A 0-D Off-Design Performance Prediction Model of the CFM56-5B Turbofan Engine

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Abstract

Gas turbines performance deterioration can be identified at the engine module level in terms of reduction in the component mass flow and efficiency. The identification of the faults will facilitate and allow to focus the financial and human resources in an effective engine maintenance work scope. In this work, a performance model for the CFM56-5B engine has been developed using the gas turbine computer simulator *GasTurb*®, to study the impact that the high pressure compressor (HPC) performance has on the overall performance of the engine. The modelling phase begins by selecting an appropriate cycle reference point, followed by the off-design, where the model is matched to the performance of an existing engine. The *GasTurb*® tool allows to assess the condition of an engine and its components, by inputting parameters of the tested engine in the software. A database using macros was created to ease the data processing and store the performance of different engines. This will allow to identify which components of the engine are at fault. The work focus primarily in the performance of the HPC and the difference in performance when using repaired or new blades, taking into account that some geometric properties of the blades cannot be restored, specifically its chord. An analysis to the HPC stages was also conducted to understand which stages affected the HPC performance the most and why. The developed study emphasizes the importance the first stages of the HPC have on its performance. With the work developed, TAP Maintenance & Engineering has the possibility to evaluate the condition of the CFM56-5B engine components and optimize its resources to reach the desired engine performance.

Keywords: Compressor blades, Performance loss, Turbofan engine, Performance model, Maintenance repair

1. Introduction

The performance of gas turbines, specifically Turbofan engines, depends on the efficiency of each engine component, that are the fan, compressor (booster and high pressure compressor), combustion chamber and turbine (low pressure turbine and high pressure turbine). A knowledge of the true state of each component is essential to evaluate its deterioration and, by doing so, to perform a Condition Based Maintenance (CBM) individually. This practice is an effective strategy to improve engine availability and reduce maintenance costs and failure hazards. With the continuous operation of the engine, deterioration affects the engine components and these become less efficient.

Gas turbines have always been studied with the use of thermodynamic models. If the behaviour of an engine and its respective components is known, the maintenance and engineering teams of Maintenance, Repair & Overhaul (MRO) companies can act accordingly to solve potential performance problems. *GasTurb*® is a commercial gas turbine computer simulator [1] that allows the user to model an engine for research and industry purposes. This software is currently on its 13^{th} version, however the work developed in this thesis will be made using *GasTurb*® 11. The capabilities between versions are very much the same, being the only major difference the user interface.

The main objective of this work is to evaluate the impact that the high pressure compressor (HPC) has on the overall performance of the CFM56-5B engine. Secondly, to develop a database using Microsoft® Excel Visual Basic (VBA) macros that will store the CFM56-5B engine components performance and provide a basis of comparison to other engines in the future. This will be accomplished using the Model Based Test Analysis (MBTA) tool that *GasTurb*® offers, and that will allow to compare the engines performance with the developed model. The database will be of crucial importance because it will allow to compare components performance between different engines. Regarding the HPC, it was studied the effects that an improvement in its efficiency would have in the overall performance of the engine. An analysis to the HPC stages was accomplished to understand which stages affect the HPC performance the most and why.

2. Maintenance Concepts, MRO Facilities and the CFM56-5B Engine

Commercial aircraft maintenance costs can be divided into three main areas: airframe, engines and components. These three areas represent the majority of an aircraft's maintenance exposure over its service life, although engine maintenance costs will often represent the most significant and, consequently, will have an important impact in the market of commercial flights. These costs grow as time on-wing increases since the level of deterioration that affects the engine is greater. Nonetheless, engines have to spend as much time as possible on-wing for the airlines operations to be profitable. When an engine comes to a shop visit, its maintenance works can be of two types:

- Performance Restoration: The components parts deteriorate as these are damaged due to heat, erosion and fatigue. This type of deterioration affects the engine core the most. During the continuous operation of the engine, its exhaust gas temperature (EGT) increases constantly, causing an accelerated wear of the parts, thus decreasing further the engine performance. A critical EGT is established by the engine manufacturer and before the engine reaches that limit, performance restoration works must be accomplished;

- Life Limited Parts Replacement (LLP): The rotating compressor and turbine shafts and disks have a defined operating life. When it is reached, these parts must be replaced and never used again.

This work will only focus on performance restoration.

2.1. TAP Maintenance & Engineering

On completion of the maintenance works and assembly of the engine, every engine must be tested before being installed on wing to ensure that it meets the contractualized performance. Test bed facilities can be of two types: high altitude test cells or sea-level test cells. In sea-level test facilities, these can also be of two different types:

- Outdoor test facility;

- Indoor test facility.

Figure 1: Indoor test facility of TAP M&E [2]

At TAP Maintenance & Engineering (M&E) the test cell facility is of the sea-level indoor type (illustrated in figure 1), where the engine runs at ambient temperatures and pressure conditions. The resulted performance is corrected to the International Standard Atmosphere (ISA) sea-level conditions. The engines are tested to a flight evaluation test schedule that covers characteristics as anti-icing, performance, mechanical reliability, oil and fuel consumptions at the variety of speed conditions to which the engine is subjected during its operational life [3]. Within this variety of test characteristics, it will only be of concern for this work the performance of the engine since the performance variables are the ones that are possible to control and evaluate in *GasTurb*®.

2.2. The CFM56-5B Turbofan Engine

The CFM56 engine is manufactured by CFM International and is a high-bypass turbofan engine. Within the CFM56-5B model, different engine rates are available. The engine that will be modelled is a CFM56-5B3, that has a bypass ratio (BPR) of 5.3 and produces approximately 32,000lbf of thrust. A cut view of the engine can be seen in figure 2.

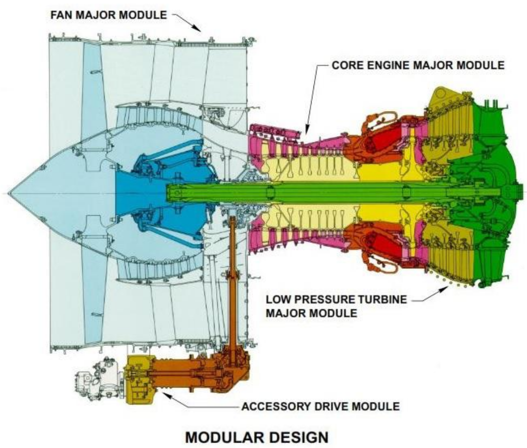

Figure 2: CFM56-5B cut view [4]

2.3. Control and Repair of HPC Blades Geometric Properties

High pressure compressor rotor blades possess a set of geometric properties that are important regarding the performance of the compressor. For investigation purposes, these measurements would be desirable, however, because it is not possible, the only geometric property that is currently possible to control at TAP M&E is the airfoil chord, in which the blade is placed on a Go/NoGo tool to verify if its chord is within the minimum limits (illustrated in figure 3). Be that as it may, this tool does not give any indication of the actual chord and no documentation is generated. Regarding the HPC of the CFM56-5B engine, it is known that the repair processes are limited within the different stages. The first three stages are made of a titanium alloy that is not repairable in chord extension due to difficulties of the weld process. From the stage 4 to 9 this restrain does not exist so these stages can fully repaired.

Figure 3: HPC blade measurement on the Go/NoGo tool

3. Aerothermodynamics and Loss Sources of Axial Compressors

Loss is defined in terms of entropy increase. The sources of entropy are, in general: viscous effects in boundary layers, viscous effects in mixing processes, shock waves and heat transfer. It is assumed subsonic and adiabatic conditions, and because of it, it is only of interest the first two sources of loss. Viscous shearing occurs wherever velocity gradients exist. In axial flow compressors velocity gradients will exist in boundary layers on the blades, annulus walls and in mixing processes. Figure 4 illustrates the different loss mechanisms present in axial-flow compressors.

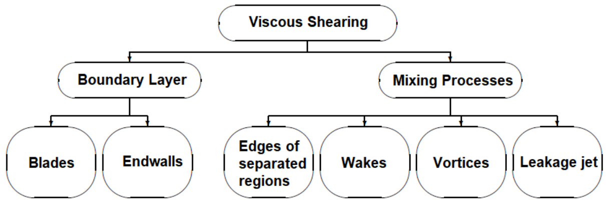

Figure 4: Diagram of loss mechanisms in axial flow compressors [5]

3.1. Compressor Loss Sources

Howell [6] categorized the losses in compressors in three different groups:

- Annulus losses;
- Secondary losses;
- Profile losses.

Annulus losses appear due to the boundary layers that develop in the compressor wall annulus. Secondary losses are associated with the vorticity of secondary flows. This a similar phenomenon to what happens in a finite wing. Lastly, profile losses are related to the boundary layers that develop in the compressor blades [7]. In figure 5 it is presented a graphic that illustrates the stage efficiency as a function of the flow coefficient and the losses considered. Annulus losses represent approximately 2.2%, secondary losses 4.4% and profile losses 4.2%. These losses tend to increase with engine operation, as erosion reshapes the annulus walls and compressor blades. Some of the performance is restorable. In the case of the compressor blades, these can be repaired or replaced by new ones.

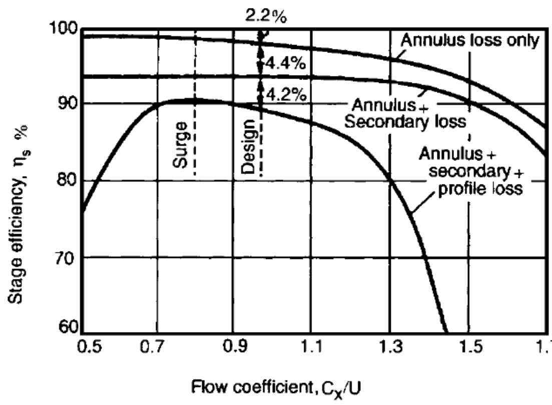

Figure 5: Losses in a compressor stage [8]

3.2. Non-Recoverable Deterioration in HPC Blades and Effect on Performance

During an engine time on service, its components are exposed to a large number of deterioration effects that leads to a variety of changes in the blade airfoils, specifically in the HPC. These effects of wear include:

- Erosion on pressure and suction surfaces;
- Chord length reduction;
- Deformation of leading and trailing edges;
- Variation of stagger angles;
- Increase in tip clearances.

Marx *et al.* [9] conducted a statistical analysis on two full ex-service HPC blade sets. The composition of each individual blade set were arbitrary (a mix of overhauled and new blades), which is common for engines that have received at least one shop visit. After being digitalized with a 3D scanner, a CAD model for each blade was generated. A noteworthy change was identified regarding chord length, beginning in stage 7 and further downstream, as well as maximum profile thickness and stagger angle. Regarding the leading edge radius and leading edge thickness, deterioration effects were more distinguished in the downstream stages, however, significant variations in the first stages were also verified.

Reitz *et.al* [10], [11] studied the influence that the variation of the previous geometric properties will have on the HPC performance by applying standard deviations to each property and taking into account that some properties are interconnected, e.g., the leading edge radius and thickness. The results of this analysis is illustrated in figure 6.

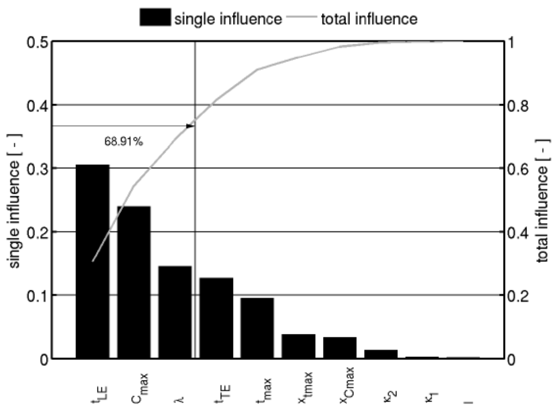

Figure 6: Pareto chart of the rotor loss coefficient of the first stage [11]

It is possible to verify that the leading edge thickness is the geometric property that most affected the rotor loss coefficient, followed by the blade chord and stagger angle (γ in figure 8). In compressor rotor blades, the incidence angle is positive. Blades are designed to operate in the optimum incidence angle, i.e., the angle at which the losses are minimum, so small variations in the incidence angle will lead to an increase in blade profile losses. Reitz *et.al* [10], [11] concluded that decreasing the stagger angle will strengthen the losses. Deviations in the incidence angle for blades that operate with positive incidence angles will lead to an increase in the loss coefficient, as illustrated in figure 7.

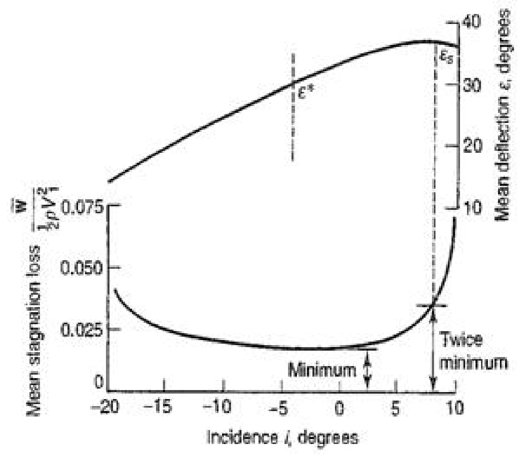

Figure 7: Stagnation pressure loss as a function of incidence angle [12]

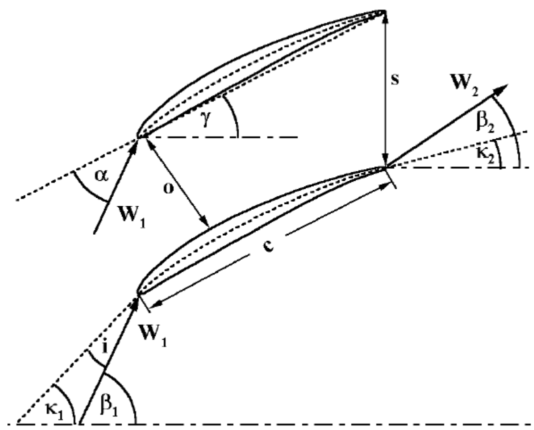

Figure 8: Compressor blade cascade geometry [13]

Tabakoff *et al.* [14], studied the influence that the HPC blade chord erosion of different stages will have on the overall HPC performance. It was concluded that the erosion of the first stage resulted in a reduced mass flow and pressure ratio, while the erosion of stage 8 had insignificant impact in the performance of the compressor. A similar result was obtained in the work of Martins [15], where it was compared the influence of the first three stages with the overall efficiency of the compressor.

4. Thermodynamic Model of the CFM56-5B Turbofan Engine

In this section it will be described how the thermodynamic model of the engine was obtained. TAP M&E had available a thermodynamic model for the CFM56-5B that is described in reference [2], however, after a thorough study, it was assessed that this model was unfit for performance studies due to some inaccurate assumptions. The engine that will be modelled is the correlation engine of TAP test bench.

4.1. EGT Margin

The EGT margin is defined as the difference between the EGT red line (or limit) and the EGT that is measured. The EGT red line for a hot day (HD), that is for an outside air temperature (OAT) of 30°C, is defined in the CFM56-5B engine shop manual in reference [16]. Beyond the EGT limit, the thermal loads are high enough that creep may occur.

A new CFM56-5B3 engine in take off regime has an EGT hot day (HD) margin of approximately 64K. At TAP M&E the standards for a healthy CFM56-5B3, after performing heavy maintenance works, is to have an EGT HD margin greater than 40K. The EGT is the temperature at the engine exhaust and it is a measure of an engine's efficiency in producing its design level thrust. The higher the EGT, the more wear and deterioration affects the engine. A high EGT is an indicator of an engine with degraded performance.

4.2. Correlation Test Report and Correction Factors

The Correlation Test Report (CTR) is the document where the performance report of the correlation engine is described. This document will be the base to develop the thermodynamic model.

Ambient conditions change from day to day, and so, it is important to correct this data to Standard Day so that it is possible to establish a basis of comparison between the performance of different engines. To correct to Standard Day, the following equations were used for temperature and pressure measurements respectively:

$$\theta = \frac{T2_{read}}{T_{ambStd}} \tag{1a}$$

$$T_{corr} = \frac{T2_{read}}{\theta} \tag{1b}$$

$$\delta = \frac{P2_{read}}{P_{ambStd}} \tag{2a}$$

$$P_{corr} = \frac{P2_{read}}{\delta} \tag{2b}$$

4.3. Cycle Reference Point

The first step is to choose a cycle reference point from the available data in the CTR. According to Kurzke [17], the ideal point would be the design point of the engine, however, any high power operating point is suited for that purpose for measurement accuracy reason because Reynolds number effects are negligible. The cycle reference point was defined as the highest available value of N1 in the CTR.

Mass flow and spool speeds (N1 and N2) are given as input and then it is necessary to select iteration variables and targets within *GasTurb®*. In figure 9 it is illustrated the iterations that were defined.

```
Iteration converged after 1 loops.

  Iteration Variables:
  1:  Burner Exit Temperature K (1000...2000)        = 1696,4
  2:  Design Bypass Ratio  (5...6)                    = 5,29581
  3:  Bypass Duct Pressure Ratio  (0,5...2)           = 0,998025
  4:  Isentr.LPT Efficiency  (0,7...1)                = 0,887917
  5:  Isentr.HPC Efficiency  (0,7...1)                = 0,848319
  6:  IP Compressor Pressure Ratio  (1...6)           = 2,46749
  7:  Bypass Nozzle Thrust Coeff  (0...2)             = 0,939064
  8:  Outer Fan Pressure Ratio  (1...5)               = 1,69001
  9:  Design Core Nozzle Angle [°]  (0...45)          = 2,82725
 10:  Isentr.IPC Efficiency  (0,5...1)                = 0,888949
 11:  Isentr.HPT Efficiency  (0,8...1)                = 0,91
 12:  Inner Fan Pressure Ratio  (1...3)               = 1,29699

  Iteration Targets:
  1:  Fuel Flow                                       = 1,57666
  2:  LPT Exit Temperature T5                         = 884,3
  3:  Bypass Nozzle Area                              = 1,00894
  4:  LPT Exit Pressure P5                            = 176,682
  5:  HPC Exit Temperature T3                         = 860
  6:  Overall Pressure Ratio P3/P2                    = 34,1412
  7:  Net Thrust                                      = 144,2
  8:  Fan Outer Exit Press P13                        = 171,24
  9:  Core Nozzle Area                                = 0,309664
 10:  HPC Inlet Temperature T25                       = 417
 11:  HPC Exit Pressure P3                            = 3459,36
 12:  Fan Inner Exit Press P21                        = 131,418
```

Figure 9: Converged iterations targets

4.4. Off-Design Modelling

After achieving a convergent cycle reference point, the next phase is to begin the off-design modelling, where the objective is to model the behaviour of the engine at different rotational speeds. In *GasTurb®*, the off-design modelling begins by selecting the components maps. Suitable maps are required to predict the component efficiencies at conditions deviating from the cycle design point [17]. Since the genuine maps aren't accessible because original equipment manufacturers (OEM) do not share that information, the best alternative is to use the maps from the *GasTurb®* library. The component map has on the y-axis the pressure ratio and on the x-axis the corrected mass flow. To tune the map to fit an operational line from the correlation engine, i.e., the parameters at different rotational speeds, it is necessary to scale the cycle reference point in the compressor for pressure ratio, mass flow and efficiency in order to match to the engine operational line. In figure 10 it is presented the HPC map.

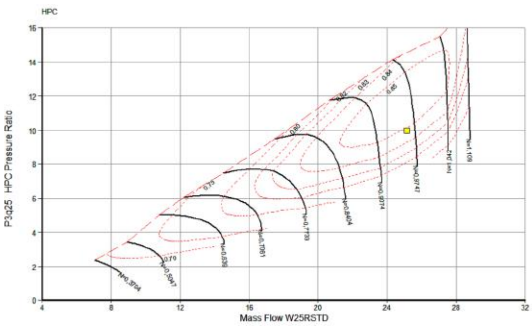

Figure 10: HPC map

After achieving suitable reference points in the components maps, it should be verified if the model is in agreement with the operational lines of the correlation engine. In figure 11 it is presented the thrust specific fuel consumption (TSFC) operational line and model validation.

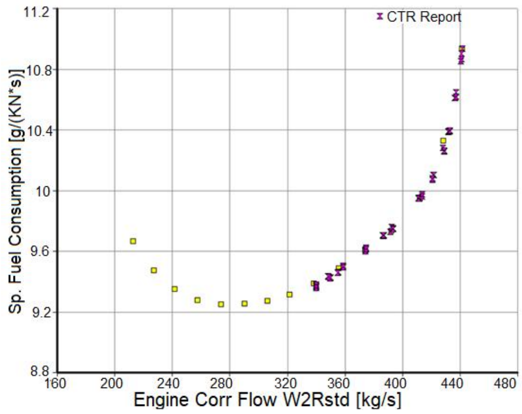

Figure 11: TSFC validation

5. Model Applications

It is possible that an engine that was subjected to heavy maintenance works still fails the performance acceptance test. This situation may occur because, for some reason, one or more of the engine's component are underperforming despite being in an overhauled condition. With *GasTurb*® tools, it is possible to detect which components are at fault.

5.1. Modifiers Tool

With the *Modifiers Tool*, it is possible to increase and/or decrease the components efficiency and analyse its effect on the performance of the engine. An individual analysis was made by applying a deterioration of 1% efficiency in each component. It was possible to conclude that:

- EGT is most affected by core components, being the HPT performance the most important, followed by the HPC and LPT;
- Fuel Flow is most affected by the LPT, followed by the Fan, HPT and HPC;
- Core speed N2 is directly linked to HPC and HPT and so it is natural that these components influence its speed the most;
- Fuel flow/Static pressure in station 3 (Wf/Ps3) is also affected the most by core components, high pressure turbine (HPT) and HPC respectively;
- Thrust is most influenced by the low pressure turbine (LPT) and the fan, which is also natural since these components are linked by the low pressure spool N1 and the fan generates approximately 80% of the engine thrust.

5.2. Model Based Test Analysis

Model Based Test Analysis (MBTA) is one of *GasTurb*® tools that allows to evaluate how each of other engine components are performing by comparing its performance with a reference, which in this case is the thermodynamic model of the engine that was developed. To perform a MBTA, the first step is to input in *GasTurb*® the measured data. Ideally all the input data should be real measured data from the engine tested, so that all the components are isolated which would allow to evaluate their true state. However, because this is not yet possible in TAP test bed, some of the input data have to be complemented with data from the model. This has some implications: if one of the components has no sensors upstream and downstream, an AnSyn factor of 1 will always be calculated because it is in perfect agreement with the model. Due to the lack of instrumentation in TAP test bed, the fan and booster will not be analysed. In figure 12 it is presented the results of the MBTA of 18 different engines, where the efficiency difference from the model is plotted agains the EGT margin. In blue it is illustrated the HPC efficiency, in orange the HPT efficiency and in grey the LPT efficiency.

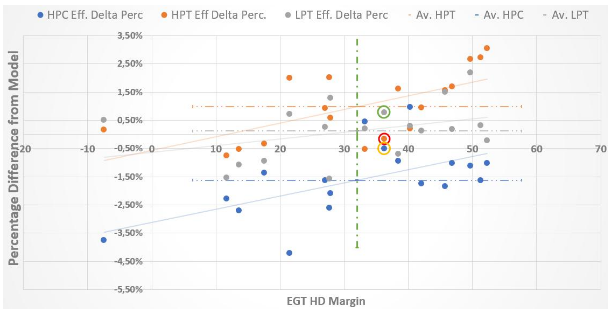

Figure 12: Efficiency percentage difference from model as a function of EGT margin

6. HPC Rotor Blades Impact on Performance

With respect to the HPC, the choice of installing new or overhauled blades can represent a penalty in the HPC performance. From stage 4 to 9, the repair process of the blades can be done without restrains, meaning that the blade can be repaired in regard to all geometric properties to attain the shape has if it were a blade in new condition. In the first three stages, the blades are made of a titanium alloy that is very difficult to weld. For that reason, the blades from these stages cannot be fully repaired regarding all geometric properties, specifically its chord. Its shape will be different from a blade in new condition, even if in its repair process the airfoil, maximum thickness, blade angles and other geometric properties are optimized to the new chord.

6.1. HPC Rotor Blades Analysis with MBTA

As mentioned earlier, it will be taken into account the possible chord loss in the first three stages, since it is not recoverable in these stages, however, the chord is not the only parameter that is changed with engine operation as mentioned in section 2.

In figure 13 it is represented the HPC blades, where it is possible to compare the dimensions between stages.

Figure 13: Blades from the CFM56-5B HPC: stage 1 to 9

The composition lists of the engines that were analysed in the MBTA were inspected to study if the HPC efficiency is related with the use of new and overhauled blades. These lists possess all the information of parts that were installed in the engine. Some of the engines analysed had been tested over 10 years ago and it proved difficult to access this type of information, which resulted in a sample of only 9 engines. It was considered the percentage of new blades of the first three stages only and also considering all the stages. The results are illustrated in figure 14. The "first three stages" points are represented with a polynomial cubic function and the "all stages" points are represented with a polynomial quadratic function. The R^2 of the functions is low and, although the trend line shows that increasing the percentage of new blades installed in the HPC increase its efficiency, these functions should not be used to predict the HPC performance due to the data not being fit to the regression lines. It is possible to verify that the use of new blades will influence the HPC efficiency, especially when considering the first three stages.

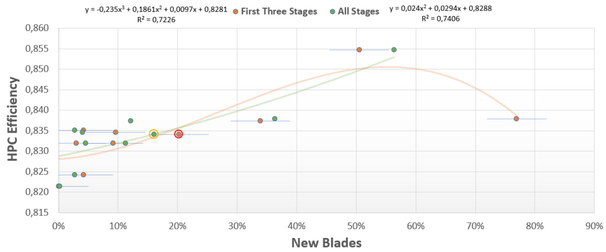

Figure 14: HPC efficiency as a function of the percentage of new blades

In figure 15 it is illustrated a bar chart with the new blades percentage per stage as a function of the HPC efficiency. All stages play an important role in the HPC performance, however, the first stage appears to influence the HPC efficiency the most. It is possible to verify that, in the case of the three most efficient compressors, the percentage of new blades installed in the first stage is high, and it is accompanied by a high efficiency. However, these statistical results are of poor accuracy to predict the performance for a HPC due to the low R^2 and small sample of engines.

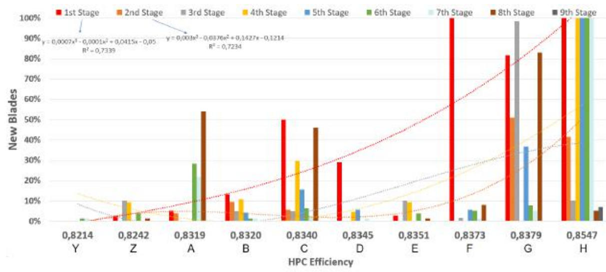

Figure 15: HPC efficiency and new blades per stage

These results are not unexpected. According to Marx *et al.* [9], it is hardly surprising that the performance of an overhauled compressor may differ considerably from one that was newly manufactured. The quality of the airfoil repairs and the aerodynamic impact of disregarded geometry parameters will affect considerably the overall performance of the HPC.

6.2. HPC Stage Performance Calculation and Impact on Overall Compressor Efficiency

Stage efficiency is dependent on total drag coefficients for each of the blade rows comprising the stage and, to evaluate these quantities, it is necessary to revert them to loss measurement. From the values of mean loss ϖ, the drag C_D and lift C_L

coefficients can be obtained. To determine these coefficients, the methodology described in Gas Turbine Theory [12] will be used.

The profile drag coefficient (C_{DP}) of a compressor blade can be found from:

$$C_{DP} = \left(\frac{s}{c}\right)\left(\frac{\varpi}{\frac{1}{2}\rho V_1^2}\right)\left(\frac{\cos^3\alpha_m}{\cos^2\alpha_m}\right) \qquad (3)$$

where s is the cascade pitch, c is the blade chord, ρ is the air density, V_1 is the inlet velocity and α_m is the average flow angle that depends on the inlet flow angle (α_1) and outlet flow angle (α_2). The lift coefficient (C_L) can be determined by the following equation:

$$C_L = 2\left(\frac{s}{c}\right)(\tan\alpha_1 - \tan\alpha_2)\cos\alpha_m - C_{DP}\tan\alpha_m \qquad (4)$$

Because the term C_{DP} is relatively small, it can be neglected in equation (4). By determining C_L it is possible to read C_{DP} from figure 16. A digitizer software was used to extract the points of figure 16, thus using the polynomials equations from the points extracted to determine C_{DP}. Using equation (3) it is now possible to calculate the pressure loss factor $\frac{\varpi}{\frac{1}{2}\rho V_1^2}$.

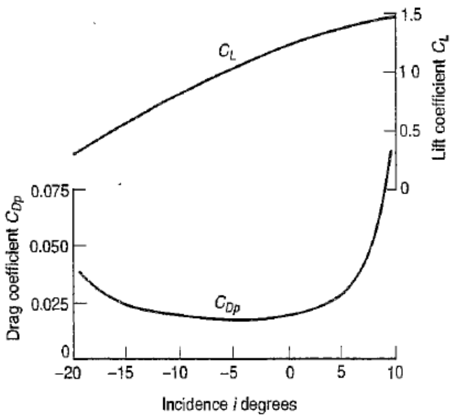

Figure 16: Lift and drag coefficients for cascade of fixed geometry [12]

Before these coefficients can be applied to the blade rows of the compressor stage, two additional factors must be taken into account: drag effects due to the walls of the compressor annulus (C_{DA}) and the secondary loss due to trailing edge vortices and tip clearance (C_{DS}). The following empirical formulas developed by Howell [6] were used:

$$C_{DS} = 0.018\,C_L^2 \qquad (5a)$$

$$C_{DA} = 0.02\left(\frac{s}{h}\right) \qquad (5b)$$

where h is the blade height. An overall drag coefficient can now be calculated, by summing the previous drag coefficients:

$$C_D = C_{DP} + C_{DS} + C_{DA} \qquad (6)$$

The argument used in deriving equation (3) for the profile drag coefficient in the case of a straight cascade will apply as well for the annular case by substituting C_{DP} for C_D thus enabling the loss coefficient $\frac{\varpi}{\frac{1}{2}\rho V_1^2}$ to be determined. The theoretical static pressure rise (ΔP_{th}) in the blade row can be determined by equalling the loss to zero:

$$\frac{\Delta P_{th}}{\frac{1}{2}\rho V_1^2} = 1 - \frac{\cos^2\alpha 1}{\cos^2\alpha 2} \qquad (7)$$

A compressor stage comprises both a rotor and a stator. The increase in enthalpy (ΔH) in the stage is shared by both the rotor and stator where the degree of reaction (R) can determined through:

$$R = \frac{\Delta H_{rotor}}{\Delta H_{stator}} \qquad (8)$$

Considering symmetrical blading in the stage and a stage reaction of 50% in the mean diameter of the blade will lead to symmetrical velocity triangles. In these conditions the blade row efficiency η_b will be the same for the rotor and stator. Since the study focus only on the rotor, the efficiency of the stage will be considered to be equal to the efficiency of the rotor. The static pressure ratio ($\frac{P_2}{P_1}$) across a compressor stage can be found by:

$$\frac{P_2}{P_1} = \left[1 + \frac{\eta_s \Delta T_s}{T_1}\right] \qquad (9)$$

where η_s is the stage efficiency, ΔT_s is the difference of inlet and outlet stage temperature and T_1 is the inlet temperature. It is of interest the efficiency of the stage considering the stagnation temperatures, however for the common case when the inlet and outlet velocities are equal ($C_3 = C_1$) there is no need to elaborate any further since the difference between the stagnation and static temperatures are equal ($\Delta T_{0s} = \Delta T_s$). To obtain an estimate of the overall efficiency of the compressor, it is necessary to repeat the previous methodology for all the compressor stages. The product of the pressure ratios will then yield the overall pressure ratio, and hence the compressor efficiency can be calculated using:

$$\eta_{is,c} = \frac{T_{01}}{T_{02} - T_{01}}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad (10)$$

The objective is to understand why the HPC performance is more sensitive to the first stages, rather than obtaining an estimate of the HPC efficiency.

By applying decrements of the stage efficiency η_s in equation (9) and calculating the HPC efficiency using equation (10), it is possible to perform a sensitivity analysis in the HPC. In figure 17 it is demonstrated the overall HPC efficiency as a function of each stage efficiency. The results demonstrate that the previous stage is more relevant than the next one.

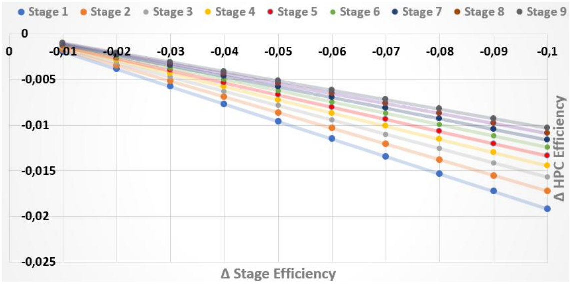

Figure 17: HPC sensitivity analysis

By evaluating equation (9) it is possible to verify why this is an expected result. Since the increase in temperature ΔT_s is equal for all stages, the inlet temperature of the stage T_1 will increase by an amount of ΔT_s for the subsequent stages, thus decreasing the pressure ratio of the following stages.

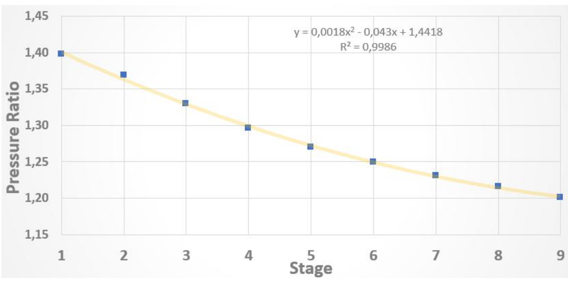

Figure 18: Pressure ratio per stage of the HPC

7. Maintenance, Performance and Cost Analysis

Test Case Engine "Y"

In the performance acceptance test, Engine "Y" had an EGT margin of -7K. In general all components, with exception of the LPT, were performing below average in efficiency and capacity. The HPC performance was approximately 2.25% below average. By possessing this knowledge of the components performance, maintenance tasks can be redirected to that specific component that is in fault. Engine "Y" AnSyn factors are replicated in GasTurb® Modifiers Tool and the cycle is ran. By applying a delta modifier of 1% in the HPC efficiency, the resulting modifiers are calculated and are again used in *GasTurb* ® Modifiers Tool. The performance parameters are exported and compared with the ones of the original cycle. A gain in the HPC and the HPT was noted, although much smaller in the case of the HPT. The most notable improvements were regarding the TSFC with a gain of -0.7% and EGT with a gain of -1.075%, which translates into an increase of the EGT margin of approximately 13K.

Although it may give some guidance to identify which component is in fault, this methodology does not pinpoints the exact problem of the specific component, and so, a more scrutinized investigation of the maintenance works has to be done.

Maintenance and Cost Analysis

A cost analysis was accomplished to the engines analysed in figure 15. Engines F, G and H are the ones where a greater investment was made in their HPC's. However, some engines HPC perform better than others even though the total investment is lower, as is the case of engines D and E when compared to engines A and B. Because no documentation is generated regarding used HPC rotor blades, it is difficult to assess the degradation level of each blade, since as long as the blades are within the minimum standards of the Go/NoGo tool, they can be installed in the HPC. In the case of engines D and E, it is possible that the installed blades in the HPC have low degradation levels, however it is only a mere possibility. With an accurate statistical model that relates the HPC performance and the chord of its blades, it would be possible to estimate and have a better control of the investment made in the HPC rotor blades, since it is not of the interest of TAP M&E to not reach or largely exceed the contractualized performance of the engine considering that it will result in fines or a lower profit margin.

8. Conclusions

To develop the model, the TAP test bed correlation engine was used. The first step was to define the engine cycle reference point. Once the cycle reference point is defined, the next step was to model the engine off-design operation. The model is able to replicate the correlation engine with precision in Maximum Continuous and Take Off regimes, that is above 80% of its maximum thrust.

A sensitivity analysis was conducted to the engine regarding the efficiency of its components. The EGT revealed to be more sensitive to the engine core (HPT and HPC respectively) while thrust is more sensitive to the fan and LPT performance. Several CFM56-5B engines tested in the past were selected and a MBTA was conducted. A database was created using Microsoft® Excel VBA macros to ease the data processing and analysis. Since the original component maps are proprietary information of the manufacturer, standard *GasTurb*® maps were used. For that reason and although the model is precise, it is not exact, and so the database will allow to compare a specific engine performance with others engines. By using the Modifiers Tool and the results of the MBTA analysis, it is possible to replicate the analysed engine performance in the model and help TAP M&E to decide where to take action regarding the engine components. One test case was used as example (Test Case "Y"), where an increment of 1% in the HPC efficiency was made. An improvement was achieved regarding the TSFC and EGT margin. By applying this methodology, TAP M&E can estimate what the performance gains are and, by doing so, analyse in which component the financial and human resources should be applied, thus avoiding unnecessary costs in components that are performing well.

Lastly, it was studied the influence that the HPC rotor blades have on the overall HPC performance. However, this analysis only took into account the condition of the blades used in the HPC, as no geometric properties were documented. The HPC performance analysis revealed a significant increase in the HPC efficiency with the use of blades in new condition, specially for the first three stages. Nonetheless, it is not possible to relate the rotor blade chord with the HPC performance as other geometric properties are also reshaped with blade erosion, such as the leading edge geometry. With the use of empirical formulas, it was possible to conclude why, in the HPC, the performance of the previous stage is more important than the next one. By applying decrements of the stage efficiency, it was possible to verify which stage affected the overall HPC performance the most. Because the stage pressure ratio decreases along the HPC, the overall pressure ratio of the compressor decreases in a greater magnitude when the first stages are less efficient.

This work provided to TAP M&E very useful tools that will allow to assess the overall engine performance. The created database will allow to store the engine components performance and compare a specific engine performance, thus permitting to evaluate which components are at fault. The HPC rotor blades study revealed that the use of blades in new condition improved the overall HPC performance, thus allowing TAP M&E to take that fact into account when an engine comes to the shop for maintenance works.

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