Advances in Airframe Load Monitoring Methodology for Individual Aircraft Tracking

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Abstract

The paper describes an Airframe Load Monitoring (ALM) methodology proposed by Australia's Defence Science and Technology (DST) Group for tracking aircraft manoeuvre and buffet loads using airframe strain sensors. The methodology is based on a direct monitoring and multi-variable analysis of high-frequency sensor data for predicting the buffet-induced dynamic loads and a multiple linear regression analysis of selected aircraft flight parameters and sensor data for predicting the airframe manoeuvre load components. The ALM methodology aims to provide a robust and verified Individual Aircraft Tracking (IAT) solution for a range of military aircraft and could support 'on condition' maintenance by accurately predicting loads for any flight condition and any changes in fleet usage patterns, thus improving fatigue tracking of the airframe. The ALM methodology offers considerable advantages over legacy approaches and has a potential to account for aircraft-to-aircraft variability and aircraft configuration changes by directly monitoring the airframe's response to in-flight loading.

Keywords: buffet, airframe loads, fatigue and usage monitoring, strain sensors.

Introduction

In an environment of budget constraints and shrinking resources, development and maintenance of an accurate and reliable fatigue and usage monitoring system is of increasing importance to ensure the safe and efficient operation of aircraft and maximising their economic life. Any such system must facilitate the estimation of fatigue accrual against the certified (substantiated by test and or demonstrated analytically) airframe fatigue life to support airworthiness requirements, the scheduling of requisite maintenance actions and management of individual aircraft usage to meet the overall fleet capability throughout the life of the aircraft.

One of the most critical elements of a fatigue accrual evaluation process is the estimation of airframe service loads as they influence the degradation of the airframe life. Significantly improved tracking of an airframe's response to external loading can be achieved using strain-based in-flight data recorders which provide a substantial increase in accuracy over conventional systems which are often based on a fatigue g meter. Strain-based aircraft monitoring systems have been implemented by many military fleet operators worldwide but such systems are typically only capable of tracking airframe quasi-steady (manoeuvre) loading due to the limited capability ('low' sampling rates and insufficient data storage capacity) of their in-flight data recorders. This is a critical limitation as the ability to monitor airframe dynamic loading is of particular importance to modern agile military aircraft as a significant part of their airframe is affected by unsteady (buffet) loading.

Aircraft buffet can be described as an airframe's structural dynamic response to aerodynamic excitation caused by various flow disturbances, such as transonic shock/boundary layer interaction, flow separation or the breakdown of vortices shed from the upstream surfaces. Besides the shock and vortex-induced buffet loads, some additional sources of airframe unsteady loading can be caused by transient effects due to abrupt and/or naturally unstable manoeuvres, weapon release and or transonic transitions. Aircraft buffet is recognised by aircraft manufacturers as a critical design criterion as it significantly impacts airframe fatigue life and can define the static strength requirements of some structure. History has shown that many fighter aircraft capable of high angle of attack (AOA) manoeuvring have experienced some airframe buffet issues. In fact, this problem is inherent in any aircraft design that relies on the generation of additional vortex lift for high AOA capabilities. However, airframe buffet is of particular concern for twin-tail fighter aircraft like the F/A-18 or F-22 where the empennage surfaces are placed in the direct path of the highly turbulent vortical flow generated at the upstream separation locations.

Fatigue Monitoring Systems as used by RAAF

The majority of current DST Group in-service experience with combat aircraft usage and fatigue monitoring systems applies to the F/A-18A/B aircraft. The F/A-18A/B comes equipped with an on-board Maintenance Signal and Data Recording System (MSDRS) which, among other things, is used to record aircraft configuration information and data to support maintenance and lifing of the airframe, various aircraft components, systems and engines. Aircraft flight path data are also recorded through the measurement of various flight parameters, thus allowing flight path reconstruction and improved usage and lifing analyses. Some of the fundamental processes employed are discussed in more detail in [1].

In addition to the flight parameters which are invaluable for IAT purposes, the MSDRS also records strain data for key strain gauges located at the wing fold, wing root, the vertical tail-fuselage attachments, the horizontal stabilator spindles and a forward fuselage location. These strains are recorded based on assigned dead-band and rise fall criteria to limit the recording to fatigue critical turning point strains to minimise storage space requirements. Flight parameters are also recorded at these times as well as at defined sample rates. Such an approach was necessary given the low sample rates and storage limitations involved; meaning ‘high’ frequency buffet loading could not be adequately captured or recorded, with the system instead aimed at characterising aircraft manoeuvre loading cycles. While limited with some respects, the F/A-18A/B tracking system provides a significant amount of data for tracking aircraft usage and fatigue life evaluation. A number of algorithms and processes were developed and used to analyse the data provided for each F/A-18A/B aircraft and utilise it for aircraft fatigue tracking and lifing. The mentioned flight path data has also been used to assess various operational scenarios to assist in lifing weapon systems [2].

It should also be noted that based on experience and insights into possible limitations of the MSDRS, an indigenous system known as the Airframe Fatigue Data Analysis System (AFDAS), was installed and trialled on the RAAF F/A-18A/B aircraft. While it had some advantages associated with higher sample rates useful in measuring empennage buffet and the ability to record more strain gauges, the system was ultimately abandoned due to data storage limitations which impeded its usefulness [2]. Therefore, fatigue tracking of the F/A-18A/B structure affected by buffet remains based on a set of flight state parameters and corresponding algorithms to provide an estimate of the buffet load magnitude and cycles rather than measuring the airframe loads directly. However, aircraft buffet loads are inherently difficult to predict and successfully account for in fatigue estimation processes due to the random and transient nature of buffet loading [3]. It is equally difficult to accurately predict and validate unsteady loads caused by abrupt or naturally unstable manoeuvres, store release, transonic transitions or loads due to thermo-mechanical effects. It should be noted that, based on DST Group experience, verification of the parameter-based approach to buffet tracking has been difficult to achieve previously on current and legacy fleets. Thus, it is common practice to apply uncertainty factors on the structural health monitoring systems where their respective accuracies cannot be substantiated, but this leads to a substantial amount of conservatism in the fleet life management [4]. Any such conservatism could lead to unnecessary inspections and maintenance actions and thus, considerably decrease fleet readiness and increase through-life structural support costs.

Advanced Airframe Load Monitoring Methodology

To overcome perceived limitations of the parameter-based approaches, an advanced method of airframe loads prediction has been proposed by DST Group. The method is based on the direct monitoring and 'off-board' processing of airframe strain sensors' output to facilitate an accurate prediction of both the manoeuvre and buffet components of airframe loads. It is assumed that the aircraft is fitted with a number of strain sensors strategically placed at selected airframe locations that are expected to provide adequate response to fatigue critical manoeuvre and buffet loading. The strain sensors should thus be able to capture effects of various modes of vibration which are predicted to be of fatigue significance to the critical structural components. It is also assumed that the sensor outputs are continuously monitored and recorded at a sampling rate that is sufficiently high to capture airframe response to a sudden fluctuation in a manoeuvre load (due to gust, landing and other events) as well as to unsteady buffet loading. If the sensor data contain sufficient information about the airframe structural dynamic response, this information can be extracted with appropriate digital signal processing techniques and used to estimate airframe loading based on the measured airframe response. Therefore, the proposed ALM approach relies on analysis of high-frequency strain sensor measurements to predict airframe total (manoeuvre and buffet) loads.

Following the proposed approach, a Dynamic Load Prediction Module (DLPM) of the ALM system is used for predicting an unsteady (buffet) component of the airframe loads, while multiple linear regression analysis of the sensor outputs complemented by associated aircraft flight parameters is used for predicting their quasi-steady (manoeuvre) components. The DLPM utilises DST Group's in-house developed algorithms [5] for Multi-Variable Frequency Response Analysis (MVFRA) of high-frequency sensor outputs. The DLPM also includes several algorithms for pre-processing sensor time history measurements. These include data integrity checks and the re-sampling of strain sensor data at a rate sufficient to recover the 'true' unsteady load magnitudes and thus, further improve fatigue life estimation.

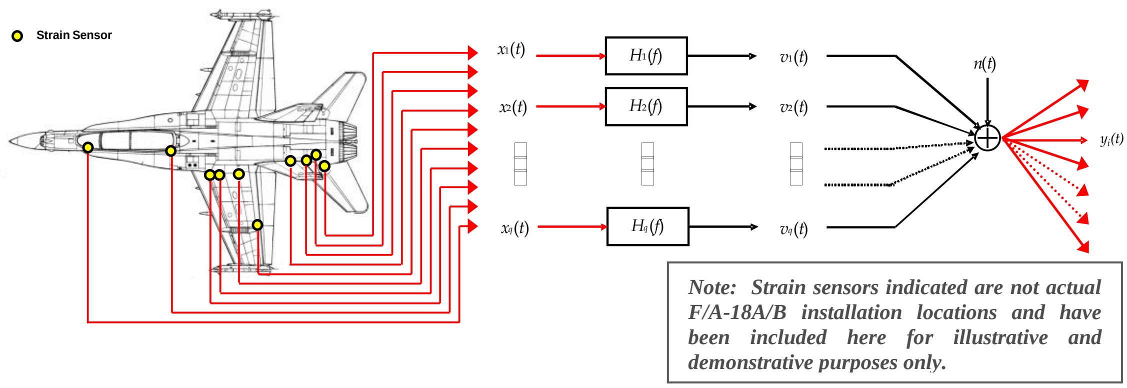
A Manoeuvre Load Prediction Module (MLPM) is used to perform some basic data integrity checks of the sensor outputs and flight parameters, followed by a multiple regression analysis for predicting the manoeuvre components of the airframe loads. The resulting manoeuvre and dynamic load sequences are then combined to produce time-aligned total (manoeuvre and buffet) load time histories which can be further processed and reduced to peak/valley sequences suitable for subsequent fatigue life analyses.

Dynamic Load Prediction

The MVFRA algorithms are utilised for characterisation of the airframe's dynamic response using the time-aligned histories of sensor outputs and airframe loads obtained during flight testing of a calibrated loads aircraft. The Frequency Response Functions (FRFs) derived during this dynamic characterisation can then be used to process sensor outputs from any fleet aircraft to predict buffet loads. One of the major advantages of the proposed approach is that the MVFRA algorithm utilises inputs from the multiple strain sensors placed at various airframe locations to improve the buffet load prediction accuracy.

Dynamic System Characterisation

The aim of dynamic system characterisation is to find a set of ‘optimum’ FRFs $H_i(f)$ which provide the best approximation of the measured system outputs $y_i(t)$ to the multiple inputs $x_i(t)$, see Fig. 1. During the dynamic system characterisation, the MVFRA algorithm is presented with the known inputs (time histories of sensor data) and corresponding measured outputs (time histories of the airframe buffet loads). To validate the algorithm’s predictive abilities, only a small subset of the available flight test data was selected for dynamic system characterisation, with sufficient validation data remaining. The multi-input FRF generation process is further referred to as ‘training’ and it is illustrated in Fig. 1, where the known inputs $x_i(t)$ and outputs $y_i(t)$ are indicated as red arrows.



Where: $x_i(t)$ - input signals (strain sensor data)
$H_i(f)$ - Frequency Response Functions (load/strain)
$v_i(t)$ - predicted linear outputs (components of the target buffet loads)
$n(t)$ - unknown extraneous component (noise, structural nonlinearities, etc.)
$y_i(t)$ - output signals (target buffet loads)

Fig. 1 System inputs and outputs used for generation of the Frequency Response Functions

Investigation of various training techniques revealed that the use of data binning during dynamic characterisation has the potential to substantially improve prediction results. Data binning is a pre-processing technique widely used in aircraft buffet studies to facilitate dynamic data analyses [6]. It is common practice to parse the data into separate ‘bins’ based on their AOA and dynamic pressure (Q) values so that individual FRFs are generated at a finite range of flight conditions (AOA-Q bins). The use of the data binning technique aims to facilitate and improve dynamic data analyses by processing more stationary ‘binned’ data and also helps address any non-linearities present by treating the system as ‘piecewise linear’.

It was also found that further improvement to the FRF estimation accuracy can be achieved by binning the data according to their AOA and true airspeed (V) values. The use of this novel AOA-V binning technique demonstrated a substantial improvement in the dynamic load prediction accuracy by clustering and analysing more uniform dynamic data. Therefore, during the training phase, dynamic system characterisation in the frequency domain was accomplished by calculating the FRFs between the time histories of the input signals (strain sensors) and the associated outputs (airframe loads) for each of the AOA-V bins. The training set represented approximately 30% of the available flight test data, with that appearing to be sufficient for dynamic characterisation and subsequent validation of the model's predictive abilities.

Dynamic Load Generation

Once the dynamic system characterisation is complete, new strain sensor time histories $x_i(t)$ and the derived FRFs $H_i(f)$ can be used to predict the airframe buffet loads $y_i(t)$ for new flight conditions. Given piecewise linear FRFs are defined, time domain characterisation of the system can be performed by generating Impulse Response Functions (IRFs) for each of the FRFs. This involves taking an inverse Discrete Fourier Transform (DFT) of the FRF. Convolution of these IRFs with the associated strain sensor time histories can be used to derive airframe buffet loading time domain response which accounts for the response of multiple structural vibration modes acting simultaneously during buffeting. Linear superposition of these load components then produces a complete time history of the target buffet loading.

Manoeuvre Load Prediction

Manoeuvre loads for the selected structural locations are calculated using a multiple linear regression analysis and are then used to produce the complete (manoeuvre plus buffet) load sequences. During the initial studies, manoeuvre loads predictions were based on the use of the steady components of the strain sensors only, where sensor time histories were used as the independent variables in multiple linear regression analyses. However, after performing several parametric studies, considerable improvement in manoeuvre load prediction accuracy was achieved by adding some flight parameters (aircraft state and environment) to the list of independent variables. Therefore in this study, several flight parameters and the quasi-steady components of the strain sensor outputs were used as the independent variables (inputs) to a linear regression algorithm for manoeuvre load predictions.

Airframe Total Load Derivation and Validation

Following the above process, the total (manoeuvre plus buffet) load sequences can be generated at various structural locations for each flight for all fleet aircraft. It should be noted that manoeuvre loads must be included in every total load sequence since they can significantly affect fatigue life results (due to a mean-stress effect), even for those structures which are known to be affected predominantly by buffet loading. These total external loads can then be multiplied by load/stress relationships derived from test and or analysis to produce stress sequences which can be further processed using turning point extraction and cycle counting algorithms. The resulting stress peak/valley sequences can then be used for IAT analysis and fatigue life assessment at various and or critical life limiting airframe locations.

Initial validation of the ALM algorithm's predictive ability was performed by generating time histories of manoeuvre and buffet loads at various structural locations and comparing their magnitudes and cycles to flight test calibrated loads data using exceedance plots, as these provide valuable insights for IAT and fatigue life estimation. A 'proof of concept' of the ALM methodology has been successfully demonstrated by confirming its ability to accurately predict the magnitudes and cycles of in-flight loads at various locations on the vertical tail and rudder, horizontal tail, as well as the wing, for the aircraft studied. However, at some structural locations (e.g. the wing tips) the predictions were not adequate and thus, further work is underway to improve the model's predictive abilities, with final prediction limitations likely defined by the available strain sensors. Finally, assessment of the dynamic characterisation's and associated FRF's sensitivity to changes in flight conditions and aircraft configuration (fuel states, external weapon carriage) is also in progress to assess the ALM's reliability and accuracy over a broader range of in-service conditions.

Conclusions

This paper describes an advanced methodology proposed by DST Group for tracking airframe manoeuvre and buffet loads for IAT purposes by using a high sample rate strain-based approach. The proposed method for airframe loads monitoring is based on a direct 'on-board' measurement and 'off-board' processing of multiple strain sensor outputs supplemented by the aircraft flight data (state parameters and environment) for more accurate prediction of both the manoeuvre and buffet components of loads experienced in-service. The ALM algorithms do not require re-validation in service after changes in missions, tactics and operational usage patterns or flight control law updates as they are based on the monitoring of the actual measured airframe response. The approach described can also account for aircraft usage variations and support 'on-condition' maintenance by reliable manoeuvre and dynamic loads prediction during any flight condition.

Thus, the ALM methodology can provide a robust, verified and significantly improved Individual Aircraft Tracking solution and represents advances in airframe health monitoring that are consistent with technology improvements provided by new generation aircraft. As such, the proposed methodology can form a foundation for development of a high-fidelity fatigue and usage monitoring system for current and future aircraft platforms. To achieve such gains, sound and forward looking IAT decision making philosophy aligned with the ALM approach can lead to significant improvements in aircraft airworthiness management and associated risk mitigation, facilitate optimized fleet management and also help maximise the return on investment for current and future military aircraft.

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