

An Approach to the Health Monitoring of a Pumping Unit in an Aircraft Engine Fuel System

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ABSTRACT

This paper provides an approach for health monitoring through an early detection of failure modes premises. It is a physics-based model approach that captures the knowledge of the system and its degradations. The component under study is the pumping unit such as those found in aircraft engines fuel systems. First, a complete component analysis is performed to determine its potential degradation and a physics-based relevant component health indicator (CHI) is defined. Then, degradations are modelled and their impacts on the CHI are quantified using an AMESim[®] physics-based model. Assuming that in-flight measures are available, a model updating is performed and a healthy distribution of the CHI is computed. Eventually, a fault detection algorithm is developed and statistical validation is performed through the computation of key performance indicators (KPI). In parallel, a degradation severity indicator (DSI) is defined and prognostic is performed based on the monitoring of this DSI.

1. INTRODUCTION

In the modern aircraft engines industry, increasing products availability is of paramount importance. Undeniably, delays and cancellations caused by unanticipated components failures generate prohibitive expenses, especially when failures occur on sites without proper maintenance staff and equipments. In order to minimize the occurrence of these unexpected costly flight failures and to extend system availability, Prognostic Health Monitoring (PHM) system has become a necessity by performing continuous diagnosis and capturing the current health state of the component.

A PHM system (Sheppard, Kaufman and Wilmer 2009) ideally performs fault detection, isolation, diagnostics (determining the specific fault mode and its severity) and prognostics (predicting accurately remaining useful life). Whereas fault detection and diagnostics have been the subject of considerable emphasis (Isermann 1997, Basseville 1998, Balaban, et al. 2009), prognostics has gradually emerged as a research topic that can push the limits of health management systems, particularly in aeronautics (Byington, et al. 2004, Orsagh, et al. 2005, Massé, Lamoureux and Boulet 2011). With the recent development of smart materials, PHM also relates to the reliability of structures or Structural Health Monitoring (SHM) (Mechbal, et al. 2006).

If significant research efforts have been done in the field of PHM, there still remains a huge gap between academic research and industrial expectations. On the one hand, the industrial approach to health monitoring rarely integrates physics-based models to simulate degradations and perform validation of fault detection and diagnostics and on the other hand, the academic approach rarely integrates all the constraints due to on-board exploitation, such as sampling frequency and storage limitations, imposed sensors number and location, or limited computation capabilities. The main purpose of this paper is to merge numerical model-based and statistical data-driven approaches to perform fault detection and prognostics on an actual system in its in-service functioning environment.

It is evidence that a lot of information could be extracted from the huge quantity of data recorded during a flight. One of the aircraft engine subsystems, which in case of failure may result in significant maintenance cost to an airliner, is the fuel system. Nevertheless, despite its critical function, the aircraft engine fuel system or its components are almost never cited as potential candidates for health monitoring. In response to this lack, we have conducted a complete study on this subject. The aim of the present paper is to apply fault

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detection and prognostic to one of the main component of the fuel system: the pumping unit. The other novelty of this work is to use a numerical model to quantify the CHI's sensibility to degradations in order to create degraded data from operating measures.

The remainder of the paper is organized in five sections following the five main parts of the proposed development method: health monitoring perimeter definition; data analysis, system and degradation modeling; simulation results and statistical validation. An additional part deals with prognostics issue. We conclude and present future works in a latter section.

2. HEALTH MONITORING PERIMETER DEFINITION

2.1. Aircraft Engine Fuel System Analysis

To perform health monitoring of the pumping unit, it is essential to study the whole aircraft engine fuel system because each component contributes to the pressurization of the hydraulic circuit.

The system is composed of the following components, as presented in Figure 1:

- The **bypass valve** regulates the flow entering the fuel metering valve
- The **fuel metering valve** doses the flow to injectors
- The **pressurizing valve** maintains a constant pressure drop between P_{hp} and P_{lp}
- The **switch valve** switches between two configurations of an external system

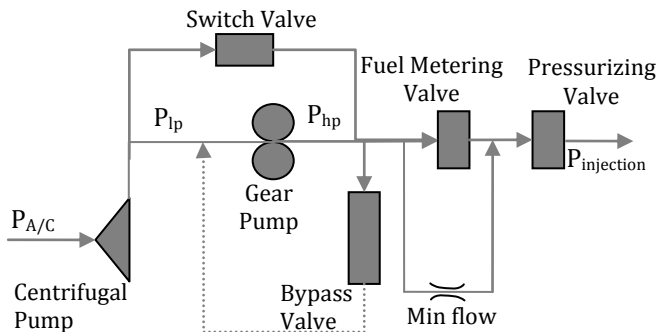


Figure 1: Architecture of an aircraft engine fuel system

In the figure above, $P_{A/C}$ is the supply pressure provided by aircraft fuel tank, P_{lp} is the low pressure at the outlet port of the centrifugal pump and P_{hp} is the high pressure at the outlet of the gear pump. $P_{injection}$ is the injection pressure in the combustion chamber.

2.2. Degradation Modes of the Gear Pump

Thanks to expertise, experience feedback and Failure Mode and Effects Analysis (FMEA), two main degradation modes were selected.

Definition 1:

For a gear pump, an internal leakage Lkg_{int} is a leakage between inlet and outlet of the pump. It's mainly due to contamination of hydraulic fluid which results in abrasion of gearings surfaces.

Definition 2:

For a gear pump, an External leakage Lkg_{ext} is a leakage to the exterior of the pump. It's mainly due to vibrations and aging of mechanical parts or joints.

2.3. Component Health Indicator

To monitor the state of the gear pump, a feature extracted from measures and named Component Health Indicator (CHI) is defined.

Definition 3:

The CHI is a physical measure (or function of it) that allows, by monitoring its changes, to inquire about the health of a component.

In the case of gear pump monitoring, the chosen CHI corresponds to the rotation speed of the pump at the opening of the switch valve, named ω_{swv} . It corresponds to the rotation speed for which hydraulic power is high enough to open the valve. Thus, an increase of ω_{swv} could indicate that the pump is less efficient. The valve opening is confirmed at fifty percent of the whole stroke. An example of ω_{swv} extraction is given in Figure 2.

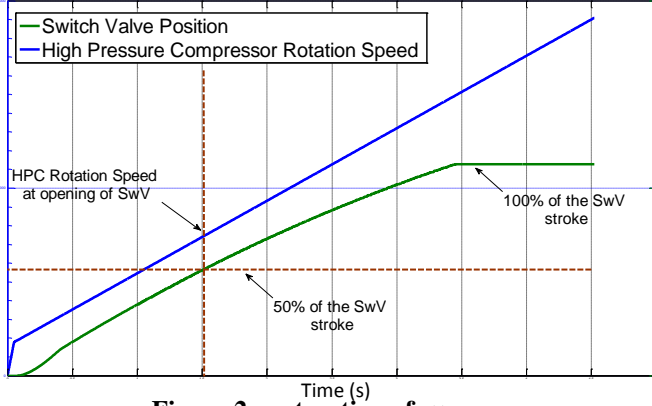


Figure 2 : extraction of ω_{SwV}

3. DATA ANALYSIS

In the case where measures are available and assuming that at the time of their recording, the system was faultless, a healthy distribution of ω_{SwV} can be computed. In this example, the healthy reference distribution comes from statistical analysis of about 400 start sequences of test flights as shown in Figure 3.

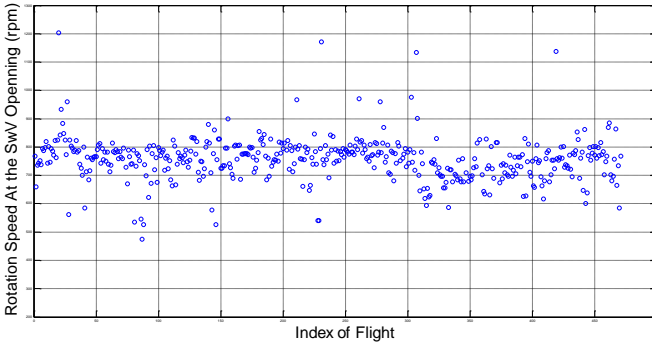


Figure 3 : Results of CHI Extraction

Then, the histogram of the distribution is given in Figure 4 with its maximum likelihood associated function. Without loss of efficiency, we assume that the distribution follows a normal law $N(\mu_{healthy}, \sigma_{healthy})$ where $\mu_{healthy}$ is the mean of the healthy distribution and $\sigma_{healthy}$ is its standard deviation.

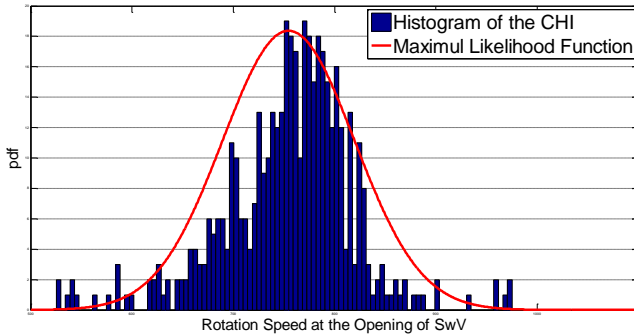


Figure 4 : Distribution of Healthy State

4. SYSTEM AND DEGRADATION MODELING

4.1. Gear Pump Behavior Modeling

Some related works on the subject have addressed the issue of modeling a gear pump and their degradations. For example, Casoli *et al.* (Casoli, Andrea and Franzoni 2005) have proposed a method to model a gear pump with AMESim[®] and Fritz and Scott have developed a wear model (Frith and Scott 1994).

In the developed AMESim[®] model the pump outlet flow is then expressed as in (1):

$$Q = \alpha \cdot \eta_{vol} \cdot disp \cdot \omega \quad (1)$$

where Q is the pump outlet flow, $disp$ the pump displacement, η_{vol} the volumetric efficiency and ω the pump rotation speed. The expression used to compute the volumetric efficiency is given in (2), i.e.,

$$\eta_{vol} = 1 - \left\{ \left[1 - \left(\beta - \frac{\gamma \cdot \Delta P}{\omega} \right) \right] \cdot \left[1 + \delta \cdot \frac{T_{inlet}}{\omega} \right] \right\} \quad (2)$$

where ΔP is the pressure drop between pump inlet and pump outlet, T_{inlet} is the fluid temperature at the pump inlet and β, γ, δ are empirical constant values.

4.2. Fuel System Modeling

The whole aircraft engine fuel system is modeled from classic AMESim[®] blocks.

The model variables are given in Table 1.

<i>Input</i>	Curve of rotation speed versus time $\omega = f_{speed}(t)$
<i>Parameters</i>	- Fuel Temperature T_{fuel} - Aircraft Supply pressure $P_{A/C}$
<i>Output</i>	ω_{SwV}

Table 1. Model Variables

4.3. Degradation Modeling

To simulate the influence of all the potential faults, we introduce them into the AMESim[®] model. Internal leakage is modeled by a diaphragm with a variable section between pump inlet and pump outlet (Figure 5a) and external leakage is modeled by a diaphragm between pump outlet and external tank at atmospheric pressure (Figure 5b).

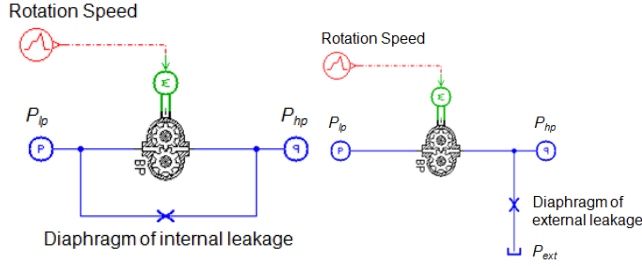


Figure 5 : AMESim® modeling of a) internal leakage and b) external leakage

5. SIMULATION RESULTS

The purpose of this part is to determine the sensibility of ω_{SwV} to degradations. The behavior of the system is simulated for nominal T_{fuel} and $P_{A/C}$. The function f_{speed} is approximated by a linear curve to simulate the behavior of the pump during the start sequence.

5.1.1. Maximal Degradation Intensity

The degradation intensity I is defined as the leakage flow crossing the diaphragm (Figure 5) at 10% of the maximal rotation speed.

The Maximal Degradation Intensity, named I_{max} is the intensity for which the system is in a non functional state. In this case, the I_{max} is reached when the pump is not able to deliver the sufficient flow needed for the start sequence.

I_{max} is calculated from specification of the minimal pump outlet flow allowed at 10% of the maximal rotation speed.

The maximal intensity is different for each degradation so both $I_{max}^{Lkg_{int}}$ and $I_{max}^{Lkg_{ext}}$ are computed.

5.1.2. Model Updating

The model updating is performed based on the comparison between $\mu_{healthy}$ and ω_{SwV} simulated in the nominal flawless state. To perform the updating, some parameters of the model, such as the displacement of the pump or the calibration of the Switch Valve sensor are adjusted.

5.1.3. CHI sensibility results

Degradations of increasing intensities up to I_{max} are simulated to quantify the sensibility of ω_{SwV} . Results are given in Table 2.

Type of Degradation	Intensity of Degradation	Value of the CHI
Internal Leakage	0	750
	Low: $I_{max}^{Lkg_{int}}/4$	826

External Leakage	Medium: $I_{max}^{Lkg_{int}}/2$	893
	High: $I_{max}^{Lkg_{int}}$	1027
	0	750
	Low: $I_{max}^{Lkg_{ext}}/4$	770
	Medium: $I_{max}^{Lkg_{ext}}/2$	834
	High: $I_{max}^{Lkg_{ext}}$	981

Table 2. Simulation Results

6. STATISTICAL VALIDATION

Statistical validation is based on the comparison between the measured distribution of the healthy state and the estimated distribution of the faulty states given by specific transformation laws applied to the CHI.

6.1. CHI Transformation Laws

Definition 4:

CHI transformation laws (CHI_{TL}) are functions calculating the variation of a CHI for a given degradation with a given intensity. The typical form of a CHI_{TL} is given in Eq. 3.

$$I^{deg} \xrightarrow{CHI_{TL}^{deg}} \Delta CHI^{deg} \quad (3)$$

For example, considering ω_{SwV} and degradation Lkg_{int} , transformation law $\omega_{SwV_{TL}^{Lkg_{int}}}$ gives the variation of ω_{SwV} , named $\Delta\omega_{SwV}^{Lkg_{int}}$ as a function of the degradation intensity $I^{Lkg_{int}}$.

For each degradation, a CHI_{TL} is defined and can be apply to a real distribution of CHI as following (4).

$$CHI^{deg} = CHI^{healthy} + \Delta CHI^{deg} \quad (4)$$

where CHI^{deg} is the estimated value of the CHI in presence of deg and $CHI^{healthy}$ is its healthy value.

The two $\omega_{SwV_{TL}}$ are computed by applying a linear regression between degradation intensities and ω_{SwV} values. The results are given in Eq. 5 and Eq. 6.

$$I^{Lkg_{int}} \xrightarrow{\omega_{SwV_{TL}^{Lkg_{int}}}} S^{Lkg_{int}} \times I^{Lkg_{int}} \quad (5)$$

$$I^{Lkg_{ext}} \xrightarrow{\omega_{SwV_{TL}^{Lkg_{ext}}}} S^{Lkg_{ext}} \times I^{Lkg_{ext}} \quad (6)$$

with $S^{Lkg_{int}}$ and $S^{Lkg_{ext}}$ coefficient of linear regressions. Figure 6 gives an exemple of how $S^{Lkg_{int}}$ is calculated.

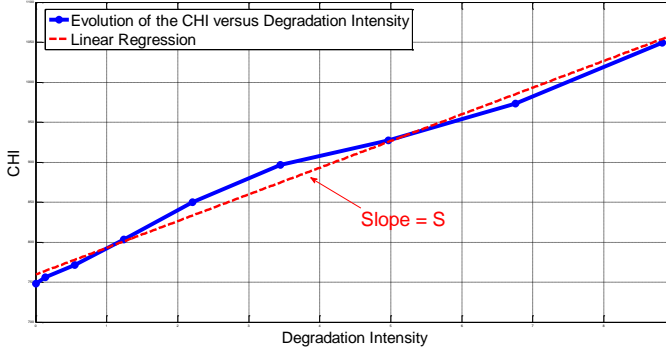


Figure 6 : Exemple of coefficient S computation

6.2. Application of the CHI Transformation Laws

Once $S^{Lkg_{int}}$ and $S^{Lkg_{ext}}$ are computed, $\omega_{SWV_{TL}}$ can be applied to the real healthy distribution to construct a degraded CHI defined by:

$$\omega_{SWV_I}^{deg} = \omega_{SWV}^{healthy} + S^{deg} \times I^{deg} \quad (7)$$

with $\omega_{SWV_I}^{deg}$ the constructed degraded value of ω_{SWV} for degradation, deg , of intensity I and $\omega_{SWV}^{healthy}$ the measured value of the ω_{SWV} . In the case of internal leakage flaw, results are given in Figure 7.

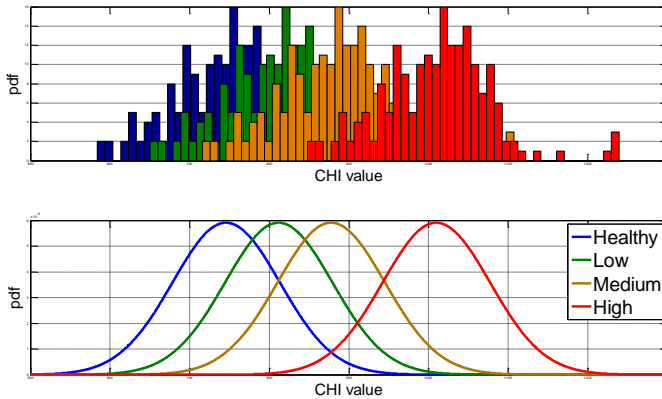


Figure 7 : Distribution of CHIs

6.3. Key Performance Indicators

In aeronautics, because of the modular architecture, the main part of maintenance operations is the troubleshooting, which consists in finding the faulty Line Replaceable Unit (LRU) to change it. It means that in the diagnostic process, only isolation and not identification is of paramount importance. As the two degradations considered in this study affect the same unit, only fault detection is addressed. A complete signal detection theory can be found in (Wickens 2002).

Definition 5:

A *Key Performance Indicator (KPI)* is an indicator of the monitoring system efficiency. Its required value is given by specifications.

For example, in aeronautics, specifications usually require a less than 5% false negatives and less than 20% false positive (Table 3).

KPI	Definition
False Positive (FP) Rate	Proportion of False Positive (false alarms) among the states for which a fault is detected (see Figure 8)
False Negative (FN) Rate	Proportion of False Negative (undetected faults) among the states for which no fault is detected (see Figure 8)

Table 3. Key Performance Indicators

6.4. Detection Threshold Selection

Thanks to $\omega_{SWV_{TL}}$, degraded data is computed from real healthy data. Once degraded data is estimated, detection threshold Thr can be defined.

Typically, the chosen value for Thr is calculated from Eq. 8 where A is a positive real.

$$Thr = \mu_{healthy} + A \times \sigma_{healthy} \quad (8)$$

The graphical meaning of A is given in Figure 8. In this figure, false negative and positive are represented for Thr calculated with $A = 2$.

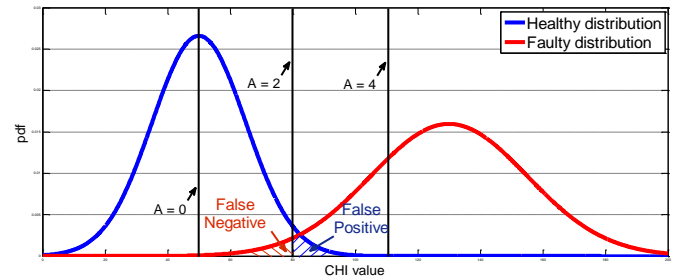


Figure 8 : definition of the coefficient A

6.5. Statistical Validation

As explained previously, only fault detection is performed in this study. For example, the KPI for medium and high degradation levels of the internal leakage are presented in Table 4 and associated ROC curves in Figure 9.

Internal Leakage → Medium			Internal Leakage → High		
A	FP	FN	A	FP	FN
0	50%	2.4%	0	50%	0%
1	16.4%	16.4%	1	16.4%	0.2%
1.5	7.1%	31.5%	1.5	7.1%	0.7%
2	2.4%	50.6%	2	2.4%	2.6%

2.5	0.7%	69.6%	2.5	0.7%	7.4%
3	0.1%	84.3%	3	0.1%	17.2%

Table 4. Performance of fault detection

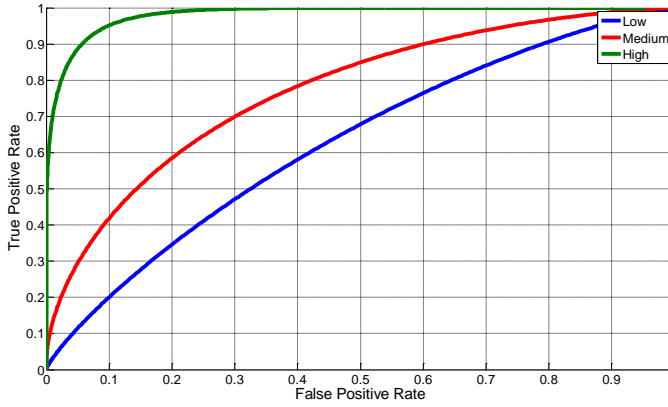


Figure 9 : ROC curves for Low, Medium and High Intensities

In aeronautics, degradations are detectable if the KPI are such as false negative rate is under 5% and false positive rate under 20%.

In conclusion, internal leakages of medium intensity are not detectable whereas those of high intensity are detectable with A equal to 1, 1.5 or 2. The results for the external leakage will not be exposed here but they are very similar.

7. PROGNOSTICS

The purpose of the prognostics is to prevent the CHI from reaching the $\omega_{SwV_{max}}$ value.

7.1. Degradation Severity Indicator

A Degradation Severity Indicator (DSI) is an index defined in order to quantify potential impacts of the degradation on the system operability. The higher the DSI, the more degraded the system.

In this paper, DSI for a start sequence N is defined as following:

$$DSI(N) = \frac{\omega_{SwV(N)} - \mu_{healthy}}{\omega_{SwV_{max}} - \mu_{healthy}} \quad (9)$$

In Eq. 9, $\omega_{SwV_{max}}$ refers to the maximal degradation intensity reachable before complete failure of the system.

7.2. Prognostics

The prognostics method defined in this paper is based on the trending analysis. The purpose is to estimate the Remaining Useful Life (RUL) of the pump by anticipating the moment when DSI will be greater than 1. The RUL is expressed in flights number. Aeronautics specifications usually require that degradations should be detected at least 20 flights before the occurring of the failure.

The method consists in calculating a linear regression on the past flights at each new flight and to predict the RUL assuming that the slope p remains the same. The value of the RUL is the estimated number of flights before crossing of the maximum DSI threshold (Figure 10). When the value of the RUL is estimated inferior to 20 flights, an alarm is sent to maintenance operators.

For the time being, there are no defined KPI for prognostics in aeronautics.

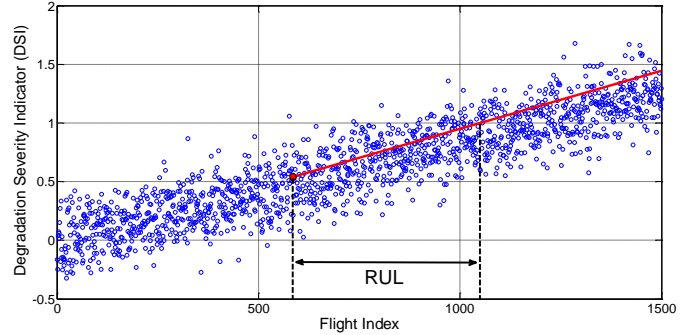


Figure 10: Remaining Useful Life Computation

To validate the method, some gradually degrading measures over 1500 flights are constructed thanks to $\omega_{SwV_{TL}}^{deg}$. Depending on the index of the flight N , the value of ω_{SwV} is given by Eq. 10.

$$\omega_{SwV}(N) = R(\mu_{healthy}, \sigma_{healthy}) + S^{deg} \times I_N^{deg}(N) \quad (8)$$

Where $R(\mu_{healthy}, \sigma_{healthy})$ designates a random selection of a ω_{SwV} value in the healthy distribution and I_N^{deg} is the function giving the intensity of the degradation versus the flight index. The function I_N^{deg} is normally derived from physics of failure but in this application, we suppose that it is a linear degradation growing from 0 to a maximal degradation intensity $\omega_{SwV_{max}}$ at flight 1000 (Figure 10).

In Figure 11, results of the alarm computation for the RUL are given and it can be noticed that some alarms occur around a hundred flights before reaching $\omega_{SwV_{max}}$. It shows that the method is efficient to anticipate failures by monitoring the DSI. However, there is still work to be done to limit false alarms.

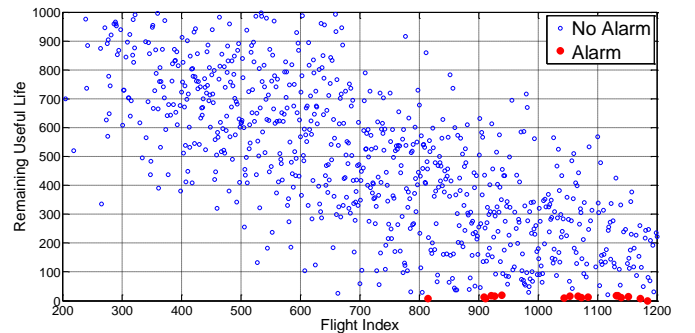


Figure 11: Remaining Useful Life Alarms

CONCLUSION

In conclusion, a method for the health monitoring of a pumping unit from the definition of physics-based indicators to the statistical validation of the Key Performance Indicators has been proposed. The main novelty of this paper is that after having defined physics-based Component Health Indicator, their sensibility is tested on a physic-based model constructed in the AMESim® environment.

The statistical validation showed that the Component Health Indicator defined was relevant to detect both internal and external leakages of a gear pump. A prognostics method was also addressed based on the Remaining Useful Life computation and proved to be efficient to anticipate maximum degradation severity threshold crossing.

For future prospects, the objective is to work on the improvement of fault detection and prognostics algorithms and to extend the PHM system to the whole aircraft engine fuel system. Besides, some KPI must be defined for prognostics.

NOMENCLATURE

ω_{swv}	CHI for the gear pump
Q	Outlet flow of the gear pump
η_{vol}	Volumetric efficiency of the gear pump
$\alpha, \beta, \gamma, \delta$	Dummy variables
T_{inlet}	Temperature at the pump inlet
ω	Rotation Speed of the Pump
T_{fuel}	Fuel Temperature
$P_{A/C}$	Aircraft Supply Pressure
$\mu_{healthy}$	Mean of Healthy Distribution
$\sigma_{healthy}$	Standard Deviation of Healthy Distribution
$I_{max}^{Lkg_{int}}$	Maximal Intensity of Internal Leakage
$I_{max}^{Lkg_{ext}}$	Maximal Intensity of External Leakage

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