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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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Thesis to obtain the Master of Science Degree in

Aerospace Engineering

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July 2014

“Every flyer who ventures across oceans to distant lands is a potential explorer; in his or her breast burns the same fire that urged adventurers of old to set forth in their sailing-ships for foreign lands.”

Jean Batten, New Zealand Aviatrix

Créditos da Imagem de Capa: Miguel Nóbrega

Acknowledgements

This dissertation marks the end of a journey to become an aerospace engineer that started back in 2008. During the last five and a half years, I lived a great variety of experiences that caused me to meet and make friendships with a great diversity of people. These people made me grow as a person and contributed to that I could overcome all obstacles which have arisen. The work presented here was performed at TAP Portugal, a company that I have always admired and followed with particular interest. I hope it can continue to carry our flag higher and farther for a long time.

First and foremost, I would like to thank Engr. António Aguiar for giving me the opportunity to develop this work and for his guidance, shared scientific knowledge and availability during the time I was at TAP. I would like to offer my special thanks to Engr. Hélder Mendes, the co-supervisor for this work, for his patience, persistence, technical knowledge and for the time and efforts dedicated to it.

I would like to express my sincere thanks to my everyday colleagues, André Simões, Tiago Duarte and Luís Vargas for the friendship, motivation and for their contribution to the continuous progress of this work. I would also like to thank Mr. Manuel Ribeiro, Engr. Manuel Tereno, Engr. Rogério São Pedro, Engr. Alexandre Garrinhas and all the other people at TAP who have contributed with their experience and with valuable information to the conclusion of this work.

My deepest thanks to my family for their unconditional support over the years and for being my biggest source of emotional strength. This work is dedicated to them. Last but not least, to my closest friends, for all the good times that we have been sharing.

Abstract

The first part of this dissertation 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 dissertation 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

Resumo

A primeira parte desta dissertação descreve a implementação de uma base de dados de Monitorização de Dados de Voo no *software* AGS (*Analysis Ground Station*), para descodificação de dados gravados num Airbus A310. Os resultados para uma seleção de parâmetros gravados são analisados e o procedimento que calcula a fase de vôo é descrito. A segunda parte da dissertação descreve o estudo e implementação de algoritmos para monitorização do desempenho de motores PW4000-100. Dois algoritmos foram desenvolvidos utilizando a linguagem de programação R. O primeiro algoritmo é responsável pela aquisição de pontos de estabilidade em cruzeiro a partir de dados de voo gravados usando condições e critérios específicos e, após validação, foi implementado no AGS. O segundo utiliza os pontos de estabilidade dos vôos processados no AGS para derivar modelos base do motor e calcular as tendências de desempenho em relação a estes modelos. Os parâmetros do motor são corrigidos com a temperatura e pressão da tomada de ar e as características de desempenho dos motores são apresentadas para condições de atmosfera padrão. Os modelos base do motor são compostos por modelos de regressão linear ajustados aos dados obtidos dos vôos realizados após os motores voltarem de *shop visits*. Os resultados da monitorização nas tendências do motor foram comparados com aqueles obtidos com o software ECM do fabricante e confirmaram o potencial da metodologia desenvolvida para monitorizar a degradação gradual no desempenho do motor e para ser usada na detecção de mudanças que podem ser representativas de falhas do motor.

Palavras-chave: Dados de Voo, Manutenção Baseada na Condição, Monitorização da Condição do Motor, Tendências de Desempenho, Parâmetros de Turbinas a Gás Corrigidos, Pontos de Estabilidade

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Abbreviations

A/C	Aircraft
A/THR	Auto Thrust
ABC	Aircraft Bleed Code
ACARS	Aircraft Communication Addressing and Reporting System
ACMS	Aircraft Condition and Monitoring System
AGL	Above Ground Level
AGS	Analysis Ground Station
AIDS	Aircraft Integrated Data System
AMM	Aircraft Maintenance Manual
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio INCorporated
ATA	Air Transport Association of America
BCD	Binary Coded Decimal
BNR	Binary
BPRZ	Bipolar return-to-zero
C.P.	Control Panel
CG	Center of Gravity
CGCC	Center of Gravity Control Computer
CM	Condition Monitoring
CPT	Corner Point Temperature
CSV	Comma Separated Values
DAR	Digital AIDS (Airbus A310)/ACMS (Airbus A330) Recorder
DFDAU	Digital Flight Data Acquisition Unit
DFDR	Digital Flight Data Recorder
DME	Distance Measuring Equipment
DMU	Data Management Unit
ECAM	Electronic Centralized Aircraft Monitoring
ECC	Engine Electronic Control
ECM	Engine Condition Monitoring
EGT	Exhaust Gas Temperature
EGTHD	EGT Hot Day
EHM	Engine Health Monitoring
EPR	Engine Pressure Ratio
FAA	Federal Aviation Administration
FD	Flight Data
FDA	Flight Data Analysis
FDIU	Flight Data Interface Unit
FDM	Flight Data Monitoring

FDR	Flight Data Recorder
FDRPL	Flight Data Recording Parameter Library
FF	Fuel Flow
FL	Flight Level
FOQA	Flight Operations Quality Assurance
FRT	Flat Rate Temperature
GDP	Gross Domestic Product
GE	General Electric
GMT	Greenwich Mean Time
HP	High Pressure
HPT	High Pressure Turbine
HT	Hard Time
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
L.A.	Linear Accelerometer
LCC	Low Cost Carrier
LP	Low Pressure
LPT	Low Pressure Turbine
LSB	Least Significant Bit
MAC	Mean Aerodynamic Chord
MOQA	Maintenance Operations Quality Assurance
MSB	Most Significant Bit
N1	Low-pressure rotor/Fan speed
N2	High-pressure rotor/Core speed
ND	Navigation Display
OAT	Outside Air Temperature
OATL	Outside Air Temperature Limit
OC	On-Condition
OEM	Original Equipment Manufacturer
OQAR	Optical Quick Access Recorder
PFD	Primary Flight Display
PKS	Air Conditioning Pack Code
PW/P&W	Pratt & Whitney
QAR	Quick Access Recorder
RPK	Revenue Passenger Kilometers
RPM	Rotations per minute
SDI	Source/Destination Identifier
SF	Subframe
SSM	Sign/Status Matrix

SV	Shop Visit
TAP	Transportes Aéreos Portugueses
TAS	True Airspeed
TAT	Total Air Temperature
TCC	Turbine Case Cooling
TO	Take Off
UTC	Universal Time Coordinated
WF	Fuel Flow

Nomenclature

Latin Symbols

a	Theta (θ) correction exponent
b	Delta (δ) correction exponent
$DEGTK_{Raw}$	Raw delta EGT
$DFFK_{Raw}$	Raw delta FF
$DN2K_{Raw}$	Raw delta N2
EGT_{Raw}	EGT value from the stability point
$EGTK$	Corrected EGT
$EGTK_{Baseline}$	Corrected EGT (from the baseline model)
$EGTK_{Measured}$	Corrected EGT (computed from the value of the stability point)
FF_{Raw}	FF value from the stability point
FFK	Corrected FF
$FFK_{Baseline}$	Corrected FF (from the baseline model)
$FFK_{Measured}$	Corrected FF (computed from the value of the stability point)
M_t	Tip Mach number
N	Number of samples of the parameter in the observation window
N	Rotational speed (RPM)
NFV	New Filtered Value
NRV	New Raw Value
$N1_{Raw}$	N1 value from the stability point
$N1K$	Corrected N1
$N2_{Raw}$	N2 value from the stability point
$N2K$	Corrected N2
$N2K_{Baseline}$	Corrected N2 (from the baseline model)
$N2K_{Measured}$	Corrected N2 (computed from the value of the stability point)
OFV	Old Filtered Value
p_0	Pressure at ISA Sea Level conditions (1013.25hPa)
p_{02}	Total pressure at the inlet
P	Generic gas path parameter
P^*	Corrected gas path parameter
P_2	Inlet Pressure (Station 2)
QE	Engine Quality Number
r	Radius of the fan blades
t	Samples per second (DMU)
T	Time Constant (DMU)
T_0	Temperature at ISA Sea Level conditions (288.15K)
T_{02}	Total temperature at the inlet

T_2	Inlet Temperature (Station 2)
TOL_I	Maximum variation of the parameter allowed in the observation window
u	Inlet velocity of the air
u_e	Exhaust velocity
VAR_I	Variance of parameter I in the observation window
w	Tangential velocity
W_I	Weight factor of parameter I
$\bar{x}$	Mean of the parameter in the observation window

Greek Symbols

α	Angle of Attack
α	Smoothing coefficient
γ	Flight Path Angle
δ	Pressure correction factor
δ_t	Pressure correction factor computed with the total pressure
η_P	Propulsive Efficiency
θ	Pitch Angle
θ	Temperature correction factor
θ_t	Temperature correction factor computed with the total temperature

Constants

R	Gas constant, 287 $\mathrm{Jdeg^{-1}kg^{-1}}$
γ	Ratio of specific heats/Adiabatic index, 1.4

1. Introduction

1.1 Motivation

The aviation industry plays an important role in the global economic activities. Over the last decades, air transportation evolved from a luxury good to an everyday good and has been characterized by an almost continuous increase in passenger traffic numbers. 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), based on current projections. Despite this growth, the airline industry has consistently reported losses that ascend to billions of dollars only in the last decade, which resulted in many premature bankruptcies. The poor performance of the air transport industry in terms of profitability can be explained by the apparent inability of the airlines to adjust to fast variations in the demand, caused by variations in the macroeconomic climate - represented, for example, by the Gross Domestic Product (GDP) [3]. External demand shocks, such as the 9/11 terrorist attacks or the financial crisis of 2007/2008, produce gaps between demand and capacity, where large reductions in revenue are not compensated quickly enough by the corresponding reduction in the airline costs. In addition to these factors, the constant fluctuations in the oil prices and the increasing competition from Low-Cost Carriers (LCC), also affect the stability of the airlines and have forced more established carriers to search for ways of reducing costs and streamlining the different areas of operation, in order to become more efficient than the competition and to guarantee their economic viability.

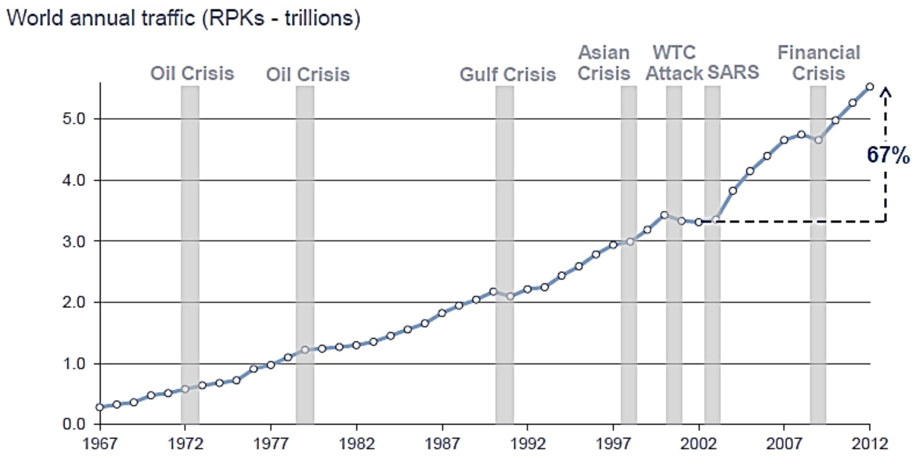


Figure 1.1 World Annual Traffic 1967-2012 (RPKs) [2]

Despite the excellent safety record of air travel, aircraft accidents always have major economical and emotional consequences. The Flight Data Analysis (FDA), also called 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, starting in the early sixties.

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. References [4] and [5] deal with some practical cases of FOQA procedures and describe their implementation using specific tools available at TAP for processing recorded flight data. 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 for improved fuel consumption, for instance.

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 work performed in [6] focuses on the development and validation of a method for on-ground data acquisition of data during cruise for aircraft performance monitoring. The objective was to have data leading to more reliable assessments of the degradation in each aircraft and to overcome the lack of flexibility from the on-board systems currently used for these functions.

Engine maintenance is often the highest maintenance cost and can have a major impact on the profitability of airlines [7]. Engine Condition Monitoring (ECM) is the process used by the operators to monitor the health of their engines on a daily basis. The performance of each engine is checked against a reference model using sophisticated computational tools, where the deterioration levels can be visualized as a function of time. This information is used for planning engine removals, alert about poor performance and to provide indications on precursors to actual engine failures that could lead to extensive repairs. Generally, the sources of data used in this process are the on-board computers.

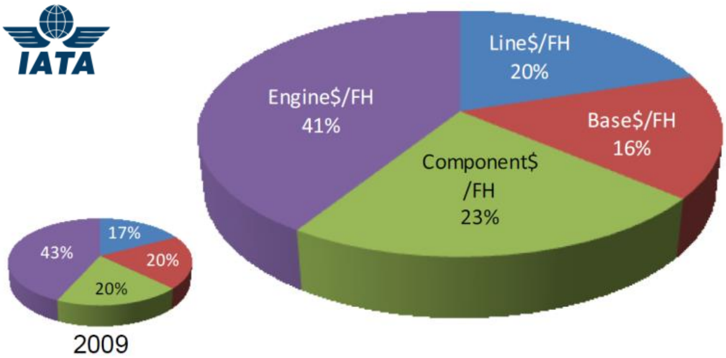


Figure 1.2 Engine Maintenance Costs distribution for 2012 and 2009 comparison [8]

The increasing recording capacity of the flight data recorders, the development of newer aircraft fitted with dedicated sensors for a more comprehensive and accurate prognostic of the aircraft/aircraft systems 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.

1.2 Objectives

The current dissertation describes the work that was performed within the Flight Data department at TAP Portugal. The first objective of the work was the implementation of an FDM database in the AGS (Analysis Ground Station) software capable of decoding the flight data from the recorders of an Airbus A310 aircraft. This required the knowledge of the on-board transmission and recording protocols. Additionally, the database includes some procedures for an improved flight analysis. These procedures allow the correct separation of the different phases during each flight and the correct identification and storage of the analysed flights.

The second and main objective of the work was the development of algorithms for engine performance analysis, for the purpose of Engine Condition Monitoring. Two separate tools were created using R programming language with direct application to the PW4168A[1] engine. The first tool is responsible for the acquisition of stability points from the recorded flight data. The stability points contain information about aircraft and engine parameters averaged over a period during cruise where a set of conditions and stability criteria were met. The logic used by the on-board computer systems was initially used for validation and, afterwards, a new set of more restrictive criteria was studied and led to a reduction in the number of points encountered in each flight. Only one stability point is captured every four hours during cruise and its selection is based on the quality number that is computed from statistical variables. The tool was then implemented in AGS. The second tool establishes a baseline model with the expected performance characteristics of the engine and calculates the performance deterioration levels of each engine. The inputs are the stability points acquired from the flights processed in AGS. The performance of the engine is modelled from a series of flights after the engine returns from shop visits with performance restoration. The engine parameter data is corrected taking into account the temperature and pressure at the engine's inlet.

The potential of the developed method to monitor the gradual deterioration of the engines will be evaluated and the capability to detect failures or malfunctions in the engine will also be studied by crossing the data obtained with information from the engine manufacturer's software.

1.3 Thesis Outline

After this introductory chapter, the thesis is organized in seven chapters:

- Chapter 2: introduces the general characteristics of the Airbus A310-325, the aircraft from which the data will be decoded. It describes the ARINC 429 protocol, used in the transmission of data between the avionics equipment of the aircraft, and the ARINC 717 protocol, which describes the format of the data stored in its recorders. The architecture of the recording system in the A310-325 is shown and the function of each recorder is described.
- Chapter 3: contains the different steps that were followed in order to implement a new database version in AGS, containing the necessary information to decode the recorded

[1] PW stands for Pratt & Whitney

parameters. The recordings are organized in a structure known as frame or dataframe. The knowledge of the protocols described in Chapter 2 is fundamental during this procedure.

- Chapter 4: this Chapter presents the results for a selection of recorded parameters, which are displayed as a function of time and grouped according to their ATA chapter. The Flight Phase computation procedure and its implementation are described afterwards, mainly due to its importance for the flight data analysis;
- Chapter 5: introduces the topic of Engine Condition Monitoring. The role of ECM in the engine maintenance program is discussed, as well as its contribution to the condition-based maintenance philosophy. The most common systems used for data collection and analysis, the type of parameters measured and the parameter trend monitoring method used to analyze the engine performance and evaluate its deterioration are also presented.
- Chapter 6: this Chapter starts by introducing the case study engine, the PW4168A. The definition of observation window, stability point and the necessary equations for the calculation of the quality number are presented. The algorithm for the extraction of stability points is described and the relevant results presented. Finally, the correction procedure used for performance trend monitoring of the PW4168A engine is also presented and uses equations that were found in the literature.
- Chapter 7: goes through the process of definition of engine baseline models, which are based on the stability points acquired from the algorithm developed in the previous chapter. The performance trend monitoring results containing the evolution of the deterioration levels with respect to the derived baseline models are shown and analyzed for two aircraft.
- Chapter 8: presents the final conclusions about what has been achieved with the current work, together with relevant topics for future work that could be followed in order to continue the work developed so far.

2. The Airbus A310-325 Aircraft

The first part of this work deals with the decoding of Airbus A310 recorded data. In this Chapter, the general characteristics of the aircraft are presented as well as the on-board protocols used for the transmission and recording of the data. Afterwards, the A310 recording system is described.

2.1 General Characteristics

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, with a large majority of them still in operation worldwide [9]. Depending on the seating layout the aircraft is certified to carry up to 275 passengers. Table 2.1 lists the specifications for the A310-325 variant, powered by PW4156A Engines.

General Characteristics	
Overall length	46.66 m
Height	15.80 m
Wing span	43.90 m
Fuselage width	5.64 m
Cabin length	33.25 m
Maximum cabin width	5.28 m
Mean Aerodynamic Chord (M.A.C.)	5.8287 m
Wheelbase	15.22 m
Crew	2 (minimum)
Seating Capacity	220 (2-class configuration)
Performance	
Powerplant	2 Pratt & Whitney PW4156A
Thrust	56 000 lbf (x2)
Range	8050 km
Maximum Operating Mach number (MMO)	0.84
Maximum taxi weight (MTW)	164 900 kg
Maximum take-off weight (MTOW)	164 000 kg
Maximum landing weight (MLW)	124 000 kg
Maximum zero fuel weight (MZFW)	114 000 kg
Maximum fuel capacity	61 070 litres

Table 2.1 Airbus A310-325 Specifications [10], [11]

2.2 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. ARINC stands for Aeronautical Radio INCorporated, a company established in 1929 by four major airlines that develops and operates systems and services to ensure the efficiency and performance in the communications in the aviation industry [12]. It has evolved to become the global industry leader in the development of specifications and standards for avionics equipment. In 2013, the company was acquired by Rockwell Collins [13].

2.2.1 ARINC 429 Protocol

The continuous increase in the flux of data from the aircraft systems dictated the need to standardize the transmission between the aircraft electrical data buses. 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, known as Mark 33 Digital Information Transfer System (DITS). The transmission and reception is made on separate ports.

The ARINC 429 protocol is one of the most commonly used protocols in the aviation industry, being installed on many commercial aircraft, including the Airbus A310/A320 and A330/A340 and Boeing 727, 737, 747, 757 and 767. However, alternative systems are being developed on most recent aircraft, such as the Boeing 777, in order to reduce the weight of the wires needed and to transmit data at higher rates [12].

2.2.1.1 ARINC 429 Electrical Characteristics

Each ARINC 429 bus uses two signal wires to transmit the messages, which consist of 32 bit words. The messages are transmitted at a bit rate of 12.5 or 100 kilobits per second, depending on the specification of the bus. 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) modulation consisting of three states: HI, LO and NULL. The information is retrieved from the voltage difference between the two wires, also called the differential voltage. The nominal transmission voltage is 10±1 volts, with either a positive or negative polarity. Therefore, to each wire corresponds a signal leg that ranges between -5V and +5V. When one leg is +5V, the other is -5V and vice-versa. One wire is called the “A” (or “+” or “HI”) and the other is the “B” (or “-” or “LO”). The differential voltage at the receiver terminals depends on the line length and the number of receivers connected to each bus, which is limited to 20 by the protocol. In addition, the voltage levels can be perturbed by noise and pulse distortion [14]. Depending on the differential voltage, the receiver terminals associate the following voltage ranges with the three signal states in table 2.2.

Voltage Differential (A to B)	Signal State
+6.5 V to +13 V	HI
-2.5 V to +2.5 V	NULL
-13 V to -6.5 V	LO

Table 2.2 Receiver Voltage Levels

Figure 2.1 shows a transmission example for a 32 bit data word, with the representation of the signal legs from wires A and B.

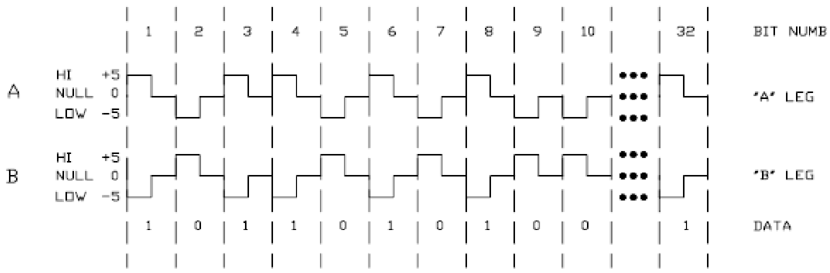


Figure 2.1 ARINC 429 Data Transmission Example [12]

The ARINC 429 bit characteristics [12] are summarized in table 2.3 for both transmission rates and a graphical representation is shown in figure 2.2. The Time Y is the time between two successive flanks and the Time X is the time the signal stays at a HI or LO level.

Parameter	High Speed	Low Speed
Bit Rate	100 kbit/s	12.5 kbit/s
Time Y (one bit)	10 µsec ± 2.5%	1/(bit rate) µsec ± 2.5%
Time X	5 µsec ± 5%	Y/2 µsec ± 5%
Pulse Rise time	1.5 ± 0.5 µsec	10 ± 5 µsec
Pulse Fall time	1.5 ± 0.5 µsec	10 ± 5 µsec

Table 2.3 ARINC 429 Bit Characteristics

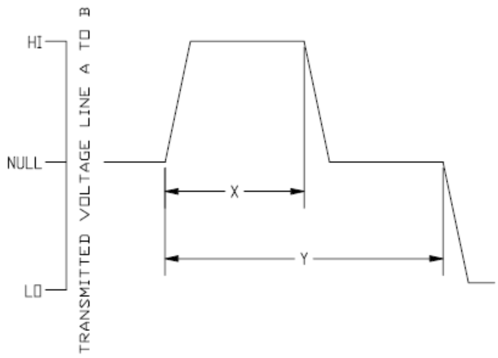


Figure 2.2 ARINC 429 Electrical Characteristics [12]

2.2.1.2 Format of the Data Word

The ARINC 429 data words have a length of 32 bits and typically use the format shown in figure 2.3, which includes five primary fields: parity bit (P), Sign/Status Matrix (SSM), data, Source/Destination Identifiers (SDI) and the Label. The bits from 1 to 32 are specified by the protocol.

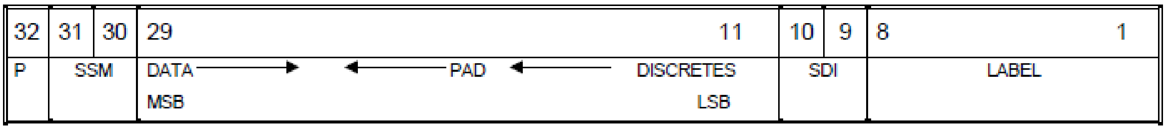


Figure 2.3 ARINC 429 Word Format [12]

<u>Parity</u>

The Most Significant Bit (MSB) in the ARINC 429 word format is the parity bit (P). 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 is ensured by setting the parity bit to ”0” when there is an odd number of “1” bits from bits 1 to 31 and to “1” when it is even. The parity bit allows the receiver to identify if transmission errors have occurred. However, this method of identifying errors is only effective when the number of incorrect bits is odd. When this is not the case, the errors can remain undetectable.

<u>Sign/Status Matrix (SSM)</u>

Bits 30 and 31 contain the Sign/Status Matrix (SSM). This field contains information about the conditions of the hardware equipment, operational mode or validity of the data content, in the form of a code. The applicable codes and their meanings, which differ depending on the type of encoded data, are indicated in table 2.4 [14].

Bit Number		Meaning		
31	30	BCD	BNR	Discrete
0	**0**	Plus, North, East, Right, To, Above	Failure Warning	Verified Data, Normal operation
0	**1**	No Computed Data	No Computed Data	No Computed Data
1	**0**	Functional Test	Functional Test	Functional Test
1	**1**	Minus, South, West, Left, From, Below	Normal Operation	Failure Warning

Table 2.4 SSM codes for BCD, BNR and Discrete Data

Data

Bits 29 to 11 contain the data from the parameter(s) in various formats. There are some standard types of data, which will be presented in the next section together with some examples, 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. When this occurs the SDI field is not used and this field is overlapped by the parameter Data field [12].

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 avionic equipment. The labels are listed in the ARINC specification [14] and are represented as octal numbers with three digits, from 0 to 377. Table 2.5 exemplifies how label 256 is computed from the transmitted bits.

Word bits	1	2	3	4	5	6	7	8
Binary	1	0	1	0	1	1	1	0
Octal	2		5			6		

Table 2.5 Label 256 computation

The most significant digit occupies two bits and the least significant digit and middle digit occupy 3 bits each. Although the maximum label number corresponds to 377, there are only 255 labels available: $3 \times 8^2 + 7 \times 8^1 + 7 \times 8^0 = 255$. In the label, the most significant bit (bit 8) is transmitted first. With the other bits from the ARINC word, the reverse order is used. The transmission order is as follows [12]:

8, 7, 6, 5, 4, 3, 2, 1, 9, 10, 11, 12, 13, …, 32

2.2.1.3 ARINC 429 Data Types

The data transmitted with the ARINC 429 protocol can be of several types. For each type, there is a specific format of encoding the data in the 32 bit words. The following types of data and their formats are addressed in this section: BCD (Binary Coded Decimal), BNR (Binary) and Discretes.

BCD (Binary Coded Decimal)

This is a very common format that is generally used to represent parameters limited to specific values. Some examples include radio frequencies or distances to radio-navigation equipment. On the other hand, the BNR type is more suitable for parameters such as temperatures, speeds, accelerations, etc. and will be explored next. Figure 2.4 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, according to the logic in table 2.4.

32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8 1
P	SSM		CHAR 1			CHAR 2				CHAR 3				CHAR 4				CHAR 5				SDI		LABEL

Figure 2.4 General BCD Word Format [12]

Four bits are allocated to each digit, except for the most significant sub-field, which encodes the digit with 3 bits only. Therefore, the maximum decimal value represented by the first digit is 7. In the event that this value is greater than 7, bits 29, 28 and 27 are set to zero (padded with zeros), and the second sub-field becomes the most significant. The most significant digit is now represented by four bits, which allow reaching a maximum value of 15: $1 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 15$.

An example of a BCD word is in table 2.6. The data indicates the distance to the DME (Distance Measuring Equipment), a radio-navigation equipment: 257.86 NM.

32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
P	SSM		CHAR 1			CHAR 2				CHAR 3				CHAR 4				CHAR 5				SDI		LABEL							
0	0	0	0	1	0	0	1	0	1	0	1	1	1	1	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	1
	+		2			5				7				8				6						201							

Table 2.6 BCD Word encoding example: Distance to DME

BNR (Binary)

The BNR type is also a very common ARINC 429 data format, in which the data is stored 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 in complement of two of the positive values: when bit 29 is "1", the number is negative and when it is "0", the number is positive. Bit 28 represents half of the maximum value (range) of the parameter, bit 27 represents 1/4th of the range, etc.

32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8 1
P	SSM		Data																	Pad		SDI		LABEL

Figure 2.5 General BNR Word Format [12]

The numerical value of the parameter is obtained by multiplying the bit values by their respective fraction of the range. In addition to the range, which constitutes an interval of the values the parameter can have, the resolution is an important parameter to consider in the computation. It defines the precision of the least significant bit of the parameter. These two properties, range and resolution, are related to each other according to the equation below [5]:

$$Range = Resolution \times 2^n \tag{2.1}$$

Where n is the number of bits used by the parameter. For many parameters it is not necessary to fill all the available bits with information. n takes values up to 20 (bits 28 to 9), in which case the SDI is not recorded. Table 2.7 gives an example of BNR encoded data for the True Airspeed (TAS). The "P" denotes pad "zero". A possible use for these pad bits are discrete parameters.

32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
P	SSM		DATA FIELD																			SDI		LABEL							
0	1	1	0	0	1	0	0	0	1	1	0	1	0	1	0	0	0	0	P	P	P	0	0	0	0	0	1	0	0	0	1
0	0		+	565 Knots																				210							

Table 2.7 BNR Word encoding example: True Airspeed

The parameter characteristics – range, resolution, number of data bits, etc. - are available from the ARINC specification and/or the Aircraft Maintenance Manual (AMM). The range for the example parameter is 2048 and the number of significant bits is 15. The resolution is equal to $2048/2^{15}=0.0625$. The TAS is always positive, so bit 29 is always set to zero. Table 2.8 shows how the value of the parameter is computed.

Bit Nr.	**Bit Value**	
	Binary	**Decimal [Knots]**
28	0	$(2048/2)*0=0$
27	1	$(2048/2^2)*1=512$
26	0	$(2048/2^3)*0=0$
25	0	$(2048/2^4)*0=0$
24	0	$(2048/2^5)*0=0$
23	1	$(2048/2^6)*1=32$
22	1	$(2048/2^7)*1=16$
21	0	$(2048/2^8)*0=0$
20	1	$(2048/2^9)*1=4$
19	0	$(2048/2^{10})*0=0$
18	1	$(2048/2^{11})*1=1$
17	0	$(2048/2^{12})*0=0$
16	0	$(2048/2^{13})*0=0$
15	0	$(2048/2^{14})*0=0$
14	0	$(2048/2^{15})*0=0$
	Parameter Value (Σ)	**565**

Table 2.8 Computation of the True Airspeed

<u>Discrete</u>

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. For instance, these parameters can describe the status of engine valves, flight surfaces, navigation modes, etc. Some examples of the two states indicated by the bit are: ARMED/NOT ARMED, AIR/GROUND, ENGAGED/NOT ENGAGED, ON/OFF, SELECTED/NOT SELECTED.

2.2.2 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. This protocol supersedes the ARINC 573 specification that defined the output format for use in Flight Data Recorders (FDR) from a continuous data stream of Harvard Bi-Phase 12-bit words, which were then formatted in frames [12]. The ARINC 717 protocol performs the same functions but includes a number of different bit rates and frame sizes, to reflect the evolution in the aircraft recording systems [15]. It also encodes the data stream in BPRZ format, the same as ARINC 429.

2.2.2.1 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 [16]. 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. If the number of recorded bits from a parameter exceeds the size of the word, more words are assigned. Figure 2.6 illustrates the relationship between the structures of a frame.

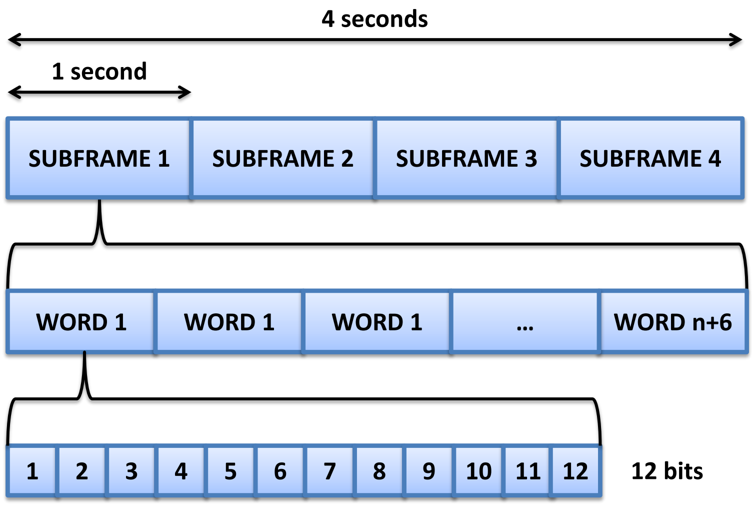


Figure 2.6 Frame, Subframe and Word

The bits from each word are numbered from one to twelve, as seen in figure above. Bit one corresponds to the Least Significant Bit (LSB) and is transmitted first, while bit 12 is the Most Significant Bit (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.

Generally, there is a recorded parameter that consists of a frame counter, which is incremented every four seconds. It is used by ground processing tools to detect lost data or recognize synchronization problems. The first word of each subframe has a constant value and is used for synchronization.

2.2.2.2 Regular Frame

Most parameters are recorded at least once every four seconds, i.e., in every frame. These parameters compose the regular 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. Table 2.9 contains some examples of recorded parameters in the A310-325 aircraft that help to clarify the previous concepts.

Parameter Name	Recording Rate	Samples per Frame	Subframes
Radio Height #1	1 Hz	4	1,2,3,4
Vertical Acceleration	16 Hz	64	1,2,3,4
Flaps Position	1/2 Hz	2	2,4
Selected Vertical Speed	1/4 Hz	1	4
Pitch Angle	4 Hz	16	1,2,3,4

Table 2.9 Examples of Regular Parameters

The number of samples per frame is simply obtained from multiplying the recording rate by the number of subframes. Higher recording rates are used for parameters that tend to vary more rapidly, such as the Pitch Angle or the Normal acceleration, while parameters that experience slow variations are recorded less frequently, such as the Selected Vertical Speed.

2.2.2.3 Superframe

The superframe parameters have a recording rate of 1/64 Hz and hence they are recorded once every 64 seconds 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, i.e., every four seconds, and ranges from 0 to 15. This counter indicates the parameter or parameters that are being recorded.

Generally, the superframe parameters contain information that doesn’t change throughout a flight or that doesn’t change as frequently as the accelerations, speeds, etc. By using superframes, one can put up to 16 of these parameters together in a word slot and free vital space for the recording of other parameters if needed. Some of the superframe parameters recorded in the frame of the A310 include information about the Hour, Day, Month, Flight Number, Gross Weight, etc.

2.3 ATA Chapters

The Air Transport Association of America (ATA) is America’s oldest and largest airline trade association. It was founded in 1936 and has since been renamed as Airlines for America (A4A). This organization has played a major role in many decisions regarding aviation, including the Airline Deregulation Act in the United States or the creation of the air traffic control system [17]. ATA was responsible for the creation and release of important standards, developed with the purpose of providing a specification for developing technical airline documentation. These standards have enabled both airlines and suppliers to increase their levels of efficiency [18].

ATA Spec 100 is one of the most widely used standards for commercial aircraft documentation and the latest version was released in 1999. The Spec 100 contains format and content guidelines for technical manuals written by aviation manufacturers and suppliers and is used by airlines and other segments of the industry for the maintenance of their products. The Spec 100 provides the aviation industry with a standard for aircraft systems numbering, also referred as ATA system or chapter numbers [19]. This standard system facilitates the learning and understanding for pilots, aircraft maintenance technicians and engineers alike [20].

2.4 ATA 31 Recording Systems: Aircraft Integrated Data System (AIDS)

The aircraft recording systems shall be configured to comply with the mandatory flight data recording requirements. They should acquire and record the mandatory parameters as received from the aircraft's systems. The list of mandatory parameters is prepared by the civil aviation authorities, on a country basis [16].

The main function of the Aircraft Integrated Data System (AIDS) of the Airbus A310 is to convert the various critical (including the mandatory) parameters into a recordable format and to record them on a Flight Data Recorder (FDR) [21]. The system can be expanded to include data processing units to monitor the condition of the connected aircraft systems. The diagram in figure 2.7 displays the architecture of the A310's AIDS. The Basic AIDS fulfills the mandatory recording requirements and is 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.).

The Expanded AIDS is obtained by adding the following equipment:

- A Data Management Unit (DMU);
- A Digital AIDS Recorder (DAR);
- An Interactive Display Unit (IDU);
- A Printer.

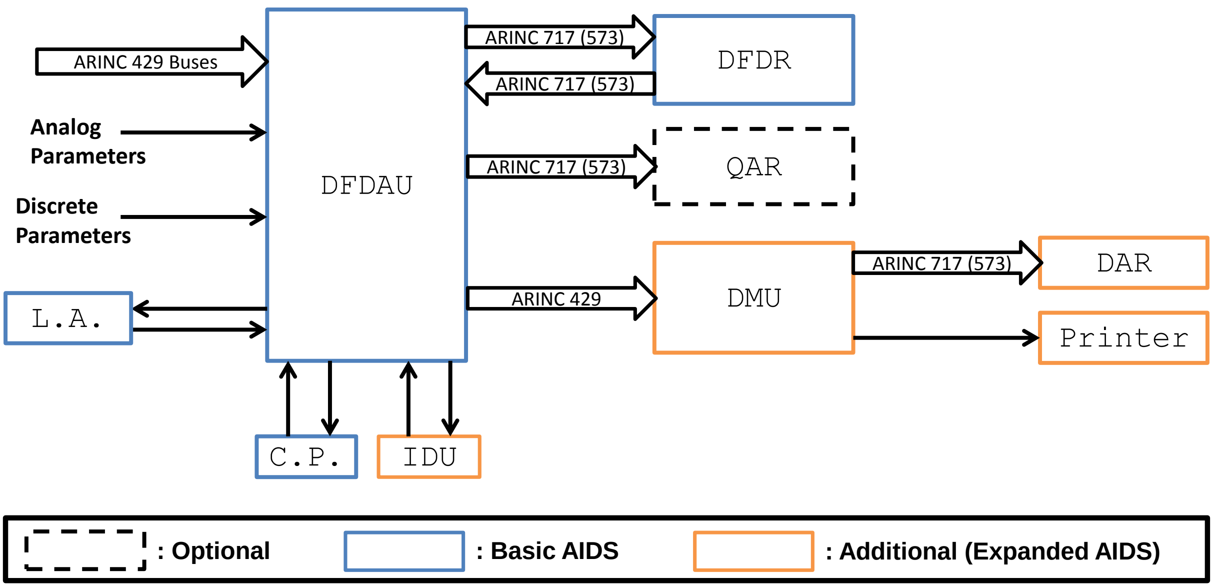


Figure 2.7 AIDS Architecture

The DFDAU acquires, conditions and processes the aircraft parameters coming from the several sensors and on-board computers [22]. These parameters are of various types: analog, discrete and DITS (ARINC 429). The analog inputs are converted to digital values. 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 (768 bits/sec). The DFDR or the “black box”, as often called by the media, is a device designed to record the mandatory flight parameters as defined by the applicable civil aviation authorities and 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. Therefore, the DFDR is not the most recommendable device to sustain an efficient and routine FDM process.

The DFDAU sends a copy of the DFDR data frame to the QAR using one pair of bi-polar data lines. The Airbus A310-325 from which the data will be decoded and analyzed is fitted with a Basic AIDS and an Optical Quick Access Recorder (OQAR), where the flight data is recorded on a magneto-optical disk. Because the QAR is located in the avionics compartment and not in the rear of the aircraft close to the tail cone like the DFDR, it is primarily used by maintenance personnel to acquire the mandatory parameter recordings. Figure 2.8 shows the physical location of the different AIDS equipment in the aircraft, including the DFDR and QAR recorders. The avionics compartment is located in the lowerfuselage forward of the nose landing gear.

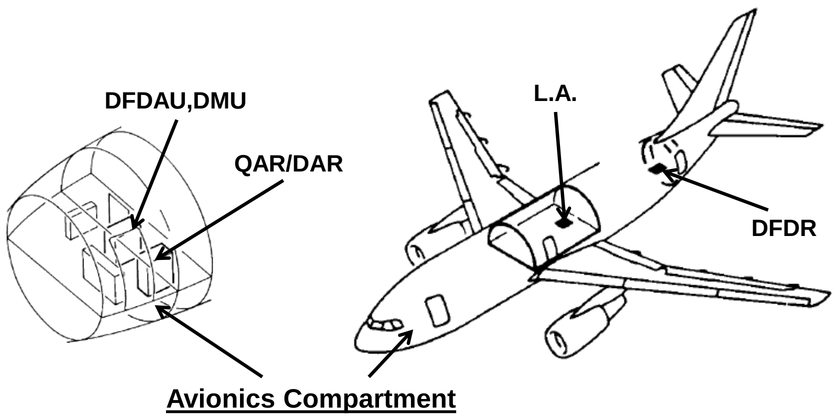


Figure 2.8 Location of AIDS equipment in the Airbus A310

The DMU is part of the Expanded AIDS. It receives digital parameters from the DFDAU through a pair of ARINC 429 data lines and processes the data for a variety of functions, including Condition Monitoring (CM). In later chapters, we will cover how the DMU assists the operator with this type of maintenance and how the processed information can be retrieved. When fitted in the aircraft, the DMU also produces a stream of data for recording in a DAR. Most QAR units can be used as DARs, in which case the recorded parameters are not limited to the mandatory parameters.

3. Dataframe Programming

This Chapter presents the different stages involved in the process of programming a database in AGS with the information required for a proper analysis of the data recorded in the A310's OQAR. The results of this implementation for different recorded parameters will be subject to a further scrutiny in the next Chapter.

3.1 Flight Data Department at TAP

The Flight Data (FD) Department at TAP Portugal is part of the Safety Management Department. The FD department is responsible for the creation and continuous execution of the airline's FDM processes. The department is provided with the necessary tools for analyzing the flight data that is stored on the recording units from the airline's fleet. Instead of relying solely on the "snapshot" information that is sent by the data processing computers, the complete flights are processed in order to generate useful information to monitor safety and risk of the whole operation as part of a Safety Management System (SMS) program. Having this into account, its members work closely with several airline's departments – Maintenance and Engineering, Pilots and Fleets, Technical Support, etc. – in order to enable the airline to increase its safety levels and reduce its maintenance and operating costs [4]. 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.

3.1.1 AGS: A tool for flight data analysis

The AGS is a computer system for flight data analysis whose primary function involves processing all the available data coming from the aircraft recorders. The AGS is capable of decoding the data frames recorded in the ARINC 717/573 format containing the flight parameters. In order to do this, this tool needs to be programmed by inserting information regarding the location of the parameters in the data frame and their ARINC 429 characteristics.

The data frames are typically different according to the A/C type, its registration and, of course, the recording device used. At TAP, there has been a continuous effort towards the standardization of the FDM processes across the different fleets of aircraft. This includes the information recorded in the data frames and also the type of devices used. The flight data from TAP's aircraft comes from DAR type recorders, which have high recording capacities (typically around 512 12-bit words per second). Because the DAR receives data from a DMU, a customized data frame can be built by configuring the latter. These two features allow a vast number of parameters to be recorded, which are not limited to the mandatory parameters. The information is then used to support several FDM activities.

3.1.1.1 Database Version

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. The programming of a Database is divided in two parts [23]:

- The **Decoding Frame** for parameter conversion in Engineering values, containing the following components:
    - the **Equipment List**;

    - the **Parameter List**;
    - the **Dataframe**;
    - the **Procedures for Additional Parameters** computation - these procedures compute additional parameters (called computed on ground parameters) from the recorded parameters for a more consistent analysis, performing parameter filtering and corrections or other parameter computations to improve the flight analysis;
- and the **Procedures for Automatic Flight Analysis** containing the following components:
    - the **Procedures for Flight Operations**: they are within the scope of the FOQA program and include studies to identify and correct deficiencies during flight operation with the aim of reducing safety risks;
    - the **Procedures for Maintenance**: these procedures are used in the MOQA program to perform computations for maintenance analysis and for monitoring functions as required by the airline's Maintenance departments.

After programming the Decoding Frame the AGS has enough information to convert the recorded parameter data in binary format to its corresponding engineering values. The procedures are a set of instructions, test conditions and computations programmed in AGS by SAGEM [24]. These procedures use a dedicated simple programming language, yet powerful, composed of instructions and that can be mixed with the standard "C" language. For instance, the procedures for additional parameters (or additional procedures) ensure that each individual flight is separated and correctly identified by its flight number, etc. These procedures compute a lot of information that is important for the correct storage of the flights and used for an accurate representation of the flight parameters throughout the flight, including the several flight phases. The procedures for Flight Operation/Maintenance are executed after the procedures for additional parameters.

3.1.1.2 Automatic Analysis Process and the AGS cycle

When the Database version is fully configured, it is used in the Automatic analysis. This is the process of decoding all flight data recordings contained in the data storage devices as defined by the operator. The treatments done during the Automatic analysis include [23]:

- the Flight Identification in terms of date, flight number, origin and destination, according to the additional procedures programmed in the database;
- the conversion of recorded parameters into engineering values;
- the computation of additional parameters;
- the storage in the database of the analyzed flights with the raw data (binary data) and associated results, for statistical analysis or later replay of the flights;
- and the generation of reports and storage of data in external files.

The Automatic Analysis is one the major tasks performed by the FD Department and is done on a daily basis. A representation of its location within the AGS activities is represented in figure 3.1. The figure shows the different ways of acquiring the flight data. In most of TAP's aircraft, the flight data is directly recorded to DAR hard-drives and then transmitted to the airline's servers via wireless networks when the aircraft is on the ground. In the Airbus A310-325 described in Chapter 2, the data is recorded on optical disks and the process is not so efficient because it requires trained personnel to remove and substitute the disks from the QAR. In addition, the data is not as readily available as when it is transmitted wirelessly.

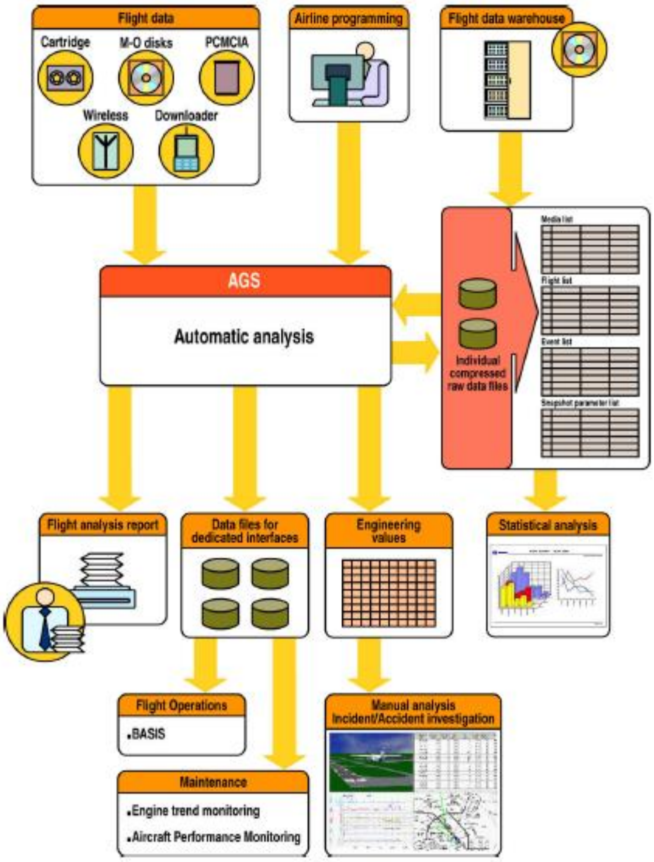


Figure 3.1 AGS activities [23]

3.1.2 Database version for the A310-325 aircraft

A new database version was implemented in AGS containing the necessary information to decode the flight data recorded in the QAR of the Airbus A310-325. This database version is identified with the number 10079[1] and contains a data frame in the format specified by the ARINC 717/573 protocol. Each subframe is composed of 64 words with 12 bits each.

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 discrete and 10 analog parameters. The complete list of parameters is in Appendix B. All these parameters are mandatory, since the QAR stores a copy of the data recorded in the DFDR. Therefore, the DFDR Word and Frame Assignment [21] was used to allocate the positions of the parameters in the dataframe. It consists of one data frame with the description of the parameters in each word slot and information about the ARINC 429 input data bits.

[1] This is an internal TAP numbering and there is no relation with similar numberings that may exist on other AGS systems.

3.2 Aircraft Definition

The addition of the aircraft to the A/C list is mandatory since all the flights analyzed are linked to the A/C registration (marked on the tail of the aircraft). AGS will use this definition to know how it will access the recording support device and to know the analysis configuration based on the Database version. The information required for the A/C definition is displayed in figure 3.2. It includes the A/C Tail registration, the airline and the A/C type.

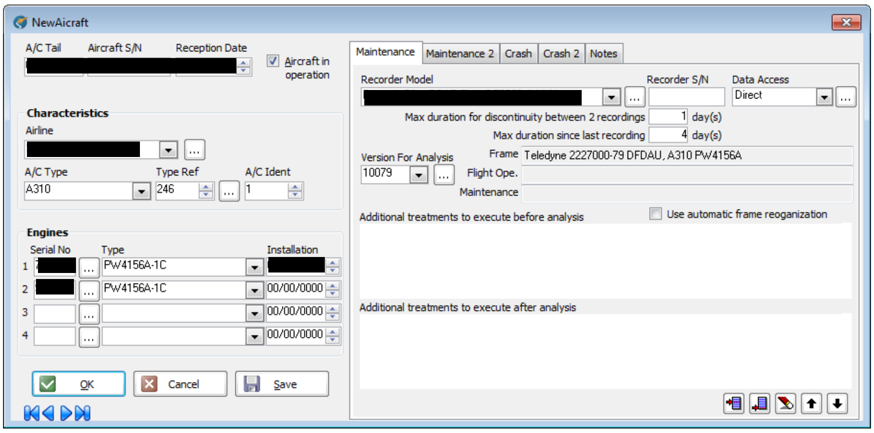


Figure 3.2 Dialogue window for New Aircraft

The upper right area allows defining the characteristics of the recorders installed on-board the aircraft. A QAR or DAR recorder is classified as a Maintenance type recorder, whereas the DFDR is a Crash type recorder, due to its characteristics. The access to the A310-325's QAR media (what actually holds the data in the storage device) is direct because the AGS reads the data directly from the optical disks. The serial number and installation date of the engines are not mandatory but may useful for an ECM analysis.

3.3 Equipment Definition

The DFDAU is connected to various sensors and data sources to collect the parameters, so it becomes fundamental that these data sources are defined in AGS. Appendix A provides a list of the ARINC 429 data buses added to version 10079. The equipment ID is an hexadecimal value that comes from the ARINC 429 specification [14]. For the analog and discrete type parameters the information related with the data source equipment is defined as EQUIP.

3.4 Parameter Implementation

This section concerns the implementation of the parameters that are recorded in the dataframe. This is required before the parameters are allocated to their respective word slots. The information to be inserted requires the knowledge of the format of the data words from the ARINC 429 protocol, which was described in the previous Chapter.

3.4.1 Parameter Definition

The parameter information that needs to be inserted in AGS comprises the following:

- Parameter Name: name used for data visualization after decoding and the name used in the procedures programming;
- Description: description associated with the parameter. It can be filled with manufacturer specification or the description available in AGS;
- Reference: the number in the manufacturer specification (AMM or other);
- Parameter Type: defines the data type of the parameter (BNR LINEAR (A*X), BCD, DISCRET, etc.);
- ATA code: this code classifies the parameters according to the standardized groups defined in ATA's Spec 100 Code, allowing grouping of parameters from the same ATA chapter;
- Source Identification: it comprehends the Equipment, Label and SDI;
- Input Raw Data: for parameters in the ARINC 429 format, this field defines the Sign bit position, the MSB bit position and the number of significant data bits. For an ARINC 429 discrete parameter, the definition of the input bit and the status of the Zero and One States provides enough information;
- Resolution/Range: the Resolution of the LSB is the smallest possible value transmitted to the acquisition unit. The Range is automatically calculated from the Resolution and the number of data bits or the Resolution can be calculated if the Range is introduced first;
- Display Format: information about the Engineering Units and the format in which the data is displayed after being decoded;
- Operational Range: defines lower and upper operating limits for the parameter that can be used to signal abnormal situations when the data is visualized.

Figure 3.3 shows the dialogue window for the implementation of a BNR LINEAR parameter, in this case the Computed Airspeed. The fields that were described above are indicated. Examples of the implementation of different types of parameters are given next.

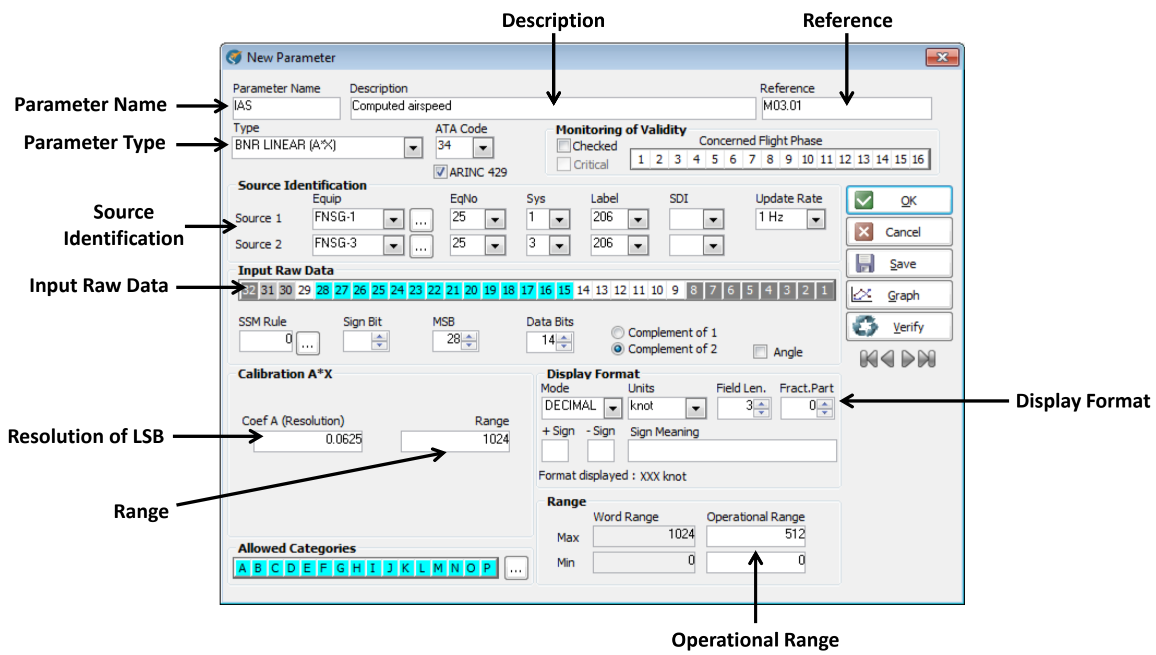


Figure 3.3 Dialogue window for Parameter Implementation

3.4.2 Examples

BCD: Flight Number

The flight number comes from the Flight Management Computer (FMC) and is encoded in BCD format. It is composed by four digits, each decoded from a separate group of four data bits. For each digit it is necessary to specify the MSB. The digits are put together via an additional procedure.

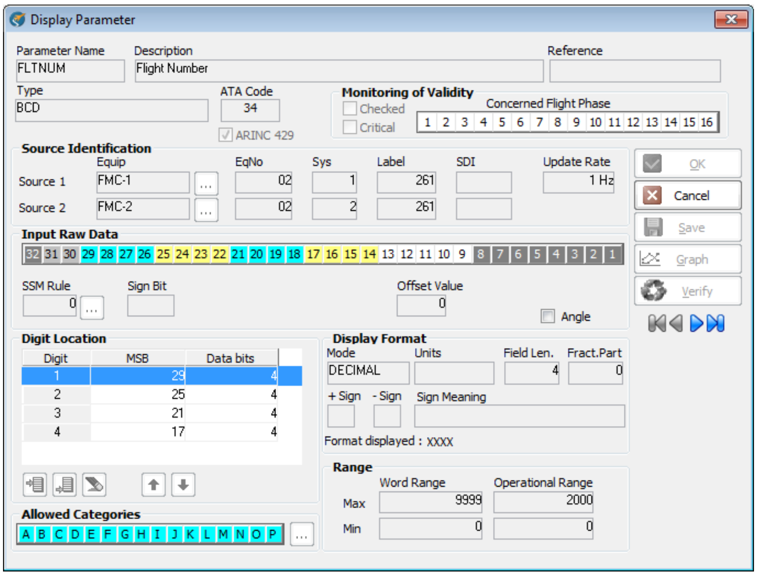


Figure 3.4 Flight Number Implementation

PACKED BITS: AFCS Longitudinal Modes

The PACKED BITS is a type of parameter in which a determined number of data bits have a specific meaning when combined. It differs from the data types presented for the ARINC 429 protocol. Figure 3.5 shows the implementation of a parameter that indicates the longitudinal modes of the Automatic Flight Control System (AFCS). Bits 21 to 18 are decoded to their corresponding decimal value (or raw value in AGS) and each value in the 1 to 15 range indicates if a certain mode is active.

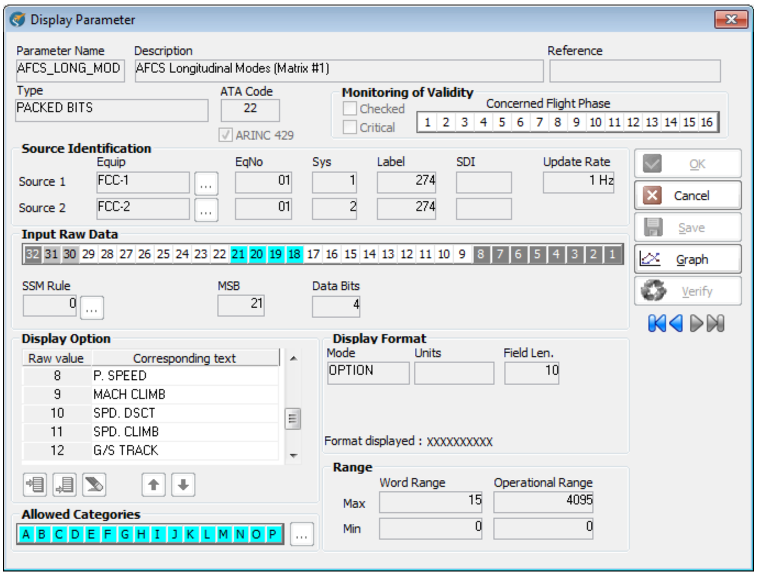


Figure 3.5 AFCS Longitudinal Modes Implementation

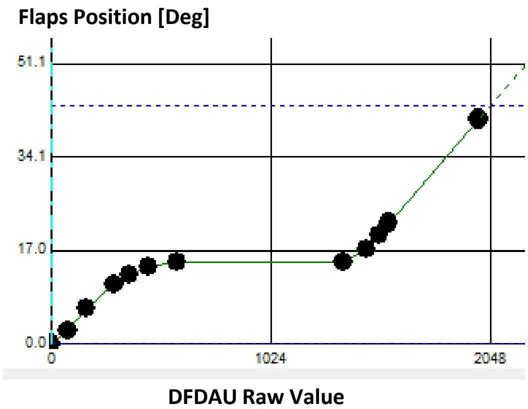
BNR COUPLE OF VALUES: Flaps Position

There are some parameters that are not acquired from the ARINC 429 data sources and need to be converted to digital values. An example of such parameter is the Flaps Position, which is acquired in the DFDAU as an analog parameter. It was implemented as a BNR COUPLE OF VALUES parameter. This type of parameter is used when a calibration law is obtained from couples of values. These values are in table format in figure 3.6a. A graphic representation of the flaps angle as a function of the recorded raw value is in figure 3.6b.

Parameter No: 20 Name: FLAPS POSITION
Signal Type: SYNCHRO

Flaps	Synchro	Synchro travel	AD Conversion count	DFDR Dig. value	DFDAU output Dig. value - 429
0 Deg	0 Deg	0%	zero count	0	0
2.54 Deg	6.77 Deg	3.87%		20	77
6.47 Deg	14.35 Deg	8.20%		41	163
10.85 Deg	25.59 Deg	14.62%		73	291
12.61 Deg	31.87 Deg	18.21%		91	363
14.12 Deg	39.55 Deg	22.60%		112	450
15.02 Deg	51.65 Deg	29.51%		147	588
15.03 Deg	119.53 Deg	68.63%		340	1360
17.35 Deg	129.09 Deg	73.76%		367	1469
20.01 Deg	134.18 Deg	76.67%		382	1527
22.1 Deg	138.26 Deg	79.0%		393	1573
41.02 Deg	175.01 Deg	100%		498	1991
	360 Deg		full count	1023	4095

(a)



(b)

Figure 3.6 Flaps position calibration law: (a) table format [21]; (b) graphic display.

3.5 Dataframe Construction

After implementing all the parameters in the database, it is necessary to create the dataframe structure by specifying where each parameter is recorded. The majority of the parameters are recorded in the regular frame. The dataframe from version 10079 also accomodates 4 superframes.

3.5.1 Regular Parameters

The regular frame parameters can be added by means of a dialogue window similar to the one displayed in figure 3.7. 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. It is a common practice to use one of these for the sign bit, if applicable. The three parts are only used for parameters recorded with more than 12 bits. AGS will use the ARINC 429 data bits information for each part to compute the correct parameter values.

The recording rate must be defined according to the number of times that the parameter/parameter part appears in the dataframe. 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 from the fact that they are equally spaced in the dataframe. Different parts from a parameter can have different recording rates. For instance, the sign bit and the most significant bits (27-24) of the Standard Altitude (ALT_STD) are recorded at 1/4 Hz (subframe 4, Word 57) and the least significant bits (24-14) are recorded at 1 Hz (subframes 1 to 4, Word 58).

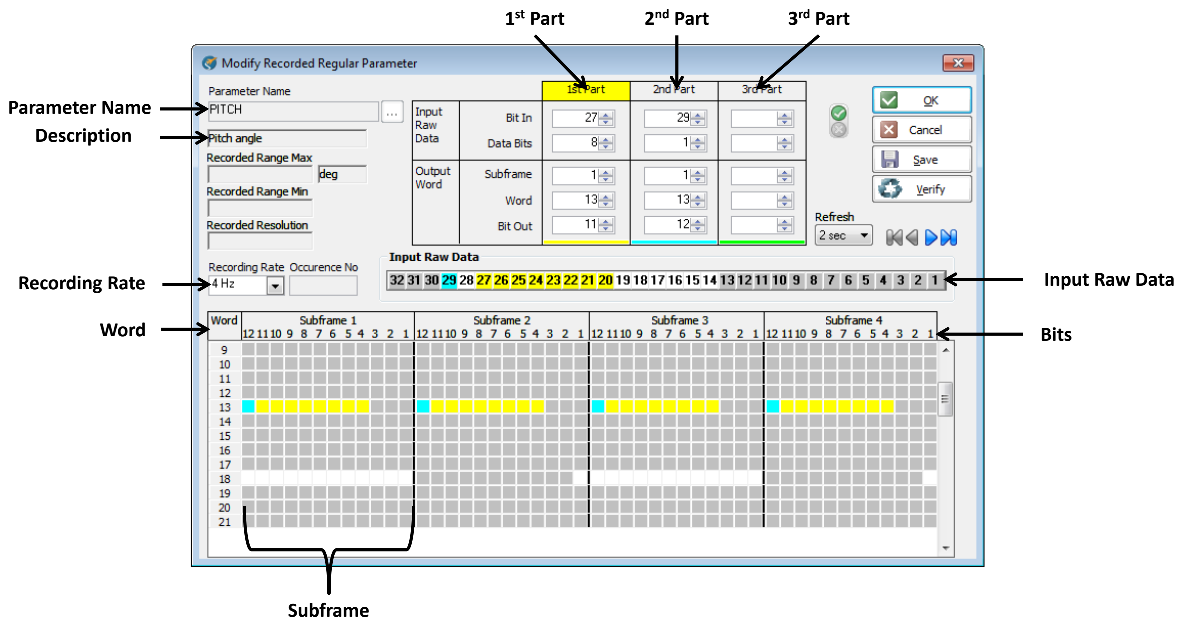


Figure 3.7 Regular parameter: Pitch Angle (PITCH)

3.5.2 Superframe Parameters

To decode the superframe parameters it is first necessary to define the location of the superframe words. Table 3.1 specifies the location of the four superframes recorded in the frame. Superframes 1 to 3 are presented in Appendix C, containing the description and name of the recorded parameters - Superframe #4 contains information about the operating status of the DFDAU. Bits 12-9 of each superframe are occupied with a counter that is updated every four seconds.

Superframe Nr.	Subframe	Word
1	1	56
2	1	57
3	4	41
4	3	51

Table 3.1 Recorded Superframes

The dialogue window for the allocation of the superframe parameters in the memory is very similar to that in figure 3.7, for a regular parameter. The superframe structure is displayed and the user can select the position of the parameter in any of the 16 cycles. Because only bits 8-1 are available for output, many of the superframe parameters occupy more than a cycle. 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. Some parameters, such as the latitude and longitude, have parts recorded in both the regular frame and superframe.

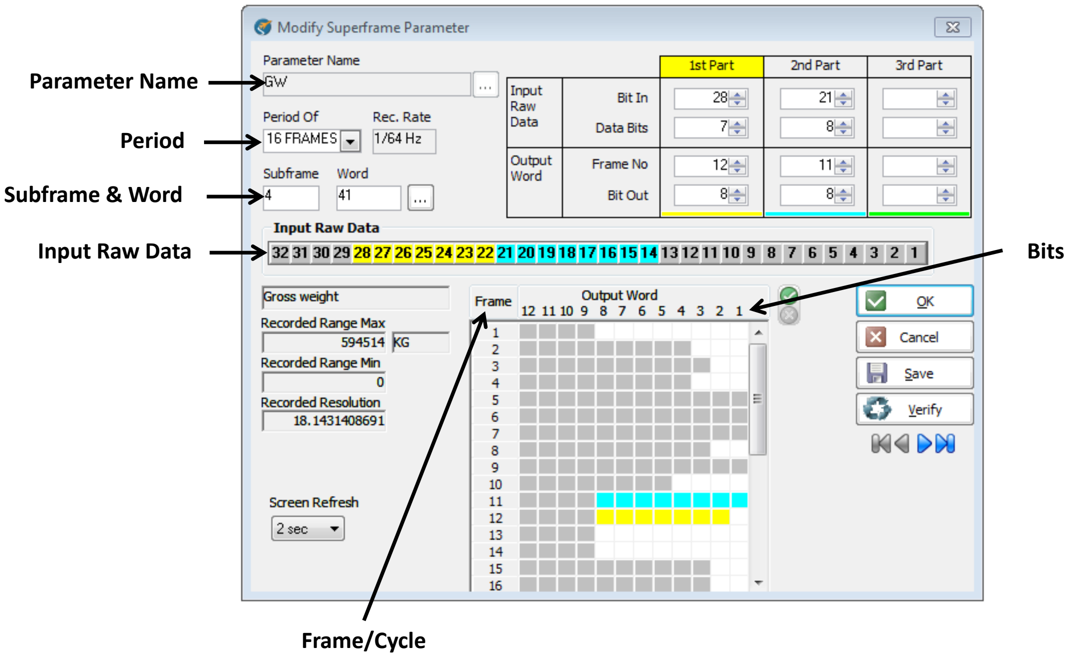


Figure 3.8 Superframe parameter: Gross Weight (GW)

3.6 Database Validation

Before all the tasks inherent to the automatic analysis can be conducted, the database version needs to be validated. The programming of a database is a process subject to a variety of user-induced errors because of all the new information that is inserted. AGS provides a validation function that is able to detect some of these errors. To ensure the consistency of the database, this validation was run several times during the implementation of the parameters and the construction of the dataframe.

The validation is a very useful procedure to detect inconsistencies between the ARINC 429 data bits and the bits that are recorded. However, it covers all the components of a database version, including the additional procedures and the procedures for automatic flight analysis and it is a good practice to run a validation whenever changes are made or new procedures added.

To ensure that the new database version doesn't actually contain errors, further validation has to be conducted by analysing the flight data decoding results. This is the main subject of the next Chapter.

4. Decoding Results and Flight Phase Computation Procedure

The first part of this Chapter presents the decoding results that were obtained after the flights were processed with the newly programmed database. The implementation of the Flight Phase computation procedure is described afterwards and relies on a collection of both recorded and computed on ground parameters.

4.1 Results for Recorded Parameters

After programming the dataframe in database version 10079, the flight data from several flights performed by the A310-325 aircraft was decoded and analyzed. This analysis consisted on the observation and interpretation of data from the recorded parameters as a function of time. The time is computed from the parameters that give the current Greenwich Mean Time (GMT) throughout the flight.

There were several types of errors found during the analysis that were not detected by the internal AGS validation procedures. The more typical were user induced, such as incorrect location of the parameter in the frame or incorrect definition of the parameter range or resolution, and were promptly solved. Other errors were attributed to improper information supplied in the documentation.

The objective of this section is to present the decoding results for several parameters that are recorded in the dataframe. Each sub-section shows parameter results from a particular ATA system that were selected so as to provide a general insight on how these systems are operated throughout the flight. The complete set of parameters displayed is in table 4.1. The data from these parameters was exported from AGS to .csv files and then handled by graphics software.

Parameter Name	Description	Parameter Type	Equip/Label/SDI	ATA
ALT_STD	Altitude standard	BNR LINEAR	FNSG-1/203/XX	34
IAS	Computed Airspeed	BNR LINEAR	FNSG-1/206/XX	34
GS	Ground Speed	BNR LINEAR	IRS-1/312/XX	34
PITCH	Pitch Angle	BNR LINEAR	FNSG-1/325/XX	34
AOAL	Angle of Attack (ADC-1)	BNR LINEAR	FNSG-1/221/XX	34
LONG	Longitudinal Acceleration	BNR SEGMENTS	EQUIP/331/00	31
VRTG	Normal Acceleration	BNR SEGMENTS	EQUIP/333/00	31
LATG	Lateral Acceleration	BNR SEGMENTS	EQUIP/332/00	31
LDG_ON_1	Landing Gear Squat Switch LH	DISCRETE	EQUIP/270/00	32
ROLL	Roll angle	BNR LINEAR	FNSG-1/325/XX	34
ATS_EGD	Autothrottle Mode Engaged	DISCRETE	TCC-1/274/XX	22
MTHR	Manual Throttle Armed	DISCRETE	TCC-1/274/XX	22
ATS_EPR	Autothrottle Thrust EPR Mode	DISCRETE	TCC-1/274/XX	22
ATS_MACH	Mach Mode Engaged	DISCRETE	TCC-1/274/XX	22
ATS_SPD	Speed Mode Engaged	DISCRETE	TCC-1/274/XX	22
ATS_RTD	Retard Mode Engaged	DISCRETE	TCC-1/274/XX	22
FLAP	Flap position (calibrated)	BNR COUPLE OF VALUES	EQUIP/137/XX	27
SLAT	Slats position (calibrated)	BNR COUPLE OF VALUES	EQUIP/127/XX	27
AIL_1	All Speed Aileron LH position	BNR LINEAR	SDAC/310/10	27

Parameter Name	Description	Parameter Type	Equip/Label/SDI	ATA
AIL_2	All Speed Aileron RH position	BNR LINEAR	SDAC/310/01	27
FQTT	Trim Tank fuel quantity	BNR LINEAR	FQI/263/00	28
CG	Center of Gravity	BNR LINEAR	CGCC/076/00	31
GW	Gross weight	BNR LINEAR	FMC-1/075/XX	34
N21	N2 Engine #1	BNR LINEAR	EEC-1/344/XX	77
N22	N2 Engine #2	BNR LINEAR	EEC-1/344/XX	77
EGT1	EGT Engine #1	BNR LINEAR	EEC-1/345/XX	78
EGT2	EGT Engine #2	BNR LINEAR	EEC-1/345/XX	78
EPR1	EPR Actual Engine #1	BNR LINEAR	EEC-1/340/00	77
EPR2	EPR Actual Engine #2	BNR LINEAR	EEC-1/340/00	77
FF1	Fuel Flow Engine #1	BNR LINEAR	EQUIP/347/10	73
FF2	Fuel Flow Engine #1	BNR LINEAR	EQUIP/347/01	73

Table 4.1 Recorded Parameters

4.1.1 Airframe Systems

4.1.1.1 Navigation (ATA 34)

Figure 4.1 displays the evolution of the pressure altitude or Standard Altitude (ALT_STD). This is the altitude in the International Standard Atmosphere (ISA) [25] with the same pressure as the part of the atmosphere in which the aircraft is flying. The ISA pressure setting used is 1013.25 hPa, corresponding to the pressure at the reference pressure surface: the Mean Sea Level (MSL). The altitude in the figure shows the typical profile on a commercial flight. During the flight, the aircraft transitions to higher flight levels because the optimum cruise altitude increases as the aircraft weight decreases (as fuel is burned) [26]. The initial cruise altitude is 31000 ft. (FL370[1]) and before starting the descent it is 36000 ft. (FL360).

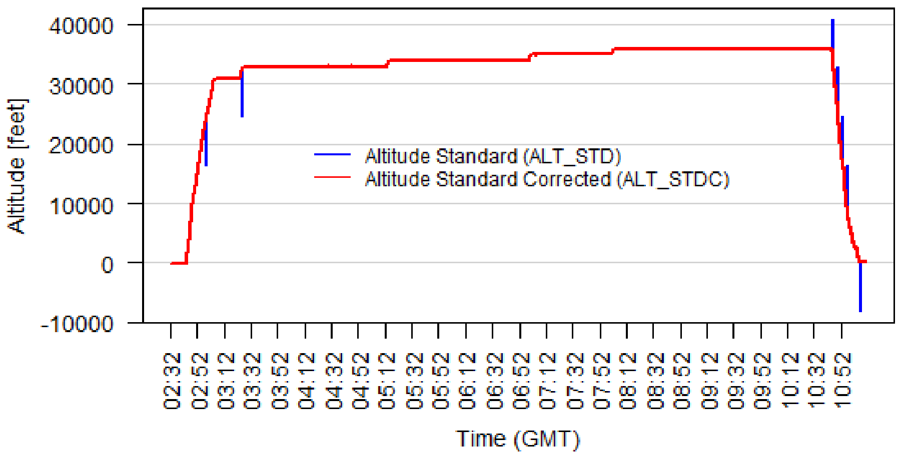


Figure 4.1 Pressure Altitude results

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), also represented in figure 4.1. The ALT_STDC parameter will be used to represent the altitude throughout the remainder of this section, whenever considered relevant for the analysis.

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[1] FL stands for Flight Level

Figure 4.2 below shows the variation of the different speeds recorded in the frame: the Computed Airspeed (CAS) and the Ground Speed (GS). In this dataframe, the True Airspeed (TAS) and the Mach number are not recorded but are computed on ground.

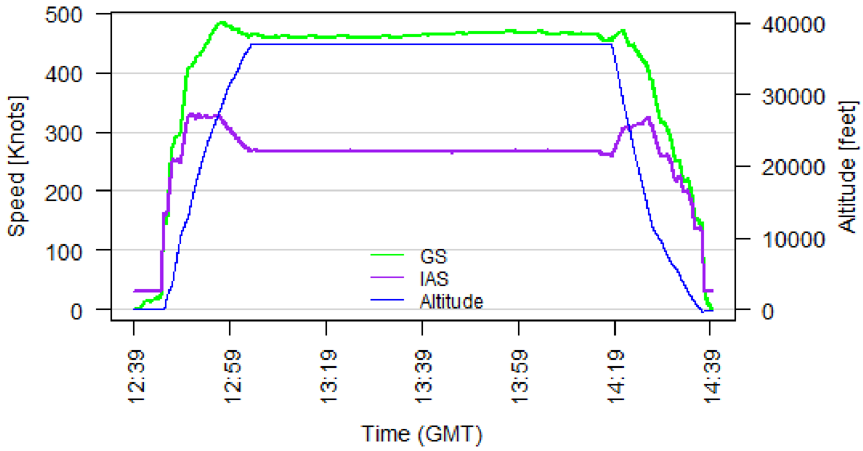


Figure 4.2 Flight Speed results

The Flight Path Angle (γ), Pitch Angle (θ) and Angle of Attack (α) are related by the following expression:

$$\gamma = \theta - \alpha \tag{4.1}$$

The three attitude angles are represented in the vertical plane in Appendix D.

The evolution of the Pitch Angle (PITCH) and the Angle of Attack (AOAL) is depicted in figure 4.3. The flight path angle can be computed on ground using equation 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.

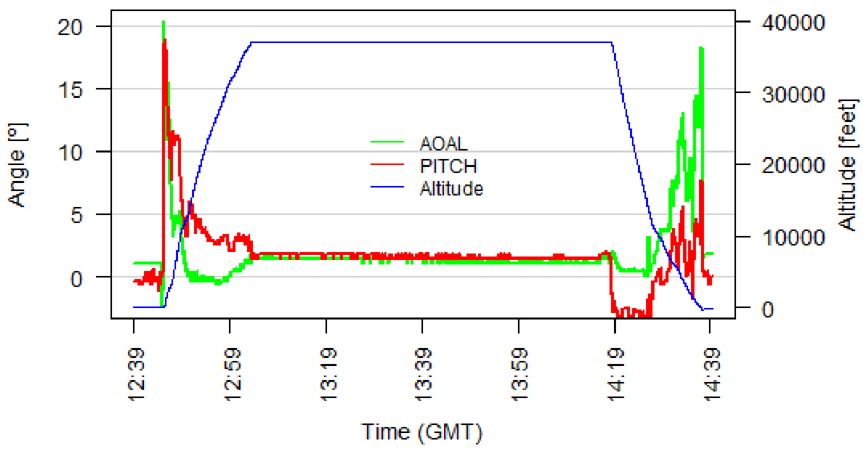
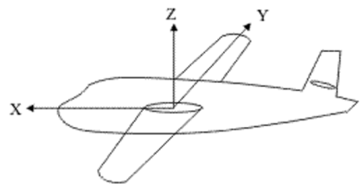


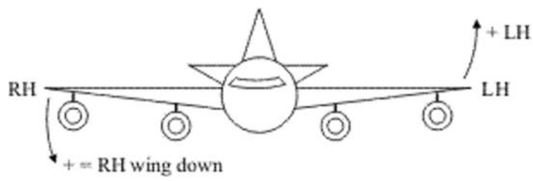
Figure 4.3 Pitch and Angle of Attack results

4.1.1.2 Indicating/Recording Systems (ATA 31)

Figure 4.5 shows the evolution of the Longitudinal (LONG) and Normal Accelerations (VRTG) during take-off and climb until the cruise altitude is reached. The Left Main Landing Gear Squat Switch (LDG_ON_1) is a discrete that assumes the value 1 on the ground and 0 in flight and is plotted together with the two accelerations to help visualize the take-off moment. The axes of the aircraft used for the accelerations and the sign convention for the Roll angle are shown in figure 4.4.



(a)



(b)

Figure 4.4 (a) Axes of the aircraft (b) Positive roll angle [27]

As expected, the Normal Acceleration remains close to 1 during most of the time with the exception of the moments after the aircraft takes off. The maximum Longitudinal Acceleration is registered during the take-off roll and initial climb stages, corresponding to the use of take-off thrust, and then it keeps decreasing as the aircraft is accelerated to its cruising speed. During cruise, both accelerations approach the 1 g and 0 g values, respectively.

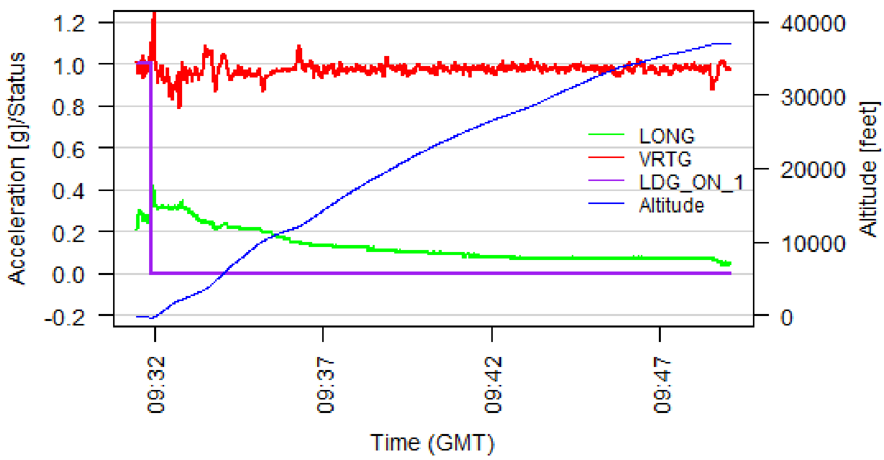


Figure 4.5 Results for the Longitudinal and Normal accelerations

Figure 4.6 displays the Lateral Acceleration (LATG) throughout the complete flight, together with the Roll Angle (ROLL). The coupling between these two parameters is evident: the biggest variations in the Lateral Acceleration occur at high Roll Angle values. A negative roll angle induces a positive lateral acceleration and vice-versa. This is in accordance with the definitions in figures 4.4a and 4.4b.

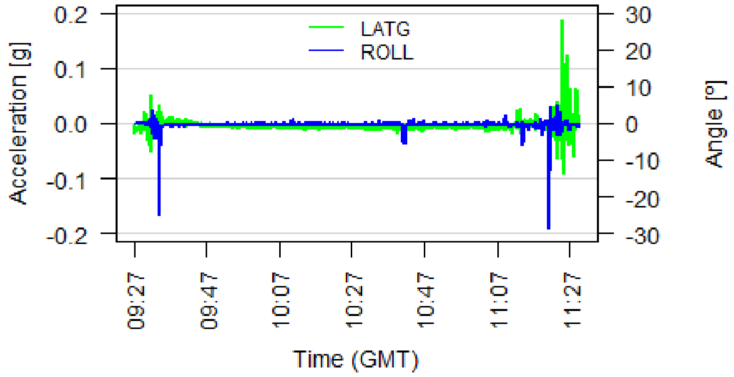


Figure 4.6 Lateral acceleration and Roll angle results

4.1.1.3 Auto Flight (ATA 22)

Figure 4.7 shows the status of the Auto Throttle Mode (ATS_EGD) and Manual Throttle (MTHR) discretes for the entire flight. It is observed that during most of the time that the aircraft is airborne the auto throttle is engaged. The manual throttle is armed on the ground when the thrust is controlled manually.

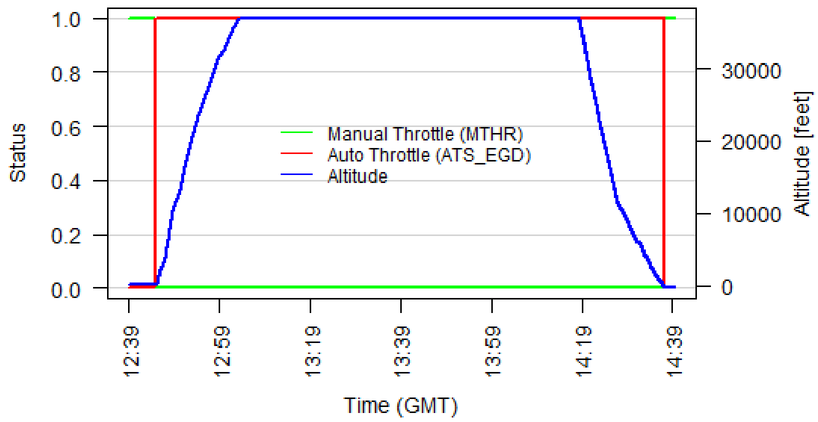


Figure 4.7 Results for the Auto Throttle and Manual Throttle discretes

The Auto Thrust (A/THR) can be engaged in three modes with different functions [11]:

1. Thrust (THR): Acquires and maintains the selected thrust limit or thrust target;
2. Speed/Mach (SPD/MACH): Acquires and maintains the selected speed or Mach Number;
3. Retard (RETARD): Retard the throttles to idle during initial descent.

The engaging of the A/THR modes is shown in figure 4.8. During the climb, a combination between the THR and the MACH modes are used. After the aircraft reaches the cruise altitude, the SPD mode is engaged and maintained throughout this flight phase. The RETARD mode is engaged during initial descent as expected. The SPD mode is again used during the approach and landing stages.

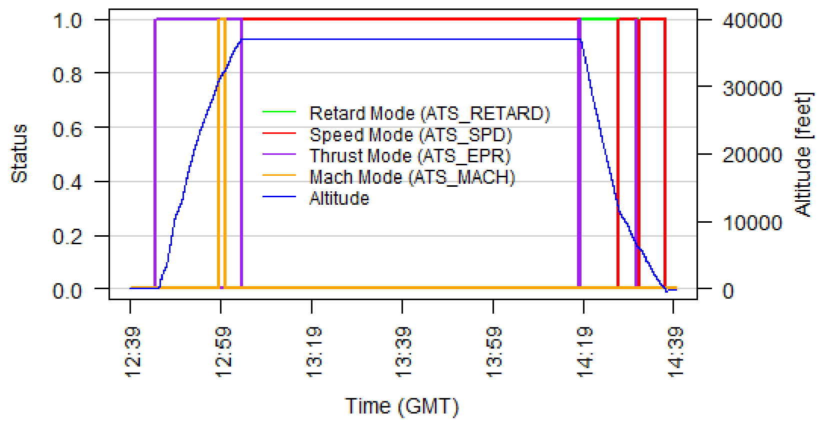


Figure 4.8 Results for the Auto Throttle mode discretes

4.1.1.4 Flight Controls (ATA 27)

The control of the aircraft is achieved by the primary flight controls (e.g.: elevator, ailerons, rudder), which provide pitch, roll and yaw control and the secondary flight controls (e.g.: flaps and slats) that consist of lift and drag augmenting devices [11]. The primary flight control surfaces are mechanically controlled, while the secondary flight controls are electrically controlled by dedicated computers. All flight control surfaces are hydraulically actuated. Appendix D provides a table that lists both the primary and secondary flight control surfaces and a picture representing these surfaces on the A310-325 aircraft.

Table 4.2 shows the position of all the Slat and Flap controls [28], as selected by the Flap and Control Lever in the cockpit, and the state of the Krueger Flap[1].

POSITION SEQUENCE	SLATS (OUTER,CENTER)	SLATS (INNER)	FLAPS (OUTER)	FLAPS (INNER)	KRUEGER FLAP
1 (0/0)	0	0	0	0	RETRACTED
2 (15/0)	17	16	0	0	EXTENDED
3 (15/15)	17	16	8	15	EXTENDED
4 (20/20)	21	20	16	22.1	EXTENDED
5 (30/40)	25.4	24	31.5	41	EXTENDED
( ): NUMBER INDICATED ON THE SLAT AND FLAP POSITION INDICATOR					

Table 4.2 Flap and Slat Control Lever Positions

The parameter SLAT records the (Outer and Center) Slats Position and the FLAP parameter the (Inner) Flaps Position. The two recorded parameters experience sudden changes and therefore the corrected parameters SLAT1C and FLAP1C are presented in figure 4.9. The corrections to the recorded parameters were made via an additional procedure with a function that eliminates the observed oscillations. The usage of these secondary flight control surfaces is depicted only during the approach and landing.

[1] Lift/Drag augmenting device located on the leading edge of the wing

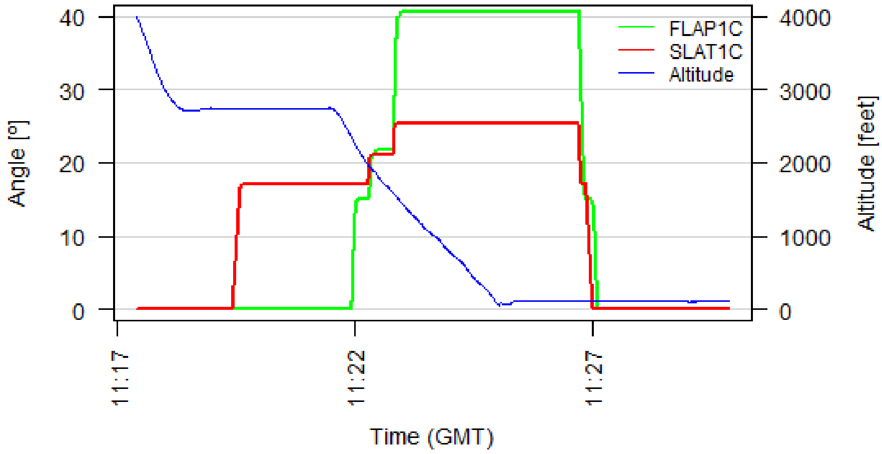


Figure 4.9 Flaps and Slats position during approach and landing

Figure 4.10 presents the actuation of both ailerons during the early stages of the flight until an altitude of approximately 9000 ft. is reached. It is observed that the values are symmetrical between each other, allowing for quicker maneuvers. The axis of symmetry is 0º when the aircraft is operating with a clean configuration (i.e. no Flaps or Slats extended) and 7º when the Slats are extended to 15º (as indicated in the Control Lever – table 4.2). This is because the aircraft is equipped with a system that drops the ailerons to improve its aerodynamic characteristics [11].

When an aileron is deflected up it decreases the lift on the related wing and when deflected down it increases its lift. In figure 4.10 at around 5000 ft the Left Aileron (AIL_1) goes up and the Right Aileron (AIL_2) goes down, causing the left wing to go down and the right wing to go up and inducing a negative roll angle.

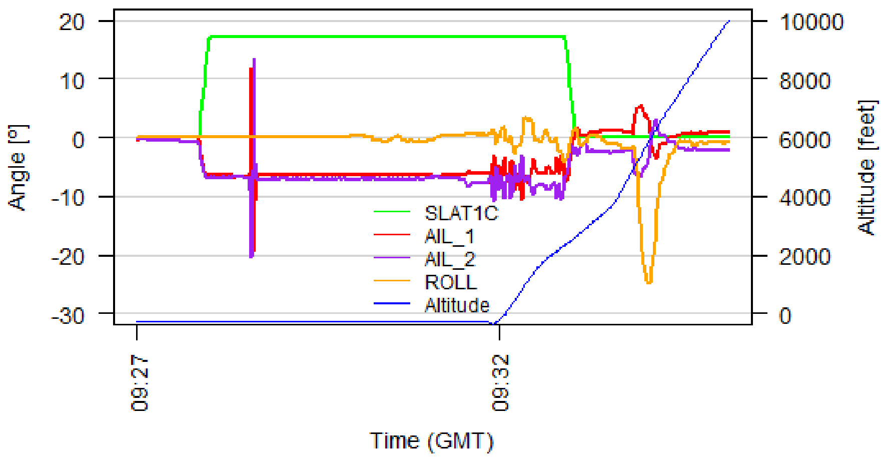


Figure 4.10 Results for the Ailerons and Slats position and Roll angle

4.1.1.5 Fuel (ATA 28)

The Fuel System includes five wing tanks and a tail trim tank. The trim tank has a capacity of 10848 lbs. (~4931 kg) and is installed in order to increase the fuel tank capacity and decrease the fuel consumption by reducing the drag during cruise, by maintaining the Center of Gravity (CG) of the aircraft close to the certified aft limit [11].

The fuel quantity in the trim tank (FQTT) is displayed in figure 4.11. The aircraft CG (CG) is also represented and is given in percentage of the Mean Aerodynamic Chord or %MAC – see Appendix E for a representation of the MAC reference line and considerations about the calculation of %MAC. Both parameters are recorded in the superframe and computed by the Center of Gravity Control Computer (CGCC). During the cruise of the selected flight the fuel quantity in the trim tank increases to almost 6500 lbs., before stabilizing around 6200 lbs. The CG is moved aft of the aircraft to almost 35%MAC as a result of this fuel transfer.

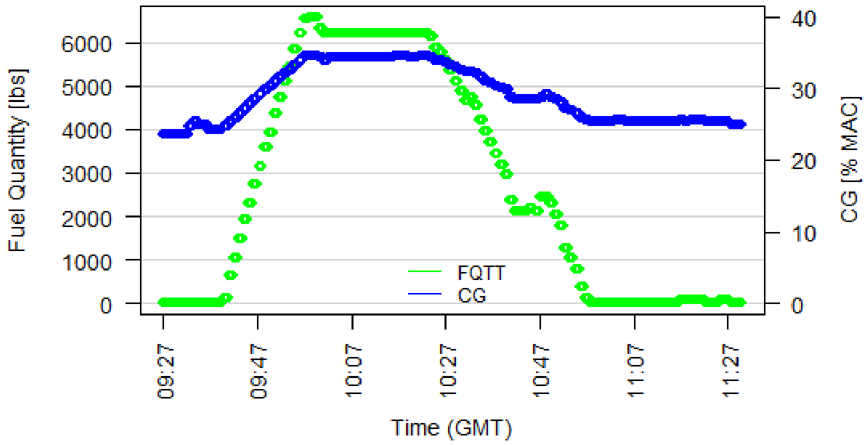


Figure 4.11 Trim Tank Fuel Quantity and CG results

The Gross Weight (GW) is also computed by the CGCC and figure 4.12 depicts its evolution. The aircraft starts the selected flight with a weight of 117549 kg and ends with 108641 kg.

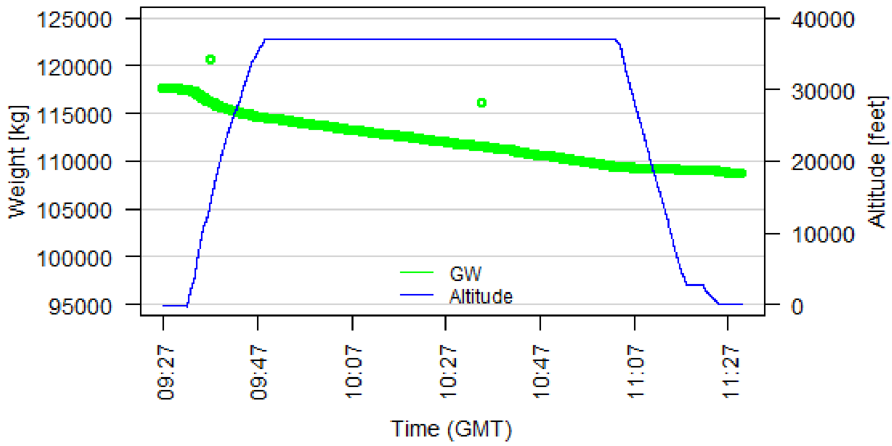


Figure 4.12 Gross Weight results

4.1.2 Powerplant

Figures 4.13a to 4.13b show the evolution of some powerplant related parameters recorded in the dataframe. These include: the high-pressure rotor speed (N2), Engine Pressure Ratio (EPR), Exhaust Gas Temperature (EGT) and Fuel Flow (FF). The low-pressure rotor speed (N1) is not recorded. A description of these parameters is given in the next chapter.

The N2 speeds in figure 4.13a reach a maximum of about 95% of the defined nominal RPM values. This maximum is achieved in the beginning of the climb. The speeds then diminish until reaching the cruise altitude, where they stabilize at around 86-87% of the nominal value. Figure 4.13b shows the evolution of the EGT. The profile is similar to the N2 parameters with a peak EGT just over 500ºC during takeoff. Figure 4.13c shows the EPR for the same flight and a maximum of about 1.55 at the top of climb. The EPR values for the take-off are situated at a lower value of around 1.35, which indicates that probably a reduced thrust setting was used. The Fuel Flow (FF) for both engines is displayed in figure 4.13d. The Fuel Flow reaches values of almost 8000 kg/hour during take-off and the fuel consumption per engine during cruise is of about 2000 kg/hour.

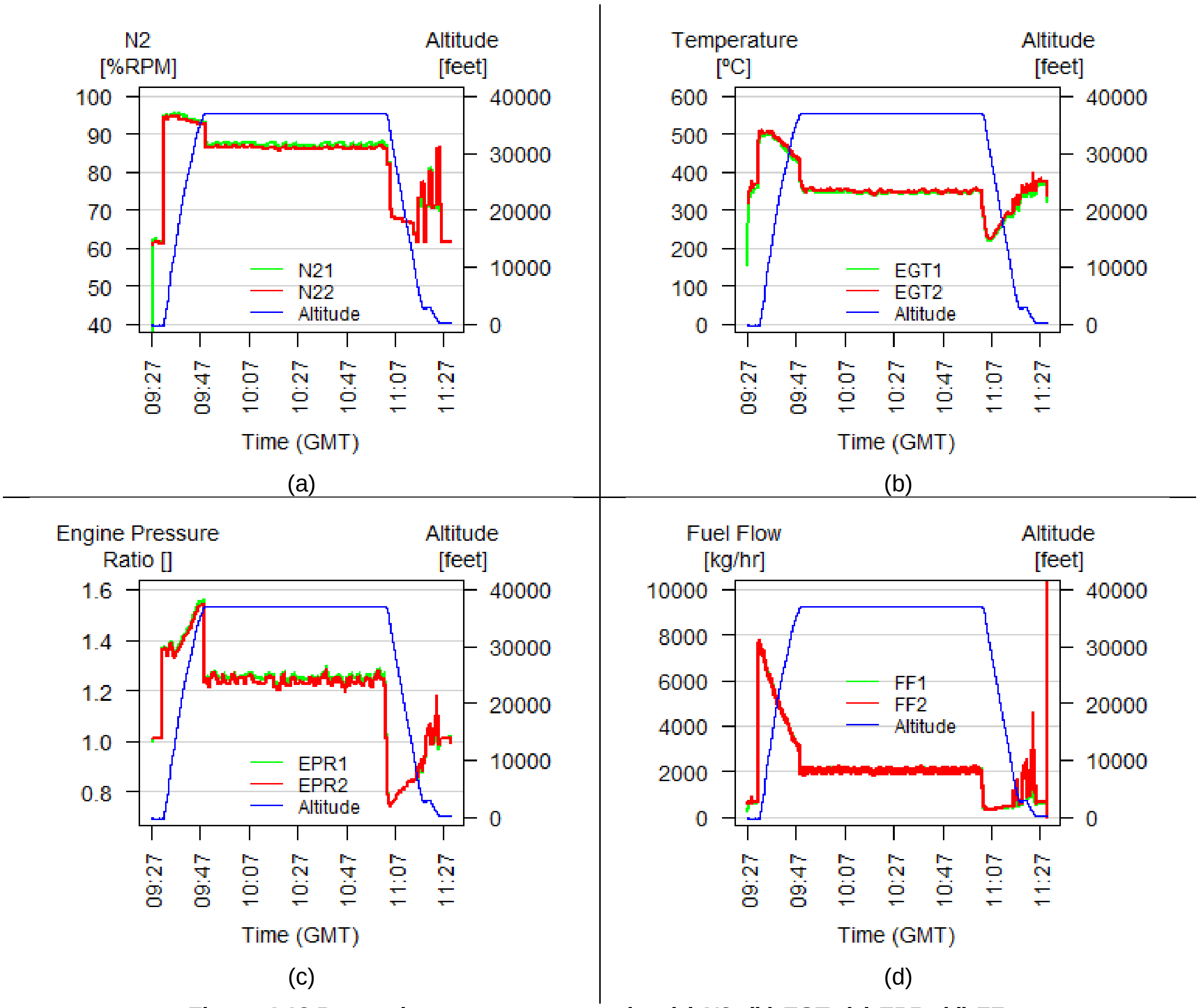


Figure 4.13 Powerplant parameters results: (a) N2; (b) EGT; (c) EPR; (d) FF.

4.2 Additional Procedures: Flight Phase Computation

In the previous section, the results for some recorded parameters were presented and the accuracy and quality of the data was checked. Following this, the Procedures for Additional Parameters have been programmed in the current database version. The primary function of these procedures is to process the recorded data while the frames are being decoded and calculate computed on ground parameters that improve the flight analysis. The procedures are executed according to their number and defined rate and can be used as subroutines to be called whenever needed. Inside each procedure, it is possible to use the value the parameter held i seconds before by using the suffix $(-i)$.

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 to monitor the aircraft and systems operation during specific stages of the flights. It is also mandatory for the correct separation of each flight contained in a media.

4.2.1 Flight Phases Definition

4.2.1.1 Airbus

The aircraft systems compute the flight phase according to an Airbus definition [21]. There are 12 flight phases in the A310-325, which are used to define the flight-phase-related inhibition of the Electronic Centralized Aircraft Monitoring (ECAM) [11]. The starting and ending conditions for each of the flight phases are described in table 4.3 and the related flight profile is displayed in Appendix F.

Flight Phase Nr.	Start Condition	End Condition
1	Electrical Power ON	2nd Engine Start
2	2nd Engine Start	1st Engine TO Power Application
3	1st Engine TO Power Application	Speed>70 Kt
4	Speed>70 Kt	Lift Off
5	Lift Off	Lift Off+1 Minute <u>or</u> Height >400 Ft (Whatever if first achieved)
6	Lift Off+1 Minute <u>or</u> Height>400 Ft (Whatever if first achieved)	Height>1000 Ft
7	Height>1000 Ft	Height<1000 Ft
8	Height<1000 Ft	Height<400 Ft
9	Height<400 Ft	Touch Down
10	Touch Down	Speed<70 Kt
11	Speed<70 Kt	1st Engine Shut Down
12	1st Engine Shut Down	5 minutes after 1st Engine Shut Down

Table 4.3 Airbus A310-325 Flight Phases Definition

This convention for the flight phases is mainly intended for system's synchronization within the aircraft and does not provide sufficient separation of the flight phases to suit the intended flight data analysis. For instance, flight phase 7 includes the cruise and most of the climb and descent phases.

4.2.1.2 SAGEM

As mentioned above, the Airbus definition for the flight phases used in the aircraft is very limited. Having that in mind, the procedure was implemented based on the definition from SAGEM that includes a total of 14 flight phases [24]. The phases are numbered from 1 to 14 and ordered according to a logical sequence from the beginning of the flight. Two of the flight phases in table 4.4 are not common to occur during normal operation: Rejected Take-Off and Go-Around. For example, the first will occur in case an engine parameter exceedance is detected during take-off and the second can occur when strong winds prevent the crew from landing the aircraft.

Nr.	Phase	FLIGHT_PHASE
1	Engine Stopped	ENGINE_STOP
2	Taxi-Out	TAXI_OUT
3	Take-Off	TAKE_OFF
4	Rejected Take-Off	REJECTED_TO
5	2nd Segment	SND_SEGMENT
6	Initial Climb	INITIAL_CLIMB
7	Climb	CLIMB
8	Cruise	CRUISE

9	Descent	DESCENT
10	Approach	APPROACH
11	Final Approach	FINAL_APPROACH
12	Landing	LANDING
13	Go-Around	GO_AROUND
14	Taxi-In	TAXI_IN

Table 4.4 SAGEM Flight Phases

The Flight Profile from SAGEM is also available in Appendix F, together with the conditions that characterize the transitions between the respective flight phases.

4.2.2 Implementation

The conditions used in the definition by SAGEM can be modified and adjusted according to the aircraft type and the operator needs. The N2 is the engine thrust parameter used by SAGEM to detect the transition to the Take-Off phase. It was first implemented in version 10079 but it was observed that in many flights the aircraft transited directly from the TAXI_OUT to the CLIMB phases. This was because the N2, recorded in the superframe, was not sampled during some take-off runs. Figure 4.14 contains data from the N2 and EPR parameters the take-off run and initial climb stages, in order to illustrate this situation. Again, the Left Main Landing Gear Squat Switch (LDG_ON_1) is used to indicate the moment in which lift-off is detected. The EPR, recorded at a rate of 1 Hz, smoothly increases during take-off to 1.35, while the N2 speeds jump from about 60% to 95% after the aircraft is airborne. This jump occurs because the high rotor speeds are only updated every 64 seconds.

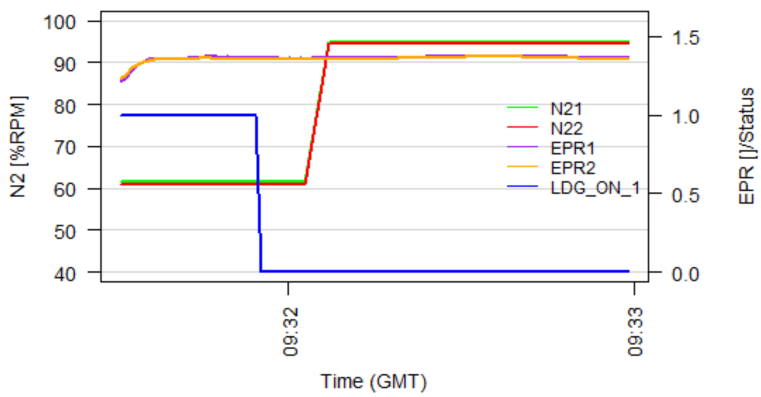


Figure 4.14 N2 and EPR results during the take-off stages

As a consequence, lift-off was not detected because it requires a flight phase equal to TAKE_OFF or GO_AROUND. The decision was made to use the EPR, instead of the N2, to detect the Take-Off. The TAKE_OFF and first stages of the climb were then correctly detected in all the flights analyzed. The N2 recordings continued to be used in the remaining flight phases.

When the Flight Phase from the aircraft is recorded as a parameter, it can be used in conjunction with the other parameters to enable the transitions between different flight phases. Although this parameter is used by the airborne computer systems, it is not recorded in the QAR and therefore is not available to compute the flight phase.

Table 4.5 lists the transitions between the flight phases and the associated conditions that were implemented in the procedure from database version 10079. The transitions to the Rejected Take-Off and Go-Around flight phases are categorized as abnormal and are not included in the table.

Previous Phase	Next Phase	Conditions for Transition

ENGINE_STOP	**TAXI_OUT**	During 10 seconds:
		- Engines not stopped:
		  o N2 from Engines #1 and #2 > 55% or
		  o Fuel Flow from Engines #1 and #2 > 50 Kg/h for 2 seconds
		- Left Main Landing Gear compressed
		Previous Phase < 2nd Segment and Engines not at TO Power

TAXI_OUT	**TAKE_OFF**	EPR from Engine #1 or #2 > 1.2 Longitudinal Acceleration > 0.05 g Ground Speed increase equal to or higher than 3 knots per second during 2 seconds Ground Speed > 25 knots Previous Phase < 2nd Segment or Left Main Landing Gear compressed
TAKE_OFF	**SND_SEGMENT**	Height > 50 ft and Engines not stopped Altitude < 8000 ft. Configuration ≥ Take-Off Configuration Pitch > 6º EPR from Engine #1 or #2 > 1.2 Previous Phase ≠ than Final Approach and Landing
SND_SEGMENT	**INITIAL_CLIMB**	Height > 400 ft. or Configuration < Take-Off Configuration Previous Phase ≤ Initial Climb or > Landing
INITIAL_CLIMB	**CLIMB**	Clean Configuration Previous Phase < Cruise
CLIMB	**CRUISE**	Altitude > 10000 ft. Clean Configuration Vertical Speed between -300 and 300 ft./second during at least 15 seconds
CRUISE	**DESCENT**	Clean Configuration Vertical Speed < -420 ft./second and Altitude > 8000 ft. during 5 seconds Previous phase = Cruise or Descent
DESCENT	**APPROACH**	Height < 3000 ft. Previous Phase ≥ and ≤ Final Approach or equal to Go Around Configuration > 0 and < 4
APPROACH	**FINAL_APPROACH**	Previous Phase ≥ Cruise Configuration ≥ 4 Height < 1000 ft. Pitch < 6º or Engine #1 or #2 not at TO Power
FINAL_APPROACH	**LANDING**	Height < 50 ft. Ground Speed > 30 kt. Engines Not Stopped Previous Phase > 2nd Segment Configuration > 4 Engine #1 or #2 not at TO Power
LANDING	**TAXI_IN**	Previous Phase ≥ Landing Left and Right Main Landing Gear compressed Engines Not Stopped Touch Down detected (STEP_TD) Ground Speed < 30 kt. or difference between current heading and heading at Touch Down detection (DELTA_HEAD) > 10º
TAXI_IN	**ENGINE_STOP**	Height < 50 ft. Engines Stopped: - N2 from Engines #1 and #2 < 55% or - Fuel Flow from Engines #1 and #2 < 50 Kg/h for 2 seconds Ground Speed < 3 kts Left and Right Main Landing Gear compressed Previous Phase < 2nd Segment or > Go Around

Table 4.5 Conditions for the normal transition between the flight phases (Database version 10079)

Most of the parameters used in the implementation are computed on ground parameters. The following table lists all the parameters used and their corresponding procedures, if applicable.

Parameter Name	Description	Procedure Number
LDGL*	Landing gear switch left	80
LDGR*	Landing gear switch right	80
ALT_STDC	Altitude Standard corrected	81
GSC	Ground speed corrected	105
EPR1C	EPR Actual Engine #1 corrected	106
EPR2C	EPR Actual Engine #1 corrected	107
N21C	N2 Engine #1 corrected	108
N22C	N2 Engine #2 corrected	108
FF1C	Fuel Flow Engine #1 corrected	109
FF2C	Fuel Flow Engine #2 corrected	109
CONF	Landing & Take-off configuration	123
TLA1C	Throttle resolver angle (TRA) Engine #1	124
TLA2C	Throttle resolver angle (TRA) Engine #2	124
HEIGHT	Height above runway	211
IVV	Inertial vertical speed	200
LONGC	Longitudinal acceleration	260
TTRANS**	Flight phase authorized sequences	507
DELTA_HEAD	Difference between touchdown heading and current heading	509
STEP_TD	Touch down step	605
PITCH	Pitch angle	Recorded

Table 4.6 List of parameters used in the Flight phase computation procedure (*Same information as LDG_ON_1 and LDG_ON_2 (0-AIR, 1-GROUND); **Array)

To be noticed that more than half of the listed parameters consist of corrected parameters which contain the same information as the recorded parameters. The corrected parameters do not experience large sudden changes that can occur during the recordings or when the data is decoded, thereby preventing inadvertent transition between the flight phases.

The HEIGHT parameter computes the altitude above ground level (or AGL altitude). At low altitudes, generally up to 2500 feet [5], 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 inertial vertical speed (IVV) is not recorded and is thus computed from the variation in the altitude.

There are three types of transitions between the flight phases: Normal, Abnormal and Forbidden. The TTRANS parameter uses the information in figure 4.15 to classify the different transitions and prevent those that are forbidden from occurring.

		CURRENT PHASE													
		EStop	TaxO	TO	RejTO	2nd S	Ini	Climb	Cruise	Desc	App	Final	LD	GA	TaxIn
NEXT PHASE	EStop	N	N	A	A	X	X	X	X	X	X	X	A	X	N
	TaxO	N	N	X	X	X	X	X	X	X	X	X	X	X	N
	TO	N	N	N	N	X	X	X	X	X	X	X	N	X	N
	RejTO	A	X	A	N	X	X	X	X	X	X	X	A	X	X
	2nd S	A	A	N	X	N	X	X	X	X	X	N	A	X	A
	Ini	A	A	A	X	N	N	X	X	X	X	A	A	X	A
	Climb	X	A	A	X	A	N	N	N	N	N	A	X	A	X
	Cruise	X	A	A	X	X	X	N	N	N	A	X	X	X	X
	Desc	X	X	X	X	A	A	N	N	N	A	X	X	X	X
	App	X	X	A	X	A	A	N	A	N	N	A	X	A	X
	Final	X	X	A	X	N	N	A	A	A	N	N	A	A	X
	LD	X	X	A	N	X	X	X	X	X	A	N	N	A	X
	GA	X	X	X	X	X	X	X	X	X	X	A	A	N	X
	TaxIn	X	X	A	A	A	A	A	A	A	A	A	N	A	N

Figure 4.15 Flight phase authorized sequences [24]

There are a total of five combinations between the flaps and slats positions that can be selected with the Flap and Slat Control Lever (see table 4.2). These combinations are called configurations. The SLAT1C and FLAP1C parameters, shown in section 4.1, are converted to the angular values assigned to each configuration with a dedicated procedure that yields the SLATC and FLAPC parameters. The CONF parameter is calculated afterwards from these two parameters using the logic in table 4.7.

POSITION SEQUENCE	SLATC	FLAPC	CONF
1 (0/0)	0	0	**0**
2 (15/0)	15	0	**1**
3 (15/15)	15	15	**2**
4 (20/20)	20	20	**3**
5 (30/40)	30	40	**4**

Table 4.7 Flaps and Slats Configuration

Figure 4.16 shows the results obtained for the CONF parameter during the take-off and landing. It is possible to see that, for this flight, configuration 2 was selected for Take-off and configuration 4 was selected for Landing.

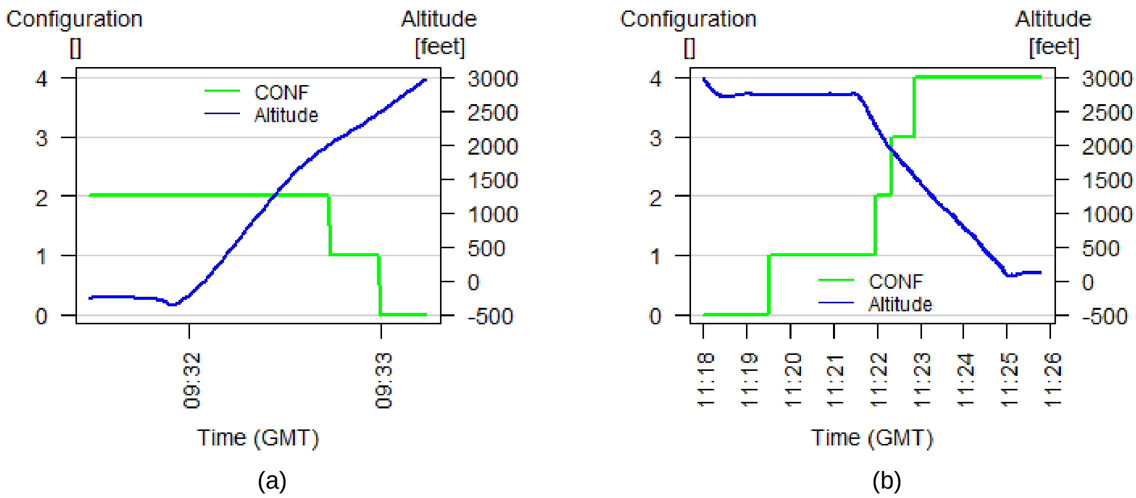


Figure 4.16 Configuration results during (a) Take-Off and (b) Landing

Finally, figure 4.17 shows the evolution of the FLIGHT_PHASE parameter throughout a selected long-haul flight. It is possible to observe that the transitions between the flight phases occur in the correct order defined in table 4.4. 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 transitions from Take-Off (3) to the 2nd Segment (5) and afterwards to the Initial Climb (6), although this is not noticeable. 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.

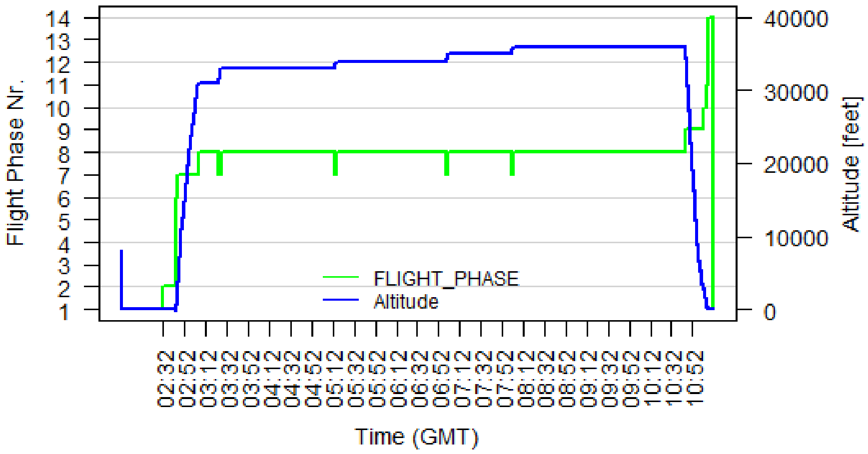


Figure 4.17 Flight Phase Results

5. Engine Condition Monitoring

In this Chapter, the fundamentals of Engine Condition Monitoring (ECM) are introduced. The Chapter starts by describing the role of ECM in the maintenance of aircraft engines and its contribution to the condition-based maintenance philosophy, which allows the airlines to conduct maintenance work on the engines based on their actual “health”, rather than following a more costly predetermined schedule. Next, the systems used in the ECM process are presented. These have evolved from the analysis and storage of data recorded manually by the flight crews to the monitoring and interpretation of engine data in real-time by sophisticated software. After this, the nature of the parameters collected for ECM purposes is discussed and the key performance parameters described. The Chapter finishes with the description of the Parameter Trend Monitoring method, which is the most common technique used to monitor the deterioration of the engine’s condition. Trend Monitoring provides assistance in the diagnosis of engine failures and enables the determination of precursors to engine events. In addition, it helps the operators to plan for engine removals more accurately. The removal intervals can even be extended based on the rate of deterioration in the engine’s performance. All these activities have the potential to contribute to lower maintenance costs.

5.1 The Condition-Based Maintenance Philosophy

Early airline maintenance programs were based on the philosophy that each part of the aircraft required disassembly for inspection. Maintenance was carried out in the aircraft after a specified number of hours in operation and the components/parts were removed and replaced by new or overhauled components. However, the introduction of larger aircraft made this process almost unbearable to airlines because of the rise in the costs associated with the replacement parts and the time that was needed to perform all the maintenance tasks.

Over the last decades, aircraft maintenance has evolved according to the existing aviation safety standards and the economic requirements from the air transport industry. This resulted in the introduction of new maintenance processes with different philosophies. The Federal Aviation Administration (FAA) recognizes three Primary Maintenance Processes [29], [30]:

- Hard-Time (HT): This is a preventive primary maintenance process. It requires that an appliance or part be periodically overhauled in accordance with the carrier’s maintenance manual or that it be removed from service.
- On-Condition Maintenance (OC): This is a preventive primary maintenance process. It requires that an appliance or part be periodically inspected or checked against some appropriate physical standard to determine whether it can continue in service. The purpose of the standard is to remove the unit from service before failure during normal operation.
- Condition-Monitoring (CM): This is a maintenance process for items that have neither “hard-time” nor “on-condition” maintenance as their primary maintenance process. CM is accomplished by appropriate means available to an operator for finding and solving problem areas. In effect, it obligates the user to apply knowledge gained by analysis of failures or other indications of deterioration to consider action to improve performance.

The Hard-Time is the oldest maintenance process used in the aircraft industry and is still applied to modern aircraft components. This type of maintenance defines a limit for the parts in terms of flight hours, cycles or calendar time. The life of these parts is controlled and when the limit is reached they are removed. The removed component can be repaired, overhauled or simply discarded. The On-Condition maintenance is an evolution from the hard-time philosophy. For some parts, it was found that it was possible to predict the probability of failure with great success by analysing some functional parameters. When these start to present abnormal values, it is assumed that failure is imminent and the part is removed from service. The on-condition maintenance tasks that are applied range from visual inspections to workshop and laboratory tests. Condition Monitoring is not a predetermined and preventative approach to aircraft maintenance like the first two processes, but 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 maintenance and operational costs. Nowadays, 70% to 80% of aircraft components have Condition Monitoring as their primary maintenance process [31].

Historically, the engines were removed and overhauled after a fixed HT interval, even if they were operating safely and in a satisfactory condition [7]. Condition-based Maintenance is a concept for maintaining gas turbine engines that is gaining acceptance between airlines and engine manufacturers [32]. One of the main objectives is to maximize the engine's operational life and overhaul only when the engine needs major maintenance work, thus saving in maintenance costs. Depending on the engine model, technical condition, etc., each engine removal for a Shop Visit (SV) may cost from less than 1 million to more than 10 million US dollars [3].

The Condition-based Maintenance is a predictive type of maintenance that determines the maintenance needs based on the actual condition of the engine rather than on a preset schedule [33]. 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 [34]. Monitoring the condition of the engines involves the task of visualizing the evolution in time (or trends) of engine operating parameters and searching for precursors of failure in its modules/components. This is mainly a prognostic analysis that is based on the fact that most failures do not occur instantaneously. 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. When the engine gets to a state where its performance levels have deteriorated to the point where it can no longer be operated within regulatory limits, ECM allows precise planning of its removal [34].

Under the Condition-based maintenance concept, the maintenance of aircraft engines is based on a combination between actual engine health/condition and part-life limitations and the engines are subject to control by the three Primary Maintenance Processes. General Electric (GE) [30] states that these processes work hand in hand with one another and they carry equal weight in a maintenance program.

5.2 Systems for Data Collection and Analysis

Several techniques and information can be used by an engineer to classify the condition of an aircraft engine. The major source of information is the in-flight behavior of the aircraft and the process starts with the recording of engine data during revenue service. The on-board systems used for acquiring data for ECM tasks can present different capabilities and various levels of complexity. The most basic system was also the most commonly used in older generation aircraft that didn't have equipment for automated data retrieval. The data is recorded manually by the pilots (or flight engineer) during the take-off and cruise phases. The crew is generally requested to take into account some constraining stability criteria in order to avoid irrelevant engine data. One of the disadvantages is that the parameters measured are limited to those with cockpit instruments. Appendix G has an example of a manual recording from the A310-325 aircraft. In addition to basic engine parameters, the flight conditions (SAT, Mach, Altitude, etc.) and air bleed status are recorded during cruise. The criteria for data acquisition are also described in this example.

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 that can measure inter-stage temperatures and pressures, for instance, as required. An important addition to these systems was the DMU that allows performing a variety of additional functions, such as recording stable cruise data using automated search criteria or recording takeoff data at the proper time using specific trigger criteria. The quantity of data archived varies by application but will typically be composed of reports that are taken at a limited number of engine operating points in each flight. The reports contain information for engine vibration monitoring, engine limit exceedance data, event history recording and engine performance monitoring. This topic will be addressed in more detail in Chapter 6.

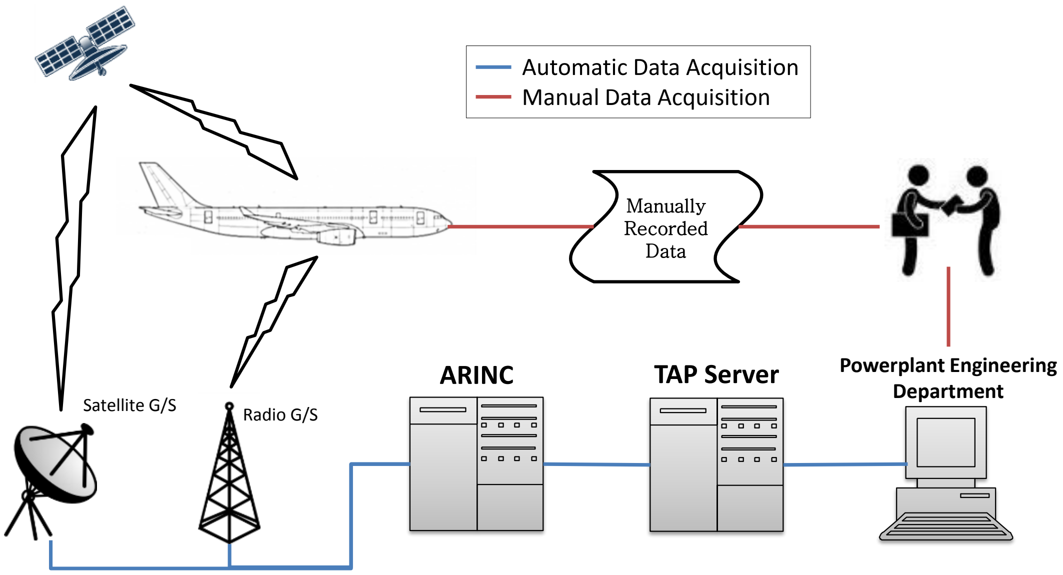


Figure 5.1 Engine data acquisition processes at TAP

There are several ways of transferring the data to the airline's departments. Figure 5.1 represents different engine data acquisition processes practiced 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) messages, either by radio or satellite. The messages are re-directed to the airline servers and then to the airline's Powerplant Engineering department. 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. Manual data acquisition methods involve fewer steps in the process, as it can be seen in figure 5.1, but they are less efficient. The major disadvantage is that it can take a long time from the moment the recordings are executed to the moment when they are analyzed. Moreover, the recorded data needs to be manually inserted by trained operators into the specialized ECM tools. An alternative method to the crew manual recordings consists of collecting the data stored in the aircraft's DMU directly from printers in the cockpit.

Once the data arrives at the Powerplant Engineering department, it is interpreted by ECM analysis software, typically provided by the Original Equipment Manufacturers (OEM) of the engines. ACARS messages are typically transmitted in a format suitable for processing in the ECM software. When this is not the case, the information needs to be converted. 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 and assess its deterioration, as mentioned before. From this assessment, engineers communicate the results and recommend possible maintenance actions or, in the most extreme cases, decide to remove the engines for a SV.

Some of the commercially available products from engine OEMs include the COMPASS (Rolls Royce), the GE Diagnostics system (General Electric) or the P&W EHM (Pratt & Whitney). Engine monitoring services are also included in the ADEM (Advanced Diagnostics and Engine Management), the most advanced system provided by P&W.

5.3 Engine Parameter Measurements

5.3.1 The Turbofan Engine

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 propulsive efficiency, η_P, is a measure of the performance of a given propulsive system and can be defined as the ratio of the thrust power (thrust times velocity) to the sum of that energy and the unused kinetic energy of the jet engine [35]. The propulsive efficiency of a jet engine can be expressed in terms of the inlet velocity of the air (u) and the exhaust velocity (u_e):

$$\eta_P = \frac{2\frac{u}{u_e}}{1 + \frac{u}{u_e}} \tag{5.1}$$

Reference [36] offers a derivation of this equation. An efficiency of 100% is attained if the exhaust velocity is equal to the inlet velocity. The turbofan engine was originally conceived as a method of improving the propulsion efficiency of the jet engine by reducing the mean jet velocity, particularly for operation at high subsonic speeds [35].

In a turbofan engine, thrust is developed by a combination of two portions: a gas turbine engine uses mechanical energy from the combustion and a ducted “fan”, which consists of a multi-bladed propeller rotated by a low-pressure turbine, uses the mechanical energy from the gas turbine to accelerate the air rearwards. The fan accelerates a large amount of air by a relatively small amount, which is more efficient than accelerating a smaller volume of air by a large amount, according to equation 5.1.

The bypass ratio is the ratio of the air bypassing the engine core (secondary flow) compared to the amount of air that goes through the engine core (primary flow). Early turbofan engines were “low-bypass ratio” engines with approximately half of the thrust produced by the “fan” stage and the other half by the primary flow. Current bypass ratios are around 5:1 (or higher) and the fan provides about 80 percent of the total thrust produced by the engine (e.g. CFM-56 engine [37]). The increase in the bypass ratio brings an increase in the core thermal efficiency and improved fuel efficiency [7].

Figure 5.2 shows a turbofan engine with a two-spool configuration and its main assemblies, also called modules. This type of engine is characterized by two independent stages of compression which are mechanically linked by two separate shafts to two independent turbines.

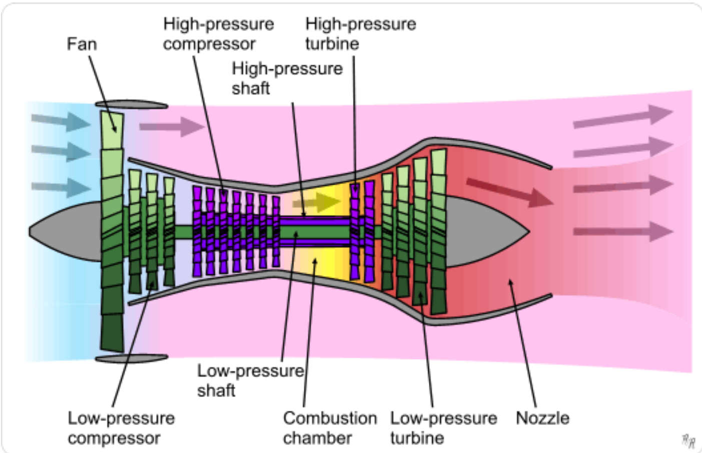


Figure 5.2 Two-Spool Turbofan Engine [38]

5.3.2 Performance and Mechanical Parameters

There are two types of parameters used for monitoring gas turbine engine condition [39]: the mechanical parameters and the performance parameters. The first group of parameters includes the engine vibrations and oil temperature, pressure and consumption. These parameters are not significantly influenced by the flight conditions and engine thrust setting. On the contrary, the performance parameters are influenced by the flight conditions and thrust setting of the engine. The following list provides a description of the key performance parameters in a turbofan engine:

- Engine Pressure Ratio (EPR): it is the ratio of the turbine discharge (exhaust) total pressure to the total pressure at the front of the fan/compressor;
- Low-pressure rotor speed or Fan speed (N1): represents the actual RPM of the low-speed rotor of the engine, and is usually expressed as a percentage of the reference rotation speed of the fan;

- High-pressure rotor speed or Core speed (N2)[1]: represents the actual RPM of the hi-pressure compressor and the high-pressure turbine, also as a percentage of some nominal value;
- Exhaust gas temperature (EGT): this is the temperature of the air that is exiting the low-pressure turbine (engine exhaust);
- Fuel Flow (FF): represents the fuel needed by the engine in its actual performance state, showing how much the engine is burning each hour.

The minimum gas path parameters that need to be recorded for engines that use the N1 as the thrust reference parameter are the N1, N2, EGT and FF. For engines that use the EPR as the main thrust reference parameter are the EPR, N1, N2, EGT and FF. The EPR is the primary thrust setting parameter on Pratt & Whitney (e.g. 4168A) and Rolls-Royce engines, while General Electric engines use the N1 (e.g. CF6-80E1).

5.4 Parameter Trend Monitoring

There is a significant variation in the flight conditions at the time that the engine recordings are taken. Even during one flight the same flight parameters change continuously due to fuel consumption and changes in the weather conditions. Therefore, a consistent procedure is necessary to obtain a relevant time evolution of the engine parameters from the recorded data. 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. The evolution of these delta parameters is then used to assess the current state of the engine and estimate how its performance has deteriorated with time.

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 conditions[2] [40]. The baseline models are generally developed by the engine manufacturers based upon flight-test data and/or in-service experience and then fed to their ECM analysis software. In addition, a baseline model can be derived from flight data of a fleet of aircraft that is then used to derive performance characteristics for an average engine. 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 used are covered in the next Chapter.

Nowadays, a vast quantity of engine parameters is recorded and is available for determining the engine’s condition. However, ECM analysis is normally based on the evolution of parameters as the engine temperatures and pressures, the rotor speeds, fuel flow, engine vibrations and oil monitoring. The vibration data is not corrected to standard day units and trending is sometimes difficult [30]. Oil

[1] Many Rolls-Royce engines have a three-spool design. For these engines, the N2 and the N3 designate the rotation rates of the medium-speed and high-speed rotors, respectively.

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

pressure can be monitored and trended and in this case a comparison is also made with a reference baseline. The engine parameters identified by manufacturers as being the main indicators of the health of the engine and more sensitive to variations in its condition are the N1, N2, FF and EGT.

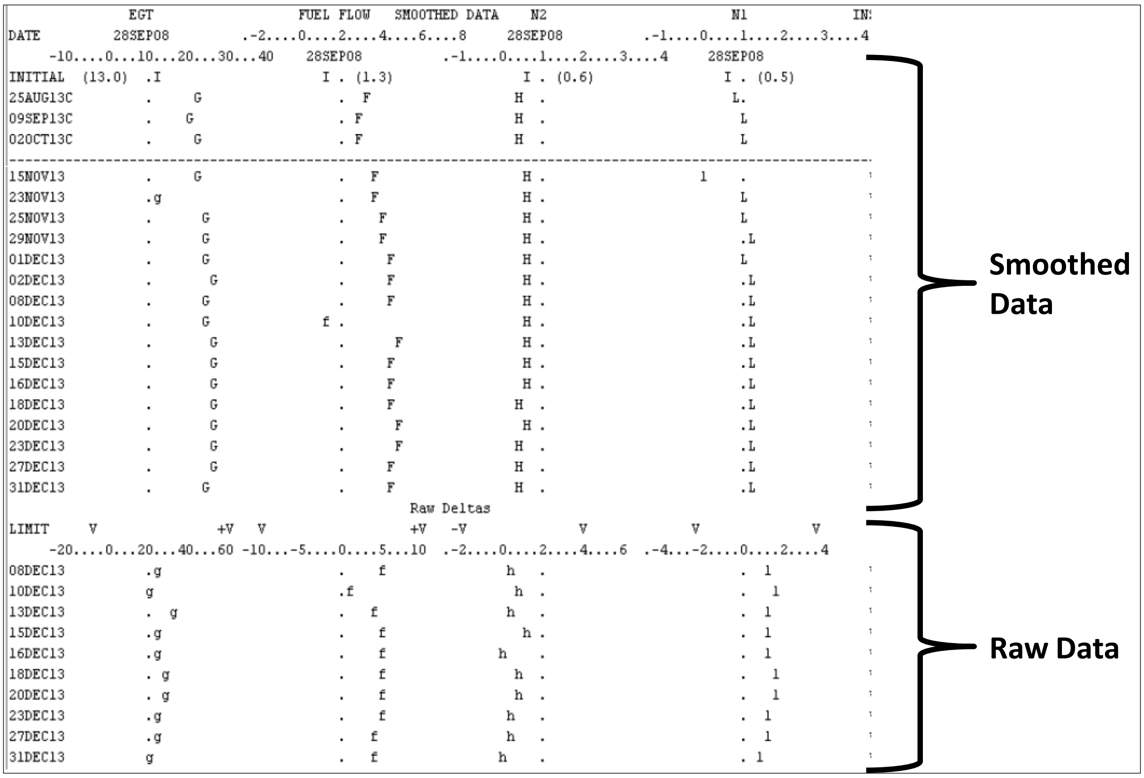
Figure 5.3 shows part of a short term Trend Plot report generated with the Pratt & Whitney's EHM software, which contains the trends of the performance parameters from a PW4156A engine equipping the A310-325 aircraft. The input data consists of manual recordings in cruise like the one in Appendix G. These plots, with the chronological trends of key engine parameters, are the most common method used by engineering departments to monitor the engine's condition.

5.4.1.1 Smoothed Parameters

It is a common practice to employ smoothing algorithms to the trend deltas that reduce the data scatter and help to monitor the deterioration of the engine. Usually, the formula that is applied takes the following shape:

$$Smoothed_{NEW} = Smoothed_{OLD} + \alpha \times (Raw_{NEW} - Smoothed_{OLD}) \tag{5.2}$$

Where α is the smoothing coefficient. It quantifies by how much the smoothed trend line is influenced by the variation between the last smoothed point and the new raw point - "raw" is not the recorded value, but the recorded value after being corrected to standard day conditions.



```
               EGT                  FUEL FLOW   SMOOTHED DATA    N2                       N1             IN:
DATE         28SEP08         .-2....0....2....4....6....8     28SEP08          .-1....0....1....2....3....4
     -10....0...10...20...30...40    28SEP08          .-1....0....1....2....3....4     28SEP08
INITIAL  (13.0)  .I                    I . (1.3)                I . (0.6)                I . (0.5)
25AUG13C         .     G                 .  F                  H  .                       L.
09SEP13C         .    G                  . F                   H  .                        L
02OCT13C         .     G                 . F                   H  .                        L
----------------------------------------------------------------------------------------------------------
15NOV13          .     G                 .   F                  H .                   l    .
23NOV13          .g                      .   F                  H .                        L
25NOV13          .      G                .    F                 H .                        L
29NOV13          .      G                .    F                 H .                        .L
01DEC13          .      G                .     F                H .                        L
02DEC13          .       G               .     F                H .                        .L
08DEC13          .      G                .     F                H .                        .L
10DEC13          .      G              f .                      H .                        .L
13DEC13          .       G               .      F               H .                        .L
15DEC13          .       G               .     F                H .                        .L
16DEC13          .       G               .     F                H .                        .L
18DEC13          .       G               .     F               H  .                        .L
20DEC13          .       G               .      F               H .                        .L
23DEC13          .       G               .      F              H  .                        .L
27DEC13          .       G               .     F               H  .                        .L
31DEC13          .      G                .     F               H  .                        .L
                                                  Raw Deltas
LIMIT     V               +V   V                  +V   -V              V             V              V
     -20....0...20...40...60 -10...-5....0....5...10  .-2....0....2....4....6  .-4...-2....0....2....4
08DEC13          .g                      .    f               h   .                        .  l
10DEC13          g                       .f                    h  .                        .   l
13DEC13          .  g                    .   f                h   .                        .  l
15DEC13          .g                      .    f                 h .                        .  l
16DEC13          .g                      .    f              h    .                        .  l
18DEC13          . g                     .    f                h  .                        .   l
20DEC13          . g                     .    f                h  .                        .   l
23DEC13          .g                      .    f               h   .                        .  l
27DEC13          .g                      .   f                h   .                        .  l
31DEC13          g                       .   f               h    .                        . l
```


Figure 5.3 P&W EHM Short Term Trend Plot Report

The smoothed EGT, Fuel Flow, N2 and FF deltas are represented in figure 5.3 by upper case letters. The most recent "raw" data can be visualized at the bottom of the graph represented by lower case letters and they are included to allow immediate identification of rapid changes in the performance levels of the engine that only become visible later in the smoothed data. Although this is not the case, smoothed and "raw" data may be overlapped in the same plot. Powerplant engineers have to look at both the smoothed and raw streams of data and search for shifts in the most recent trends in terms of the evolution of the EGT, FF, N1 and N2 deltas.

5.4.1.2 Gradual vs. Rapid Performance Shifts

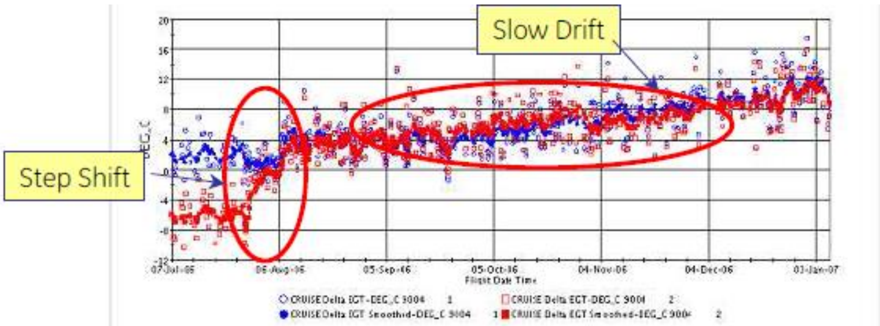


Figure 5.4 Slow Drifts vs. Step Shifts [30]

There are two major types of movements that can be identified in a trend [30]. Both are graphically represented in figure 5.4. A Step Shift is a shift that occurs in the data in a short period of time and is characterized by a sudden increase or decrease on the associated trend, whereas a Slow Drift is a slow movement in the trend that occurs over a longer period of time.

As the engine accumulates flight cycles, the life of many parts is consumed and its performance deteriorates [41]. This can be 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. On the other hand, Step Shifts in the observed delta parameters can 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.

Fingerprints

The detection of abnormal trends in the critical engine performance parameters is proving to be an efficient technique for providing warning information of ongoing problems or impending failures prior to serious malfunctions in the gas turbine engines [32]. Although it can be difficult to quantify the exact parameter shifts for each degradation type [34], there are certain kinds of anomalies in the engine's operation that result in specific changes in the delta parameters being monitored. They are identified by combined evolutions of key performance parameters and allow the problem to be localized within the engine's modules. The general patterns from a specific engine model are supplied by the manufacturer in the form of the so-called fingerprints.

GE projects these shift patterns from a computer thermodynamic model containing the engine-cycle model [30] operating at specific flight conditions.

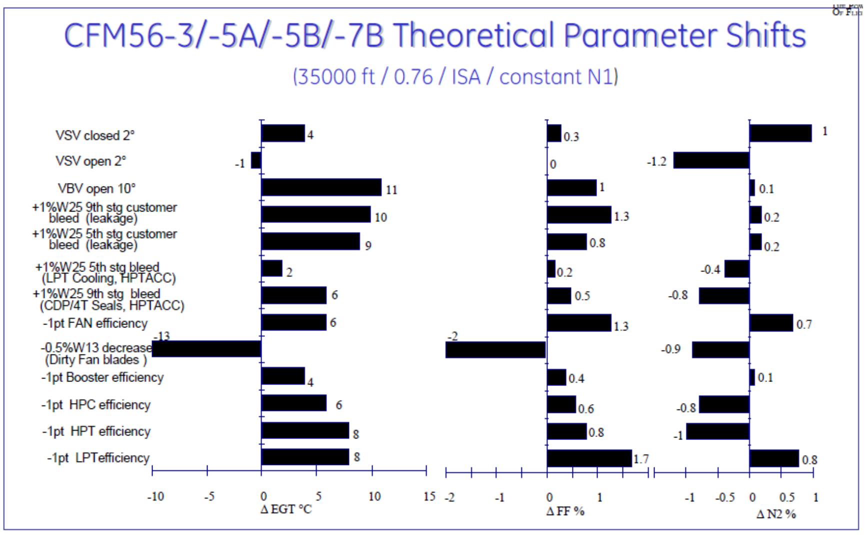


Figure 5.5 Fingerprints for the CFM-56 family of engines [30]

The impact of several types of damage and deterioration – loss of modular efficiency, bleed leakage, etc. - on the overall performance parameters of the engine (EGT, FF and N2) is organized into "Theoretical Parameter Shifts" tables, which are similar to the fingerprints. The operator uses these tables as a starting point in the closer interpretation of the problems and relies on his skills built from previous experience [34]. Figure 5.5 illustrates theoretical parameter shifts for a CFM-56 engine operating at constant altitude, Mach, temperature and thrust setting (N1). In addition, fingerprints can present causes for explaining similar trend shifts observed in more than one engine on the same aircraft. Usually when this happens the problem is attributed to an instrumentation error.

5.4.1.3 Divergence

The former paragraphs have covered the method of monitoring the health of an engine based on a comparison with a baseline model. On multi-engine aircraft there is another method, which consists of comparing each individual engine parameter with the average value from all the engines in the aircraft. The Divergence is a parameter used for these types of comparisons, which is mathematically obtained from the following expression:

$$XDivergence_{\ eng1} = X_{\ eng1} - \frac{X_{\ eng1} + X_{\ eng2}}{4} \qquad \textbf{(5.3)}$$

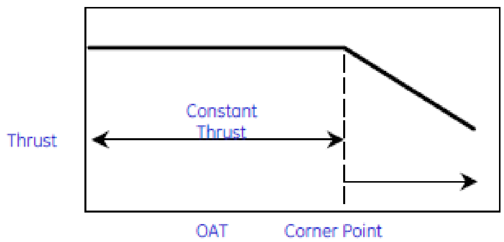
Which is applicable to a twin engine aircraft and X can be any performance parameter. The main advantage of using the divergence is that the measured parameters can be used and no corrections are required. Any possible shifts caused by TAT, Altitude or Mach number, are eliminated [40].

5.4.2 Take-off Considerations

The appropriate indicator of the overall performance of the engine is based on the core flow temperature and is measured at the turbine exit [42]. It is usually referred as EGT or TGT (Turbine Gas Temperature). This temperature is measured on the gas path at the Low Pressure (LP) turbine inlet or at the LP turbine exit. Higher temperatures for the same thrust indicate an increase in the fuel burned and a decrease in the engine's efficiency, meaning that deterioration is affecting the engine.

5.4.2.1 EGT Margin

To meet aircraft performance requirements, engines are designed to provide a constant Thrust up to a designated Corner Point (CPT) or Flat Rate Temperature (FRT). Below this temperature the Thrust is limited by software (pin programming), the same engine being able to provide different levels of thrust. 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 [42]. 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. As a consequence, the Thrust is also reduced when the OAT increases.



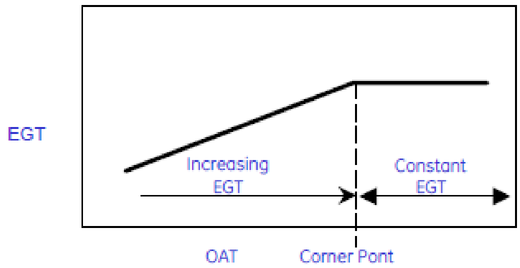


Figure 5.6 EGT Considerations [30]

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, which is acquired automatically in modern aircraft, is projected to the reference condition of full take-off power, on a FRT day at sea level, using characteristics from the Manufacturer's thermodynamic model of the engine. This projected temperature represents the expected EGT if the take-off actually occurred with the reference conditions. The projected EGT is subtracted from the certified EGT redline to yield the EGT Margin or EGT Hot Day Margin (EGTHD Margin). Therefore, the EGT Margin is not just the difference between the peak EGT and the EGT Red Line, since it is very unlikely that a take-off occurs at the same reference condition and temperature.

The EGT Margin is routinely used to monitor the health of the engines using appropriate ECM tools, together with the trends from the cruise performance parameter deltas. Trends in the takeoff EGT Margin can also be used to detect shifts in the engine's performance, which can dictate the need for inspections and/or maintenance [42]. EGT Margin trends can also be used to forecast the remaining time of the engine on the wing in terms of time or engine cycles, by predicting the point at which the margin will be completely eroded. The EGT Margin for new engines is defined to meet most take-off conditions and to allow airlines to operate the engine on-wing during an acceptable amount of time [43]. The EGT Margin should not be used as the sole criterion to plan engine removals, although it is one of the primary engine removal causes. Life Limited Parts constraints, cruise trends and the number of EGT over limit occurrences and associated maintenance tasks should also be considered prior to an engine removal decision.

5.4.2.2 Outside Air Temperature Limit

For the engines in which the take-off EGT is nearly constant with the OAT after the FRT, the Outside Air Temperature Limit (OATL) is another indicator of the engine health. The OATL is a projection of the highest ambient temperature at which an engine should be able to produce full thrust without exceeding the certified EGT red line [42]. Both the OATL and EGT Margin are similar measures of performance based on take-off data. They are not independent assessments of temperature limitations in the engine. If the OATL is equal to the FRT of the engine, the EGT Margin is zero.

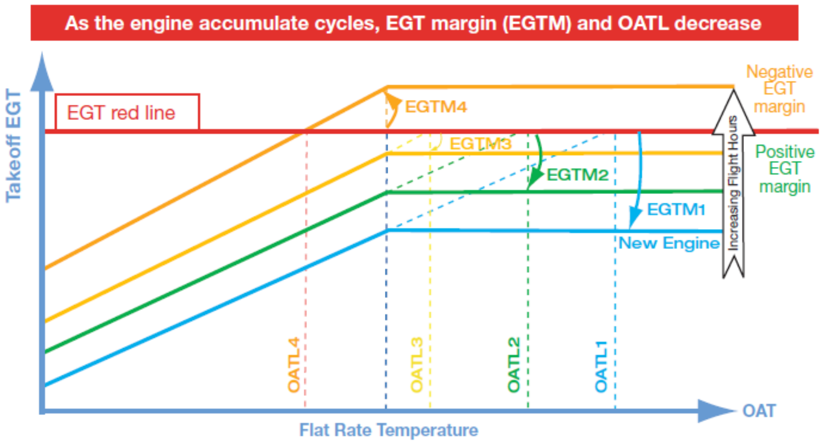


Figure 5.7 Deterioration effect on the EGT Margin and OATL [42]

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 that will be presented in this Chapter 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 provided by the OEM's software.

The PW4168A engine was selected as the case study engine and will be presented in the first place. The algorithm responsible for the extraction of stability points from the flight data is described next. These points contain the fundamental aircraft and engine data for the required analysis. In order to understand how they are acquired, some definitions need to be introduced and understood. Finally, the correction procedure and the formulas used in the current work are presented. The correction procedure employs some dimensionless parameters that take into account the inlet temperature and ambient pressure and calculates the engine parameter values in Standard Day conditions.

6.1 Case Study: PW4168A Engine

The quantity of flight data available from the A310-325's QAR is limited to the parameters that are programmed in the DFDR frame. Some key engine performance parameters from the PW4156A are not recorded, such as the N1, and others are not recorded with the desired frequency, like the N2. In addition, there is not much historical flight data available from the aircraft. These reasons make the implementation of good quality ECM processes based on recorded flight data to the PW4156A engine very difficult. The following studies were then conducted on the PW4168A engine, which powers TAP's A330-223 aircraft. These aircraft are equipped with a Digital ACMS Recorder (DAR), with a recording capacity of 512 words per second. The DAR collects data from the DMU, which offers the possibility of programming which parameters are to be recorded and inserting information about their range, accuracy and recording rate.

6.1.1 Description of the Engine

The PW4000 100-inch engine was developed specifically for the A330 wide-bodied twinjet and entered into service in 1994. It is a dual rotor (two-spool configuration), axial flow turbofan engine with separate primary and fan duct exhaust systems. TAP's long-haul fleet currently operates 7 A330-223 aircraft, which are equipped with the PW4168A engine version. This version delivers a maximum static take-off thrust of 68,600 lbs. at sea level conditions and has a bypass ratio of 4.9.

General Characteristics	Nominal Performance (Sea Level, Static)
• Diameter, Fan tip: 2.54 m (100 inches) • Length: 4.14 m (163.1 inches)	• Take-off thrust: 68,600 lbs • Flat rated temperature: 30ºC • Bypass ratio: 4.9 • Overall pressure ratio: 32.4 • Fan pressure ratio: 1.75

Table 6.1 Specifications of the PW4168A Engine [44]

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. For instance, the EPR is the ratio of the turbine discharge total pressure (Station 4.95) to the compressor inlet total pressure (Station 2) and the EGT is the total temperature of the low pressure discharge gas flow (Station 4.95).

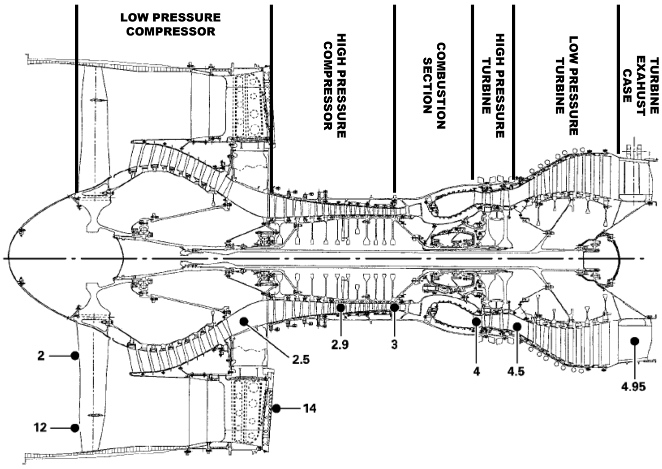


Figure 6.1 PW4168A: Gas Path configuration areas and Engine Stations

Engine Cruise Report <01>

The main component of the Aircraft Condition and Monitoring System (ACMS) of the Airbus A330-223 aircraft is the DMU, which acquires and processes data coming from the ARINC 429 data buses of the aircraft. One of the tasks performed in real time by this unit, besides sending data for recording in the DAR, is the generation of reports – the "Airbus Standard Reports" – according to specific trigger conditions, which have been defined and validated by the manufacturer [45]. These conditions, associated limits, new specific trigger criteria and the information displayed on the reports can be reprogrammed by the operator using external tools. 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 where the majority of the values displayed are averaged values from the stable frame, i.e., the period of time in which the trigger conditions and criteria were met. Other parameter values correspond to the value at the moment of trigger.

```
              <Free programmable 64 characters>
              <Free programmable 64 characters>
               A330 ENGINE CRUISE REPORT <01>      PAGE 01 OF 01
   ACID   DATE    UTC      FROM TO   FLT         CODE CNT
C1 XXXXXXX 99AAA99 99.99.99 AAAA AAAA XXXXXXXXXX 999X 999 ..
   PRV PH   TIEBCK DMU IDENTIFICATION    MOD AP1 AP2
C2 099 99.9 XXXXXX SXXXXX VXXXXX CXXXXX XXX 999 999 ..
   TAT   ALT   MN     SYS (.... BLEED  STATUS ....) APU
C3 X99.9 X9999 0.999 999 9.99 111 11 1 11 111 9.99 1 ..
C4 X99.9 X9999 0.999 999 ..
   ESN     EHRS  ERT   ECYC  ECW1  EVM   QE
C5 999999 99999 99999 99999 XXXXX XXXXX 999 ..
C6 999999 99999 99999 99999 XXXXX XXXXX ..
   EPR   EPRC  N1     N2    N2R   EGT  P5     FF     P2
N1 9.999 9.999 999.99 999.9 999.9 X999 99.999 99999 99.999 ..
N2 9.999 9.999 999.99 999.9 999.9 X999 99.999 99999 99.999 ..
   P25    T25   T295  P3    T3    HPTC LPTC  SVA    B25
S1 99.999 X99.9 X99.9 999.9 X99.9 X99.9 X99.9 X99.99 X99.9 ..
S2 99.999 X99.9 X99.9 999.9 X99.9 X99.9 X99.9 X99.99 X99.9 ..
   GLE   PD TN  OIQH  OIP OIT   OC VF   VC   VH   VL
T1 999.9 99 X99 X9.99 999 X99.9 1  99.9 9.99 9.99 99.9 ..
T2 999.9 99 X99 X9.99 999 X99.9 1  99.9 9.99 9.99 99.9 ..
   PHF PHT BBF  BBT
V1 999 999 9.99 9.99 ..
V2 999 999 9.99 9.99 ..
                  NO STABLE FRAME CONDITION
```

Figure 6.2 Format of the A330's Engine Cruise Report <01> [46]

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. As mentioned in the previous sections, one of the means of achieving this consists of using in-flight data processed by the aircraft's DMU that is then compiled into reports. 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. This period is typically 100 or 120 seconds and a point in these conditions is also called a Stability Point.

Depending on the flight conditions and the logic contained in the DMU, there can be several stability points found for a particular flight. The method used to select which one is the ideal to represent the engine's performance depends on the recording system. In the A330-223 aircraft, the DMU selects the best stability point based on the quality number parameter, which is a measure of the parameter dispersion in the period where the conditions and criteria are met.

This section presents the development of an algorithm for extracting stability points from flight data recorded in the DAR. The flights are exported from AGS with engineering values and then they are processed by the algorithm. First, the stability criteria and trigger conditions employed by the DMU for the Engine Cruise Report 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 is to acquire stability points with better quality than those acquired by the aircraft's DMU and to use these points for a trend monitoring analysis.

6.2.1 Observation Window and Stable Frame

Most of the parameters that make part of a Stability Point are averaged over a period of time that was identified as meeting all the conditions and stability criteria. 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. They include, for instance, a range for the Altitude, Mach number and fan speeds where stable frames can be searched and impose some conditions on the status of the anti-ice and bleed discretes, for instance. When the Basic Conditions are met, the DMU searches for stable frames. It looks at the parameter data in each 100 seconds of flight and then computes the difference between the maximum and minimum values. If the difference is not above the parameter's stability criterion and if this is verified for every parameter then the period is a stable frame. Stability Criteria are defined for parameters such as the Ground Speed, Total Air Temperature, Fuel Flow, Vertical Acceleration, etc.

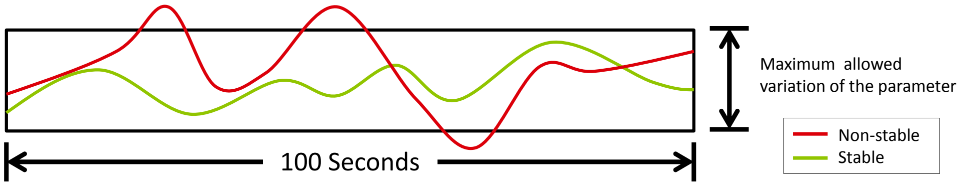


Figure 6.3 Stable and non-stable variation of a parameter inside an Observation Window

Individual vs. Gliding Observation Windows

There are two distinct methods of searching stable frames. This first method 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. The advantages of this method are obvious: if i is small (e.g. 1 second) the number of observation windows considered for the stable frame search increases significantly, with the next window containing all the data of the previous window except the first i seconds. Thus, a lot of observation windows discarded by the first method can be included in the second, leading to stability points with better quality.

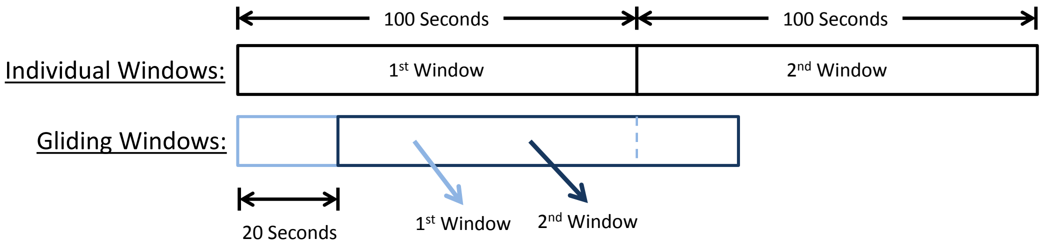


Figure 6.4 Individual and Gliding Window methods

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

The number of stability points encountered during a flight depends mainly on the flight conditions experienced, the duration of that flight and the stability criteria. If several stability points are identified it is necessary to have a consistent procedure that selects the best of them, which will then be used for generating trend monitoring results. Stability points are selected based on the quality number that is computed for the corresponding stable frame period [45]. 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:

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

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 of the parameter defined as:

$$\mathrm{VAR}_I = \frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1} \tag{6.2}$$

With N equal to the number of samples of parameter I in the observation window. The mean $\bar{x}$ is calculated using the formula below:

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N} \tag{6.3}$$

Notice that the variance measures how close the parameter values in the observation window are to the mean. The stability point is better when the overall variance of its parameters is lower. For a stable frame parameter, the calculated mean is the value that will be recorded in the stability point. In our computations the weighting factor is equal to 1 for all parameters, similar to what is currently used in the aircraft [46].

6.2.3 Algorithm for Extraction of Stability Points

The algorithm to extract Stability Points from the recorded flight data was developed using the R programming language. To acquire these points, the logic from the Engine Cruise Report was initially implemented in the algorithm and consists of two main parts:

- Basic Conditions
- Stable Frame Criteria.

After validating the algorithm, this was used to study the implementation of a new set of stability criteria. This is one of the advantages of using recorded data rather than the processed reports from the DMU: the ability to refine existing calculation routines and study their effect on the results, from flights that have already occurred. Over the next sub-sections the Basic Conditions, Stable Frame Criteria and the parameters needed for the computations will be presented and the algorithm described.

6.2.3.1 Basic Conditions

The Basic Conditions are used to enable or disable the search for stable frames and to avoid that Stability Points are generated whenever the parameters are of no use. The discrete and binary type parameters used for these conditions are displayed in tables 6.2 and 6.3, respectively.

Discrete Type Parameters

Parameter	Description	Equipment/Label/SDI	Recording Frequency
FNAI1	ENG 1 NACELLE ANTI-ICE VALVE POS (OFF)	ZC/076/11	1 Hz
FNAI2	ENG 2 NACELLE ANTI-ICE VALVE POS (OFF)	ZC/076/11	1 Hz
WAO1	WING ANTI-ICE OUTER POS - LEFT FILTERED	DMU-1/263/11	1 Hz
WAI1	WING ANTI-ICE INNER POS - LEFT FILTERED	DMU-1/263/01	1 Hz
WAI2	WING ANTI-ICE INNER POS - RIGHT FILTERED	DMU-1/263/10	1 Hz
WAO2	WING ANTI-ICE OUTER POS - RIGHT FILTERED	DMU-1/263/00	1 Hz
XBV_POS2	CROSS BLEED VALVE POSITION	BMC-1/055/01	1 Hz
APUBV_O	APU BLEED VALVE OPEN	APU-ECB/037/01	1 Hz
EG_PRV_POS	ENG PRV POSITION	BMC-1/066/01	1 Hz
O_EGPRV_POS	OPPOSITE ENG PRV POSITION	BMC-1/067/01	1 Hz
EG_HPV_POS	ENG HPV POSITION	BMC-1/066/01	1 Hz
O_EGHPV_POS	OPPOSITE ENG HPV POSITION	BMC-1/067/01	1 Hz

Table 6.2 Discrete Parameters used in the Basic Conditions

Binary (BNR) Type Parameters

Parameter	Description	Equipment/Label/SDI	Recording Frequency
ALT_STD	ALTITUDE STANDARD (1013.25MB)	ADC-1/203/01	1 Hz
MACHR1	MACH NUMBER ADC1 [TAP]	ADC-1/205/01	1 Hz
N11	N1 ACTUAL ENGINE 1	DMC_ECAM/346/01	1 Hz
N12	N1 ACTUAL ENGINE 2	DMC_ECAM/346/10	1 Hz
TAT	TOTAL AIR TEMPERATURE	ADC-1/211/01	1 Hz

Table 6.3 Binary Parameters used in the Basic Conditions

The following table describes the logic for true Basic Conditions with the corresponding parameters. For the discrete parameters, the bit's value is also specified.

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_HPV_POS=O_ENGHPV_POS
Cross Feed Valve Closed	XBV_POS2=0
APU Bleed Valve Closed	APUBV_O=0

Table 6.4 Logic for True Basic Conditions and Parameters used

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

6.2.3.2 Stable Frame Criteria

When the Basic Conditions for the observation window are checked, the differences between the maximum and minimum values of the parameters in table 6.5 are computed. These parameters are the Stable Frame Parameters.

Stable Frame Parameters

Parameter	Description	Eq/Label/SDI	Recording Frequency
IALT	INERTIAL ALTITUDE	IRS-1/361/	1 Hz
GS	GROUND SPEED	DMC_EFIS/312/01	1 Hz
ROLL	ROLL ANGLE	IRS-1/325/01	2 Hz
TAT	TOTAL AIR TEMPERATURE	ADC-1/211/01	1 Hz
N21	N2 ACTUAL ENGINE 1	DMC_ECAM/344/01	1 Hz
N22	N2 ACTUAL ENGINE 2	DMC_ECAM/344/10	1 Hz
EGT1	EGT ENGINE 1 (T495)	DMC_ECAM/345/01	1 Hz
EGT2	EGT ENGINE 2 (T495)	DMC_ECAM/345/10	1 Hz
GVRTI	VERTICAL ACCELERATION	IRS-1/364/01	8 Hz
MACHR1	MACH NUMBER ADC1 [TAP]	ADC-1/205/01	1 Hz
N11	N1 ACTUAL ENGINE 1	DMC_ECAM/346/01	1 Hz
N12	N1 ACTUAL ENGINE 2	DMC_ECAM/346/10	1 Hz
PT21	LOCAL PT2 ENGINE 1	EIVMU-1/131/01	1 Hz
PT22	LOCAL PT2 ENGINE 2	EIVMU-1/131/10	1 Hz
FF1	FUEL FLOW ENGINE 1 (kg/hr)	DMC_ECAM/244/01	1 Hz
FF2	FUEL FLOW ENGINE 1 (kg/hr)	DMC_ECAM/244/10	1 Hz
EPR1	Actual EPR ENG #1	EIVMU-1/340/01	1 Hz
EPR2	Actual EPR ENG #2	EIVMU-1/340/10	1 Hz
HPT1	SELECTED HPTC POSITION ENGINE 1	EIVMU-1/330/01	1 Hz
HPT2	SELECTED HPTC POSITION ENGINE 2	EIVMU-2/330/10	1 Hz
LPT1	SELECTED LPTC POSITION ENGINE 1	EIVMU-1/331/01	1 Hz
LPT2	SELECTED LPTC POSITION ENGINE 1	EIVMU-1/331/01	1 Hz

Table 6.5 Stable Frame Parameters

The difference for each parameter is computed in order to be compared to a defined quantity, the tolerance, which constitutes the stability criterion. Table 6.6 contains the stability criteria used in the aircraft and initially implemented in the algorithm.

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

Table 6.6 Initial Stability Criteria

6.2.3.3 Filtering of Parameters

The on-board systems of the aircraft also filter the parameter data, in order to reduce the noise typically encountered in the readings. The formula used to filter these readings is the following:

$$NFV = OFV + \frac{t}{T}(NRV - OFV) \qquad \textbf{(6.4)}$$

Where:

NFV = New Filtered Value
OFV = Old Filtered Value
NRV = New Raw Value

t = Samples per Second
T = Time Constant

The division t/T is constant for the filtered parameters and equal to 1/3. The result of implementing the formula above is that instead of using directly the parameter reading (NRV), the value used is equal to the OFV plus one third of the difference between the first and the latter. Table 6.7 lists the parameters that are filtered in the algorithm developed.

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

Table 6.7 List of Filtered Parameters

6.2.3.4 Description

Figure 6.5 contains the flowchart for the algorithm developed with the R language, 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 from the parameters listed in tables 6.2, 6.3 and 6.5. In addition to these parameters, others have been exported containing the Flight Phase (FLIGHT_PHASE), the recorded date and time (DATE and TIME_R, respectively) and the aircraft tail registration (AC_TAIL_23, AC_TAIL456 and AC_TAIL7). It is also important to notice that the number of decimal places for each parameter in the exported flights also needs to be defined and taken into account.

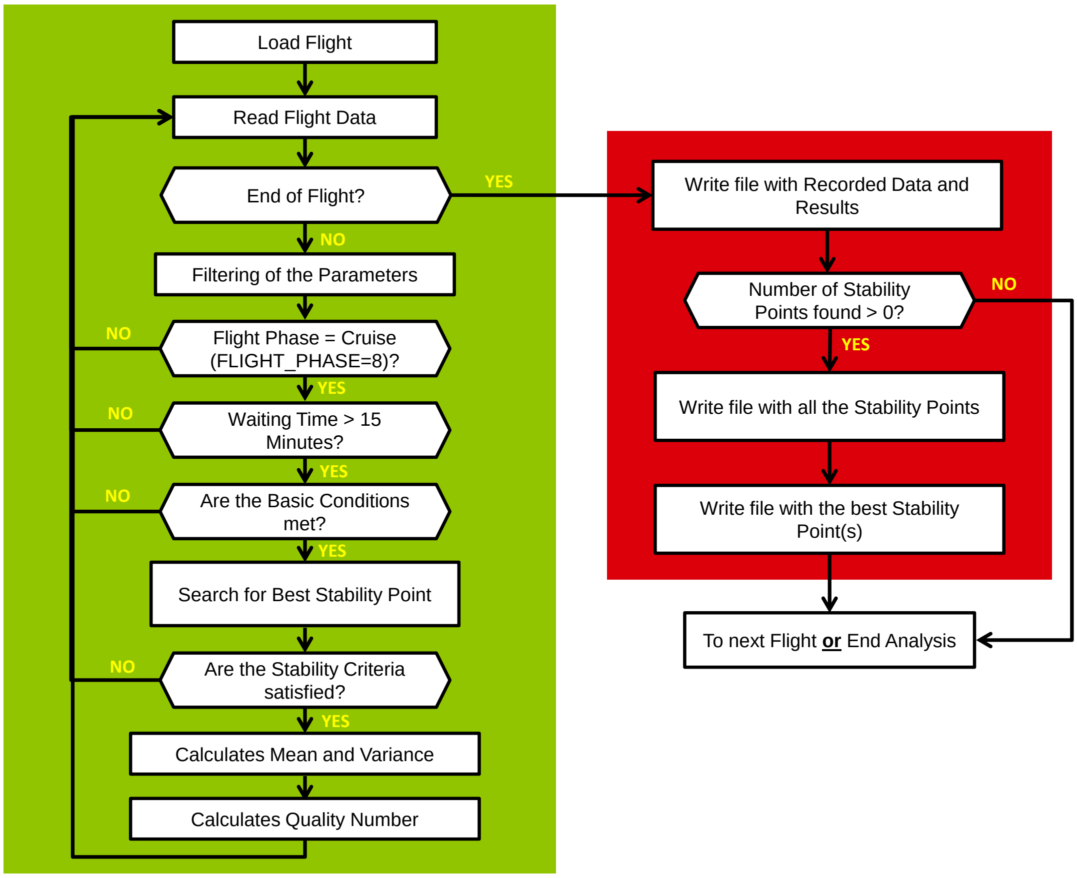


Figure 6.5 Flowchart of the Algorithm for Extraction of Stability Points

The algorithm starts by loading the flight data in the file to a dataframe, a structure similar to a table, which is then converted to a matrix for quicker computations. Afterwards, there is a cycle that reads every line of data. Most parameters are recorded with frequencies lower than 8Hz so many entries are missing data. R has some handy functions that allow dealing with the situation. For instance, auxiliary variables were created with information from the last recorded value and new filtered values are only calculated when the recorded parameter value is updated.

There are some conditions that need to be checked before searching for stability points. The first condition is based on the Flight Phase. Instead of the FM_FWC parameter used in the aircraft, the algorithm checks the FLIGHT_PHASE parameter computed from the Flight Phase Computation procedure. 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 first time in the flight;
2) After a search period of 240 minutes (4 hours) for Stability Points.

Because long-haul flights performed by A330-223 aircraft have durations of 8, 9 and more hours, it is possible to generate stability points from different periods of the flight with data acquired at different altitudes, temperatures, engine settings, etc. Finally, the Basic Conditions in the observation window are checked using the logic presented in table 6.4. If they are true, the algorithm will search stability points for a maximum of 240 minutes. It computes the difference between the maximum and minimum parameter values, using filtered values where applicable, and checks these against the tolerances defined in table 6.6. When the differences are lower, a stability point is generated and the quality number for the stable frame is calculated using equation 6.1.

Figure 6.6 uses a representative flight profile to better illustrate the conditions described above. Notice that the counter implemented for the search period is only incremented when the Basic Conditions are true. The figure also shows the point in which the Engine Cruise Report is generated by the DMU.

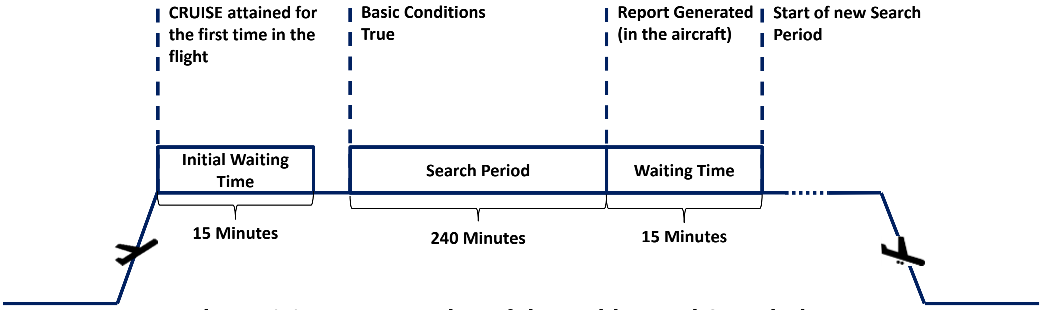


Figure 6.6 Representation of the Waiting and Search times

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 in the processed flight, 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 from different aircraft of the A330-223 fleet in order to make the results the most representative possible. The criteria from the aircraft in table 6.6 were initially used for generating stability points. After this implementation, it was found that stability points were not being generated from a high number of flights (approximately 50%). The reason why this happened was because in many of these flights the anti-ice discretes maintain the ON status and therefore the Basic Conditions were never met. However, this is an expected situation during normal operation and the studies proceeded with the flights with stability points.

Flight Results

Figure 6.7 illustrates some of the results obtained from a flight processed by the algorithm. The pressure altitude is represented by the ALT_STDC parameter and clearly illustrates the climb, cruise and descent flight phases. The flag_cruise variable indicates when the aircraft is in Cruise. From the moment the aircraft finishes its initial climb up to a stable cruise altitude until starting the descent for landing, the aircraft is in cruise. 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 that are indicated with the black circle on the left of figure 6.7. The functioning of the counter variables for the search and waiting times is illustrated here 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. For the flight pictured below, there is more than one search period. The stability_point variable indicates when a stability point is found and it's numbered after the corresponding search period.

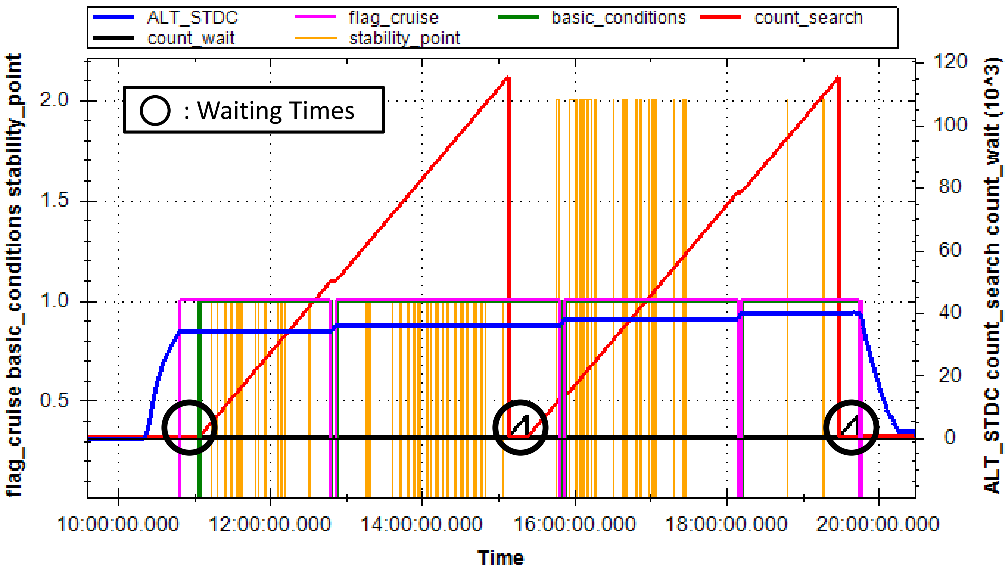


Figure 6.7 Flight Results: Search Periods, Waiting Times and Stability Point

Study of new Stability Criteria

The results in figure 6.7 show that a large number of stability points are encountered during the flights using the aircraft 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 6.8 displays the tolerances for the Converged Stability Criteria, together with the tolerances from the aircraft used initially by the algorithm. The new criteria are the result of an iterative process: each time the tolerances were reduced, the flights were processed by the algorithm and the number of stability points checked. After this iterative process, only approximately 10% of the exported flights did not generate any stability point and a significant reduction in the number of points in each flight was obtained. The tolerances for the engine performance parameters (N2, EGT, N1 and FF) are considerably lower in the new criteria. The tolerance for the EPR was not altered because the recording resolution of the parameter is already lower than the value used in the aircraft. In practice, this means that the value of the EPR is kept constant in every stable frame.

Parameter	Aircraft Stability Criteria	Converged Stability Criteria
IALT	100 ft.	35 ft.
GS	5 Knots	2 Knots
ROLL	0.8º	0.6º
TAT	1.1ºC	0.5ºC
N21, N22	1.0%	0.2%
EGT1, EGT2	22ºC	3ºC
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 6.8 Aircraft and Converged Stability Criteria

The comparison between both criteria is done in the next Chapter, where the results related with the engine baseline models and trend monitoring are covered. Since the stability points acquired with the Converged Stability Criteria correspond to periods of the flight with higher stability, it is necessary to assess the potential of deriving more accurate engine baseline models from them.

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 [47]. 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.

The purpose of correcting measured data from a gas turbine test is to make the results comparable to those from other engines or with acceptance test criteria [48]. Data correction algorithms are also applied to monitor the engine deterioration. The classical parameter corrections employ a number of dimensionless parameters that are derived from dimensional analysis [47]. This has been the primary technique for establishing the classical parameter corrections. References [47] and [36], describe the principle of dimensional analysis using the work by Buckingham [49] and provide illustrative examples applied to turbojet and turbofan engines, respectively. The equations presented in the next sections use a different method that relies on basic calculus and some thermodynamic principles.

6.3.1 General Formulation

Consider the two-spool, mixed flow[1], turbofan engine and its station numbers as illustrated in figure 6.8. The following discussion will use this type of engine as reference. The numerical demonstration was taken from Reference [47].

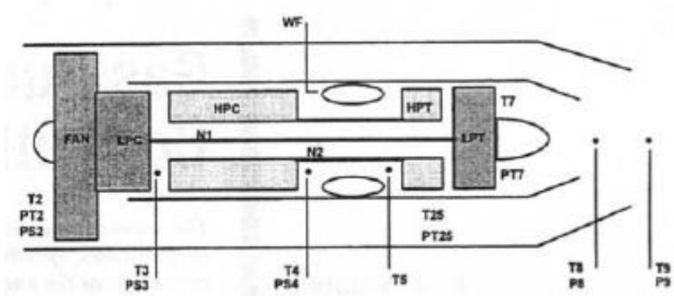


Figure 6.8 Twin spool mixed flow turbofan [47]

In this discussion, a generic gas path parameter is denoted by P and its equivalent corrected parameter by P^*. Generally, 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, as mentioned initially. The

1. Mixed Flow in turbofan engines means that the cold air bypassing the core section of the engine and the hot air exiting this section are exhausted through a single exit nozzle.

corrected parameter P^* would be constant regardless of the change in the inlet condition (T_2, P_2) and represents the value that the parameter P would have at a fixed reference inlet condition. The reference condition can be defined arbitrarily, but it is a common practice to select standard day atmospheric conditions at sea-level for correction purposes (T_0=288.15 K and p_0=1013.25 hPa). We assume, without loss of generality, that $P = f(T2, P2, P^*)$. Thus, it follows that

$$dP = \left(\frac{\partial P}{\partial T_2}\right) dT_2 + \left(\frac{\partial P}{\partial P_2}\right) dP_2 + \left(\frac{\partial P}{\partial P^*}\right) dP^* \tag{6.5}$$

$$\begin{aligned} \frac{dP}{P} = \left(\frac{\partial P/P}{\partial T_2/T_2}\right)_{\substack{P_2=const \\ P^*=const}} \frac{dT_2}{T_2} + \left(\frac{\partial P/P}{\partial P_2/P_2}\right)_{\substack{T_2=const \\ P^*=const}} \frac{dP_2}{P_2} \\ + \left(\frac{\partial P/P}{\partial P^*/P^*}\right)_{\substack{P_2=const \\ T_2=const}} \frac{dP^*}{P^*} \end{aligned} \tag{6.6}$$

For the following expression, the simplifying assumption is made that the first two partials are constant (the third is constant and equal to one), and denote them by a and b, respectively

$$\frac{dP}{P} \approx a\frac{dT_2}{T_2} + b\frac{dP_2}{P_2} + \frac{dP^*}{P^*} \tag{6.7}$$

Next, we define the dimensionless parameters (or correction factors) $\theta = T_2/288.15$ and $\delta = P_2/1013.25$ and arrive at

$$\begin{aligned} \frac{dP^*}{P^*} \approx \frac{dP}{P} - a\frac{d\theta}{\theta} - b\frac{d\delta}{\delta} \Rightarrow \\ \Rightarrow P^* \approx \frac{P}{\theta^a \delta^b} \end{aligned} \tag{6.8}$$

Equation 6.8 is the most widely used parameter correction formulae. Notice that the corrected parameter maintains the same units and is calculated with the theta (θ) and delta (δ) exponent corrections. Table 6.9 summarizes some of the common gas turbine parameter corrections and the standard classical values for the exponents a and b.

Parameter	$\boldsymbol{a}$	$\boldsymbol{b}$	**Corrected Parameter**
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 6.9 Common Gas Turbine Parameter Corrections

Notice the letter K to indicate a corrected parameter. We will follow this nomenclature in the forthcoming chapters. Reference [47] also offers a derivation of these (and additional) classical corrections, from simple thermodynamic relationships and assumptions that do not require extensive knowledge of the thermodynamics of the gas turbine operation.

Mach number similarity parameters are also applied in the correction procedure [48]. Consider the Corrected Rotational Speed N_1^* or Corrected Fan Speed. The tangential velocity (w) is related to the rotational speed (RPM) by the radius (r) of the fan blades, and simultaneously to the tip Mach number

(M_t) and square root of the inlet temperature T. This can be translated mathematically to the following equation

$$w = rN = M_t\sqrt{\gamma RT} \tag{6.9}$$

Where γ and R are the ratio of specific heats and the gas constant, respectively. Taking logs of the expression and differentiating and assuming a constant Mach, we obtain

$$\frac{dN}{\mathrm{N}} = \frac{dM_t}{M_t} + \frac{1}{2}\frac{dT}{T} = \frac{1}{2}\frac{dT}{T} \Rightarrow \tag{6.10}$$

$$\Rightarrow \frac{dN}{\mathrm{N}} - \frac{1}{2}\frac{dT}{T} = 0 \Rightarrow \frac{N}{\sqrt{\theta}} = constant \tag{6.11}$$

If we use an additional parameter to describe the axial Mach number, then the inlet flow angle is fixed and the velocity triangles at the inlet in terms of the Mach numbers are the same as the baseline reference condition. Because the Mach number describes the compressibility effects and the flow angles dictate losses and work done in turbomachines, the efficiencies, temperature ratios and pressure ratios are not altered during the correction procedure.

<u>Approximations and Limitations</u>

Generally, the exponents a and b will depend on the engine and cycle. The quality of the parameter correction procedure can be improved when applying some corrections to the exponents a and b. Reference [48], for instance, details how the exponents for theta and delta may be determined by running a full thermodynamic computer model of the engine over a range of inlet temperatures and pressures and exhaust conditions. Although this high level model may be available to the engine manufacturers, operators usually do not possess detailed information to run engine simulation models. There are, however, empirical methods that utilize actual engine data collected over a temperature and/or pressure range and consist more on a statistical approach to the parameter correction procedure. In [47], the author proposes an empirical formula that can be used for temperature and pressure corrections in the same manner. This simple method was then tested against more complex and iterative statistical methods and the exponents returned were essentially the same.

The impacts of changes in the viscosity with altitude (Reynolds number effects) are not considered with equation 6.8. While the effects of the Reynolds number might not be important for some engine models, there can be errors involved in the comparison of corrected parameters, at a reference condition, if these effects are not accurately predicted. The ratio of specific heats and the gas constant are assumed to be invariant in the atmosphere. This is a typical assumption when performing dimensional analysis on gas turbine engines.

The ratio of specific heats and the gas constant are assumed to be invariant in the atmosphere. This is a typical assumption when performing dimensional analysis on gas turbine engines.

6.3.2 Application to the Case Study Engine

6.3.2.1 Correction Factors

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 (see table 6.5) from the stability points. The correction factors are calculated for standard day conditions using the equations below:

$$\theta_t = \frac{T_{02}}{T_0} = \frac{T_{02}}{288.15} \quad \textbf{(6.12)}$$

$$\delta_t = \frac{p_{02}}{p_0} = \frac{p_{02}}{1013.25} \quad \textbf{(6.13)}$$

Where T_{02} is the total temperature at the inlet and p_{02} is the total pressure at the inlet. The subscript t indicates that the correction factors are computed with the total temperature and total pressure. Because the inlet does no thermodynamic work [36], the free stream total temperature (TAT) is used for the total temperature at both engine inlets.

6.3.2.2 Parameter Corrections

In the PW4168A, there are four key engine performance parameters being monitored: EGT, Fuel Flow, N2 and N1. The recorded parameters from both engines are listed in table 6.5. They are filtered with equation 6.4 and then averaged in the observation window of the stability point. The values from each point are corrected for changes in the inlet condition using the equations below, which are similar to others previously presented in this section.

- Corrected EGT:

$$EGTK = \frac{EGT_{Raw} + 273.15}{\theta_t} \; [K] \quad \textbf{(6.14)}$$

- Corrected Fuel Flow:

$$FFK = \frac{FF_{Raw}}{\sqrt{\theta_t}\delta_t} \; [kg/hour] \quad \textbf{(6.15)}$$

- Corrected N2:

$$N2K = \frac{N2_{Raw}}{\sqrt{\theta_t}} \; [\%] \quad \textbf{(6.16)}$$

- Corrected N1:

$$N1K = \frac{N1_{Raw}}{\sqrt{\theta_t}} \; [\%] \quad \textbf{(6.17)}$$

The subscript Raw denotes the parameter value from the stability point. 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 used to correct the fuel flow and 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 Chapter. The source of engine parameter data are the stability points that are acquired with the algorithm described in the previous Chapter that was adapted for implementation in AGS. This implementation is the first subject of the Chapter. After that, the definition of the engine baseline models and the corresponding results are presented. To derive these models, it was necessary to access the airline records for engine removals and installations and to take into account the effects of bleed air in the performance characteristics of the PW4168A engine. The trend monitoring results, showing the evolution in time of the performance parameter deltas, for two selected aircraft are then presented and compared with the results obtained with the engine manufacturer's ECM software. The results shown in this Chapter are generated with a tool developed with the R programming language that is responsible for establishing the baseline models from the stability points generated in AGS and calculating the deterioration levels of the engines for trend monitoring.

7.1 Implementation of Procedures in AGS

The algorithm for the extraction of stability points described in the previous chapter was adapted and implemented in AGS using dedicated procedures. Table 7.1 lists the procedures that have been implemented in the database version for TAP's A330-223 fleet. The implementation of these procedures is the subject of the current section.

Procedure Nr.	Description	Execution Rate
504	Filtering of Parameters – ECM	1Hz
505	Filtering and Delta parameters [GVRTI] - ECM	8Hz
506	Filtering and Delta parameters [ROLL] - ECM	2Hz
1000	Basic Condition for cruise stability detection	1Hz
1018	Stable condition for cruise stability detection - ECM	1Hz
8018	Interface for ECM trend monitoring (CRUISE)	1Hz

Table 7.1 List of Procedures for ECM implemented in the A330-223 fleet database version

The flowchart in figure 7.1 is very similar to the one used to describe the algorithm developed in R (see figure 6.5) and provides visual information about how the procedures are related between them. The processes are run over the recorded data according to the execution rate and in ascending order.
Procedures 504, 505, 506 filter the required parameters and have different execution rates because of the different parameter recording rates. While procedure 504 has an execution rate of 1Hz, procedure 505 is executed at 8Hz to filter the GVRTI parameter and procedure 506 at 2Hz to filter the ROLL parameter. Although the entire process in figure 7.1 only searches for new stability points from second to second, these procedures ensure that all the recorded values are filtered and that the variation of the parameters in the observation window is correctly calculated.
Procedure 1000 checks the Basic Conditions in the observation window, the cruise flight phase and if the initial waiting time is superior to 15 minutes. When these conditions are true, stability points are searched. Procedure 1018 calculates the variation of the stable frame parameters in the observation window and checks if they exceed the stability criteria. When the criteria are satisfied, it calculates the

quality number (QE) and compares it to the lowest quality number found in the search period. Whenever the new computed QE is lower, the best stability point for the period is updated.

At the end of each search period or at the end of the flight (if the last search period doesn't reach the 240 minutes), procedure 8018 outputs a file with information from the best stability point of the last period. These files are then put together to be used in the derivation of the engine baseline models, which are described next, and to generate the trend monitoring results.

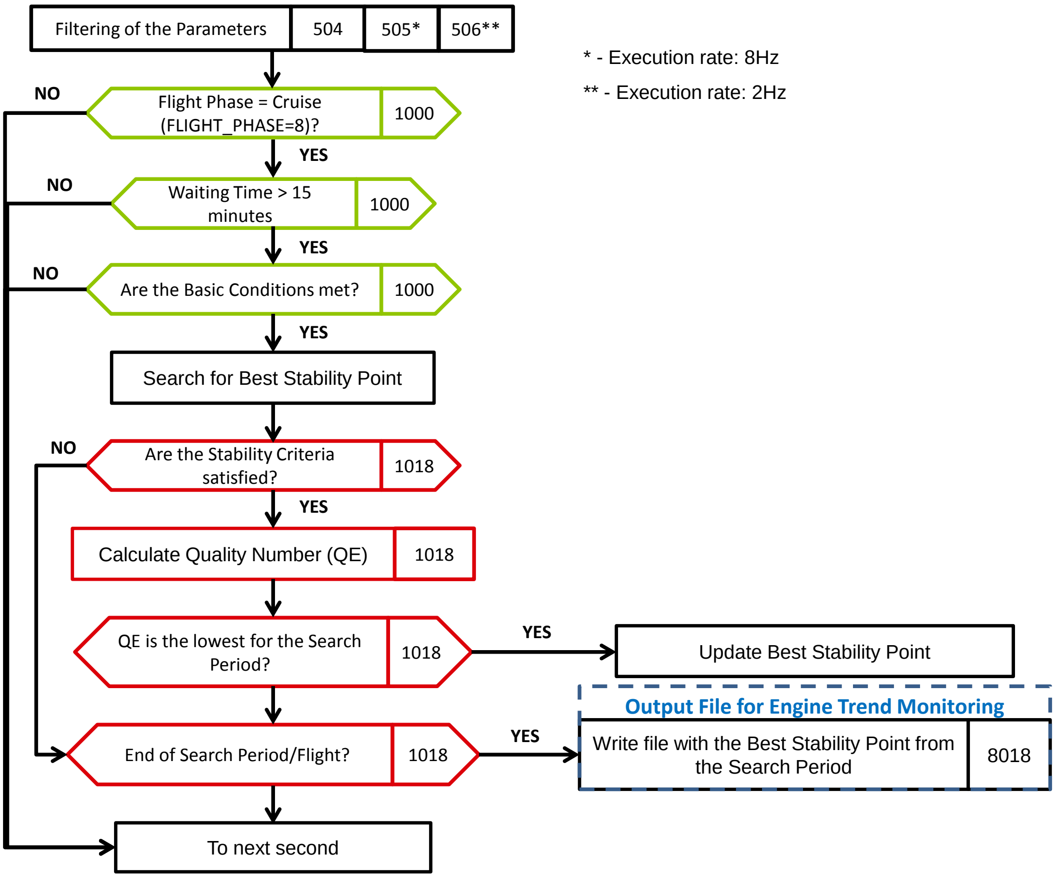


Figure 7.1 Flowchart: Implementation of Procedures for ECM in AGS

7.2 Engine Baseline Model

In Chapter 5, the process of parameter trend monitoring was described as the process by which the recorded engine data is corrected and then compared to a baseline model of the engine. The difference in the experienced and expected performance is calculated as a delta parameter and the evolution of these parameters as a function of time is then used to assess the engine's condition.

With earlier generation turbofan engines, the expected engine characteristics were made available to the operators and trend monitoring was conducted by manually calculating the delta parameters. Figure 7.2 shows the cruise characteristics of the JT3C-6, a two-spool turbojet engine. The EGT, FF, N1 and N2 are corrected and plotted as a function of the EPR. The changes in the Reynolds number are also illustrated with the different altitude lines. Nowadays, the recorded data is processed automatically by ECM tools from the OEMs of the engines and delta parameter trends are immediately available to the operator. Although these tools use an engine baseline model for these computations, this information is generally not available to the operator.

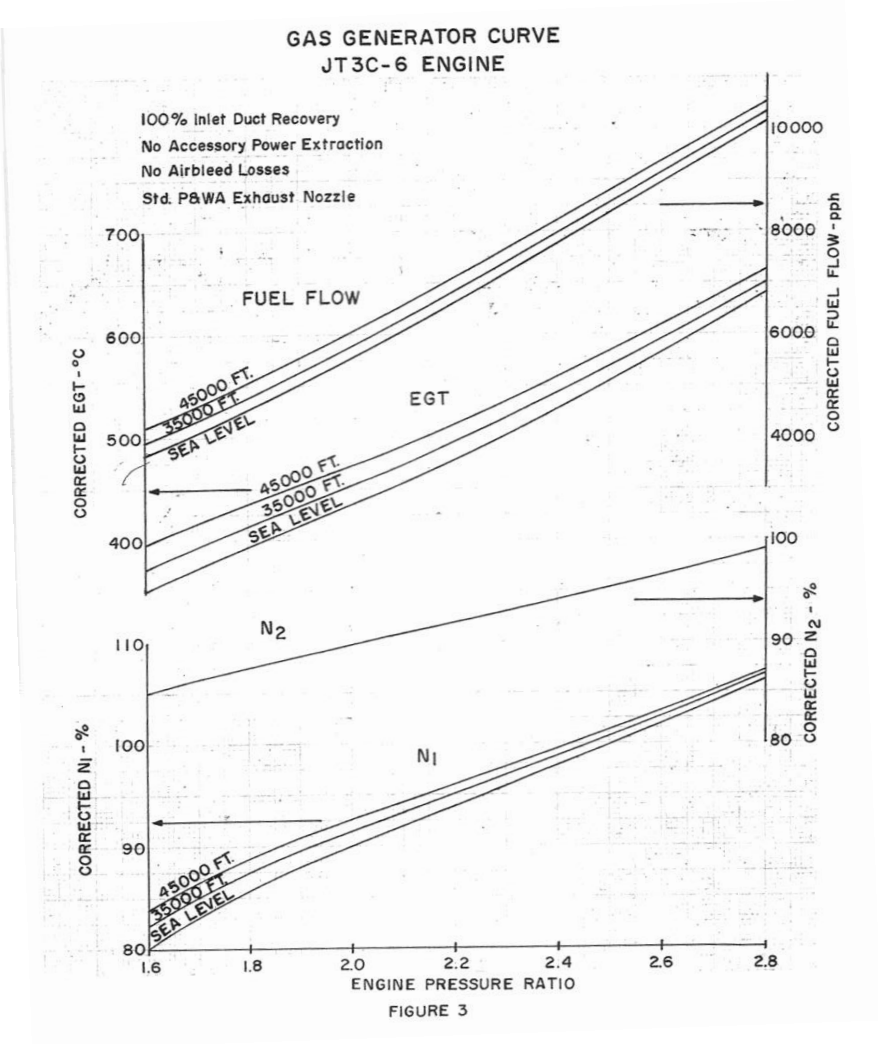


Figure 7.2 Cruise Performance Characteristics of the JT3C-6 engine [39]

This section presents the study that was undertaken with the objective of defining the cruise performance characteristics of the PW4168A engine and compose baseline models from the data acquired with the algorithms developed. The engine parameter data in the baseline models is corrected with the dimensionless correction factors and the equations discussed in section 6.3. The models will be used to perform a trend monitoring analysis totally based on flight data, instead of using generic engineering models by the manufacturer, which are not known for the case-study engine.

7.2.1 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. From these records, it was possible to see that some of the reasons for engine removals include insufficient EGT Margin, "Service Convenience" and also damages in the LP and HP turbines. The engine installations occurred after shop visits with Performance Restoration. In these visits, the core section and/or other modules of the engine are disassembled and parts are inspected, balanced and repaired or replaced as necessary. The objective is, as the name indicates, to restore lost performance and return the engine to on-wing operation.

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

Table 7.2 Engine Installations after Shop Visits with Performance Restoration

The two aircraft listed in table 7.2 have been selected for deriving engine baseline models for the fleet. This selection was mainly based on the EGT Margin of the installed engines. The indicated EGT Margin is a test cell margin and there are differences to on-wing EGT Margins. Due to TAP confidentiality policies, the A/C tails correspond to fictitious registrations, which do not exist at the date this work was done.

7.2.2 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. Bleed air corresponds to high pressure air supplied by the Pneumatic System of the aircraft that is used for several air conditioning, wing anti-icing and other functions. The air is normally bled from the intermediate pressure stages of the HP compressor, in order to minimize the fuel penalty. To acquire the stability points in Cruise it is necessary that the wing and nacelle anti-ice valves are closed, in accordance with the Basic Conditions exposed before.

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 parameters recorded. These codes are computed from the Engine Cruise Report using the Engine Control Word 1 (ECW1) and then input to the P&W EHM software [50]. However, the ECW1 is not recorded in the A330-223 aircraft. As an alternative, the ABC and PKS codes can be computed from the recorded data using the ENGINE BLEED P/b switch and the PACK FLOW Selection switch discretes. An additional procedure was implemented in AGS that computes the ABC and PKS codes. The codes are included in the file with the information on the stability points that is output. Table 7.3 illustrates the logic used.

Cockpit Switch	Parameter AGS	Status	Codes
ENGINE BLEED Pushbutton Switch	ABLD_PB_POS (Engine 1)	OFF (=0)	ABC1=0
		ON (=1)	ABC1=1
	O_ABLD_PB_POS (Engine 2)	OFF (=0)	ABC2=0
		ON (=1)	ABC2=1
PACK FLOW Selection Switch	BLD_MIN_PACK (Aircraft)	ON (=1)	PKS=1
	BLD_NOM_PACK (Aircraft)	ON (=1)	PKS=2
	BLD_MAX_PACK (Aircraft)	ON (=1)	PKS=3

Table 7.3 Logic for ABC and PKS codes

7.2.3 Results

The baseline model for the PW4168A engine derived from the data of CS-PWA aircraft will be presented next. The points used in the definition of each baseline model represented here 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.

7.2.3.1 Baseline Model with EPR

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

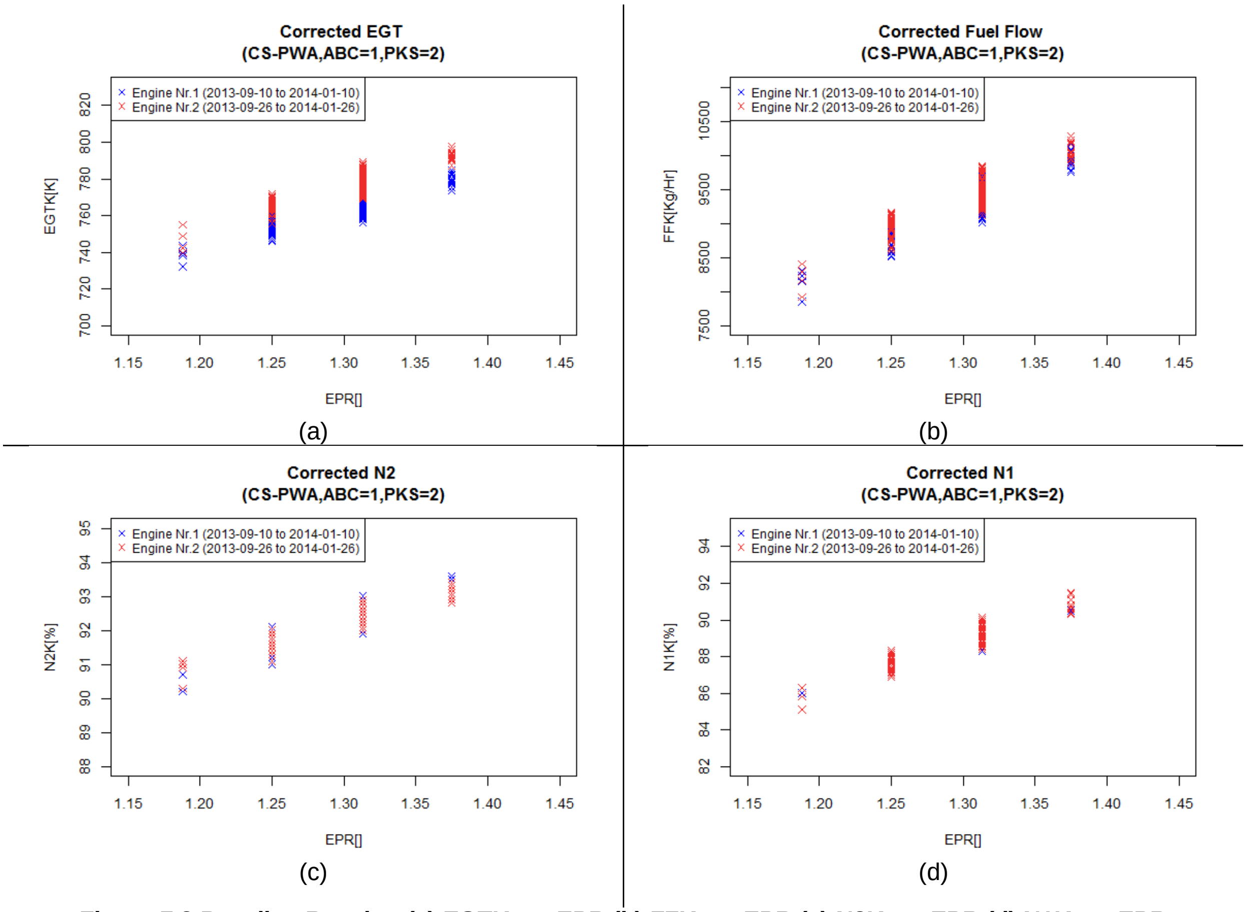
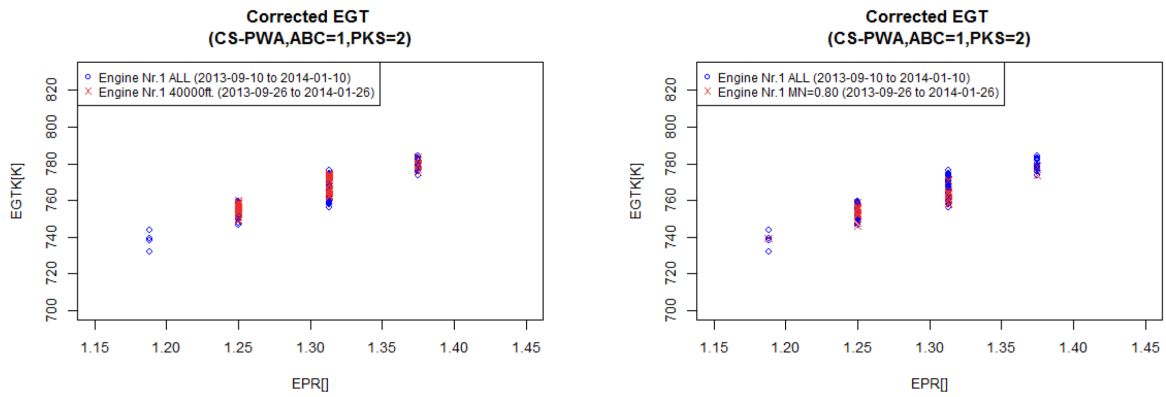


Figure 7.3 Baseline Results: (a) EGTK vs. EPR (b) FFK vs. EPR (c) N2K vs. EPR (d) N1K vs. EPR

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. This results in a great amount of points for each recorded EPR value. Figure 7.4a highlights the EGTK vs. EPR results for Engine 1 at an altitude of 40000ft and figure 7.4b at a Mach number of 0.80. In both plots the number of points is reduced but the scatter in the data is still high, meaning that the points were probably acquired when the actual EPR was different from the recorded value.



(a) (b)

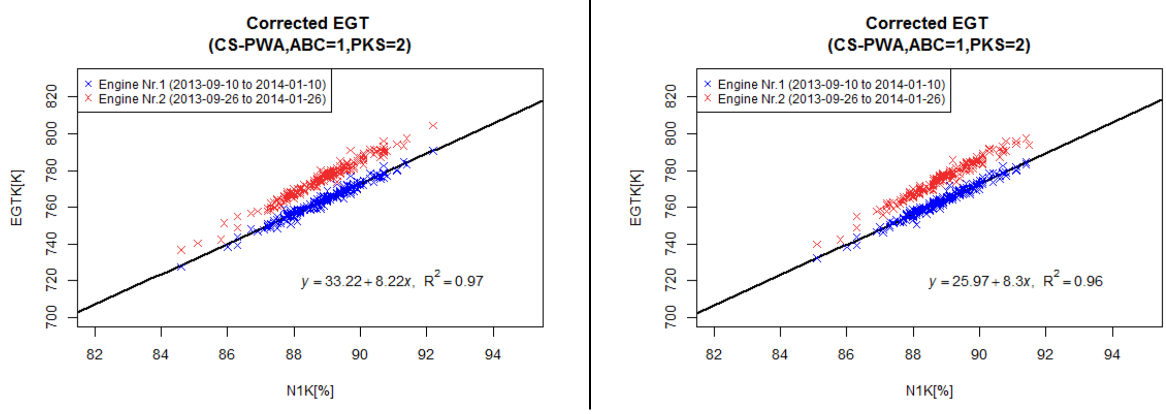
Figure 7.4 Baseline Results for EGTK vs. EPR at (a) 37000ft and (b) MN=0.80

The results obtained with the EPR as the thrust reference parameter are limited to the recording accuracy of this parameter, as demonstrated in the previous figures. The excessive scatter in the data doesn't allow the derivation of an accurate baseline model, even when the points are confined to a certain altitude or Mach number. As a consequence, it was necessary to adapt the baseline models to a new thrust reference parameter.

7.2.3.2 Baseline Model with N1

The N1 was selected as the thrust reference parameter instead. The disadvantage is that the evolution of the delta N1 parameter is used to monitor the performance deterioration of the PW4168A engine in the P&W EHM software. With this definition only three performance parameters will be trended and monitored using the stability points: the EGT, FF and N2. The results in figure 7.5 represent the expected performance characteristics of the PW4168A engine for these three performance parameters after being corrected and as a function of the N1K. The plots on the left (figure 7.5a) contain data that was acquired using the Aircraft Stability Criteria and the plots on the right (figure 7.5b) contain the data acquired with the Converged Stability Criteria (see table 6.8). The data was collected from the CS-PWA aircraft in the same bleed conditions and over the same periods of time as those presented in figure 7.3.

Aircraft Stability Criteria (202 Stability Points)	**Converged Stability Criteria (187 Stability Points)**



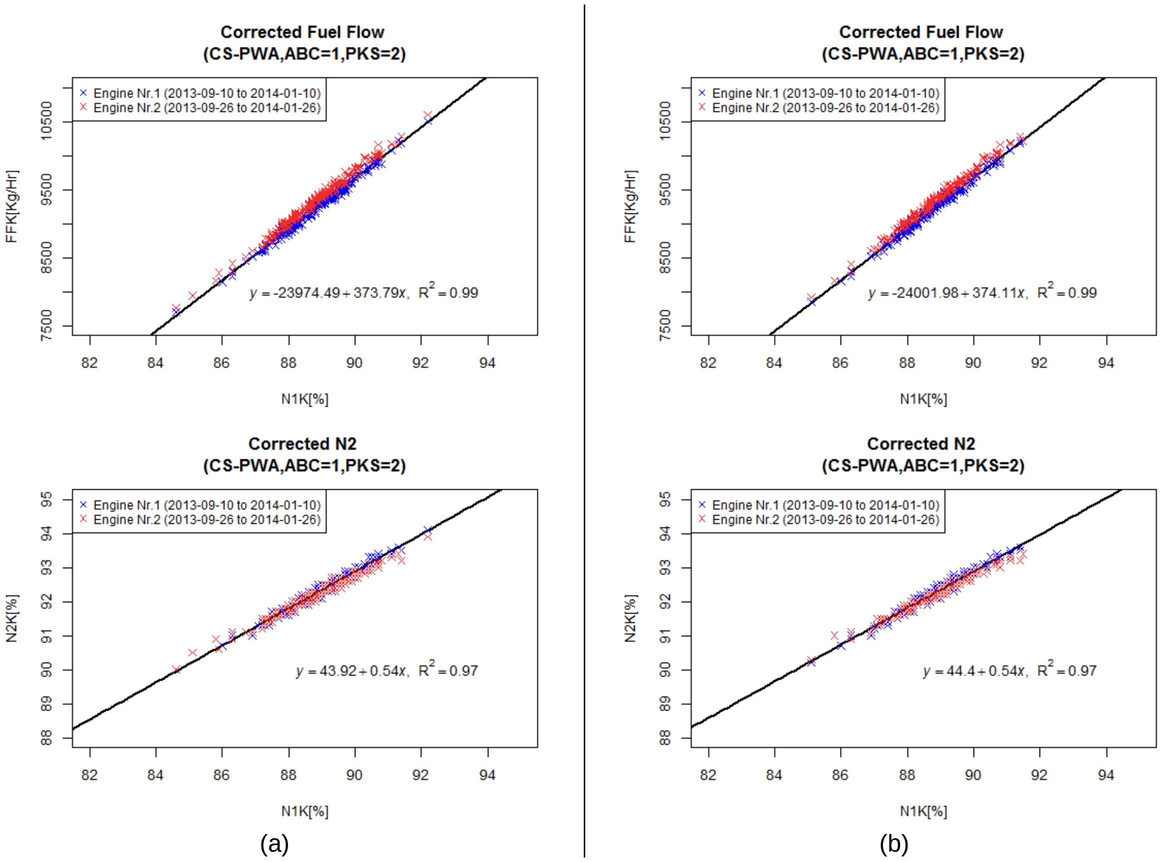


Figure 7.5 CS-PWA Baseline Model Results: (a) Aircraft Stability Criteria (b) Converged Stability Criteria.

The characteristics are much clearer in comparison with those in figure 7.3. The corrected EGT and FF values in the left and right plots are higher for Engine 2 than for Engine 1. The latter was installed in the aircraft with 42ºC of EGT Margin and the first with 30ºC, which allows to conclude that the margin is in fact a good indicator of the relative performance of the engines. The N2 values from both engines are very close.

Simple linear regression models were fitted to the data from Engine 1 using the least squares approach. The equations for these models are displayed in the plots from figure 7.5, together with the fitted model and the r-squared values. The displayed values show that the models obtained with both criteria fit well the corrected engine data. As expected, the number of points represented in figure 7.5b is lower due to the more restrictive criteria. Aside from the difference in the number of points considered, the results obtained with the two criteria are very similar. Nevertheless, the results presented in the remainder of this Chapter will use the points acquired with the Converged Stability Criteria, mainly because they eliminate the possibility of acquiring data relative to periods of time when there was excessive variation in the engine parameters. From the results above, it was also concluded that it was not essential to consider different model equations for different altitudes to take into account the changes in the Reynolds' number.

Figure 7.6 shows the distribution of the stability points by Air Conditioning Pack Code (PKS), during the period of time from which the baseline model in figure 7.5b was derived. From the 214 points, 187 were acquired with a normal pack flow selection (PKS=2), which corresponds to around 120 flights.

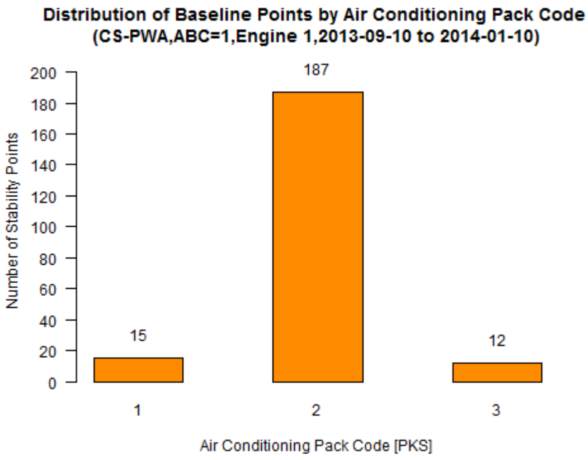


Figure 7.6 Distribution of Baseline Points by PKS Code

Figures 7.7a and 7.7b show the distribution of the stability points from the baseline model by Mach Number and by altitude and search period, respectively. The Mach numbers range from 0.78 to 0.83 and the most frequent are the 0.80 and the 0.81. The altitudes range from 35000ft to 41000ft and most of the points from the 2nd and 3rd search periods are acquired at higher altitudes.

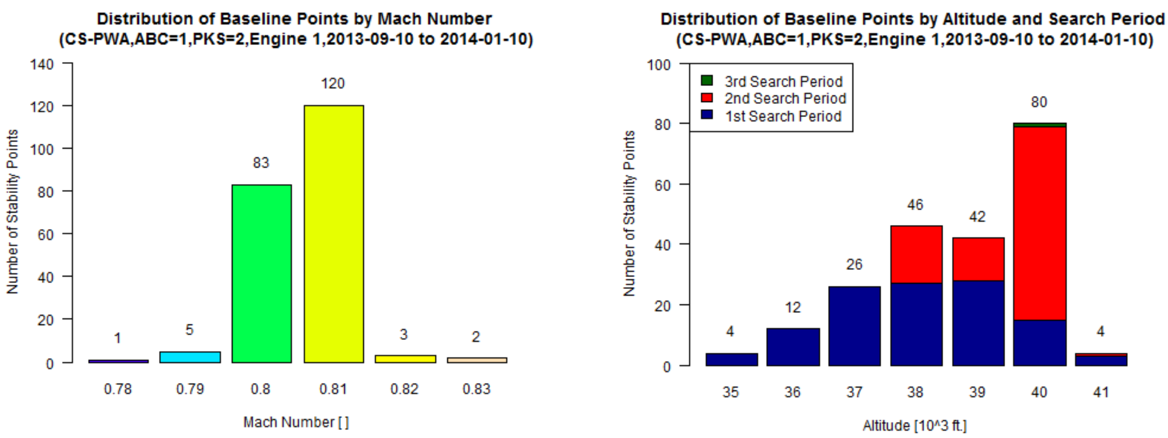


Figure 7.7 Distribution of Baseline Points by (a) Mach Number and (b) Altitude and Search Period

7.3 Trend Monitoring

In this section, we describe the necessary procedures in order to calculate and plot the cruise performance trends and then present the corresponding results from the two aircraft studied: CS-PWA and CS-PWB. The trends shown correspond to the evolution in time of the delta parameters calculated from the difference between the corrected measured data and the baseline models like the one described in the previous section. The results will be used to test the methodology that was developed in the previous section and to search for indications of deterioration that could be indicative of engine failures.

7.3.1 Calculation and Plotting of the Cruise Trends

Figure 7.8 illustrates how the delta parameters are calculated. The measured point contains the corrected 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 for the same bleed and pack flow conditions in which the point was acquired. The difference between the parameter value from the measured and the baseline points yields the delta parameter. The delta is positive when the point is above the baseline curve and negative when it is under.

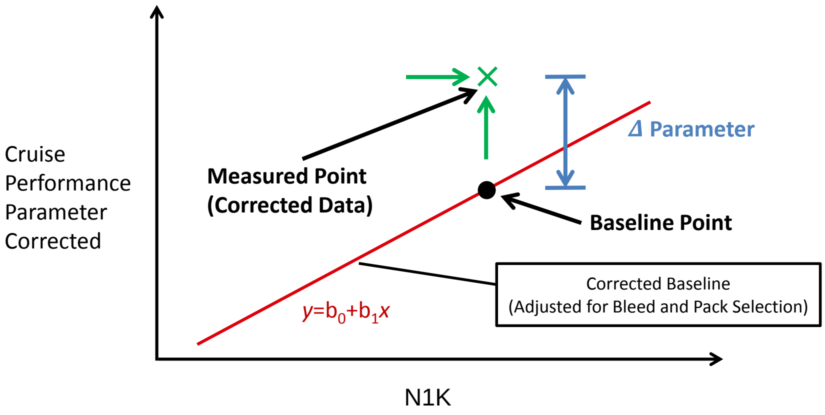


Figure 7.8 Delta Parameter Calculation

Depending on the parameter monitored, the delta parameter can be expressed as an absolute or a relative difference. The equations used in the results of this section are written below.

- Delta EGT:

$$DEGTK_{Raw} = EGTK_{Measured} - EGTK_{Baseline} \ \ [ºC] \tag{7.1}$$

- Delta FF:

$$DFFK_{Raw} = \frac{FFK_{Measured} - FFK_{Baseline}}{FFK_{Baseline}} \times 100 \ \ [\%] \tag{7.2}$$

- Delta N2:

$$DN2K_{Raw} = \frac{N2K_{Measured} - N2K_{Baseline}}{N2K_{Baseline}} \times 100 \ \ [\%] \tag{7.3}$$

The delta EGT is expressed in degrees Celsius and the delta FF and N2 as percentages.

Smoothed delta parameters are calculated from the raw delta parameters above using equation 5.2 with a smoothing coefficient of 0.2:

$$Smoothed_{\ NEW} = Smoothed_{\ OLD} + 0.2 \times (Raw_{NEW} \_ Smoothed_{\ OLD}) \tag{7.4}$$

The smoothed deltas help to provide more distinct trends of the gradual deterioration an engine is experiencing.

The calculation of the cruise performance trends is one of the main tasks included the process represented in figure 7.9, which is executed by a dedicated program written in R. The program receives the stability points from AGS as input for the analysis – an example of the information contained in these points is displayed. Firstly, the EGT, FF (WF), N1 and N2 values from each of these points are corrected with the equations in section 6.3. Then, the Engine Baseline Model is derived from the corrected engine data of the stability points for the specified time interval (three months after engine installation, as mentioned previously) and engine. The raw and smoothed cruise trends are calculated next with equations 7.1 to 7.4 and output in the form of plots. The results are also output in table format to .csv files for a more detailed analysis.

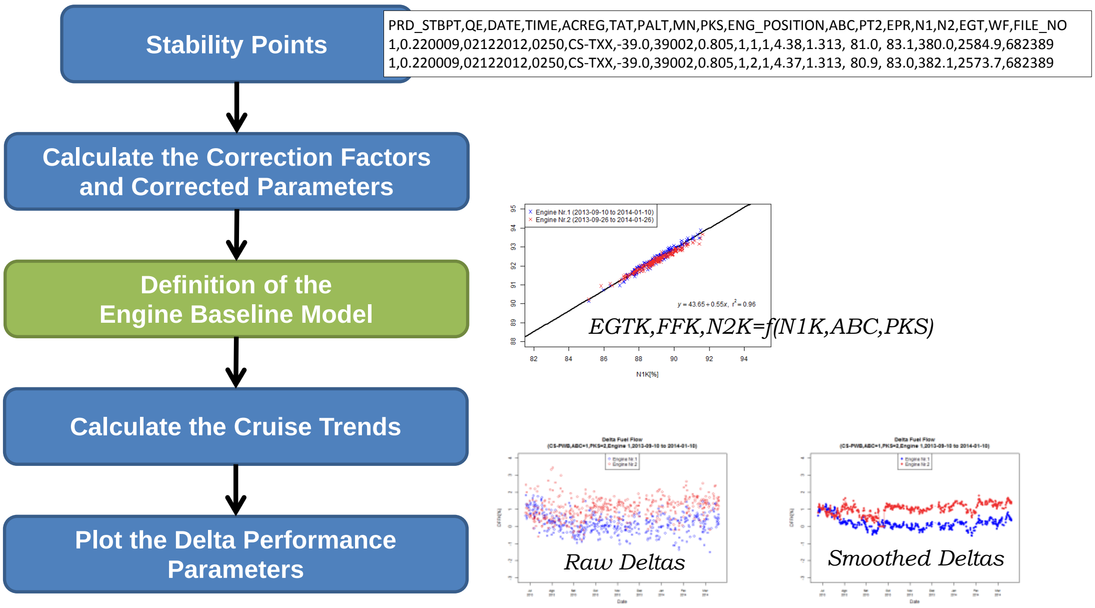


Figure 7.9 Process of Plotting the Cruise Performance Trends

7.3.2 Results

7.3.2.1 CS-PWA

Figure 7.10 is a timeline with the engines' removals and installations on the CS-PWA aircraft that are relevant for the analysis. It indicates that both engines were substituted during September 2013.

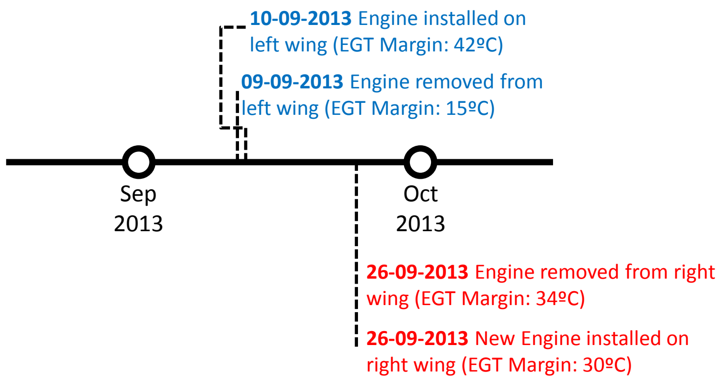
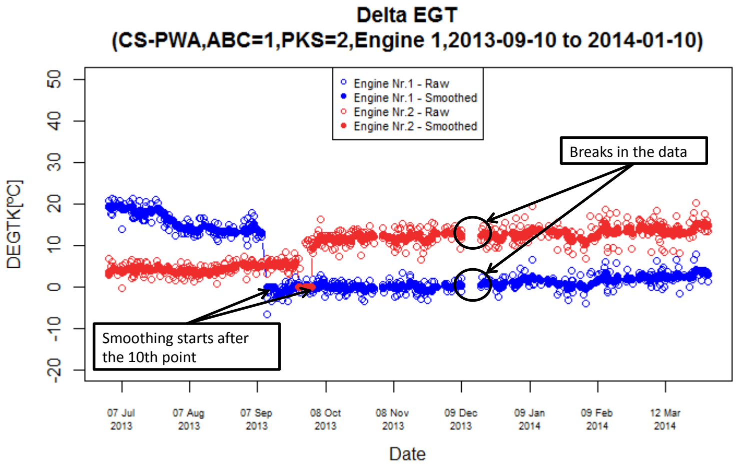


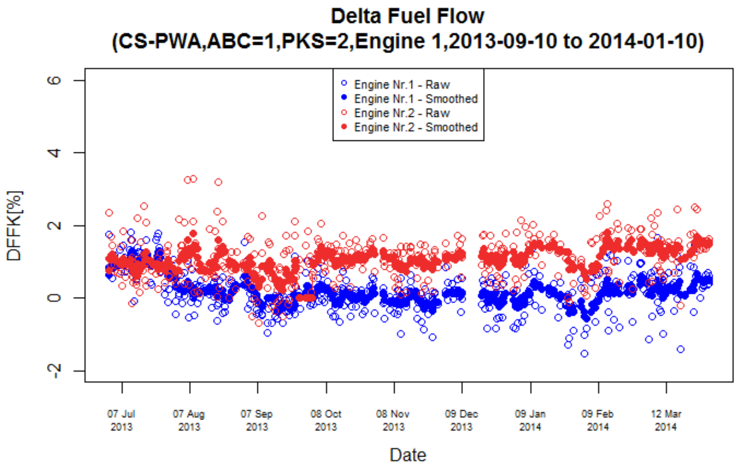
Figure 7.10 CS-PWA: Timeline for Engine Removals/Installations

Both the raw and smoothed delta parameters are represented in each one of the plots in figure 7.11, for the period from July 2013 to March 2014. The baseline model used for the comparison of the data is specified in the title of these plots. In this case, it is the same model from engine nr.1 whose results were presented in figure 7.5b.

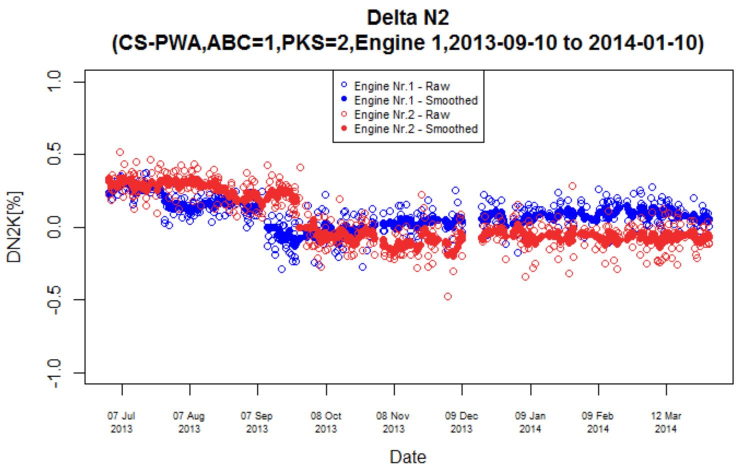
Figure 7.11a contains the plot for the delta EGT. The engine substitutions are clearly illustrated by the step shifts in the deltas during September 2013. The smoothing always starts with the 10th stability point acquired after a new engine installation. The aircraft was out of service during December, which resulted in some breaks in the data from both engines. Because the baseline model was derived from engine nr.1 in the period from 2013-09-10 to 2014-01-10, the delta EGT values in this period stay close to zero, as expected. The engines with higher EGT Margins show better performance levels, i.e., lower deltas. This is true for the four engines represented. It is interesting to notice the increase in the delta EGT after engine nr.2 was substituted. In this case, the engine was replaced for “Service Convenience” and not because there were problems with its operation.



(a)



(b)



(c)

Figure 7.11 Cruise Performance Trends for the CS-PWA aircraft: (a) Delta EGT; (b) Delta FF; (c) Delta N2.

Figure 7.11b contains the results for the delta FF. There is more scatter in the data than that from the delta EGT plot. The engine substitutions are not as evident as in figure 7.11a and there is a small reduction in the delta values after engine nr.1 was replaced. In figures 7.11a and 7.11b it is possible to observe some gradual deterioration in the performance of the engine with the smoothed delta EGT and smoothed delta FF parameters.

Finally, figure 7.11c contains the results for the delta N2. The values are almost all within the range of -0.5% to 0.5%. However, the engine substitutions are much visible here than in figure 7.11b. After the engine installations indicated in figure 7.10, the delta N2 values from engine nr.1 were higher than those from engine nr.2. This is in contrast with what occurred with the delta EGT and delta FF parameters.

7.3.2.2 CS-PWB

The timeline for the engines' removals and installations on the CS-PWB aircraft is represented in figure 7.12 and indicates that engine nr.1 was substituted once and engine nr.2 twice during the period between February and June 2013.

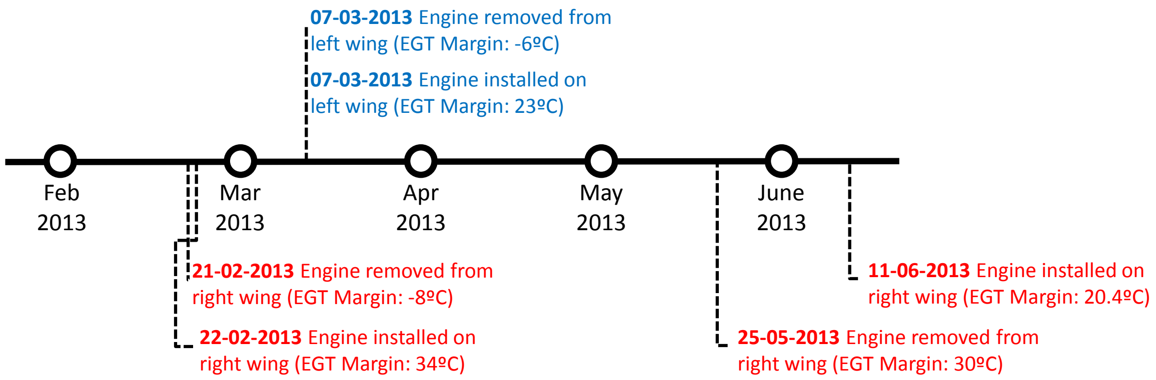


Figure 7.12 CS-PWB: Timeline for Engine Removals/Installations

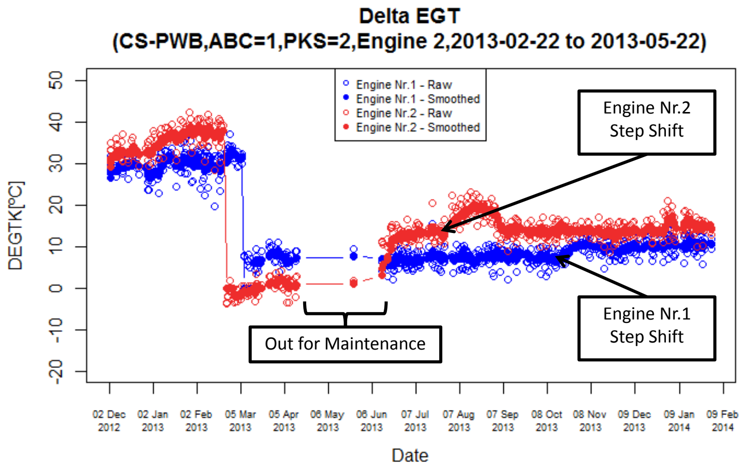
The plots in figure 7.13 contain the raw and smoothed delta parameters from December 2012 to February 2014. The flights from engine nr.2 after the installation in February 2013 were used for the baseline model, which is represented in Appendix I.

Figure 7.13a contains the results for the delta EGT. The initial deltas are very high for both engines. When engine nr.1 was replaced in February 2013 and engine nr.2 in March 2013, they presented negative EGT Margins. A few months after new engines were installed the aircraft was out of service for maintenance for about two months. During this period, engine nr.2 was replaced again by an engine with a lower EGT Margin than the previous, which led to higher delta values.

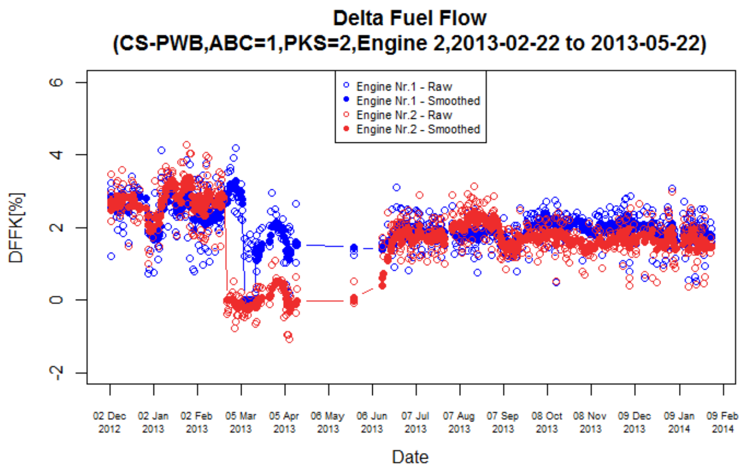
There are two step shifts, which occur outside the dates for the engine removals/installations indicated in figure 7.12. Both shifts are characterized by an increase in the delta EGT and delta FF and a decrease in the delta N2K. The first occurs in the beginning of August for engine nr.2 and the second in mid-October for engine nr.1. The two situations were detected with the P&W EHM software and were related with faults in the Turbine Case Cooling (TCC) System. The TCC System controls and distributes fan air to externally cool the high and low pressure turbines cases to [46]: increase case life and reduce turbine blade tip clearance[1] during take-off, climb and cruise operation for better fuel

[1] The tip clearance is the distance between the blade-tip and the engine casing.

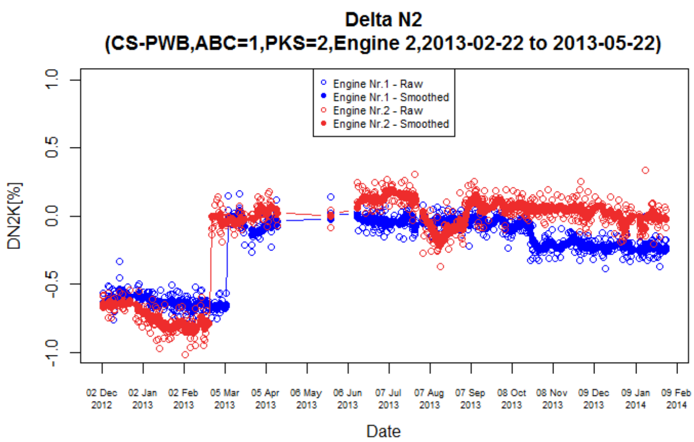
efficiency. The system is basically made up of three components: actuator, cables and valves. The diagnosis of the two faults and the corresponding maintenance actions that were conducted in order to restore the performance of the engine are described next. The data obtained with the P&W EHM is also presented for comparison with the results in figure 7.13.



(a)



(b)



(c)

Figure 7.13 Cruise Performance Trends for the CS-PWB aircraft: (a) Delta EGT; (b) Delta FF; (c) Delta N2.

Engine #1 Shift

In addition to being detected with the P&W EHM software, the ECAM system of the aircraft also detected a fault in the TCC system that was reported by the flight crew, which indicated a failure in the HPTCC (High Pressure Turbine Case Cooling) actuator. The actuator is the only component of the TCC system that provides feedback to the EEC (Engine Electronic Control). Thus, the failures in the valves and cables can only be effectively monitored with the P&W EHM software.

The failure in the actuator was not confirmed by maintenance personnel. Even so, the replacement of the actuator was scheduled and an inspection of the complete TCC system was ordered by the Powerplant Engineering department. During this inspection, only a faulty HPTCC cable was found and, as a result, it was decided to replace this cable instead of the actuator. The Long Term Plot Report for this engine is displayed in figure 7.14. The evolution of the EGT, FF (WF), N1 and N2 smoothed deltas and EGT Margin is displayed together with an indication of the date in which the cable was replaced. Notice that the FF data is more scattered than the remaining engine data. The same thing happened in the results from figures 7.11b and 7.13b.

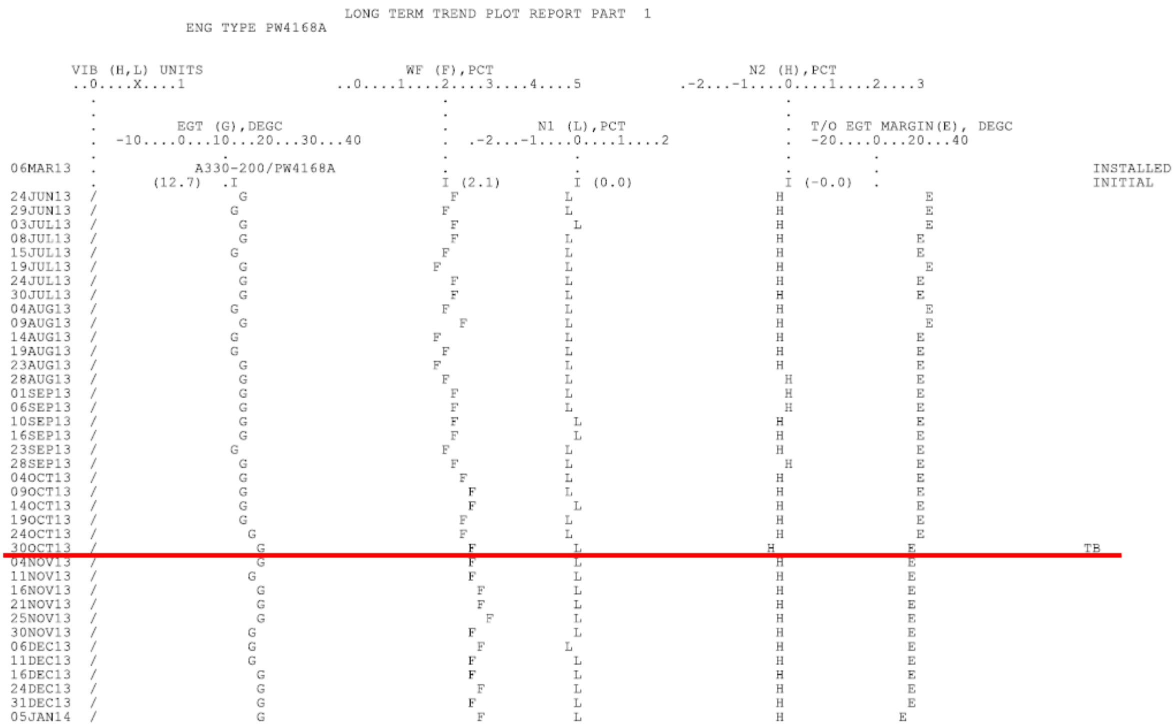


Figure 7.14 P&W EHM: CS-PWB Engine #1 Long Term Trend Plot Report

The shift is characterized by an increase in the delta EGT and delta FF, similarly to what is displayed in figures 7.13a and 7.13b, respectively. There is a small increase in the delta N1 but the delta N2 is practically unaffected. In figure 7.13b there is a decrease in the delta N2 levels. In this case, the ECM analysis and the corresponding maintenance actions (inspections, repair, etc.) didn't allow the engine to fully restore the lost performance. The biggest improvement occurs in the EGT Margin, which dropped by approximately 5ºC.

Engine #2 Shift

This shift also occurred due to a fault in the TCC system, as mentioned previously. In this case, the variation of the delta parameters indicated a clear and distinct loss in the performance of the engine, as illustrated by the Long Term Plot Report for engine #2 in figure 7.15. 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. This situation is clearly illustrated in the figure below.

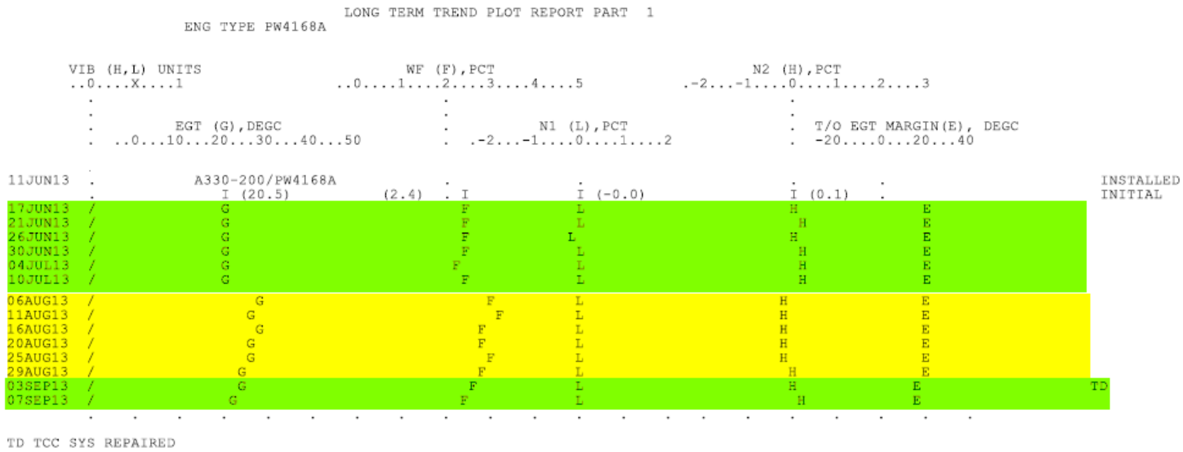


Figure 7.15 P&W EHM: CS-PWB Engine #2 Long Term Trend Plot Report

The shift in figure 7.15 is characterized by an increase in the delta EGT and delta FF, and a decrease in the delta N2. The same pattern can be observed in the results from figure 7.13. The most remarkable aspect is that the shifts in figures 7.13 and 7.15 are practically identical: +10ºC in the delta EGT, +0.5% in the delta FF and approximately -0.25% in the delta N2. 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 baseline performance of the engine used by the manufacturer software.

8. Conclusions

For an airline, tracking engine operations is of the utmost importance, both from a safety and an economic point of view. The current dissertation is part of this everyday effort from people within TAP Portugal. It makes the best use of the engine data available from on-board recorders of a fleet of aircraft equipped with PW engines to produce tools for ECM performance trend monitoring.

8.1 Achievements

The first part of this dissertation dealt with the implementation of an FDM database for the decoding and analysis of flight data that is recorded on-board an Airbus A310. The aircraft and its recording systems were presented in Chapter 2, as well as the data transmission and recording protocols used in the aircraft. The programming of the database in AGS was the subject of Chapter 3 and required the knowledge of the previous protocols. In Chapter 4, the decoding results for a selection of parameters were displayed and allowed to confirm the extreme quality of the recorded flight data. The limitations in the recordings of the QAR became evident when the Flight Phase computation procedure was described, since it was necessary to compute additional parameters and to adapt some of the transitions according to the parameters available. All these topics were covered and the results that were displayed show the correct implementation of these procedures in the database, which can be expanded to include FOQA and MOQA procedures.

The second part of the dissertation (Chapter 5, 6 and 7) focused on the main objective of the work which was the development of tools for performance trend monitoring, within the scope of Engine Condition Monitoring. In Chapter 5, the role of ECM in the maintenance of aircraft engines was presented and the importance of trend monitoring in the diagnosis and prognosis of engine faults, as well as in the support of engine management decisions, was discussed. The necessary ECM concepts and definitions to understand the upcoming results were also introduced in this Chapter.

In Chapter 6, the PW4168A engine was briefly presented. The algorithm that processes the recorded flights and acquires the stability points was described and the results that were shown enabled to understand this process. Afterwards, the rationale of the engine parameter corrections was exposed and the corresponding equations applied to the case study engine were presented. The two algorithms/procedures were then used to generate the results in Chapter 7.

The initial engine baseline model results in Chapter 7 underlined the necessity to improve the DAR parameter recordings of the EPR, which in turn required the N1 to be used as the thrust reference parameter. Afterwards, the results showed clear characteristics for the performance of the engine and simple linear regressions were fitted to the data. The models obtained with two different stability criteria were similar and it was not necessary to take additional variables - like altitude or speed – into account. The trend monitoring results allowed evaluating the methodology of the work developed. In the results from the first of two aircraft, it was possible to observe some gradual deterioration in both engines, occurring over a period of several months. In addition, the deterioration levels of the engines with higher EGT Margins were lower and showed that this parameter is a good indicator of the overall efficiency of the engine. In the second aircraft, both engines evidenced a shift in the delta parameters occurring at different times. The engines' maintenance records and the results obtained with the P&W EHM software were then collected and the relevant information presented. They allowed confirming that the observed shifts were, in fact, indicative of engine faults. In both situations, the shift patterns in the plots from the P&W EHM and those obtained from the flight data were similar. For the engine #2 fault, the variations in the EGT, FF and N2 deltas were practically identical.

8.2 Future Work

The methodology that was followed in this work relied exclusively on recorded flight data to create engine baseline models and generate the performance trends by comparing engine data with these models. The results that were presented have confirmed the potential of this approach, which can be used as a complement to the engine's manufacturer ECM software. Powerplant engineers can use the tools that were developed for an improved insight of the engine's operation.

One direct evolution from this work is to apply the same methodology to the CFM56 and CF6 engines that equip the remaining of TAP fleet. The tools that were developed with the R programming language may be adapted for this purpose. However, this requires a previous study of the aircraft and its aircraft systems, namely the stability criteria used and the recorded parameters that are required. During the course of this work it was identified the need to improve some of the on-board recorded data. Once this is done, better data will be available that can be used to improve the whole process.

This work is part of a continuous improvement cycle, always aiming at the maximum safety. Future actions may also include the use of statistical methods and data-mining techniques to improve the detection of trends out of the data, based on manufacturer data or requirements from the airline's engineering departments.

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Appendix A. ARINC 429 Data Sources

System	Equip. ID	Data Source (Port [22])	Description
Automatic Flight System	01	FCC-1 (#11), 2 (#12)	Flight Control Computer
	03	TCC-1 (#4), 2 (#4)	Thrust Control Computer
	A1	FCU (#25)	Fuel Control Unit
Independent Instruments System	31	GMT-CLK (#7)	GMT Clock
	29	SDAC (#14)	System Data Analog Converter
	26	FWC-1 (#13)	Flight Warning Computer
	23	GPWS (#23)	Ground Proximity Warning System
Navigation System	10	ILS-1 (#8), 2 (#35)	Instrument Landing System Receiver
	07	RALT-1 (#9)	Radio Altimeter
	11	VOR-1 (#10), 2 (#24)	VHF Omnidirectional Range Receiver
	02	FMC-1 (#16), 2 (#36)	Flight Management Computer
	25	FNSG-1 (#15), 2 (#33), 3 (#15 or #33)	Flight Navigation Symbol Generator
	09	DME-1 (#29), 2 (#30)	Distance Measuring Equipment
	35	TCAS (#26)	Traffic Alert and Collision Avoidance System
	C5	FNCP-1 (#31), 2 (#34)	Flight Navigation Control Panel
	06	ADC-1 (#17)	Air Data Computer
	04	IRS-1 (#20), 3 (#20)	Inertial Reference System
Engine Fuel and Control Systems	1A	EEC-1 (#1)	Electronic Engine Control
	05	FQI (#3)	Fuel Quantity Indicator
	3E	CGCC (#5)	Center of Gravity Control Computer

Table A.1 ARINC 429 Data Sources in database version 10079

Appendix B. List of Recorded Parameters

Analog Input Parameters

Name	Description
BRAKE_LPA	Brake Pedal Deflection LH
BRAKE_RPA	Brake Pedal Deflection RH
VRTG	Normal (Vertical) Acceleration
LONG	Longitudinal Acceleration
LATG	Lateral Acceleration

Name	Description
SLAT	Slat position (calibrated)
FLAP	Flap Position (calibrated)
SPD_BRK_HDL	Speed Brake Handle
FF2	Fuel Flow Engine #2
FF1	Fuel Flow Engine #1

Table B.1 List of Analog input parameters

Discrete Input Parameters

Name	Description
HF	HF keying
VHF	VHF keying
REV_INPOS1	Reverser In Position Engine #1
REV_UNLOCK_1	Reverser Unlock Engine #1
REV_INPOS2	Reverser In Position Engine #2
REV_UNLOCK_2	Reverser Unlock Engine #2
HYD_L_PRES_Y	Hydr System YELLOW Low Press
HYD_L_PRES_G	Hydr System GREEN Low Press
HYD_L_PRES_B	Hydr System BLUE Low Press
ECAMCP_4	ECAM CP Code 4
ECAMCP_3	ECAM CP Code 3
ECAMCP_2	ECAM CP Code 2
ECAMCP_1	ECAM CP Code 1
TA_ALERT	Traffic Alert
SPOIL_GND_ARM	Ground Spoiler Not Armed
AC1_BUS_OFF	AC Bus 1 OFF
LDG_SEL_NUP	Landing Gear Selector Not Up
LDG_SEL_NDW	Landing Gear Selector Not Down
AC_TYP	A/C type*

Name	Description
AC_IDT	A/C number**
FLIDENT	Fleet identification***
ECAMDU_SYS_OFF	ECAM DU System Off
ECAMDU_SYS_FLT	ECAM DU System Fault
ECAMDU_WRN_OFF	ECAM DU Warning Off
ECAMDU_WRN_FLT	ECAM DU Warning Fault
AIW_ALTR1	Wing Anti-Ice Valve LH Alternate UNCL
AIW_NORM1	Wing Anti-Ice Valve LH Normal UNCL
AIW_NORM2	Wing Anti-Ice Valve RH Normal UNCL
AIW_ALTR2	Wing Anti-Ice Valve RH Alternate UNCL
EVENT	Event (Depressed)
AIE2	Inlet Anti-Ice Valve Engine #2 OPEN
AIE1	Inlet Anti-Ice Valve Engine #1 OPEN
START_VLV_2	Start Valve Pos. Engine #2
START_VLV_1	Start Valve Pos. Engine #1
LDG_ON_1	Landing Gear Squat Switch LH
LDG_ON	Landing Gear Squat Switch NOSE
LDG_ON_2	Landing Gear Squat Switch RH

*Discretes 82 to 87; **Discretes 92 to 99; Discretes 88 to 91

Table B.2 List of Discrete input parameters

Digital Data Inputs (DITS) ARINC 429

- **Automatic Flight System:**

Flight Control Computer (FCC)

Name	Description
FD_1	FD #1 Engaged
AP1_CWS	A/P CWS #1
AP_EGD1	A/P CMD #1
AFCS_LONG_MOD	AFCS Longitudinal Modes (Matrix #1)
AFCS_LAT_MOD	AFCS Lateral Modes (Matrix #2)
PITCH_GA	Pitch Go Around (GA) Mode

Name	Description
YAW_TO	Yaw Takeoff Mode
LNDTRA1	Landing Track
FD_2	FD #2 Engaged
AP2_CWS	A/P CWS #2
AP_EGD2	A/P CMD #2

Table B.3 List of Digital input parameters: Flight Control Computer (FCC)

Thrust Control Computer (TCC)

Name	Description	Name	Description
ATS_EGD	Autothrottle Mode Engaged	ATS_MACH	Mach Mode Engaged
MTHR	Manual Throttle Armed	ATS_EPR	Autothrottle Thrust EPR Mode
ATS_ALVR	ATS Arming Lever Off	ATS_ALPHA_FLR	Alpha Floor Mode Engaged
VNAV_MODE	VNAV Mode – Profile Engaged	ATS_RETARD	Retard Mode Engaged
ATS_CL	ATS Clutches Off (Takeoff)	ATS_SPD	Speed Mode Engaged

Table B.4 List of Digital input parameters: Thrust Control Computer (TCC)

Flight Control Unit (FCU)

Name	Description
ALT_SEL	Selected Altitude (Manual)
SPD_SEL	Selected Airspeed (Manual)
SPEEDV_SEL	Selected Vertical Speed
HEAD_SEL	Selected Heading
MACH_SEL	Selected Mach

Table B.5 List of Digital input parameters: Flight Control Unit (FCU)

- **Independent Instruments System:**

GMT Clock

Name	Description
UTC_HOUR	GMT/UTC (Hour)
DAT_DAY	Date (Day)
DAT_MONTH	Date (Month)
UTC_MIN_SEC	GMT/UTC (Minutes, Seconds)

Table B.6 List of Digital input parameters: GMT Clock

System Data Analog Converter (SDAC)

Name	Description	Name	Description
ELEV	Elevator Position	SPOIL_L3_R	Spoiler 3 LH Ret
SPOIL_R2_R	Spoiler 2 RH Ret	SPOIL_L2_R	Spoiler 2 LH Ret
SPOIL_R1_R	Spoiler 1 RH Ret	SPOIL_L1_R	Spoiler 1 LH Ret
SPOIL_L7_R	Spoiler 7 LH Ret	RUDD	Rudder Position
SPOIL_L6_R	Spoiler 6 LH Ret	AIL_2	All Speed Aileron RH Position
SPOIL_L5_R	Spoiler 5 LH Ret	XFEED	X Feed Valve Closed
SPOIL_L4_R	Spoiler 4 LH Ret	AC2_BUS_OFF	AC Bus 2 OFF
SPOIL_R5_R	Spoiler 5 RH Ret	PCKM_MODSEL2	Pack Manual Mode Select #2
SPOIL_R4_R	Spoiler 4 RH Ret	PCKM_MODSEL1	Pack Manual Mode Select #1
SPOIL_R3_R	Spoiler 3 RH Ret	OIQ_1	Oil Quantity Engine #1
SPOIL_R7_R	Spoiler 7 RH Ret	OIP_1	Oil Pressure Engine #1
SPOIL_R6_R	Spoiler 6 RH Ret	OIT_1	Oil Temperature Engine #1
AIL_1	All Speed Aileron LH Position	OIQ_2	Oil Quantity Engine #2
EG2FV	Fire Valve Eng 2 Not Fully Closed	OIP_2	Oil Pressure Engine #2
EG1FV	Fire Valve Eng 1 Not Fully Closed	OIT_2	Oil Temperature Engine #2
BLD_VLV2	Bleed Valve Open Eng 2	VIB_N1FNT1	N1 Vibration Engine #1 (EVM)
BLD_VLV1	Bleed Valve Open Eng 1	VIB_N2FNT1	N2 Vibration Engine #1 (EVM)
APUBV	APU Bleed Valve Not Fully Open	VIB_N1FNT2	N1 Vibration Engine #2 (EVM)
STAB	Stabilizer Position	VIB_N1FNT2	N2 Vibration Engine #2 (EVM)

Table B.7 List of Digital input parameters: System Data Analog Converter (SDAC)

Flight Warning Computer (FWC)

Name	Description
LND_ASAP	Land ASAP
AFT_CG_WARN	Aft CG Warning
FLVR2_C	Fuel Lever Engine #2 Closed
FLVR1_C	Fuel Lever Engine #1 Closed
FIRE_APU	APU Fire
DC_BUS_OFF	DC Normal Bus OFF
SP5_FAULT	Spoiler 5 Fault/Off
SP32_FAULT	Spoiler 3+2 Fault/Off
SP14_FAULT	Spoiler 1+4 Fault/Off
SP7_FAULT	Spoiler 7 Fault/Off
SP6_FAULT	Spoiler 6 Fault/Off
FIRE2	Engine #2 Fire
FIRE1	Engine #1 Fire
VMO_MMO_OVS	VMO/MMO Overspeed

Name	Description
SMOKE	Smoke Warning
GEAR_N_DW_LOK	Gear Not Locked Down
STALW	Stall Warning
CBAW	Cabin Altitude (Warning)
FLAP_FAULT	Flaps 1+2 Fault
SLAT_FAULT	Slats 1+2 Fault
YAW_FAUL2	Yaw Damper 2 Fault
YAW_FAUL1	Yaw Damper 1 Fault
PT2F	Pitch Trim 2 Fault
PT1F	Pitch Trim 1 Fault
OVS	Overspeed (VFE, VLE, VMO, MMO)
CONFW	Configuration (Warning)
LOW_PRESS_2	Engine #2 Low Oil Pressure
LOW_PRESS_1	Engine #1 Low Oil Pressure

Table B.8 List of Digital input parameters: Flight Warning Computer (FWC)

Ground Proximity Warning System (GPWS)

Name	Description
GPWS	GPWS Modes Warning

Table B.9 List of Digital input parameters: Ground Proximity Warning System (GPWS)

- **Navigation System:**

Instrument Landing System Receiver (ILS)

Name	Description
ILS_FRQ1	ILS-1 Frequency
ILS_FRQ2	ILS-2 Frequency
LOC_DEV1	ILS-1 Localizer Deviation
LOC_DEV2	ILS-2 Localizer Deviation
GLID_DEV1	ILS1 glideslope deviation
GLID_DEV2	ILS2 glideslope deviation

Table B.10 List of Digital input parameters: Instrument Landing System Receiver (ILS)

Radio Altimeter

Name	Description
RALT1	Radio Height #1

Table B.11 List of Digital input parameters: Radio Altimeter

VHF Omnidirectional Range Receiver (VOR)

Name	Description
BEA_MK	Marker Beacon Passage (Outer OR Middle OR Inner)
VOR_FRQ1	VOR-1 Frequency
VOR_FRQ2	VOR-2 Frequency
SEL_CRS1	Selected Course #1
SEL_CRS2	Selected Course #2

Table B.12 List of Digital input parameters: VHF Omnidirectional Range Receiver (VOR)

Flight Management Computer (FMC)

Name	Description
SPD_TGT	Airspeed target
FLTNUM	Flight Number (LSH)
FLTNUM	Flight Number (MSH)
GW	Gross Weight (LSH)
GW	Gross Weight (MSH)
NDBUPD	FMC Database Update (Day-Month-Cycle)*
NDBUPD	FMC Database Update (Day-Month-Cycle)**

Name	Description
EPR_TARGET	EPR Target
BTW	Bearing to Waypoint
LATP	Pres. Pos Latitude (COARSE)
LATP	Pres. Pos Latitude (FINE)
LONP	Pres. Pos Longitude (COARSE)
LONP	Pres. Pos Longitude (FINE)
MACH_TGT	Mach Target

*Day; **Month

Table B.13 List of Digital input parameters: Flight Management Computer (FMC)

Flight Navigation Symbol Generator (FNSG)

Name	Description
AOAL	Angle of attack (ADC 1)
PFD_CPT_FAULT	Pilot PFD Fault
ND_CPT_FAULT	Pilot ND Fault
PFD_FO_FAULT	F/O PFD Fault
ND_FO_FAULT	F/O ND Fault
CP_CPT_FAULT	Pilot CP Fault
FNSG13_FAULT	FNSG 1 or 3 Fault
CP_FO_FAULT	F/O CP Fault
FNSG23_FAULT	FNSG 2 or 3 Fault
HEAD_MAG	Magnetic Heading
IAS	Computed airspeed
PITCH	Pitch angle

Name	Description
ROLL	Roll angle
RALT2	Radio Height #2
AOAR	Angle of attack (ADC 2)
GPWS_WSH_WAR	Windshear warning
TAT	Total Air Temperature
DH_SEL_CPT	Selected DH Pilot (COARSE)
DH_SEL_FO	Selected DH F/O (COARSE)
ALT_STD	Altitude Standard (1013 mb) (COARSE)
DH_SEL_CPT	Selected DH Pilot (FINE)
DH_SEL_FO	Selected DH F/O (FINE)
ALT_STD	Altitude Standard (1013 mb) (FINE)

Table B.14 List of Digital input parameters: Flight Navigation Symbol Generator (FNSG)

Distance Measuring Equipment (DME)

Name	Description
DME1_DIST	DME distance-left
DME2_DIST	DME distance-right

Table B.15 List of Digital input parameters: Distance Measuring Equipment (DME)

Traffic Alert and Collision Avoidance System (TCAS)

Name	Description
TCAS_SENS_3	TCAS Sensivity Level (bit 17)
TCAS_SENS_2	TCAS Sensivity Level (bit 16)
TCAS_SENS_1	TCAS Sensivity Level (bit 15)
TCAS_RA	Resolution Advisory

Table B.16 List of Digital input parameters: Traffic Alert and Collision Avoidance System (TCAS)

Flight Navigation Control Panel (FNCP)

Name	Description
ND_MOD1_CPT	EFIS Mode Displayed on ND Captain (ILS VOR NAV)
ND_MOD1_FO	EFIS Mode Displayed on ND F/O (ILS VOR NAV)
ND_MOD2_CPT	EFIS Mode Displayed on ND Captain (PLAN ROSE ARC MAP)
ND_NM_CPT	EFIS Mode Displayed on ND Captain (NM)

Name	Description
ND_MOD2_FO	EFIS Mode Displayed on ND F/O (PLAN ROSE ARC MAP)
ND_NM_FO	EFIS Mode Displayed on ND F/O (NM)
FPA_SEL_CPT	Selected Flight Path Angle Pilot
FPA_SEL_FO	Selected Flight Path Angle F/O

Table B.17 List of Digital input parameters: Flight Navigation Control Panel (FNCP)

Air Data Computer (ADC)

Name	Description
ALT_CPT	Pilot Altitude BARO Set (FINE)
ALT_FO	F/O Altitude BARO Set (FINE)
ALT_CPT	Pilot Altitude BARO Set (COARSE)
ALT_FO	F/O Altitude BARO Set (COARSE)

Table B.18 List of Digital input parameters: Air Data Computer (ADC)

Inertial Reference System (IRS)

Name	Description
DRIFT	Drift Angle
WIN_DIRR	Wind Direction
WIN_SPDR	Wind Speed
GS	Ground Speed

Table B.19 List of Digital input parameters: Inertial Reference System (IRS)

- **Engine Fuel and Control Systems:**

Electronic Engine Control (EEC)

Name	Description	Name	Description
EPR1	EPR Actual Engine #1	EPR2	EPR Actual Engine #2
TLA1	Throttle Resolver Angle Engine #1	EGT1	EGT Engine #1
TLA2	Throttle Resolver Angle Engine #2	N21	N2 Engine #1
EPR_CMD_ENG2	Thrust (EPR) Command Engine #2	EEC2_FAULT	EEC 2 Fault
EPR_CMD_ENG1	Thrust (EPR) Command Engine #1	EEC1_FAULT	EEC 1 Fault
EPR2	EPR Actual Engine #2	N22	N2 Engine #2
		EGT2	EGT Engine #2

Table B.20 List of Digital input parameters: Electronic Engine Control (EEC)

Fuel Quantity Indicator (FQI)

Name	Description
FQTT	Trim Tank fuel Quantity

Table B.21 List of Digital input parameters: Fuel Quantity Indicator (FQI)

Center of Gravity Control Computer (CGCC)

Name	Description
CG	Center of Gravity

Table B.22 List of Digital input parameters: Center of Gravity Control Computer (CGCC)

The full ARINC429 and ARINC 717/573 characteristics for the listed parameters are available under request to joao.prfreitas171@gmail.com

Appendix C. Superframe Words

Note: Parameter name between brackets [ ]

Superframe #1

	Subframe 1, Word 56											
Cycle	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	1	Trim Tank Fuel Quantity [FQTT]							
3	0	0	1	0	0	0	0	0	0	0	0	0
4	0	0	1	1	Oil Quantity Engine #1 [OIQ_1]							
5	0	1	0	0	Oil Pressure Engine #1 [OIP_1]							
6	0	1	0	1	Oil Temperature Engine #1 [OIT_1]							
7	0	1	1	0	Pilot Altitude BARO Set (FINE) [ALT_CPT]							
8	0	1	1	1	F/O Altitude BARO Set (FINE) [ALT_FO]							
9	1	0	0	0	Selected Flight Path Angle Pilot [FPA_SEL_CPT]							
10	1	0	0	1	0	0	0	0	0	0	0	0
11	1	0	1		Selected Heading [HEAD_SEL]							
12	1	0	1	1	Selected Course #1 [SEL_CRS1]							
13	1	1	0	0	Selected DH Pilot (COARSE) [DH_SEL_CPT]							
14	1	1	0	1	Selected DH F/O (COARSE) [DH_SEL_CPT]							
15	1	1	1	0	Pres. Pos Latitude (COARSE) [LATP]							
16	1	1	1	1	N2 Engine #1 [N21]							

Table C.1 Superframe #1

Superframe #2

	Subframe 1, Word 57											
Cycle	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	1	Center of Gravity [CG]							
3	0	0	1	0	0	0	0	0	0	0	0	0
4	0	0	1	1	Oil Quantity Engine #2 [OIQ_2]							
5	0	1	0	0	Oil Pressure Engine #2 [OIP_2]							
6	0	1	0	1	Oil Temperature Engine #2 [OIT_2]							
7	0	1	1	0	Pilot Altitude BARO Set (COARSE) [ALT_CPT]							0
8	0	1	1	1	F/O Altitude BARO Set (COARSE) [ALT_FO]							0
9	1	0	0	0	Selected Flight Path Angle F/O [FPA_SEL_FO]							
10	1	0	0	1	0	0	0	0	0	0	0	0
11	1	0	1		0	0	0	0	0	0	0	0
12	1	0	1	1	Selected Course #2 [SEL_CRS2]							
13	1	1	0	0	Selected DH Pilot (FINE) [DH_SEL_CPT]							
14	1	1	0	1	Selected DH F/O (FINE) [DH_SEL_CPT]							
15	1	1	1	0	Pres. Pos. Longitude (COARSE) [LONP]							
16	1	1	1	1	N2 Engine #2 [N22]							

Table C.2 Superframe #2

Superframe #3

	Subframe 4, Word 41											
Cycle	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	1	GMT/UTC (Hours) [UTC_HOUR]					0	0	0
3	0	0	1	0	Date (Day) [DAT_DAY]						0	0
4	0	0	1	1	Date (Month) [DAT_MONTH]					0	0	0
5	0	1	0	0	Flight Number (LSH) [FLTNUM]							
6	0	1	0	1	Flight Number (MSH) [FLTNUM]							
7	0	1	1	0	Flight Leg (Spare)							
8	0	1	1	1	A/C type [AC_TYP]						0	0
9	1	0	0	0	A/C number [AC_IDT]							
10	1	0	0	1	Fleet Identification [FLIDENT]				0	0	0	0
11	1	0	1		Gross Weight (LSH) [GW]							
12	1	0	1	1	Gross Weight (MSH) [GW]							0
13	1	1	0	0	0	0	0	0	0	0	0	0
14	1	1	0	1	DFDAU Program Ident							
15	1	1	1	0	FMC Database Update (Day) [NDBUPD]						0	0
16	1	1	1	1	FMC Database Update (Month) [NDBUPD]						0	0

Table C.3 Superframe #3

Appendix D. A310: Attitude Angles and Flight Control Surfaces

Flight Path Vector and Attitude Angles

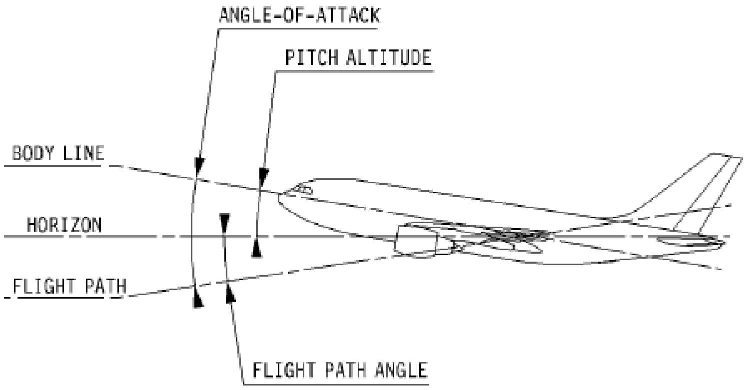


Figure D.1 Representation of the Flight Path angle, Pitch angle and Angle of Attack [11]

ATA 27: Flight Control Surfaces

PRIMARY CONTROLS	SECONDARY CONTROLS
• 2 Elevators [3], hinged to the Trimmable Horizontal Stabilizer • Trimmable Horizontal Stabilizer (THS) [4] • 1 Aileron [1] per wing • 5 outboard spoilers (Nos. 3 to 7) [2], on each upper wing surface, as roll spoilers • Rudder [5]	• Flaps: one double slotted inboard flap [6] and on single slotted outboard flap [7] • Slats: three slat sections per wing [8] associated with a Kruger flap [9] located on the leading edge of each wing • Spoilers: there are 7 spoilers (Nos. 1 to 7) on each upper wing surface which are used as speed brakes [10], roll spoilers [2] or ground spoilers (all 7 surfaces)

Table D.1 List of the Flight Control surfaces on the Airbus A310

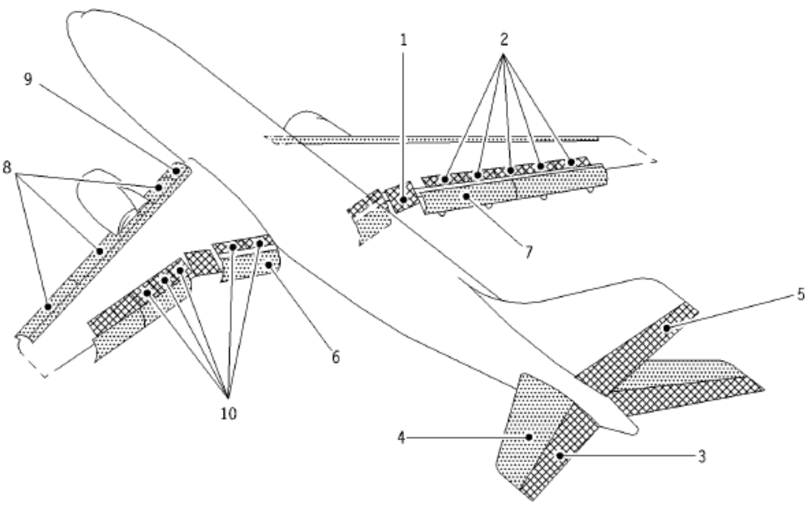


Figure D.2 Representation of the Primary and Secondary Flight Control surfaces on the A310 aircraft [11]

Appendix E. A310: Mean Aerodynamic Chord and Center of Gravity Calculation

The position of the Center of Gravity (CG) is recorded in database version and expressed in terms of percentage of MAC (Mean Aerodynamic Chord). The MAC is a reference line used in the design of the wing and its position relative to the wing and the fuselage is accurately known [51]. Figure E.1 indicates the position and dimension of the MAC or AMC (Aerodynamic Mean Chord), which is 5.8287m long. The position of the point located at 25% of the MAC's length is the reference when it comes to measuring moments. The CG is calculated with the formula below:

$$\%MAC = \left(\frac{Harm_{CG} - Harm_{Leading\ Edge\ of\ MAC}}{Length\ of\ MAC}\right) \times 100 \tag{E.1}$$

There the $Harm_{CG}$ and $Harm_{Leading\ Edge\ of\ MAC}$ correspond to the distance from station 0 - located 6.3825m forward of the fuselage nose [10] - to the CG and leading edge of the MAC, respectively. Substituting with the values available the expression becomes:

$$\%MAC = \left(\frac{Harm_{CG} - 25.2119}{5.8287}\right) \times 100 \tag{E.2}$$

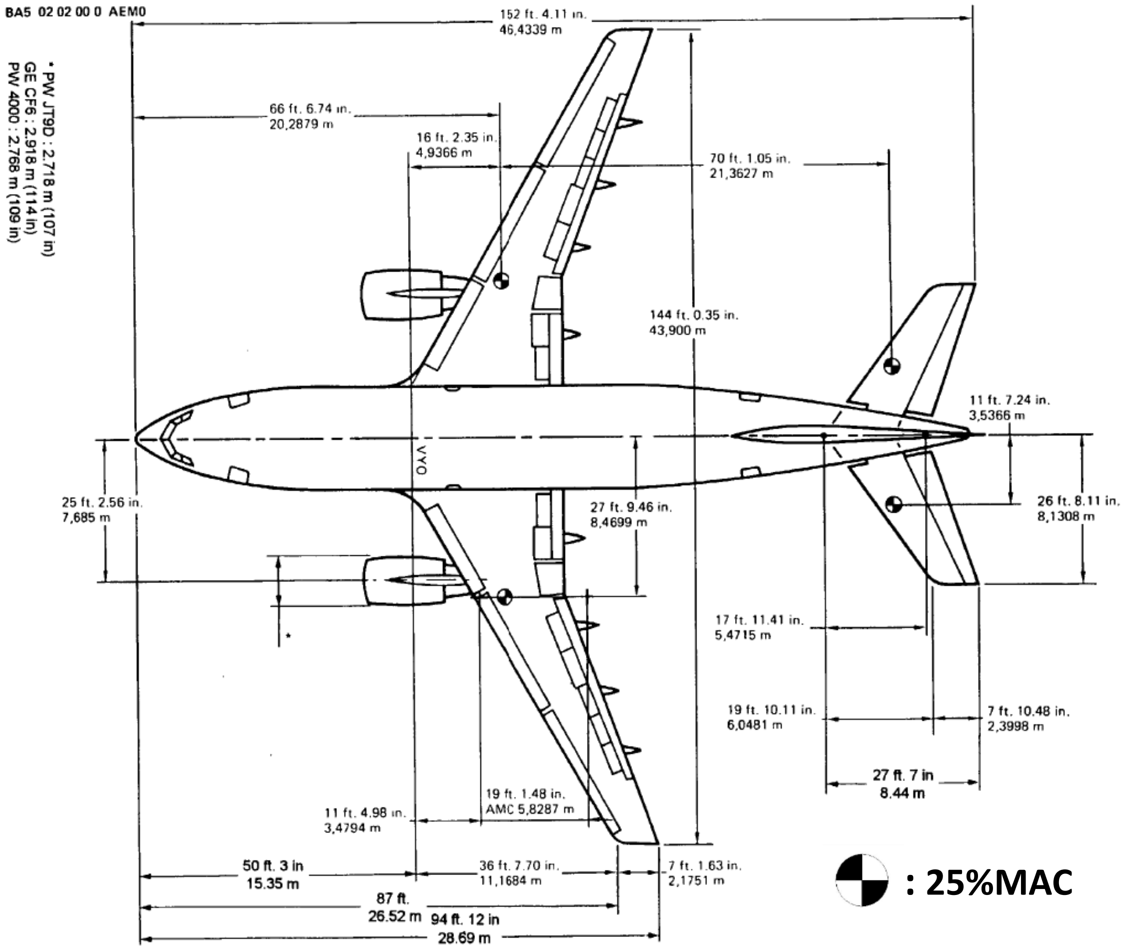


Figure E.1 A310: Airplane Dimensions [52]

Appendix F. Flight Phase Profiles

Airbus A310

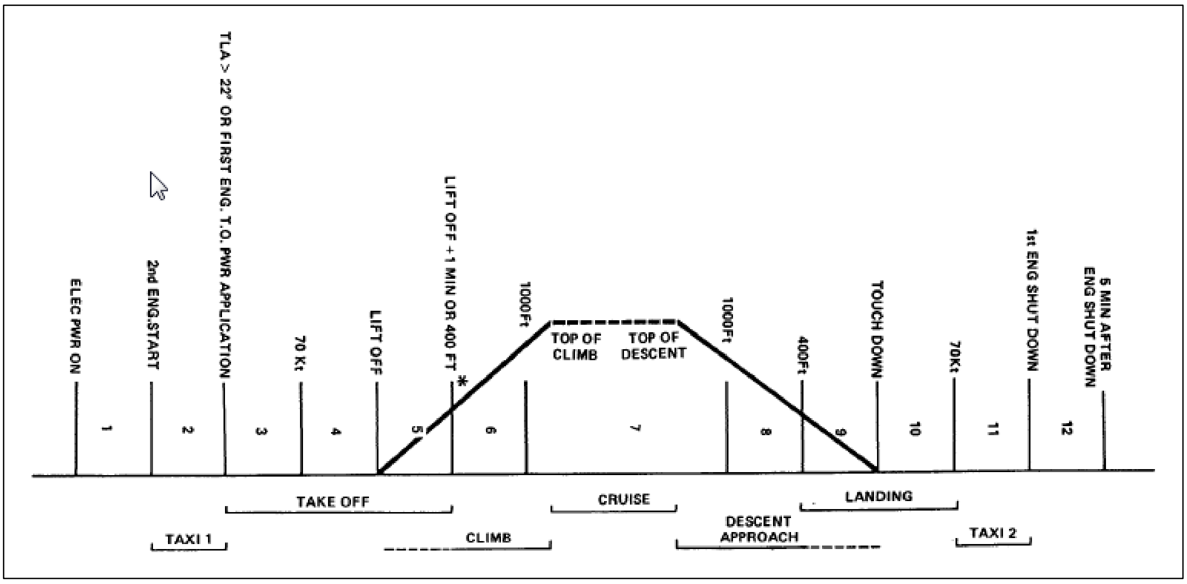


Figure F.1 Flight Profile with Airbus Flight Phases [21]

SAGEM

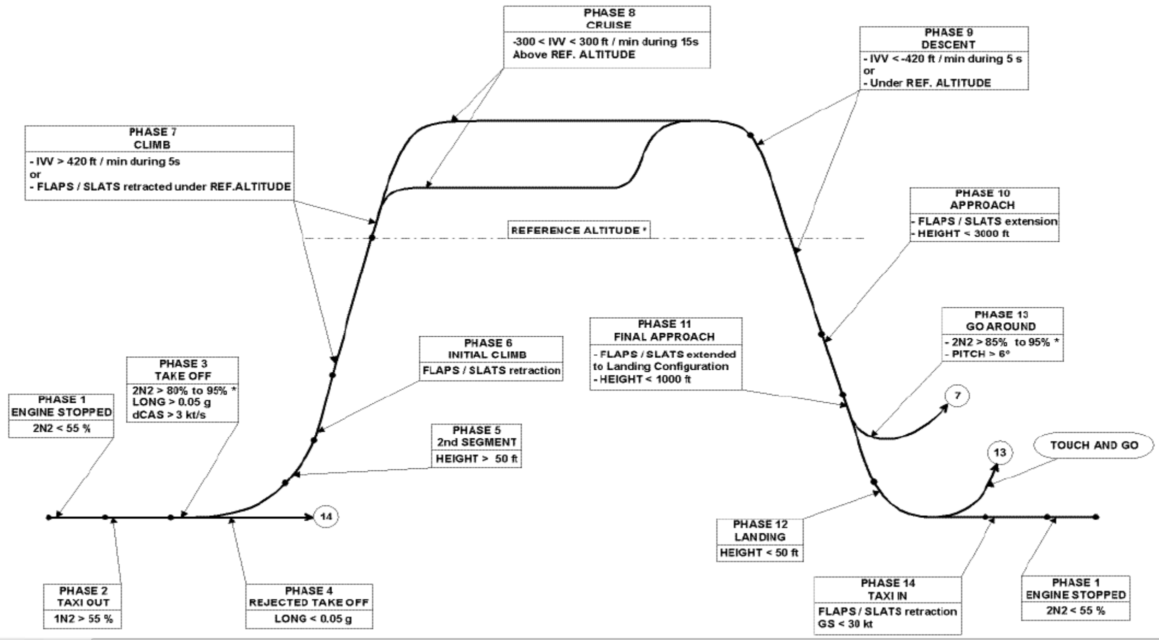


Figure F.2 Flight Profile with the SAGEM Flight Phases [24]

Appendix G. A310-325: ECM Instrument Reading Example

[redacted]	ENGINE CONDITION MONITORING	A310-304/325
	INSTRUMENT READING	[redacted]

ECM INSTRUCTIONS

1 Record data during stable cruise:
Stabilize for 5 minutes with no throttle movement
2 Confirm normal air bleed configuration
3 Disengage auto throttle
4 Adjust throttles to maintain stable MACH at >0.70
5 For mach number enter three digits after decimal point, e.g. for mach 0.810 enter 810
6 Precede temperatures by + or –as appropriate: Do not leave blank
7 DO NOT take readings while flying in unsteady or turbulent atmosphere

NOTE: Please fill out the form for each flight over one hour

GE	FLIGHT No.	JOURNEY LOG #	RECORDED BY	ID #	FLIGHT TIME

GMT/DATE MM/DD	GMT / HOUR HH:mm	ALT	TAT	IAS CAP	IAS F/O	MACH CAP	MACH F/O	GROSS WEIGHT X 1000 KG	SAT	C OF G % MAC

	BLEED ON	BLEED OFF	A/C PACKS OFF	A/C PACKS FULL	A/C PACKS ECO	X-FEED ON	X-FEED OFF	N1	EGT	N2	FUEL FLOW	OIL TEMP.	OIL PRES.	VIB N1	VIB N2	THROTTLE LEVER ANGLE	FLEX T/O DATA	
ENGINE 1																	MAX N1	
ENGINE 2																	REDUCED N1	

P&W	[redacted]

GMT/DATE MM/DD	GMT / HOUR HH:mm	ALT	TAT	IAS CAP	IAS F/O	MACH CAP	MACH F/O	GROSS WEIGHT X 1000 KG	SAT	C OF G % MAC
[redacted]	[redacted]	310	-07	298	298	.797	.799	149.0	-38°c	35.8%

	BLEED ON	BLEED OFF	A/C PACKS OFF	A/C PACKS FULL	A/C PACKS ECO	X-FEED ON	X-FEED OFF	EPR	N1	EGT	N2	FUEL FLOW	OIL TEMP.	OIL PRES.	VIB N1	VIB N2	THROTTLE LEVER ANGLE	FLEX T/O DATA	
ENGINE 1	✓			✓			✓	1.230	87.0	399	90.6	2.82	128	198	0.4	0.2	28	MAX EPR	1.556
ENGINE 2	✓			✓				1.238	87.1	409	90.5	2.86	136	194	1.6	0.4	28	REDUCED EPR	—

Appendix H. Codes from the Algorithms developed

Code for the extraction of Stability Points

Code available under request to joao.prfreitas171@gmail.com

Code for the definition of the Engine Baseline Models and the plotting of results for Trend Monitoring

Code available under request to joao.prfreitas171@gmail.com

Appendix I. Baseline Model Results: CS-PWB aircraft

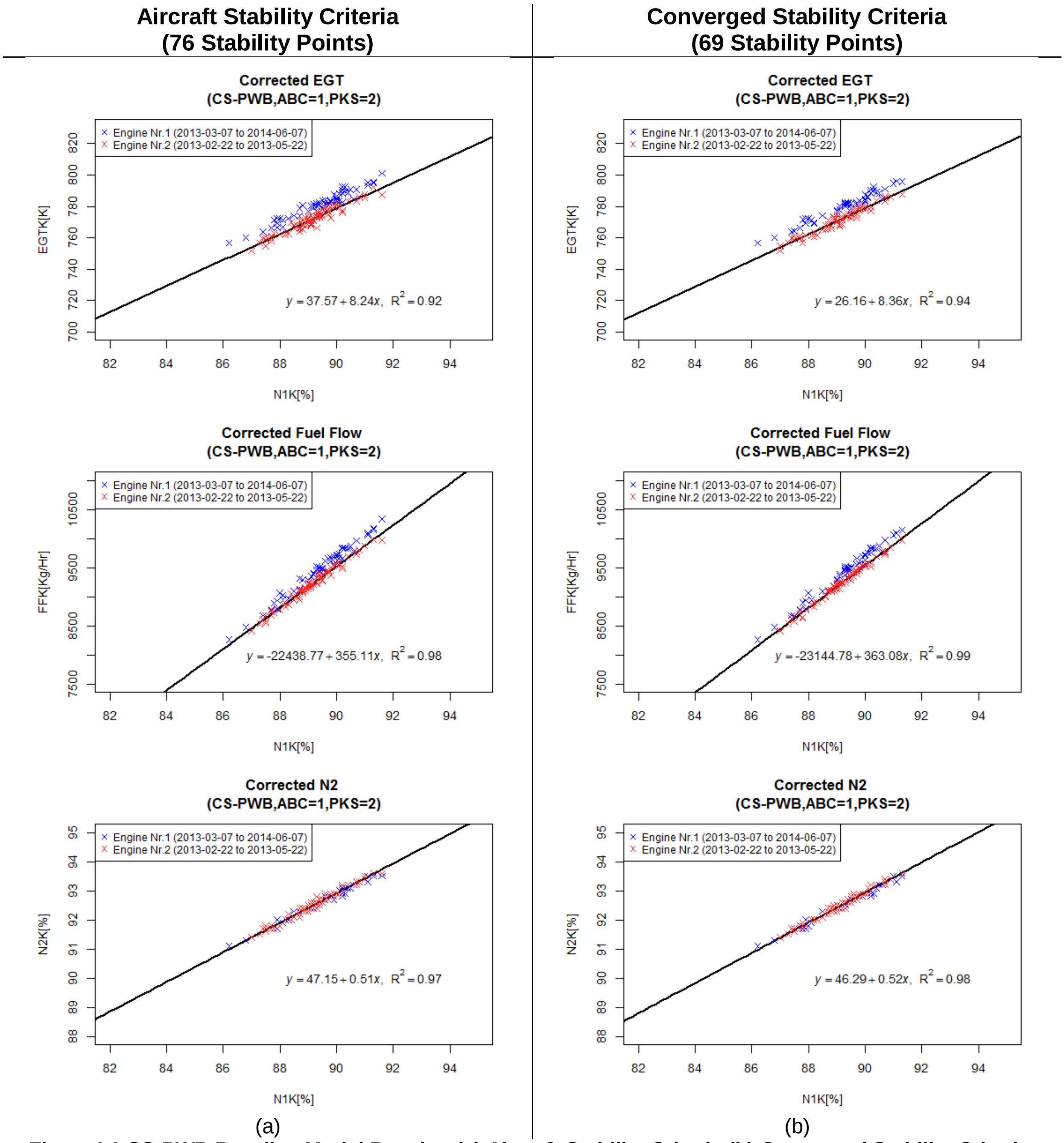


Figure I.1 CS-PWB Baseline Model Results: (a) Aircraft Stability Criteria (b) Converged Stability Criteria.

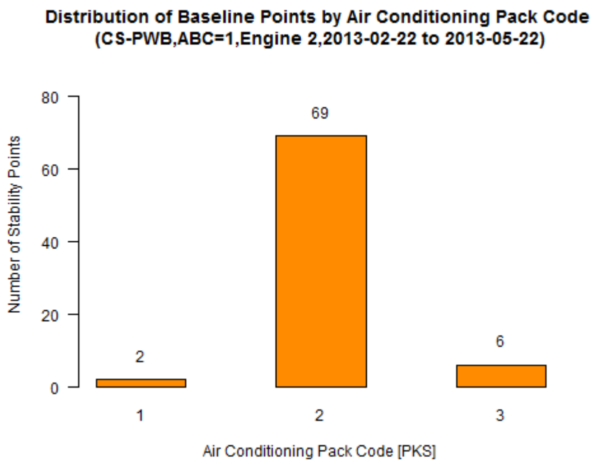
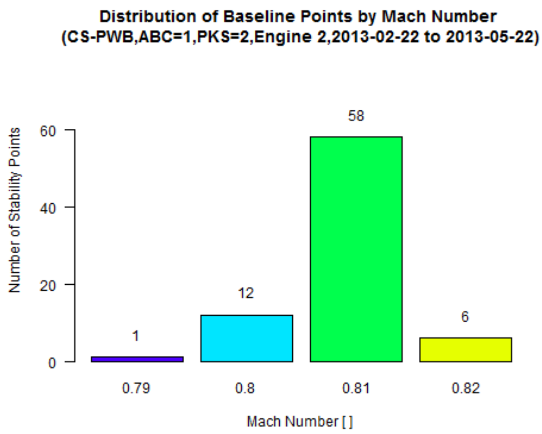
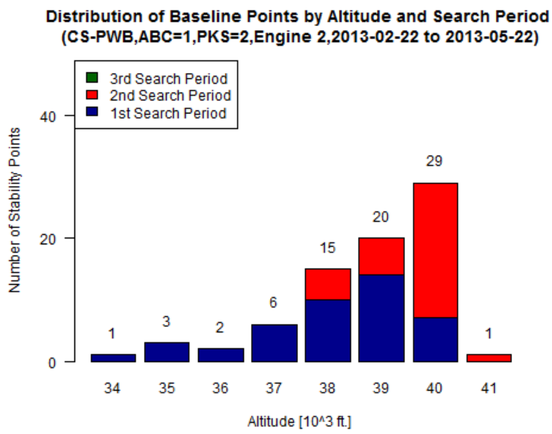


Figure I.2 Distribution of Baseline Points by PKS Code



(a)



(b)

Figure I.3 Distribution of Baseline Points by (a) Mach Number and (b) Altitude and Search Period