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An overview of the improvements made to the F/A-18F and EA-18G fatigue tracking system: Individual Aircraft Tracking with a Safe Life philosophy

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Abstract

The Boeing Company uses proprietary engineering software and strain-life data to predict the fatigue life expended for each tracking location on the F/A-18 Hornet. This software undergoes a continual improvement cycle each year with oversight from the US Navy. The improvements made over the past decade to the tracking system of the F/A-18 Hornet, Super Hornet and Growler have been wide ranging. DSTG's expertise in fatigue tracking and long-lasting relationship with the US Navy, has provided recommendations which have contributed to significant improvements to this tracking software functionality and with how it processes data to assess data quality. These improvements made to data quality and fatigue assessments will be explored and provide a case study for improving other aircraft tracking systems.

Keywords: Structural Health Monitoring, F/A-18, Individual Aircraft tracking, Fatigue Monitoring, Fatigue Testing.

Introduction

DSTG and the RAAF have been part of the development and validation of the F/A-18 fatigue tracking system since the early 1990's, when supporting the F/A-18 A/B “Classic” Hornet. Today this involvement continues with supporting the improvement and maturation of the fatigue tracking system and data analysis, but now with a focus on the F/A-18F Super Hornet and the EA-18G Growler.

At its core, the F/A-18 tracking system calculates the fatigue damage accrued for each aircraft flight with reference to that accrued during the certification fatigue test, used to assess the airframe's durability. The tracking system utilises in-flight recorded strain gauge and parametric data to calculate fatigue damage. The strain data is obtained from a small number of strain sensors, which have the same location and orientation on each Super Hornet and Growler, as well as the certification full scale fatigue test (FSFT) article. This allows direct load-to-load comparison to be made between the aircraft and the FSFT utilising the recorded strain data.

Strain gauges for combat aircraft tracking

Strain gauge-based tracking systems are commonly used on United States Navy (USN) aircraft, but parametric-based systems are more prevalent in other aircraft fleets. Strain based systems offer some advantages, especially when it comes to monitoring manoeuvre heavy spectra experienced by agile military aircraft, as detailed in Reference [1] and summarised in Table 1.

Table 1: Summary of key benefits and disadvantages of strain and parametric-based fatigue tracking systems identified in Reference [1] .

Strain Gauge	**Parametric Systems**
Benefits: • Direct load measurement at location of interest • Responsive to abrupt manoeuvres, gust and buffet loads • Gauge replicated on fatigue test article so direct comparison can be made	Benefits: • Time history retained • Allows automation of health checks • Reduced data health checks
Disadvantages: • Placement important to ensure sensor response records principal loading • Gauge installation and maintenance can be difficult • Gauges require calibration (either physical or parametric) • Increased data processing to ensure gauge health	Disadvantages: • Indirect load measurement – reliance on complex load transfer functions • Limited by set of recorded parameters • Large loads development program required • Software and post-processing intensive • Data validation needed • Sensitive to changes in Configuration, Role and Environment

The benefits of strain gauges are that they provide direct load measurement at the location of interest, and are responsive to abrupt manoeuvres, gusts and buffet loads. Furthermore, when gauges are replicated on the fatigue test article, direct fatigue accrual comparison can be made between an aircraft and the certification test. However, they are sensitive to placement and require maintenance, regular calibration and increased data processing to ensure the fidelity of the data recorded. In contrast, parametric systems require the time history data to be retained, and allow for automated health checks. However, they rely on complex load transfer functions, are limited by the set of parameters recorded, necessitate a large loads development program and are sensitive to changes in aircraft configuration, role and environment.

Tracking Method

Structural Appraisal of Fatigue Effects (SAFE) is the Boeing-supplied software used to calculate the Fatigue Life Expended (FLE) of each individual F/A-18 aircraft. This software undergoes continual development to improve functionality and data management under the guidance of the USN. The fatigue damage accrual estimation algorithm used in SAFE is based on a strain-life fatigue methodology and the software includes some internal checks for detecting faulty strain sensors and corrupted data.

The F/A-18 is designed under a Safe Life philosophy, using a severe fatigue test spectrum and a test factor of 2 as the basis of its fatigue life substantiation. The tracking system primarily compares an individual aircraft’s usage to these fatigue tests, deriving a FLE for each flight. The FLE is calculated at several locations that align with major load paths on the wings, empennage and fuselage, to assess an airframe’s fatigue damage accrual versus that accrued during the FSFT. The FLE is calculated as a percentage of the equivalent damage on the FSFT;

therefore, when it has reached a value of 1.0 the airframe has reached its life limit. The FLE value also tracks life-limited structural items, which may have their own FLE limit as outlined in the Service Life Bulletin.

Figure 1 illustrates the F/A-18F Safe Life philosophy. A severe design spectrum is applied to a fatigue test article for 2 design lifetimes [2], resulting in a demonstrated fatigue life[1]. Utilising the applied test spectrum, a Stress-Life curve is produced, which is used to determine the pegging stress (also known as the reference stress) for the life that corresponds to the demonstrated test failure or end of the fatigue test. The corresponding fatigue life (FLE) can then be calculated for each aircraft flight, utilising the tracking gauge strain spectrum, reference stress and a safety factor (typically equal to 2.0).

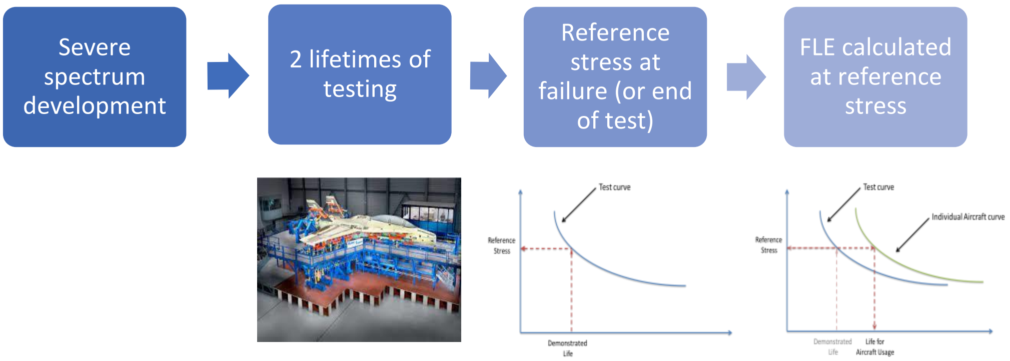

Figure 1: Graphical representation of how the calculated damage in SAFE is referenced back to the full scale fatigue test

Requirements for Tracking

Section 3 and Chapter 12 of the Defence Aviation Safety Design Requirements Manual [3] discuss Individual Aircraft Tracking Systems and state "*the specified System will produce reliable, repeatable and suitably-conservative outputs so that Airworthiness Limits are not exceeded in-service.*" Based on RAAF and DSTG experience with the Classic Hornet, the following is a list of key components to ensure the tracking system outputs are reliable, repeatable and suitably conservative.

1. Damage algorithm produces reliable, repeatable and conservative results.
2. Have effective data capture rates and extensive data quality checks.
3. Have suitable fidelity to the recorded data, in terms of data sampling as well as the recording rates on the aircraft based memory system.
4. Suitable calibration of instrumentation used to record the data.
5. Suitably conservative fill-in for identified corrupt and missing data.

The points listed above will be discussed with reference to the Super Hornet and Growler tracking system in the following paragraphs.

Damage algorithm

If the damage algorithm does not produce reliable, repeatable and conservative results, then the fatigue tracking system is not suitable for use. Validation and verification of the damage algorithm are usually performed by assessing the rate of damage accrual predicted for a representative fleet aircraft against the actual damage accrual demonstrated for the aircraft's spectrum loads via coupon testing. The damage algorithm for the Super Hornet is consistent with that utilised for the Classic Hornet, providing familiarity for the RAAF in its use and functionality.

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[1] If the end of test has been reached without failure the demonstrated life is the test duration.

To assess the validity of the fatigue damage model for the Super Hornet, DSTG performed coupon testing for RAAF fleet spectra and the certification test spectrum. The relative severity between a RAAF fleet spectrum and the certification test spectrum predicted via the damage algorithm was then assessed versus the relative severity implied by the coupon test results. The accuracy of the fatigue damage algorithm predictions varies, depending on the difference in severity between the test and the aircraft spectrum. The greater the variation in severity between these spectra, the lower the overall accuracy obtained. However, the relative severity between test spectrum and aircraft (i.e. more severe or less severe) remained acceptable. SAFEv300 incorporates an additional safety factor of 2.0 into the damage calculation; therefore, for the purposes of RAAF IAT and fleet tracking, the fatigue damage model was deemed acceptable.

Data Capture

Data capture rates are operator specific and can be easily influenced by maintenance culture. For example, downloading and analysing data after every flight reduces the risk of data being overwritten on the on-board memory storage and allows for earlier identification of corrupt hardware. Improving data capture rates can be actively supported via an engaged maintenance culture. High data capture rates have been consistently maintained for the RAAF Hornet, with a goal of capturing at least 90% of flight data. This is assisted by regular processing and interrogation of data every two weeks, which enables early identification of missing flights, strain sensor issues, and missing or corrupt parametric data. Addressing these issues promptly can prevent the accumulation of large amounts of unusable data, thereby improving the overall quality and reliability of the data.

In the early days of RAAF Classic Hornet operation, data from multiple flights was recorded on magnetic tapes on aircraft and required manual transfer by maintainers. This contributed to lower rates of data capture and necessitated the use of a robust fill-in algorithm based on mission profiles to replace missing data. However, the Super Hornet and Growler use solid state data devices which are downloaded after every flight, resulting in excellent data capture rates and less reliance on damage fill-in.

Fidelity

Improving data accuracy has been the main focus of DSTG improvements to SAFE, especially in terms of the reliability of strain sensor data. These improvements have focused on strain sensor calibration, sensor initialisation accuracy and strain data quality checks. This was built upon the RAAF Classic Hornet experience where significant effort was required to account for strain gauge drift.

Improving the accuracy of the recorded strain data has enhanced the reliability and confidence in the resulting fatigue damage predictions. Small variations in the measured strain response can have a significant impact on the calculated fatigue damage. For example, a systemic a 10% error in strain due to poor calibration could result in up to a 50% variation in the calculated fatigue damage.

Calibration

F/A-18 strain gauges primarily respond to bending moment at locations such as the wing root and fuselage. However, various factors can cause the strain gauge readings on an aircraft to differ from those obtained at the same location on a fatigue test article for the same load case. Therefore, all fleet aircraft strain gauges require some degree of calibration to ensure their responses mirror those of the certification test. Moreover, strain gauge response can vary significantly over time. For example, “gauge drift” was a persistent issue at the wing root location on the Classic Hornet, resulting in large non-linear shifts in gauge response. To combat these effects and ensure fleet recorded strains are comparable to those recorded on the fatigue test that underpins the durability of the airframe, strain gauges must be continually calibrated.

Most strain gauges on the Super Hornet and Growler are now calibrated to regression equations obtained from flight test-based strain data for particular points in the sky. However, this has been a gradual process of refining the associated regression equations to account for changes in store configurations and data processing of the original fatigue test data. These improvements are the result of significant development work performed by Boeing and the USN.

The US Navy considered the option of ground-based physical calibration of aircraft strain gauges. However, this approach was ultimately rejected due to several factors. Firstly, the cost per calibration is relatively high compared to in-flight calibration. Additionally, ground-based calibration can only be performed at infrequent intervals and this may not be regular enough to compensate for issues like gauge drift. Finally, the maintenance burden associated with the removal of control surfaces required for ground calibration was considered onerous, especially for aircraft that are frequently operated from aircraft carriers.

The certification fatigue test strain gauges were initialized at an $N_z = 0$ point in the sky, so that a strain of 0 is recorded under 0 bending moment. However, Super Hornet and Growler strain gauges are initialized at the start of each flight, which does not correspond to an Nz = 0 point in the sky due to the aircraft's mass affecting the gauge response. As a result, the fleet aircraft gauge response under 0 bending moment is not equal to 0, leading to an offset between the fatigue test and fleet aircraft strain gauge responses, as illustrated in Figure 2. To address this issue, SAFE has been enhanced to include a correction that removes the effect of inertia, while accounting for the aircraft's current configuration. This correction eliminates the offset between the fatigue test and fleet aircraft strain gauge responses.

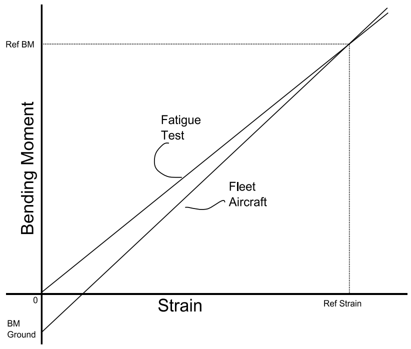

Figure 2: A fleet aircraft's strain gauge response has a offset (and slope if pegged to the same reference strain) at 0 bending moment compared to the fatigue test. An initialisation correction can be applied to correct the offset (and slope).

Data Fill-in

Data recording systems can be affected by external factors that may cause data loss or recording of spurious data. To account for this, gap-fill is employed to estimate the fatigue accrual for flights where data is identified to be lost or unreliable. If the data is determined to be corrupt or missing, actual damage cannot be calculated for that flight.

In cases where there are gaps in the data, gap-fill fatigue damage values for the tracking location are calculated using the fatigue accrual rate of valid data. To ensure safety, a conservative approach is taken and tracking location rate data around the 2nd standard deviation is used, along with the duration of the corrupt flight. The corresponding damage value calculated for substitution or gap-fill is then added to the good fleet data to obtain the gap-filled FLE for each aircraft.

Other Improvements

Implementing robust data quality control measures is essential for improving the reliability and accuracy of any fatigue damage calculation performed within a tracking system. SAFEv300 includes its own data quality checks for recorded data, but is able to still process valid flight data even if a strain sensor is identified as having corrupt data. The OEM continues to update the data screening criteria within SAFE, as operators increase their understanding of flight recorded data.

Strain gauge drift remains an important factor to monitor, but the extent of this issue has decreased compared to the RAAF Classic Hornet. The Classic Hornet experienced significant drift over time, which needed to be modelled and corrected for using polynomial equations. With the reduced gauge drift experienced by the Super Hornet and Growler, there has been more time to focus on improving in-flight strain response calibration routines. Additionally, higher data fidelity has been achieved for recorded strain sensor and parametric data compared to that of the Classic Hornet. Ongoing upgrades to aircraft software and data recording capacities have also enabled higher data recording rates, contributing to more accurate and reliable fatigue damage calculations.

Accurate aircraft weight data is essential for calibrating strain gauges in SAFE. Over the lifespan of an aircraft, factors such as painting, modifications, and equipment changes can lead to significant changes in the basic weight of the aircraft. To ensure accurate records, DSTG requested that the historical record of aircraft weights be stored and used, allowing for the tracking of significant changes to RAAF aircraft. In addition to the basic aircraft weight, stores carriage is also crucial in determining the weight of the aircraft and calibrating aircraft. A significant amount of effort has been dedicated to interpreting stores records and determining correct stores carriage and weights, ensuring that the calibration of strain gauges is as accurate as possible.

Conclusion

The SAFE tracking software and associated tools are being continuously updated and improved, with a focus on enhancing data quality and ensuring gauge serviceability. Collaborative efforts with Boeing, the USN, and the RAAF are ongoing to integrate SAFE-specific tracking improvements into the Super Hornet and Growler fatigue management system, ensuring the Hornet IAT system accurately assesses how the fleet is accumulating fatigue damage and that aircraft are not operated outside or beyond their certified limits.

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