# Flight Data Tools Applied to Engine Health Monitoring

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December 2016

**Abstract**

The increased competitiveness generated by the proliferation of low-cost airlines around the world and entry of airline companies from the middle east, the growing concerns regarding the environmental impact of aviation and the need to conduct a safe operation requires an exquisite optimization of resources for any airline company so they can still remain profitable. Flight data departments can and should play an important role as they provide critical information for the operation of many other departments such as maintenance, safety or performance. It is important that airlines are able to assess the condition of any engine of their fleet. The tools developed in the current dissertation can provide, in an interactive way, the plots of engine key performance parameters, oil consumption and some statistical studies over the specified period. It was also designed and developed a database that greatly improved the data processing and computational effort. All the tools were developed to enhance the assessment of the engine condition by following its gradual degradation or by detecting some engine part fault. This improvement is expected to lead to an increased maintenance planning efficiency aiming to contribute to the overall efficiency of the company and, consequently, an operational costs reduction.

**Keywords:** Flight Data, Engine Condition monitoring, Engine Key Performance Parameters, Oil Consumption

## 1. Introduction

The constant growing of the airline industry since its early stages and its resilience to external shocks never changed the fact that airlines always dealt with small profit margins. In the past decade the business model of the airline companies has changed with the proliferation of low-cost airlines around the world and entry of airline companies from the Middle East. Despite the noticeable difference between the approach of these two new players, no one can deny that they have very interesting results. Not only has competitiveness increased but also concerns have grown regarding the environmental impact of aviation and the need to conduct a safe operation, demanding an exquisite optimization of resources for all airline companies so they can still remain profitable. According to IATA - Maintenance Cost Task Force (MCTF) engine maintenance is responsible for up to 40% of the yearly direct maintenance cost (DMC)[6]. With the development of diagnostic and monitoring methods allow the reduction of cost by continuously monitoring fleet performance. Appropriate maintenance action can be performed in early stage, increasing the time of the engine on wing. This time increase can be used for planning and determining the overhaul action needed.

## 2. Turbo fan engine

Engines are responsible for vital functions of the aircraft. The engine provides not only the thrust that is required for the aircraft to fly but also the pressurized air to feed the pneumatic system that drives the air conditioning system and wing anti-ice system for example. Different types of engines can be used by aircraft but modern airlines use turbofan engines because of their high thrust and appealing fuel efficiency [4].

### 2.1. Engine core

The engine core can be denominated as the propulsion System. It comprehends all the engine parts that generate thrust required for the aircraft. All the engine air goes through the fan to be compressed and divided into two flows: primary flow and secondary flow. The ratio between the secondary airflow and the primary one is called the bypass ratio $\beta$ as the following expression [4]

$$\beta = \frac{\dot{m}_f}{\dot{m}_c} \tag{1}$$

$\dot{m}_f$ secondary flow and $\dot{m}_c$ primary flow The incoming air is captured by the engine inlet. Some of the incoming air passes through the fan and continues into the core compressor and then to the

Figure 1: Example of a Turbofan Engine: GE90-115B[8]

combustion chamber, where it is mixed with fuel and combustion occurs. The hot exhaust mixture passes through the core and fan turbines and then out the nozzle. The air that goes through the fan has a velocity that is slightly increased above free stream. A turbofan net thrust has two components one from the core and the other from the fan and can be calculated using the equation 2 1 [4].

$$T = \dot{m}_e * v_e - \dot{m}_o * v_o + \beta * \dot{m}_c * v_f \qquad (2)$$

where $T$ represents the thrust, $\dot{m}_e$ the exhaust air flow,$\dot{m}_o$ the fan air flow, $v_e$ the exhaust air velocity,$v_f$ the air fan velocity,$v_o$ inlet air velocity.

2.2. Valve system

The air system of a turbofan engine serves various functions including providing damping of bearing forces supplying pressurized air for the pneumatic system through valve systems, cooling air for the different parts of the engine and guaranteeing optimal compressor performance during certain engine operating conditions. The air system is controlled by the Full Authority Digital Engine Control (FADEC) through Electronic Engine Control (EEC).
The various valve systems bleed air from the primary airflow so it will affect the engine performance. The amount of air withdrawn from the primary air flow is directly related to the aircraft flight phase and outside atmospheric conditions during engine operation. The effect of the bleed configuration on engine trend performance is discussed in ref [5]

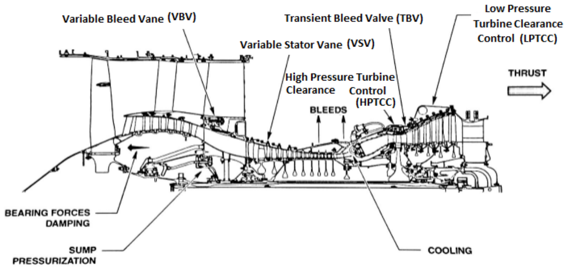


Figure 2: Air System for CFM56-5B [2]

2.3. Oil system
The oil system can be considered the arterial system of an aircraft engine. Cooling and lubrication is one of the most important aspects of the operation of any engine, especially when the temperatures and the shafts rotating speeds are very high. Since the

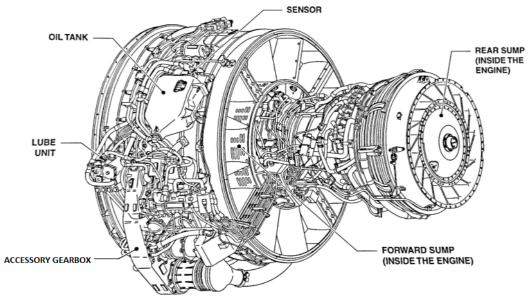


Figure 3: Oil System for CFM-5B adapted from [2]

oil goes through a closed circuit an increase in oil temperature or a decrease in oil pressure can be a precursor of very serious engine faults or leaks in the oil system that can lead to engine shut down in flight.

2.4. Deterioration of a Turbo fan engine
Any engine like every machine exhibits the effect of wear and tear over time, the degradation of one of the engine's parts can lead to a loss of performance or to a failure. Another way for the engine to fail is due to the degradation of its components with time.Another very important source contributing to its degradation is all the chemical activity inside the engine. Different elements contribute to its corrosion, oxidation, fouling and other contaminations[12].

## 3. Implementation

Engine maintenance planning can be made more efficient by applying the method of diagnosis called Engine Conditions Monitoring. An Engine Condition Monitoring and Diagnosis (ECMD) process will infer engine status or changes in its condition

Figure 4: Example of Turbine and Compressor deterioration [12]

while the engine is still in operation [12]. Many diagnostic methods are proposed many variants of diagnosis with different features and complexity have been developed and reported in the open literature[9] and [10].The tool developed, subject of the current thesis, is based on a steady-state diagnosis with a mathematical approach with a conventional decision making procedure for diagnostic proposes. There are different approaches for engine health assessment, but they all should be based on data collected in-flight to make full use of engine condition monitoring (ECM)[3].The process and benefits behind the use of the FDR are extensively explained in [5]. For this study, the on-wing operational data used came from Digital AIDS (Aircraft Integrated Data System) Recorder. The data collected is then fed to Analysis Ground Station (AGS) a tool developed with SAGEM of which the main function is to perform monitoring of flight data. Several models can be used for monitoring engine performance. The linear approximation or classical approach has proven to be successful for practical purposes and existing commercial systems are based on it [5]. It is also the method used for the ECM tool developed.

### 3.1. Engine Key Performance Parameters

The parameters shown in table 1 are used to measure the engine performance and therefore are the most common ones used for engine condition monitoring. The values of the parameters do not give any information by themselves. They are influenced by ambient conditions like temperature and pressure or even the bleed valve configuration as mentioned in [7],[1] Although the relevance of said parameters can change according to engine model and manufacturer[7]. The EGT margin is the parameter that best represents the engine degradation state[3], it is at its maximum value when the engine is new or has just been overhauled. The classical approach is based on delta parameter calculation. The difference between the value of a parameter and the expected, reference, at a given engine point of operation is called Delta. Figure 5 exemplifies how the calculation is done.

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) | N/A |

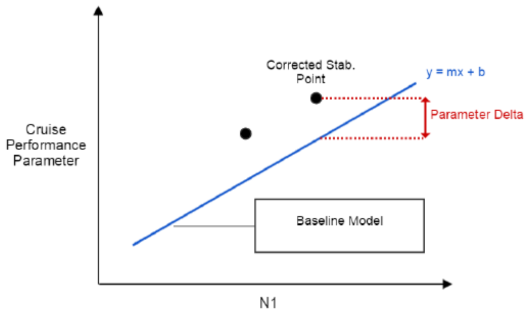


Figure 5: Schematic for engine performance parameter's Delta calculation [5].

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[5].

$$\triangle EGT(t) = EGT_{Stab.Point}(t) - EGT_{Baseline}(t)[°C] \tag{3}$$

$$\triangle FF(t) = \frac{FF_{Stab.Point}(t) - FF_{Baseline}(t)}{FF_{Baseline}(t)} \tag{4}$$

$$\triangle N2(t) = \frac{N2_{Stab.Point}(t) - N2_{Baseline}(t)}{N2_{Baseline}(t)} \tag{5}$$

### 3.2. Database

A database is a collection of data that is organized so that it can be easily accessed, managed and updated. Currently structure of the database comprises twelve tables. By observing the figure 6 Its easily noticed that this structure relies on four tables, the core of the database, since all tools, in a way or another, depend on information stored in them.

### 3.3. Rehm

Trend analyses for any aircraft-engine pair of an airline fleet can be made using Rehm developed Tool [5], [11]. The diagram of the script that calculates the stability points, used to calculate the delta parameter and base line is present in figure 7.

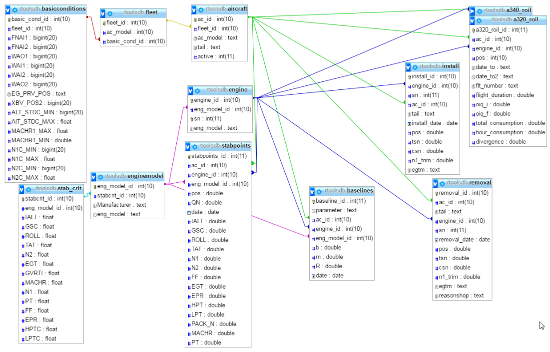

Figure 6: Database Structure and Relations

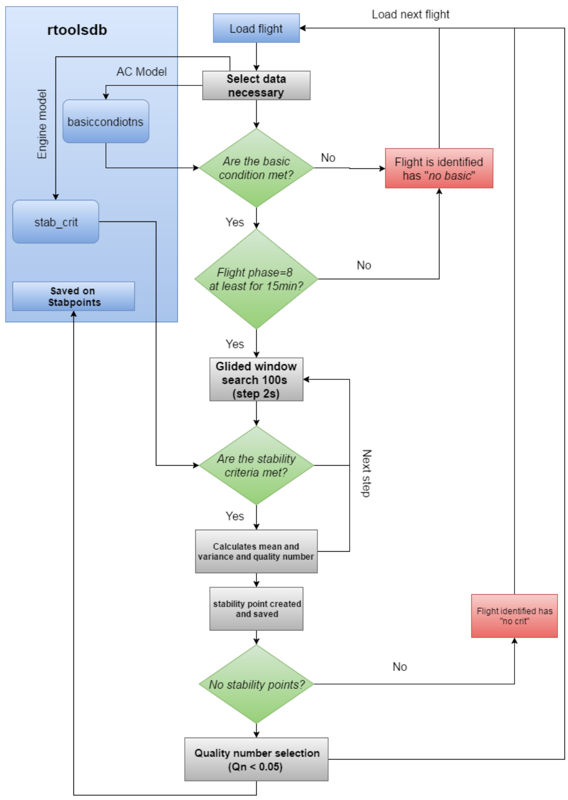


Figure 7: Rehm Stability point Calculation Algorithm

## 3.4. Roil

With the purpose of improving all the processes behind the oil consumption analysis, the Roil Tool, was developed in collaboration with TAP ME. The importance of the oil system in the normal function of the engine was already stated. It can be used as another variable to evaluate the engine performance. The oil consumption of an engine is also used to set the price when there is a need for renting or leasing an engine by an airline which are very common methods used by the operators when there is an unexpected shop visit or the need to monetize engines in hangar. Based on empirical knowledge and some studies made prior to this development at TAP ME, it was defined a set condition for the values used for the estimation: The initial oil quantity is recorded 30 seconds prior to the beginning of the take-off phase, it is expected that during this phase the oil levels are stable as the aircraft should be standing still facing the runway,

The final oil quantity is recorded after the first engine shut-down. Furthermore, the oil quantity has to be constant during 3 seconds and the thrust levers must be at the IDLE position for the point to be extracted.

The difference between the final oil quantity and the initial oil quantity will be the value used as oil consumption. There is an additional set of information projected to provide statistical data regarding the oil consumption per hour. This additional set of information includes a histogram and a table with the number of observations (or points), mean value, standard deviation, maximum and minimum values of the current aircraft engine and date range selected.

## 3.5. RTracker

Another tool developed is the Rtracker. This tool is an easy way to access the history of the installation and removals of the engines of the fleet. Information about the engine namely, wing position, time since new, cycles since new, exhaust gas temperature margin, on the date of shop visit or on a new install is presented to the user.

## 3.6. User interface

A login page was created where a register has to be done. This restricts the access to the information to the people who actually need it. The login is guaranteed via database was created a database to manage the user's accounts and access. Figure 8 shows the login page that can be accessed via at TAP Portugal. All the tools have similarities in the

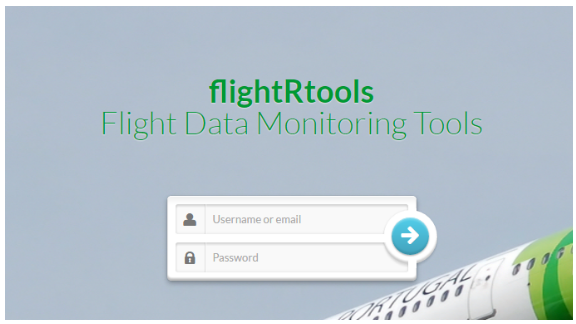


Figure 8: fligthRtools Login Page

options menus. Which are the search options that can be done for aircraft tail number, engine serial number or data, as shown in figure 9 All the tools have similarities in the options menus. Which are the search option that can de done for aircraft tail,

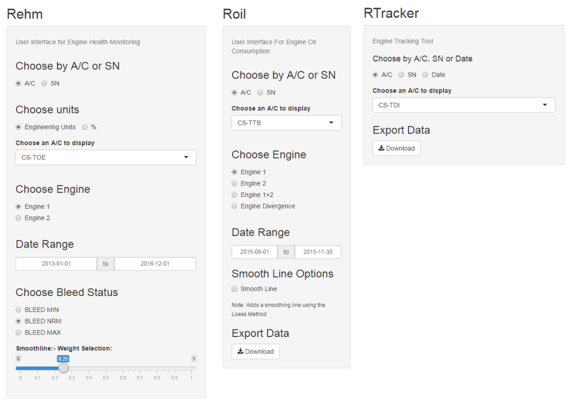


Figure 9: User interface for all the Rehm Roil and Rtracker

engine serial number or data, has shown in figure 9.

## 4. Results

### 4.1. Rehm Tool Results

The figure contains all the data available for this engine, it comprehends three and a half years of operation, between 2013 and mid 2016. There are four

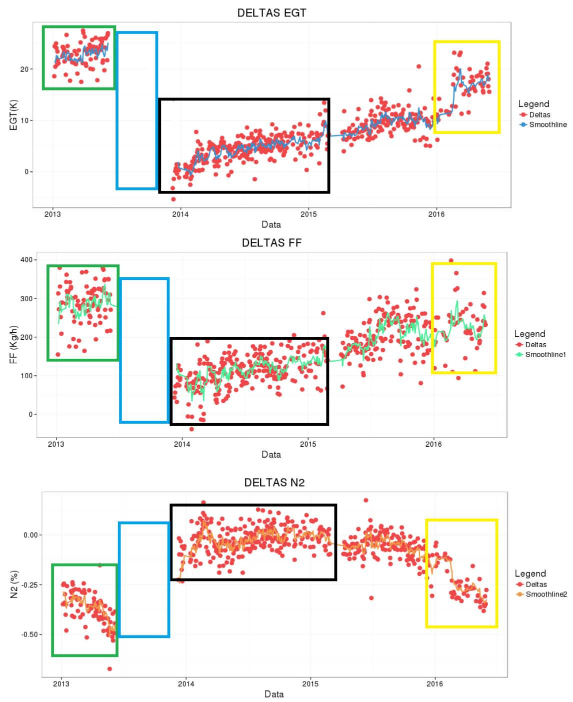


Figure 10: Output of Rehm for the Case study

regions delimited in the figure in which we can easily identify different characteristics:The green zone is an example of low efficient engine operation patterns, which are defined by high values of the delta parameters for the EGT and FF variables and a decreasing trend on the N2. Since delta of both EGT and FF remain high, but fairly stable, throughout the whole period, it can be concluded that an incident-free time frame for this engine is present. We can conclude that the low efficiency showed in this period is the result of deterioration along time and not from an engine part sudden failure; the blue region which doesn't have any data available. This is an indication that this engine was not in operation or that in the considered period the algorithm wasn't able to calculate any stability points. After consulting Rtracker, it was verified that this engine was removed from the aircraft due to loss of performance. This fact reinforced what was stated regarding the green region; the black zone comprehends more than one year of operation.The engine was installed on a new aircraft at the end of 2014. The gap between the values between this region and the green one are evident. In the first period of this region the values of the delta parameters are much closer to the reference, which indicates a newly installed engine. Across this period it is clearly observable the expected degradation of engine performance by accumulation of the cycles and use, since there is no sudden shift in any delta parameter. The decreasing engine performance over time is represented by an increasing trend in the EGT parameter and fuel flow parameter, while the N2 parameter has the opposite trend; The yellow zone highlights a sudden shift of all parameters. Despite being able to identify the change in the parameters, which lead to decrease of performance through Rehm, it is able to identify the engine part causing the shifts. What we are able to conclude is that the problem wasn't solved by the end of the study or the problem was solved but the damage was permanent and therefore, it was not possible to recover performance. After receiving the feed back from TAP ME for this case it was confirmed that since early 2016 this engine has presented some problems with the nacelle cool valve and several maintenance actions were performed trying to find the source of the problem.

Another comment that can be made is that despite the cause of the shift not being identified or solved by the end of the study, didn't lead to considerably higher levels of fuel consumption (the trend of the delta fuel consumption is fairly stable). However, during this period, engine parts were enduring an undesirable higher temperature which can speed up the engine degradation. That being said, it can be stated that this shift didn't have an immediate impact on the operation's cost of the aircraft but the acceleration of the degradation process could result in a much higher expense in the future. Analysing all the four regions simultaneously, several comments can be made. The delta EGT parameter is the one that assesses the engine health more accurately. When an engine is subject to maintenance action it will not always reflect on performance enhancement. The conclusions made previously prove that the objectives of developing the Rehm tool were accomplished.

### 4.2. Roil Tool Results

An example of the output of the Roil Tool will be presented next. This case comprises four months of

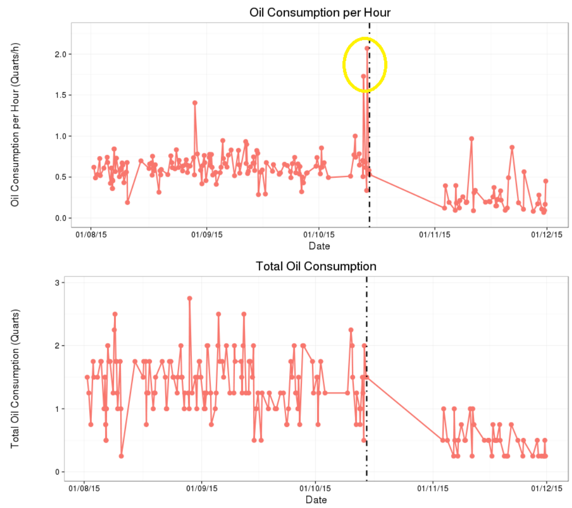


Figure 11: Output of the Roil Tool for the case study

operation of an aircraft. The black dash line in the graphics identifies a change in the engine installed on the aircraft wing. Days before the change in the engine, some outliers are identified in the oil consumption per hour and, according to the graphic, it almost triplicates.It can also be noted that the new engine installed has low values of fuel consumption which is to be expected.

## 5. Conclusions

In an industry as competitive as aviation, the optimization of resources and operation gains even more relevance due to factors like airlines experiencing low profit margins and being highly influenced by external factors such as fuel price fluctuations.Engine performance is without any doubt one of the main concerns of airlines. Since a good performance is associated with lower fuel consumptions, lower exhaust gas temperature and less pollution, it leads to cost savings directly and indirectly. Hence, it is important that airlines are able to assess the condition of any engine of their fleet without any major effort and follow its gradual degradation in order to increase maintenance planning efficiency. For that reason some methods were developed, as the one used in the current thesis regarding engine performance trend monitoring. The Rehm tool was able to demonstrate the gradual deterioration of the engine performance due to cycle accumulation and identify parameter shifts caused by faults in engine components.

### 5.1. Achievements

Engine performance is without any doubt one of the main concerns of airlines. Since a good performance is associated with lower fuel consumptions, lower exhaust gas temperature and less pollution, it leads to cost savings directly and indirectly. Hence, it is important that airlines are able to assess the condition of any engine of their fleet without any major effort and follow its gradual degradation in order to increase maintenance planning efficiency. More accurate information about the condition of the engine can be withdrawn by monitoring oil quantity and consumption of the engine. The Roil Tool results show the consistency required for this kind of analysis with the exception being the Pratt&WHittney4168 engine therefore The Roil maintenance procedure was already implemented, by the Flight Data Department in AGS to be performed daily. One of the main advantages of the program developed is the very friendly user interface and its search option, the development of the database allows the possibility of searching by engine serial number which was one of the greatly appreciated features by TAP ME since none the available software has this option available. Another advantageous result of the program interaction with the database is the amount of data and the velocity in which the information is provided to the user.

## 6. Future work

For the engine condition monitoring tool, by using data available via the database already created, the integration of machine learning concepts to the software could result in the creation of its own fingerprints for the parameter delta's shifts which would allow the tool to successfully identify the faulty engine part. Also, performing trend analyses for other engine parameters, like engine vibration, can contribute to a better assessment of the engine condition. For the oil consumption analysis, it was still not possible to successfully estimate oil points need for the Roil Tool for the PW engine. So further studies must be performed to set different conditions that can be met by this engine model without compromising the accuracy of the data. The implementation of a notification via email can be a great help in detecting sudden changes in parameters. Since it allowed the user to have knowledge of the event without having to be logged into the tool. Thus the problem could be detected sooner.

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