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A UNIFIED APPROACH TO FATIGUE USAGE MONITORING OF FIGHTER AIRCRAFT BASED ON F/A-18 EXPERIENCE

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Abstract. In the current environment of decreasing budgets, the need for an accurate and reliable fatigue usage monitoring system is of ever increasing importance to ensure the safe and economical utilisation of aircraft which are expected to last longer than ever before. Strain based in-flight data recorders are perceived to provide an increase in accuracy over the traditional fatigue *g* meter, and have thus been implemented by many military fleet operators worldwide particularly for agile aircraft. Although this may be the case, these new generation recorders and the systems required for fatigue damage interpretation are complex, and many problems are associated with their use.

Military design requirements mandate the incorporation of fatigue monitoring data recorders, however the specifications allow much scope in the implementation of the system and interpretation of the data. Therefore, there exist numerous and varied philosophies for the usage monitoring of aircraft worldwide.

This paper proposes a unified approach for fatigue usage monitoring of modern fighter aircraft and is based on experience primarily with the F/A-18, and discusses the requirements for future fatigue monitoring systems based on strain and flight parameter measurements. Areas covered include the choice of gauge locations, need for flight parameters, data collection rates, calibration of damage models to durability tests, reliability of strain sensors, data integrity, and the in-flight calibration of strain sensors. The review also addresses the significance of each step in the fatigue damage calculation procedure.

Introduction

With the increasing complexity, structural optimisation, utilisation and cost of advanced performance military aircraft, coupled with ever decreasing budgets, the effectiveness and reliability of systems used to ensure the structural integrity or airworthiness of the weapon systems are more important than ever.

As has been the convention for some time, military aircraft will continue to be procured with incorporated in-service (or fatigue) usage monitoring systems. In fact this requirement is mandated by the appropriate design regulations (eg.):

Def Stan 00-970, "...each aeroplane should be fitted with a compact, robust and reliable recording instrument which monitors the usage of the major structural components. This may record an indirect parameter such as normal acceleration, or a direct parameter such as strain for each component to be monitored. Each parameter should be chosen so that the most damaging loading actions on the component can be determined"(1).

MIL-A-87221, "....An airborne data acquisition system is required that collects and stores flight data which can be used to determine maintenance and inspection intervals..... The data acquisition system shall be capable of recording operational usage data and shall be compatible with the airframe and all air vehicle systems when installed and used. The system shall interface with the air vehicle systems and record the required data within required accuracies"(2).

Both these typical requirements specify the need for a data recording system, albeit with differing emphasis, but they allow much scope for the implementation of the systems and interpretation of the data.

A limited review of open literature has found many examples(eg. 3,4,5,6) of the implementation of usage monitoring hardware, but there is an obvious lack of reporting on the details of the philosophy intended for selection of the hardware requirements and the utilisation of the collected data. It is therefore not surprising that numerous and varying philosophies are used by various operators to monitor accumulation of fatigue damage for individual aircraft types.

In light of the above contentions, this paper is intended to propose a unified philosophy and highlight problems to be overcome in achieving a reliable monitoring system for primary load carrying (safety of flight) members. The author has drawn from his experience, primarily with the Royal Australian Air Force's (RAAF)

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F/A-18 and F-111 operational monitoring systems, and elaborates on some preliminary thoughts on this subject[7].

In Service Monitoring Objectives

The minimum objectives of a service usage monitoring system are considered to be to:

1. enable the safe fatigue life or inspection intervals to be determined for individual aircraft by:
   a) accumulating fleet and Squadron usage statistics, in terms of mission type severity, Point In The Sky (PITS - velocity, normal acceleration and altitude) utilisation, stores utilisation and sensor status;
   b) tracking individual aircraft damage accumulation against design loads, or more importantly against fatigue substantiation tests;
2. accumulate operational statistics to assist in the design or acquisition of new assets, or defining variation to operational roles to decrease fatigue damage;
3. determine when maintenance action is required for individual aircraft;
4. account for increases in operational weight during the life of the airframe; and
5. provide feedback to the operators on a timely basis.

It is also possible to reproduce in-flight loading from usage monitoring systems for the conduct of fatigue tests, as has been done for F/A-18[8].

The role of a fatigue monitoring system should be to minimise the impact of usage variations on the operational readiness of the fleet, flight safety and through life cycle costs. Its implementation should ensure a system which enables the estimation of fatigue accumulation on a scientifically robust basis so as to be as *accurate as possible*.

The methodology should be applicable to a sample of fleet aircraft ("operational loads monitoring") or to each aircraft in the fleet, dependant upon fleet size and operator requirements.

Fatigue Usage Monitoring Tools

Current fatigue usage monitoring techniques are summarised in Table 1, along with their perceived advantages and disadvantages.

Flight hour and flight cycle counting are inappropriate for monitoring advanced agile military aircraft due to the variations in missions performed and configurations between aircraft.

Table 1: Monitoring Techniques

Advantages	Disadvantages
1. Flight Hours	
• No equipment needed • Cheap	• Assumes each aircraft flies identical spectrum • Manual time recording
2. Landing/Flight Counts	
• Simple/Cheap	• As above • Only applicable to landing and pressurised structure
3. Counting Accelerometers (Nz Based)	
• Simple/Cheap • Robust	• Only components affected by Nz can be monitored • Nz normally recorded at a nominal CG location • Asymmetrical loads not considered • Fixed Nz "trigger" levels • Time history lost • Weight and PITS must be assumed (conservative) • Transfer function between Nz and stress at critical location required • Manual extraction of data
4. Range Pair Counters (Strain based)	
• Relatively cheap • Directly monitors principal component • Some data processing conducted on-board	• Time history lost • PITS must be assumed • Difficult to validate data • Reliability of sensors • Sensor calibration difficult
5. Multi-Channel Recorders (Parametric Systems)	
• Can monitor flight parameters as well as strain (very accurate) • Time history retained • Can be used for other investigations (incidents, over-stressing)	• Expensive and normally production fitted • Software and processing intensive • Sensors require calibration • Reliability of sensors • Data validation needed
6. Optical Fibre Strain Monitoring[5]	
• Insensitive to electro- magnetic interference • Replaces strain gauges - improved reliability • High strain resolution	• Developmental

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Strain based in-flight data recorders are perceived to provide an increase in accuracy over the conventional fatigue Nz or *g* (normal acceleration) meter, and have thus been implemented worldwide by many military fleet operators, for high performance aircraft.

This increased accuracy is principally achieved because judicious placement of the strain gauges can automatically account for both aircraft weight and stores effects, and the variation of principal loads, such as Wing Root Bending Moment (WRBM), at various PITS constituting the flight envelope. For example, a comparison of (WRBM) strain and Nz fatigue damage, using the same damage model, was conducted for a fleet of F/A-18 aircraft[9]. The transfer function relating Nz to the critical location was chosen to represent average PITS. This investigation revealed that the damage calculated from Nz data was conservative, in general by a factor of approximately two. Although this does not imply which data set produces the most accurate estimate of fatigue damage, it does indicate the level of difference achieved in analysing the two data sets.

Further, for agile aircraft with significant fuselage lift contributions, the maximum WRBM may not correspond to the maximum Nz[9]. It was shown for the F/A-18 that the two maxima can lag one other by as much as 2 seconds. Systems in modern military high performance aircraft that rely solely on Nz would experience a similar discrepancy. Counting accelerometer data is normally augmented by pilot sheets containing mission and stores data which are assumed to apply for an entire flight. Although this represents an increase in accuracy, considerable processing is required to arrive at a damage estimate.

Strain range pair data counters have the advantage of a limited capability of on-board data processing, thus lessening the amount of data storage and processing required once the data is extracted from the aircraft. These systems were introduced in times when data storage limitations and data processing time were significant considerations. However, modern computers have alleviated these considerations to a large extent. Further, difficulties with validating data in a tabular range pair format, with the absence of associated flight parameters[10], and determining strain gauge calibration factors[11] (described later) are considered to outweigh the potential advantages of range pair counters. Therefore these are not considered further in this paper.

As optical fibre strain monitoring is currently only developmental, its use is not considered in this paper.

For the above reasons strain peak and valley based systems are addressed in this paper. However it will be shown that parametric based techniques have a significant role to play in a strain based system and these can also provide an alternative monitoring capability. The resulting systems required for accurate fatigue damage interpretation are complex. Many problems can arise with their use, and some of these are addressed in this paper. The first issue to consider is that of gauge placement.

Loads or "Hot Spot" Via Strain Monitoring.

Before deciding on the locations of strain gauges, the philosophy to be used to meaningfully relate the strain recordings to fatigue accumulation must be established. The choice of gauge locations are determined from the following considerations:

Loads Monitoring. Judicious placement of the strain gauges can account for aircraft weight and stores effects, and the variation of principal loads, such as WRBM, at various PITS constituting the flight envelope. Thus the location of the strain gauge must be such that its response is predominantly influenced by the principal loading inducing the fatigue damage at the critical locations considered. An example of such a philosophy is the F/A-18 [7, 9, 12].

To achieve this benefit the location of the gauges must be carefully chosen. In particular, care must be taken to ensure that the location of the sensor:

- can be calibrated to the damage inducing load;
- is dominated by the principal load (e.g. WRBM) and insensitive to other loading actions;
- is in an area of low stress gradient;
- can be directly related† to the stress at critical structural locations;
- is not prone to gauge "drift" (varying response to a nominal load over time‡, discussed later);
- is accessible for ready sensors replacement;
- is positioned as close as practicable to a backup sensor in the advent that the primary sensors fails;
- is replicated on the fatigue test article so that direct comparisons can be made[1]; and
- is protected from the environment and service wear.

Hot Spot Monitoring. The alternative philosophy is intended to place strain gauges such that they directly monitor the strain at the critical location. An example of such a philosophy is the RAAF's F-111[13,14].

Several problems can arise from this philosophy, namely:

- the sensor may not be dominated by the principal damage inducing load. A particular problem here is

† Preferably by a linear relationship for both positive and negative loads.

‡ F/A-18 WR lugs are an example of this.

that it may be difficult to calibrate the sensor response;

- the hot spot may have a high stress gradient. Due to the fixed active length of a strain gauge and positioning errors, there is no guarantee that the maximum strain is actually monitored;
- if a new hot spot arises, and the gauge does not respond predominantly to the load affecting this new location, then there will be no data available for assessment. Even if the option of placing an additional gauge exists, the problem of "filling-in" for past damage still exists; and
- the hot spot may not be readily accessible and thus the sensors are not readily replaceable.

For these reasons direct hot spot monitoring will not be further pursued in this paper.

Parameter Based Monitoring.

An alternative philosophy to the strain gauge methods is the use of flight parameters to estimate the dominant load affecting each critical component, and the subsequent use of transfer functions to relate this to stresses at critical locations. This approach has similar advantages to the strain monitoring philosophy, and further:

- as there are no strain gauges, the logistical burden of replacing unserviceable gauges is not a issue. The RAAF have experienced significant numbers of gauge changes on their F/A-18 fleet(15). The time lag between when a sensor becomes unserviceable and when remedial action is taken, contributes to reductions in the over-all data recovery rates;
- there is no requirement to calibrate sensors or loads on the fleet aircraft, as the calculated load is normally derived from a calibrated flight test aircraft which demonstrates the "baseline" response for fleet analysis.

However, comprehensive flights trials are required to obtain sufficient loads data to cover all aircraft operations PITS if the aircraft is monitored solely on parameters.

Analyses conducted using multiple parametric equations(16) and Velocity-normal acceleration (G)-Height (VGH) techniques(9) produced conservative results within 5% and 1% for these respectively when compared to the results based on (WRBM induced) strain for one particular usage spectrum.

This suggests that reasonable accuracy can be achieved using parameters only. However, the major advantage of a strain based system over parameter based systems is that the strain can be related directly to strain measurements on the fatigue test article against which the fleet monitoring is being calibrated. The unified approach proposed in this paper uses the strain based approach as the major fatigue tracking system complimented by parametric flight data measurements to aid in data verification. The following sections provide details of an optimised strain based system and indicates areas where parametric data are used.

Components of a Strain Based Fatigue Tracking System

Once the type of in-flight recorder§, the position of strain gauges, and the flight parameters to be recorded have been determined and installed for a given aircraft type, there is still much processing to be conducted before the in-flight data can be used to assess the fatigue usage of an aircraft. After data retrieval a fatigue tracking system requires the following capabilities:

1. Pre-Processing of Collected Data:

Generally, a code is required to format aircraft unique data so that it can be processed. It should provide the capability to identify the aircraft (tail number) and active sensors, missing sensor initialisation and determine data hours (generally from landing and take off codes). It should also provide an option to deal with data recorded out of order.

2. Data Checking Module, which should provide, as a minimum, the following functions:

   - Extract strain, flight parameter and Nz data;
   - Validate data and replace bad data by using flight parameters relationships;
   - Compensate for missing data;
   - Perform sensor calibration;
   - Determine inoperative sensors (by comparing recorded against parametric based strain) and create a sensor log;
   - Calculate CG and weight of aircraft accounting for stores configuration and fuel usage;
   - Normalise weight (to test article basic configuration);
   - Initialise other flight parameter variables (e.g. angle of attack - α);
   - Tabulate VGH exceedance data; and
   - Identify mission types.

3. Sequence Counting Module:

The module may be required to build a Rain Flow Counted** (RFC) strain spectrum. Depending on

§ With the capability to record the recommended flight parameters and strains at the required rates.
** Otherwise known as range-pair or hysteresis loop counting.

computing capability it may also discretise and block the sequence to optimise processing time.

4. Fatigue Damage Module, which;

   Calculates damage and fatigue indices for each critical location, based on crack initiation or growth algorithms calibrated against the appropriate durability test. It should also update the cumulative "all time" damage database for each aircraft, and check if the accumulated damage equals target values, and warn if the damage rate exceeds a predefined design rate.

5. Post-Processor Module, which;

Updates the database file for each aircraft processed, and the documentation file of the current software run. Produces a summary report, which includes all detected data anomalies and usage statistics.

6. Reporting to Fleet

The results must be interpreted and provided to the operator in a timely fashion. This is essential for pro-active fleet fatigue management.

Each of these nominated steps are critical to the fatigue monitoring of the fleet. It should be stressed that the through life cost of maintaining the above ground based system far exceeds the cost of the on-board data recorder(17), and thus should be given appropriate consideration before the particular hardware and integrated processing system is chosen.

Some of the more important issues identified above are discussed in detail in the following sections.

<u>Interpreting and Processing Measured Strain</u>

The following is a proposed procedure for utilising recorded strain to monitor a critical location, based on developments to the F/A-18 monitoring philosophy(9), using WRBM induced strain as an example. Here a gauge has been placed close to the Wing Root (WR) structure and has been demonstrated to respond predominantly to WRBM.

- The aircraft's on board Data Recording System (DRS) should record WR strain when a peak or valley of WR strain is identified by the DRS. This is done to minimise data storage, yet assures that maximum/minimum WR loads are retained. Recording at a peak or valley is referred to as "triggering" and when a sensor is "triggered", the DRS should records its strain, plus all other sensor strains and the required flight parameters (time synchronised).
- Strain and flight parameter data on the DRS should be down loaded periodically from the aircraft, and appended with data from the pilot data sheets. The DRS should record mission time (or "weight off wheels" (WOW) time), however when reporting to the fleet, pilot flight time is more appropriate. It is normal for WOW time to differ from pilot flight time(9), as pilots will account for some pre- and post-flight time.
- The strain data from each strain sensor should be initialised at the beginning of each flight by first removing any strain offset, so that each sensor ostensibly reads zero when wing flight loads are zero. This process should take into account possible different configurations of wing stores (weights) at take off.
- Because the response sensitivity of strain sensors varies between aircraft (discussed later), the strain data should then be calibrated so that the same wing load reference condition on each aircraft produces the same strain sensor value. This calibration can be performed using parametric data from the DRS. This takes account of varying sensor sensitivities and any drift in gauge response which may have occurred with time.
- The strain data should be checked by comparing the measured strains with strain predicted from other sources, such as parametric equations relating strain to Nz and other flight parameters. Flight parameters should also be checked against reasonable aircraft performance limitations. Any data deemed to exceed set error limits, or any missing data, are replaced using data "fill-in" techniques.
- The strain data are then normalised with respect to the relevant fatigue test measurements by dividing (or normalising) by the reference strain value which is obtained from applying the reference WRBM loading condition to the appropriate fatigue test structure being used as the data reference. This effectively converts recorded strain into a non-dimensional WRBM sequence.
- The resulting normalised non-dimensional sequence is then sorted into a sequential peak valley form, before it is RFC (to form cycles of maximum peaks and valleys for fatigue analysis), and possibly discretised into pre-defined levels and stored for further processing. The latter may be done in order to reduce the processing time, however inaccuracies may be introduced due to the use of limited fixed range levels.
- The normalised cycle-counted data are then multiplied by a reference stress related to the reference load which converts the data into stresses at the critical location at which fatigue damage is to be calculated. This reference stress value has been chosen using the fatigue life/crack growth prediction routine, such that at the chosen reference stress level,

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