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A POTENTIAL STUDY OF PROGNOSTIC-BASED MAINTENANCE FOR PRIMARY FLIGHT CONTROL ELECTRO-MECHANICAL ACTUATORS

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ABSTRACT

The operating costs of civilian aircraft are crucial to air carriers. These costs currently offset more than 95% of their revenues, and maintenance represents around 10-20% of these operating costs. Thus, minimizing unscheduled maintenance is an important cost saving opportunity. Currently, primary flight actuators are based on electro-hydraulic technologies, and they are maintained by scheduled operational tests in accordance with the Maintenance Steering Group-3 (MSG-3) process. This paper discusses the potential of utilizing Prognostic-Based Maintenance (PrM) to minimize unscheduled maintenance of primary flight control actuators. Two perspectives will be considered: the MSG-3 based maintenance program and electro-mechanical actuation (EMA) - EMA is a promising technology for actuation in future aircraft. PrM and some of MSG-3 maintenance tasks have similar features that may be used to implement new PrM applications. Further, the EMA perspective involves a case study of a PrM system dedicated to monitoring the rolling contact fatigue of an EMA ball bearing. The PrM potential for aircraft systems has been investigated in numerous studies on the system level; however, practical utilization necessitates more focus on the component level related to specific failure modes.

KEYWORDS

Fatigue spall faults, MSG-3, predictive maintenance, prognostic horizon, vibration and current sensors,

I INTRODUCTION

High operational costs make it difficult for airliners to provide competitive low-cost services for passengers and at the same time achieve attractive revenues for investors. In 2014, the air transport market generated revenues of $769 billion of which air operators earned just $16.4 billion: i.e. a net profit of only 2.13% (IATA, 2015). Maintenance activities make up about 10-20% of total operating costs (Dupuy, 2011; Suwondo, 2007). These then, represent a significant cost saving opportunity. The majority of these costs are related to planned, scheduled activities; other costs arise from unscheduled events (Chevallier, 2013; Suwondo, 2007).

Prognostics and health management (PHM) systems have been studied in relation to two different applications: safety and maintenance (Keller & Maggiore, 2012). An example of a safety related application was discussed by (Torhorst, Hölzel, & Gollnick, 2014; Keller & Maggiore, 2012). There, a highly reliable PHM system was looked at in regard to improving designed reliability as an alternative to increasing hardware redundancy in some aircraft systems; However, reaching sufficient reliability levels for PHM safety applications still has several economic and technical challenges comparing with hardware redundancy (Keller & Maggiore, 2012).

On the other hand, Prognostic-Based Maintenance (PrM) leads to an upgrade of scheduled tasks that are independent of safety critical features (Keller & Maggiore, 2012). For example, if a PrM failed to detect a failure, a control actuation function (e.g. roll) is still protected by automatic reconfiguration in terms of the actuator redundancy. Flight control computers have built-in monitoring functions, which will activate such reconfiguration.

Currently, civilian aircraft make use of electro-hydraulic fly-by-wire (FBW) actuators for primary flight control surfaces. The More Electric Aircraft (MEA) is among the concepts being pursued, in future aircraft design, to improve fuel consumption and reduce operational costs (Rosero, Ortega, Aldabas, & Romeral, 2007). One of the main objectives of the MEA is to integrate electro-mechanical actuators (EMAs) as replacements for electro-hydraulic FBW actuators. The main challenge concerning using EMAs for primary control surface is their susceptibility to jamming, which restricts their use in redundant configurations. The dual redundancy of primary flight controls is an obligatory design requirement, which is independent of the actuation technology in use (Ramesh, 2015).

An example of a promising approach to protecting EMAs against the risk of jamming is to incorporate an anti-jam mechanism - which will disconnect a jammed actuator (Flatt, 2008). Here, we assume that EMAs are already qualified for actuating primary flight control surfaces similar to the one of the Airbus A320. The selection of the A320 is due to the fact that its maintenance manuals as well as its actuation architecture details are more accessible compared to others. In addition, the A320 is the world's best-selling narrow-body airplane category; it is expected that around 70% of the total demand for civil aircraft in the next two decades will be for this category (Airnation, 2014). Beyond other design difficulties and operational potentials of utilizing EMA for primary flight controls, this paper focuses only on technical maintenance needs.

Optimizing aircraft maintenance costs by incorporating PrM has been cited in numerous studies (Hölzel et al., 2012; Knotts, 1999; Sandborn & Wilkinson, 2007; Torhorst, Hölzel, & Gollnick, 2014). The term PrM is used here instead of the term PHM, in order to limit the scope of our study to the maintenance applications of PHM.

As concluded by previous studies, PrM can contribute to the reduction of aircraft operating costs in two ways:

- PrM provides a reduction in maintenance costs by enabling on-need maintenance rather than scheduled inspections for an item. The ideal PrM has the ability to measure maintenance necessities without entailing unnecessary scheduled downtime for inspections, tests, or labor expenses.
- PrM enhances technical dispatch reliability by providing a cost-feasible earlier warning time prior to unscheduled maintenance. The fault detection and trending capabilities of PrM can recognize faults and associated time-based repair activities; thus, minimizing technical delays.

Maintenance tasks should be assigned to civil aircraft systems according to a specific maintenance process: Maintenance Steering Group-3 (MSG-3), and its revisions since 1980 (Kinnison, 2004). The MSG-3 based maintenance program includes the requirement to perform certain maintenance tasks on a periodic or usage basis (Kinnison, 2004). Realizing PrM in relation to aircraft systems involves many challenges such as:

- PrM is considered a methodology, which is new to aircraft systems. Thus, comprehensive investigations regarding various requirements (e.g., installation, airworthiness approval, and operational conditions) are required.
- PrM feasibility has been widely studied at the system level; however, it does not involve some technical aspects such as fault-failure characteristics and their influences on PrM capability.

In this paper, the typical PrM architecture of: ISO 13374:2012 (ISO, 2012a) is compared to MSG-3 based scheduled tasks for primary actuators in order to show the potential for applying PrM under the body of MSG-3. Such initiatives may produce a rapid and cost-effective integration process for PrM concepts in regard to aircraft maintenance systems - without the need to build a completely separate PrM away from MSG-3 methodology. In addition, a case study of a PrM system dedicated to monitoring the rolling contact fatigue (RCF) of an EMA ball bearing is explored. The RCF is the primary failure mode of the electric motors, which are critical parts to many different EMA designs (Mobley, 2002).

This paper is organized into five sections. Section 2 gives an overview of the MSG-3 based maintenance program, a summary of current maintenance tests for the primary flight controls of the A320 and a generalized architecture for PrM. The scenario of using scheduled maintenance for the new actuation technology of EMA is evaluated in Section 3 - in comparison to the use of PrM. A proposed mapping between PrM architecture and some of MSG-3 based maintenance tasks is discussed in Section 4. Finally, Section 5 explores the potential benefits of applying a PrM system to monitor an EMA subject to RCF degradation.

II BACKGROUND

2.1 Summary of MSG-3 features

Maintenance is *the process of ensuring that a system continually performs its intended function at its designed-in level of reliability and safety* (Kinnison, 2004). As a typical engineering system, the aircraft and its sub-systems are subjected to in-service degradation.

A so-called Maintenance Steering Group (MSG) consisting of aircraft manufacturers, aviation authorities (e.g. FAA, EASA) and air carriers' representatives developed a methodology (called MSG-3) intended to deliver cost-effective scheduled maintenance programs ensuring continued airworthiness for all new civil aircraft commissioned since 1980 (Kinnison, 2004). The MSG-3 process defines specific scheduled tasks for each system through failure-effect oriented decision logic. Aircraft maintenance tasks are divided into three areas: airframe systems and power plant tasks, structural item tasks, and zonal tasks. The airframe systems consist of all on-board systems such as flight controls, landing gear, and hydraulic systems. In this study, we focus on the primary flight controls group (i.e., airframe tasks). The development of a new maintenance program encompasses three main steps (according to MSG-3), and is followed and completed by a continuous performance monitoring process as follows:

- **Level 1 analysis - failure categories**

Failures are analyzed by several tools, e.g. failure modes effects and criticality analysis (FMECA), in order to identify dominant failure modes and effects.

- **Level 2 analysis – maintenance tasks decision**

The MSG-3 process requires the selection of one or more maintenance tasks (Table 1) for each failure mode identified during Level 1 analysis. The maintenance tasks are checked according to the specific order given in Table 1. For example, if an operational check is considered effective and sufficient to avert a failure, other higher tasks (i.e., functional, restoration, and discard) will be ignored (Kinnison, 2004). This shows the inherent advantage of MSG-3, as the cheaper tasks (e.g., operational check) are verified before more expensive tasks (e.g., functional and discard) are considered.

- **Maintenance task interval determination**

This is defined based on failure rate data and the accumulated experience of the MSG-3 work groups. Generally, for civilian aircraft, there are four different categories of scheduled maintenance. These are designated as the 'line'/'transit', 'A', 'C' and 'D' categories. The required maintenance intervals are specified by the aircraft manufacturers; however, the aircraft operators may partially modify them according to their fleets' needs, also due to aircraft aging. These modifications require an approval from local civil authority.

- **Maintenance performance monitoring**

The commercial utilization of the aircraft depends on the needs of the local airlines/operators, as they typically work in dissimilar geographical regions with diverse operational requirements. This reduces the ability of the standard maintenance planning document (MPD) to cope with the large number of variants that almost are attributes of the airlines (Marušić, Alfirević, & Pita, 2009). Therefore, the applied maintenance program is adapted to the specific requirements of airline operations.

The airline's maintenance reliability program (MRP) must be applied to statistically monitor events associated with the airworthiness of an aircraft as well as the reliability of the maintenance program (Kinnison, 2004; Marušić et al., 2009). The MRP (Figure 1) provides an appropriate means of monitoring the effectiveness of the maintenance program, via the following functions (Kinnison, 2004; Marušić et al., 2009):

- Collecting data - usually on an annual basis (e.g., flight time & duration, unscheduled removal, pilot reports, maintenance logbook, delays and cancellations);
- Comparing statistical trends with average world fleet trends and defining corrective actions if those trends are lower than the specified threshold.

Possible corrective actions e.g.:

- Changes in maintenance procedures and/or intervals;
- Changes in aircraft system design.

Table 1. Prioritized MSG-3 tasks in order from top (cheapest) to bottom (most expensive) (Kinnison, 2004).

Task	Description
Lubrication/ servicing	Provide that which is necessary for an item to maintain inherent reliability.
Operational check	• A qualitative check on a system's functionality. • Does not involve performance limits or measurements. • Does not involve external equipment, i.e. (self - failure test).
Functional check or inspection	• A quantitative check for an individual item (i.e. not a whole system) on its performance against certain measurable parameters • May require the use of additional equipment.
Restoration	Necessary procedures to recover an item to a specific standard. This may involve, for example, the replacement of a sub-component, or cleaning or overhauling.
Discard	The complete removal of an item at a specific life limit.
Combination of tasks	The Combination of two or more of tasks.

2.2 MSG-3 tasks for the A320

In this section, the typical maintenance tests associated with the current electro-hydraulic FBW technology are explored in order to demonstrate the requirements of the MSG-3 based maintenance program.

The service design goal of primary flight control actuators matches nominal aircraft structural fatigue life, which is 60,000 FH for the A320 (Rößler, Peters, Tusch, Hilfer, & Herrmann, 2009). This implies that these actuators should be operative for the entire aircraft life - without designed replacement (Costes, Verbigier, Begout, & Andrieu, 2012). The typical maintenance task for primary flight control actuators is to perform scheduled tests for possible in-service degradation i.e., latent faults (Airbus, 2010). A complete functionality loss or the partial failure of an actuator may be the result of a cumulative degradation, or it may be due to other noncumulative causes such as accidents, failures from nearby systems, or sudden failures. Scheduled maintenance tests aim to account only for failures driven by a cumulative in-service degradation that are not covered by in-flight failure detection system (SAE, 2007). In this paper, we ignore the heavy maintenance tasks that are performed, for primary actuators, once every three to four years.

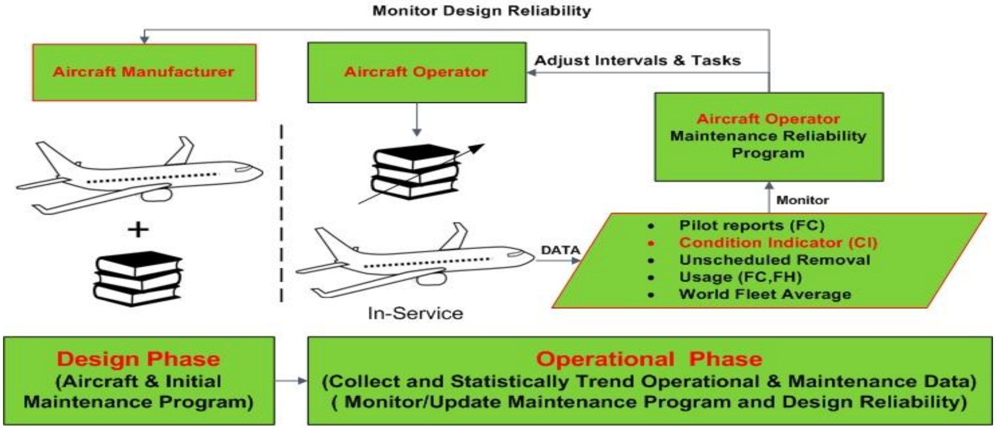

Figure 1. An overview of maintenance reliability program (MRP). The condition indicator of an item is not involved in current MRP. The reason for adding CI is discussed in Section 4.

Light maintenance tasks are more frequent, occurring up to five times a year according to the Airbus MPD for the A320 (Airbus, 2010). The built-in test equipment (BITE) operational check is performed for aileron and elevator flight controls at 500 FH intervals – as defined under FAA flying regulations. The aforementioned interval is close to the 'A' maintenance check, which is commonly made between 500-600 FH. The nominal interval is 500 FH, and this matches about five annual checks based on the average annual utilization of 2500 FH for the A320 (Rößler et al., 2009). Incidentally, the A320 rudder actuators are not considered in this study because they are not FBW.

Maintenance BITE checks are interactive, and are activated only by maintenance personnel on the ground. The BITE measures FBW actuator damping coefficient K_a. The K_a for a flight control actuator is useful for assessing the actuator performance; this may be affected by latent faults e.g. oil leakages and seal degradation (SAE, 2007; Wang, Tomovic, & Liu, 2016). A range of K_a is checked in terms of tolerable degradation limits; an expensive overhaul for the FBW actuator is required upon a certain threshold of degradation (SAE, 2007; Wang et al., 2016).

The main limitation of these BITEs is that they evaluate immediate degradation without checking, any further fault progression. For example, the degradation could be tolerable within acceptable limits (e.g. maximum value of K_a) during a scheduled BITE test; however, a latent propagation that exceeds limits may occur after BITE tests have been performed and passed.

2.3 A generalized PrM architecture

The most commonly used functional architecture for realizing PrM principles is that defined by ISO 13374:2012 (ISO, 2012a), *Condition Monitoring and Diagnostics of Machines—Data processing, communication and presentation* as enhanced by the development recommendations specified in *ISO 17359:2011 Condition monitoring and diagnostics of machines – General guidelines* as shown in Figure 2. ISO-13374 usually requires a preliminary stage of criticality analysis and failure modes analysis, as stated in ISO 17359, and it has six functional blocks as described in the following paragraphs.

- **FMECA and failure physics**

The first step towards investigating a PrM system is to conduct intensive Failure Mode, Effects and Criticality Analysis (FMECA). FMECA is a process for identifying relevant failure modes and corresponding effects based on similar designs experience or in-service reliability data. The health monitoring capabilities, in general, cannot cover all failures modes: only those, which have significant economic and/or safety potential impacts. Most failures have early indications, which are in the form of faults. If the fault is measurable via sensing technology, then further health monitoring based maintenance (according to ISO 13374) is conceivable; otherwise, an appropriate corrective or preventive maintenance plan should be applied (ISO, 2012a; Mobley, 2002).

- **Data acquisition and data manipulation**

This stage involves specifying effective sensing technologies for measuring or estimating states of interest. A state may indicate the presence of a general degradation parameter (e.g., excessive friction or temperature), or a specific fault such as cracking or localized metal flaking. Manipulating the state consists of essential signal processing operations to transform sensor data to a usable format for the next stage.

- **State detection**

The manipulated state is further processed in the state detection stage with the objective of isolating the state or the fault. Fault isolation is defined by Isermann (Isermann, 2006) as "*Determination of the kind, location and time of detection of a fault*".

- **Health assessment**

This stage deals with monitoring the fault's progression; this process is defined as, "*characterization of the change in severity of a fault over time"*, ISO 13372 (ISO, 2012b). The severity or the fault size is tracked, through the condition indicator (CI). This is analyzed as a time variant parameter in order to calculate the instantaneous growth rate of the severity.

- **Prognostics**

The objective of prognostics, according to ISO 13372:2012 (ISO, 2012b), is the "*analysis of the symptoms of faults to* *predict future condition and remaining useful life*". Prediction of the future condition is possible through trending the time-variant CI from the health assessment stage. The remaining useful life (RUL) can be determined by estimating the time progression of the CI trend when it intersects with its maximum value (i.e., maximum allowable degradation prior to a critical repair). The fault progression is influenced by many factors such as aircraft utilization, environmental impacts, and fatigue life. Some studies in the literature investigate complex usage models to estimate RUL, considering significant variants (Vachtsevanos, Lewis, Roemer, Hess, & Wu, 2006).

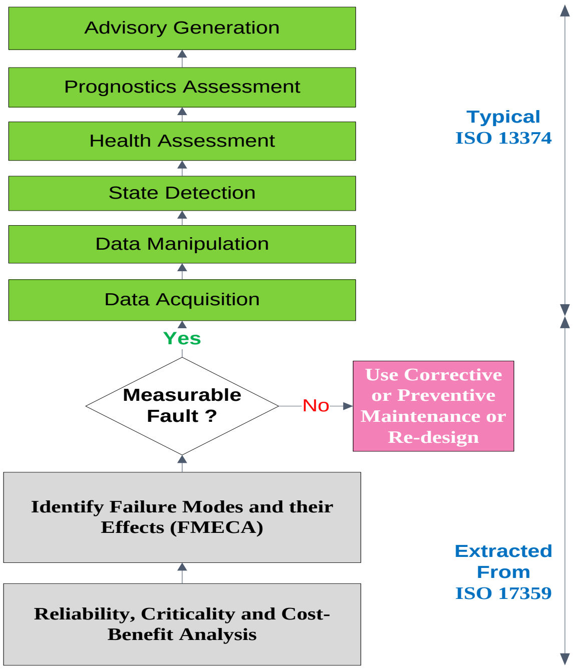

Figure 2. The PrM development and functional architectures based on ISO 13374:2012 (ISO, 2012a) and ISO 17359:2011 (ISO, 2011).

III SCHEDULED MAINTENANCE SCENARIO FOR EMA

The strategy of an MSG-3 based maintenance program for primary flight control EMA may lead to similar scheduled operational tests for possible EMA degradations such as: rolling fatigue for bearings and ball-screw; and backlash or general wear and lubricant initiated faults. The process of changing FBW actuation technology to EMA will not significantly reduce unscheduled events since the maintenance tasks to be applied are based on same scheduled tasks of MSG-3 due to following aspects:

- **MSG-3 is developed on standard utilization**

Aircraft manufacturers provide the recommended scheduled maintenance plan based on MSG-3 via a technical document, the maintenance-planning document (MPD) (Kinnison, 2004). The MPD is developed by assuming standard flight missions (i.e., average utilization and flight duration) and environmental effects (Marušić et al., 2009). However, unscheduled maintenance events are still unavoidable due to the varying local operational conditions the different air operators have to work with.

- **MSG-3 is based on a large population**

Preventive maintenance systems (e.g., MSG-3 based) include check intervals estimated to achieve the best maintenance performance. These are based on statistical distributions founded on the statistics of a large population of an item (e.g., flight actuator) (Mobley, 2002). This process leads to unscheduled events for air operators. Conversely, PrM is developed to account for each individual item by monitoring its degradation according to specific usages and operational and environmental effects (Mobley, 2002). For example, a PrM for 1000 actuators has typically 1000 different health assessment indicators i.e. one different value for each actuator. However, from a scheduled maintenance viewpoint, an inspection interval of a certain number of flight-hours (FH) can be an effective average maintenance interval for all 1000 items, so collectively minimizing the need for unscheduled actions.

- **Interchangeability of flight missions**

Several operational variations influence actuator life, including flight duration and operating abnormalities (Cooper, 2014). For example, a flight cycle of one FH will have higher cycling fatigue (i.e., takeoff and landing) than another one of 1.5 FH. There are also operating abnormalities, which affect actuator service life. For example, the actuator may work beyond its maximum load for short intervals. This is not a fault, and it is tolerated by the fault detection system. However, the actuator usage (i.e., material accumulative degradation) is significantly increased (Costes et al., 2012). This presents unavoidable deviation between the theoretical estimated life (i.e., inherent reliability) and the actual service reliability.

IV PRM SCENARIO BASED ON MODIFIED MSG-3 TASKS

Here, we discuss the similarity between PrM functional architecture, i.e. ISO 13374:2012 (ISO, 2012a) explained in Section 2.3, and MSG-3 maintenance requirements.

- **Data acquisition and state manipulation**

In reference to the generalized ISO 13374:2012 (ISO, 2012a) of Figure 2, the data acquisition and state manipulation processes may be implemented in maintenance BITE units via the implementation of two upgrades. The first one is to convert BITE from its current interactive functionality (i.e. manually activated) to automatic functionality. For example, a BITE unit is attached to the flight control EMA that automatically monitors EMA degradation (e.g. through measuring electrical current or vibration) in the course of each pre-flight check. Normally, a civil aircraft will have a pre-flight check for primary flight controls, and this will involve actuator movement. For the A320, there may be five pre-flight checks stored daily in the BITE unit, depending on the designed sampling interval of the diagnosis and prognosis techniques in use. The second upgrade is the possibility of transferring these stored measurements of BITE to an air operator maintenance center for further fault diagnosis and prognosis. If off-line processing is assumed, this might be achieved by using the local WIFI network of the airport to send stored measurements during the on-ground phase.

- **State detection**

This stage is similar to performing an operational test in MSG-3. Both activities aim to provide a qualitative assessment of a fault. A qualitative test does not involve any condition indicator or severity quantification. Further processing of the data for health assessment requires the measurability of the fault - as stated in ISO 17359:2011 (ISO, 2011) and shown in Figure 2.

- **Health assessment**

This stage is similar to performing a functional test in MSG-3: both activities involve a periodic quantitative test. A quantitative test implies that there is a monotonic condition indicator, which provides the ability to track (i.e. quantify) fault severity. The functional test of MSG-3 scheduled maintenance is associated with a relatively long interval of several flight hours, whereas the PrM health assessment uses quite short intervals (e.g., a few milliseconds, or few hours). To customize the functional test to fit within the typical health assessment terminology, the test should be automatically performed rather than manually instigated, as in BITE. In addition, its executing interval, e.g. several hundred FH, must be decreased to several FH - depending on fault growth rate and the prognosis technique in use.

Table 2. Proposed mapping of MSG-3 and ISO 17359:2011.

L	Modified MSG-3 task	PHM ISO TC108
4	Reliability program (MRP) to trend and extrapolate fault CI	Prognosis and advisory generation
3	Functional test to estimate fault CI	Health assessment
2	Operational test to confirm fault detection	State detection
1	BITE hardware modified to be automatically activated in short intervals	Data acquisition and state manipulation

- **Prognostics and advisory generation**

A major challenge of fault prognosis is to manage the expected high uncertainty, which is associated with predicting future condition. We propose here an approach to performing the required CI trending process for RUL estimation (explained in Section 2.3) using MRP. The MRP already involves most of the operating and performance data. The MRP will -involve, in time-based packages, fault CI - as well as all available operating conditions (Figure 1) - from the health assessment stage, and then statistically extrapolate them into the future in order to predict future conditions. The RUL will be estimated using all operational experience of MRP. This may provide a more realistic utilization of the prognostics principles than using complex usage models for each individual item or system. A summary of the proposed mapping between the objectives of a PrM system according to ISO 17359:2011 (ISO, 2011) and the current standard maintenance tasks of MSG-3 is given in Table 2

V PRM FOR MONITORING ROLLING FATIGUE – A CASE STUDY

In this section, we briefly explore reasonable performance metric for a PrM system dedicated to a mechanical fault in a key EMA component: a localized rolling contact fatigue (RCF) spall in a ball bearing. In addition, this exploration is very nearly applicable to the failure of the ball screw. The RCF is the primary failure mode of the electric motors, which are critical parts of many different EMA designs (Mobley, 2002).

5.1 Fault-failure mode of concern

The RCF has two phases: an initiation, which occurs before the formation of a localized fatigue fault (i.e. spall), and a progression phase up to maximum spall size (i.e., failure condition). There are two types of prognosis: fault prognosis and usage prognosis (Mobley, 2002). The first one estimates RUL after fault initiation, i.e. monitoring fault progression, which is considered in this paper. In contrast, usage prognosis aims to estimate RUL before initiating the fault by using physical or empirical usage models (Mobley, 2002).

5.2 Sensing technology

The potential of a PrM system is significantly proportional to how early a fault can be recognized (Torhorst et al., 2014; Vachtsevanos et al., 2006). The EMA provides several electrical measurements (e.g., phase currents and voltages), which are available in all modern EMAs. However, their capacity to detect incipient spall faults is limited compared to that of vibration and acoustic sensors (Mobley, 2002; Sawalhi, 2007). The cost of incorporating additional sensors (e.g., accelerometers for measuring vibration) should be justified by their cost-saving impacts on the maintenance operations.

5.3 Fault detection

This stage deals with the qualitative features of the fault. Is it necessary to launch an immediate maintenance operation after detecting the fault, or is there a tolerable margin for prognostics because the severity is less than a certain threshold?

A tribological study indicates an initial spall size of 0.2 mm^2 (Swansson & Favaloro, 1984), which may be used as a datum level. Of note, a maximum safe spall size may vary between different EMA design specifications. One of the ball bearing manufacturers mentions a maximum size of 0.01 inch^2 or ≈ 6 mm^2 (Sawalhi, 2007). Consequently, the spall will be assumed tolerable if its size lies between 0.2 and 6 mm^2. A spall size of larger than 6 mm^2 may indicate a non-tolerable failure condition.

Multiple spalls can be considered an advanced degradation state (i.e., failure). Such a situation cannot be guaranteed to keeping propagation to a predictable and relatively safe trend. The fault detection technique should process sensor data and decide upon further health assessment and prognostic processing if:

- The existence of a spall is confirmed with reasonable confidence.
- The fault is a single spall or separable multiple spalls; otherwise, the effective monitoring of spall progression is not possible and an immediate maintenance overhaul is required.

5.4 Health assessment

A health assessment for spall faults requires a condition indicator (CI), which has the following attributes (Ismail, Sawalhi, & Pham, 2015): monotonic trend, high sensitivity and presenting statistical confidence i.e. the standard deviation of CI. Achieving these with acceptable efficiency is still a significant research challenge according to the current condition monitoring literature (Randall, 2011); however, we have published two possible approaches that give promising results for the ball-bearing (Ismail et al., 2015) and for the ball screw (Ismail, Balaban, & Spangenberg, 2016).

5.5 Prognostics horizon

The ultimate goal of a PrM system is to provide, as early as possible, a reasonable prediction time for a future condition. This performance metric is denoted as prognostic horizon (PH). The PH is the maximum achievable lead-time starting from the confirmed detection of a small fault and ending at an instant in the future, at which that fault's severity will reach its maximum limit (Vachtsevanos et al., 2006). The exploration of a feasible PH range for flight control EMAs can be related to possible aircraft downtime opportunities. For an aircraft similar to the A320, which has a daily utilization of 5-6 FH (Rößler et al., 2009), we propose a minimum PH of about 6 FH in order to have the ability to move any repairing activities to the next overnight shift. A maximum PH of 500-600 FH may achieve the greatest benefits because the repair can be moved to the nearest scheduled downtime for ‘A’ check maintenance. The aircraft systems can be categorized into two groups: the first has its optimum maintenance performance with current scheduled maintenance checks, while the other has its optimum performance with a PrM system. Examples of the first group are all minimum-equipment-list (MEL) items that have a long rectification time. The MEL is an essential tool to manage unscheduled repairs. If an item has a non-zero MEL rectification time, this implies that the aircraft can dispatch with it in inoperative (i.e. faulty) condition for a maximum time equating to the MEL rectification interval. If this interval satisfies operator needs, the PrM will be useless.

We can explore three examples in regard to the A320: ailerons, elevators, and spoilers. An inoperative aileron has a MEL rectification intervals of 10 days, the PrM can be of benefit by increasing its rectification time. An inoperative elevator has a zero MEL time; the PrM can have its greatest potential benefit for an item without MEL conditions. An inoperative spoiler is equivalent to the aileron case of 10 days MEL time. Although spoilers are categorized as secondary flight controls, they have the same effects of disturbing dispatch conditions.

CONCLUSION

The potential benefits of utilizing prognostics based maintenance (PrM) have been explored via three approaches. The first, aims to integrate the standard functionality of PrM with the maintenance regulation of MSG-3. Both standards are similar in their objectives; thus, PrM systems may be implemented using MSG-3 originated tasks. The second approach is concerned with the prognostic stage of PrMs. Predicting future maintenance needs by investigating usage models is negatively influenced by multiple operational variants and uncertainties. Instead, we proposed utilizing the data from operators’ reliability program as an assistant knowledge to estimate the future health state of PrM items. The third approach is one focusing on exploring possible PrM performance metrics (e.g. prognostic horizon) with regard to a specific failure, rolling contact fatigue of an EMA. PrM benefits are influenced by the random nature of a fatigue fault's initiation and progression rate. While the detection of fatigue faults, (e.g. using vibration), is well established, the tracking of the fault severity is a methodology, which is still in its infancy. This problem can be mitigated by incorporating a preliminary fault detection stage to confirm fault existence as well as to isolate inadequate prognostic conditions. The greatest benefit of a PrM is seen when MEL ‘GO’/’GO IF’ conditions are not applicable to an item (e.g. the A320 elevator), whilst the least benefit is associated with items, which have MEL conditions for dispatching (e.g. A320 ailerons as well as spoilers).

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