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EVALUATION OF TOTAL ENGINE PERFORMANCE DEGRADATION BASED ON MODULAR EFFICIENCIES

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ABSTRACT

The current maintenance and overhaul of large civil jet engines is completely based on-condition and is widely customized to the individual requirements of the operation. Therefore, a very important factor for an effective and economic engine maintenance program is the investigation and appreciation of the current engine condition, as well as its individual deterioration mechanism.

This paper is introducing a method to analyze the engine performance deterioration between two typical off-wing maintenance events (shop visits) so as to draw conclusions for maintenance planning and operation. In order to perform a precise evaluation the performance analysis is conducted on a modular level. Therefore the engine is divided into the following major modules: FAN, LPC, HPC, combustor, HPT, LPT and exhaust nozzle.

The basis for the evaluation is the overhauled engine condition after a shop visit (pass-off test run) and the deteriorated engine condition after operation (incoming test run). These two points in the engine life cycle provide specific engine conditions that are to be analyzed by scientific and commercial software, and combined with a self-developed engine performance model in order to obtain the desired results: The individual engine deterioration during operation demonstrated by the differences of the modular performance between incoming test run and the last pass-off test run.

In addition, to ensure the continuous monitoring of the performance status between the two test runs, it is important to analyze the “on-wing operation”. This is done using MTU’s Engine Trend Monitoring (ETM) system, which generates performance data based on the available in-flight data.

In this paper an analysis example is used to present the analytic method and the obtained results. Reasons of deterioration are evaluated separately in reference to different environmental influences from specific geographical regions.

In summary this paper introduces a solution to track the total engine performance based on modular evaluation values, starting at improvements for pass-off and incoming test runs as well as performance degradation during the on-wing time.

1. INTRODUCTION

The continuous monitoring of the engine performance is gaining importance for planning of effective and economic engine maintenance and overhaul.

With this background, an analysis method was developed, to use test-cell measurements in combination with on-wing condition monitoring for continuous engine performance evaluation. Additionally this approach considers the influence of different geographical operation areas on the engine performance degradation.

There are two data sources considered as the basis in this analysis. First is the data provided by engine test runs of an overhauled engine after a shop visit by means of a pass-off test run, and the deteriorated engine condition after operation by means of an incoming test. This data is reviewed to provide results by modeling and synthesis calculation using GasTurb™. Second is the on-wing performance monitoring via the MTU Engine Trend Monitoring (ETM) system. This ensures the continuous performance monitoring between maintenance actions, or shop visits, as shown in an simplified engine operating loop (Figure 1).

Based on the individual engine performance deterioration the operational and line maintenance planning of an airline can be adjusted (e.g. route changes, engine cleaning programs) in order to reduce the deterioration rate and increase the remaining engine life and utilization. If the deterioration exceeds the operational limits of the engine and is deemed not to be reversible on-wing an engine removal followed by base maintenance (shop visit) is necessary. In this case the results out of the deterioration mechanism based performance analysis can be used as planning information to determine the modular workscope and spare part preparation for the shop visit. If this planning can be detailed prior to the engine disassembly, based on the analysis result instead of the hardware condition, a significant benefit of reducing the overhaul time will be gained.

In this analysis GasTurb™ and MTU-ETM are tools of the analysis method and will be described briefly, however the main focus is on the analysis method.

Based on an example of a General Electric CF6 engine, the results of the performance analysis and deterioration mechanism caused by environmental influences will be presented.

1.1 NOMENCLATURE

AnSyn	Analysis by Synthesis
BPR	Bypass Ratio
EGT	Exhaust Gas Temperature
ETM	Engine Trend Monitoring
FF	Fuel Flow
HP	High Pressure (System)
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ISA	International Standard Atmosphere
LP	Low Pressure (System)
LPC	Booster, Low Pressure Compressor
LPT	Low Pressure Turbine
MACO	Maximum Continuous power setting
MOPS	Modular Performance Synthesis Program
N_1/N_2	Low/High Pressure spool speed
TAKO	Take-Off power setting
TBC	Thermal Barrier Coating
TT	Total Temperature
W	Capacity
WRstd	Capacity corrected to standard day conditions
η, ETA	Isentropic Efficiency
π, PI	Pressure Ratio

2. COMBINED ENGINE ANALYSIS METHOD

The target of the combined analysis is to evaluate the performance status of an engine at any time during the cycle shown in Figure 1. In order to support the operational planning and line maintenance, as well as the base maintenance planning for the next overhaul, the entire analysis has to be referenced to an engine baseline condition.

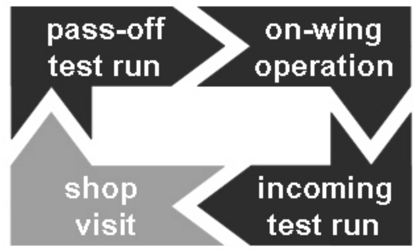

Figure 1: Simplified engine operation & overhaul loop

This baseline condition describes the typical performance for a specific engine type and version after a full overhaul event; therefore it contains the performance margin which can be exhausted by the engine during the subsequent operation. In order to fulfill the operational planning and realize the planned engine on-wing time a crucial requirement is the knowledge of any operation-specific deterioration mechanism leading to higher deterioration rates or special damage pattern (Ref. 7)

Figure 2 shows the method for a complete engine analysis to evaluate the engine specific performance deterioration with the left column showing the engine cycle introduced in Figure 1 in more detail. After a full overhaul event (shop visit) the engine is tested in a standardized test run (pass-off test run) to demonstrate that the engine meets the re-certification limits and additional customer requirements. The data from this pass-off test run is used to assess the engine modular performance in reference to the baseline using the performance analysis based on GasTurb™.

Once the engine is installed on-wing and is in operation, the engine and aircraft internal data acquisition system is continuously generating snapshots of data for which the individual aircraft can be understood as a test-bed replacing the test cell. In order to analyze the data, and evaluate the engine performance during operation, an analysis system based on MTU's ETM is employed to reflect the different reference system (right column of Figure 2). This analysis allows not only a continuous performance observation and tracking during operation, but also an opportunity to identify and assign different deterioration mechanisms to individual phases of operation.

The combination of both systems is done by analyzing identical engine condition using both methods. This is the case for:

a) The engine installation condition by using the pass-off test run data together with the installation data from the ETM system.

b) The engine removal condition by using the last ETM data points and conducting an additional test run in a pass-off test cell using the engine in its incoming condition (incoming test run).

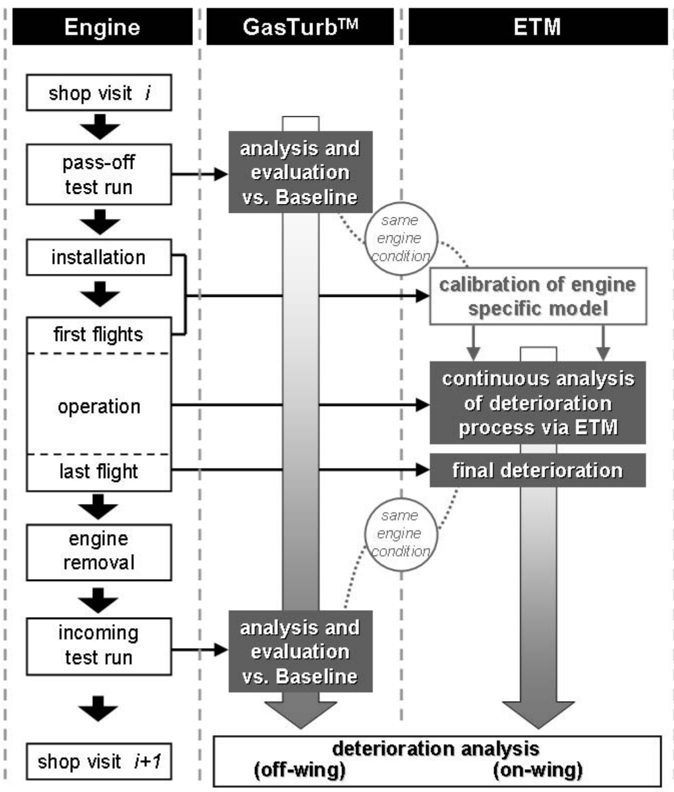

Figure 2: Complete engine analysis method

2.1 OFF-WING ANALYSIS (GasTurb^{TM})

The basis for the off-wing engine performance analysis is an engine type specific thermodynamic gas path model with a pre-defined power setting level (e.g. TAKO) as a reference. This model basis is consistent for the off-wing analysis using GasTurb^{TM} (middle column of Figure 2) and the on-wing analysis using ETM (right column of Figure 2).

Both gas path models are dependant on a modular performance calculation with reference stations, as shown in Figure 3 including the engine secondary airflow system.

Creating a reference Model

The reference model is created for TAKO (Take-Off) power setting condition which has the advantage of the highest thermal and mechanical stresses, thus any deterioration effects can be detected at the earliest using this power setting. In addition, using a high power point is usually best for measurement accuracy reasons (Ref. 4). Furthermore there are test cell measurements and in-flight ETM available for this power setting condition.

In order to model the reference baseline for the off-wing analysis, an average of selected engines based on overall performance close to the expected nominal behavior at TAKO and MACO is defined by using the test-cell scans of these engines to calculate the appropriate cycle reference point.

Based on the measured data, the following calculation sequence is used:

1. Independent preparation of each data scan separately *(Test cell and ISA correction)*
2. Investigation and verification of values *(e.g. use of turbine capacity method)*
3. Formation of an average model by using prepared scans *(cycle reference point)*

According to the principle of large engine testing facilities (specific test cell with open-loop layout) the measured results have to be corrected in order to generate comparable results. These corrections have to reflect the test cell correlation itself as well as the ISA and target corrections of all measured parameters.

ISA: International Standard Atmosphere at sea level:

$$P_{ISA} = 101{,}325\ kPa$$

$$T_{ISA} = 288{,}15\ K$$

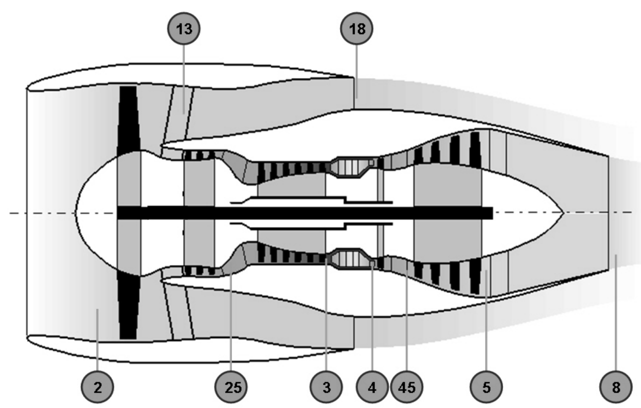

Figure 3: Engine Stations (GasTurb^{TM}, modified)

Investigation and Verification of Missing Values

Since typically only the standard engine instrumentation is used during pass-off and incoming tests, the number of available parameters for analysis is significantly reduced compared to a typical development testing scenario. Based on the engine standard instrumentation, one problem of a two spool turbofan is the unknown core entry mass flow (WRstd25) and high pressure turbine entry temperature (TT4).

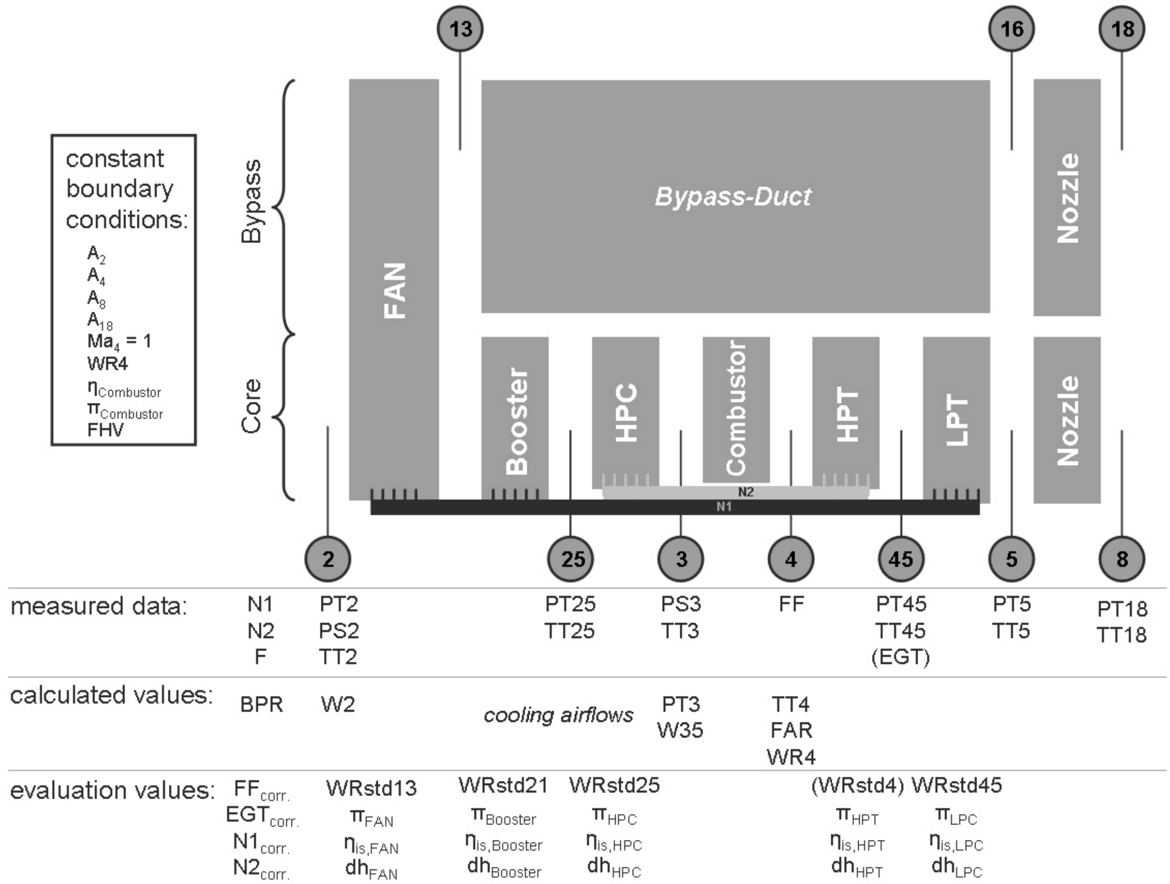

Figure 4: Schematic model creation for GE CF6-80C2

These unknowns and some additional values are determined iteratively using the turbine capacity method (TCM) according to Walsh P.P. and Fletcher P. (compare to Ref. 6). This method is based upon critical flow conditions in the HP turbine cross section area, A4 (Ma_4=1), and the energy balance between compressor exit and high pressure turbine entry (Ref.1)

The Cycle Reference Point

The engine and power setting specific cycle reference point is modeled with the software GasTurb^{TM}. Establishing the gas path model and engine station numeration (Figure 3 and 4) allows for definition of the performance characteristics, the geometry, and the secondary air flow of the cycle reference point.

GasTurb^{TM} is a scientific software that allows the user to calculate complete engines cycles with consideration of the cooling air flows. With this reference it is also possible to simulate the model with test cell data in off-design mode. The working fluid in this model is assumed to behave like a half-ideal gas for which the gas properties (specific heat, entropy and gas constant) are a function of temperature and gas composition, but independent from pressure. (Ref. 5)

To generate the cycle reference point it is important to define an “average engine” out of several mean performed engine test runs. The parameters of this pre-defined average engine are put into GasTurb^{TM} design mode to calculate the thermodynamic cycle of the internal secondary air system through iterative methods until all calculated temperatures and pressures are consistent with the average engine.

In order to simplify the model, all pressure losses within the ducting system (e.g. transition duct from Booster to HPC) are considered part of the modules itself (in this case Booster and HPC) with the exception of the fan stator exit to the fan nozzle. This duct is considered separately based on its size and the amount of mass flow through this area.

The pressure losses in the combustion chamber and exhaust nozzle are considered to be constant in this analysis (Ref. 2).

Off-Design

After modeling the cycle reference point, different engine conditions (e.g. deteriorated engine condition after operation) can be analyzed in an “off-design mode”. The required iteration process to calculate the off-design points are based on the Newton-Raphson-Algorithm (Ref. 5).

Since the off-design calculation is based on the engine model defined by creating the cycle reference point all engine specific geometries are fixed. Nevertheless, especially for the analysis of incoming test runs of deteriorated engines, it is important to consider a potential change of the HP turbine entry cross section area (A4) as this value influences high pressure system performance behavior as well as the entire engine bypass rate. This is done by measuring the turbine entry cross section area after disassembly of an incoming engine. The measured data is used for off-design calculations of the related incoming test run only. The pass-off test run analysis A4 cross section is set to the baseline value since these geometries are controlled and restored to a nominal value during a shop visit.

2.2 ON-WING ANALYSIS (ETM)

Engine Trend Monitoring (ETM) is an MTU tool for in-flight engine condition monitoring. During a flight the required data on the airplane status and engine performance is measured and transferred, typically via ARINC (Aeronautical Radio Incorporated), into the ground-based calculation process shown in Figure 5.

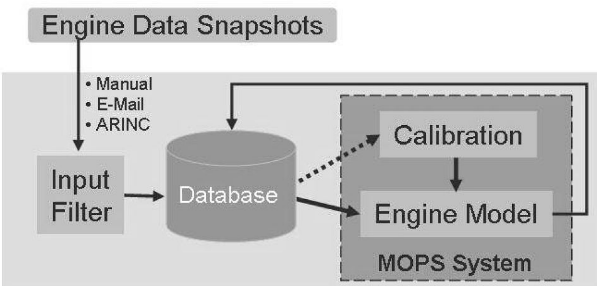

Figure 5: ETM system

In principle, the ETM performance analysis process is very similar to that of GasTurb™ however the data is prepared in a different manner. In the ETM tool, to avoid false readings from the engine instrumentation and the use of non-stabilized data points an input filter is used to compare the measured data with an expected range for the individual setting.

In addition, in order to allow a very sensitive monitoring for consistent detection and avoidance of potential malfunctions at the earliest opportunity, the reference model for the calculation is not only defined as an engine type average but also calibrated with the thermodynamic behavior of the individual engine during the first 50 flight cycles.

The internal core (MOPS - Modular Performance System) of the ETM system uses the calibrated reference engine for comparison of the actual engine behavior. The calibrated engine and actual engine are compared based on the standard engine performance metrics (FF, EGT, N_1, N_2, etc.). Thus, the individual engine deterioration after calibration and installation can be monitored and analyzed using the ETM system.

Environmental influences

Previous investigations of engine deterioration mechanisms showed a general classification of the environmental conditions and the influence of these conditions on the deterioration rate of the engine. The two main effects - described in Ref. 7 – were:

Natural effects on engine operation are predominantly the contamination and erosive effects of sand and dust. Sand particles from deserts and coastal regions are the major source of this type of pollution.

Anthropogenic effects are primarily represented by chemical and industrial pollution. Due to the fact that the exact chemical active elements could not be completely identified, anthropogenic factors were defined as all types of industrial pollution.

Both effects have different impacts on the engine performance. In Ref. 7 the operation of the investigated engine population was assigned to the following categories by using the departure / arrival airport location for classification.

Category A: Airports in areas of natural environmental effects causing mainly erosive damage pattern

Category B: Airports in areas with anthropogenic effects as described previously

Category C: Airports in common regions which are not classified as either A or B

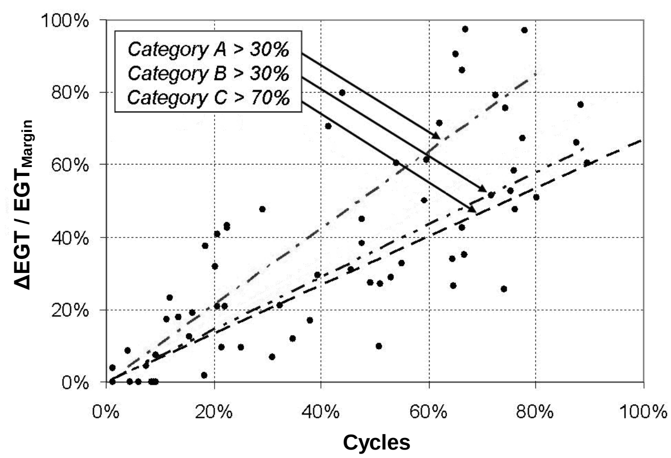

Figure 6: Deterioration for different operation (Ref. 7)

In Figure 6 the deterioration rates are represented by EGT increase for an analyzed fleet of more than 60 engines of the same type but operated in different areas. The important result is that an operation going through category A airports by more than 30% shows a significantly increased deterioration rate compared to operation through others regions. In addition, there is a very high individual fluctuation of the deterioration rate depending on the amount of category A operation of the individual engine or airplane. These previous results lead to the requirement of a very detailed performance analysis for individual engines mainly operated in category A environments since their deterioration rate may be doubled in comparison to normal operation.

2.3 EVALUATION VALUES

In this performance analysis the engine is structured in the modules FAN, LPC, HPC, combustor, HPT, LPT , and nozzle. The following parameters are defined as evaluation values and used for the subsequent engine performance evaluation (compare to Figure 4):

- WRstd [kg/s] capacity (corr. to std. day)
- PI, π [ ] pressure ratio
- ETA, η [ ] isentropic efficiency
- dh [W/(kg/s)] change of specific enthalpy
- $FF_{corr.}$; $EGT_{corr.}$; $N_{1\ corr.}$; $N_{2\ corr.}$

A comparison between these evaluation values at the off-design and reference points is used to evaluate the performance loss or performance change of each module. Therefore these evaluation values are expressed as follows.

$$\Delta_{\%} = \frac{\text{offdesign evaluation value - cycle reference evaluation value}}{\text{cycle reference evaluation value}} \cdot 100\%$$

This method allows discussion of the individual module performance for the analyzed engine relative to the baseline engine performance model.

2.4 MAINTENANCE CONCLUSIONS

Evaluation of the engine performance behavior can identify specific areas of deterioration that can be adapted into the shop visit and maintenance actions. The degradation evaluated via ETM is transferred into the baseline system using an incoming test run. By analyzing the modular performance in comparison to the baseline, the deterioration per module can be identified for the specific operation which allows focused workscoping of each module in order to restore the performance as individually required. This gives a very detailed and early planning basis of the required overhaul work with regards to the degree of disassembly, material and repairs required.

3. ANALYSIS EXAMPLE USING A GE CF6-80C2 TURBOFAN ENGINE

The analysis presented in this paper is performed on the data of a General Electric CF6-80C2 turbofan engine. This engine has shown a significantly increased EGT, accompanied by increased specific fuel consumption, after approx. 800 cycles of operation in the middle-east region. On the CF6-80 the HP turbine outlet temperature is used as the EGT reference (EGT=TT45, compare also Figure 4).

The available data for this particular engine are shown in the following list:

- Pass-off test run #1
  outgoing status before the operation
- ETM data
  continuous operation performance status
- Incoming test run data
  >> Incoming test run #A
  Test run in deteriorated condition
  >> Incoming test run #B after cleaning
  Test run in deteriorated condition after engine core cleaning is performed
- Pass-off test run #2
  outgoing status after subsequent shop visit
  – for reference only –

The available amount of data for this engine is typical for a mature engine in service. Therefore the described performance analysis method has to be capable to identify the mechanism of deterioration as well as to quantify the losses within the engine modules based on this data.

Since the engine has also shown some significant deterioration in the HP turbine entry cross section area (A4) due to thermal overload, the current A4 area was measured during disassembly. The area was found to have increased by approx. 5% (compare Figure 12) and was adjusted accordingly in the performance model calculations for the incoming test runs #A and #B.

In addition, it should be mentioned that the used engine is a rather extreme example for typical deterioration rates after only approx. 800 cycles on-wing instead of the usual on-wing time of 3000-3500 cycles between subsequent shop visits. The advantage of choosing this engine as an example for analyzing the deterioration in reference to environmental influences is the permanent operation profile of this engine in the middle-east region which defines a pure 50% category A profile.

3.1 OFF-WING PERFORMANCE EVALUATION VIA PASS-OFF AND INCOMING TEST RUN

The following charts show the evaluation values of the pass-off test runs, #1 and #2, as well as the incoming test runs, #A and #B, using the GasTurb™ analysis method.

In this analysis the evaluation parameters are plotted as deviations of the analyzed test run versus the baseline performance model. The overall engine condition compared to the baseline can be identified using the corrected low spool speed (N_1), exhaust gas temperature (EGT) and fuel flow (FF) as parameters for the energy input and output.

The modules of the high pressure system (HPC, HPT) as well as the modules of the low pressure system (FAN, Booster, LPT) should each be reviewed simultaneously with respect to their energy balance. With the assumption of constant efficiency and pressure loss, the combustor shows no significant changes. This assumption was supported by the condition of the combustor during disassembly, after incoming test run #B, which revealed almost no deterioration in terms of geometrical changes or cracks / burning within the module.

Starting with the analysis of test run #1, the upper section of Figure 7 shows the module performance of the investigated CF6-80C2 engine prior to the start of the operation in comparison to the CF6-80C2 performance baseline. In general the engine shows only a very minor deviation from the baseline by comparing fuel flow (0,6% below baseline) and EGT (0,3 above baseline) which is also supported by the modular analysis including only a slightly reduced booster performance and increased LPT pressure ratio.

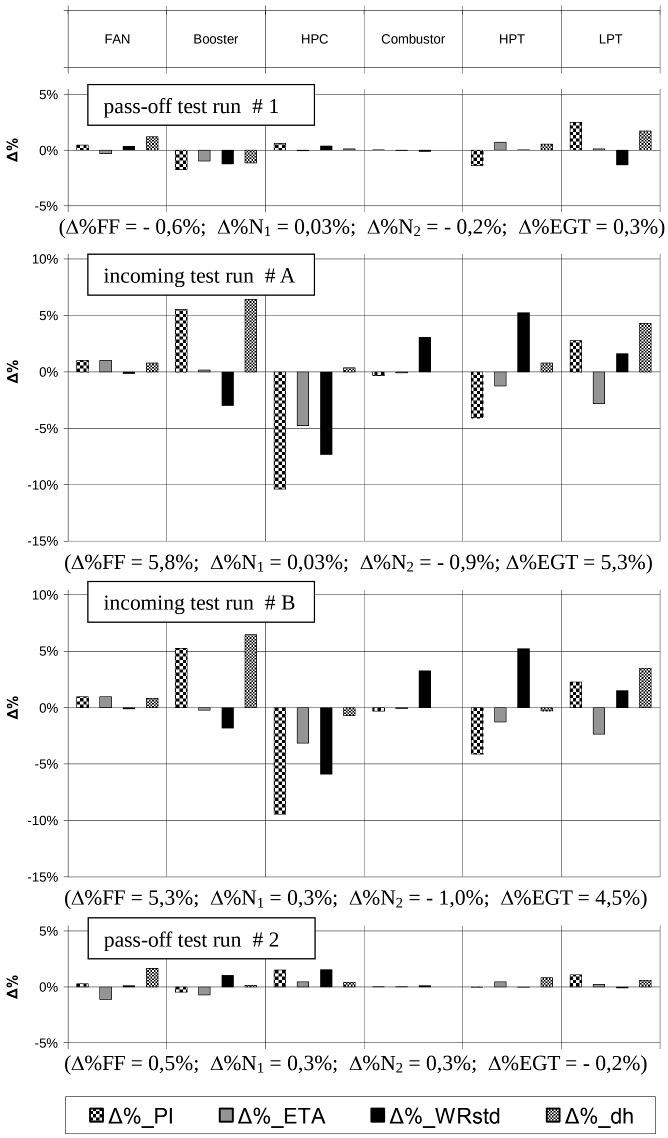

Figure 7: deviations between the test runs and the baseline model for investigated CF6-80C2 engine

As expected, the performance values change significantly during the engine operation as observed by comparing both of the incoming test runs, #A and #B, with the former outgoing condition (test run #1).

After the subsequent performance restoration shop visit the analysis of the pass-off test run (test run #2) in the lower part of Figure 7 shows again an overall behavior very close to the baseline.

As previously mentioned, the engine control of the CF6-80 uses the low spool speed (N_1) as the governing parameter for thrust control thus – in order to maintain the required thrust level – the N_1-speed is kept constant as shown in Figure 7.

In the analysis of test runs #A and #B, as shown in the middle of Figure 7, two major deterioration effects are influencing the engine performance which can also be seen on the engine hardware. The first effect is the significantly changed HPC performance which shows a drop in pressure ratio of approx. 10% and in flow of approx. 7% while the HPC speed has dropped by only 0,7%. The other effect is the increased HP turbine throat area leading to an increased turbine capacity by approx. 5%, also shown in Figure 12. This capacity increase was adjusted in the calculation and can be found for run #A and #B in Figure 7 (%Δ_WRstd). The typical result of an increased turbine capacity is a reduction in the turbine pressure ratio leading to an reduced HPC pressure ratio as well as a reduced shaft speed (N_2 shaft). The resulting lower HP operating point will be recovered by a higher energy input using an increased fuel flow in order to keep N_1-speed and therefore thrust constant, which can also be identified in Figure 7. In total the EGT is increased by 5% which means an approx. 55 K higher HPT temperature level. This effect is accompanied by a reduced HP turbine efficiency that leads to a reduced HP operating line.

Comparing the expected consequences of the changed HP turbine to the HP compressor behavior in Figure 7, the remarkable performance decrease indicates another significant deterioration of this component. The pressure rise has dropped by not only the expected effect out of the turbine, but also an additional 4-5% which is accompanied by a significant reduction in efficiency and flow. This is mainly caused by a deterioration of the HP compressor blades due to erosion and contamination, also shown in Figure 10.

As a result of the lower HP performance and working line the load balance between the HP and the LP system has changed as well. The LP compressor (Booster) is throttled by the following HP compressor leading to an increased pressure ratio and decreased flow, while the efficiency of the component itself remains unchanged. This new operating point also leads to a significantly higher specific enthalpy increase. In the aft section of the engine the pressure ratio used by the LP turbine is only slightly increased compared with the pass-off test run #1. With the background of maintaining the same N_1-speed and thrust respectively this is driven by a slightly decreased efficiency in the LP turbine itself.

The fan remains unchanged in its performance since it shows no deterioration within the analyzed operation.

The difference between the incoming test runs #A and #B is primarily the result of an engine core cleaning using the coke cleaning process at the testing facility. This cleaning uses abrasion effects to clean the core engine however the majority of the effects are observed on the HPC airfoils. Therefore, the results are most noticeable in the HP compressor while the other component performances remain unchanged. The efficiency, pressure ratio and flow of the HPC are all increased by approx. 1-2% in run #B compared to run #A.

Thus the throttle effect of the HPC to the booster (LPC) is slightly decreased. On the other hand, there is no measurable effect of the cleaning in the HPT since the effect is too low compared to the increase of turbine capacity.

3.2 ON-WING PERFORMANCE EVALUATION VIA ENGINE TREND MONITORING

As per Figure 2 the engine was analyzed using the ETM method during its on-wing time. The focus for on-wing performance monitoring is typically on the EGT. Therefore Figure 8 shows the percentage deviation of the measured EGT in reference to the calculated EGT within the ETM gas path model (Δ%_EGT).

Since the monitoring of ETM snapshots was first introduced 200 cycles after re-installation of the engine and - as described in section 2.2 - the ETM program requires an additional 50 cycles to calibrate the reference model, useful snapshots are available from the 250^{th} cycle forward. In addition, during the monitored operation some snapshots are neglected due to inaccurate measurements or unusual bleed-air configurations.

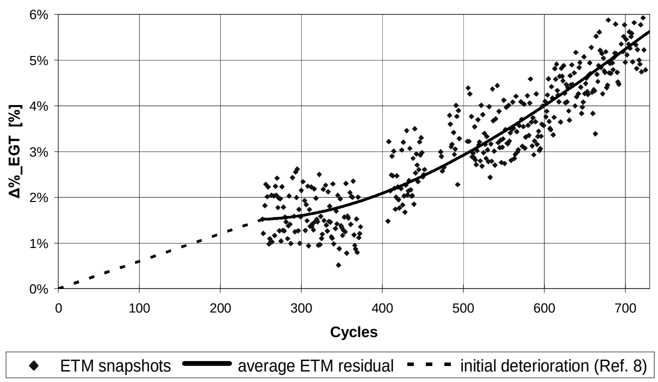

Figure 8: percentage deviation of EGT between measured and calculated value calculated via ETM

To consider the deterioration behavior of the first 250 cycles a statistical deterioration function as described in Figure 6 was applied (Ref. 8) for the specific operation and engine position on outer wing.

Although the EGT deterioration is influenced by the individual flight condition leading to an overall scatter of approx. 2% (at a level of approx. 1150 K ISA condition), a trend can be seen and the EGT deterioration shows to be not constant over the operation. While the increase is comparably low between the 250^{th} and 350^{th} cycle, the deterioration rate is increasing leading to an almost constant rate of approx. 1,25% per 100 flight cycles. After approx. 725 cycles an accumulated deterioration of approx. 5,5% is reached. This value shows a very good correlation to the EGT deterioration of 5,3% measured during incoming test run #A (compare Figure 7). The deterioration of approx. 60 K is a typical EGT margin for such an engine and, once this margin has been exhausted, the engine had to be taken off-wing.

3.3 OVERALL ENGINE PERFORMANCE EVALUATION

Combining both analysis methods of Figure 2 (GasTurb™ - based and ETM-based) the engine performance deterioration using the EGT between pass-off test runs #1 and #2 can be described as shown in Figure 9.

(1) Initial deterioration before ETM-start (based on fleet average for comparable operation) (Ref. 8)

(2) EGT deterioration during on-wing operation identified with ETM

(3) EGT recovery due to compressor cleaning

(4) Engine performance restoration at shop visit

Using this example, the transfer of ETM on-wing analysis into off-wing analysis can be demonstrated and results in the aforementioned small difference in EGT deterioration of approx. 0,2% (corresponding to 2 K) as shown in Figure 9.

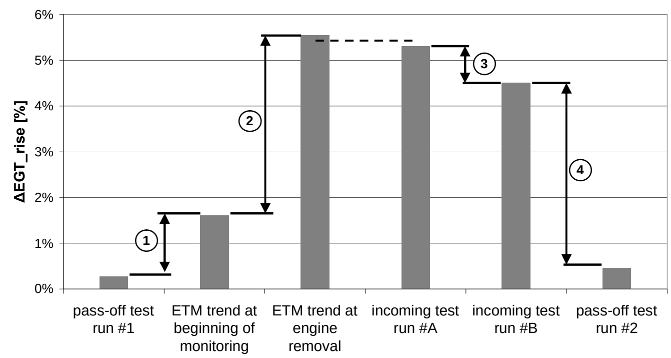

Figure 9: EGT deterioration between two shop visits

3.4 DAMAGE PATTERN

The hardware deterioration mechanism leading to the decreased performance, as discussed in section 3.1, can be explained by analyzing the engine hardware. Focus on the HP compressor and HP turbine hardware is justified since these two modules were identified as the main contributors (see Figure 7) to the EGT deterioration.

The portion of operation in category A regions was significantly higher for the investigated engine (approx. 50%) in contrast to the fleet average analyzed in Figure 6 (Ref. 7.).

The erosive effect of sand ingestion on ground (during take-off and landing) and furthermore on flights at lower levels (during climb and approach) leads to a severe damage of the HP compressor blades as shown in Figure 10. Supplementary, sand deposits are clearly visible on the airfoil surfaces although core cleaning has been performed during testing.

The following damage in the HPC module was found in the analyzed engine:

- Deposits on airfoil surfaces (blades & vanes)
- Deteriorated airfoil geometry (chord length & contour)
- Blade chord length below repairable limit
- Blade trailing edge thickness below repairable limit

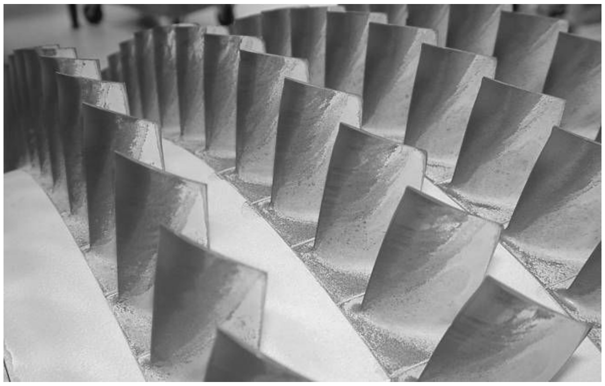

Figure 10: Erosive effects on HPC blades

These effects cause the HP compressor performance deterioration discussed during the analysis based on Figure 7. The efficiency decrease caused by deposits in the gas path can be partially recovered by cleaning methods; however, based on the particle trajectories, some areas on the airfoil suction sides cannot be adequately cleaned.

The cleaning recovery effect of approx. 1-2% HPC pressure ratio and efficiency seems to be small compared to the total deterioration. Nevertheless it has to be considered that the contamination and thus the efficiency drop starts from day one of such operation. The non-reversible portion of the compressor deterioration in terms of erosion has to be compensated by increased fuel flow in order to recover the engine total thrust. Just these compressor caused effects lead to an increase of the HP turbine temperature level of approx. 1% (compare Figure 7), or approx. 10 K.

Reviewing the HP turbine hardware the deteriorated condition due to the local sand contamination is found to be compounded by the increased turbine temperature level resulting from the decreased compressor efficiency.

The following damage patterns were analyzed on the HPT blades and vanes (See Figures 11 and 12):

- Deposits on airfoil outer surfaces
- Increased tip clearance and cracks due to airfoil tip rubbing and burning
- Deposits in cooling cavities and blocked cooling holes, causing a reduced cooling airflow and heat transfer

The surface deposits on the HP airfoils are typically the quickest to accumulate and, while such deposits are at least partially reversible within the HPC, removal (cleaning) within the HPT is difficult for the outer surfaces and nearly impossible for the inner cavity surfaces even while the blades and vanes are at piece part level.

The erosive effect on the HPC airfoils starts to occur, in general, with day one of such operation; however, the effect on engine performance will become more significant once the erosion affects the main geometry of the blades such as the blade tip chord length. In contrast to this the effects of sand contamination in the HPT are different. Depending on the temperature and flow path of the sand entering the HPT, there are two different mechanism of deterioration (compare Ref. 3). On the one hand particles in a partially molted condition will bond to the surface that is hit under a large angle. In contrast to this, particles with a more solid condition and a smaller angle of impact towards the airfoil surface show a more erosive effect. Since the latter first attacks the thermal barrier coating (TBC) of the first stage nozzle and blades, and since the turbine airfoils are less sensitive towards slight geometry changes with respect to their efficiency, the main effects of the contamination will be on the turbine cooling.

Internal sand contamination of the airfoils reduces the internal heat transfer as well as the entire cooling flow, especially the film cooling flow since nearly all impingement and film cooling holes are partially or completely blocked (see also Ref. 3). As a result of the external contamination disturbing the cooling film and the erosive effect removing the TBC there is an increased airfoil metal temperature.

Figure 11: HPT blade deterioration pattern

Figure 12: HPT vane damage pattern (T/E bulging)

These mechanisms lead to a time-delayed onset of HP turbine performance deterioration. In addition, the partially blocked HPT cooling airflow reduces secondary airflow (bleed at HPC outlet), which partially recovers the HP system efficiency. Therefore the engine deterioration driven by the HPT is delayed, however after it is established the effects show with an accelerated growth.

Once the metal temperature of the HPT airfoils is permanently raised, due to the reduction in cooling air and deteriorated TBC, and the effect is combined with the higher fuel flow required to compensate for the reduced HPC efficiency, the airfoils will show a significant deterioration in terms of burning (see Figure 11) and geometry changes (see Figure 12). One major effect caused by this is the opening of the turbine throat area, called “trailing edge bulging”.

Finally, the operation area of the middle-east region has to be considered with regards to the elevated ambient temperature level. In particular, during daytime operation the higher outside air temperature leads to an increased turbine temperature level even without any type of deterioration. Comparing the hardware results of the disassembled modules with the performance analysis in section 3.1, the highlighted main contributors of HPC erosion and HPT thermal distress can be physically identified. With respect to the on-wing deterioration mechanism in Figure 8, it has to be concluded that during the first half of the on-wing time of this engine the decreased efficiency and contamination effect of the HPC was the main contributor to the deterioration; however, during the second half of the on-wing time (Starting approx. at 400 Cycle in Figure 7) the HPT deterioration becomes more significant.

4. CONCLUSIONS AND OUTLOOK

A method to analyze engine on-wing performance deterioration using on-wing and off-wing data has been introduced. The target of this analysis was to evaluate the performance deterioration caused by an individual engine operation on a quantifiable modular basis as well as highlight the deterioration mechanism in order to optimize the overhaul and build-up planning for individual engines. In order to facilitate this purpose, the off-wing performance baseline had to be combined with the on-wing performance analysis to be able to transfer the results from one system into the other.

Using one engine with a significant deterioration as an example for the off-wing analysis, the on-wing monitoring and for comparison with the baseline produced very good correlations for the engine deterioration. The use of the modular analysis, in combination with the hardware evaluation, supports an explanation of the deterioration mechanism and the total amount of deterioration per module. One important result is the chronological development within the deterioration mechanism and the deterioration rate. On the particular engine example in this paper, the environmental effects lead to a combination of contamination and erosion in the HP system. This adverse effects caused a increased temperature level in the HP turbine which – together with the eroded TBC – resulted in severe thermal distress.

The compressor cleaning between two incoming test runs showed that this process can be used as a appropriate method to remove contamination effectively which resulted in an reduced HP system temperature level due to recovered HP compressor efficiency. This demonstrates the requirement of an adapted cleaning method for the HP turbine airfoils in order to minimize the adverse effect of sand contamination and cooling hole blocking which, once started, ultimately leads to non-reversible deterioration and damage.

In summary, the environmental effects of the regional operation spectrum in the middle-east region caused a significantly increased deterioration rate to the engine in focus and as a result the engine performance margin was exhausted in approx. 800 flight-cycles.

A similar observation was also made for the other engines installed on the same aircraft. However the outer wing engines, especially the engine in focus (wing position #4), were characterized by a higher deterioration rate. This can be explained by a higher load of sand and dust during airport taxiing, take-off and in particular thrust reverser supported landing for outer engines when compared to the inner positions.

Based on the promising results of the developed analysis explaining the mechanism and amount of individual operation related deterioration, a further development of this method is planned by analyzing additional deterioration mechanisms as well as conducting modular analysis on the on-wing data.

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