The Use of Modelling within Prognostic Health Management Systems for a Fowler Flap System

Graham Hardwick[1] and Isabella Panella[2]

[1]Chief of Systems - Performance, UTC Aerospace Systems, Stafford Road, Wolverhampton, U.K.

[2]APS System Engineering Manager, UTC Aerospace Systems, Stafford Road, Wolverhampton, U.K.

Keywords: Prognostic, Health, Management, Commercial, Aircraft, Secondary, Flight, Control, Systems, Fowler, Flap, System, Power, Drive, Unit.

Abstract: The aviation industry has been utilising prognostic health management (PHM) to improve scheduled maintenance, reduce expensive aircraft on ground events (AOG) and improve active safety. PHM systems utilise legacy and real time aircraft data in conjunction with simulation models to forecast the remaining useful life (RUL) of components and systems which allow maintenance decisions to be managed. This work presents an industry based approach to PHM for one of the aircraft line replacement units (LRUs), specifically, the power drive unit (PDU) within a "generic" commercial aircraft secondary flight control system. The modelling infrastructure and its importance as a building block for the construction of a prognostic health management framework are highlighted. Example failure modes of a PDU are provided and potential benefits of PHM to mitigate these failure modes are examined. Finally simulation results from a physical model of the system in Simulink have been generated.

1 INTRODUCTION

In the aviation industry, there is an increased pressure for airlines to reduce costs whilst increasing their operating performance.

Airline costs are dependent on airline running costs as well as the need for systems upgrades and replacement, whilst guaranteeing their integrity within legacy systems.

As reported by (A. Brüggen and L. Klose, 2010), the significant airline running costs that need to be addressed can be grouped into three major areas:

1. Cost of personnel, both ground and airborne support crews, represented by personnel such as, for instance, flight crews, pilots, engineers, administrators, baggage handling ground staff;
2. The costs of marketing, business development, and sales;
3. The technical costs of operating a fleet, represented by:
   a. Fuel;
   b. General maintenance overheads (facilities, maintenance administration and recording), maintenance equipment such as spare parts and oil, aircraft servicing such as de-icing, electricity and water supply;
   c. Traffic servicing, represented by landing, taxi or parking charges and air traffic control outlays.
   d. Aircraft/capital as in depreciation of aircraft or leasing costs, and other capital costs, including outlays for working capital.

Specifically, when looking at the cost of operating a fleet, AOG and its inability to be in service represents the major cost for an airliner.

The AOG condition can be due to scheduled or unscheduled maintenance.

The ability to forecast when LRU's need to be replaced or maintained, bundle multiple components maintenance to minimise the number of AOGs events, forecasting the probability of failure of a given LRU to enable the airline to perform the maintenance activities in their own hanger are extremely important in the attempt to minimise the overall fleet costs.

Moreover, current commercial aircraft and their systems have changed dramatically since their first introduction and the new civil aircraft market requires increased cost saving and competitiveness, whilst virtually every aircraft component that must

Hardwick, G. and Panella, I.
The Use of Modelling within Prognostic Health Management Systems for a Fowler Flap System.
DOI: 10.5220/0006900701510159
In *Proceedings of 8th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2018)*, pages 151-159
ISBN: 978-989-758-323-0

be maintained has advanced during that time, including flight systems, passenger comfort systems, engines, and structural materials.

The issues of upgrading existing technologies in a cost effective manner, of innovating current technical solutions to ensure more cost effective practices, the need for improved safety and collaboration not just at airframe level but within a collaborative air space and fleet management space, lead to a revise approach on life-cycle management, which requires to be more focused on data exchange and real time information extraction.

2 INTEGRATED VEHICLE HEALTH MANAGEMENT

A platform capable of achieving an integrated operational information exchange for fleet management and an individual platform capable of addressing the ability to evaluate the RUL of a systems, support fault detection, up to logistic management of the fleet with the objective of guaranteeing *total asset availability* has been identified to be the integrated vehicle health management system (IVHM).

The “health state” refers to the ability to determine the overall health state of the vehicle. By using diagnostic and prognostic algorithms, the vehicle and its systems are monitored to detect and isolate failures. This requires autonomous data extraction from multiple heterogeneous systems, an assessment of the impact that each fault can have on an individual component and on the overall platform, and the forecasting capabilities to identify the timeline for the fault to become critical.

Mitigation involves the real-time assessment of the impact of the failures on the vehicle and its current mission. Once the impact is assessed, system redundancy management reconfigures the vehicle to maintain a safe operating condition and continue the mission, if possible. In those cases in which reconfiguration is not sufficient to continue the mission, the flight crew may modify the mission

IVHM is seen as a key development in order to reduce the lifecycle total ownership costs of modern platforms to improve in-service operation. The envisaged benefits of IVHM are:

- Ensure the ability to support fleet’s overhauling management and monitoring;
- Ease in integrating it to legacy systems – integrated modular avionics (IMA), full authority digital engine controls (FADEC);
- Ease development of new cutting edge technologies within the individual subsystems
- Optimisation of network information flow, by selection of data to transfer to the networked elements.

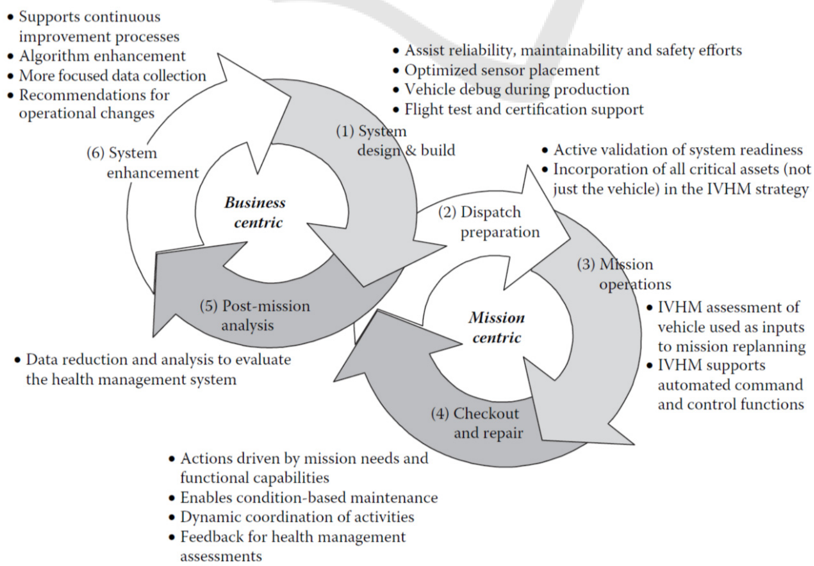

Figure 1: Enterprise Wide Approach in IVHM (Spitzer, 2006, figure 22.2, pp 369).

As described by (Baines, Benedetti, Greenough and Lightfoot, 2009) IVHM is development of both diagnostic and prognostic systems that when implemented enables real-time, continuous monitoring of vehicle health and predicts the remaining useful life of a system.

Diagnostic is based on the evaluation of the root causes of a fault that has occurred based on historic database and can considered a deterministic automated root-cause analysis carried out a posteriori. Prognostic is the process of forecasting future failure of the LRU or system based on historic data combine with the real-time system performance. (Kwok L. Tsui, Nan Chen, Qiang Zhou, Yizhen Hai, 2015) define prognostics as "the process of predicting the future reliability of a product by assessing the extent of deviation or degradation of the product from its expected normal operating conditions".

The set of hardware and software that enables the support of prognostic infrastructures is also known as the Prognostic Health Management infrastructure.

In this work, the modelling and simulation infrastructure required to develop PHM architecture is described for the high lift system is described. The model presented is a generic Fowler flap system and the generic approach to a prognostic health management framework detailed, from the fault database management to the modelling and simulation. A subset of failure modes of the PDU failure mode examples are also discussed, specifically the PDU brake failure and the PDU filter blockage. PHM development opportunities in those cases are explored.

3 HIGH LIFT SYSTEMS

UTC Aerospace Systems design, manufacture, and integrate secondary flight control systems for a variety of commercial aircraft, from wide body to single aisle configuration, from business jets to the A380.

Commercial aircraft utilize secondary flight control surfaces, such as flaps and slats to modify the wing profile in order to increase aerodynamic lift for a given air speed. This allows aircraft landing speeds/distances to be reduced.

At any given speed, the increase of lift from the wing can be achieved by increasing:

a) The wing surface area, and/or
b) The lift coefficient

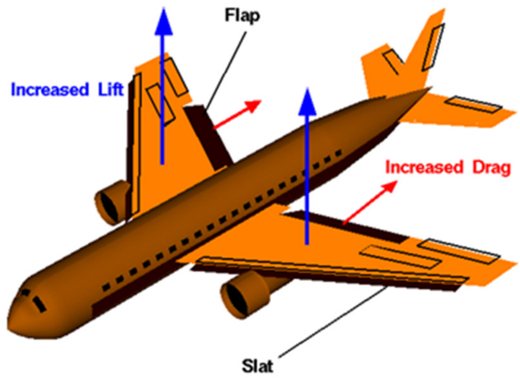

Figure 2: Slat and flap (Slat and Flap, https://www.grc.nasa.gov/www/k-12/airplane/flap.html).

High-lift systems enable to increase the area of the wing and to change the shape of the wing aerofoil to support a change in lift coefficient. There are two types of high-lift systems: the leading-edge slats and the trailing edge flap (Figure 2).

Due to the complexity of the system and the multitudes of mechanical, hydraulic, and electrical components, which provide an example of complex multi-physics system, it is essential to follow a model based design (MBD) approach in its design lifecycle.

The authors will present the step by step implementation of the modelling and simulation infrastructure and describe its adoption to support the following analysis:

- Generate performance envelopes,
- Support a fault database management system to support the listing of the component failure effects / consequences,
- Generate dynamic load cases for a component, sub-system, system,
- Determine the systems/components ability to withstand load cases.

4 SIMULATION MODEL DESCRIPTION

This section provides a description of the functional architecture of the hydraulically powered Fowler flap system and associated physical model. The functional architecture is provided in figure 3 and is based upon the work presented by (Hardwick and Panella, 2017).

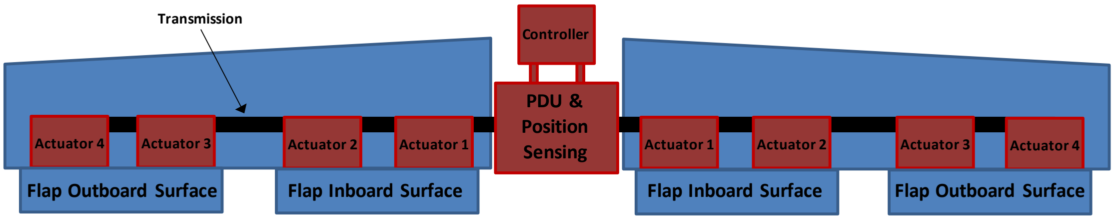

Figure 3 - Generic High-Lift architecture.

The functional architecture describes a generic medium sized commercial aircraft flap system, characterized by a single transmission line and distributed actuators spaced symmetrically with respect to the aircraft centreline. This architecture presents only a flap system and does not include the slat actuators.

The physical layout includes elements of the functionalities that a high lift system needs to present which are:

- Four mechanical rotary geared actuators (RGA) per wing provide the actuation from the transmission to the flap carriage; The mechanical advantage from the transmission to the flap carriage is increased by the use of gearboxes. This allows the transmission to drive large aerodynamic loads.
- The actuators are driven by a hydraulic Power Drive Unit via transmission shafts which is located on the aircraft centreline. The PDU has two independant channels for redundancy and position sensing capability via resolvers; This communicates with the secondary flight controller which controls the hydraulic valves which regulate the flow to the hydraulic motors. The motors drive a mechanical gearbox that drives the transmission.
- The secondary flight control system communicates with the PDU, position sensors and safety devices which arrest the system during failure case scenarios. It also interfaces with the main aircraft flight controller.
- Synchronous movement of both wings is achieved by using transmission shafts connect the PDU to the actuators.

The sequence of operation of the system is as follows. The flight controller provides a new position command to the secondary flight controller. The secondary flight controller compares the position demand to the present PDU position. If the error is above a set threshold then the controller opens the hydraulic control valves and releases the system brakes. The control for this simple example is based upon position control. When the PDU position reaches the demanded position the control valves are closed and all brakes are engaged.

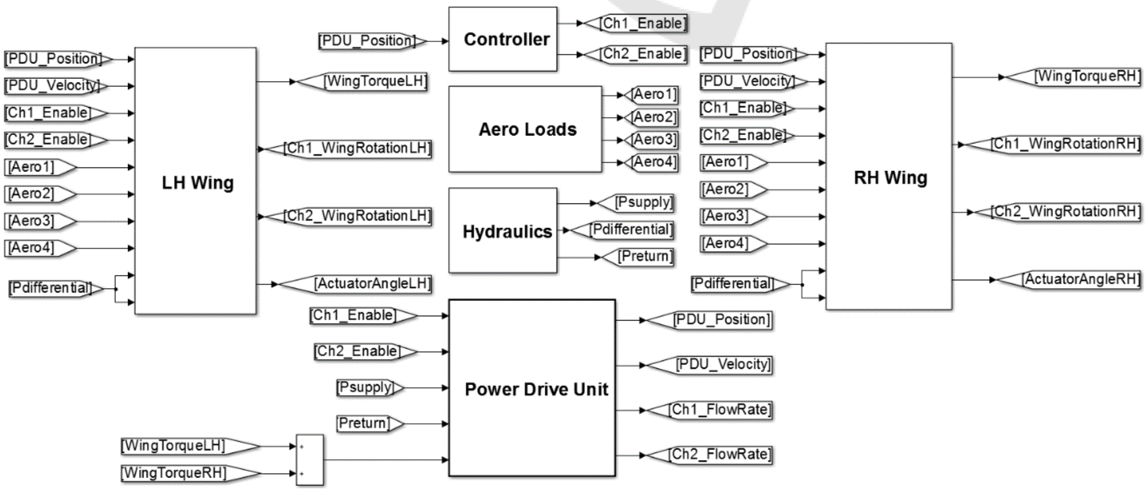

Figure 4: architecture of a generic secondary flight control system in Simulink – (Hardwick and Panella, 2017).

Based on the functional description of the flap system, the authors now intend to map the functional representation into a physical model with the aim to capture the physical behaviour of a PDU. To represent this operational scenario, a first order dynamic modelling of the secondary flight control system was created. These equations were translated into a state-space model within the Matlab / Simulink modelling environment using a variable step ordinary differential solver (ODE). The model built captured the non-linear time invariant nature of the system through its continuous states and the representation of its non-linear behaviour. The Simulink model employed in this paper is derived from the work presented by (Hardwick and Panella, 2017). The following provide a brief summary.

Transmission shaft blocks connect the PDU to the actuators which include component inertia, stiffness, and damping. Efficiency of the universal joints and inline gearboxes are included together with rotational drag torque.

The PDU model incorporates two hydraulic channels that contain a motor and control valve to activate the motor. The PDU enable signal controls both the brake in the PDU and the control valve. The motors convert the hydraulic power into mechanical. These both drive a gearbox which has a common output shaft. The control valve dynamics in the PDU was modelled using a first order transfer function.

$$\text{Valve Transfer Function} = 1/(1 + T_c.(s)) \quad (1)$$

Movement of the control valve determines the pressure drop across (ΔP) the motor. The pressure drop is converted to a motor torque (T_m) by multiplying by the motor displacement (K_{mot}) and incorporating drag (T_{drag_m}) and motor efficiency (η_{mot}) as shown by equation 2:

$$T_m = \Delta P * K_{mot} * \eta_{mot} - T_{drag\_m} \quad (2)$$

Hydraulic motor acceleration is calculated by dividing the motor torque by the motor inertia. Integrating the acceleration provides the angular velocity of the motor. Both motor speeds are transferred through a gearbox where the PDU output shaft position and velocity states are passed to the wing.

Figure 4 highlights the system architecture mapped in the Simulink modelling environment. This contains the following subsystems:

- "Controller" contains the Secondary flight controller model;
- "Power Drive Unit" contains the power drive unit mode as described in figure 5;
- "LH and RH Wing" contains the left and right wing models;
- "Aero Loads and Hydraulics" blocks represent the aerodynamic loads and hydraulic system interfaces with the PDU.

The PDU and the controller are connected to the rest of the model using "GoTo" blocks, described as:

- Ch1/2_Enable – Secondary flight controller to PDU enable electrical signal.
- PDU_Position – PDU to secondary flight controller position sensing
- Aero1(N) – Aerodynamic loads between the interface and wings
- Psupply – Hydraulic supply pressure between aircraft and PDU.

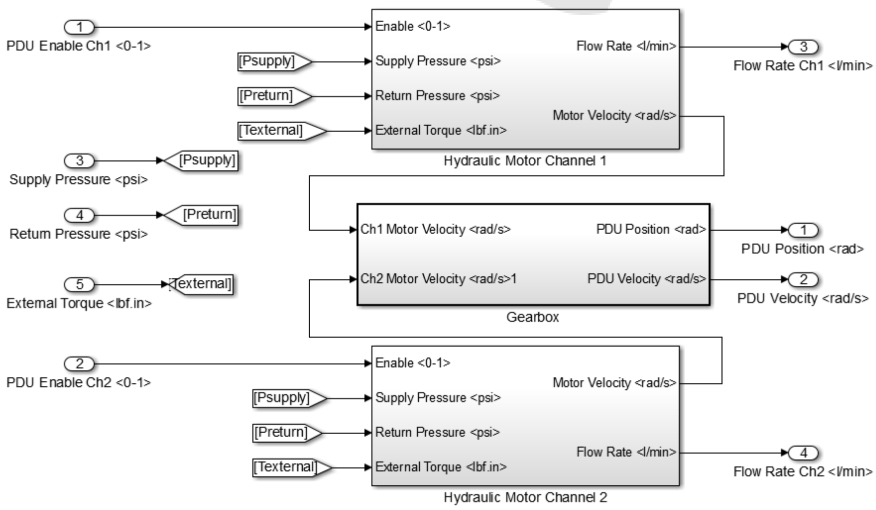

Figure 5: Power Drive Unit Model – (Hardwick and Panella, 2017).

A "generic" high lift model has been developed to protect intellectual property concerns for specific customer programs. Therefore verification of this model against physical test data model cannot be presented. However, model verification has been performed for customer programs at numerous stages of the system engineering process for example at component level and at full system rig level. Excellent model correlation has been achieved at both individual component and full system level over a range of environmental temperatures, aerodynamic loads across multiple programs.

5 POWER DRIVE UNIT FAILURE MODES

In this section, the analysis of generic failure modes for the Fowler flap system PDU is presented.

The rational of selecting the PDU as a case study for fault analysis and as a LRU for future PHM work is justified by the fact that any failure presented by the PDU would present the following challenges:

- PDU repair or replacement with delays in the aircraft future operations. Increase in AOG time.
- Availability of spare parts depending on port in which the aircraft is located. Dispatching of a LRU to a given location would cause a significant increase in the AOG time.

If PDU failures could be forecasted, the aircraft could have been directed to a suitable maintenance facility and PDU repair/replacement could take place as part of a scheduled maintenance, minimising the AOG time.

The first step in the design of a PHM is the creation of a fault database, which support the description of the component fault modes.

The fault modes are based on the operational limits of the components and can be represented by look up tables capturing the envelope of performance of the LRU.

In order to understand the significance of the fault, each fault mode is assigned a weight or probability of its manifestation. This is evaluated mathematically through fault tree analysis and failure mode effects analysis (FMEA).

The probability distribution and the analysis of the failure mode consequences/impact through a sensitivity analysis of the failure modes provide the foundation to create a contingency plan to mitigate the risk of the fault realising.

Depending on the fault and its impact on the system, different strategies to manage the health of the system could be implemented, from design to maintenance such as:

- Design upgrade;
- Additional redundant systems;
- Further safety monitoring systems to detect issues if they cannot be mitigated;
- Inclusion of addition maintenance checks such as a built in test (BIT).

Table 1 provides a subset of the failure modes that can occur within the PDU and the system level effects which have been simplified to aid illustration.

The columns of the table represent the following:

1. Failure number – reference number to support quick reference to fault case through the paper.
2. Failure Location – the location of the fault is referring to the Simulink model presented in Figure 4.
3. Failure description – Brief description of the fault.
4. Fault Monitor Triggered– Will an existing system fault monitor identify the fault and provide automatic corrective action (where necessary) and annunciate the fault to the support functions.
5. Failure Effect – Fault impact on the PDU.
6. System Issue - Fault impact on the System.

Failure numbers 1 and 3 indicate the complete loss of hydraulic supply pressure and loss of PDU brake capability. Both of these failures will trigger a "system fault monitor" within the control system which would detect the issue. For example failure number 1: "Blockage of the hydraulic filter inside the PDU channel 1" will cause the PDU channel 1 to become stationary. The control system would diagnose this via the motor velocity sensor indicating that the motor is stationary while the control system is commanding movement. If the motor velocity signal remains zero for a predefined time then a "channel jam" fault monitor would trigger. This fault monitor would shut down the affected channel and annunciate the condition to the PHM system.

Failure number 3 "Complete loss of the Channel 1 PDU Brake" will prevent the PDU brake to engage. The system would not arrest and move past the demanded position as indicated by the PDU position sensor. The control system would diagnose this by triggering the uncommanded movement fault monitor. This fault monitor will automatically shut down the system because uncommanded movement of the system is hazardous to the aircraft. The control system would also annunciate the condition to the PHM system.

Failures 1 and 3 are also known as reactionary failures, which imply that if they occurred, they would automatically shut down the system/channel. This would lead to the loss of operation the system for the remainder of the flight. However, if these failures could be anticipated via a prognostic system then the remaining useful life predicted and maintenance of the PDU could be scheduled at an appropriate time.

A way to support a PHM implementation is to add additional sensors dedicated to the monitoring of the PDU and the development of further algorithms within the control system.

For example the “Blockage of the hydraulic filter inside the PDU channel 1” will likely be preceded prior by “reduction of hydraulic flow due to partial blockage inside the filter” which is failure number 2. This failure would produce a reduction in performance velocity/torque envelope of the PDU. This would be monitored over time and change in behaviour communicated to the PHM system which would estimate remaining useful life and make the appropriate maintenance decisions.

Similarly “Complete loss of PDU brake due to wear” which is failure number 4 will likely be preceded prior by failure number 3 “Partial loss of PDU brake due to wear”. This failure would indicate increased stopping distances when the brake is commanded to engage. This stopping distance can be tracked over time and communicated to the PHM system which would determine the degradation rate and plan appropriate maintenance decisions.

6 PHM APPLICATIONS TO THE POWER DRIVE UNIT

This section will demonstrate how modelling and simulation is used within PHM applications. The example PDU failures as provided in table 1 will be used as case studies. Firstly the approaches used to simulate the failures will be provided. Then the modelling results will be provided along with the sensors required used to monitor the health condition will be described and then insights into the algorithms required will be provided.

6.1 Power Drive Unit Blockage

The first failure simulated will be the progressive blockage of hydraulic supply line within the PDU (failure 2 in table 1) which could be due to a clogging filter. The blockage is parametrised in the model by multiplying the PDU manifold effective passage area by a constant. A constant value of one indicates that the passage area in the model is not changed and hence no blockage occurs. However, a value of half indicates that only half the effective passage area is available and therefore for a given supply pressure and environmental temperature the restriction will directly reduce the available flow rate.

Table 1: Example of Flap System Failure Modes – PDU.

No	Failure Location	Failure Description	Fault Monitor Triggered?	Failure Effect	System Issue
1	PDU channel 1	Blockage of hydraulic filter inside PDU	Yes – Channel jam monitor detects	PDU channel 1 would not move	PDU channel 2 would continue operation and hence system would continue at half speed operation.
2	PDU channel 1	Reduction of hydraulic flow due to partial blockage inside the filter	No	PDU channel 1 would operate with reduced performance	PDU channel 1 operates but with reduced performance. PDU channel 2 would continue operation and hence system would continue below full operating performance.
3	PDU Brake	Complete loss of PDU brake due to wear	Yes – System uncommanded movement monitor detects	PDU channel 1 brake cannot engage	System would reach the target position but then over run the position due to no brake. The uncommanded movement monitor would detect and arrest the system
4	PDU Brake	Partial loss of PDU brake due to wear	No	PDU brake will function will have reduced capability	System would reach the target position and stop. Stopping distance may marginally increase.

Figure 6 provides the performance envelope of the power drive unit of output torque vs output velocity for levels of blockage in the PDU manifold. As the quantity of blockage increases it can be seen that the PDU output velocity decreases for a given output torque. When the PDU has a maximum blockage (value of zero) the PDU operates only on one channel and the maximum velocity capability is halved. It is noted that these curves are valid for a given fluid temperature and supply pressure available. If these parameters change then the performance envelope will be modified.

This failure mode is similar to the oil/filter blocking on aircraft engines as described by (Bastard, Lacaille, Coupard and Stouky, 2016). However, direct sensors of pressure drop are not available hence simulation can be used to map these performances into the secondary flight control system that monitors the following sensors:

- Output rotational velocity
- Output torque
- Hydraulic fluid temperature

The PHM system would contain a real-time simulation model that would provide the expected level of performance of the power drive unit. This model would input the PDU design parameters temperatures and measured external torques. It would compare the measured output velocity of the PDU relative to the expected performance model, based on test trends mapped against flight cycles. The difference between the actual and simulated velocity results would provide health monitoring information and would assess the RUL of the PDU status. Forecasting algorithms based on simulated flight cycles would support decision making on timelines for the PDU's maintenance.

PHM in this example will anticipate when degradation of performance occurs and will intervene before the PDU channel becomes completely non-operational, i.e. failure number 1. This increases availability of the PDU channel and allow maintenance to occur at suitable time.

6.2 Degradation of PDU Brake

The next case study illustrates how system modelling can provide input into PHM systems via the degradation of the PDU brake described by failure 4 in table 1. The PDU brake arrests the secondary flight control system when it reaches the target position. However, as this is a mechanical brake it may be subject to wear which may start degrading the performance of the brake but not produce a complete loss.

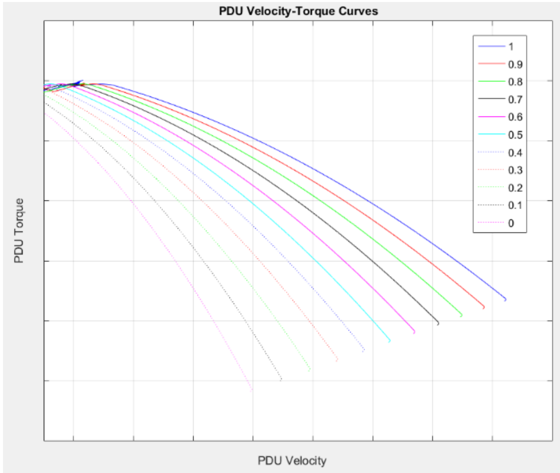

Figure 6: PDU output torque vs velocity for different amounts of PDU blockage.

The model simulates degradation of the brake by progressively reducing the torque capability from a scale between 0 = most capable to 1 = least capable. The slipped distance is the difference between the final position of the PDU output shaft to the position when the brake was commanded to engage and can be sensed using the PDU position sensor.

Figure 7 provides the degradation in slipped distance with respect to PDU brake capability for this model and indicates as the brake capability is reduced the slipped distance increases.

The PHM system could either contain a real-time simulation model or simulation output results mapped into a lookup table that would provide the expected braking distance. It would compare the measured slipped distance of the PDU relative to the expected braking performances. The PHM system difference would monitor the increase slipped between the actual and simulated output would assess the RUL of the PDU and provide decisions regarding the maintenance of the PDU to occur at a suitable time.

7 CONCLUSIONS

This work highlighted the major costs for a typical airline where the AOG case is considered a significant contributor to costs. IVHM and PHM have been described within the commercial aircraft business that are platforms that reduce AOG events by utilising legacy and real time data in conjunction

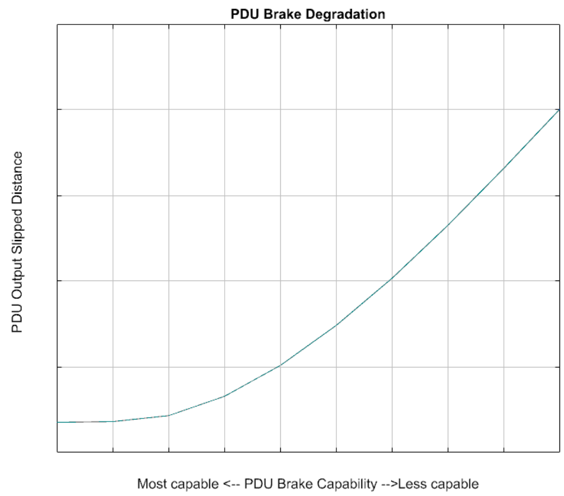

Figure 7: PDU Slipped Distance vs PDU Brake Capability.

with simulation to predict the health of component and subsystems. The paper provided an industry example of how PHM can be applied to a generic PDU within a secondary flight control system. The system architecture was presented along with the physical model within Simulink based upon previous work presented by (Hardwick and Panella, 2017).

Two example failure modes of the PDU were provided:

- PDU brake failure
- PDU filter blockage

These failure modes were used as example case studies to demonstrate how modelling and simulation can be used to generate data for the fault monitoring and algorithms within the PHM process. It is proposed that the simulation models that have been verified using new product data should be further developed to by verified utilising aircraft life-cycle test data. Then PHM algorithms may be developed using the modelling and simulation tools.

NOMENCLATURE

AOG- Aircraft on Ground
BIT - Built in Test
FADEC- Full Authority Digital Engine Controls
FMEA - Failure Mode Effects Analysis
LRU - Line Replacement Unit
IMA - Integrated Modular Avionics
IVHM - Integrated Vehicle Health Management System
MBD - Model Based Design
ODE - Ordinary Differential Solver
PDU - Power Drive Unit
PHM- Prognostic Health Management
RGA - Rotary Geared Actuator
RUL - Remaining Useful Life

REFERENCES

Baines, T.S, Benedettini, O, Greenough, R.M. Lightfoot, H.W. 2009. State-of-the-Art in Integrated Vehicle Health Management. Advances in Intelligent Systems and Computing. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 223(2), 157-170.

A. Brüggen and L. Klose, “Journal of Air Transport Management How fleet commonality influences low-cost airline operating performance : Empirical evidence,” J. Air Transp. Manag., vol. 16, no. 6, pp. 299–303, 2010.

Hardwick, S., Panella, I. 2017. Dynamic Modelling of Commercial Aircraft Secondary Flight Control Systems. Simultech 2017 Proceedings of the 7th International Conference on Simulation and Modeling Methodologies, Technologies and Applications. INSTICC, SCITEPRESS.

Kwok L. Tsui, Nan Chen, Qiang Zhou, Yizhen Hai, WenbinWang. 2014. Prognostics and Health Management: A Review on Data Driven Approaches. Mathematical Problems in Engineering, Volume 2015,. Hindawi.

Slat and Flap, https://www.grc.nasa.gov/www/k-12/airplane/flap.html

C. R. Spitzer, C. R., *Avionics: Elements, Software and Functions*. 2006.

Zadeh, Desoer, 1963. “Linear System Theory – The State Space Approach” McGraw Hill, New York

Bastard, G. Lacaille, J. Coupard, J. Stouky, Y. 2016. Engine Health Management in Safran Aircraft Engines. Annual Conference of the Prognostics and Health Management Society 2016.