

Study and Implementation of Algorithms for in flight performance analysis of the PW4000-100 Turbofan engine for the purpose of Engine Condition Monitoring

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Abstract

The first part of this paper describes the implementation of a Flight Data Monitoring (FDM) database in the Analysis Ground Station (AGS) software for decoding recorded data on an Airbus A310. The results for a selection of recorded parameters are analysed and the procedure that computes the flight phase is described. The second part of the paper describes the study and implementation of algorithms for performance trend monitoring of PW4000-100 engines. Two tools were developed using the R programming language. The first tool is responsible for the acquisition of stability points in cruise from recorded flight data using specific conditions and criteria and, after validation, it was implemented in AGS. The second one uses the stability points from the flights processed in AGS to derive engine baseline models and calculate the performance trends with respect to these models. The engine parameter data is corrected using the inlet temperature and pressure and the performance characteristics of the engines are displayed for standard day conditions. The engine baselines are composed by linear regression models adjusted to the data obtained from the flights after the engines return from shop visits. The trend monitoring results were compared to those obtained with the manufacturer's ECM software and confirmed the potential of the methodology developed to monitor the gradual deterioration in the engine's performance and to be used in the detection of shifts that might be representative of engine faults.

Keywords: Flight Data, Condition-Based Maintenance, Engine Condition Monitoring, Performance Trends, Corrected Gas Turbine Parameters, Stability Points

1. Introduction

The aviation industry plays an important role in the global economic activities. In 2013, airline scheduled operations handled 3.1 billion passengers, up from 2.9 billion passengers from 2012 [1]. Airbus [2] predicts that air traffic will double in the next 15 years at an annual growth rate of 4.7% in RPK (Revenue Passenger Kilometers).

Despite the excellent safety record of air travel, aircraft accidents always have major economical and emotional consequences. The Flight Data Monitoring (FDM) is a program used in the prevention of aeronautical accidents that consists in the decoding and analysis of the data from the aircraft recorders on a routine basis. TAP Portugal was one of the first airlines in the world to use its flight data in a preventive way through the implementation of an FDM program containing both FOQA (Flight Operations Quality Assurance) and MOQA (Maintenance Operations Quality Assurance) procedures. The objective of FOQA procedures is to identify divergent practices amongst crew members or difficulties to adhere to the established standard procedures. The information is then compiled into reports and corrective actions may be taken, leading to improvements in the safety performance of the airline. The MOQA procedures are used for maintenance purposes and are mainly executed as a diagnosis tool, to help the various airline maintenance departments to identify and correct on-going problems and failures in the aircraft equipment or to conduct studies.

Flight data can also be used to continuously monitor the performance of the aircraft and the condition of its systems. In addition to the diagnostic analysis, monitoring the aircraft/aircraft systems greatly relies on a prognostic analysis, where engineering personnel predict the time left until component failure based on its deterioration levels. This type of analysis is known to reduce the risk of potential failures during operation and allows planning for maintenance in anticipation.

The increasing recording capacity of the flight data recorders, the development of newer aircraft fitted with dedicated sensors and the prospect of transmitting real-time information, give FDM programs almost unlimited

capabilities to enhance safety levels and reduce airline operating costs, allowing airlines to respond to the harsh economic requirements.

2. The Airbus A310-325 Aircraft

The Airbus A310 is a wide body transport jet airliner powered by two turbofan engines. The A310 made its maiden flight in 1982 and during its production run 255 units have been delivered to different customers. The A310-325 variant is powered by 2 PW4156A Engines, providing 56,000 pounds of thrust each.

2.1 On-board Transmission and Recording Protocols

The communication between the main systems in the Airbus A310 is made through the ARINC 429 protocol. The format in which the data is stored in the different recording units on-board the aircraft is specified by the ARINC 717/573 protocol.

2.1.1 ARINC 429 Protocol

The ARINC 429 is a protocol that defines how the different avionics equipment and aircraft systems should communicate with each other. They are interconnected by wires in twisted pairs and the communication is done with a unidirectional data bus standard.

2.1.1.1 ARINC 429 Electrical Characteristics

Each ARINC 429 bus uses two signal wires to transmit the messages, which are transmitted at a bit rate of 12.5 or 100 kilobits per second. The transmission is asynchronous, with consecutive words separated by at least 4 bits with null value (zero voltage), eliminating the need for an external clock signal. The bits are transmitted using a bipolar return-to-zero (BPRZ) and the information is retrieved from the voltage difference between the two wires. The number of receivers connected to each bus is limited to 20 by the protocol.

2.1.1.2 Format of the Data Word

The ARINC 429 data words have a length of 32 bits. The format is shown in figure 2.1 and includes five fields.

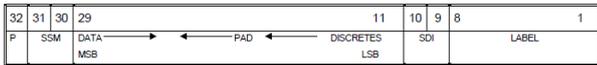


Figure 2.1 ARINC 429 Word Format [3]

Parity: The Most Significant Bit (MSB) is the parity bit. The ARINC 429 uses an odd parity, which means that the total number of “1” bits in each 32-bit word should be odd. This bit is effective in the identification of transmission errors when the number of incorrect bits is odd.

Sign/Status Matrix (SSM): Bits 30 and 31 contain information about the conditions of the hardware equipment, operational mode or validity of the data content, in the form of a code.

Data: Bits 29 to 11 contain the data from the parameter(s) in various formats. There are some standard types of data and non-standard types specifically implemented by the manufacturers. Usually, not all the bits are used, only those necessary to cover the range and resolution of the information transmitted.

SDI: Bits 10 and 9 form a two-bit code that gives the Source/Destination Identifier (or SDI). This is used to identify the receiver to which the information is destined when there are multiple receivers. It is also used to identify the source of the transmission or, in some cases, for transmission of data.

Label: Bits 8 to 1 contain a label identifying the data type of the 32-bit word and the parameters associated with it. A label is assigned to each parameter that is transmitted through the aircraft’s avionics equipment. The labels are listed in the ARINC 429 specification [4] and are represented as octal numbers.

2.1.1.3 ARINC 429 Data Types

BCD (Binary Coded Decimal): Figure 2.2 displays the general format of a BCD word. The data field in a BCD word contains up to five sub-fields, which represent different decimal digits. The SSM field gives the sign.

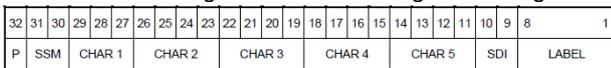


Figure 2.2 General BCD Word Format [3]

Four bits are allocated to each digit, except for the most significant sub-field, which encodes the digit with 3 bits only.

BNR (Binary): The BNR format stores the data as a binary number. The general format and fields are represented in figure 2.5. Bit 29 is the sign bit and bit 28 is the most significant bit of the data field. Negative numbers are encoded with two’s complement format. Bit 28 represents half of the maximum value (range) of the parameter, bit 27 represents 1/4th of the range, etc.

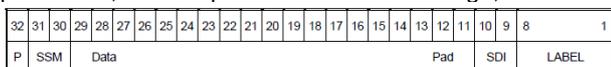


Figure 2.3 General BNR Word Format [3]

Discrete: The Discrete type of data is used whenever the parameter can be encoded with only one bit. The discrete data is accommodated in the unused pad bits of data words or in dedicated words, which can store up to 19 different parameters.

2.1.2 ARINC 717/573 Protocol

The ARINC 717 protocol was created to describe the equipment and installation standards capable of meeting mandatory flight data recording requirements prescribed by the FAA (Federal Aviation Administration) and other aviation authorities.

2.1.2.1 Data Frame Description

The format in which the data is stored in the different recording units on-board the A310-325 aircraft is specified by the ARINC 717 protocol. The stream of data

transmitted to these units is organized in a frame (or dataframe). Each frame corresponds to four seconds of recorded flight data and represents information about the parameters being sampled with time.

A frame is divided into four subframes and each takes one second to be recorded. The subframes are composed by 64, 128, 256, 512 or 1024 12-bit words (2^{n+6} , with n from 0 to 4). The words in ARINC 429 format are converted to the ARINC 717 12-bit format by aircraft data acquisition units.

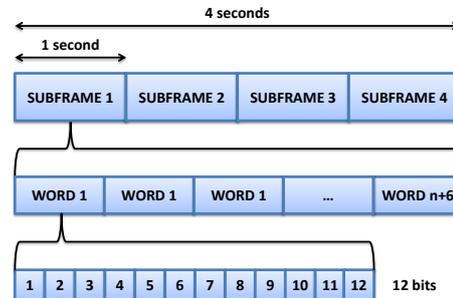


Figure 2.4 Frame, Subframe and Word

Bit one corresponds to the Least Significant Bit (LSB) and is transmitted first, while bit 12 is the MSB and the last to be transmitted. By having information about the subframe(s), word(s) and bit(s) it is possible to locate the parameter recordings in the frame. This information, together with the parameter ARINC 429 characteristics and the recorded bits, provides the necessary tools to compute its value from the recorded flight data.

2.1.2.2 Regular Frame

Most parameters are recorded at least once every four seconds, i.e., in every frame. The recording rate of a regular frame parameter is directly related with the number of times that parameter appears in the dataframe. If the parameter is recorded once per second (1 Hz), it appears once per subframe and a total of four times per frame. The parameters can be output at lower rates of 1/4 Hz or 1/2 Hz, and appear in one or two subframes, respectively. When a parameter is recorded at rates higher than 1 Hz, there are various samples per subframe and each one is called an instance of the parameter.

2.1.2.3 Superframe

The superframe parameters have a recording rate of 1/64 Hz and appear once every 16 frames. Superframe parameters are recorded on dedicated words within a subframe that are named as “superframes”. The four most significant bits (12 to 9) of the superframe contain a counter that is incremented at the end of each frame. Superframe parameters contain information that doesn’t change throughout a flight or that does not change as frequently as the accelerations, speeds, etc.

2.2 ATA¹ 31 Recording Systems: Aircraft Integrated Data System (AIDS)

The main function of the Aircraft Integrated Data System (AIDS) of the Airbus A310-325 is to convert the various critical (including the mandatory) parameters into a recordable format and to record them on a Flight Data Recorder (FDR). The aircraft from which the data will be decoded and analyzed is fitted with a Basic AIDS composed by the following equipment:

- A Digital Flight Data Acquisition Unit (DFDAU);
- A Digital Flight Data Recorder (DFDR);
- A three-axis linear accelerometer (L.A.);
- A Control Panel (C.P.);
- A Quick Access Recorder (QAR).

¹ Air Transport Association of America

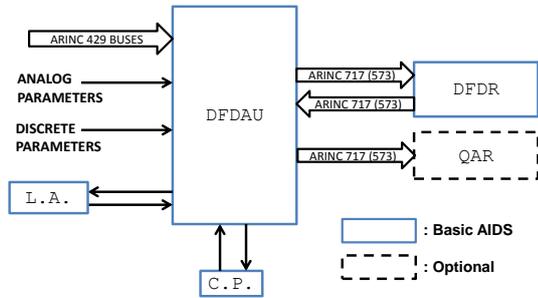


Figure 2.5 AIDS Architecture

The DFDAU acquires, conditions and processes the aircraft parameters coming from the several sensors and on-board computers [5]. The DFDAU then transmits the required parameters to the DFDR in the format specified by the ARINC 717/573 protocol at a rate of 64 12-bit words per second. The DFDR, commonly known as the “black box”, is designed to withstand the conditions likely to be encountered in an aircraft crash. The DFDR has the ability to store data collected during up to 25 hours of flight and when it reaches its maximum capacity the oldest data is overwritten by the new data.

The DFDAU sends a copy of the DFDR data frame to the QAR, which records the data on a magneto-optical disk. The QAR is located in the avionics compartment and not in rear of the aircraft close to the tail cone like the DFDR and is used by maintenance personnel acquire the mandatory parameter recordings.

3. Dataframe Programming

The flight data reading and processing tasks are carried at computer ground stations by a flight data analysis tool: the Analysis Ground Station (AGS) from SAGEM. AGS is capable of decoding the data frames recorded in the ARINC 717/573 format containing the flight parameters. AGS works on a Database basis, which is the configuration used to perform the flight data analysis for a particular aircraft or fleet of aircraft. A new database version was implemented containing the necessary information to decode the flight data recorded in the QAR of the Airbus A310-325.

3.1 Parameter Implementation

Before the parameters are allocated to their respective word slots, the information regarding their ARINC 429 characteristics needs to be inserted in AGS. A total of 219 parameters from various signal types were implemented: 172 coming from the digital buses of the aircraft in the ARINC 429 format, 37 discrettes and 10 analog parameters. All these parameters are mandatory.

3.2 Dataframe Construction

3.2.1 Regular Parameters

The majority of the parameters are recorded in the regular frame. The regular frame parameters can be added to the dataframe structure by means of a dialogue window similar to the one displayed in figure 3.1. The dataframe is represented in the bottom part of the window – word, bits and subframes - and allows the user to visualize and select the location of the parameter in the word slots. Each parameter can contain up to three parts, which need to be allocated separately. The recording rate for each part must be defined. AGS will use the ARINC 429 data bits information for each part to compute the correct parameter values. For parameters with several instances in each subframe, it is only necessary to select the location of one of them. AGS will automatically assign the location of the remaining instances.

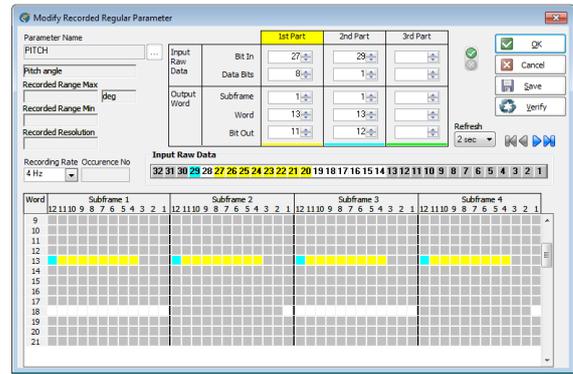


Figure 3.1 Regular parameter: Pitch Angle (PITCH)

3.2.2 Superframe Parameters

The frame recorded in the QAR also accomodates 4 superframes. To decode the superframe parameters it was first necessary to define the location of the superframe words and the corresponding location of the counters. In total, 31 of these parameters were added to the dataframe and they all have a period of 1/64 Hz, which means that they are only updated every 64 seconds.

4. Decoding Results and Flight Phase Computation Procedure

After programming and validating the dataframe in database version 10079, the flight data from several flights performed by the A310-325 aircraft was decoded and analyzed. Some procedures that compute new parameters from the recorded data were also implemented to the database, allowing an improved flight data analysis. In this section, examples of decoding results are presented and the implementation of the Flight Phase Computation procedure is discussed.

4.1 Results for Recorded Parameters

Figure 4.1 displays the evolution of the pressure altitude or Standard Altitude (ALT_STD) as a function of the current Greenwich Mean Time (GMT). This is the altitude in the International Standard Atmosphere (ISA) [6] with the same pressure as the part of the atmosphere in which the aircraft is flying. The profile shows some spikes during the climb and descent phases of the flight. This situation is corrected via an additional procedure that calculates the Standard Corrected Altitude (ALT_STDC), ensuring a smooth profile as depicted in the same figure.

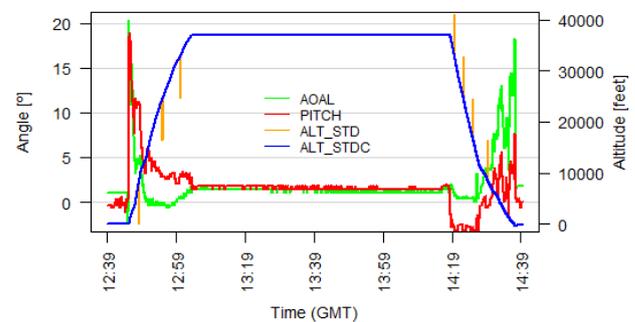


Figure 4.1 Altitude, Pitch and Angle of Attack results

The evolution of the Pitch Angle (PITCH) and the Angle of Attack (AOAL) is also presented in figure 4.1. During most of the climb the Pitch Angle is kept at a higher angle than the Angle of Attack, resulting in a positive Flight Path Angle and an ascending trajectory. The opposite occurs during the descent. In cruise, the Pitch Angle and the Angle of Attack have approximately the same value and during this phase the trajectory is horizontal. The biggest difference between these two parameters occurs in the

final moments of the flight before Landing, when the Angle of Attack is much higher than the Pitch Angle.

4.2 Additional Procedures: Flight Phase Computation

The Flight Phase Computation procedure is of extreme importance for the flight analysis. This procedure computes the Flight Phase based on several recorded and computed on ground parameters. The Flight Phase parameter (FLIGHT_PHASE) is used in a variety of maintenance and flight operations related procedures and is also mandatory for the correct separation of each flight contained in a media.

4.2.1 Flight Phases Definition

The procedure was implemented based on the definition from SAGEM that includes a total of 14 flight phases [7], similarly to what happens in the databases for TAP's fleet.

Nr.	Phase	Nr.	Phase
1	Engine Stopped	8	Cruise
2	Taxi-Out	9	Descent
3	Take-Off	10	Approach
4	Rejected Take-Off	11	Final Approach
5	2 nd Segment	12	Landing
6	Initial Climb	13	Go-Around
7	Climb	14	Taxi-In

Table 4.1 SAGEM Flight Phases

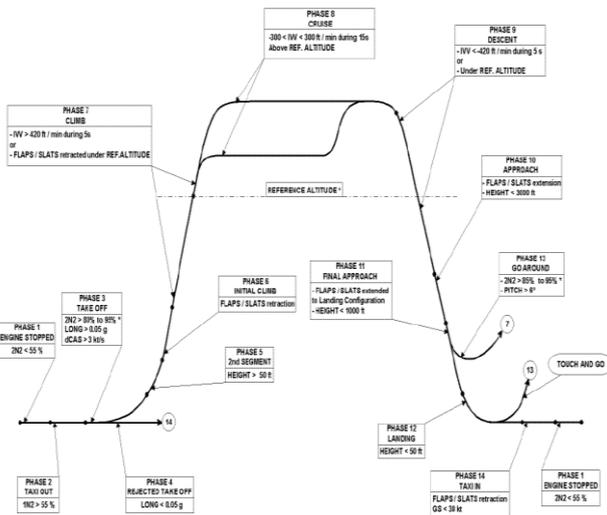


Figure 4.2 Flight Profile with the SAGEM Flight Phases [7]

4.2.2 Implementation

The conditions for the transition between the flight phases were modified and adjusted according to the limitations of the recordings in the QAR. The N2 (high pressure rotor speed of the engine) was substituted by the EPR (engine pressure ratio) to make the detection of the Take-Off. This is because the N2 parameters are recorded in the superframes and most of the times they are not updated during the take-off runs. This resulted in abnormal transitions from the Taxi-Out to the Climb phases, for instance. The use of the EPR, recorded at 1 Hz, ensures the normal transition from Taxi-Out to Take-Off and afterwards to the 2nd segment and subsequent phases. The vertical speed (IVV) is not recorded and is computed from the variation in the altitude. The HEIGHT parameter computes the altitude above ground level (or AGL altitude). At low altitudes – up to 2500 ft. - it corresponds to the value given by the radio altimeter. Thus, the true vertical distance to the ground is used. At higher altitudes the radio altimeter doesn't give accurate readings and, therefore, the HEIGHT parameter consists of an estimate that is computed from the corrected standard altitude (ALT_STDC) and the altitude standard of the origin and destination runways. The Flaps and Slats configuration is

computed from the Flap and Slat position recordings selected with the Flap and Slat Control Lever.

The results of the implementation are represented in figure 4.17, which shows the evolution of the FLIGHT_PHASE parameter throughout a selected long-haul flight. The transitions between the flight phases occur in the correct order defined in table 4.1. The transitions to higher flights levels in cruise are indicated by the periods where the FLIGHT_PHASE transitions from Cruise (8) to Climb (7) and then back to Cruise (8). The aircraft does not go through a Rejected Take-Off (4) or a Go-Around (13), as expected in normal operation. Results similar to those in the figure below were encountered for the other flights and demonstrate the correct implementation of the procedure and its usefulness to the analysis.

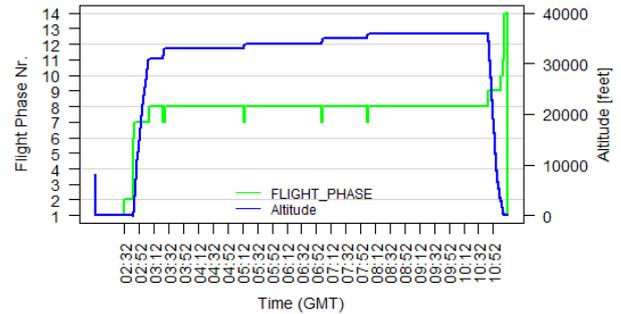


Figure 4.3 Flight Phase Results

5. Engine Condition Monitoring

In this section, the fundamentals of Engine Condition Monitoring (ECM) are introduced.

5.1 The Condition-Based Maintenance Philosophy

Over the last decades, aircraft maintenance has evolved according to the existing aviation safety standards and the economic requirements from the air transport industry. The Federal Aviation Administration (FAA) recognizes three Primary Maintenance Processes [8]:

- Hard-Time (HT);
- On-Condition Maintenance (OC);
- Condition-Monitoring (CM).

The Hard-Time is a preventative maintenance process that defines a limit for the parts in terms of flight hours, cycles or calendar time. The On-Condition maintenance is also a preventative process where an appliance or part is periodically inspected or checked against some appropriate physical standard to determine whether it can continue in service. The On-Condition maintenance tasks range from visual inspections to workshop and laboratory tests. Condition Monitoring is a predictive approach where the components/parts can actually fail in service. The target of condition monitoring is to define improvements in the maintenance programs by increasing the aircraft availability and reducing costs.

Condition-based Maintenance is a concept for maintaining gas turbine engines that is gaining acceptance between airlines and engine manufacturers [9]. The maintenance needs are determined based on the actual condition of the engine rather than on a preset schedule [10]. The objective is to maximize the engine's operational life and overhaul only when the engine needs major maintenance work. With the Condition-based maintenance concept, aircraft engines are subject to control by the three Primary Maintenance Processes [8]. In order to have a regular overview of the proper functioning of the engines, Engine Condition Monitoring is applied. It consists of a wide range of activities where the health of aircraft engines is assessed and followed on a routine basis, from the moment the engine is put on-wing until its removal [11].

The information is then used to ensure that preventive action is taken at an early stage before safe operation is affected and that the root causes of the problem are identified.

5.2 Systems for Data Collection and Analysis

The most basic system for collecting engine data consists of manual recordings by the flight crew. The crew is generally requested to take into account some constraining stability criteria. One of the disadvantages is that the parameters measured are limited to those with cockpit instruments. Modern commercial aircraft are equipped with data acquisition systems that automatically record data for monitoring purposes. They are capable of recording a much larger number of engine parameters, coming from an increased number of sensors in the engines.

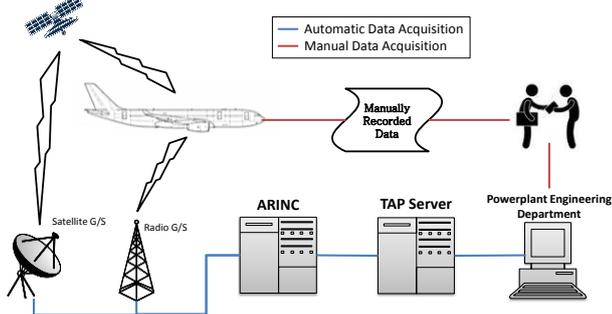


Figure 5.1 Engine data acquisition processes at TAP

The most efficient method for automatic data acquisition consists of transmitting the in-flight recorded data to ground stations via ACARS (Aircraft Communications Addressing and Reporting System). Although the cost of using ACARS is higher when compared to the other methods, there is the added benefit of making the information immediately accessible to the engineers, who can conduct real-time/near real-time assessments and plan in advance any required maintenance actions to be undertaken on the aircraft, thereby optimizing the time on the ground. The major disadvantage of manual data acquisition processes is that it can take a long time from the moment the recordings are executed to the moment when they are analyzed.

Once the data is available it is interpreted by ECM software, typically provided by the Original Equipment Manufacturers (OEM) of the engines. The primary function of the software tools is to perform parameter trend monitoring. This is the primary process used by Powerplant engineers to assess the engine's condition.

5.3 Engine Parameter Measurements

There are two types of parameters used for monitoring gas turbine engine condition [12]: the mechanical parameters and the performance parameters. The first group of parameters includes the engine vibrations and oil temperature and pressure. These parameters are not significantly influenced by the flight conditions and engine thrust setting, contrary to the performance parameters.

Today, most of the airliners in operation are equipped with turbofan engines. They produce lower noise levels than earlier generation jet engines and have considerably improved fuel economy. The key performance parameters in a turbofan engine are the EPR, the Low-pressure rotor speed or Fan speed (N1), the High-pressure rotor speed or Core speed (N2), the Exhaust gas temperature (EGT) and the Fuel Flow (FF).

5.4 Parameter Trend Monitoring

Parameter trend monitoring is the process in which the in-flight results are processed and then compared to a baseline model of how the engine is expected to perform

in the experienced conditions. The difference between the measured data and the reference model is called the trend delta or parameter delta.

5.4.1 Cruise Performance Trends

The most widely used method in the industry for cruise trend monitoring is to compare parameter data from each engine to a "baseline" engine model presented in standard day conditions² [13]. The baseline models are generally developed by the engine manufacturers based upon flight-test data and/or in-service experience. For the comparison between the raw recorded data and the "corrected" baseline model to be possible, it is necessary to correct the engine parameter data so that the deviations are determined. The correction procedure and the expressions are covered in the next section.

Gradual vs. Rapid Performance Shifts: There are two major types of movements that can be identified in a trend [8]: Step Shifts and Slow Drifts.

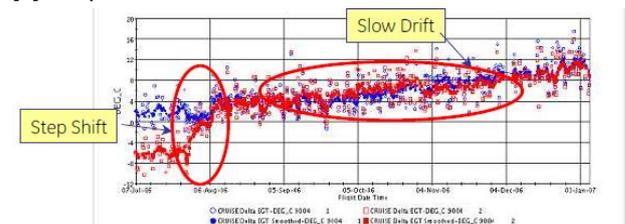


Figure 5.2 Slow Drifts vs. Step Shifts [8]

As the engine accumulates flight cycles its performance deteriorates due to several reasons: dust/dirt ingestion and accumulation on the turbine and compressor blades, increasing tip clearances on the compressor and turbine blades, erosion of the airfoils, hot section oxidation, etc. Slow Drifts represent the gradual deterioration of the performance of the engine that is caused by these factors. Step Shifts indicate mechanical changes in the engines that may propagate to failure and lead to the occurrence of incidents, such as in-flight shutdowns and aborted take-offs. The effective monitoring of the cruise trends helps to minimize the risks associated with unexpected engine failures, which result in unscheduled engine removals with additional maintenance costs to the airline, and to avoid excessive degradation of the engine's performance by checking the performance delta parameters against potential problem limits.

5.4.2 EGT Margin

To meet aircraft performance requirements, engines are designed to provide a constant Thrust up to a designated Flat Rate Temperature (FRT). Below this temperature the Thrust is limited by software. When the Outside Air Temperature (OAT) is lower than the FRT, the EGT is less than the limit. This limit is called the EGT Red Line and is demonstrated during endurance tests required for engine certification [14]. When OAT is higher than FRT, the fuel flow has to be reduced in order to keep the EGT below the limit and protect the turbine hardware.

The EGT Margin is an estimate of the difference between the certified EGT Red Line and a projection of the engine EGT to full (non-derated) take-off reference conditions. The observed/recorded peak EGT during the take-off is projected to the reference condition of full take-off power, on a FRT day at sea level. This projected temperature represents the expected EGT if the take-off actually occurred with the reference conditions.

The EGT Margin is routinely used to monitor the health of the engines, together with the trends from the cruise performance parameter deltas. EGT Margin can be used to forecast the remaining time of the engine on the wing

² Temperature: 288.15 K, Pressure: 1013.25 hPa (Sea-level ISA atmospheric conditions)

by predicting the point at which the margin will be completely eroded.

6. Study of Algorithms for ECM Trend Monitoring

The main objective of this work is the development of algorithms for performance trend analysis of engines. The methodology presented in this section and the next relies only on recorded flight data to derive the engine baseline models and determine its deterioration levels. The objective is to use this approach in complement to the trend monitoring tools provided by the OEM's software.

6.1 Case Study: PW4168A Engine

The studies were conducted on the PW4168A engine, which powers TAP's A330-223 aircraft. It is a dual rotor (two spool), axial flow turbofan engine with separate primary and fan duct exhaust systems. The engine delivers a maximum static take-off thrust of 68,600 lbs. at sea level conditions and has a bypass ratio of 4.9.

Figure 6.1 identifies the different Gas Path configuration areas on the PW4168A engine and the Engine Stations. The latter correspond to location points in the engine gas path that are used to describe the engine's operation. The EPR is the ratio of the turbine discharge total pressure (Station 4.95) to the compressor inlet total pressure (Station 2). The EGT is the total temperature of the low pressure discharge gas flow (Station 4.95).

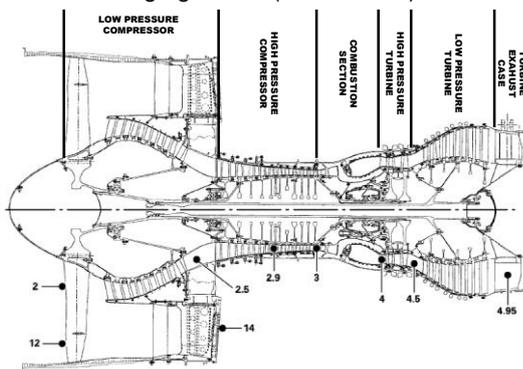


Figure 6.1 PW4168A Turbofan engine

Engine Cruise Report (01): The main component of the Aircraft Condition and Monitoring System (ACMS) is the Data Management Unit (DMU). One of the tasks performed in real time by this unit is the generation of the "Airbus Standard Reports" according to specific trigger conditions. Within the scope of this work, the interest is on the Engine Cruise Report (01), used for engine trend monitoring of TAP's A330-223 fleet. It consists of a collection of both aircraft and engine information.

6.2 Stability Points

To monitor the performance of an engine and to evaluate its deterioration, it is important to collect data that is representative of the engine's behavior. The Engine Cruise Report, in particular, contains information about the aircraft and the engine's operation relative to a point during the Cruise flight phase, where a set of conditions and stability criteria were respected during a certain period. A point in these conditions is also called a Stability Point. This section presents the development of an algorithm for extracting stability points from flight data recorded in the DAR (Digital ACMS Recorder). First, the stability criteria and trigger conditions employed by the DMU were used. Then, a new set of more restrictive stability criteria was applied, leading to a reduction in the number of stability points for each flight. The objective of this study was to acquire stability points with better quality and use these points for a trend monitoring analysis.

6.2.1 Observation Window and Stable Frame

A period of time identified as a stability point is called in the A330-223 aircraft a Stable Frame and has a duration of 100 seconds. Before searching for stable frames, there are some conditions that need to be verified first. They are used to avoid report triggering in flight phases where the parameters are of no interest and are called the Basic Conditions. When the Basic Conditions are met, the DMU searches for stable frames. It looks to the parameter data in each 100 seconds of flight and then computes the difference between the maximum and minimum values and compares it to the parameter's stability criterion.

This first method of searching stable frames consists of performing computations for each individual 100 seconds observation window in the flight. Individual means that each window is independent from the others, covering data from different periods of time. The second method uses a gliding window, where the observation window advances i seconds. If i is small (e.g. 1 second) the number of observation windows considered for the stable frame search increases significantly. The A330-223's DMU searches for the best stable frame using a gliding window method with an advancing front of 20 seconds ($i = 20$). In the algorithm developed, the advance in the gliding window is equal to the period with which the flights were exported from AGS.

6.2.2 Quality Number

If several stability points are identified it is necessary to have a consistent procedure that selects the best of them. Stability points are selected based on the quality number [15]. The Engine Quality Number (QE), is the sum of each of the individual quality numbers of the M stable frame parameters and is computed using the following formula:

$$QE = W_A \frac{VAR_A}{(TOL_A)^2} + W_B \frac{VAR_B}{(TOL_B)^2} + \dots + W_M \frac{VAR_M}{(TOL_M)^2} \quad (6.1)$$

Where W_i is the weight factor, TOL_i is the tolerance or the maximum variation of the parameter allowed in the observation window and VAR_i is the variance.

6.2.3 Algorithm for Extraction of Stability Points

The algorithm was developed using the R programming language and consists of two main parts: the Basic Conditions and the Stable Frame Criteria.

6.2.3.1 Basic Conditions

The conditions in table 6.4 must remain true during the observation window before stable frame calculations for the maximum and minimum values are performed and stability points encountered.

Logic for True Condition	Parameter(s)
Nacelle Anti Ice Status Off	FNAI1=1, FNAI2=1
Wing Anti Ice Status Closed	WAO1=1, WAI1=1, WAI2=1, WAO2=1
20000ft.<Altitude<41100ft.	ALT_STD
0.6<Mach Number<0.86	MACHR1
70<N1K<120 N1K=N1/(?2^0.5) ?2=(TAT+273.15)/288.15	N11, N12, TAT
Symmetrical Engine Bleed Configuration	EG_PRV_POS=O_ENGPRV_POS, EG_HP_V_POS=O_ENGHPV_POS
Cross Feed Valve Closed	XBV_POS2=0
APU Bleed Valve Closed	APUBV_O=0

Table 6.1 Logic for True Basic Conditions and Parameters

When available, the parameters that are corrected in AGS using additional procedures - ALT_STD, N11C, N12C - were used. This holds true for the stable frame parameters.

6.2.3.2 Stable Frame Criteria

Table 6.6 contains the stability criteria initially implemented in the algorithm.

IALT	100 ft.	MACHR1	0.008
GS	5 Knots	N11, N12	1.8%
ROLL	0.8°	PT21, PT22	0.05 PSIA
TAT	1.1°C	FF1, FF2	200 kg/hr
N21, N22	1.0%	EPR1, EPR2	0.05
EGT1, EGT2	22°C	HPT1, HPT2	5%
GVRTI	0.05 g	LPT1, LPT2	5%

Table 6.2 Aircraft Stability Criteria

6.2.3.3 Filtering of Parameters

The on-board systems of the aircraft also filter the parameter data. The formula used to filter these readings is the following:

$$NFV = OFV + \frac{t}{T}(NRV - OFV) \quad (6.2)$$

Where:

NFV = New Filtered Value t = Samples per Second
 OFV = Old Filtered Value T = Time Constant
 NRV = New Raw Value

The division t/T is constant for the filtered parameters and equal to 1/3.

Basic Parameters	ALT_STDC, MACHR1
Stable Frame Parameters	ROLL, TAT, N21C, N22C, EGT1C, EGT2C, GVRTI, N11C, N12C, FF1C, FF2C

Table 6.3 List of Filtered Parameters

6.2.3.4 Description

Figure 6.2 contains the flowchart for the algorithm, which is essentially divided in two parts. The first part is responsible for reading and processing the files containing the flight data and the second part writes the results to dedicated files. The flights were exported from AGS in .csv format with a parameter rate of 8Hz to take into account all the recorded values.

The algorithm starts by loading the flight data in the file. Afterwards, there is a cycle that reads every line of data.

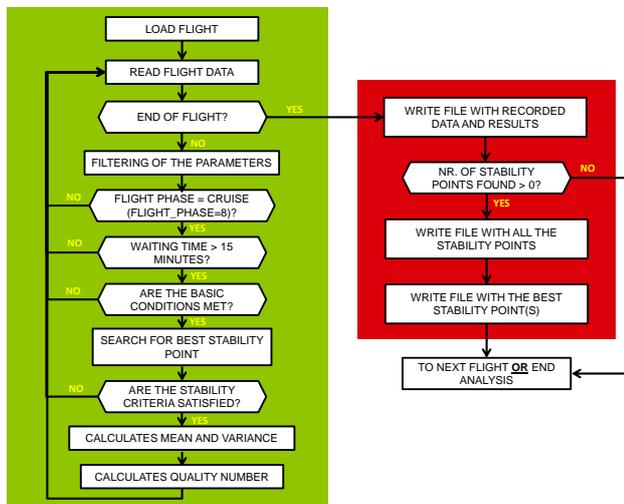


Figure 6.2 Algorithm for Extraction of Stability Points

The first condition is based on the Flight Phase parameter (FLIGHT_PHASE). Stability Points can only be generated in Cruise, when FLIGHT_PHASE=8. Next, a condition for the Waiting Time was implemented. The Waiting Time corresponds to a period of 15 minutes when stability points cannot be searched or generated that occurs in two situations:

- 1) After Cruise is attained for the 1st time;
- 2) After a search period of 240 minutes.

Finally, the Basic Conditions in the observation window are checked using the logic presented in table 6.1. If they are true, the algorithm will search stability points for a maximum of 240 minutes. If the differences between the maximum and minimum values of the stable frame parameters are lower than the tolerances in table 6.2, a stability point is generated and the quality number for the

stable frame. When the cycle reaches the end of the flight, a file with the recorded data and the results is written. If stability points are encountered two additional files are written: one containing the data from all the stability points found and another containing the best point from each search period.

6.2.4 Results

The algorithm was tested with a selection of flights performed by different aircraft. After this implementation, it was found that stability points were not being generated from approximately 50% of the flights. This was because in many of these flights the anti-ice discretés maintain the ON status and therefore the Basic Conditions were never met. However, this is an expected situation during normal operation.

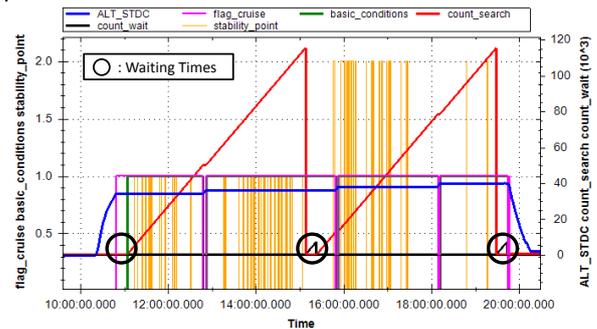


Figure 6.3 Flight Results obtained with the algorithm

Figure 6.3 illustrates some of the results obtained from a processed flight. The altitude (ALT_STDC) is also represented to illustrate the climb, cruise and descent flight phases. The flag_cruise variable indicates that the aircraft is in Cruise from the moment it finishes its initial climb up to a stable cruise altitude until starting the descent for landing. The exception is made to some periods where the aircraft transitions between flight levels. The basic_conditions variable indicates when the Basic Conditions are met. For this flight, Basic Conditions exist during most of the cruise, except for the initial 15 minutes after cruise is reached for the first time. The counter variables for the search and waiting times are illustrated with red and black lines, respectively. After the basic conditions are met for the first time, a search period of 4 hours (144000 eighths of second) for stability points begins. The search time is incremented whenever the basic conditions are true and in cruise. After 4 hours, there is a waiting time of 15 minutes before starting a new search period. The stability_point variable indicates when a stability point is found and it's numbered after the corresponding search period (1 or 2, in this case).

Parameter	Aircraft Stability Criteria	Converged Stability Criteria
IALT	100 ft.	35 ft.
GS	5 Knots	2 Knots
ROLL	0.8°	0.6°
TAT	1.1°C	0.5°C
N21, N22	1.0%	0.2%
EGT1, EGT2	22°C	3°C
GVRTI	0.05 g	0.04 g
MACHR1	0.008	0.0035
N11, N12	1.8%	0.3%
PT21, PT22	0.05 PSIA	0.04 PSIA
FF1, FF2	200 kg/hr	50 kg/hr
EPR1, EPR2	0.05	0.05
HPT1, HPT2	5%	5%
LPT1, LPT2	5%	5%

Table 6.4 Aircraft and Converged Stability Criteria

For the flights studied there were thousands of stability points encountered. This showed the potential to study a new set of more restrictive criteria. Table 6.4 displays the tolerances for the Converged Stability Criteria, together with the tolerances from the aircraft. The new criteria are

the result of an iterative process: each time the tolerances were reduced, the flights were processed and the number of stability points checked. After this iterative process, only approximately 10% of the exported flights did not generate any stability points.

6.3 Engine Parameter Corrections

Ambient conditions have a significant impact on the various parameters along the engine's gas path, such as flows, temperatures, pressures, speeds, etc. These not only vary with the power condition, but also with the temperature and/or pressure at the engine's inlet [16]. A change in these conditions contributes to an attendant change in the gas parameter's value, so it would be difficult to characterize the aero-thermodynamic relationships between the different gas turbine engine parameters (even at a constant engine operating point) unless the ambient conditions are accounted for. Generally, these relationships are determined by using corrected engine parameters.

6.3.1 General Formulation

A change in the inlet temperature (T_2) and pressure (P_2) is accompanied by an attendant change in any downstream gas path parameter P . The corrected parameter P^* represents the value that the parameter P would have at a fixed reference inlet condition (T_2, P_2). It is a common practice to select standard day atmospheric conditions at sea-level as the reference condition. The most widely used parameter correction formula has the following form:

$$P^* = \frac{P}{\theta^a \delta^b} \quad (6.3)$$

Where θ and δ are the relative temperature and relative pressure, respectively. They are defined as $\theta = T_2/288.15$ and $\delta = P_2/1013.25$. Generally, the exponents a and b will depend on the engine and cycle. However, there are some classical corrections and approximations that are commonly used for all gas turbine engines. Table 6.9 summarizes some of these corrections [16].

Parameter	a	b	Corrected Parameter (K)
Rotor Speed (N)	0.5	0	$NK = \frac{N}{\sqrt{\theta}}$
Fuel flow (FF)	0.5 (classical)	1	$FFK = \frac{FF}{\sqrt{\theta}\delta}$
Temperature (T)	1 (classical)	0	$TK = \frac{T}{\theta}$

Table 6.5 Common Gas Turbine Parameter Corrections

6.3.2 Application to the Case Study Engine

The computation of the theta and delta correction factors is done using the total temperature and the total pressure at the PW4168A engine's inlet, respectively. The computation is done with the average values of the TAT, PT21 and PT22 parameters from the stability points.

$$\theta_t = \frac{T_{02}}{T_0} = \frac{T_{02}}{288.15} \quad (6.4)$$

$$\delta_t = \frac{p_{02}}{p_0} = \frac{p_{02}}{1013.25} \quad (6.5)$$

The free stream total temperature (TAT) is used for the total temperature at both engine inlets.

In the PW4168A, there are four key engine performance parameters being monitored: EGT, Fuel Flow, N2 and N1. The values contained in each stability point are corrected for changes in the inlet condition using the equations below.

$$EGTK = \frac{EGT_{Raw} + 273.15}{\theta_t} [K] \quad (6.6)$$

$$FFK = \frac{FF_{Raw}}{\sqrt{\theta_t}\delta_t} [kg/hour] \quad (6.7)$$

$$N2K = \frac{N2_{Raw}}{\sqrt{\theta_t}} [\%] \quad (6.8)$$

$$N1K = \frac{N1_{Raw}}{\sqrt{\theta_t}} [\%] \quad (6.9)$$

The EGT is converted from degrees Celsius to kelvins. The theta correction factor, θ_t , is equal in both engines because it is computed from the TAT. The delta correction factor, δ_t , is computed from the respective total pressure at the engine's inlet.

7. Baseline Model Definition and Trend Monitoring Results

The engine baseline model and trend monitoring results are presented in this section. The source of engine parameter data are the stability points that are acquired with the algorithm described in the previous section after it was adapted and implemented in AGS.

7.1 Engine Baseline Model

This section presents the study that was undertaken with the objective of defining the cruise performance characteristics of the PW4168A engine. The engine parameter data in the baseline models is corrected with the correction factors and the equations from section 6.3.

7.1.1 Engine Selection for Baseline

As a starting point, it was necessary to access the records for engine removals and installations on TAP's A330-223 fleet. This was done in order to select a set of engines to be used for deriving the baseline models.

A/C Tail	Pos.	REMOVED ENGINE		INSTALLED ENGINE	
		EGT Margin	Date of Removal	EGT Margin	Date of Installation
CS-PWA	1	15°C	09-09-2013	42°C	10-09-2013
CS-PWA	2	34°C	26-09-2013	30°C	26-09-2013
CS-PWB	1	-6°C	07-03-2013	23°C	07-03-2013
CS-PWB	2	-8°C	21-02-2013	34°C	22-02-2013

Table 7.1 Engine Installations after Shop Visits³

The two aircraft listed in table 7.2 have been selected for deriving the engine baseline models. This selection was mainly based on the EGT Margin of the installed engines.

7.1.2 Bleed and Pack Selection

Bleed air can have a major effect on the performance curves of an engine and needs to be accounted for in order to provide accurate estimates. To take into account the bleed air effects in the ECM analysis, an Aircraft Bleed Code (ABC) and an Air Conditioning Pack Code (PKS) are computed from the recorded data using the ENGINE BLEED P/b switch and the PACK FLOW Selection switch discretetes.

7.1.3 Results

The points used in the definition of the baseline models were collected over a period of three months after the respective engines were placed on the wing. This period was found to be a good compromise between the number of points, the range of conditions experienced and the gradual deterioration the engine experiences.

7.1.3.1 Baseline Model with EPR

The results in figure 7.3 represent the variation of the corrected EGT, as a function of the EPR, for the two engines on the CS-PWA aircraft. The data from each engine was collected using with the Converged Stability Criteria in table 6.4, over the periods of time indicated, with bleed air being extracted from the engines (ABC=1) and a normal pack flow selection (PKS=2).

³ Due to TAP confidentiality policies, the A/C tails correspond to fictitious registrations, which do not exist at the date this work was done.

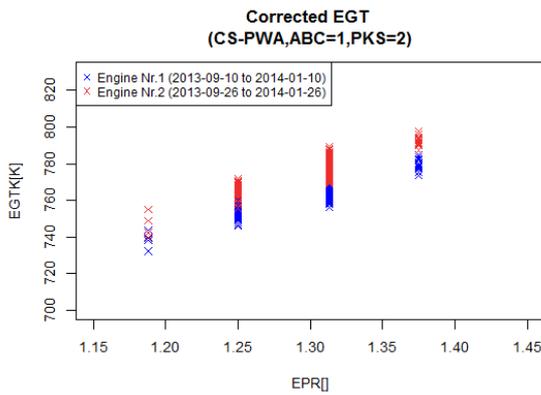


Figure 7.1 Baseline Results: EGTK vs. EPR

From the analysis of these results, it becomes clear that the EPR is restricted to certain values. This occurs because the EPR parameters are recorded with a resolution of 0.0625, meaning that the points were probably acquired when the actual EPR was different from the recorded value.

7.1.3.2 Baseline Model with N1

The N1 was selected as the thrust reference parameter instead. The results in figure 7.2 represent the expected performance characteristics of the PW4168A engine for the corrected EGT. The data was collected from the CS-PWA aircraft in the same conditions as those in figure 7.1.

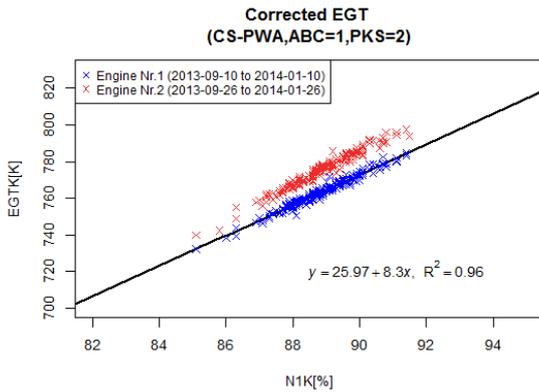


Figure 7.2 CS-PWA Baseline Model Results

The characteristics are much clearer in comparison with those in figure 7.3. The corrected EGT values are higher for Engine 2 than for Engine 1. The latter was installed in the aircraft with 42°C of EGT Margin and the first with 30°C, which allows to conclude that the margin is in fact a good indicator of the relative performance of the engines. Simple linear regression models were fitted to the EGTK, FFK and N2K data using the least squares approach. The R² values showed that the models obtained with both the aircraft and the converged criteria fit well the data. As expected, the number of points obtained with the latter criteria is lower due to the more restrictive tolerances. Aside from this, the results obtained with the two criteria were very similar. Although the Reynolds number effects are not considered with equation 6.3, it was also concluded that it was not essential to consider different model equations for different altitudes.

7.2 Trend Monitoring

7.2.1 Calculation of the Cruise Trends

Figure 7.8 illustrates how the delta parameters are calculated. The measured point contains the corrected engine value from the cruise performance parameter at a given corrected thrust (N1K). For this thrust, a baseline value is calculated using the equation of the model that was derived. The difference between the parameter value

from the measured and the baseline points yields the delta parameter.

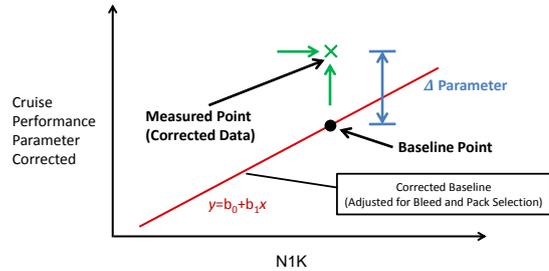


Figure 7.3 Delta Parameter Calculation

The equations used in the results of this section are written below.

$$DEGTK_{Raw} = EGTK_{Measured} - EGTK_{Baseline} \text{ [}^{\circ}\text{C]} \quad (7.1)$$

$$DFFK_{Raw} = \frac{FFK_{Measured} - FFK_{Baseline}}{FFK_{Baseline}} \times 100 \text{ [%]} \quad (7.2)$$

$$DN2K_{Raw} = \frac{N2K_{Measured} - N2K_{Baseline}}{N2K_{Baseline}} \times 100 \text{ [%]} \quad (7.3)$$

Smoothed delta parameters are calculated using equation 5.2 with a smoothing coefficient of 0.2. The calculation of the cruise performance trends is one of the main tasks executed by a dedicated program written in R. The program receives the stability points from AGS and corrects the EGT, FF, N1 and N2 values from each point. Then, the Engine Baseline Model is derived from the corrected engine data of the stability points for the specified engine and time interval. The raw deltas are calculated next with equations 7.1 to 7.3 and smoothed. The cruise trends are output in the form of plots.

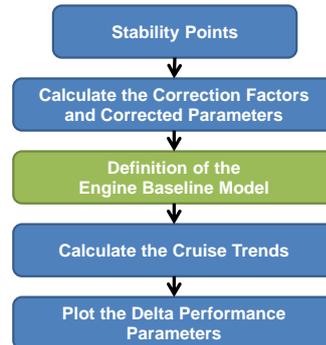


Figure 7.4 Process of Plotting the Cruise Performance Trends

7.2.2 Results

The plots in figure 7.5 contain the results for the results for the CS-PWB aircraft from December 2012 to February 2014. The flights from engine nr.2 after the installation in February 2013 were used for the baseline model.

The results for the delta EGT show very high initial deltas for both engines. When engine nr.1 was replaced in February 2013 and engine nr.2 in March 2013, they presented negative EGT Margins. The breaks in the data correspond to a period of approximately two months when the aircraft was out of service for maintenance.

There are two step shifts, which occur outside the dates for the engine removals/installations in figure 7.5. Both shifts are characterized by an increase in the delta EGT and delta FF and a decrease in the delta N2K. The two situations were detected with the P&W EHM software and were related with faults in the Turbine Case Cooling (TCC) System, which is responsible for reducing the turbine blade tip clearance⁴ during take-off, climb and cruise operation for better fuel efficiency.

⁴ Distance between the blade-tip and the engine casing.

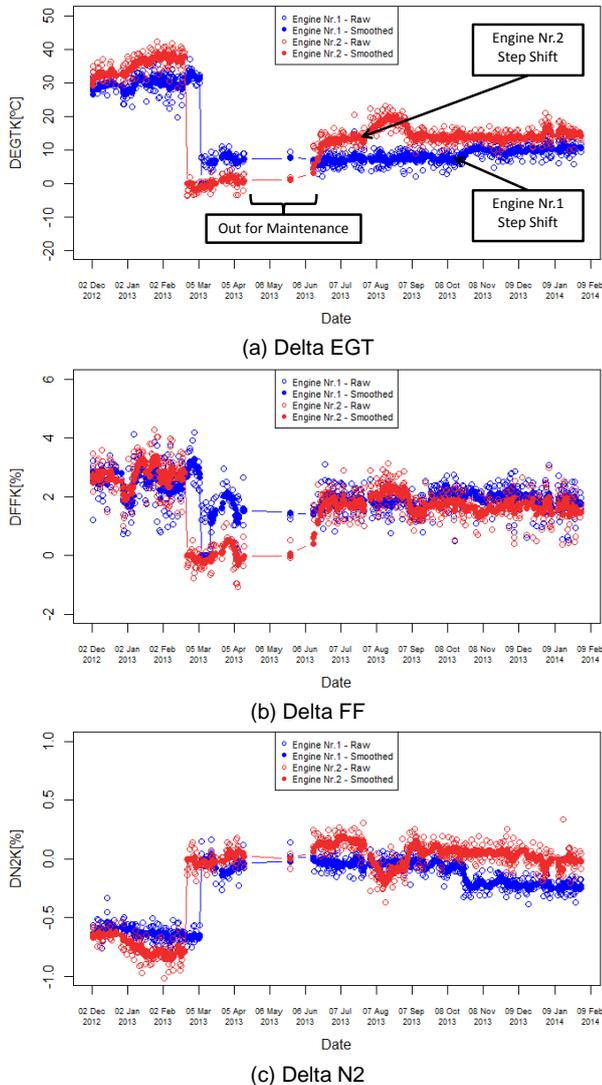


Figure 7.5 CS-PWB: Cruise Performance Trends

The P&W EHM results for engine nr.2 are illustrated by the Long Term Plot Report in figure 7.6. Having into account the manufacturer fingerprints for the PW4168A engine and the skills built from previous experience, powerplant engineers have ordered the inspection of the TCC system. From this inspection, maintenance personnel have found a faulty HPT valve which was promptly substituted and the engine returned to the previous performance as illustrated in figure 7.15.

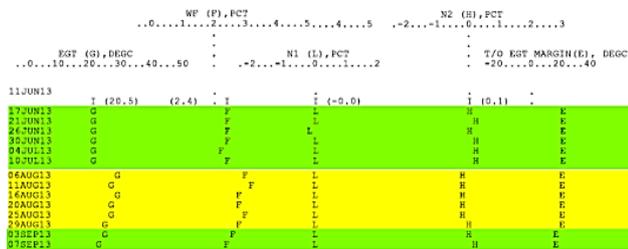


Figure 7.6 P&W EHM Long Term Trend Plot Report

The same pattern in the delta EGT, delta FF (WF) and delta N2 parameters can be observed in figure 7.13. The shifts in figures 7.13 and 7.15 are practically identical in terms of their amplitude. In addition, the deterioration levels of the engine before the failure and after maintenance work was conducted are similar in both figures. This might indicate that the performance of the engine used to derive the baseline model from the data is similar to the performance of the engine used by the manufacturer software.

8. Conclusions

The current work makes the best use of the engine data available from on-board recorders of a fleet of aircraft equipped with Pratt & Whitney engines for tracking engine operations with performance trend monitoring tools. The decoding results confirmed the extreme quality of the recorded flight data on-board the Airbus A310. The implemented database can be expanded to include FOQA and MOQA procedures. However, this is limited to the recordings in the QAR that became evident when the flight phase computation procedure was discussed. The results obtained with the algorithm for the extraction of stability points presented motivated the study a new set of stability criteria. The baseline models derived with another tool showed that the results acquired with the two sets of criteria were similar, aside from the difference in the number of points. The classical parameter corrections resulted in clear performance characteristics of the engines that were fitted with linear regression models. The trend monitoring results confirmed that engines with higher installed EGT Margins display better performance. The maintenance records confirmed that the observed shifts in the results were representative of engine faults. In addition, they were similar to those obtained with the manufacturer's ECM software and confirmed that the tools that were developed may be used as a complement to this software to help powerplant engineers in the diagnostic/prognostic of the engine's operation.

9. References

- [1] ICAO, "Safety Report - 2014 Edition," 2014.
- [2] Airbus, "Future Journeys 2013 2032," Global Market Forecast, 2013.
- [3] Condor Engineering, "ARINC Protocol Tutorial," 2000.
- [4] ARINC, "ARINC Specification 429 Part 1-17: Mark 33 – Digital Information Transfer System (DITS)," 2004.
- [5] Teledyne Controls, "Functional Specification of Digital Flight Data Acquisition Unit for Airbus A300 and A310 Aircraft," Los Angeles, California, 1993.
- [6] Mustafa Cavcar, "The International Standard Atmosphere (ISA)," *Anadolu University, Turkey*, 2000.
- [7] Sagem, *Analysis Ground Station V12 - Method for Database Programming*. Paris, France: SAFRAN, 2008.
- [8] General Electric, "Diagnostics Trend Interpretation Training," 2008.
- [9] Irem Y Tumer and Anupa Bajwa, "Learning about how aircraft engines work and fail," *AIAA Paper AIAA-99-2850*, 1999.
- [10] S K Sethiya, "Condition Based Maintenance (CBM)," *Secy. to CME/WCR/JBP*, 2006.
- [11] R. Vingerhoeds, P. Janssens, B. Netten, and M. Aznar Fernandez-Montesinos, "Enhancing off-line and on-line condition monitoring and analysis," *Control Engineering Practice*, vol. 3, no. 11, pp. 1515-1528, 1995.
- [12] Pratt & Whitney Aircraft, "Malfunction Analysis Through Gas Generator Comparisons and Mechanical Trends," Aircraft Gas Turbine Operation Information Letter 1965.
- [13] GE Aircraft Engines, CF-6 - Guidelines for Parameter Trend Monitoring, 1993, Transmittal Sheet.
- [14] Arnaud Bonnet, "Avoiding high speed rejected takeoffs due to EGT limit exceedance," *Safety First - The Airbus Safety Magazine*, no. 4, pp. 8-13, 2007.
- [15] Airbus, Getting to Grips with Aircraft Performance Monitoring, 2002.
- [16] Allan J Volponi, "Gas turbine parameter corrections," *Journal of engineering for gas turbines and power*, vol. 121, no. 4, pp. 613-621, 1999.