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Development of a Prediction model for the CFM56-7B Engine

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Bernardo Girão

Dedicatória

Gostaria de dedicar esta dissertação aos meus pais, porque mesmo no meio de dificuldades nunca deixarem de investir na minha educação e também por todo o apoio incondicional ao longo destes anos.

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Resumo

Com o desenvolvimento de ferramentas de software e a sua aplicação nas oficinas de manutenção de aeronaves, é possível prever quais os módulos ou componentes que estão com defeito e redirecionar os recursos certos para inspecionar e corrigir o problema economizando assim tempo, dinheiro e o mais importante, garantir a segurança da aeronave. Foi com base neste princípio que esta dissertação foi desenvolvida. Em colaboração com a TAP&ME, foi desenvolvido um modelo de previsão para o Motor CFM56-7B, um dos motores mais utilizados na história das companhias aéreas comerciais, utilizando o software GasTurb. O GasTurb é um software de analise de desempenho do motor que permite a entrada de dados provenientes do banco de ensaios do motor e, como a perda de desempenho do motor turbofan pode ser correlacionada a nível modular, é possível reconhecer quais os componentes que estão a funcionar abaixo do esperado. Um modelo termodinâmico foi construído usando como âncora um ponto de referência do teste de correlação de um motor em boas condições funcionando a condições particulares, seguido pela fase off-design que consiste em combinar o modelo com o desempenho de um motor a funcionar dentro de um intervalo de parametros, como velocidade específica, fluxo de massa e relação de pressão, diferentes do analisado previamente. Isto oferece à TAP um ”modelo de ouro” que pode ser usado como forma de comparação com outros motores, permitindo uma otimização de recursos como custo e dinheiro tornando-se uma ferramenta desejável para uma empresa como esta.

Palavras-chave

Modelo de previsão, Motor turbofan, GasTurb, Perda de desempenho, Modelo termodinâmico, Off-Design, Modelo de Ouro

Abstract

With the development of software tools and their application in maintenance shops, it is possible to predict which modules or components are malfunctioning and redirect the right resources to inspect and fix the problem, saving time, money and most importantly ensuring the safety of the aircraft. This thesis focuses on the development of a prediction model for the CFM56-7B Engine based on the previous principle, one of the most widely used engines in commercial airline history, in coaboration with TAP&ME. The GasTurb software was used to tailor the model. Gasturb is an engine performance modeling software that allows the input of data from the engine testbed. By correlating the turbofan engine performance loss at a modular level, it is possible to identify which component is not performing as expected.

A thermodynamic model was construct using has anchor a cycle reference point from a correlation test report from a well-functioning engine running at certain conditions. The off-design phase involved matching the model to the performance of an engine working under a range of conditions such as specific speed, mass flow and pressure ratio.

This ”Golden model” that can be used by TAP as a benchmark for other engines, enabling a optimization in resources such as cost and money making it a desirable tool for a Maintenance Repair overhaul (MRO) company to have.

Keywords

Prediction Model, Turbofan Engine, GasTurb, Performance Loss, Thermodynamic Model, Off-Design, Golden Model.

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Nomenclature

EGT	Exhaust Gas Temperature	$[K]$
FN	Net Thrust	$[kN]$
L	Characteristic Length	$[m]$
N1	Low pressure spool speed	$[rpm]$
N2	High pressure spool speed	$[rpm]$
Re	Reynolds Number	$[-]$
SFC	Specific Fuel Consumption	$[g/kN*s]$
TSFC	Thrust Specific Fuel Consumption	$[g/kN*s]$
V	Velocity Of the Fluid	$[m/s]$
Wf	Fuel Flow	$[kg/s]$
W2Rstd	Engine Corrected FLow	$[kg/s]$

Greek Symbols

Δ	Variation
η	Efficiency
μ	Dynamic viscosity
ρ	Density

List of Acronyms

AGB	Accessory Gear Box
AnSys	Analysis by Synthesis
BOAC	British Overseas Aircraft Corporation
BPR	Bypass Ratio
CBM	Condition-Based Maintenence
CFMI	CFM international
CTR	Correlation Test report
DGAC	Direction Générale de l'Aviation Civil
FAA	Federal Aviation Administration
FM	Facility Modifiers
GE	GE Aviation
HPC	High Pressure Compressor
HPT	HIgh Pressure Turbine
ICAO	International Civil Aviation Organisation
IGB	Inlet Gear Box
IGV	Inlet Guide Vane
ISA	International Standard Atmosphere
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MBTA	Model Based Test Analysis
MRO	Maintenance Repair overhaul
OAT	Outside Air Temperature
OEM	Original Equipment Manufacturer
OGV	Outlet Guide Vanes
SNECMA	Societé Nationale D'Etude et de Contruction de Moteurs d'Aviation
TAP	Transportes Aéreos Portugueses
VBV	Variable Bleed Vanes
VSV	Variable Stator vanes
WPG	Workscope Planning Guide

Chapter 1

Introduction

Since the first flight of a powered aircraft in 1903 by the Wright Brothers, the way that aircraft are propelled has changed a significantly. The introduction of jet engines in commercial flight started in 1952 when the British Overseas Aircraft Corporation (BOAC) began the world's first commercial jet service with the 44-seat De Havilland Comet 1A which flew from London to Johannesburg. This marked a turning point in commercial flights by decreasing air travel time and enabling planes to climb faster and fly higher. Since then, the jet engine has improved tremendously. Nowadays, engines are 3 times more efficient, have a power-to-weight ratio 2 to 4 times higher, and have improved reliability and by 100–200 times and 5–10 times,respectively [1].

The turbofan jet engine is now the aero propulsion system of choice. A turbofan engine is a variation of the basic gas turbine engine and powers most modern commercial airliners. The thrust in these engines is generated by a combination of jet core efflux and bypass air, which is been accelerated by a ducted fan driven by air flow provided by the jet core. A turbofan engine that derives most of its thrust from the jet core efflux is referred to as a low bypass engine, while one that drives most of its thrust from the fan is referred to as a high bypass engine. The core of a turbofan consists of high and low-pressure, multi-stage compressors, a combustion section, and high and low-pressure multi-stage turbine units. The incoming air enters the engine inlet and passes the fan where the air is accelerated and then separated into two streams, the primary and the secondary airflow.

In (Figure 1.1) a schematic of a turbofan engine and its components is shown. The primary airflow passes the booster, or low-pressure compressor (LPC), and the High-Pressure Compressor (HPC), where the higher compression occurs, it is then guided to the combustion chamber where is mixed with fuel and ignited. After leaving the combustion chamber the gases are directed to the High-Pressure Turbine (HPT) and Low-Pressure Turbine (LPT), where they expand and are finally expelled through the exhaust system via a convergent nozzle. The secondary airflow goes through the fan, passes the outlet guide vanes (OGV), and exits the engine. The HPC and HPT modules are connected by a shaft (high-speed spool) that rotates at speed N2. The LPT is also connected to the fan by a second shaft (low-speed spool) that rotates at speed N1. By using the gases that exit the HPT to rotate the LPT, thermic energy is going to be efficiently converted into mechanical energy which will then move the fan. At cruise condition, the LPT extracts more energy from the HPC than the booster needs. This excess of energy is transmitted to the fan and contributes to around 80 % of the impulse generated by the engine. The remaining 20 % is created by the reaction resulting in the primary airflow leaving the exhaust system.

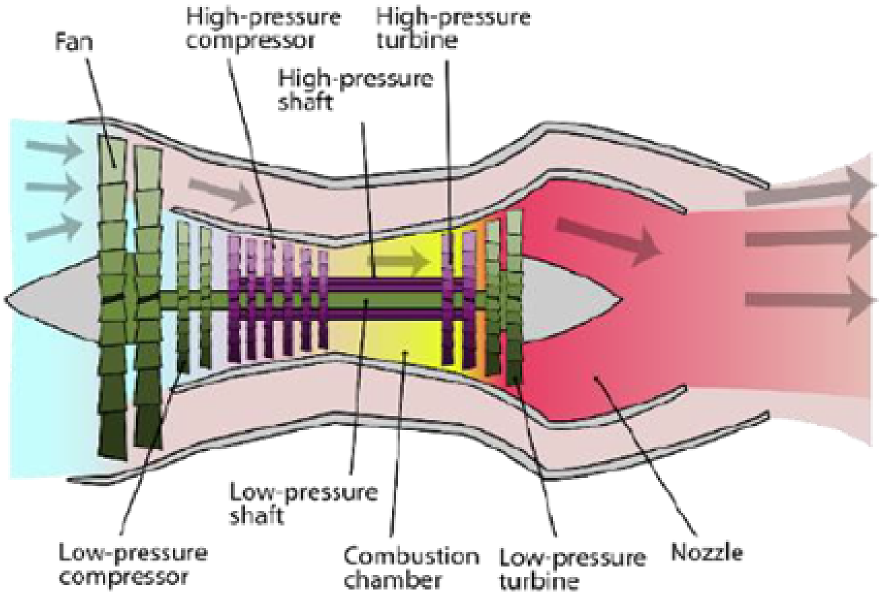

Figure 1.1: Turbofan Engine Schematic [2].

The good performance of these components has a final contribution to the efficiency of the engine, so the knowledge of the true state of each component is necessary to see if the engine needs maintenance or just a replacement of each module. To reduce the maintenance costs and the failure hazards and improve the engine availability, it is possible to perform condition-based maintenance (CBM) on each module to evaluate these conditions and the effects on the continuous deterioration effects created by high temperatures and high pressures. In CBM, sensors and spot readings are located in tactical parts of the modules to evaluate the change of some properties and then compare them to what they needed to be for a good performance of the engine. The main advantage of CBM is that this maintenance can minimize the total cost of inspections and repairs, and by doing a continuous data recovery is it possible to notice pending failures, which would allow for planned repairs based on asset degradation, as opposed to costly time-based repairs (fixed intervals) or emergency breakdowns[3]. If an engine is operating with lower efficiency, the fuel flow (Wf) must be increased to produce the same amount of thrust. This increase in fuel flow will also increase the exhaust gas temperature (EGT) and the thrust-specific fuel consumption (TSFC). If a specific

EGT is reached, to restore its performance, the engine needs to undergo a shop visit in order to do a performance restoration. This makes the EGT a crucial parameter for engine performance. However this is not the only parameter that needs to be considered. To truly know the state of the performance of the engine, it is necessary to know the individual components' performance and their effects in some crucial parameters like EGT, TSFC, Wf, and FN. To study this influence on the overall engine performance, it is recurrent the use of thermodynamic models, in which the behavior of each component is known and can be used by the engineering team to solve potential performance problems related to the turbofan engine.

One of the tools most used by the MRO team to simulate a gas turbine machine behavior is the Gasturb software. Gasturb is a user-friendly software that enables the evaluation of the thermodynamic cycle of various gas turbine architectures, both for engine design and off design. This program was created by Joachim Kurzke, a gas turbine specialist with more than 30 years off experience in the field, who has published work on this type of performance analysis[4].

1.1 Motivation

Despite being an airliner, TAP is also a prestigious MRO company with clients from all over the globe. The majority of their repair and overhaul activity is focused on components from airplanes of other airliners. With the increasing costs and pressure on MRO companies, new tools and strategies are been developed to help them maintain competitiveness in a market where maintenance works can cost millions. With the evolution of software tools and other resources to analyze the degradation of components, these companies changed their philosophy from time-based maintenance to condition-based maintenance. This approach prevents a component from being out of service for extended periods and save a great number of resources. To apply this philosophy to the engine field, it is essential to have some knowledge of the component maps from the engines. However, these maps are only available to the Original Equipment Manufacturer (OEM). Therefore, a reliable simulation of the engine using software is a very vital tool for a MRO company to have. By acknowledging that this model is trustworthy, resources can be directed towards the component that is responsible for the low-performance, resulting in cost saving, and ensuring safety and reliability to the component.

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1.2 Objectives

The main objective of this thesis is to model the CFM56-7B engine in the GasTurb software, a user-friendly engine performance modeling software. Secondly, data from test reports from engines that visited the Engine Shop will be introduced in the software and by using a model test-based analysis tool, the degradation of the components will be studied. This is going to be compared to the technical reports of the engines with the objective of checking if the model can show the consequences of the maintenance activities.

1.3 Thesis outline

This thesis is divided into 6 chapters. Chapter 2, introduces some aircraft engine maintenance planning concepts used by MRO companies. It also provides a brief introduction to the TAP&ME and its MRO facilities, including the characterization of the engine Test Bed.

Chapter 3 is where the engine under study is introduced. The engine is going to be divided into 3 major modules, which are described and their function in the engine performance is explained.

The modeling of the CFM56-7B engine is made in Chapter 4. It begins with a brief introduction to the thermodynamic stations and a description of the EGT Margin, correlation Test Report, and the software used to construct this model. The modeling process starts with the cycle reference point, followed by the off-design tailoring. Some remarks are also made regarding the malfunction of some sensors used in the modeling process.

In Chapter 5, the model application tools are described. In order to study the effect of component deterioration on engine performance the MBTA tool is used. In this chapter is also explained the reasons for the deterioration of the module that composes the engine.

The MBTA validation is presented in Chapter 6, where various engine tests were analyzed using the Gasturb model. Furthermore, a test case is analysed to certify the accuracy of the model created in previous chapters.

In the last chapter, the conclusions of the work in this thesis are presented.

Chapter 2

Maintenance Concepts and MRO Facilities

An analysis of global air traffic done by ICAO (The International Civil Aviation Organization) [5] reveals clear signs of a strong global recovery in air traffic since the covid pandemic. The number of air passengers carried from January to April 2022 increased by 65% compared to the same period in 2021, while aircraft flight departures increased by 30%. To keep up with this growth it is imperative that aircraft manufacturers, engine manufacturers, and their maintenance and repair headquarters remain focused on the safety of the aircraft and their airworthiness. The economic aspects of jet engine maintenance comprise not only the direct costs of labor and parts to keep the engines flying, but also the associated costs of fuel used, spare inventories, and facilities required. It is noted that maintenance cost is made up of 2 major elements: the cost per repair and the time between repairs, and that there is a relationship between these elements. For an air company like TAP to be profitable, it must focus on the improvement of these two points.

2.1 Engine maintenance planning concepts

The concept of maintenance refers to the work required during the engine's service life to ensure it operates safely, reliably, and cost-effectively. The costs of aircraft maintenance represent approximately 10% - 15% of an airline's operating expenses, of which 35% - 40% are engine-related as shown in Figure 2.1. The most significant item in engine maintenance is a material replacement, which can account for 60% - 70% of the engine's direct maintenance cost. This is simply because parts wear out and must be either replaced or repaired.

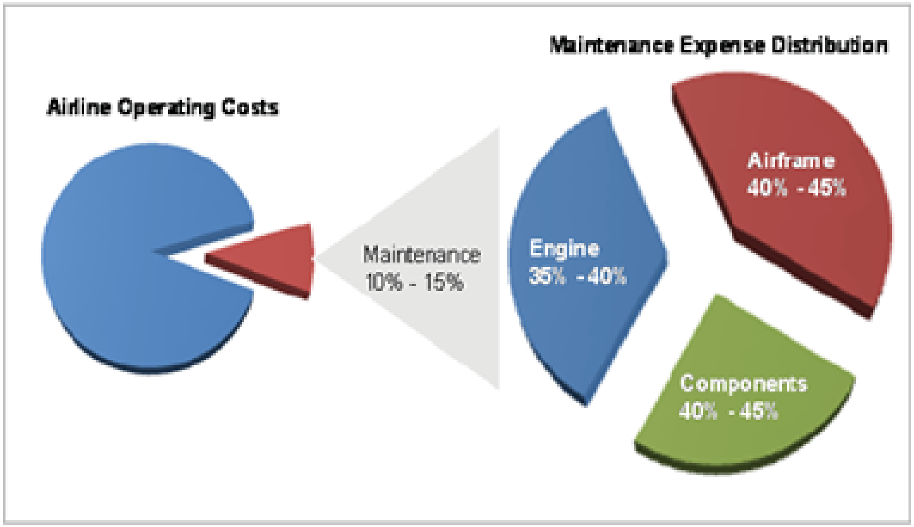


Figure 2.1: Engine Maintenance Costs Distribution [6].

Engine maintenance is required for three main reasons:

- Operational: To keep the engine in a serviceable and reliable condition so as to generate revenue;
- Value Retention: To maintain the current and future value of the engine by minimizing its physical deterioration throughout its life;
- Regulatory Requirements: To meet at least the minimum standards of inspection and maintenance required by the regulatory authorities.

We can define an engine shop visit as a maintenance intervention in the engine shop that occurs to have a separation of major mating engine flanges of a reactor. Additionally, an engine removal is classified as a shop visit [7].

Engine shop maintenance is based on two concepts [6]:

- Performance Restoration: The core engine deteriorates as parts are damaged due to heat, erosion, and fatigue. As the engine operates, the Exhaust Gas Temperature (EGT) increases, inducing accelerated wear and cracking of the airfoils, resulting in decrease performance. During a performance restoration, the core module is typically dismantled, and airfoils (rotors and stators) are inspected, balanced, and repaired or replaced as necessary. Also, a new critical EGT is established by the Original Equipment Manufacturer (OEM) based on the engine materials and their properties;
- Life Limited Part Replacements: The rotating compressor and turbine hubs, shafts, or disks within the engine have a specifically defined operating life, at the end of which, the parts must be replaced and not used again.

Another important point is the different levels of workshops that an engine can be subject to. This is established in the Engine´s Workscope Planning Guide (WPG), it refers to the maintenance planning guide published by each engine manufacturer that details the suggested level of required maintenance on each module as well as a list of recommended service bulletins [6]. These are usually specified by 3 levels of workscopes.

- Minimum Level Workscope: Typically applies to situations where a module has limited time since the last overhaul. The key tasks accomplished with this workscope level are external inspections, and to some extent, minor repairs. It is not necessary to disassemble the module to meet the requirements of a minimum-level workscope.

- Performance Level Workscope: Normally requires a teardown of a module to expose the rotor assembly. Airfoils, guide vanes, seals, and shrouds are inspected and repaired or replaced as needed to restore the performance of the module. Cost-effective performance restoration requires the determination of the items with the greatest potential for regaining both Exhaust Gas Temperature (EGT) and Specific Fuel Consumption (SFC) margin.

- Full Overhaul Workscope: Full overhaul applies to a module if its time/cycle status exceeds the recommended (soft-time) threshold, or if the condition of the hardware makes a full overhaul necessary. The module is disassembled to piece parts and every part in the module receives a full serviceability inspection and, if required, is replaced with new or repaired hardware.

An example of the workscope levels of maintenance of an engine that performed a shop visit in TAP facilities is shown in figure 2.2. This is just part of the report because of privacy policies. However, it is possible to notice that the Fan/booster and the inlet gearbox (IGB) modules underwent a full overhaul workscope, while the bearing and fan case modules performed a minimum level workscope.

FAN			
FAN & BOOSTER	FULL		Accomplishment of SBs 72-0632 + 72-0634
BRG 1 & 2 SUPPORT	MIN		Inspect accessible areas
IGB	FULL		Full disassembly and repair as applicable
FAN CASE	MIN		Inspect and repair as applicable
CORE			Split into mini-modules

Figure 2.2: Example of the levels of workscopes on a CFM56-7B Engine.

2.2 TAP Maintenance and Engineering and their MRO facilities

TAP Maintenance and Engineering is a MRO´s organization based in Portugal with two main centers in Brazil. It comprises a total workforce of about 4,000 employees. TAP MRO provides maintenance and engineering support for Airbus A300-600, A310, A330, A340, A320 family, Boeing and Embraer fleets for the TAP Air Portugal company and also for other companies worldwide, making their reputation as one of the most reliable airlines in the world. Over the years the good quality of their work received international recognition from both customers and manufacturers, confirming the $Care^2Quality$ [8].

The MRO $Care^2Quality$ services range from airframe, engines and components:

- $Care^2Airframe$: It includes base maintenance ranging from light to heavy maintenance and line maintenance with a team of highly qualified technicians perform a wide variety of services including pre-flight, transit, and daily/weekly checks and troubleshooting.
- $Care^2Engines$: It includes MRO services to commercial and military aircraft engines with the mission of avoiding premature engine removals and overhauls. The engine department also specialises on repair, testing and overhaul of the engine's models CFM56-3, -5A, -5B, -5C, -7B and LEAP .
- $Care^2Components$: It incorporates overhaul, repair, test, and modification for more than 15,000 components used in Airbus, Boeing and Embraer fleets and their engines.
- $Care^2Engineering$: Provides customised maintenance solutions and technical services

2.3 TAP Test Bed

After every maintenance action that is done on an engine and its module assembly, it is a common practice to test it before installing it on the aircraft. This is done to ensure that it meets the performance requirements and the acceptance criteria. To be tested, these engines go through some exams on a thrust test bed. Depending on the goal of the performance analysis of the engine test bed, this comes with certain instrumentation for various objectives. If the objective is performance investigation, it is common to perform analysis on pressures and temperatures that are measured at virtually every station, as well as power or thrust, shaft speeds, fuel, airflow, and others. However, if it is for production pass-off or endurance testing, only a minimum of measurements are taken beyond those of the production control system, such as ambient conditions, power or thrust level, and fuel flow [9]. Engine test beds can be characterized based on whether they are indoor or outdoor facilities as well as the type of ambient condition, which refers to the altitude where the engine is operating. These distinctions have some consequences on the type of data collected and also how their data treatment.

TAP&ME test cell facility is an indoor sea level thrust test bed where the airflow path to the engine is crucial, as flow disturbance must be minimized . The engine nozzle efflux enters a detune, which exhausts hot gases and provides sound attenuation [9]. Since the engine operates at ambient temperatures and pressure conditions, these are needed to correct its performance results to the International Standard Atmosphere (ISA) sea-level conditions (Eq.4.3) (Eq.4.4). The TAP&ME test cell is a large state-of-the-art test facility having a cross-section of approximately $9.75m \times 8.65m$. Its configuration is of the "L" type as shown in Figure 2.3.

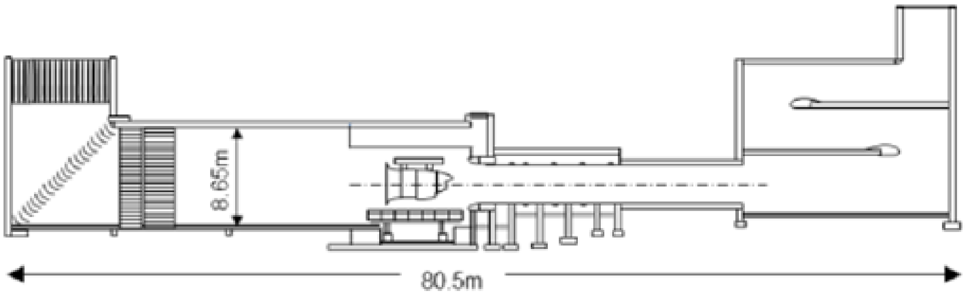


Figure 2.3: Schematic of the test cell of the "L" type [10].

Chapter 3

CFM56-7B Engine

The CFM56-7B is one of the variations of the famous CFM56 manufactured by CFM International (CFMI), a company composed by two major aircraft engine manufacturers, Figure 3.1, GE Aircraft Engines from the United States of America and Sanfran Aircraft Engines, formerly know from SNECMA (societé Nationale D'Etude et de Contruction de Moteurs d'Aviation) from France. The origin of the CFM56 name comes from the letters "CF", used for the designation of the commercial fan used by GE in their reactors (CF6-6,CF6-50, CF6-80), the Letter "M" from the French word Moteur used by SNECMA and the "56" comes from the number of the project [7]. This manufacture has been selected by the Boeing Company as the exclusive powerplant for its Next-Generation 737 family. This engine was jointly certified in 1996 by the US Federal Aviation Administration (FAA) and the French Direction Générale de l'Aviation Civile (DGAC). It is perfectly tailored for the short-to-medium range 737-600/-700/-800 and -900 aircraft, as well as to the Boeing Business Jet models, taking full advantage of CFM International's vast experience while providing substantial improvements versus the industry-leading CFM56-3.

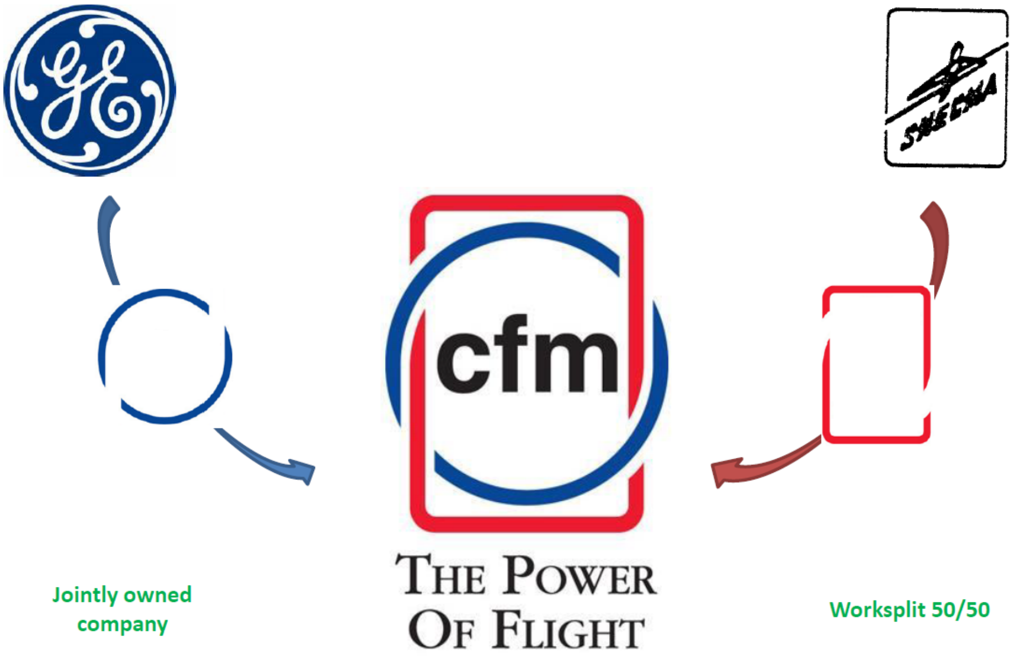
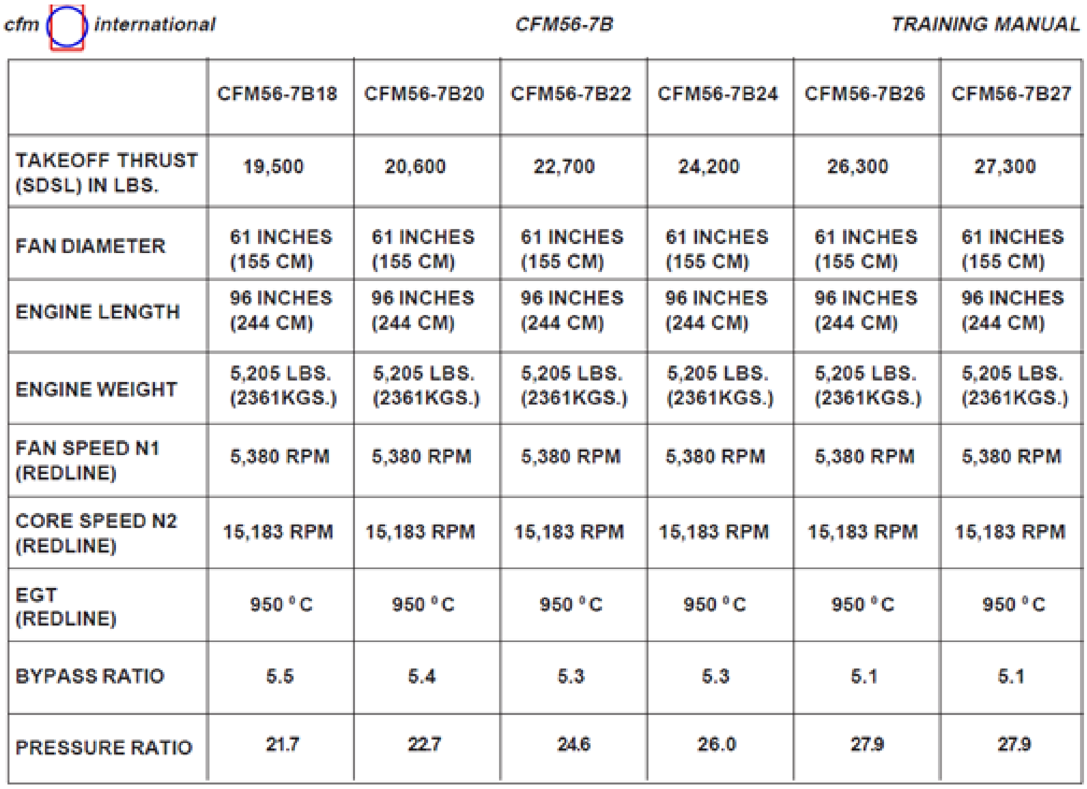


Figure 3.1: Creation of CFM [7].

The CFM56-7B improvements are mainly due to its 61-inch diameter solid titanium wide-chord fan and its new core and low-pressure turbine turbomachinery, all designed with the most advanced three-dimensional (3D) aerodynamic design methods in comparison with the CFM56-3B, the industry-leading engine from CFM. The CFM56-7B showed several improvements like lower operating temperatures with higher exhaust gas temperature (EGT) margins for increased engine on-wing durability, a significant fuel improvement of 8 percent and a 15 percent reduction in maintenance costs as compared to the CFM56-3C engine [11]. The engine has developed in 6 versions, with different BPR (Ranging from 5.10 to 5.50) and varying maximum thrust from 19,500 lbs to 27,300 lbs. Nevertheless, the engine that is going to be modeled in chapter (4) is the CFM56-7B27. The CFM56-7B variations and applications are showed in the image below (Figure 3.2).



cfm international *CFM56-7B* *TRAINING MANUAL*

	CFM56-7B18	CFM56-7B20	CFM56-7B22	CFM56-7B24	CFM56-7B26	CFM56-7B27
TAKEOFF THRUST (SDSL) IN LBS.	19,500	20,600	22,700	24,200	26,300	27,300
FAN DIAMETER	61 INCHES (155 CM)	61 INCHES (155 CM)	61 INCHES (155 CM)	61 INCHES (155 CM)	61 INCHES (155 CM)	61 INCHES (155 CM)
ENGINE LENGTH	96 INCHES (244 CM)	96 INCHES (244 CM)	96 INCHES (244 CM)	96 INCHES (244 CM)	96 INCHES (244 CM)	96 INCHES (244 CM)
ENGINE WEIGHT	5,205 LBS. (2361KGS.)	5,205 LBS. (2361KGS.)	5,205 LBS. (2361KGS.)	5,205 LBS. (2361KGS.)	5,205 LBS. (2361KGS.)	5,205 LBS. (2361KGS.)
FAN SPEED N1 (REDLINE)	5,380 RPM	5,380 RPM	5,380 RPM	5,380 RPM	5,380 RPM	5,380 RPM
CORE SPEED N2 (REDLINE)	15,183 RPM	15,183 RPM	15,183 RPM	15,183 RPM	15,183 RPM	15,183 RPM
EGT (REDLINE)	950 °C	950 °C	950 °C	950 °C	950 °C	950 °C
BYPASS RATIO	5.5	5.4	5.3	5.3	5.1	5.1
PRESSURE RATIO	21.7	22.7	24.6	26.0	27.9	27.9

Figure 3.2: CFM56-7B versions and their specifications and applications [12].

Like all engines, CFM56-7B is composed of many parts, all of which play an important role in the proper function of the engine. With purpose of simplifying all this, it is packed in three major modules; the Fan Major Module, Core Major Module and the Low Pressure Turbine Major Module as well as one accessory module like is showned in Figure 3.3. The three major models referred before are divided into 17 mini modules. Since the project of the CFM56 aims to reduce costs in exploration and maintenance and reduce engine stop times, 10 of these 17 mini modules can be completely replaced at a modular level.

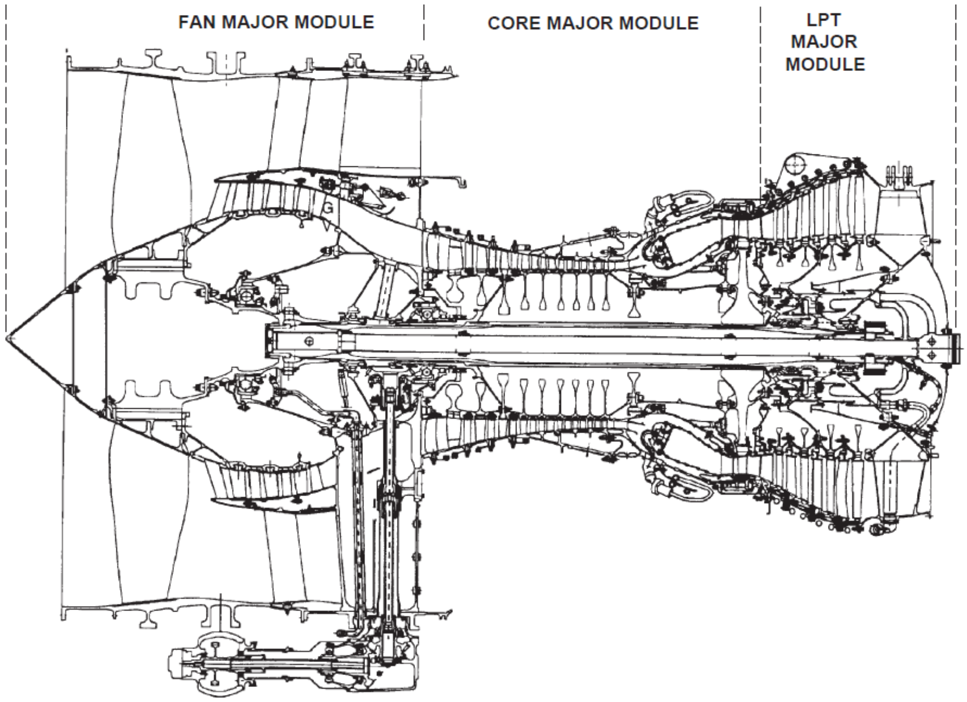


Figure 3.3: CFM56-7B constitution [12].

3.1 Fan Major Module

The Fan major module (Figure 3.4) is a crucial part of the low-pressure mechanisms of the engine. This module is composed by the following minimodules:

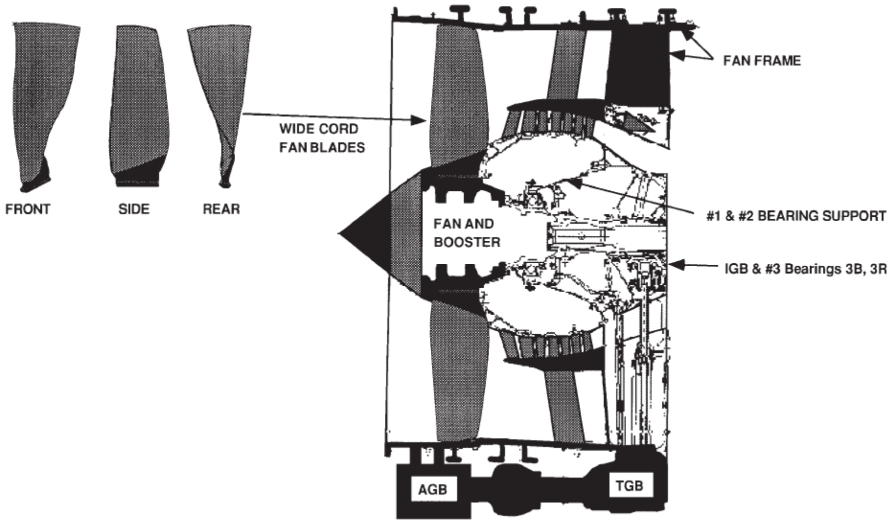


Figure 3.4: Fan Major Module [12].

- Fan and Booster: The fan and booster minimodule is responsible for many important aspects in the function of the turbofan engine. These involve producing approximately 80% of the take-off thrust, supplying airflow for thrust reversers, pre-compression of the air on the LPC prior to the HPC. One of the characteristics that distinguish this minimodule from others like the minimodule from the 5B is that on the 7B the booster is composed of 3 stages instead of 4 and also the number of blades on the fan this being 24 blades without midspan shroud;

- #1 and #2 bearing support: The #1 and #2 bearing support provide frontal substructure to the low pressure shaft N1. In the 7B, instead of these being assembled together, they are assembled separately;

- Gearbox and #3 Bearings: The inlet gearbox provides frontal support to the high pressure shaft N2 rotor. It also allows torque transmission between the HPC (N2 shaft) and the accessory gearbox;

- Inlet Fan Frame: The Fan frame, among other functions, provides forward support for both rotors, transmits the thrust from the thrust reverser and the engines to the aircraft, separates the primary flow from the secondary airflow, and provides assembly points for the outlet guide vanes (OGV) and it accommodates the variable bleed vanes

(VBV) system. This system is used to bleed air from the primary to the second airflow. In the 7B engine, this frame is made of aluminum making it lighter but more fragile and consequently, more susceptible to suffer damage from erosion or impacts.

3.2 Core Major Module

The Core Engine Module is the high pressure section (Figure 3.5) and is composed by the following minimodules.

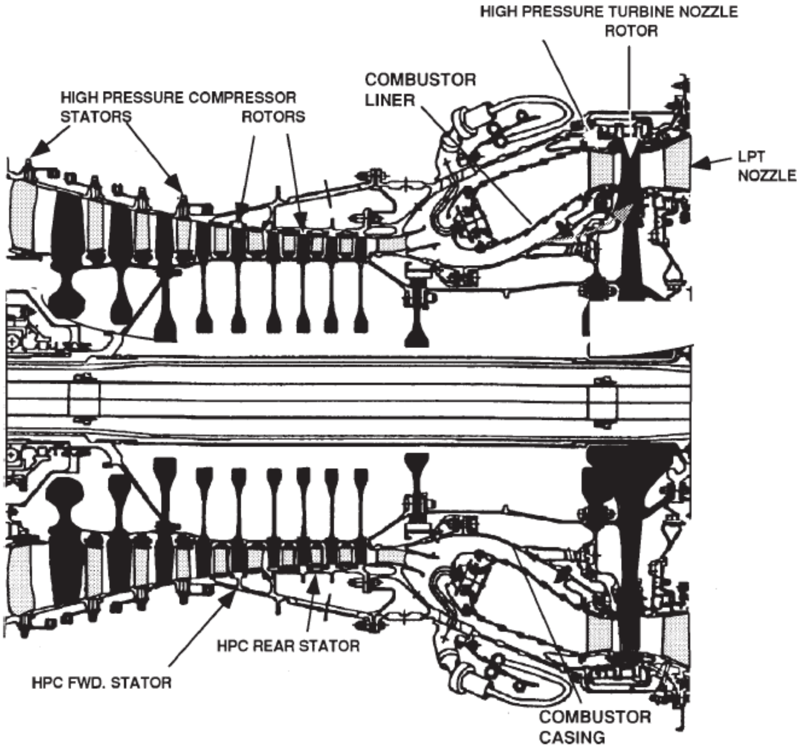


Figure 3.5: Core Major Module [12].

- High pressure compressor rotor: The HPC rotor minimodule is one of the most important parts of the engine because it has the function of significantly increasing the pressure of the flow before entering the combustion chamber;
- High pressure compressor forward stator: The HPC front stator has the function of transforming the velocity of the flow that comes from the booster into pressure. It also regulates the air velocity before entering the HPC making use of the inlet guide vanes (IGV´s). In the first stages of the minimodule is where the variable stator vanes (VSVs) are found. This component has the objective of regulate the flow entering the other stages of the HPC changing the velocity of the airflow;

- High pressure compressor rear stator: Here the air pressure is increased and delivered to the combustion chamber. It also accomodates feature for the baroscope ports to inspect the HPC rotor 6 and 9 stages;

- Combustion casing: This miniodule has among other functions providing the structural interface between HPC, combustor, and LPT and decreasing of the airflow velocity before the combustor;

- Combustor Chamber: The combustion chamber is where the air from HPC is mixed with fuel supplied by 20 fuel nozzles. Its configuration allows the production of an efficient fuel/air mixture providing uniform combustion.

- High pressure turbine nozzle: The HPT nozzles redirect and accelerate the airflow from the combustion chamber onto the HPT Blades (HPT rotor module) at an angle that will give the best performance during all operating conditions. The 7B variation of the engine has 21 segments that are capable of performing their function;

- High pressure turbine rotor: This minimodule is also a very important since it has the function of converting the energy that comes from the combustion reaction in the combustion chamber into mechanic energy and providing her to the HPC. The remaining energy is delivered to the LPT. The HPT rotor, is the engine rotating module that is subjected to the most severe operating conditions due to high pressure airflow, high temperature and high rotating speed (N2). Therefore, it is built from higly resistant metallic alloys. The 7B variation is composted by 80 HPT blades;

- Low pressure turbine nozzle stage #1: The LPT nozzles and HPT shrouds make the connection between the core module and LPT Module directing the exhaust gas onto the LPT 1 blade;

3.3 Low Pressure Turbine Major Module

The Low Pressure Turbine Module (Figure 3.6) completes the Low Pressure section of the engine and is composed by the following minimodules.

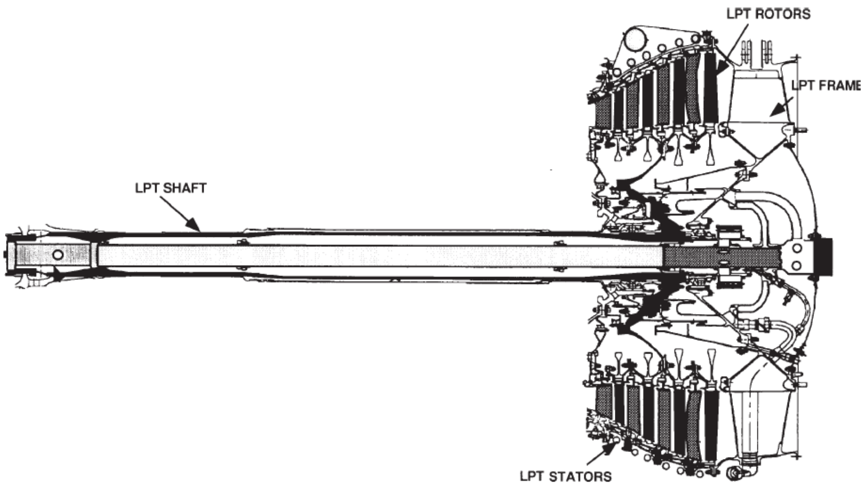


Figure 3.6: Low Pressure Major Module [12].

- Low pressure turbine rotor and nozzle vanes: This minimodule is here part of the remaining energy is extracted from the primary airflow that comes from the HPT. It converts this energy into mechanic energy that is used to move the low pressure compressor (Fan and booster). This is composed by 4 stages;
- Low pressure turbine shaft: This module provides a physical connection between the LPT and the fan shaft transmiting torque between the LPT and the LPC;
- Low pressure turbine frame: This minimodule is where the weight from the engine is transmitted to the aircraft. It also provide attachment points for the exhaust assembly and center body. The turbine frame in the 7B has a tangential structure that improves its durability;

3.4 Accessory Drive Module

The accessory Drive Module is composed by 2 minimodules:

- Transfer gearbox: Transmits torque (N2) between the Inlet Gear Box (IGB) and the Accessory Gear Box (AGB). In the 7B variation it's mounted in a 9 o´clock position in relation to the Fan.
- Accessory Gear Box (AGB): Has the function of supporting and driving the aircraft and their engine accessories. The housing of the AGB is also positioned in a left position in relation to the Fan.

Chapter 4

Thermodynamic model of the CFM56-7B

In this chapter, it will be described how the thermodynamic model of the engine was obtained. TAP&ME already had tried to create a the model for the CFM56-7B, however this model proved unsuitable for its purpose. It was an adaptation of a thermodynamic model developed for another variation of a CFM engine. As it will be further discussed, such model needs a detailed execution in order to be a reliable tool for an MRO company like TAP&ME. Also by comparing this final work with the previously developed model, it was noticeable that the previous work did not take into account the correlations necessary for the standard day model. For the design of this "Golden model", is imperative that the measured data of the engine that is being modeled are well-founded. The process of constructing the thermodynamic model is going to be described in three sub-chapters, that are all connected to each other, following the method described by Kurzke [13].

4.1 Thermodynamic Stations

In order to model the engine in the Gasturb software, some information is needed regarding each component thermodynamic station. The thermodynamic stations available in Gasturb are shown in Figure 4.1

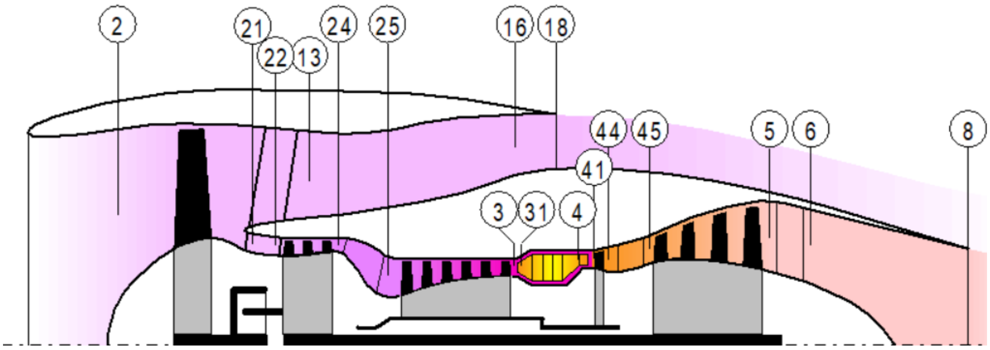


Figure 4.1: Thermodynamic Stations in Gasturb [4].

In this context it is possible to analyze data regarding temperature, pressures, and airflow. Unfortunately, the TAP test bed (Figure 4.2) had some sensor limitations that affected both directly and indirectly the information regarding the performance of the various components. To completely isolate a component for their analysis, it would be required temperature and pressure sensors immediately before and after each the component flow path. TAP&ME has chosen to only have installed the necessary sensors to evaluate the engine's overall performance. This precaution is taken because a sensor poorly attached can break loose, causing irreparable damage to the engine. In the analyse of a gas turbine engine, the general performance characteristic depends mainly on the shape of the compressor and turbine maps ([14]). When certain global parameters are in agreement, the model is likely to remain within a valid range. TAP test bed and Gasturb stations also vary in nomenclature, so, in the construction of this model the nomenclature that is going to be used for the thermodynamic stations will be the one from Gasturb, except for station 49.5 that is exclusively used by TAP test bed to measure the EGT (FIgure4.2).

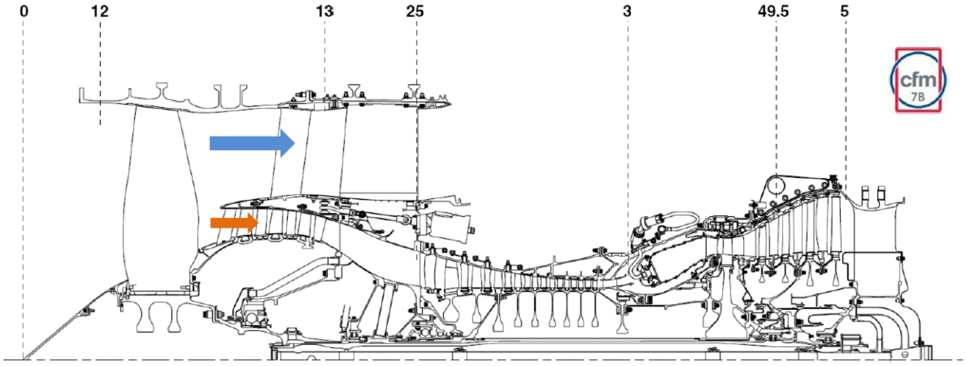


Figure 4.2: Thermodynamic Stations in TAP TestBed [2].

4.2 EGT Margin

As previously referred , the EGT is the temperature at the engine exhaust and is one of the best indicators of an engine deterioration of an engine. As an engine accumulates more time-on-wing, the efficiency decreases, and more fuel loading is required to achieve the same required thrust level. Eventually the EGT rises to a point where only a little margin remains. This indicates that the engine must be removed for refurbishment, or visit the engine shop for maintenance. Due to this, EGT can be used as a unit of measure of an engine's efficiency in delivering its design-level thrust (Figure4.3).

The EGT margin is traditionally defined by the difference between the EGT red line (or EGT limit for Hot day) and the EGT that is measured during the take-off phase of a flight. EGT is measured at the peak of take-off action since this is where the engine is generating the highest thrust, resulting in elevated temperatures and pressures.

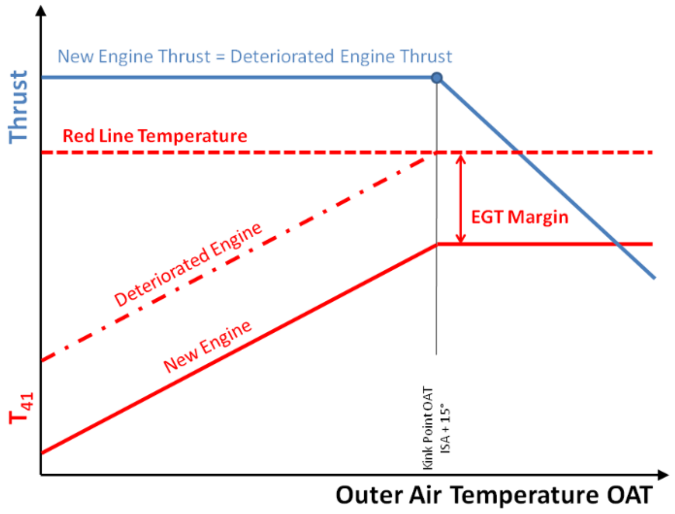
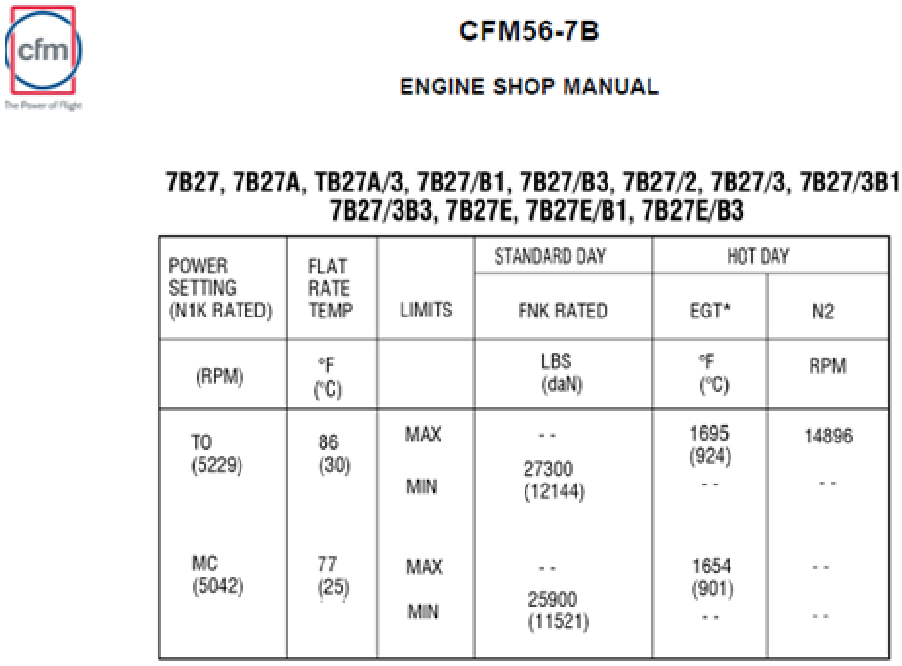


Figure 4.3: EGT Margin Deterioration [15].

The EGT red line for a hot day (HD), which corresponds to an outside air temperature (OAT) of 30°C, is defined in the CFM56- 7B engine shop manual and is shown in Figure 4.4 Since there are several rates possible for each engine model, there are also different EGT HD limits established by the CFM for each one. The rate that is going to be used is the 27, as further explain in section 4.4. TAP&ME defines that a good operating engine has a EGT Margin Hot Day greater than 30°C.



CFM56-7B

ENGINE SHOP MANUAL

7B27, 7B27A, TB27A/3, 7B27/B1, 7B27/B3, 7B27/2, 7B27/3, 7B27/3B1, 7B27/3B3, 7B27E, 7B27E/B1, 7B27E/B3

POWER SETTING (N1K RATED)	FLAT RATE TEMP	LIMITS	STANDARD DAY	HOT DAY	
			FNK RATED	EGT*	N2
(RPM)	°F (°C)		LBS (daN)	°F (°C)	RPM
TO (5229)	86 (30)	MAX	- -	1695 (924)	14896
		MIN	27300 (12144)	- -	- -
MC (5042)	77 (25)	MAX	- -	1654 (901)	- -
		MIN	25900 (11521)	- -	- -

Figure 4.4: Definition of EGT red line for HD for the for the CFM56-7B27 Engine [16].

In the thermodynamic cycle of a turbofan engine, the burner discharge temperature (T4), represents the hottest section in the engine. Due to the harsh conditions in this area, it is not possible to place a sensor there. The LPT inlet temperature (T45) is affected by the secondary air system, in order to decrease the temperature of the LPT nozzles. To avoid these problems, the solution for measuring the EGT was to position at the sensor in the inlet of the second stage of the LPT station like is represented in Figure 4.5. This station is denoted as T49.5 in TAP test bed nomenclature.

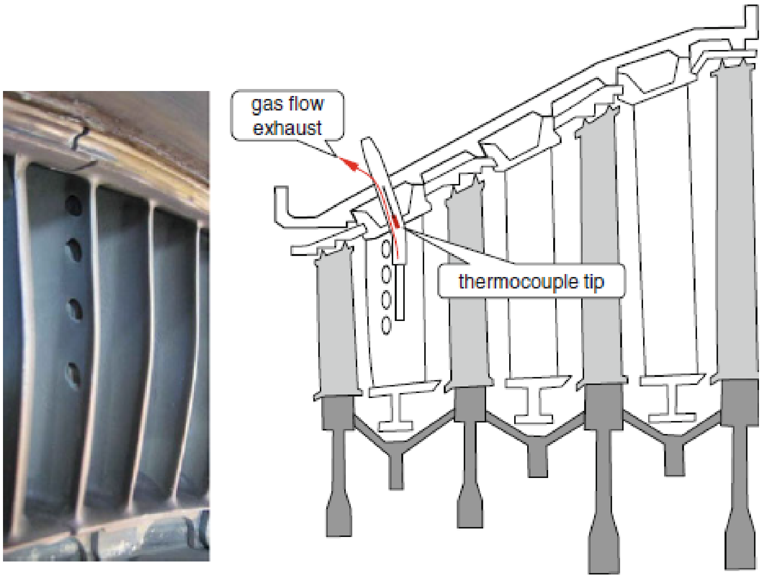


Figure 4.5: EGT Measurement in the CFM56 engine [17].

4.3 Correlation Test Report and Correction Factors

A complete thermodynamic model of a new engine is created by the company developers, based on the vast amount of data gathered throughout its development process. These details and data are usually kept confidential, with only parameters used for control purposes being accessible to outsiders [13]. It is Tap&ME interest to have this model for the CFM56-7B engine, as it aids in performance prediction and life monitoring of the ones that enter the engine shop. To develop this engine model is needed to have a solid trustworthy base of data. To achieve this goal, it will be used the CFM56-7B Correlation Test Report (CTR) [10], which was created from the data of a correlation engine. The correlation engine is an engine whose performance was known by the manufacturer, and was considered a stable. This has the purpose of correlating its performance in TAP test bed with the data from the CFMI facilities, where it had been previously tested and measurements were made at various stations. By correlating the deviations in the TAP test bed, it is possible to calculate the facility modifiers

(FM) for this engine. These FM values allow to align the performance of an engine across different test cells. The FM are applied to the high-pressure spool speed (N2), fuel flow (WF), air mass flow (W2), EGT and net thrust (FN). The facilities modifiers are calculated using the polynomial equation described in Eq(4.1), where X stands for the dry standard day thrust (FNR) in TAP test bed and A's refer to the the coefficients provided in the CTR [10].

$$FM = A0 + A1 \cdot X^2 + A3 \cdot X^3 + A4 \cdot X^4 \tag{4.1}$$

The FM values are applicable for a FNR from 11,700 lbs to 27,060 lbs. To achieve the final value of each referred parameter it is necessary to multiply the measured parameter by the respective FM. Another correlation that it is used is the inlet pressure (P2) - airflow correlation. P2 is also a function of parameters, the low pressure spool speed (N1R) and the ambient pressure (P0). This parameter is calculated following the equation (4.2) and its applied to a N1R from 3,700 to 5,260lbs

$$PT2 = (A0 + A1 \cdot N1R) \cdot P0 \tag{4.2}$$

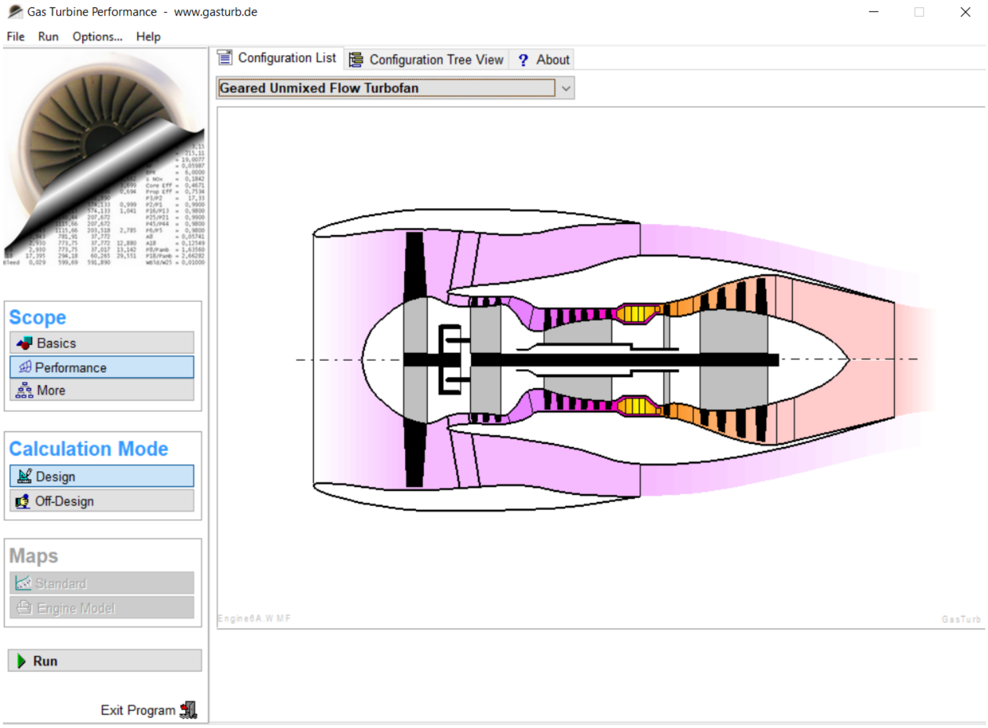
The several tests conducted in the CTR had different ambient conditions that affect the pressures and temperatures measured. It is imperative to correct the measured pressures and temperatures to standard day conditions. This ensures a legit database for a reliable comparison between the performance of different engines. The corrections to Standard day, are applied using the equations (4.3) for pressures and (4.4) for temperatures. In these equations the standard ambient pressures and temperatures are 101.325kPa and 288.15K, as defined by the International Standard Atmosphere (ISA)

$$Pcorrected = P_{read} \cdot \frac{P_{ISA}}{P2_{read}} \tag{4.3}$$

$$Tcorrected = T_{read} \cdot \frac{T_{ISA}}{T2_{read}} \tag{4.4}$$

4.4 Gasturb software and cycle reference point

According to Kurzke[13], the first step to obtain a reliable performance model for the engine in study is finding a suitable cycle reference point with the data available. Before we start tailoring the cycle design point around the data available, some adjustments are needed to be done in the software. When launching Gasturb, three different types of gas turbine simulations are presented. In order to complete our objective of developing a prediction model of the engine CFM56-7B, the ”performance” simulation it is selected. Also, Gasturb offers us various types of engine configurations. The engine in question is a turbofan engine. While there are numerous types of turbofan engines simulations available in the software, it is imperative to choose the “Geared unmixed flow turbofan” 4.6 since this can simulate the LPC module. However, it is essential to set the gear ratio to 1, ensuring that the fan and booster rotate at the same speed of the LPT and the HPC at the same speed as the HPT. After the Gasturb scope is set in the right starting setting we can start the first step.



Geared Unmixed Flow Turbofan

Figure 4.6: Selection of the engine configuration.

As stated before, the first step is to choose the right reference point from the data that composes the CTR. As Kurzke [13] stated, the cycle reference point is the design point of the engine. However, any high-power operating point is suited for that purpose because, in these conditions, the Reynolds number effects are negligible. The Reynolds Number can be easily calculated using equation (4.5):

$$Re = \frac{\rho \cdot V \cdot L}{\mu} \tag{4.5}$$

Where ρ is the density of the fluid, L the characteristic length, V the velocity of the fluid and μ the dynamic viscosity. In a study conducted by Wassel [18] on Reynolds number effects in compressor performance, it was demonstrated that as a notable impact on flow-pressure ratio and the efficiency-pressure ratio. As the Reynolds number decreases, the separation between laminar and turbulent flow shifts close to the trailing edge of the compressor blades airfoil. This results in a increase in drag coefficient, which subsequently reduces the cascade efficiency and, consequently, the corrected air flow causing a decrease in compressor efficiency [19].

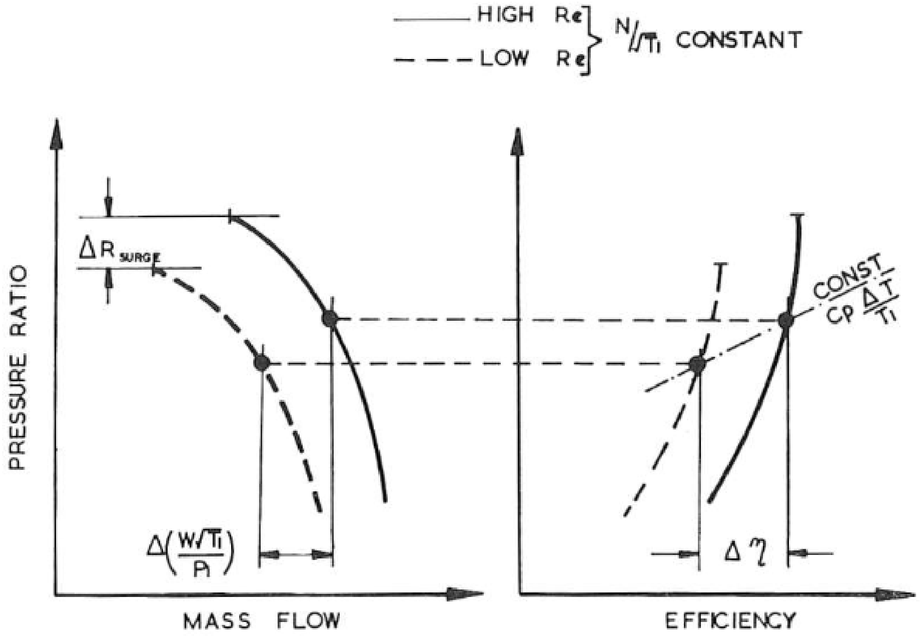
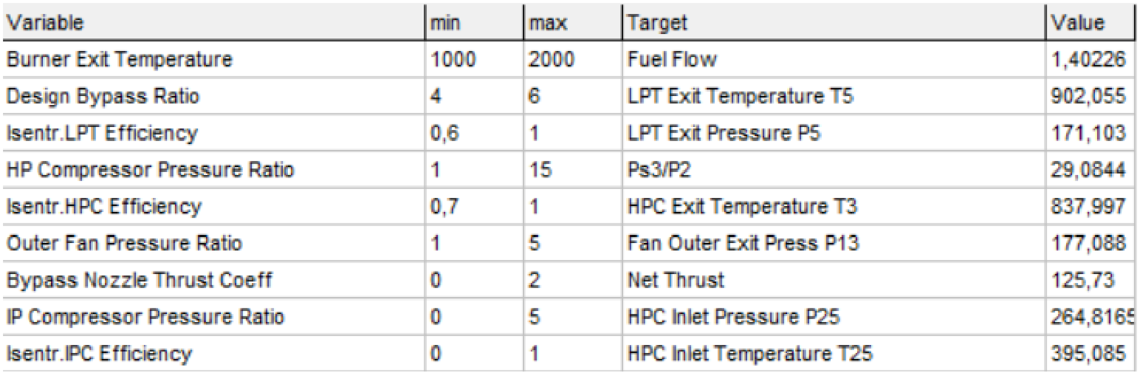


Figure 4.7: Effect of different Reynolds number on compressor performance[18].

For this reason, to prevent engine performance losses, the cycle reference point will be defined as the higher available value of N1 in the CTR. However, the point that has the highest N1 in the CTR has conditions that go beyond the data that can be used in equation (4.1) and (4.2). Therefore, the point that was chosen was the point 20 of the CTR. The difference between points 20 and 55 were not that much in terms of N1R and FNR, but to be totally accepted by the modifiers it needs to be point 20. By defining this point, we can also assure that the positioning of the VSV's and VBV's will not interfere with the final data. For high-speed regimes, the VBV's are closed and the VSV's are fully open allowing them to operate at maximum efficiency. By doing this we can ensure that the bleed schedule will not affect the mass flow and other parameters in the cycle.

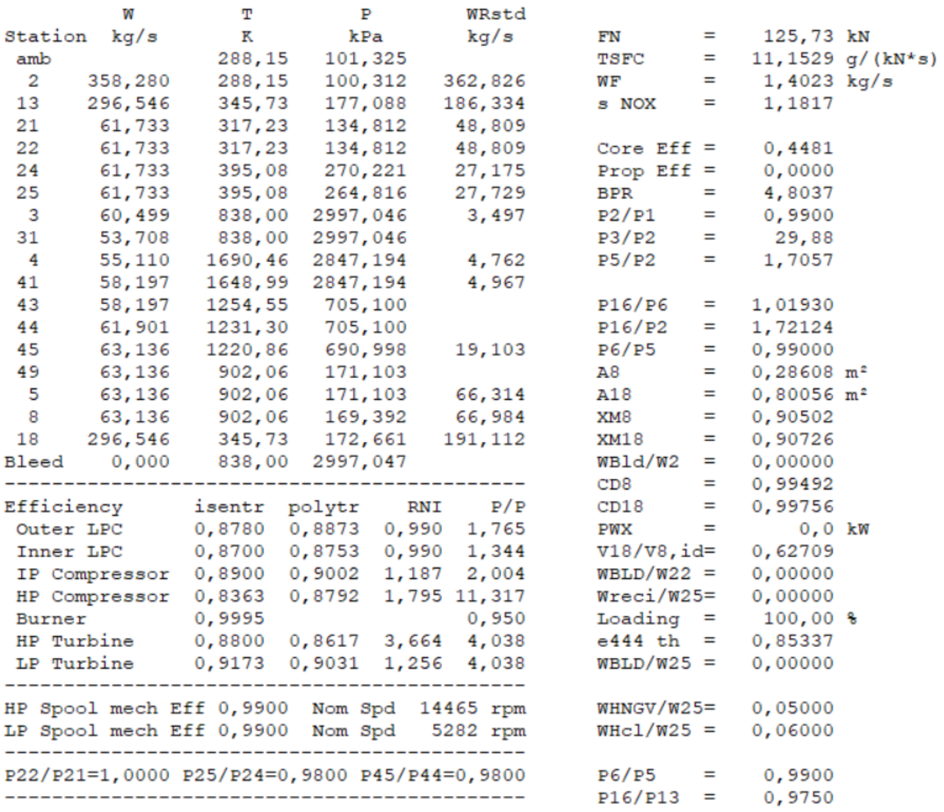
Once the reference point (point 20) has been chosen, the Facilities modifiers and the standard day corrections can be applied to the data regarding the test bed conditions. Using engineering judgment to fix the unknown model details [13], it is possible to start the process of adjusting the engine parameters to establish the design point for the engine. This will serve as an anchor point for the Off-design model tuning. The configuration of this point will allow setting the cycle parameters and component performance levels to meet the specification of this engine. These parameters are typically the compressor pressure ratios, burner exit temperature, total mass flow, bypass ratio, and component efficiencies. While some of this data is not publicly available and remains known only by the manufacturer, it is known that they belong to a certain range of values. It is crucial to define a reasonable interval for these values, otherwise, it can lead to a non-converged solution. The Gasturb software allows the user to iterate unknown parameters, using these as variables and setting a known target directly related to them. As an example, we can iterate the variable ”Isentropic LPT Efficiency” using as target P5 (LPT Exit Pressure) as these are directly related. It is also fundamental to refer that no component maps are needed for this cycle design mode calculations [13].The iterations used to reach the cycle design point are described in Figure 4.8 .



Variable	min	max	Target	Value
Burner Exit Temperature	1000	2000	Fuel Flow	1,40226
Design Bypass Ratio	4	6	LPT Exit Temperature T5	902,055
Isentr.LPT Efficiency	0,6	1	LPT Exit Pressure P5	171,103
HP Compressor Pressure Ratio	1	15	Ps3/P2	29,0844
Isentr.HPC Efficiency	0,7	1	HPC Exit Temperature T3	837,997
Outer Fan Pressure Ratio	1	5	Fan Outer Exit Press P13	177,088
Bypass Nozzle Thrust Coeff	0	2	Net Thrust	125,73
IP Compressor Pressure Ratio	0	5	HPC Inlet Pressure P25	264,8165
Isentr.IPC Efficiency	0	1	HPC Inlet Temperature T25	395,085

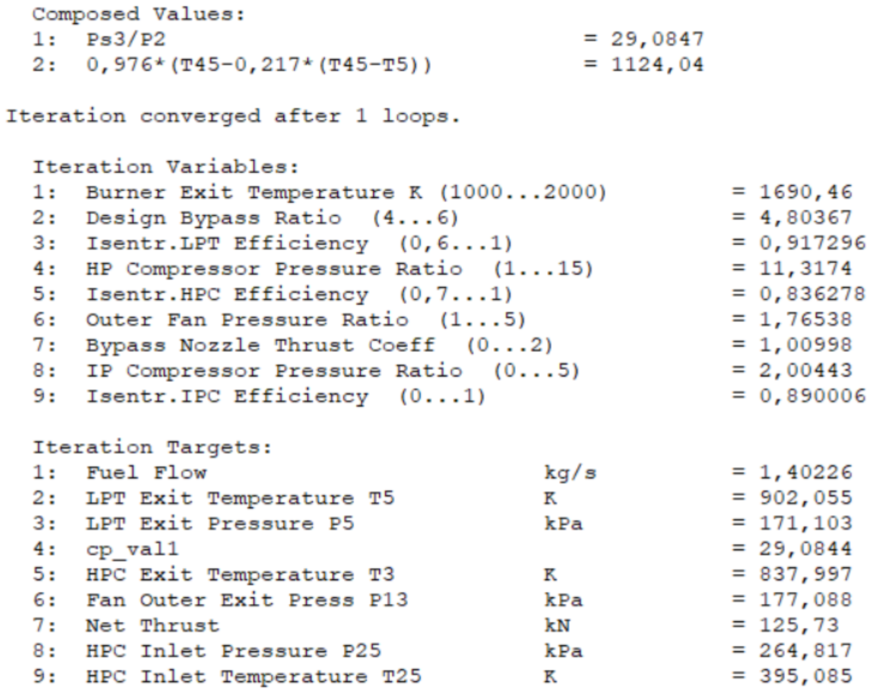
Figure 4.8: Iteration variables and targets to model the cycle reference point.

Upon reaching a converged solution, it is possible to obtain the output of the thermodynamic cycle concerning the cycle design point. This is shown in Figure 4.9, along with the corresponding iteration targets in Figure 4.10.



```
          W         T         P        WRstd
Station  kg/s       K        kPa       kg/s       FN       =    125,73 kN
 amb              288,15   101,325                TSFC     =   11,1529 g/(kN*s)
  2    358,280    288,15   100,312   362,826      WF       =    1,4023 kg/s
 13    296,546    345,73   177,088   186,334      s NOX    =    1,1817
 21     61,733    317,23   134,812    48,809
 22     61,733    317,23   134,812    48,809      Core Eff =    0,4481
 24     61,733    395,08   270,221    27,175      Prop Eff =    0,0000
 25     61,733    395,08   264,816    27,729      BPR      =    4,8037
  3     60,499    838,00  2997,046     3,497      P2/P1    =    0,9900
 31     53,708    838,00  2997,046                P3/P2    =     29,88
  4     55,110   1690,46  2847,194     4,762      P5/P2    =    1,7057
 41     58,197   1648,99  2847,194     4,967
 43     58,197   1254,55   705,100                P16/P6   =   1,01930
 44     61,901   1231,30   705,100                P16/P2   =   1,72124
 45     63,136   1220,86   690,998    19,103      P6/P5    =   0,99000
 49     63,136    902,06   171,103                A8       =   0,28608 m²
  5     63,136    902,06   171,103    66,314      A18      =   0,80056 m²
  8     63,136    902,06   169,392    66,984      XM8      =   0,90502
 18    296,546    345,73   172,661   191,112      XM18     =   0,90726
Bleed     0,000    838,00  2997,047                WBld/W2  =   0,00000
--------------------------------------------      CD8      =   0,99492
Efficiency      isentr  polytr     RNI     P/P      CD18     =   0,99756
 Outer LPC      0,8780  0,8873  0,990  1,765      PWX      =       0,0 kW
 Inner LPC      0,8700  0,8753  0,990  1,344      V18/V8,id=   0,62709
 IP Compressor  0,8900  0,9002  1,187  2,004      WBLD/W22 =   0,00000
 HP Compressor  0,8363  0,8792  1,795 11,317      Wreci/W25=   0,00000
 Burner         0,9995                 0,950      Loading  =    100,00 %
 HP Turbine     0,8800  0,8617  3,664  4,038      e444 th  =   0,85337
 LP Turbine     0,9173  0,9031  1,256  4,038      WBLD/W25 =   0,00000
--------------------------------------------
HP Spool mech Eff 0,9900  Nom Spd  14465 rpm      WHNGV/W25=   0,05000
LP Spool mech Eff 0,9900  Nom Spd   5282 rpm      WHcl/W25 =   0,06000
--------------------------------------------
P22/P21=1,0000 P25/P24=0,9800 P45/P44=0,9800      P6/P5    =    0,9900
--------------------------------------------      P16/P13  =    0,9750
```

Figure 4.9: Gasturb Output Single Cycle Results.



```
  Composed Values:
  1:  Ps3/P2                               = 29,0847
  2:  0,976*(T45-0,217*(T45-T5))           = 1124,04

Iteration converged after 1 loops.

  Iteration Variables:
  1:  Burner Exit Temperature K (1000...2000)          = 1690,46
  2:  Design Bypass Ratio  (4...6)                     = 4,80367
  3:  Isentr.LPT Efficiency  (0,6...1)                 = 0,917296
  4:  HP Compressor Pressure Ratio  (1...15)           = 11,3174
  5:  Isentr.HPC Efficiency  (0,7...1)                 = 0,836278
  6:  Outer Fan Pressure Ratio  (1...5)                = 1,76538
  7:  Bypass Nozzle Thrust Coeff  (0...2)              = 1,00998
  8:  IP Compressor Pressure Ratio  (0...5)            = 2,00443
  9:  Isentr.IPC Efficiency  (0...1)                   = 0,890006

  Iteration Targets:
  1:  Fuel Flow                         kg/s           = 1,40226
  2:  LPT Exit Temperature T5           K              = 902,055
  3:  LPT Exit Pressure P5              kPa            = 171,103
  4:  cp_val1                                          = 29,0844
  5:  HPC Exit Temperature T3           K              = 837,997
  6:  Fan Outer Exit Press P13          kPa            = 177,088
  7:  Net Thrust                        kN             = 125,73
  8:  HPC Inlet Pressure P25            kPa            = 264,817
  9:  HPC Inlet Temperature T25         K              = 395,085
```

Figure 4.10: Converged Iteration Targets.

As referred in section 3.2 the BPR of the CMF56-7B27 is 5.1. This value is different than the one in the output of the cycle reference point, which has a value of 4.8. This discrepancy is because the BPR value in the CFM manual is a representative value, this is also why the BPR value was used as an iteration variable and not the target. This value can be slightly different because of the reasons presented in chapter (3). However this represents a value of 5.8% of the deviation of the manufacturer value.

During the fourth iteration, the target used was not directly measured in the engine. Instead is the division of the static pressure at the inlet of the combustion chamber (PS3), measured directly on the engine, and the inlet fan pressure (P2).

Another value that was calculated as a composed value was the EGT. Even though this is one of the most important parameters for performance analysis in an engine, it is a difficult value to obtain due to the lack of the availability of this parameter in the software. Therefore, the EGT was not used as an iteration target, but rather as a value to compare the differences between the model and the CTR values. In a study conducted by Francisco Batista [20] on the CFM56-5B, it is described that this measurement can be calculated with the use of equation (4.6), being this equation the equivalent to the data recovered in the second stage of the LPT, as it was explained in section 4.2. The equation derives from a private communication between Kurzke and TAP&ME, regarding the study of the CFM56-5B. Due to the similar construction between the CFM56-5B and the CFM56-7B, this equation can be applied to the CFM56-7B variation. To get to this equation, Kurzke studied the decrease of temperature along the LPT stages. By assuming the aerodynamic loading is equal and the temperature drop between stages varies along the LPT due to the rotor blade diameter being different, (with the first stage being the smallest), it is possible to correlate the temperature drop in the first stage, which is also the smallest. In equation 4.6, the values from the temperature at the LPT inlet (T45) and the LPT exit (T5) are used to calculate the EGT. The value 0.217 is a guess for the relative temperature drop in the first stage of the LPT, and the 0.9664 is the recovery factor due to the work extraction [20]. Using this equation showed a 1.3% deviation from the value from the CTR.

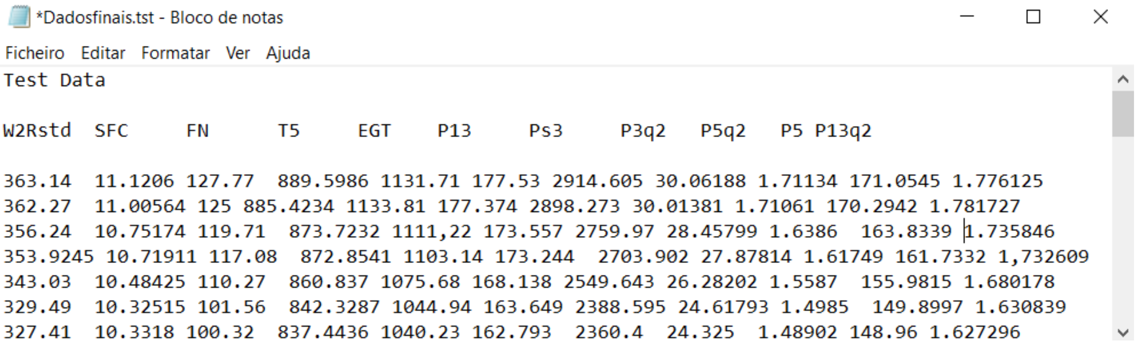
$$EGT = 0.9664 \cdot [(T45 - 0.217 \cdot (T45 - T5)] \tag{4.6}$$

4.5 Off-Design

After established the desired cycle design point, and achieving a converged solution, the off-design phase can begin. In on-design modeling, the performance of the gas turbine engine is known for a specific speed, pressure ratio, and mass flow for which the components are designed. While this provides a solid starting point, it is imperative to understand the variation of the performance of the engine over the complete operating range of speed and power in which operates. This phase is referred to as the off-design calculation of the model [21].

According to the method described by Kurzke [13], it is necessary to find suitable component maps to predict component efficiencies under conditions that deviate from the cycle design point. As stated by Kurzke [22] the OEM does not provide the general public with the original component maps and, is not practical to calculate them due to the need for detailed geometric information, which is also only accessible to the OEMs. The solution to this problem is to use generic maps from similar compressors and turbines available in the Gasturb software library, and adapt them to the data available [22]. This adaptation involves making adjustments to the efficiency values, and re-labeling the speed lines in these maps. It is important to mention that these changes applied to the original maps must be done in such a way that the inherent correlation between speed, pressure ratio, efficiency, mass flow, and specific work, remains unhurt since these correlations are strongly connected with the compressor and turbine flow physics[22].

To adapt the generic maps to the off-design conditions, 50 operating points from the CTR [10] were used. The data from the CTR can be introduced into Gasturb using the file format .tst [4]. This will provide a comparative figure that is going to be read by the software before calculating an operating line. Subsequently, a plot is going to be generated that displays the results from a single operating line together with the data from the .tst file. The .tst file structure is represented in Figure (4.11) .



```
Test Data

W2Rstd  SFC      FN       T5       EGT      P13      Ps3      P3q2    P5q2    P5 P13q2

363.14  11.1206 127.77  889.5986 1131.71 177.53 2914.605 30.06188 1.71134 171.0545 1.776125
362.27  11.00564 125 885.4234 1133.81 177.374 2898.273 30.01381 1.71061 170.2942 1.781727
356.24  10.75174 119.71  873.7232 1111,22 173.557 2759.97 28.45799 1.6386  163.8339 1.735846
353.9245 10.71911 117.08  872.8541 1103.14 173.244  2703.902 27.87814 1.61749 161.7332 1,732609
343.03  10.48425 110.27  860.837 1075.68 168.138 2549.643 26.28202 1.5587  155.9815 1.680178
329.49  10.32515 101.56  842.3287 1044.94 163.649 2388.595 24.61793 1.4985  149.8997 1.630839
327.41  10.3318 100.32  837.4436 1040.23 162.793  2360.4  24.325  1.48902 148.96 1.627296
```

Figure 4.11: Comparative Figure File.TST.

For comparison with the model, is it recommended to use global parameters like pressure ratio, total mass flow, thrust, or SFC. The SFC parameter has great importance because it is equivalent to the thermal efficiency of the engine for a specific flight condition [22]. Another parameter used is the EGT for the reasons referred to before in section 4.2. Parameters like T5, P5, and P13 are also taken from the CTR which are usually the parameters most difficult to obtain compliance with the model. Joaquim Kurzke [13, 22], explained the procedure to adapt the model to the CTR data. This procedure is summarized on the following topics.

The component map in Figure 4.12 consists of two axis: the X-axis represents the corrected mass flow, and the Y-axis represents the pressure ratio in each component. The Y-axis changes from component to component since each one is associated with different thermodynamic stations. When compared to the operating points of the CTR, the pressure ratio is very important to verify if the model is corresponding with the real data from the Test Bed.

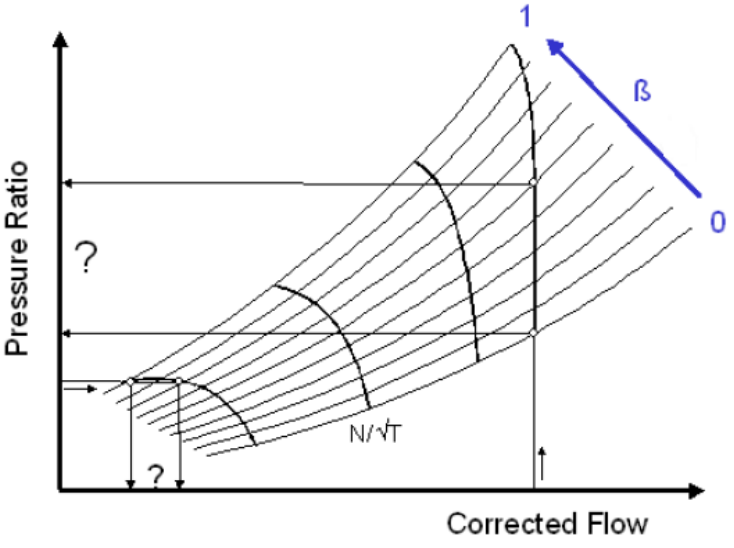


Figure 4.12: Generic Compressor Map [4].

Each map yields two correlations along an operating line:

1. Corrected Mass flow: Efficiency;
2. Corrected Mass Flow: Corrected speed;

In order to adapt this map to the data taken from the CTR, this correlation must be adjusted separately for each component map. The procurement is done easily in Gasturb by scaling the efficiency and the spool speed of each component map, aiming for both correlations to be in line with the given data [13]. Kuzrke suggests starting by dealing with both correlations separately and beginning with the first correlation. Nonetheless, efficiencies are not available in the CTR, however, by having knowledge of some parameters as temperatures and pressures, it is possible to establish a relationship between the data from the CTR and the model. If the model agrees with the operating points obtained from the test bed regarding each thermodynamic station, the efficiencies will naturally be corrected. The next phase is to adjust the relative corrected speed, which can be done easily if the efficiencies of the components are correct. Additionally, these adjustment done to the relative corrected speed can be achieved without impact on the efficiency at a given compressor flow and pressure ratio. The precedent follows a relabelling of the speed lines on the Fan and HPC maps with the regard that the fan and the boosters share the same speed distribution due to the turbofan configuration. Shifting the location of the cycle reference point, will have consequences on the part load efficiency distribution without changing the cycle reference point features. If the cycle reference point is relocated in a map region with poor efficiency, then efficiency will increase towards the part load. Consequently locating the cycle reference point in a map region at the peak efficiency, will lead to decrease in efficiency towards the part load. This is an iterative method where is necessary to constantly verify the effects of changes on the components and also the agreement between the thermodynamic cycle simulation and the data from the CTR data until a suitable reference point for all components is found [13]. At least, the final step is to verify the effect of the VBVs and VSVs on the off-design modeling. TAP ME does not possess the operations schedule for this engine. However, this analysis is using take-off power points, and in this types of regimes the bleeding schedule of the valves will not interfere with this operation point since they are closed in order to provide the maximum power for the engine. So their effect was neglected for this procedure.

4.6 Remarks regarding the validation

After following this procedure and once the model is accurate with the data from the CTR, a complete thermodynamic model of the engine becomes available. This model enables the possibility to analyze and obtain every value of pressure, temperature, and airflow in each thermodynamic station for all the engine operating points.

The analysis showed some abnormal data in the station positioned at the exit of the LPT. Despite efforts to adjust the model to the data of the CTR, it was not possible to achieve a solution without changing the conditions of the other maps in a considerable way. After discussions with the TAP engineers, the problem was identified. The pressure and temperature probes located in this thermodynamic station had reliability issues. The T5 probe used was not the best fit for the job because it was easily damaged and could lead to some accumulation of errors [23]. This probe was a test tool, (figure 4.14), that connected the sensor to the probe. This cable was not made of rigid material, making it prone to breakage and produces an associated errors.

Figure 4.13: Malfunctioning T5 probe[23].

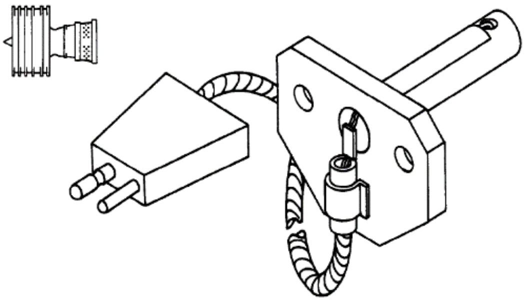


Figure 4.14: Malfunctioning T5 probe.[23]

In order to increase the probe reliability, TAP opted to acquire a T5 probe (Figure 4.16) that is part of an optional engine monitoring kit. This probe is more robust and will be used in future tests of CFM56-7B engines. This one is located at the 4 o´clock position on the LPT rear frame. As it is shown in Figure 4.16 it consists of a metal body, housing two thermocouple probes and a rigid lead that transmits the signal from the probe to the main junction box.

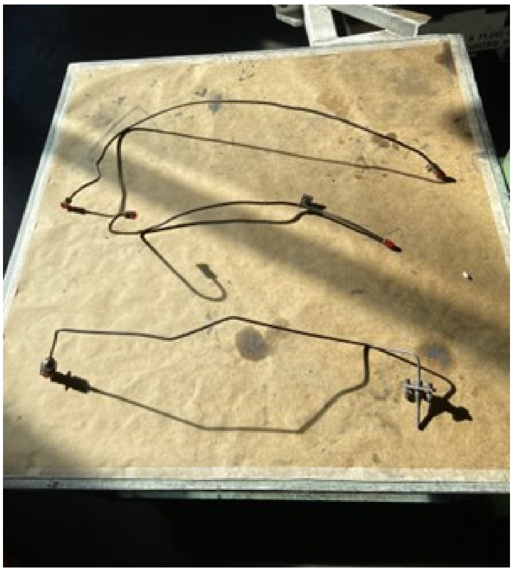


Figure 4.15: T5 probe monitoring kit[23].

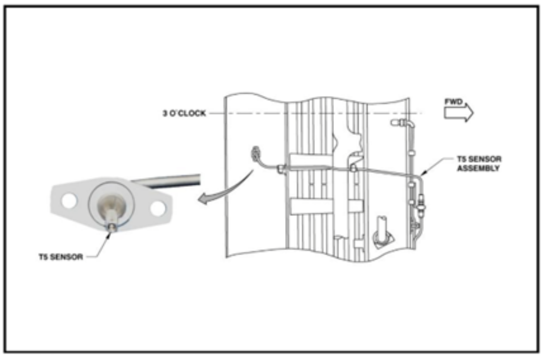


Figure 4.16: T5 probe monitoring kit[23].

Regarding the PT5 sensor, this would collect the pressure through a flexible metallic mesh tube, with a high-temperature Teflon interior, as shown in figure 4.17. Over time, this tube would fracture, leading to pressure losses. At the moment there is already a rigid metallic tube, made at measure, to increase the reliability of the reading.

These malfunctions would consequently associate an error regarding the data of the EGT measured (Figure4.23), since this was composed value composed that used the reading of T5(Eq4.6.

Figure 4.17: Old PT5 probe.

As of the time of this report, there is no test of an engine that has used this new upgrade regarding the LPT exit thermodynamic station,consequently, it is expected some minimal errors associated with this upgrade in the final data of the off-design model. The comparison between the model and the values from the CTR are presented next, with values from the CTR in purple and the ones from the model in yellow (Figure 4.18 to 4.26).

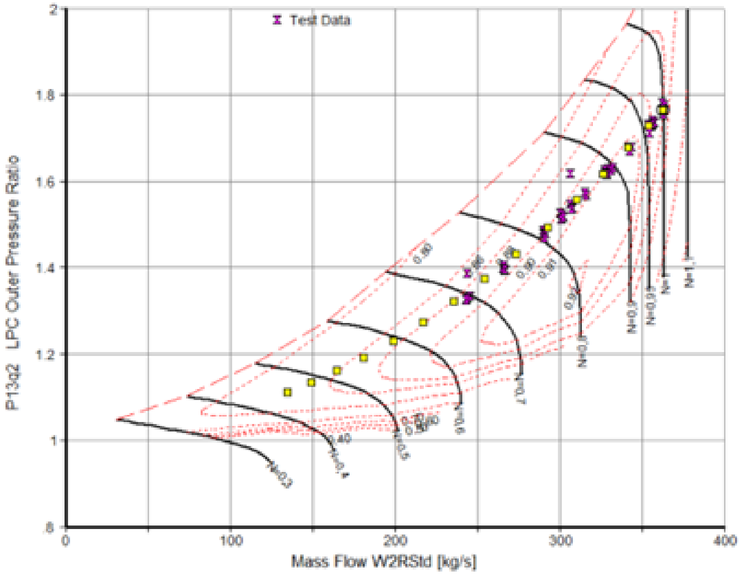


Figure 4.18: LPC Map.

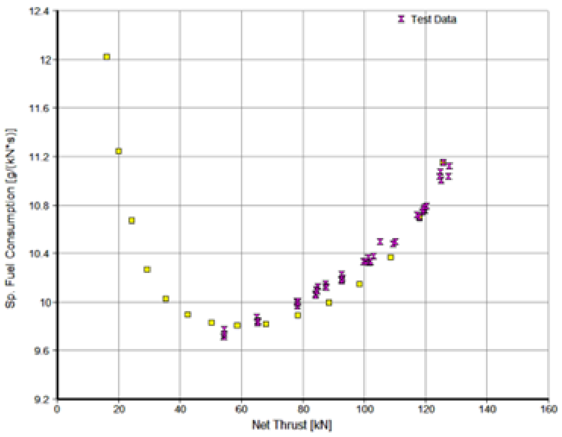


Figure 4.19: SFC vs Net Thrust.

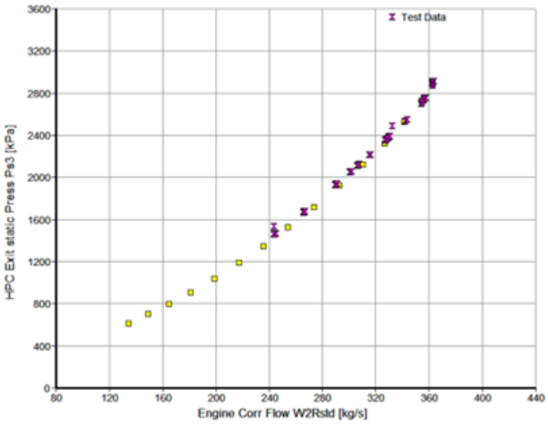


Figure 4.20: PS3 vs W2rstd.

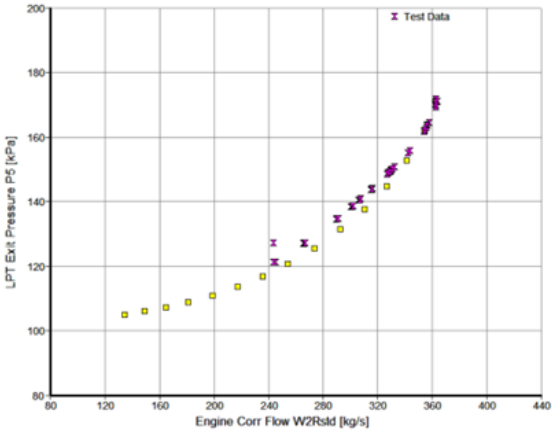


Figure 4.21: P5 vs W2rstd.

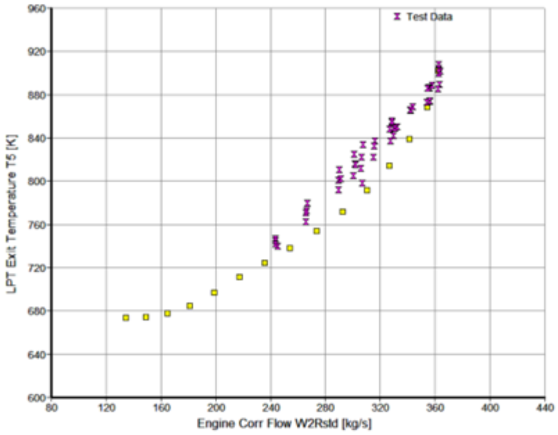


Figure 4.22: T5 vs W2rstd.

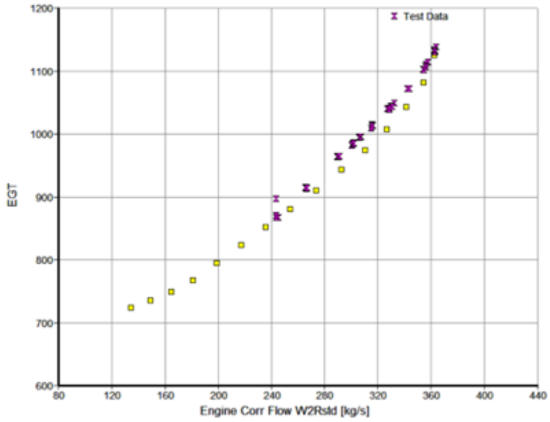


Figure 4.23: EGT vs W2rstd.

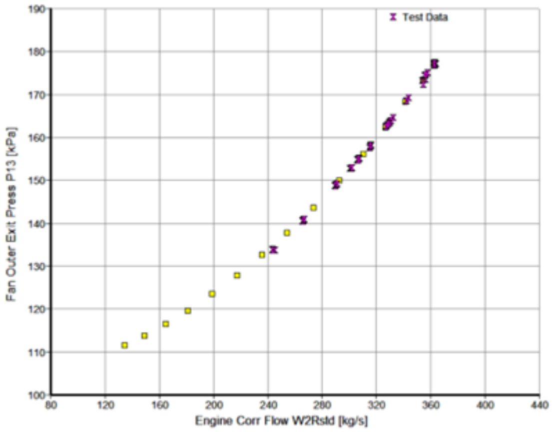


Figure 4.24: P13 vs W2rstd.

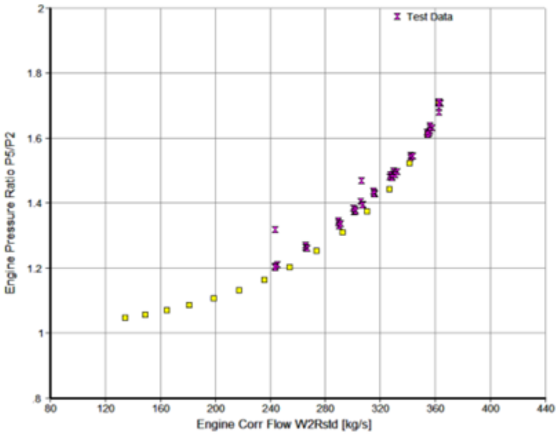


Figure 4.25: P5/P2 vs W2rstd.

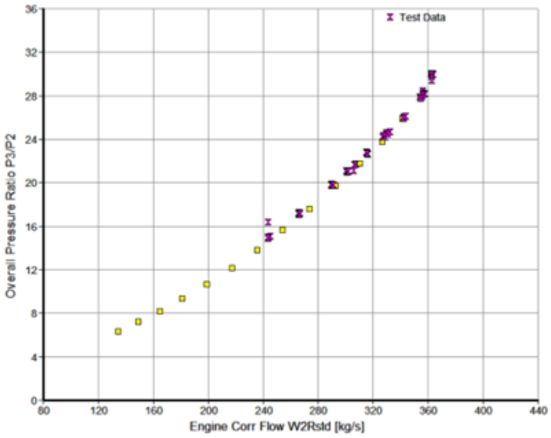


Figure 4.26: P3/P2 vs W2rstd.

Chapter 5

Engine model applications

Once the final off-design model is completed and validated with the test bed data, it can be used to simulate the degradation effects in every model of the turbofan engine. Since the data used to model the cycle reference point is from an engine considered to be stable with minimum levels of degradation, this model has a high potential on helping the TAP&ME engineers in analyzing the performance of other CFM56-7B engines. By performing such analyses, it is possible to allocate the exact financial and human resources to the engine modules with poor performance, knowing for sure which one is responsible for low performance

The different modules that constitute a turbofan engine, especially the engine compressor, core, and power turbine operate in harsh environments whith high temperatures and pressures. Due to this, these parts can show wear and tear over the lifetime of the gas turbine and consequently have some impact on the operation of the machine.

In a study conducted by Rainer Kurz and Klaus Brun [24] about how degradation develops and affects the performance of the gas turbine is stated that are numerous ways of degradation. These can be;

- Fouling - caused by the adherence o particles to the airfoil, and annulus surfaces caused by oil, or water mists that increase the roughness and the shape of the airfoil,

- Hot corrosion, defined by the loss or deterioration of material from flow path components caused by chemical reactions between the component and certain contaminants,

- Corrosion, caused by the inlet contaminants and by fuel and combustion derived contaminants,

- Erosion, removal of material from the flow path by hard or incompressible particles

- Damage-caused by the strike of foreign objects in the flow path components and abrasion, caused by the prolonged contact between rotation surfaces and a stationary one.

All these influences lead to a simultaneous loss of similar magnitude in efficiency of each component and consequently, a decrease in engine performance.

5.1 Model Based Test Analyses

In maintenance shops, it is not possible to extract the absolute values of component flow capacitives and efficiencies because the instrumentation is not sufficiently accurate for that purpose. However, with the data available from the test bed, it is possible to compare the results with data from other engines or with those from a nominal engine [14].

Model-based test analyses is a tool that allows the user to evaluate the performance of each engine by matching the data from the test bad to the data of a benchmark model such as the one developed in the chapter 4. The program calculates modifiers for the component maps in a special test analysis mode which make the model match exactly with the measured data. As stated by Kurzke in [17], the magnitude of the model adjustment factors reflects the actual component performance test results. By performing these analyses, it is possible to know if an engine has a component working under the expected performance, making it a helpful tool for a MRO company like TAP.

Model-based performance analysis is also known as an analysis by synthesis (AnSyn)[17]. It is a type of analysis that has a combination of two or more entities, where one is matched to the other. For two, or more models to be in agreement a scaling factor (AnSyn factor) must be applicated. The AnSyn factors are calculated using simple fractions, as shown in equations (5.1) and (5.2):

$$AnsynEfficiencyFactor = \frac{MeasuredEfficiency}{ModelEfficiency} \tag{5.1}$$

$$AnsynFlowFactor = \frac{MeasuredFlowcapacity}{ModelflowCapacity} \tag{5.2}$$

If a factor of 1 is applied to the model, it means that the component is working in agreement with the model that is being compared, indicating no signs degradation. If the factor is greater than 1, it means that the component performs better than predicted, while a factor lower than 1 it represents that has a malfunction.

Gasturb allows the user to load the data of the model constructed in the previous chapters, and the next step is to input the data from the engine test bed regarding each thermodynamic station. Kurzke alerts that not only do the compressor and turbines deteriorate during service due to the reasons named earlier, but the sensors also degrade over time, all of which makes data interpretation not that exact. [17].

Table 5.1: Gasturb parameters and their Availability

Relative Humidity	✓
Mass Flow W2	✓
Low Pressure Spool Speed N1	✓
High pressure Spool Speed N2	✓
Inlet Temperature T2	✓
Inlet Pressure P2	✓
Fan Outer Exit Temperature T13	N/A
Fan Outer Exit Pressure P13	✓
Fan Inner Exit Temperature T21	N/A
Fan Inner Exit Pressure P21	N/A
Booster Exit Temperature T24	✓
Booster Exit Pressure P24	N/A
HPC Exit Temperature T3	✓
HPC Exit Pressure P3	✓
Fuel Flow Wf	✓
HPT Exit Pressure P44	N/A
LPT Inlet Temperature T45	N/A
LPT Outlet Pressure P5	N/A
LPT Outlet Temperature T5	N/A
Ambient Pressure P0	✓
Measured Thrust FN	✓

In Chapter 4 is addressed the overall problem of the lack of probes and sensors needed to isolate some components of the engine necessary for a full performance analysis of the CFM56-7B engine. By doing a quick comparison between the data from the tests and the data from the model revealed that some data like P5 and T5 showed some incoherent values. This confirms that these probes have malfunctions and cannot be trusted for the analyses of the engine performance. Table 5.1 is shows the Gasturb engine stations needed for the analysis of the engine and their referred availability.

The model-based test analyses input window in Gasturb, offers the option of iterating some parameters in order to find missing values for the station. However, this method can lead some problems in the final analysis because if a value for a thermodynamic station is obtained from the model, the AnSyn factor will always be 1 and this compromises the analysis of the state of degradation of that component. To avoid this issue, it was decided that this method would only be used to iterate the parameter T13. As stated by Kurzke [17] accurately measuring the rise in temperature in the fan module in a high-bypass engine can be challenging. This leads to measurements of inaccuracies in the balance of power between the fan and the LPC 5.1. The efficiency of the outer Fan is not expected to change significantly during service. Therefore, by performing a visual inspection it is possible to see if erosion, increased tip clearance, or foiling is affecting the component. If none of those factors are present is reasonable to assume that the fan outer efficiency is equal to the one in the model, ensuring that the value for the fan efficiency does not disrupt the values of the other efficiencies factors for other modules.

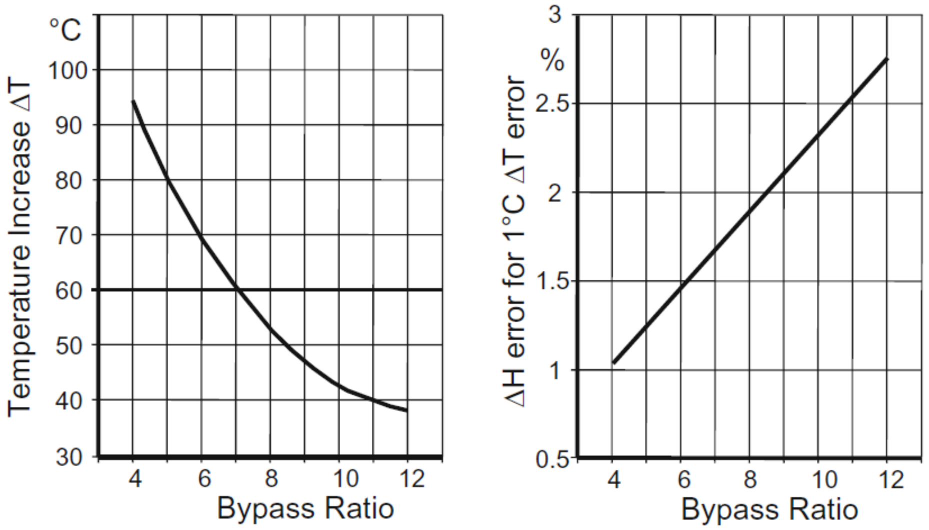


Figure 5.1: The effect of T13 uncertainty on fan work uncertainty [17].

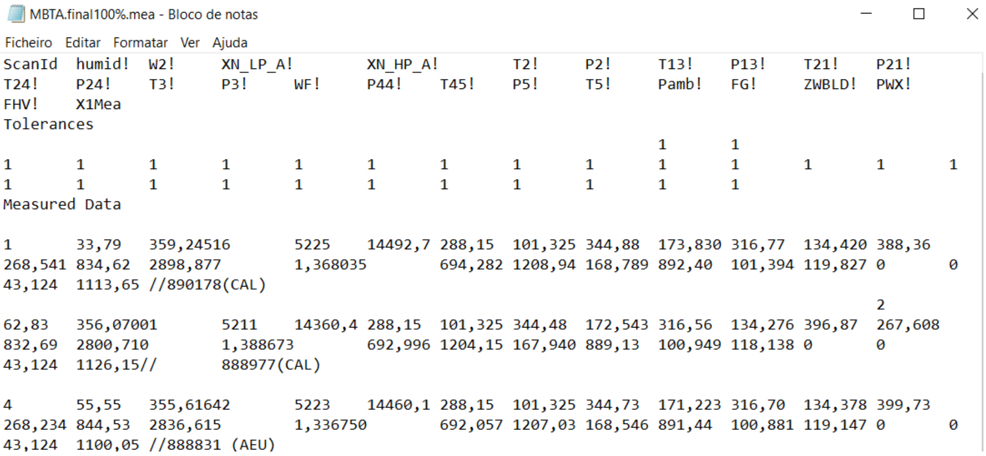
Using hybrid data is another method for analysis. The work developed by Kurzke [14], suggests the use of data from the model created in the chapter 4, since it was used data from a benchmark engine for his tailoring, to complement the unavailable data needed. During a performance test, the engines are tested in different operating conditions such has LP spool speed. Therefore the technicians overwatching the test can set this as a target regarding the objective of the test. In this analysis, the objective was to compare the engines with the model in take-off regimes. The model used to complement the data employ the cycle reference point as a reference. This means that the LP spool speeds or N1R will be higher than the ones in the tests. Like the technicians in the workbench, Gasturb also allow us to change the N1R and match the conditions necessary to use data from the model. This is done using Gasturb limiters tool. This tool allows the user to set a maximum and a minimum to some parameters like LP speed, fuel thrust, or fuel flow. By positioning the maximum according to the test, it's possible to extract the exact data needed for every flight condition. There is only one final step to use the data to complement the model. This step consists of converting the parameters for the same ambient conditions as the ones in the engine that is putted to test, so, measured temperatures and pressures have to be converted to the same ambient conditions as the data extracted from the model. Has stated before, the data from the correlation report is already converted to standard day conditions. To achieve this, equations (4.3) and (4.4) are used in the data from the engine test cell.

In synthesis analysis the data from the engine performance test is going to be adapted to the data from the benchmark model. To do this, a matching scheme must be selected. This is the parameter is going to guide the matching process, therefore being one of the most important aspects for this type of analysis. This parameter is not going to be modified and will show the scaling factors on the other variables, serving as a anchor for the whole process. Gasturb offers some methods that can be used as this parameter.

- HP turbine capacity- matches the HPT capacity of the model with the engine tested .
- Lp turbine capacity- matches the LPT capacity of the model with the engine tested.
- T45 heat balance- matches the T45 measured with T45 of the model.
- T5 heat balance- matches the T5 measured with T5 of the model.

The T45 heat balance was chosen as a method of adaptation since it was the one that gave the best results

Data measured from the test bed can be introduced manually on the MBTA analysis input table or using a multiple-point data input file. This allows the user to analyze several points simultaneously. Test data for multiple points can be read from a file with the extension.mea where each parameter follows the Gasturb nomenclature, along with the software reading commands. Figure (5.2) is part of the MEA file created for the analysis of several engine tests.



```
ScanId  humid!  W2!     XN_LP_A!        XN_HP_A!        T2!     P2!     T13!    P13!    T21!    P21!
T24!    P24!    T3!     P3!     WF!     P44!    T45!    P5!     T5!     Pamb!   FG!     ZWBLD!  PWX!
FHV!    X1Mea
Tolerances
                                                                        1       1
1       1       1       1       1       1       1       1       1       1       1       1       1       1
1       1       1       1       1       1       1       1       1       1       1
Measured Data

1       33,79   359,24516       5225    14492,7 288,15  101,325 344,88  173,830 316,77  134,420 388,36
268,541 834,62  2898,877        1,368035        694,282 1208,94 168,789 892,40  101,394 119,827 0       0
43,124  1113,65 //890178(CAL)
                                                                                                2
62,83   356,07001       5211    14360,4 288,15  101,325 344,48  172,543 316,56  134,276 396,87  267,608
832,69  2800,710        1,388673        692,996 1204,15 167,940 889,13  100,949 118,138 0       0
43,124  1126,15//       888977(CAL)

4       55,55   355,61642       5223    14460,1 288,15  101,325 344,73  171,223 316,70  134,378 399,73
268,234 844,53  2836,615        1,336750        692,057 1207,03 168,546 891,44  100,881 119,147 0       0
43,124  1100,05 //888831 (AEU)
```

Figure 5.2: .mea file of the Test Bed Data.

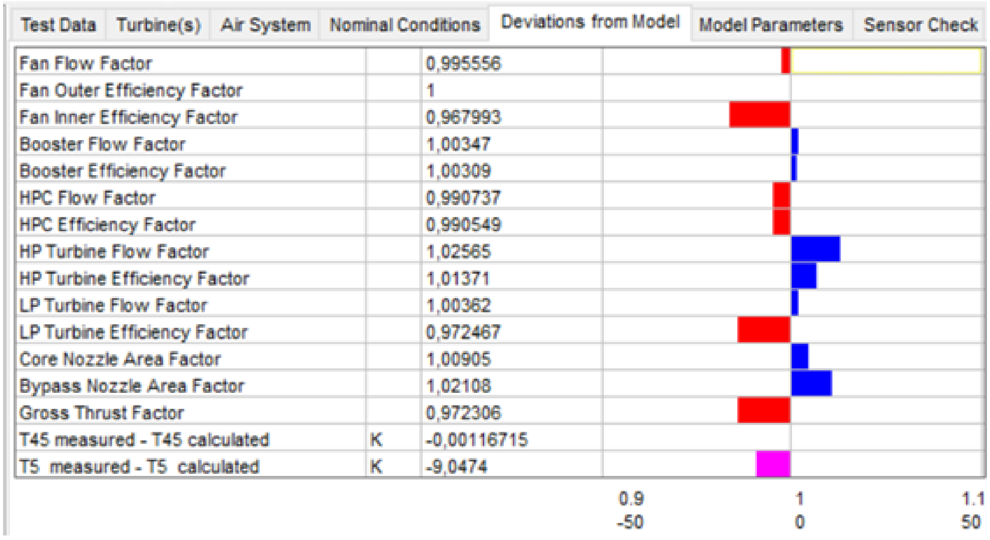
Chapter 6

MBTA validation and results

This chapter will present the MBTA validation and results. This was possible by collecting data from some tests done on the CFM56-7B engine. As said before, engine performance tests can be done at different rates. Since the model was constructed around the CFM56-7B27 ratio, it was possible to extract only 8 performance tests from different engines since the model is not suitable for other rates. A database was created using Excel VBA macros to ease the data treatment process. In addition to the necessary information regarding the thermodynamic stations, information about the EGT was added since this is one of the most important parameters in engine performance analyses (section4.2). Once all the data from the model is running at the corrected spool speed and corrected to the standard day conditions, it can be introduced in the MBTA Gasturb module. This one reached a valid solution, however, it is TAP&ME interest that not only Gasturb has a valid solution, but also a trustworthy one, as this method is intended to be used to evaluate the degradation state of the CFM engine. As it was said in section 2 TAP&ME is an MRO company, so, when a component arrives at their facilities it can be with different maintenance objectives. In the engine shop, many actions can be done to an engine, varying between inspections and overhaul activities to heavy maintenance in the respective modules. Nonetheless, every engine that enters the engine shop needs to be tested on the workbench to check if it is running according to the expected conditions. The 8 performance tests analyzed are from acceptance tests, so, by comparing the MBTA data to the work done before by the engineering and maintenance team, it is possible to see if the model in Gastub is trustworthy. Of the 8 performance tests, one is going to be described next. Due to privacy policies between TAP&ME and the aviation companies owners of these engines, the subject is going to be referred to as “Engine A”.

6.1 Engine A

The data regarding the acceptance test of engine A was introduced in the MBTA following the procedure described before. Using the data from station 24 as obtained from the engine test bed, would have yield an invalid result for the booster efficiency. This would have implied that the booster was operating with an efficiency out of the range defined during the design phase of the modeling. In typical acceptance tests, it is not usual to place the T25 and P25 sensors, since this values are not needed for the analysis and could lead to problems if they break loose. Instead, the calculation of this parameter is done by the test engine software, which uses a system of iterations to get these values. Due to this, it was decided to use the correspondent value of T24 from the model to mitigate potential errors in the analysis. This led to an enhancement in the results, since the value from the booster efficiency would not affect the performance of the HPC. The results of engine A operating under take-off conditions are shown in Figure 6.1.



Fan Flow Factor		0,995556
Fan Outer Efficiency Factor		1
Fan Inner Efficiency Factor		0,967993
Booster Flow Factor		1,00347
Booster Efficiency Factor		1,00309
HPC Flow Factor		0,990737
HPC Efficiency Factor		0,990549
HP Turbine Flow Factor		1,02565
HP Turbine Efficiency Factor		1,01371
LP Turbine Flow Factor		1,00362
LP Turbine Efficiency Factor		0,972467
Core Nozzle Area Factor		1,00905
Bypass Nozzle Area Factor		1,02108
Gross Thrust Factor		0,972306
T45 measured - T45 calculated	K	-0,00116715
T5 measured - T5 calculated	K	-9,0474

Figure 6.1: MBTA results for engine A under Take-off Regime

By analyzing the deviation from the model, the disparities between the effects of the degradation of each module in the overall engine performance is clear. It is important to notice that the model of the CFM56-7B created in the chapters before, has its foundation in the data from the CTR [10]. The engine used in the development of this document it is not entirely new unit, but is an engine that is in good condition. As it was said in section 5.1 if the scaling factor is smaller than 1 (red bar) it means that this component is working worst than the one used to construct this module, and if the factor exceeds 1 (blue bar), it implies the opposite, in other words, if this happens it means that that module suffered some repairs or other level of overhoul that had improved his performance.

By comparing the MBTA output with the technical report of this engine, it is possible to confirm the correspondence of the model with the actual shop visit treatment. The technical report detailing the maintenance activities undertaken on this engine shows that this engine entered the workshop with the objective of a core performance restoration. In the HPC mini module area, it is shown that the engine was fully disassembled and repaired as applicable.

However, the Gasturb software shows an anSyn factor below 1 indicating that this component is operating below the desired efficiency. Kurzke [17] emphasises, that this software is a tool to help the engineer to evaluate the true state of an engine. Moreover, he notes that the Ansyn factors are not precise since it is not possible to do a full performance of the minimodules due to the lack of sensors upstream and downstream of the component. However, this shows a deviation of approximately 1% in both HPC efficiency and flow factor implying that this component is operating close to the desired expectations. On the other hand, the HPT factors sugest that this component is working over expectations. This is supported by the technical report since this component went under performance restoration activities in this module. The LPT also went under some reparation activities more specifically in the LPT rotor/stator and on the LPT shaft. However, the Ansyn Factor indicates that this component is running below the expected efficiency. Even though this component went thought some minimal reparation, this value can be explained by a problem in the component that is not associated with the parts repaired. Unfortunately, the complete analysis of one component is impossible due to the complexity of the module and if the performance is not affected in a significant way this tends to be discarded.

Due to the lack of sensors in the Fan and booster, it is not possible to analyze the component with the same accuracy as the other modules. Nevertheless, the technical report stipulates that the fan and booster were removed only for inspection and light work that would not influence its performance by itself When performing the acceptance test one of the most important values to attain is the value of the EGT. In the acceptance test, the recorded value was 1113.65K. By setting a composed value referring to the EGT in the MBTA analysis it is possible to determinate the value of this parameter under these conditions. Consequently it is noteworthy that the EGT has a value of 1114.8K, representing an error of 0.1% compared to the real observed value in the acceptance test. This shows that even with the lack of sensors in some modules, is a reliable way to evaluate the true state of the engine. However, it is important to notice that a Model-Based method can be helpful for engine performance analysis but it should not replace a comprehensive data analysis [17].

Chapter 7

Conclusion

This chapter will present the achievements of this thesis, the difficulties encountered throughout the development of the present work, and a list with proposed recommendations and suggestions for future development in this area. Due to the engine manufacturers privacy policy, some information gathered during the development of an engine regarding component maps, pressure ratios, and thermodynamic parameters are hidden from the public.

For the purpose of engine life monitoring , it is of great importance that a MRO companies such as TAP have access to model-based performance analyses that can simulate component maps. These tools aid the engineering team evaluate the operational condition of an engine, and making informed decisions regarding maintenance and repair activities. This thesis's objective was to develop a prediction model of one of the most common turbofan engines, the CFM56-7B, that could be used by the Tap&ME engineering team enabling them to allocate their resources effectively and address specific component malfunctions. In order to create this model, performance parameters from the TAP engine test bed correlation report for the 27 rate were utilized.

The modeling software chosen was GasTurb, a user-friendly program that allows the user to create the thermodynamic model using their own data. The CFM56-7B engine was chosen because it is amongf the most commonly used engines by airliners that opt for TAP&ME services for their repair and overhaul activities. In order to achieve this goal, a method described by Joaquim Kurzke [14], one of the specialists in turbofan engines, was followed. The first step was to establish the engine design point that will give us the starting operating point. To ensure precision, the point chosen to model the operating point was the maximum power point from the correlation test report, thus ensuring that the Reynolds number and the VBV's and the VSV's effect are negligible. Once this point is defined the next step is to find the operating line of the engine components, or in other words, the operating points for different engine conditions and different power settings. By creating a comparative figure between the model operating points and the points from the CTR, for other thrust settings it is possible to conclude that these two types of points would coincide with great precision confirming the model´s validity.. Gasturb tool model Based Test Analysis was used to check if the model was ready to use with real data. Every engine that enters the Engine Shop is obligated to do an acceptance test. During this test the engine is rigorously examine to ensure its proper functioning following any repair or overhaul activities. The premise was to compare the GasTurb MBTA tool results with the engine technical reports and see if the repairs that were made to the engine reflected in the simulation. Regrettably, the availability of tests conducted on this engine at the CTR rate was limited, resulting in only 8 tests being analysed. Another difficulty that was encountered was the lack of sensors needed for a complete performance analysis of this engine. This had some impact on the accuracy of the results since not every run was exact. However, for some engine, it would show the effects of certain repairs, particularly in the core and HPT major modules since these were the modules that had more sensors working properly. Another parameter that was observed was the EGT, a parameter used by the engineers to evaluate the state of the engine, this would show a relative error of less then 0.1% compared with the engines tested. Concluding, this thesis offers to TAP ME a valuable tool that will help engineers to analyze the performance of the CFM56-7B engines by revealing which component is responsible for the low engine performance, thus saving financial and human resources.

7.1 Future work

The model created in this thesis can be further improved, not only to function with precision in points close to the take-off regime but also in every point of operation of this engine. This model is also only applied to the CFM56-7B engine working at the 27 rate. In order for this to be used in every 7B engine it would be important to adapt this model to the other rates that this engine can perform. At last, with an update in the range of sensors available for this engine, it would be possible to analyse the engine using the MBTA tool in detail without making use of hybrid data.

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