Implementation of an Engine Condition Monitoring tool for Airbus Aircraft

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Abstract

The growth and development of the aviation industry means an increase in the on-flight data available to perform studies with the objective of enhancing airline operations. Data is collected through systems aboard the aircraft, being posteriorly decoded and stored at the Flight Data department. Statistical analysis, such as the one done by the application developed during the current dissertation, can be performed using this data. The developed tool allows the analysis of engine performance parameters through time and identifies situations that require intervention or may indicate malfunction of an engine's component. An algorithm that optimizes data processing in terms of time and computational resources required was also developed, as well as an interactive application that allows a dynamic analysis of the evolution of said parameters.
Keywords: Flight Data, Engine Condition Monitoring, Performance Trends, Corrected Gas Turbine Parameters, Stability Points.

1. Introduction

With the fast passed globalization and the growing need to bring people and goods closer together, airline companies became one of the most important players in the transport industry. Air transportation evolved from a luxury good to an accessible good and the number of passengers and flights has been increasing [8]. Even though maintenance costs are usually not the most significant costs of the airline activity [1], they are, usually, the ones most affected by management decisions which gives them a high degree of controllability. One way of reducing said costs, is by constantly monitoring the performance of the fleet's engines to assure they are running in the most safe and efficient way possible. This process is called Engine Condition Monitoring (ECM). ECM also allows for a better scheduling of maintenance stops and provides a precursor to actual engine failures that could lead to more extensive repairs. Technological advancements in both hardware aboard the aircraft and ground stations allow the use of more powerful statistic analysis. The increase of recorded data at disposal on flight recorders, the development of better sensors and the increased computational capabilities allow for a more comprehensive and accurate prognostic of problems of systems aboard the aircraft. Flight Data Monitoring (FDM) software is now, more than ever, able to promote a more efficient use of resources and a safer operation.

2. Condition-based Maintenance

The concept behind Condition-based maintenance is having the right equipment in the right condition at the right time. It is based on the analysis of real-time data to draw conclusions about the health of a given piece of equipment. This concept is based on the fact that most failures do not occur instantaneously, but rather through a deterioration process that can be monitored. This approach allows performing maintenance only when the equipment is actually needing it thus saving money otherwise spent on unnecessary maintenance stops. Despite its usefulness, there are several challenges to take into account. First of all, the investment costs of implementing the structure needed to perform the data collection and posterior analysis are considerably high. Secondly, introducing these changes in the maintenance philosophy of the company, will demand a greater level of synergy between the company's departments which can be difficult to accomplish due to the size of the organization. Also, the technical side of the implementation is not simple. Even if some types of equipments can be easily observed by measuring

common values such as temperature or pressure, it is not trivial to turn the measured data into actual knowledge about the health condition of the equipment.

2.1. Trend Monitoring

During normal operation all engines will experience rubbing, thermal stress, mechanical stress, dirt accumulation, foreign object ingestion and other events which will eventually result in a measurable decrease in efficiency. By continuously monitoring the evolution of key parameters that can translate engine condition, deterioration in engine performance can be detected as well as early signs of engine faults and thus appropriate measures can be undertaken. Parameter trend monitoring is by definition the process by which in-flight parameter measurements are processed and then compared to a baseline model that represents the expected behaviour of a given engine, taking into account ambient and thrust conditions, as if it was newly installed or at its best performance. The difference over time between measured data and the baseline model is called the parameter Delta. Monitoring the evolution of these deltas is what gives knowledge about the current state of an engine and allows an estimation of how its performance has deteriorated with each flight cycle. A summary of the engine condition monitoring parameters considered in the current document is made in Table 1. These parameters are considered to be the performance indicators, also known as engine Performance Parameters.

Table 1: Summary of parameters used in ECM

Parameter	Units
Exhaust gas temperature (EGT)	°C
Fuel flow (FF)	kg/hr
Low-pressure fan speed (N1)	%
High-pressure rotor speed (N2)	%
Engine Pressure Ratio (EPR)	N/A
EGT Margin (EGTM)	°C

2.1.1 EGT Margin

The EGT margin parameter deserves to be highlighted since it is one of the most important criteria used for engine removal due to excessive performance loss. EGT Take-off Margin is a durability and operability parameter. It represents the difference between actual (uncorrected) EGT levels, for a given take-off condition[1], and the EGT limits, also known as redline, established by the engine's manufacturer. Gas path temperatures above design limits can dramatically reduce hot section part life. The nefarious effects of overheating may include, corrosion of hot section metals, creep and stress rupture resilience of turbine blades and rotating components may be reduced by a factor of approximately two for a fifty degree increase in temperature, and additional inspection requirements, or premature engine removal. Figure 1 shows the representation of a hot section and the result of excessive EGT values.

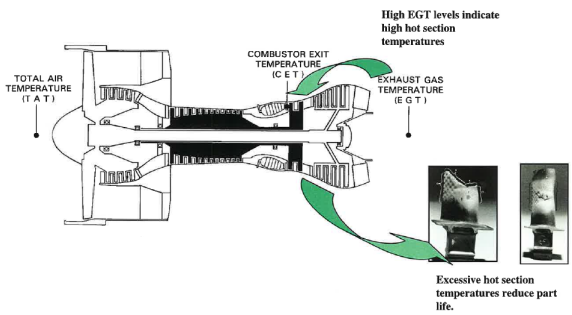

Figure 1: Pratt & Whitney engine. Effects of excessive EGT values [10]

As the engine deteriorates the EGT gets hotter and its margin decreases. With time, the EGT margin may become negative, which means it is no longer possible to reach Take-off thrust at the Flat Rate Temperature (FRT). The FRT is the temperature up to which the engine manufacturer guarantees the engine will produce the rated thrust. Also note that below the FRT, also called Corner Point Temperature (CPT), thrust can be limited by software for a more efficient take-off.

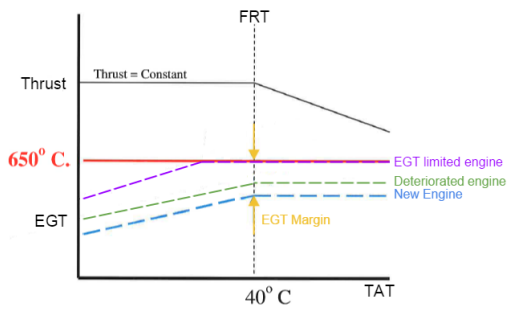

Figure 2: EGT Margin on different engine conditions. Adapted from [10].

EGT margin is one of the main indicators of engine deterioration and normally airline companies have a limit for the number of times it

[1] EPR, Mach Number, Altitude, Total Air Temperature and bleed conditions

can be exceeded. It also serves as an indicator of engine performance degradation, allowing the airline to monitor its evolution. After the number of exceedances is depleted or the EGT margin is consecutively low the engine will be subject to maintenance intervention. As the engine ages, due to normal engine wear, the EGT margin will start to gradually decrease. Indeed, due to a loss of efficiency, the engine will burn more fuel, which will lead to a higher EGT. The rate of degradation of these parameters is highly dependent on the rate at which the aircraft accumulates flight hours and cycles, the environments in which it operates and the care with which it is operated. The first step in generating EGT margin estimates is to collect actual take-off data. The accuracy of the data collection has a significant impact on the accuracy of the EGT margin estimate. To properly estimate the EGT margin, all relevant take-off data must be collected at the time EGT reaches a peak. The next step is to scan the data for the maximum value of EGT that occurs between the first time CAS[2] exceeds 120 knots and Radio Altitude (RALT) exceeds 1500 feet or climb is detected. Once the maximum value for the interval is found it is averaged with data obtained during the previous three seconds. It is recommended that during the data averaging period all isolation valves are closed and cowl and wing anti-ice valves and pneumatic system discrete do not change. Operators will sometimes try to recover some of the lost EGT Margin by performing small scale interventions on the engine. These include engine washes which, as it is possible to see in Figure 3, will recover some of the performance lost through the accumulation of flight cycles.

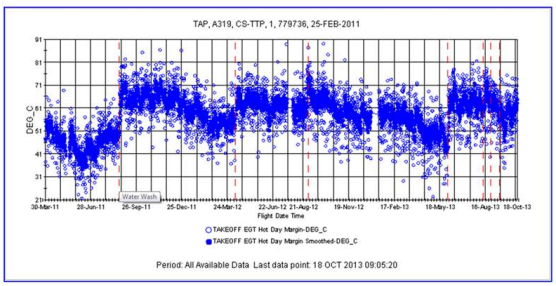

Figure 3: Engine Wash and its effects on the EGT Margin.

The red lines represent the dates where the engine wash was performed. Notice how the EGT margin instantly raises after these events and how it gradually starts to decay over time until the engine is washed again.

2.1.2 Baseline model and trend monitoring

Parameter trend monitoring is the process by which the recorded engine data is corrected and then compared to a baseline model of the engine. The difference, over time, between the measured performance and the expected performance based on the engine's baseline is the parameter Delta, allowing to assess an engine's condition. In the early days, baseline models would be provided to the operators by the manufacturers and trend monitoring would be conducted by manually calculating the parameter Deltas. Figure 4 showcases an example of traditional cruise characteristic curves for a JT3C-6 turbojet engine. In this case the EGT, FF, N1 and N2 are plotted as a function of the EPR and for different Mach Number. Today's ECM tools automatically record data from the engines and perform trend analysis, making this information available to the operators.

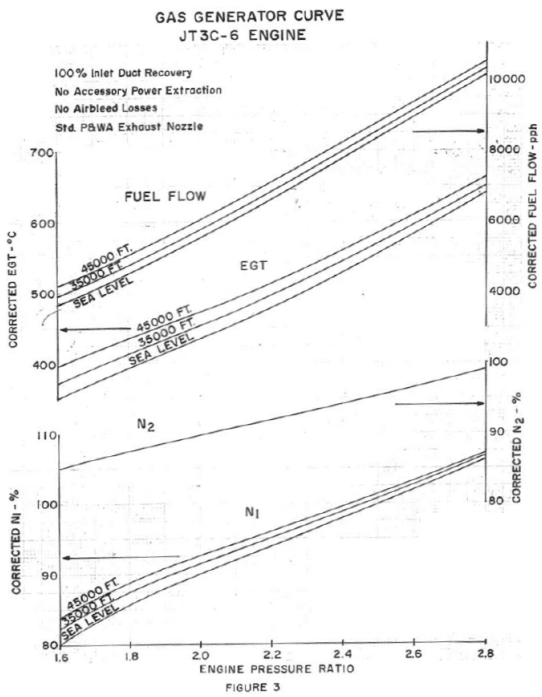

Figure 4: Cruise Performance Characteristics for the JT3C-6 engine [4].

Baselines allow for an estimation of the expected engine behaviour for different thrust conditions. The models presented in Figure 4 use the EPR as thrust reference, but this is not mandatory and other references can be used. Engine manufacturers derive their Baseline models by

[2]Calibrated airspeed is the speed shown by a conventional airspeed indicator after correction for standard see level condition.

testing each engine before leaving factory in new condition, and assuming that an engine is at its best performance when new, these Baselines are a good reference for measuring performance degradation. The fact that manufacturer's Baselines are no longer available to the operators makes conducting studies like the one made in the current document infeasible unless a Baseline is derived from in-flight data.

2.2. Parameter Corrections

The measured engine parameters values vary not only with the power condition but also with ambient conditions at the engine's inlet [13]. A change in the inlet temperature and/or pressure is coupled with a change in the gas path parameter's values, which makes it difficult to establish a common ground for the thermodynamic relationships between gas turbine parameters unless ambient conditions are accounted for. This issue is solved by correcting the engine parameters. For convenience will a two shaft turbofan with station numbers, as shown in Figure 5, will be assumed.

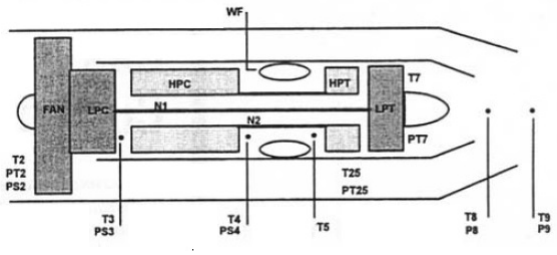

Figure 5: Twin spool mixed flow turbofan [13].

2.2.1 Formulation

For a given gas path parameter k, the equivalent corrected parameter will be represented by k'. Generally speaking a change in the inlet conditions, temperature T_2 and pressure P_2, will imply a change in any downstream gas path parameters k. The purpose of the corrected parameter k' is to give a constant approximation to a value regardless of changes in inlet conditions, in other words it represents the value that k would have at some fixed inlet condition. The reference conditions can be set freely, however, it is common practice to select standard day conditions[3]. It is fair to assume without loss of generality that $k = f(T_2, P_2, k')$ thus following equations 1 and 2.

$$dk = \left(\frac{\partial k}{\partial T_2}\right) dT_2 + \left(\frac{\partial k}{\partial P_2}\right) dP_2 + \left(\frac{\partial k}{\partial k'}\right) dk' \quad (1)$$

[3] $T_0 = 288.15$ K, $P_0 = 1013.25$ hPa

$$\frac{dk}{k} = \left(\frac{\frac{\partial k}{k}}{\frac{\partial T_2}{T_2}}\right)_{\substack{P_2=const \\ k'=const}} \frac{dT_2}{T_2} + \left(\frac{\frac{\partial k}{k}}{\frac{\partial P_2}{P_2}}\right)_{\substack{T_2=const \\ k'=const}} \frac{dP_2}{P_2} + \left(\frac{\frac{\partial k}{k}}{\frac{\partial k'}{k'}}\right)_{\substack{P_2=const \\ T_2=const}} \frac{dk'}{k'} \quad (2)$$

Assuming that the first two partials are constant (the third clearly is constant and equal to unity) and substituting them for coefficient "a" and "b", respectively, we can simplify 1 and 2 as follows:

$$\frac{dk'}{k} \approx a\frac{dT_2}{T_2} + b\frac{dP_2}{P_2} + \frac{dk'}{k'} \quad (3)$$

If we now define two dimensionless parameters $\theta = T_2/T_0$ and $\delta = P_2/P_0$ it is possible to deduce an expression for k'.

$$\frac{dk'}{k'} \approx \frac{dk}{k} - a\frac{d\theta}{\theta} - b\frac{d\delta}{\delta} \Rightarrow k' \approx \frac{k}{\theta^a \delta^b} \quad (4)$$

Equation 4 is the parameter correction expression in use for the rest of this document. Table 2 summarizes some of the common gas turbine parameter corrections and commonly used values for coefficients a and b.

Parameter	**a**	b	Corrected Parameter
Rotor Speed (N)	0.5	0	$N' = \frac{N}{\sqrt{\theta}}$
Fuel Flow (FF)	0.5	1	$FF' = \frac{FF}{\sqrt{\theta}\delta}$
Temperature (T)	1	0	$T' = \frac{T}{\theta}$
Pressure (P)	0	1	$P' = \frac{P}{\delta}$

Table 2: Summary of common gas turbine parameter corrections ECM [13].

2.2.2 Limitations

The quality of the parameter corrections can be improved by using more sophisticated models to estimate the coefficients "a" and "b" instead of using typical or empirical values. Reference [7] offers details on how the coefficients may be estimated by running a full thermodynamic computer model of the engine over a range of inlet temperatures, pressures and exhaust conditions. The main issue is that the engine model is not accessible to operators, who do not possess detailed information to run high end simulations. This can be solved by making use of some empirical methods that use in-service data collected from the engine and some statistical analysis tools. An example of this kind of approach can be seen in reference [13]. Note that equation 4 doesn't take into account changes in viscosity with altitude. Even tough the effects of

differences in the Reynolds number might not be significant for some engine models, there can be errors related to the comparison of corrected parameters if this effect is not taken into account. Also, the ratio of specific heat and the gas constant are assumed to be insensitive to changes in the atmosphere which does not correspond to the reality even thought this is a common assumption when performing dimensional analysis on a gas turbine engine.

2.3. Performance deterioration detection

The simplest way to identify deterioration in engine performance or engine events that need to be looked into by the maintenance personnel is by analysing the trend of the engine's performance parameters over time and identify the effects of said events. Abnormal situations related to the engine condition, like mechanical changes in the engine that may result in failure or lead to the occurrence of incidents, normally imply an abrupt shift in the corresponding parameters. On the other hand, the effects of accumulated flight cycles resulting in wearing of engine's components and a decrement in its performance can be identified by a gradual increase over time of the parameter's Delta values. In the first situation described, also known as Step Shift, data suffers a shift that occurs in a short period of time as opposed to the Slow Drifts that are associated with a slow variation in the parameter's trend that occurs over a longer period of time. An effective monitoring of cruise trends helps minimizing the risks associated to unexpected engine failures and avoid excessive degradation of the engine's performance. Figure 6 showcases an example of an actual incident caused by a Low Pressure Turbine Clearance Control valve failure.

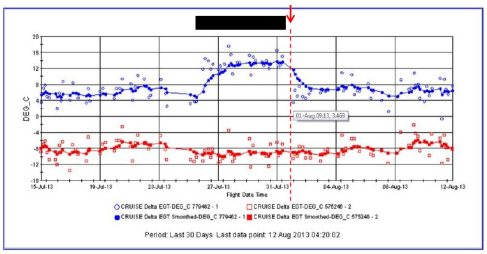

Figure 6: Delta EGT plot of an A320-200 engine.

Notice the abrupt change in the values of the Delta EGT for the engine in position 1, marked in blue, and another shift when the valve was replaced, marked with a vertical dashed red line. This kind of behaviour is what the engine maintenance personal is looking for when performing engine parameter trend analysis. Unfortunately the time period represented in figure 6 is not broad enough for a significant performance deterioration to be evident in the parameter Delta, however as discussed before loss of performance from accumulation of flight cycles is visible through a gradual increase over time of the Delta values.

2.4. Typically observed parameter shifts

Detecting abnormal trends in key performance parameters is an effective way of detecting possible ongoing problems or impending failures in gas turbine engines [11]. But even though it is possible to detect problems with a given engine by looking for Step Shifts in the engine's parameter deltas, it is also important to identify the source of the problem so appropriate actions can be undertaken. This can be solved by taking advantage of the fact that some anomalies produce similar shifts every time they manifest. By recording this standard shifts operators are able to estimate the source of the problem just by measuring the key engine's parameters deltas [12]. These standard shifts are also called anomaly's fingerprints and normally each engine manufacturer supplies a document containing a register of the fingerprints of the most common anomalies. The operator will use tables containing information from the fingerprints document as a starting point for a closer interpretation of the anomaly and in conjunction with its experience will be able to better assess the situation.

3. ECM and cruise trend analysis considerations

To monitor the performance of an engine it is necessary to be able to interpret data that can be representative of the engine's health. For data to be considered valid for trend analysis it needs to respect a set of conditions which makes it eligible to be considered a Stability Point for a given flight, as defined in [9]. Depending on the flight conditions there can be several stability points for a specific flight or in the worst case none.

3.1. Stability Point search criteria

The set of conditions used to search for stable frames can be divided into Basic Conditions and Stability Criteria. Their purpose is to avoid triggering reports when the parameters are of no interest. Basic Conditions may include ranges for values like Altitude(Alt), Mach Number(MN), N1 and even contemplate binary parameters like the engine's bleeds status. They serve as a first filtering criteria to exclude values that have no chance of being eligible for a stability point

calculation. As for the Stability Criteria they are used to rule out time frames where the values are not stable enough to translate accurate information about the engine's condition.

3.2. Fixed Window and Gliding Window stable frame search

There are two methods to perform stable frame search. The simplest method consists of making adjacent and consecutive windows with an equivalent length of a stable frame (100 seconds for instance), and then verify if all basic conditions and stability criteria are met for each individual window. This means that each measured value belongs only to a single window, the windows do not overlap each other. Another method for performing the search is called Gliding Window Search and implies overlapping the windows consecutively, taking a single window at time n and advancing it consecutively by i, getting N windows starting at $\{n; n+i; n+2i; n+3i; ...; n+Ni\}$, where N is given by equation 5.

$$N \leq \frac{t_a}{i}, N \in \mathbb{N} \tag{5}$$

Note that t_a represents the period of time where analysis is being performed and expressed in the same time unit as i. Figure 7 exemplifies the difference between both methods described.

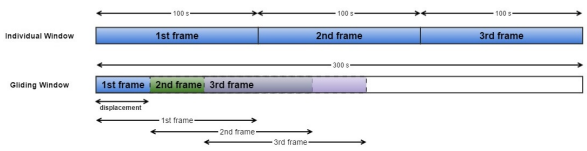

Figure 7: Fixed Window Vs GLidding Window search method [2]

For the development of the current work the selected method for stable frame search was the Gliding Window method with a 1 second displacement.

3.3. Quality Number

Using the conditions described in the previous sub-sections many stable frames will be found and therefore many stability points will be calculated. It is then necessary to have a consistent way of identifying and selecting only the ones that best represent what is happening to both the aircraft and its engines. It would also not be practical or efficient to store so many values per flight. Reference [3] suggests a criteria for selecting the best stability points from each flight. By calculating the Quality Number (QN) corresponding to each Stability Point, using equation 6, it is possible to have a measure of how reliable a stability point is.

$$QN = W_a \frac{{s^2}_a}{Tol_a} + W_b \frac{{s^2}_b}{Tol_b} + \cdots + W_P \frac{{s^2}_p}{Tol_p} \tag{6}$$

W_i represents the weight factor for each parameter $p \in P$, being P the set of all analysed parameters, and Tol_i its tolerance according to the defined Stability Criteria. The unbiased sample variance, s^2, can be calculated using equation 7.

$${s^2}_p = \frac{n}{n-1}{\sigma^2}_p = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2 \tag{7}$$

Note that n is the number of readings, or samples, in the observation window for a given parameter p and x_i a reading made at time i. The mean $\overline{x}$ can be obtained using the formula below:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{8}$$

The variance gives a measure of the dispersion of the samples to the mean. The stability point will be of better quality when the overall variance of its parameters is lower. As stated before a stability point will then be the set of all calculated $\overline{x}_p$, over the duration of a frame, with p belonging to the set of all analysed parameters P.

$$StabilityPoint = \{\overline{x}_1; \overline{x}_2; \overline{x}_3; \cdots; \overline{x}_P\} \tag{9}$$

3.4. Application of parameter corrections

To be able to compare measurements made under different ambient conditions it is first necessary to correct these values. After extracting all stability points of interest but before performing any sort of trend analysis it is first necessary to correct the calculated values of the considered parameters so they have a common ground between them. This is accomplished by first calculating the dimensionless constants θ and δ using the following expressions:

$$\theta_t = \frac{T_{02}}{T_0} = \frac{T_{02}}{288.15} \tag{10}$$

$$\delta_t = \frac{PT_{02}}{P_0} = \frac{P_{02}}{1013.25} \tag{11}$$

These corrections factors are calculated for standard day conditions using values extracted from each stability point, more precisely the total air temperature at the inlet and the total pressure at the inlet of the low pressure compressor, represented in equations 10 and 11 as T_{02} and PT_{02} respectively. The notation used here is in

accordance with the one used in Figure 5. The sub-index, t, denotes that the values were computed with total temperature and pressure. If we assume that the inlet does no thermodynamic work [5], the free stream total temperature, or TAT, can be used as the total temperature at both engine inlets.
If we consider, for instance, that the parameters being trend monitored are the EGT, FF, N2 and N1, which are considered to be the four key performance parameters, the corrected values for each of these parameter is calculated as follows:

$$EGT' = \frac{EGT + 273.15}{\theta_t}[K] \tag{12}$$

$$FF' = \frac{FF}{\sqrt{\theta_t}\delta_t}[Kg/hour] \tag{13}$$

$$N2' = \frac{N2}{\sqrt{\theta_t}} \tag{14}$$

$$N1' = \frac{N1}{\sqrt{\theta_t}} \tag{15}$$

The corrected EGT is converted from degrees Celsius to Kelvin. As mentioned before the correction factor θ_t will be the same for both engines as it is computed from the TAT. As for the δ_t it is used to correct the FF and is computed from the respective total pressure at the engine's inlet.

3.5. Engine Bleed and its effects

Highly pressurized air is extracted from the engine to feed the aircraft's pneumatic systems that drive the air conditioning systems, wing anti-ice, amongst others. This can have major effects on the performance of an engine and needs to be taken into account. The air is normally bled from the intermediate stages of the High Pressure compressor. Keep in mind that the Basic Conditions dictate that the anti-ice valves must be closed for the duration of the analysis for data to be valid for ECM purposes. The ideal would be to use values not affected by bled air, but since this is not possible, as the systems described above are vital for the aircraft normal operation, we can only mitigate the side effects of engine air bleed in the performance assessment. Most automated data collection systems aboard the aircraft are not able to quantify the amount of air that is being bled, but they can give an estimate of the order of magnitude of the bleed effect in the engine's performance. This information can be extracted from the Engine Cruise Report using the Engine Control Word 1 (ECW1) or, when this is not an option, it can be inferred from the position of the switches in the cockpit. From this information three different bleed modes can be identified:

- Minimum Pack
- Normal Pack
- Maximum Pack

The Pack Flow Selection regards the functioning mode of the air-conditioning system. This information is crucial since stability points can now be separated according to the amount of pressure being withdrawn from the engine. The effects of engine air bleed in the performance parameters are made clear in Figure 8

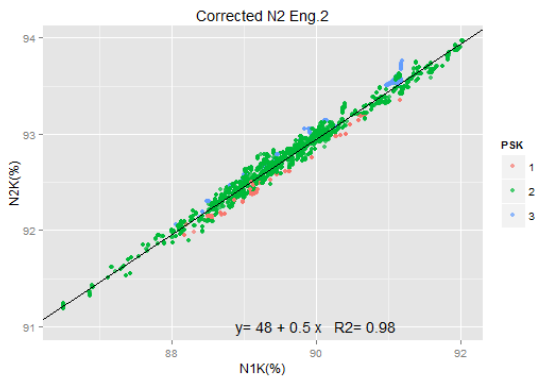

Figure 8: High-pressure fan speed vs low-pressure fan speed showcasing different pack flow selection.

The PSK code 1, 2 and 3 correspond to a Minimum, Normal and Maximum bleed status respectively. By taking a closer look at Figure 8 it is possible to notice that for a given N1 the values of N2 are consistently higher for Maximum Pack Flow than for the other modes. A higher N2 implies an increase in FF which means a decrease in efficiency and therefore a loss in performance. For the same reason parameter corrections were needed to take into account different ambient conditions, Stability Points should also not be compared if calculated under different Pack Flow Selection. The ideal would be to only take into account stability points generated from Minimum Pack Flow Selection, since it is the mode that least affects engine performance, but the majority of stability points have a Normal Pack Flow. The percentage of Stability Points with a Minimum Pack Flow Selection is low, approximately 7%, which is not sufficient to perform trend analysis. For this reason when developing the tool for ECM both Minimum and Normal Pack Flow Selection will be taken into account, as will be described in the next section, and Stability Points with Maximum Pack Flow Selection will be discarded.

3.6. Baseline Definition

To perform parameter trend monitoring it is necessary to define a baseline for the engine to have a reference to measure the performance decay. As discussed before, engine's manufacturers obtain Baseline values by testing each engine when they are new. As operators can't replicate these conditions the only option to perform this kind of analysis is by deriving a baseline from data recorded in-flight. The best way to do this is by using data from a period of time when the engine's performance is at its peak and use it as reference. The most obvious would be to do this when the engine was new or with few flight cycles and store the measurements to trace the Baselines, but in most cases this is no longer an option. One of the major indicators of engine performance is the EGT margin and it can be used as a parameter to choose the best period of time to use for baseline calculation. EGT margin is at its maximum after shop visits, best case scenario after the engine has been overhauled, and will decay with each flight cycle [6]. For the development of the current thesis the baselines will be calculated from the best Stability Points found in the first 90 days of service after an engine has been overhauled. This period of time was selected based on empirical knowledge, taking into account the necessary time to collect enough data to generate the baseline model but keeping in mind that the longer the period the more engine loss of performance can contaminate the data. For the reasons presented two different Baselines are considered, one respecting a minimum Pack Flow Selection and the other a normal Pack Flow Selection. Each parameter delta will be calculated as the difference between the corrected Stability Points and the corresponding Baseline with the same Pack Flow Selection.

3.7. Trend Monitoring

The process of Trend Monitoring implies the calculation of the parameter's Deltas. Trend Analysis corresponds to the evolution over time of the parameter's Deltas calculated from the difference between the corrected data extracted from the Stability Points and the Baseline models. Depending on the parameter being analysed, its delta can be expressed in the same units as the parameter or as a dimensionless ratio as seen in the following equations.

$$\triangle EGT(t) = EGT_{Stab.Point}(t) - EGT_{Baseline}(t)[^{\circ}C] \tag{16}$$

$$\triangle FF(t) = \frac{FF_{Stab.Point}(t) - FF_{Baseline}(t)}{FF_{Baseline}(t)} \tag{17}$$

$$\triangle N2(t) = \frac{N2_{Stab.Point}(t) - N2_{Baseline}(t)}{N2_{Baseline}(t)} \tag{18}$$

4. Development of an ECM tool

The tool developed had the objectives of being able to work for different aircraft and engine models composing TAP's fleet and also optimizing the tool's ability to process flights in order to increase the number of flight hours worth of data that could be processed each day. The improvements made allowed for a significant increase in the capacity to process flight-data with the intent of calculating Stability Points. The tool has two core functions: (1) process flights and store the Stability Points corresponding to that flight; (2) use said points to perform trend analysis on demand for a given engine over a specific period of time. The first requisite taken into account, when developing the software, was the possibility of working with different aircraft/engine combinations. To do this, a function was created ro read text files (.txt) with the information needed to create the Basic Conditions and Stability Criteria for each aircraft type. To analyse flight-data from a specific aircraft the program needed the configuration files for the respective aircraft, one for the Basic Conditions and the other for the Stability criteria. The development of an User Interface for the ECM tool as well as making it available remotely, were on of the most needed implementations. It allows cross checking data between different departments as well as increasing the accessibility to an analysis tool which will ultimately contribute to an increase in safety and efficiency in maintenance processes. The development an User Interface through a web-server was done using R and a packaged called Shiny using GGVIS as the plots generator. The application offers the option of changing the parameter being plotted through a drop-down menu or changing the engine being monitored by selecting a different check-box and also allows the selection of the period being analysed through an interactive calendar.

5. Results - Case Study

To test the ability of the developed ECM tool to correctly identify engine performance loss or situations affecting its correct functioning, a real case of a component fault was selected. The intention was to verify if by using the software developed in the current thesis it would be possible to clearly identify this event as was done using the manufacturer analysis tool. The selected event corresponded to a High Pressure Turbine Clearance Control (HPTCC) valve failure. This event was detected by P&W's software through

the visual analysis of the performance parameters deltas as seen in Figure 9.

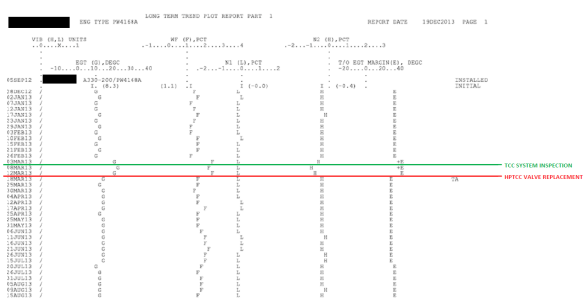

Figure 9: P&W long term trend plot report of a PW4168A engine.

Notice how the EGT values, plotted with G's, and the FF , plotted with F's, register a sudden increase, after the green line, and return to its previous behaviour, after the red line representing the HPTCC valve replacement. The faulty valve can be seen in Figure 10.

(a) HPTCC valve lever position (b) HPTCC valve butterfly position

Figure 10: Faulty HPTCC valve.

The problem with this valve was that its butterfly, as seen in 10(b), was opened when it should be closed according to the valve's lever position, see 10(a). Since the variations detected on the report are common in HPTCC valve faults, Maintenance used a borescope to check the butterfly position.
The ECM tool developed in the current thesis was used to process all flight-data corresponding to the period where the incident happened plus the flights needed to calculate the Baselines (corresponding to the 90 days after engine installation for both positions). The Delta EGT and Delta FF from engine 2 were calculated and plotted in the interactive ECM tool web application. The results obtained are represented in Figure 11 and 12.

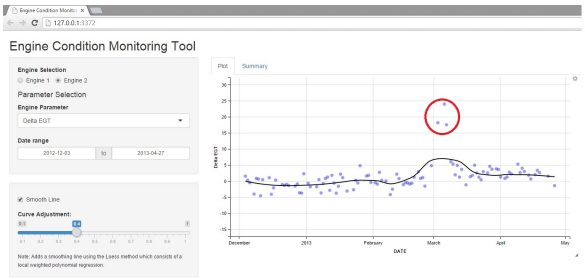

Figure 11: Delta EGT[°C] Eng. 2.

One can easily note the shift in the beginning of March that corresponds to the one detected with P&W's software. The values return to normality once the valve is replaced. This is also noticeable, but in a smaller scale, in the FF Delta, see Figure 12

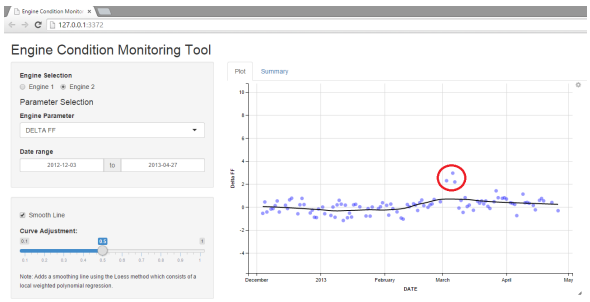

Figure 12: Delta FF[%] Eng. 2.

Also note that in both figures it is possible to notice a small increase in the Deltas over time, where the mean Delta value from December to February is lower than from March to May for both EGT and FF. This is in accordance with the slow degradation of performance resulting in a slow and gradual increase over time of the performance parameter Deltas.
From the results presented one can conclude that the objectives of the dissertation were accomplished. The ECM tool was able to identify gradual deterioration of engine performance and identify faults in engine components like the HPTCC valve fault presented.

6. Conclusions

In a competitive environment such as the air transport market it is of utmost importance to make sure the operation is being conducted efficiently while keeping high safety standards. Transportadora Aérea Portuguesa (TAP)) is the leading Portuguese airline and, like other airlines, is affected not only by the severe competition of the commercial aviation industry but by the low profit margins and high fluctuations of the price of

fuel which has made the company seek strategies that improve the efficiency of their operation and consequently reduce operating costs.

6.1. Achievements

Engine condition monitoring is a methodology that evaluates aircraft engine health condition, it is the main process behind condition-based maintenance which helps make maintenance planning more efficient. Analysis such as engine performance parameters trend monitoring allow the monitoring of performance degradation over time and any engine events that require intervention. From the results presented one can conclude that the objectives of the dissertation were accomplished. The ECM tool was able to identify gradual deterioration of engine performance and identify faults in engine components like the HPTCC valve fault presented. The main advantage of the developed program is that it is dynamic in the sense that anyone can process data flights and perform trend analysis interactively on a web application without having to be familiarized with statistic tools like R. Also the development of the User Interface and web-server will contribute greatly to the integration of different departments at TAP that require access to this data.

6.2. Future Work

The ECM tool developed still relies on the graphical interpretation of the results obtained, it would be interesting to integrate some machine learning concepts to the software. The use of pattern recognition algorithms would allow the tool to store information about the shifts caused by certain events in the parameter deltas and gradually create a list of the most common events and the typical shifts they produce. By crossing information of this list with maintenance reports containing the reasons for engine removals or maintenance events and its causes the tool would be able to label these patterns and create its own fingerprints database for the parameter deltas shifts. Another possible improvement might be the creation of an algorithm to calculate the take-off EGT Margin and add this performance parameter to the analysis. The data needed to calculate the EGT Margin was not included in the data frames used in the work developed but with the extraction of the correct parameters this calculation would be possible.

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