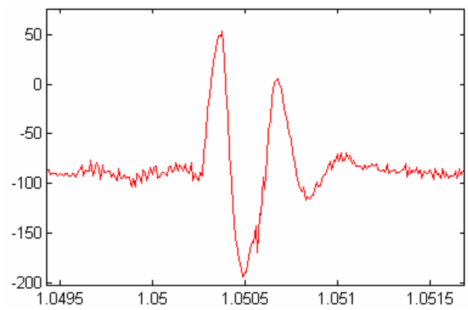

Figure G-5 - Combat Aircraft Tailplane Stress (zoom plot around 1.05E5 data points)

Figure G-6 illustrates the fin bending stress for a combat aircraft with associated flight parameters.

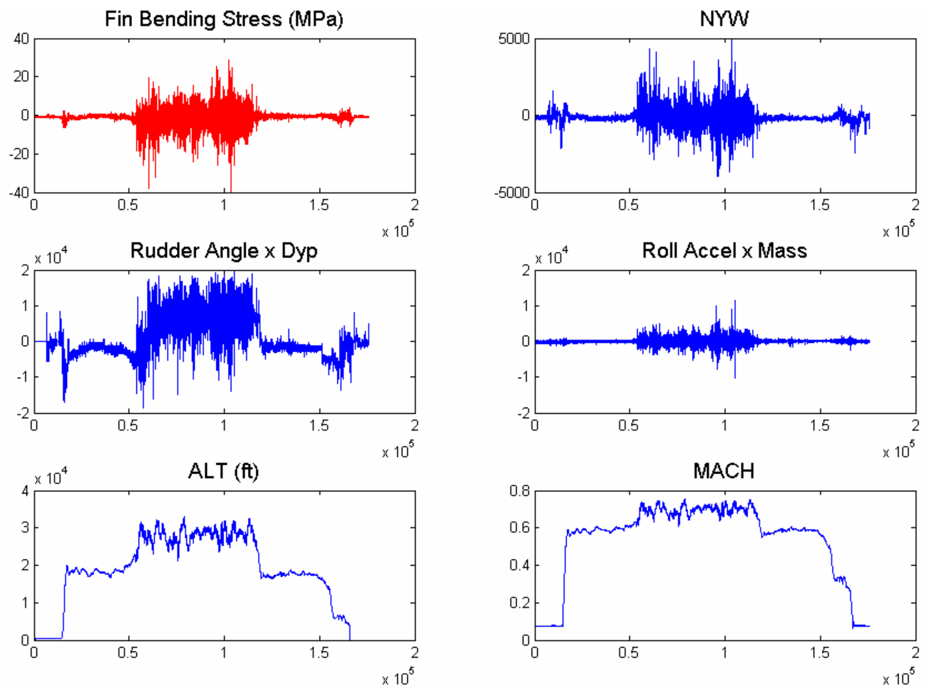

Figure G-6 - Combat Aircraft Fin Bending Stress, Lateral Acceleration (conditioned by mass), Rudder angle (conditioned by dynamic pressure), Roll acceleration (conditioned by mass) and , ALT and MACH Plot

Figure G-7 illustrates the fin bending stress for a combat aircraft with associated flight parameters.

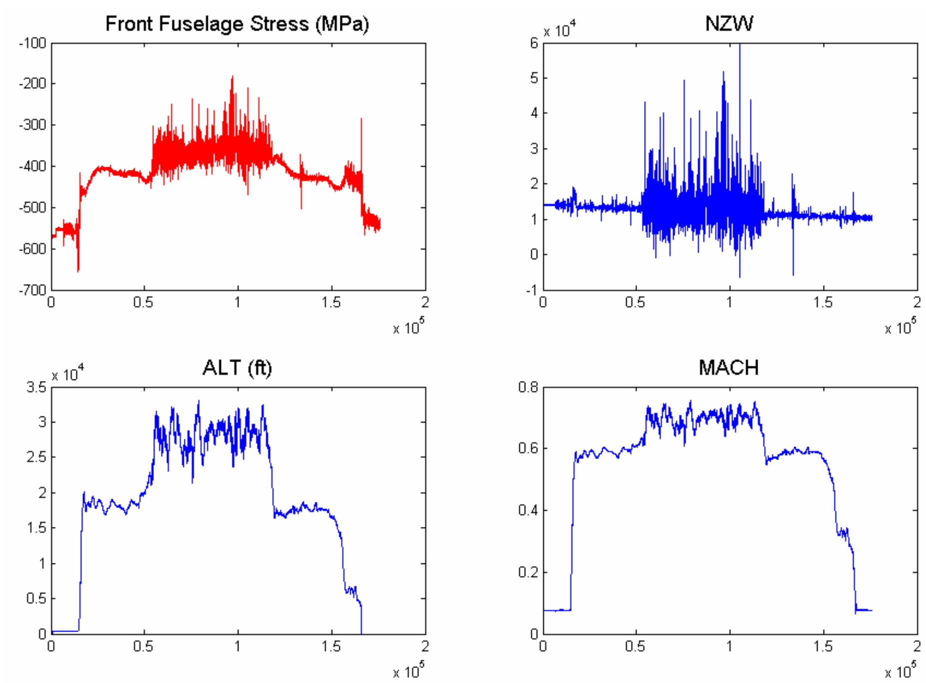

Figure G-7 - Combat Aircraft Front Fuselage Bending, NzW, ALT and Mach

TRAINER AIRCRAFT PLOTS

As one might expect, the character of the time-history plots for the trainer aircraft (Figures G-8 to G-10) are similar to the combat aircraft. The correlation between inner wing stress and NZW is very high (see Figure G-8) and the change in stress level seen in the wing and tailplane at take-off / landing is noticeably less than in the combat aircraft. This is due to the trainer being flown with a clean wing, whereas the combat aircraft has external stores and fuel tanks fitted.

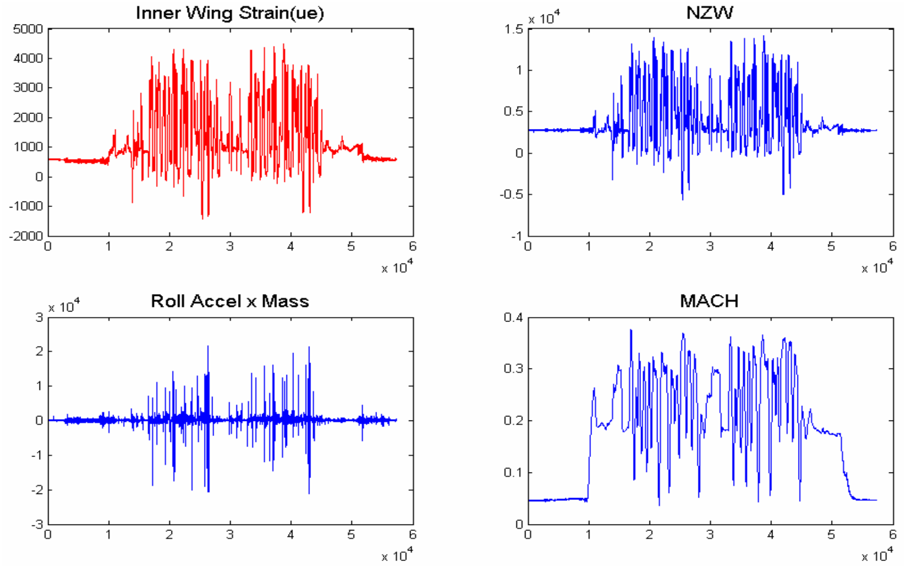

Figure G-8 – Trainer Aircraft Wing Bending Strain, NzW, Roll Acceleration (conditioned by mass) and Mach number

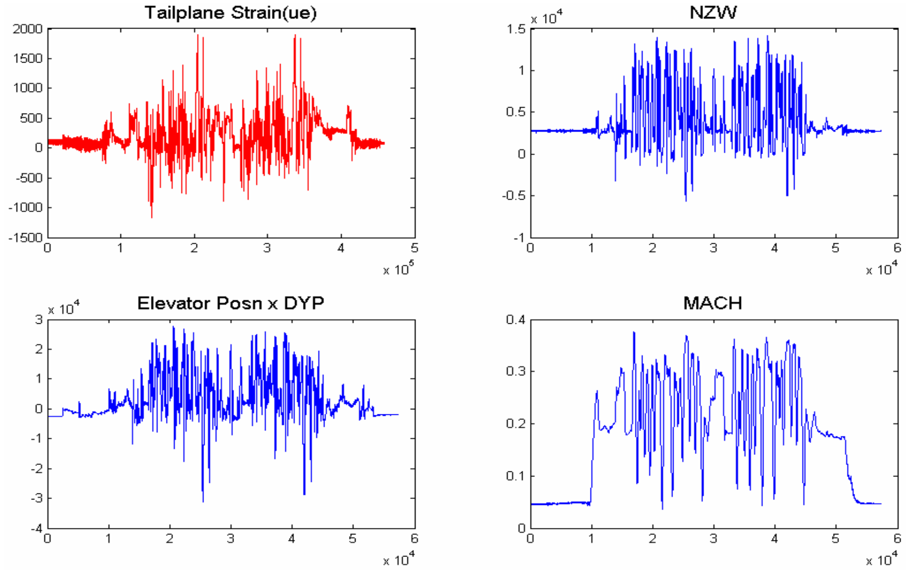

Figure G-9 – Trainer Aircraft Tailplane Bending Strain, NzW, Elevator position (conditioned by dynamic pressure) and Mach number

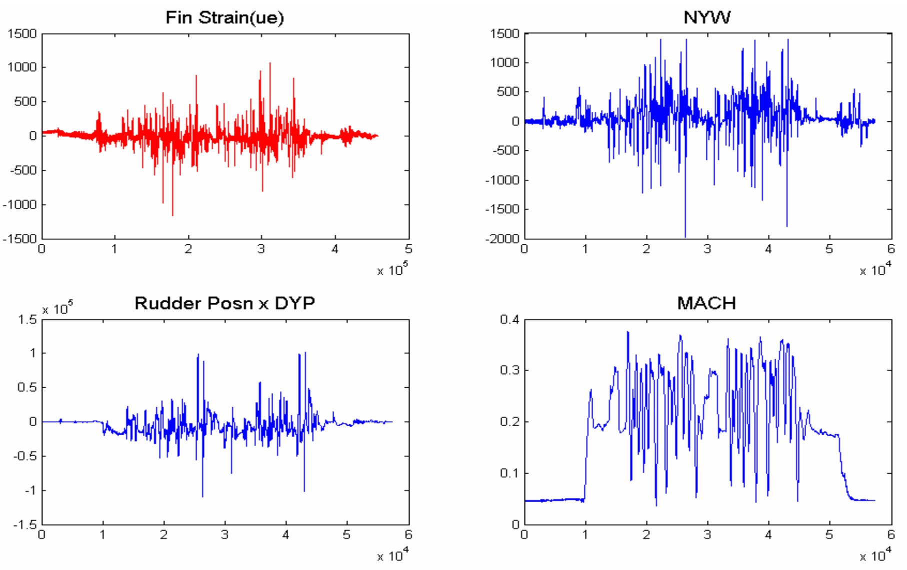

Figure G-10 – Trainer Aircraft Fin Bending Strain, NyW, Rudder position (conditioned by Dynamic pressure) and Mach number

LARGE TRANSPORT AIRCRAFT PLOTS

Figures G-11 to G-18 illustrate typical time history plots for a large transport type aircraft (courtesy of Marshall Aerospace) for the wing bending moment, fuselage bending and pressure loading), tailplane (bending) and fin (bending) and associated flight parameters. Figures G-11 to G-14 are from a logistics type mission and Figures G-15 to G18 are from a crew training mission on the same scales and which included a number or roller landings. The ground-air-ground (GAG) cycle for the wing and tailplane is clearly evident on these figures. (File length variations are due to differing sample rates and data plotting by data points rather than time.)

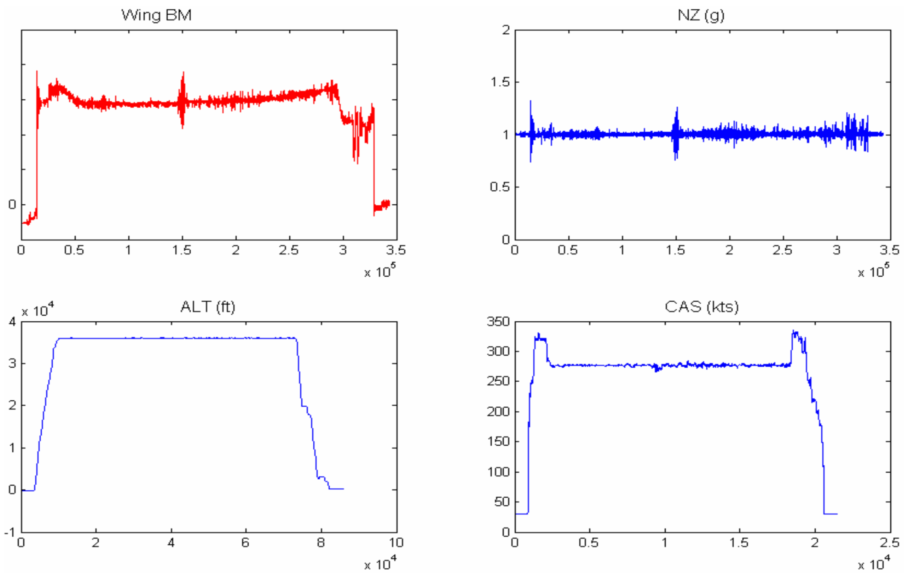

Figure G-11 – Transport Wing Bending, Normal Acceleration, Altitude and Computed Airspeed – 'Logistics' Mission

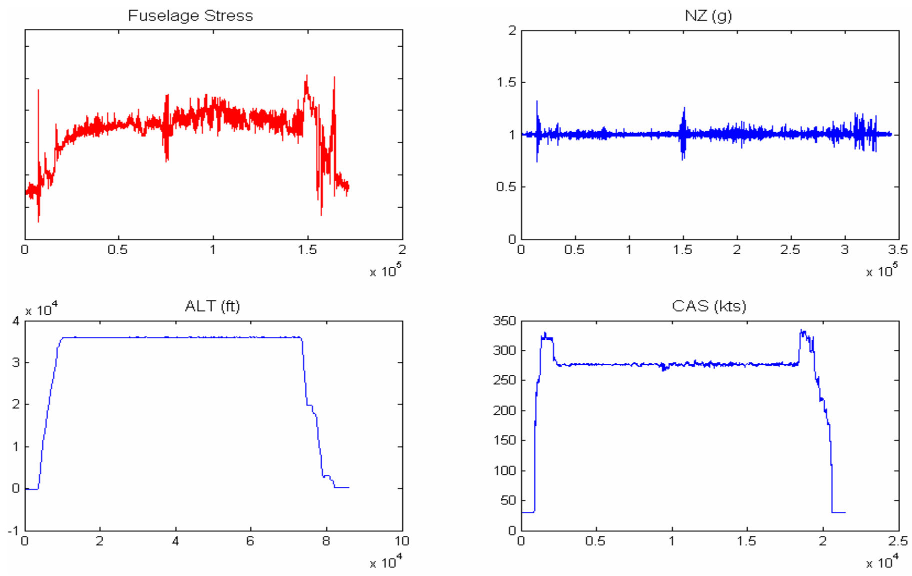

Figure G-12 – Transport Fuselage (Bending and Pressure), Normal Acceleration, Altitude and Computed Airspeed – 'Logistics' Mission

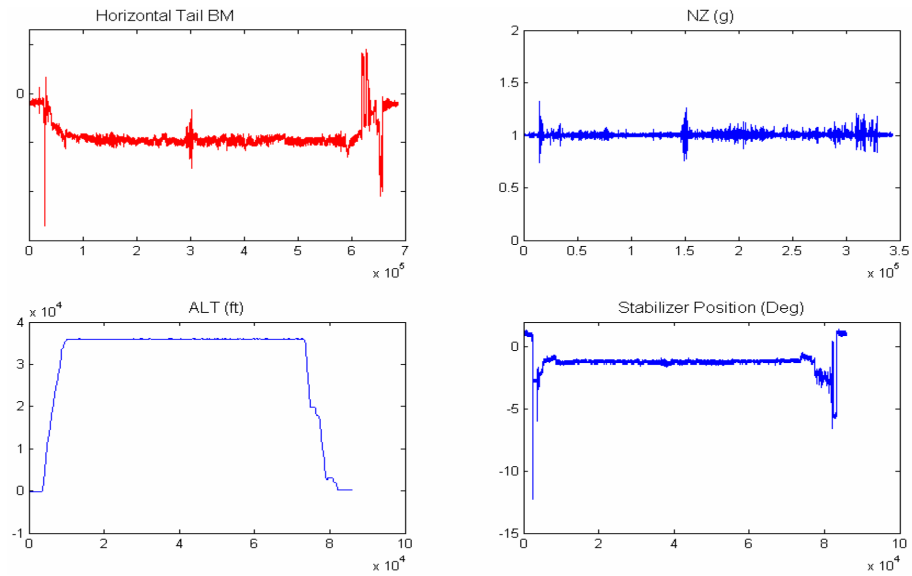

Figure G-13 – Transport Tailplane Bending, Normal Acceleration, Altitude and Stabilizer Position – 'Logistics' Mission

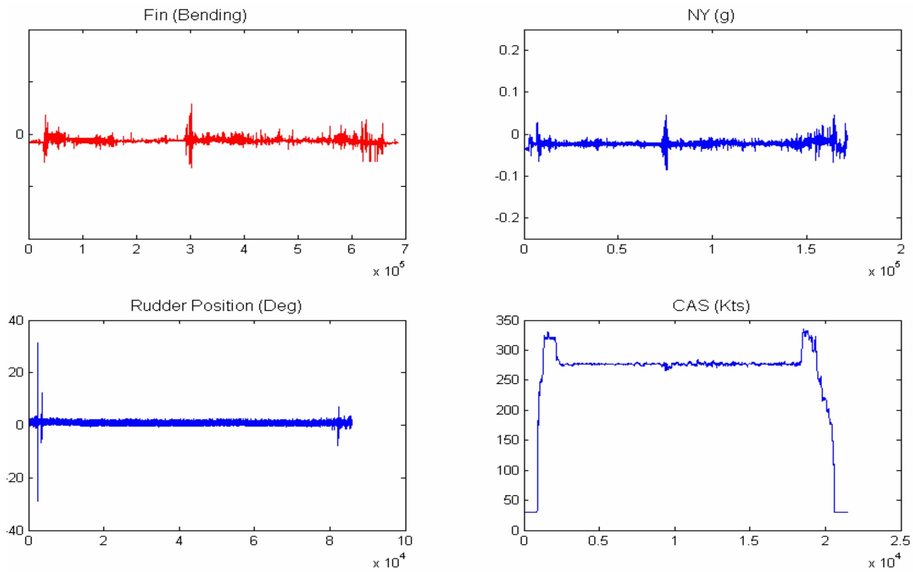

Figure G-14 – Transport Fin Bending, Lateral Acceleration, Rudder Position and Computed Airspeed – 'Logistics' Mission

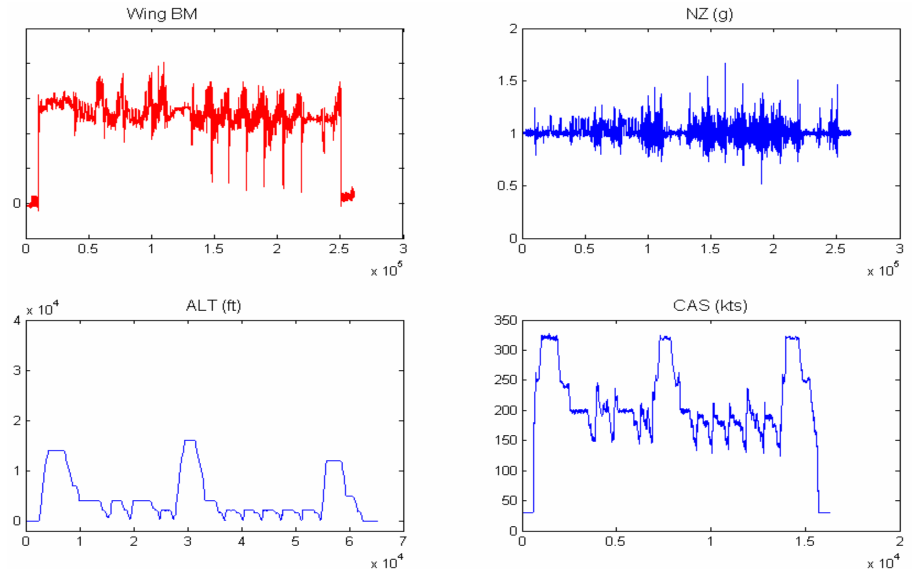

Figure G-15 – Transport Wing Bending, Normal Acceleration, Altitude and Computed Airspeed – 'Training' Mission

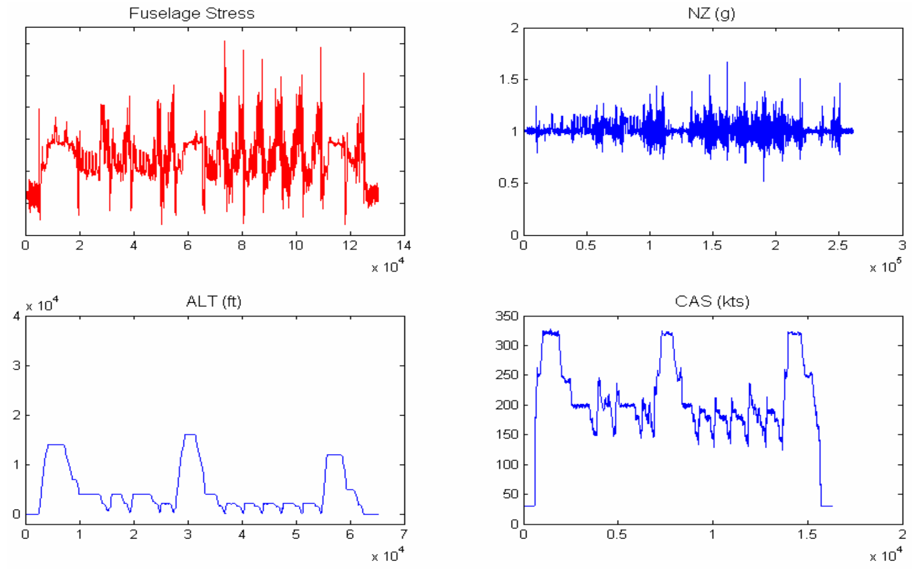

Figure G-16 – Transport Fuselage (Bending and Pressure), Normal Acceleration, Altitude and Computed Airspeed – Training' Mission

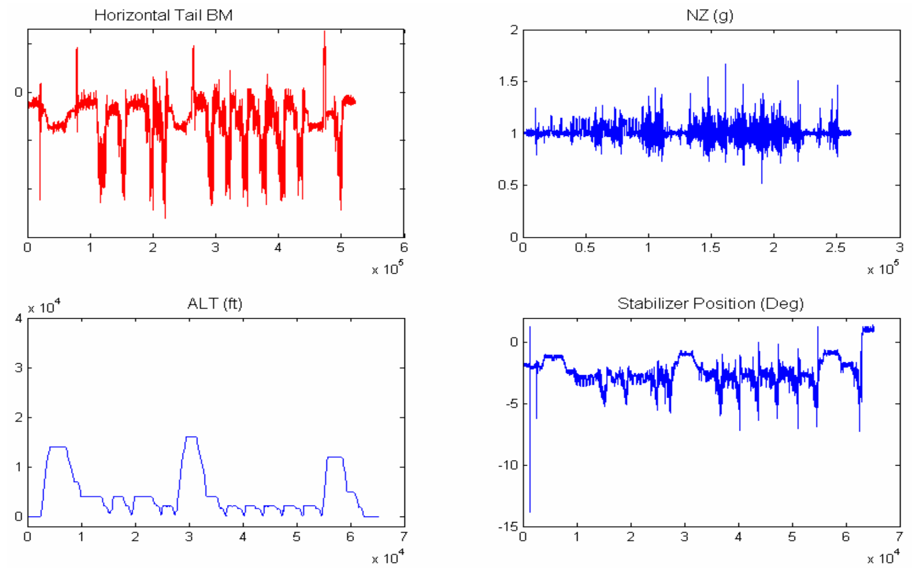

Figure G-17 – Transport Tailplane Bending, Normal Acceleration, Altitude and Stabilizer Position – 'Training' Mission

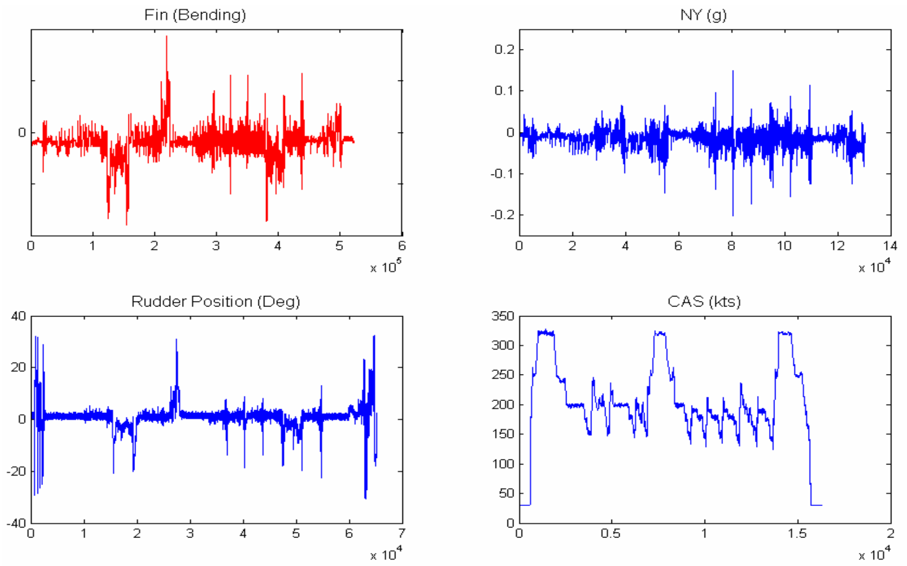

Figure G-18 – Transport Fin Bending, Lateral Acceleration, Rudder Position and Computed Airspeed – 'Training' Mission

TRANSPORT AIRCRAFT MISSION EFFECT

Figures G-19 to G-22 illustrate the wing stresses in a small transport / business jet aircraft under various mission types, with associated flight parameters. The effect of low level (land based) operations is clearly evident in Figure G-20. Also, the effect or roller landings is clear in Figure G-22.

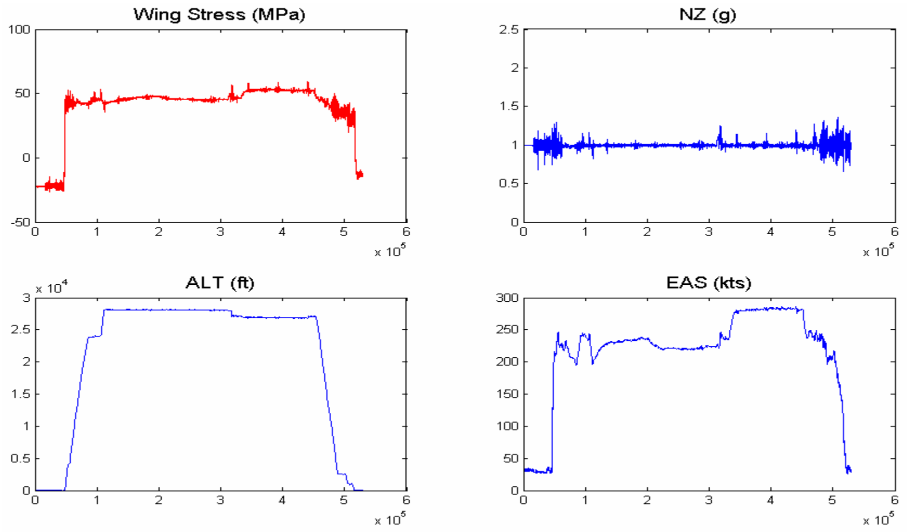

Figure G-19 – Transport Aircraft Wing Stress, Nz, ALT and Airspeed – Civil / Logistic Mission

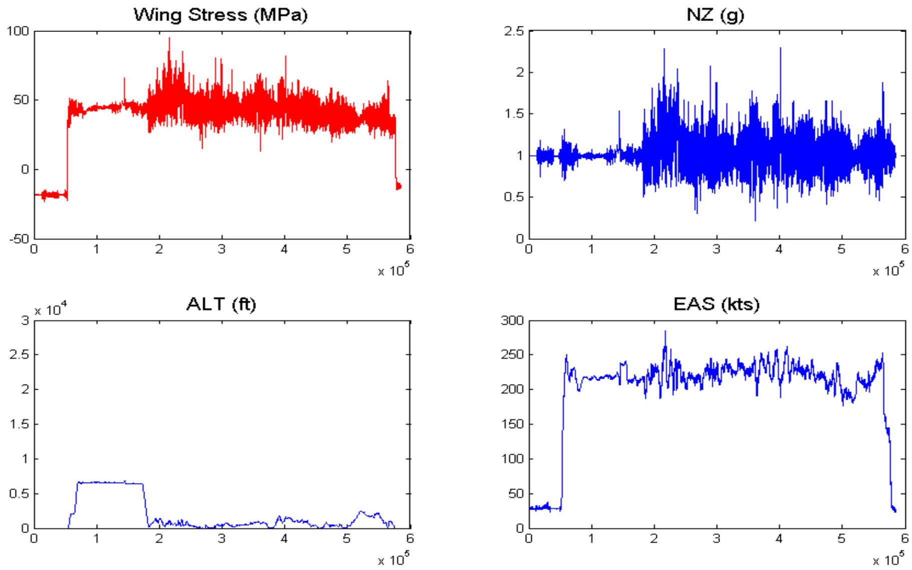

Figure G-20 – Transport Aircraft Wing Stress, Nz, ALT and Airspeed – Low Level (Land) Mission

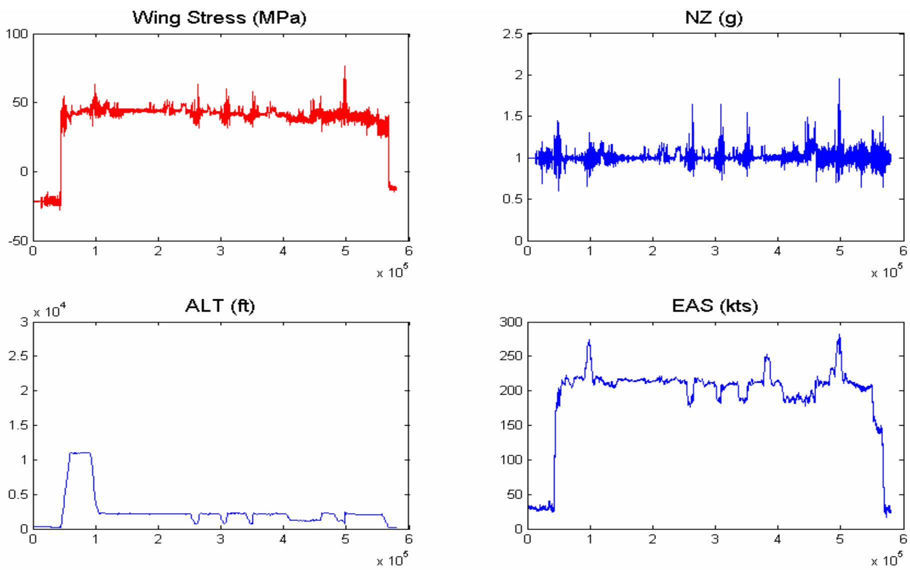

Figure G-21 – Transport Aircraft Wing Stress, Nz, ALT and Airspeed – Low Level (Maritime) Mission

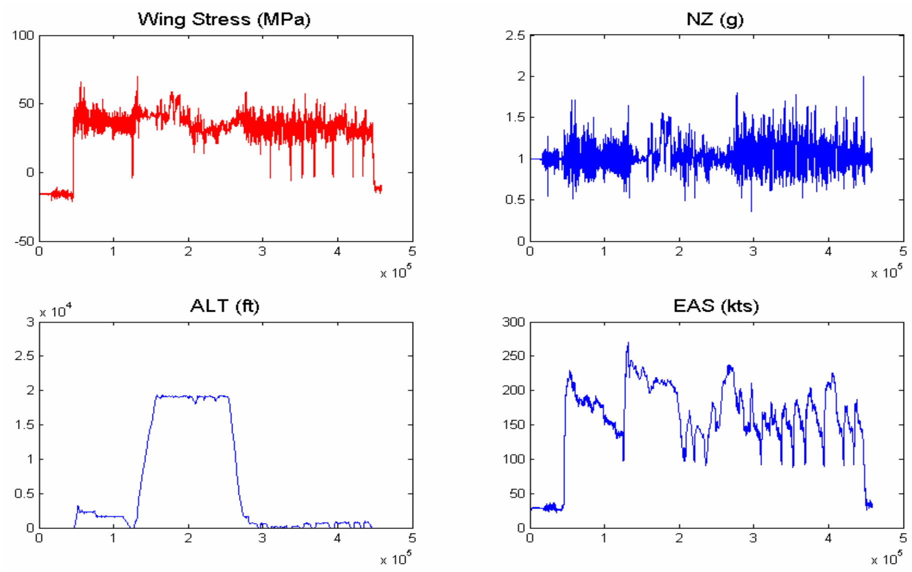

Figure G-22 – Transport Aircraft Wing Stress, Nz, ALT and Airspeed – Training Mission (Circuits)

Appendix I: Trials Directive Template

This Appendix contains a Trials Directive Template for use in future OLM programmes, as required. It is assumed that the Trials Directive would be issued by the MoD Project Office or equivalent organisation. The Trials Directive content will vary considerably and will be dependent upon the extent of documentation available from other sources and the processes used for modification installation, such as a full designer-approved modification or as a service modification.

FILE REFERENCE:

DATE:

See Distribution:

OPERATIONAL LOAD MEASUREMENT PROGRAMME TRIALS DIRECTIVE TEMPLATE

References: (Including)

A. UK Ministry of Defence, Joint Service Publication, JSP553, Military Airworthiness Regulations, 1st Edition (Top –level policy for OLM requirements).

B. UK Ministry of Defence, Defence Standard 00-970, Part 1/2, Design and Airworthiness Requirements for Service Aircraft, Section 3.

C. UK Ministry of Defence, Joint Air Publication, JAP 100A-01, Chapter 11.1.

D. References to any previous OLM activity for type.

E. Designer Organisation Aim, Process, Installation, Analysis and Maintenance, Reports (as required and various).

F. Service Engineering Modification Leaflet (as required).

G. OLM Process and Procedures Aircraft Topic 2(R)1 Leaflets (as required).

H. AEDIT Report covering maintenance issues (as required) – possibly published in Topic 2(R)1.

INTRODUCTION

Include a brief introduction explaining the need to undertake OLM. For example … The structural integrity of UK military fixed-wing aircraft is assured using a variety of inter-related means. Amongst these, analytical models are used at every stage of the aircraft's life from initial design onwards; additionally, the durability of the design is normally demonstrated by the use of a Full-Scale Fatigue Test (FSFT). Thereafter, once the aircraft enters Service the usage is monitored to compare it with the design assumptions and fatigue test spectra. Routine usage monitoring for an aircraft takes the form of measuring key parameters such as levels of g exceedance and flying hours and processing the data using fatigue formulae, for example (modified as appropriate for the aircraft type).

References A, B and C require that during the life of an aircraft fleet the continued applicability of the adopted processes to current utilization is confirmed by carrying out either a permanent or a periodic Operational Loads Measurement (OLM) Programme. An OLM Programme utilizes in-flight direct strain and associated flight parameter measurements e.g. airspeed, Mach number and altitude, to gain a more detailed picture of in-Service structural behaviour than that provided by the usual fatigue monitoring procedures alone. OLM provides the Designer with accurate information on structural loading and enables those manoeuvres or other in-flight events which cause high static loads or high rates of fatigue life consumption to be identified. Additionally, the OLM provides information to the Designer to allow validation or amendment to the fatigue monitoring system and provides a system for measuring loads in areas of the structure not directly covered by the fatigue monitoring system, often termed "unmonitored" structure. Outline any previous OLM history relevant to the aircraft type and give references (e.g Reference D).

AIM

The aims of the OLM programme are: (this section may include all or some of the following aims):

- To substantiate the fatigue spectra used in design, qualification and review fatigue clearances
- To substantiate the monitoring systems (including identification of further monitoring requirements)
- To capture fatigue test spectra data
- To identify particularly damaging activity or manoeuvres
- To assist in substantiating of the Statement of Operating Intent and Usage
- To identify local stresses in structural features

OLM SYSTEM DESCRIPTION

The OLM system is described in detail in Reference E or F as required. Within this section a brief explanation of the OLM fit including number of strain gauges and parameters, sample rates and the general location of these gauges should be provided. Simple diagrams can prove useful in this section.

Provide a brief description of the data acquisition and recording system and how the system is powered and the triggers for recording with Reference to designer or service information (e.g. References E or F).

TRIALS MANAGEMENT

This section should provide contact details for all key personnel involved in the management and conduct of the OLM programme and give unit personnel clear direction as to the appropriate point-of-contact. As an example the list of contacts might include:

- MoD OLM Programme Project Manager and Deputy
- Designer OLM Project Manager
- Unit OLM Project Officers
- Designer OLM Data Analysis Team Leader
- Designer OLM Instrumentation Team Leader (e.g. FTI)

CONDUCT OF TRIAL

Trial Aircraft. Details of trial aircraft and operating units.

OLM Modification. This section should include details of the process used for installation and authorisation of the OLM equipment modification, such as full Designer Mod (possibly under special order only (SOO) modification process) or service modification (References D and E) and identify Modification leaflets / Topic 2(R)1 entries (attach advanced copies if documents have not yet been formally published).

Trial Duration. Detail the trial duration and any transfers between units / squadrons. Provide clear indications of estimated timescales and data capture requirements and authority for revision of the schedule.

Pre-and Post Transfer Serviceability Checks. Detail pre and post transfer serviceability checks and reporting required between units / squadrons (ideally referenced to Topic 2(R)1 (References G and H) or similar documentation which may need to be attached if not yet published).

Aircraft Utilization. It is essential that the OLM aircraft are used to gather data from all flight conditions initially; thereafter, any particular areas of concern can be identified and the OLM aircraft can then be used to gain a greater understanding of particular sorties or manoeuvres. Although it is essential that the OLM aircraft are used representatively of the fleet as a whole, this still requires management to ensure that data are collected from all relevant SPCs and the Unit OLM Project Officers should be instructed with ensuring that the aircraft are tasked to meet the data capture requirements identified in the OLM Flying Schedule at Annex A.

Trial Flying. Subject to OLM equipment serviceability, flight data are to be recorded for every sortie flown by the aircraft during the trial period.

Supported Detachments. Details of data recording and management responsibilities for supported detachments should be identified, including ground station support.

Unsupported Detachments and Land away. Details of data recording and management responsibilities for unsupported detachments and land away should be identified, including ground station support. Ideally aircrew involvement in OLM data management should be avoided and modern systems should have sufficient capacity to cope with unsupported detachments.

Limitations. This section should identify any limitations caused by the OLM installation and should identify any action required. For example, it may be impractical to protect adequately and OLM equipment fitted near a gun and hence gun firing may be prohibited for the OLM aircraft. Appropriate limitation (MoD Form 703 entries) will be required.

DATA MANAGEMENT

Data Management Process. A clear description of the OLM data management process should be provided, ideally with accompanying flow diagrams and data dispatch reporting requirements, including data required to match OLM data with flight records, such as copies of MoD Form 725 data for manually recording aircraft.

Media Management. Where removable media are used (e.g. PCMCIA cards) details of identification, control, supply, protection and handing of media should be provided. Where possible, media should be pre-identified and where postal dispatch is required, pre-addressed jiffy bags etc have proven invaluable in reducing losses of captured data.

Changes to F725s. A mechanism should be established to ensure that any subsequent changes to flight records (such as from unit or central validation of MoD Form 725s) should be relayed to the OLM Data Analysis Team.

Unit Data Dispatch Reporting. Unit Project Officers should be responsible for data dispatch reporting (e.g. weekly) and the process should be defined in a pro forma (such as Annex B).

Data Receipt Reporting. The OLM Data Analysis Team should report to the OLM Programme Project Manager arisings of dispatched data not being received from Units after a predefined period (e.g 1 week for UK based operations). This will allow timely follow-up action by the OLM Programme Project Manager.

DATA ANALYSIS

Brief details of the data analysis process should be described in this section and any feedback to be provided to the units on sensors serviceability and lost data should be identified. A process for authorisation of remedial action following discovery of unserviceable data should be described. A process for carrying out and authorisation of remedial action following discovery of unserviceable data should be described.

ENGINEERING IMPLICATIONS

Maintenance Policy. The maintenance policy for the OLM system should either be identified here or, if promulgated elsewhere (e.g Reference G), then references should be provided. Additionally, procedures, training and spares support should be identified.

Operating Procedures. System description and operating procedures should be contained in References E or F and attached to the Trials Directive (Enclosure 1). Any additional procedures should be identified here.

Training Requirements. Experience from previous OLM Programmes suggests that a significant number of failures to capture data could have been avoided with better operator training and awareness. Therefore, 2 training elements should be addressed:

Familiarisation Training. Ideally undertaken when the OLM aircraft are delivered or transferred to a Unit or Squadron. Points of contact should be identified.

Operator Training. More detailed training may be required for selective unit personnel for detailed operation and diagnostics of OLM equipment. Points of contact should be identified.

OLM System Scheduled Maintenance (Unit Personnel). Scheduled maintenance requirements and associated reporting for the OLM System, such as weekly status checks should be detailed in References G and H.

OLM System Scheduled Maintenance (External Support). OLM system scheduled maintenance requiring external support (such as annual recalibration of parametric sensors) should be identified and points-of-contact detailed.

Implications of the OLM System on Aircraft Rectification and Scheduled Maintenance. The implications of the OLM System on aircraft rectification and scheduled maintenance should be detailed in Reference H**.**

Rectification. A rectification guide including diagnosis, remove/refit and post-rectification functional checks, commensurate with OLM system maintenance policy should be identified (ideally Topic 2(R)1 Leaflet (Reference H).

Spares Support. OLM spares support procedure and holdings should be identified.

On-Call Support. Details of on-call support and points of contact should be identified.

Fault Reporting. A mechanism for reporting all OLM system faults should be established and managed by the OLM Programme Project Manager. An example fault reporting pro forma is at Annex C. In addition, faults on the OLM System should be made MDS reportable (if applicable for aircraft type).

OLM Management - Maintenance Documentation. Any supplementary maintenance register entries required for OLM activity, such as media removal /replace should be detailed (ideally this should be included in the Topic 2(R)1 Leaflet (Reference G).

TRIAL PROGRESS AND MONITORING

This section should contain the data analysis reporting that will be undertaken and outline scheduled reviews and OLM Management meetings involving unit OLM Project Officers.

AUTHORISATION SIGNATURE

OLM Programme Project Manager

Annexes:

A. Example OLM Programme - Aircraft Utilization.
B. Example OLM Weekly Media Dispatch Report.
C. Example Fault Reporting Procedure.

Enclosures:

1. OLM Build and Operational Brochure.
2. Operational Load Measurement (OLM) - 2(R)1 Leaflet
3. Maintenance Implications Topic 2(R)1 Leaflet

ANNEX A TO
OLM TD
DATED

OLM PROGRAMME - AIRCRAFT UTILIZATION

OLM PROGRAMME - INITIAL PROGRAMME XXX SORTIES TO BE RECORDED (Combat / Trainer Type Example SPCs)			
SPC	SORTIE DESCRIPTION	MIN SORTIES TO FLY IN EACH SPC	NOTES (e.g.) Role Fit Requirements etc
01	General Handling	X	
02	Instrument Flying	X	
03	Hi-Lo-Hi Level Navigation	X	
04	Formation Flying	X	
05	Ferry Flying & Banner Towing	X	
06	Navigation	X	
07	Air Combat	X	
08	Ground Attack Profiles	X	
09	Air Display	X	
10	Air Defence	X	
11	Air-to-Ground Attacks	X	
12	Air-to-Air Refuelling Training	X	

Total

ANNEX B TO
OLM TD
DATED

Facsimile/E-mail Transmission

UNCLASSIFIED MESSAGE

From:

Unit OLM Project Officer.......

To:

Designer OLM Analysis Team

Copy to:

OLM Programme Project Manager

OLM WEEKLY DATA DISPATCH REPORT

REPORT PERIOD ....

OLM MEDIA IDENT	F725 SHEET / FIELD	DATE FLOWN	SPC	NOTES *

* Notes are intended to cover unusual circumstances that may affect OLM data, such as failed starts, engine flame out etc.

DATE: .... NAME .... SIGNATURE: ....

ANNEX C TO
OLM TD
DATED

E-mail / Facsimile Transmission

UNCLASSIFIED MESSAGE

From:	To:
Unit OLM Project Officer	OLM Programme Project Manager

OLM SYSTEM FAULT REPORT

The attached copy of MOD Form 707B(ADP) SNOW No ....

detail a fault found on the OLM System and the rectification action taken.

The following further assistance is required*:

....
....
....
....
....
....

* Delete if no further assistance required.

PAGE 1 of ....

DATE: .... NAME .... SIGNATURE: ....

Appendix J: OLM Programme Directory

This Appendix contains a list of UK OLM programmes undertaken or in progress, divided into combat aircraft, large aircraft and trainer aircraft. Also an example directory entry has been completed for the recent Dominie TMk1 wing OLM programme and a blank template is provided for future OLM reporting (OLM Action 112).

Combat Aircraft

- Buccaneer
- Tornado (IDS and ADV)
- Jaguar (Fin, OLM1, OLM2, Landing Gear)
- Harrier II

Large Aircraft

- Victor
- Hercules (C130K) (‘Ground Trial, Full OLM)
- Nimrod Mk2
- VC10
- Tristar
- E3 Sentry
- Hercules (C130J)

Trainer Aircraft

- Jet Provost
- Hawk (OLM1 and OLM2)
- Tucano
- Viking
- Vigilant
- Dominie

OLM Directory Entry - Example

OLM DIRECTORY ENTRY – DOMINIE TMK 1 WING OLM PROGRAMME - SER NO: XXX

AIMS:
- To compare the fatigue stress spectra in the Dominie TMk1 lower wing during typical RAF usage with the civil aircraft (HS125) damage tolerant analysis assumed spectra.
- Substantiate wing monitoring FMF.

OLM SENSORS AND DATA SOURCES:
- 12 Strain gauge full bridges on wing lower surface at the centre spar intersection (6 port, 6 stbd) located adjacent to DT critical locations W04 (rib 3), W05 (rib 5) and W06 (rib 7).
- Normal accelerometer and inclinometer. Aircraft tappings for WOW and No2 Engine Generator (recording trigger). ARINC 429 data bus for ALT, CAS, OAT, TIME (bus)
- All channels sampled at 64 S/s. Anti aliasing filters set to 16 Hz.

OLM DATA ACQUISITION AND RECORDING SYSTEM:
- ACRA KAM500 Series 2 DAU with solid state memory card writing to 512Mb Compact Flash

OLM SYSTEM EMBODIMENT ROUTE / AIRCRAFT EMBODIED :
- 'DAOS' Mod produced (QinetiQ) and fit authorised under RAF STF procedure. Fitted to aircraft XS727 'D' during major maintenance (2004) by SERCO / QinetiQ.

CALIBRATION METHODS:
- Strain Gauges: Airborne calibration to defined PITS validated against 32 ground cases. Boundary element models used for stress transfer function from strain gauge bridge location to DT critical features. Anti-drift checks by repeats of airborne calibration and cross check against predicted strain values from flight parameters using ANN models.
- Parametric Data: Manufacturer's calibration with "tilt" test confirmation. Airborne cross checks.

ANALYSIS METHODS:
- Stress cycles input to reverse-engineered DT analysis using AFGROW also Stress-life calcs.
- Fatigue meter emulation (Nz data) and comparison with stress-life and crack growth damage undertaken.

TRIAL CONDUCT:
- Data capture 14 Jan 05 to 8 May 06. 319 (aim 300+) sorties captured (692 FH). 92% capture rate over period. 29 sorties lost due to A-to-D card failure (suspect transient ac surge voltage). 1 month to obtain and fit loan replacement card (no spares procured – accepted project risk).

DATA QUALITY:
- Data quality excellent. All captured strain data good. Occasional Nz anomalies.

RESULTS:
- Overall RAF usage similar to 'severe' DT spectrum.
- Low-level flying and training sorties more severe than DT spectrum but balanced by benign sorties.

MAIN REPORT REFERENCES:
- Reed S C, Dominie TMk1 Operational Loads Measurement Programme – Design Report, QinetiQ/FST /STT/CR044656, December 2004.
- Reed S C, Dominie TMk1 Operational Loads Measurement Programme – Final Report, QinetiQ/D&TS/ AIR/CR0606483, Issue 2, July 2006.

LESSONS:
- EMC shielding/protection tx/rx is required for whole system including power cables.
- Ground test mode and test equipment should be included in system design.
- Inclusion of time (e.g. UTC) highly recommended, rather than "bus running time".

ENTRY AUTHOR: Steve Reed, QinetiQ(Frn) **DATE**: 8 Feb 07

OLM Directory Entry - Template

OLM DIRECTORY ENTRY - SER NO: XXX	
AIMs: •	Aircraft Picture
OLM SENSORS AND DATA SOURCES: •	
OLM DATA ACQUISITION AND RECORDING SYSTEM: •	
OLM SYSTEM EMBODIMENT ROUTE / AIRCRAFT EMBODIED : •	
CALIBRATION METHODS: •	
ANALYSIS METHODS: •	
TRIAL CONDUCT: •	
DATA QUALITY: •	
RESULTS: •	
MAIN REPORT REFERENCES: •	
LESSONS: •	
ENTRY AUTHOR:	**DATE**: