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OPERAND: An Innovative Multi-Physics Approach to Individual Aircraft Tracking

Oleg Levinski [1], Robert Carrese [2], David Conser [1], Pier Marzocca [2], and Marcus McDonald [1]

[1] *Aerospace Division, Defence Science and Technology, PO Box 4331, Melbourne, Victoria, 3001, Australia*
[2] *Aerospace Engineering and Aviation, Royal Melbourne Institute of Technology*
GPO Box 2476V, Melbourne, Victoria, 3001, Australia

Abstract

This paper describes the progress of a collaborative effort between DST and RMIT University in developing a novel approach to individual aircraft tracking inspired by the Aircraft Digital Twin concept. OPERAND (Operational Analysis and Asset Diagnostics) is a multi-physics analysis suite for structural health monitoring based on the integration of current state-of-the-art software techniques, data-driven methods, and model-based approaches. This innovative structural diagnostics and prognostics framework has the potential to revolutionise aircraft fleet management, provide substantial savings to aircraft operators and optimise aircraft availability for improved operational effectiveness. It aims to enable pro-active condition-based aircraft maintenance through high-fidelity airframe fatigue tracking by significantly improving airframe global load and stress predictions for any flight condition or change in aircraft configuration.

Keywords: individual aircraft tracking, OPERAND, structural dynamics, aeroelasticity, digital twin, data analytics.

Introduction

Structural health management for Defence air platforms is traditionally driven by scheduled inspection intervals and pre-emptive maintenance based on interpretation of structural certification test results, or, reactive based on unique or unexpected fleet in-service incidents. However, in the current environment of budget constraints and shrinking resources, a major shift towards actionable and pro-active condition-based maintenance is required to ensure the safe and efficient operation of aircraft, significantly reduce the fleet management and sustainment costs and improve availability.

The effectiveness of airframe life management depends upon the reliability and accuracy of the fatigue life monitoring system used for individual aircraft tracking (IAT). This system aims to estimate the airframe fatigue accrual to manage usage of individual aircraft and meet fleet operational capability needs. One of the most critical parts in the fatigue accrual evaluation process is the estimation of airframe service loads and stresses in order to predict the degradation of the airframe and components fatigue lives relative to lives derived from certification test programs. Detecting and tracking global airframe loading and local structural anomalies caused by fatigue and wear are key components in the development of a structural diagnostics capability able to significantly improve sustainment of current and future air platforms.

Current Approach to Aircraft Loads Monitoring

Despite considerable progress in physics-based numerical modelling and the availability of high-performance computing resources, the approach to the aircraft service loads evaluation for IAT has not changed dramatically over the last half-a-century. As buffet-induced dynamic loads often are drivers of fatigue critical loading, their accuracy is critical to airframe fatigue tracking. However, fatigue life monitoring of such buffet-affected structures is still characterised using aircraft flight parameters and look-up tables to define the airframe service loads present in flight. While quasi-steady manoeuvre loads can be estimated with 'reasonable' accuracy, aircraft buffet loads are inherently difficult to predict and validate due to their random and transient nature [1-4]. Typically stochastic parameter-based methods define the 'assumed' dynamic loads based on initial flight trials of pre-production test aircraft obtained using it's specific structural and flight configurations, applicable flight control laws, envisaged operational scenarios, etc. While often flight test based, these loads are analytical in a sense as they are not airframe loads directly measured per fleet aircraft. As such, the estimates provided by such a fatigue tracking system may be highly inaccurate. Besides that, the differences between fleet in-service usage and the original design assumptions can further change airframe load distributions and may lead to unexpected and thus unmonitored fatigue-critical structural 'hot spots.' This leads to additional operator risk which must be managed if airworthiness is to be ensured.

It should be noted that, based on DST Group experience, verification and acceptance of a parameter-based approach to buffet-induced loads tracking has been problematic for legacy aircraft. Thus, it is common practice to apply some uncertainty or safety factors on the structural health monitoring system loads where their accuracies cannot be substantiated. Moreover, additional uncertainty factors may need to be applied when an aircraft's usage in the Australian operating environment or as the platform's CRE (Configuration Role and Environment) differs or changes substantially over time from the original design usage applied in the certification test program(s). This effectively means that the certified structural life of the aircraft may need to be conservatively reduced to meet Australian airworthiness requirements [5]. Any such conservatism in the fleet life management may lead to unnecessary inspections and maintenance actions and thus, considerably decrease fleet readiness and increase through-life structural support costs. Ensuring this is done in a conservative manner when so many uncertainties are involved is clearly a challenge.

The Future of Structural Health Monitoring

Significant improvements in structural life prediction and management can be achieved by implementing an integrated approach to aircraft operation and sustainment. Numerous uncertainty factors and safety margins used in the fatigue life calculation process can be minimised or even eliminated by integrating an ultra-high fidelity numerical model of the aircraft with a 'smart' health monitoring system and a comprehensive historical database for each individual aircraft covering its operation, maintenance, upgrades and repairs. This new paradigm, known as the Aircraft Digital Twin (ADT), can be best described as an integrated multi-physics, multi-scale, probabilistic simulation of an as-built system that uses the best available models, sensor information, and input data to mirror and predict activities and performance over the life of its corresponding physical twin [6, 7]. According to the ADT concept, a number of different engineering disciplines covering various physics such as aerodynamics, structural dynamics, thermodynamics, material science, fracture mechanics, etc., are fully integrated to create a single unified aircraft model with an historically unprecedented level complexity. This digital model is also assumed to be extremely accurate in geometric detail, including manufacturing anomalies, and in material detail, including the statistical microstructure level, specific to this aircraft tail number [6]. So when developed, the ADT is expected to 'mirror' real aircraft behavior when exposed to the same flight conditions.

It is understood, however, that realization of the full ADT capability will require significant scientific and technical developments. It may take decades to reach the goal, but it is important to pursue such aspirational outcome-oriented work by following the main principles of the ADT concept. For example, in the current structural life prediction process, each type of physics has its own independent model. There is a computational fluid dynamics (CFD) model, computational structural dynamics (CSD) model, thermodynamic model, stress analysis model, etc. With the ADT, all such models are required to be interconnected with each other so the physics involved are seamlessly linked, just as such physics are linked in the physical structure [6].

Two major components of the ADT architecture are the CFD and CSD models as they form a foundation of the ADT with respect to airframe loading. These models must be properly coupled so that the effect of aeroelastic excitation and structural deflections on the aerodynamic flow can be captured as the structural response is driven by the external loading and the airframe loads are motion-dependent. The response of the structure to all other applied loads, such as high-frequency acoustically-induced dynamic loads and thermal fluxes, must also be taken into account to ensure the damage state of the structure evolves with known levels of uncertainty. Therefore, the coupled CFD/CSD solver must be able to model the entire range of physics acting on the structure; thermodynamics, global aeroelastic vibrations and local deformation, both quasi-static and dynamic, for subsequent accurate simulation of the stress field throughout the aircraft for each virtual flight in its entirety [6].

It is assumed that the physical aircraft will be delivered to the fleet together with its as-built ADT which can be ‘flown’ virtually through the same missions and flight profiles as its physical counterpart. These ‘virtual’ modeling or predicted results can then be compared to sensor readings recorded at the airframe critical locations for calibration, updating and continuous improvement of the digital model as the aircraft ages. Prognostics for the airframe can also be developed by ‘flying’ the ADT through possible future missions to forecast the evolution of material states and the progression of damage to compute a probabilistic distribution of the remaining life. This information can be used to determine when and where structural damage is likely to occur, and when to perform maintenance [6]. Therefore, the aircraft structural health management process will become preventative, integrated and ‘personalized’, with the majority of effort concentrated on predicting and managing the airframe damage state throughout each aircraft’s unique service life [8].

High-Fidelity Structural Diagnostics Framework

Multi-physics analysis plays an important role in engineering design, and over the past decade there has been a growing trend to address this class of problems using coupled CFD and CSD solvers. A significant number of approaches have been developed to model the aerodynamic and structural systems with varying levels of fidelity so that numerical modelling can be achieved via a range of techniques with varying levels of complexity. However, there has been limited effort made to integrate the physics in the individual models into a single comprehensive representation of the aircraft [7]. There have also been limited attempts to leverage this technology for condition-based structural health monitoring such that the rich information provided by multi-physics analysis is exploited in conjunction with in-service flight measurements as well as initial flight test based data. Such an approach could provide substantially increased confidence when determining airframe in-flight loads and stress distributions, fatigue-critical flight conditions and thus improved airframe fatigue tracking and aircraft availability.

The development of the OPERAND framework has thus been initiated to fill this gap in the field of condition-based aircraft structural health monitoring. OPERAND represents an integrated multi-physics analysis suite which intends to provide high-fidelity structural diagnostic and prognostic assessment capabilities for fleet aircraft. It was developed using the major components of commercial off-the-shelf (COTS) software to handle the structural and aerodynamic fields. Additional focus was placed on the numerical implementation of the CFD/CSD flow-structure interface, responsible for two-way coupling of the physics of the different temporal and spatial scales.

The OPERAND analysis suite includes a number of solution strategies for the construction of the time-invariant and time-dependant state-space systems [9, 10]. This required the development of the coupled CFD/CSD models of various levels of complexity and their fusion with the aircraft sensor data that forms a foundation for high-fidelity IAT capability. Increasing the level of fidelity comes at the expense of increased computational cost, and hence the user must decide on an appropriate balance between the accuracy of the nonlinear aeroelastic predictions and the associated computational cost. Although fully-coupled high-fidelity CFD and CSD simulations are not indispensable in nonlinear aeroelastic studies, the requirement for CFD-based aerodynamics is becoming a necessity in some regards. Specifically, if the aeroelastic system is time-variant, the aerodynamic forces acting on the structure should be resolved in the time domain via transient CFD based simulations. It should also be noted that OPERAND includes a number of nonlinear CFD based reduced-order models (ROM) which may act as an efficient alternative to full CFD simulation which have gained attention in the last decade [9].

The OPERAND framework is constructed as an open-loop aeroelastic system interfaced with COTS CFD and CSD solver packages and leveraging state-of-the-art data projection techniques. It is designed using the Mathworks MATLAB® environment, providing an intuitive and sequential Graphical User Interface (GUI) to construct various analysis scenarios [9-12]. The OPERAND allows physical measurements, acquired from structural health monitoring sensors discretely located on the airframe, to be augmented with virtual sensors obtained from the aircraft calibrated digital model. The addition of virtual sensors provides a higher resolution to in-flight acquired measurements, enabling higher confidence in reproducing a given flight scenario in a virtual environment. Furthermore, this process inherently allows in-flight physical measurements to be used as mechanisms for calibrating and updating the behaviour of the digital model by using state-of-the-art data fusion techniques. Fig. 1 shows the analysis modules included in the OPERAND framework.

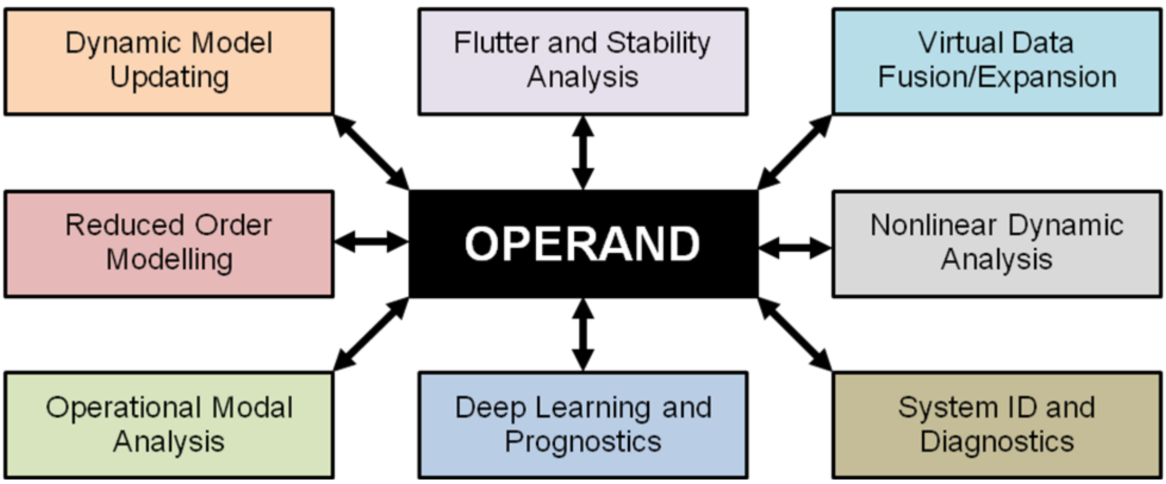

Fig. 1: OPERAND framework analysis modules

The necessity of constructing a multi-fidelity aeroelastic prediction framework for IAT arose from the need to obtain a consistent predictive tool, regardless of the state or regime of the flow. It is also beneficial to exploit the advantages of both high-fidelity and reduced-order modeling, as typically both approaches are applicable and acceptable when characterising the aeroelastic behavior of an arbitrary system over various flight regimes. Each of these solution techniques results in a time-accurate prediction of the aeroelastic system's response and provides a framework for real-time aeroelastic loading assessments. Moreover, it provides scope to enable the use of this information by other disciplines, e.g., propulsion and or flight dynamics. Also, utilising extensively validated COTS and custom-built tools provided sufficient confidence in predicting the structural and aerodynamic behavior, thereby resulting in a trusted platform for the advanced structural diagnostic framework [9].

Individual OPERAND modules are designed to be executed in a logical sequence. For example, Fig. 2 shows an analysis sequence tailored for dynamic model updating for flight diagnostics. In-flight sensor measurements are first expanded to virtual locations utilizing a ground-calibrated CSD model. This data expansion technique provides the necessary inputs to identify the airframe structural dynamic response (in-flight modes of vibration). The CSD model, augmented with the high-resolution description of the in-flight modes of vibration, can then be updated such that the aerodynamic loading or any adverse dynamic behaviour is accounted for.

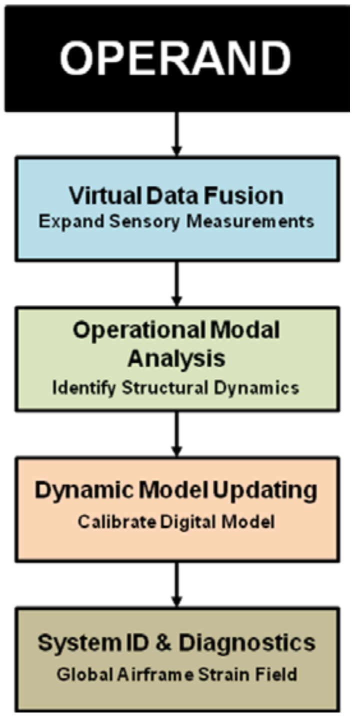

Fig. 2: OPERAND analysis sequence for flight diagnostics

With the flight-calibrated dynamic model the user may now probe any arbitrary location of the structure for the local stress distribution and the fatigue accrual evaluation required for a comprehensive assessment of the airframe structural health over the flight profile. A number of innovative system identification techniques are also implemented in the OPERAND suite to track nonlinear signatures observed in the airframe dynamic response to inform the user of any potential structural anomalies caused by fatigue and wear.

This sensory data fusion and expansion process is the first logical step towards constructing and maintaining a high-fidelity digital model of an individual fleet aircraft. The intention is to use it in conjunction with acquired ground vibration test data and in-flight measurements to provide real-time structural diagnostics capabilities and for the identification and improved assessment of fatigue-critical flight regimes. Additionally, as the aircraft digital model is continuously updated, i.e., through legacy data analysis and deep learning techniques, this understanding of the trends in airframe structural health with respect to aircraft usage can provide a model trusted for prognostic assessments. The ability to obtain a reliable estimate of the airframe service loads and airframe stress distributions for fatigue life assessment by simulating future flight profiles would have significant advantages for fleet aircraft management and sustainment.

Conclusions

In the current environment of budget constraints, development and maintenance of accurate and reliable fatigue and usage monitoring system is of increasing importance to ensure the safe and efficient operation of aircraft and to maximise their economic life. The innovative

OPERAND methodology being developed via a collaboration between DST and RMIT University aims to provide a robust, verified and significantly improved solution for individual aircraft tracking. It 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 the development of a smart structural health diagnostics and prognostics system for scheduling of requisite maintenance actions and management of individual aircraft usage and operational lives to collectively meet the desired overall fleet capability. This can lead to significant improvements in aircraft fleet management and associated risk mitigation, facilitate optimised fleet management and also help maximise the return on investment for current and future aircraft platforms.

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