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GAS PATH ANALYSIS ON KLM IN-FLIGHT ENGINE DATA

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ABSTRACT

Gas-path-analysis (GPA) based diagnostic techniques enable health estimation of individual gas turbine components without the need for engine disassembly. Currently, the Gas turbine Simulation Program (GSP) gas path analysis tool is used at KLM Engine Services to assess component conditions of the CF6-50, CF6-80 and CFM56-7B engine families during post-overhaul performance acceptance tests. The engine condition can be much more closely followed if on-wing (i.e., in-flight) performance data are analyzed also. By reducing unnecessary maintenance due to incorrect diagnosis, maintenance costs can be reduced, safety improved and engine availability increased.

Gas path analysis of on-wing performance data is different in comparison to gas path analysis with test cell data. Generally fewer performance parameters are recorded on-wing and the available data are more affected by measurement uncertainty including sensor noise, sensor bias and varying operating conditions. Consequently, this reduces the potential and validity of the diagnostic results. In collaboration with KLM Engine Services, the feasibility of gas path analysis with on-wing performance data is assessed. In this paper the results of the feasibility study are presented, together with some applications and case studies of preliminary GPA results with on-wing data.

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NOMENCLATURE

ECM	Engine Condition Monitoring
EGT	Exhaust Gas Temperature
DOC	Direct Operating Costs
GPA	Gas Path Analysis
GSP	Gas turbine Simulation Program
HPC	High Pressure Compressor
HPT	High Pressure Turbine
KLM	Royal Dutch Airlines
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
SFC	Specific Fuel Consumption
RH	Relative Humidity
Wc	Corrected mass flow
Δ	Operator denoting difference
η	Isentropic efficiency

Subscripts

bp	Bypass flow
c	Core flow

INTRODUCTION

Gas turbine engines are important assets in the civil aviation industry. Safe, reliable, and cost-effective operation are critical for successful business of airlines. Over time, component deterioration reduces engine efficiency. On a system level, the effects are: increased exhaust gas temperature (EGT) and specific fuel consumption (SFC), thereby reducing safe and economical operation. Effective maintenance is essential to maintain high levels of overall engine efficiency, reliability, and availability. Gas path analysis (GPA) has been recognized as an important diagnostic method that can determine individual component condition parameters from measured performance parameters. GPA enables component condition estimation without the need for engine disassembly.

Relating measured performance parameters to component condition parameters is complicated. In practice many factors influence the diagnostic outcome. The most common factors are [1, 2]:

- Lack of measurement points
- Measurement uncertainty
- Non-linear gas turbine behavior

Much research in the field of GPA has been focused on limiting the effects of these obstacles by improving existing methods or developing new methods. To date this has resulted in a range of different GPA methods that can be grouped in three categories: model-based methods [3–6], empirical methods [7–9], and hybrid methods [1]. Although some methods show great potential, none of these methods provide a complete solution to all problems.

The number and location of installed sensors in a gas turbine required for control and monitoring functions is determined by the engine manufacturer. Usually the instrumentation is a given and cannot be changed in existing engines.

Non-linear model-based GPA methods have the potential for accurate engine diagnosis over a wide operation range both on-wing and in the test cell. The large amount of data available from on-wing performance measurements can potentially be used to reduce measurement uncertainty effects.

GAS PATH ANALYSIS AT KLM ENGINE SERVICES

Currently, the Gas turbine Simulation Program (GSP) gas path analysis tool is used at KLM Engine Services for the analysis of post-overhaul acceptance test data of the CF6-50, CF6-80 and CFM56-7B engine families. GSP is a component based performance simulation tool that is capable of modeling virtually any gas turbine configuration [10]. An adaptive modeling capability was developed that has been implemented in the generic component based simulation environment of GSP [5, 6]. With this adaptive modeling capability any GSP model can be converted into a diagnostic model for gas path analysis purposes without the need for extra coding.

After maintenance, the performance of each engine is verified with a post-overhaul acceptance test in a controlled test cell environment. These performance tests provide accurate performance data for gas path analysis. This enables monitoring of post-overhaul component condition data and provides detailed engine health status before re entry into service. Detailed component condition information is also valuable to monitor the maintenance effectiveness at KLM Engine Services. More important, if an engine fails the post-overhaul acceptance test, GPA can be used to determine the root cause of the poor performance. The resulting component condition data facilitates more efficient maintenance planning during the shop revisit.

Engines are responsible for roughly 25% of the total direct operating costs (DOC) of aircraft [11, 12]. Inflating aviation fuel prices strongly affect engine related DOC and, therefore, the overall airline expenses. Although fuel related costs have been significantly reduced by technological advances, such as increased bypass ratio and reduced tip clearance by means of active clearance control, fuel still accounts for roughly one third of the DOC. To compensate for inflating fuel prices, airline operators demand longer on-wing times and reduced maintenance costs.

Engine usage and maintenance can be planned more effectively if individual component condition data is available while operated on-wing. With conventional engine condition monitoring (ECM) techniques, parameters such as the exhaust gas temperature and specific fuel consumption are monitored. Without further analysis, these performance parameters only provide system-level engine condition information. Using on-wing performance data for GPA, enables individual component condition parameter estimation while the engine is in service. Instead of system-level performance parameters, individual component condition parameters are monitored, providing detailed engine condition information. Based on this component, condition can be determined and the required corrective action taken when necessary. Consequently, unnecessary maintenance due to incorrect diagnoses can be reduced.

MODEL ADAPTATIONS FOR GPA

Component maps and reference engine performance data are required to create an accurate cycle model for off-design gas turbine performance simulations. For GPA purposes, additional information such as engine-specific sensor locations and geometric data are necessary to relate measured performance parameters to simulated parameters. Cycle calculations, necessary for the adaptive modeling calculations, require total properties. However, at some stations in a gas turbine, static pressure is measured instead of total pressure. Cross flow area information is then used to relate static properties to total properties.

Because of limited measured performance parameters, component conditions can not be determined for all turbomachinery components. For the engine families analyzed at KLM Engine Services, special adaptations to the models were necessary to use the available measured performance data. The generic modeling capability of GSP is particularly advantageous to accommodate the required adaptations.

One required adaptation was related to the model layout of the low pressure compressor section. Both the CF6 and the CFM56-7B engine families have a compressor configuration that consists of a fan, a low pressure compressor (booster), connected to the low pressure turbine shaft, and a high pressure compressor, connected to the high pressure turbine shaft. Since no performance parameters are measured at the fan-booster interface, there is no use for separate conditions for the fan core and booster components. Because both turbomachinery components share the same shaft, they are modeled as a single component in the GSP model. Consequently, the number of condition parameters are reduced, thereby enhancing GPA iteration stability. This required a new component map that combined the performance characteristics of both components together.

Another required adaptation was related to the model layout of the low pressure turbine section of the CFM56-7B engine. In this engine model, the exhaust gas temperature (EGT) sensor is embedded in the nozzle guide vane stage following the first low pressure turbine rotor. Because GSP is a 0-D performance model, the state of the working medium is calculated only at component inlet and outlet planes. Consequently, performance parameters measured inside a component cannot be used in the adaptive modeling calculation to determine the component condition parameters. The solution was to split the low pressure turbine, and model it as two separate turbine components that share the same shaft.

GPA WITH ON-WING ENGINE PERFORMANCE DATA

Gas path analysis using on-wing performance data is different compared to gas path analysis of data obtained from a controlled test cell environment. Often fewer performance parameters are measured on-wing, while the available data are more affected by measurement uncertainty. Also, atmospheric conditions and engine power setting may vary considerably during operation, and performance degradation occurs in all components but at different rates. These variations all affect engine performance. Component deterioration generally occurs gradually, and clear distinction is very difficult in data that are strongly affected by variable atmospheric conditions and power setting, and measurement uncertainty. All these effects make GPA with on-wing measured performance data more challenging than GPA with data measured in a test cell.

Fewer Measured Performance Parameters

During performance tests in a test cell, gas turbines generally have more sensors installed than during on-wing operation. To certify engines for on-wing operation after overhaul, detailed engine performance assessments are required. Therefore, engines are equipped with sufficient sensors to determine their performance to the required level of detail during the post-overhaul acceptance test. Because certain performance parameters cannot be measured during on-wing operation and engine operators can prefer a reduced set of installed sensors, often fewer performance parameter are available for on-wing GPA.

One performance parameter that is not directly measured on-wing is engine thrust. Engine thrust represents the thermodynamic state of the core and bypass nozzles. During post-overhaul acceptance tests in a test cell, load cells are used to accurately measure engine thrust. Because thrust measurements are not possible on-wing, an alternative parameter is required to represent the thermodynamic state of the nozzles. For high bypass turbofan engines a large proportion of the thrust, in the order of 85% of the total thrust, is generated by the bypass flow. The pressure ratio over the fan bypass nozzle gouverns the thrust generated by the bypass flow. Therefore, the fan bypass outlet pressure represents the state of the bypass nozzle, which makes this performance parameter a good alternative to the thrust parameter.

A comparative analysis has been performed to verify the use of fan outlet pressure as an alternative parameter to represent the thermodynamic state of the exhaust nozzles. Of the performance parameters measured during the performance acceptance test of the CF6-80 engine in the KLM Engine Services test cell, 14 parameters can be used for GPA purposes including engine thrust and fan outlet pressure. Table 1 provides the list of the available measured performance parameters. Tt0, Pt0 and RH define the atmospheric condition, and N1 defines the engine power setting. The 10 remaining parameters represent the thermodynamic state of the engine. However, using the thrust and the fan bypass outlet pressure simultaneously in the AM calculations results in an ill-conditioned system. Therefore, from the available set of performance parameters 9 component condition parameters can be determined simultaneously. For the comparative analysis, the performance test data from recently overhauled engines was used. The AM calculations were done twice; first with the direct thrust measurement and subsequently with the fan bypass outlet pressure. The results of this analysis are presented in figure 2. The top chart shows the performance parameter variations necessary to adapt the engine model to measured performance of a particular engine for both simulation runs. This chart illustrates that for first AM calculation, measured thrust (FN) was used, whereas for the second AM calculation the fan outlet pressure (Ps14) was used. The bottom two charts illustrate component condition deviations relative to the reference engine condition. The results indicate only a minimal differences in the diagnostic outcome. Similar results were obtained for other engines. These results validate the use of fan outlet pressure for GPA of on-wing data as a suitable alternative for thrust measurements.

Another parameter not measured during on-wing operation is the relative humidity (RH). Although of the three ambient parameters humidity has a minor effect on gas turbine performance, its effects are not negligible [13]. Changes in humidity levels af-

TABLE 1. MEASURED PERFORMANCE PARAMETERS AVAILABLE FOR GPA PURPOSES.

Parameter	Description
Tt0	Ambient temperature
Pt0	Ambient pressure
RH*	Relative humidity
N1	Fan shaft speed
Ps14	Fan bypass static outlet pressure
Tt25	Booster outlet total temperature
Pt25	Booster outlet total pressure
Tt3	HPC outlet total temperature
Ps3	HPC outlet static pressure
N2	Core shaft speed
Tt49	HPT outlet total temperature
Pt49	HPT outlet total pressure
Wf	Fuel mass flow
FN*	Engine thrust

* parameter not measured during on-wing operation.

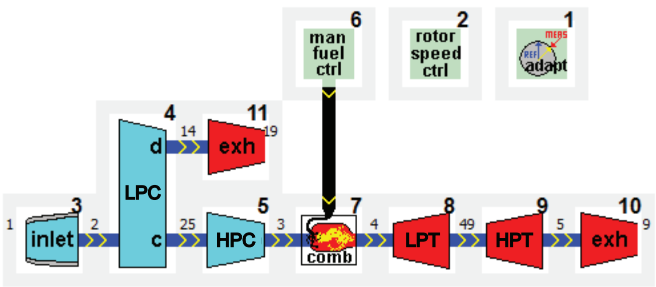

FIGURE 1. COMPONENT NAMES AND STATION NUMBERS OF THE CF6-80 GSP MODEL

fect the molecular composition of air and thus the physical properties such as specific heat and specific gas constant. These, in turn, have a direct affect on engine performance. During on-wing operation, aeroengines encounter large variations of ambient temperature and pressure, which affect humidity levels. The lack of relative humidity measurements during on-wing operation means that the effects of this parameter cannot be taken into account in the AM calculation. Neglecting humidity effects, especially when large variations can occur, may lead to incorrect component condition estimations [14].

Measurement Uncertainty

Measurement uncertainty affects diagnostic results of model-based GPA methods [12,15]. With GSP GPA, an analysis

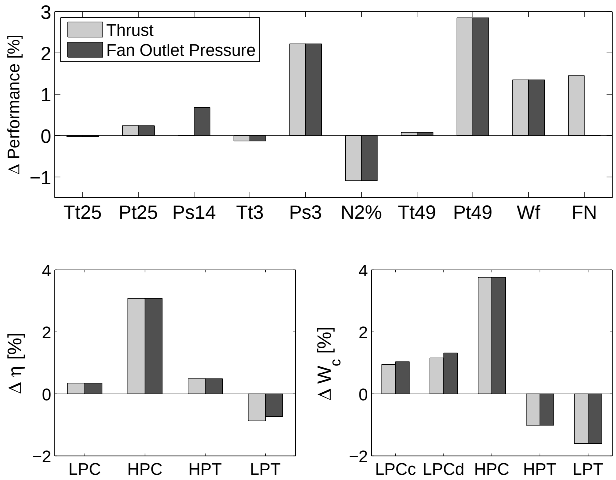

FIGURE 2. GPA RESULTS; COMPARING THE USE OF FAN OUTLET PRESSURE INSTEAD OF DIRECT THRUST MEASUREMENTS.

has been done on the effects of sensor noise. For this analysis, component deterioration is simulated for the high pressure compressor and high pressure turbine of a CF6-80C2 engine. The simulated deterioration levels are shown in the second column of table 2. To simulate the effects of sensor noise, random variations were added to simulated on-wing performance parameters, with the exception of the shaft RPM. Because shaft rotational speed measurements are generally very accurate, noise effects on these parameters are neglected in this analysis. Four levels of sensor noise are used, namely: $\pm 0.5\%$, $\pm 1\%$, $\pm 2\%$ and $\pm 4\%$. For each level of simulated sensor noise, 20 sets of perturbed performance parameters were generated. GPA was used to analyze both the clean and noise affected performance data.

The results of this analysis are presented in figures 3 and 4. The whiskers of the box plot indicate the range of the component condition deviations still within the 1.5 interquartile range. The bottom and top of the blue box are the 25^{th} and 75^{th} percentile of the data. The red line in the middle of the box is the median. Values that exceed the 1.5 interquartile range are considered as outliers, and are indicated by the red cross markers. The dotted lines indicate the simulated component condition deviation. The results show that relatively small performance parameter variations, due to sensor noise, can have significant effects on the diagnostic outcome. The results also indicate that effects of sensor noise are not equal for all condition parameters. Some component condition parameters shown much larger deviations for a specific noise level in comparison to other condition parameters. In addition, the condition deviation extrema increase for increasing levels of sensor noise. Based on these character-

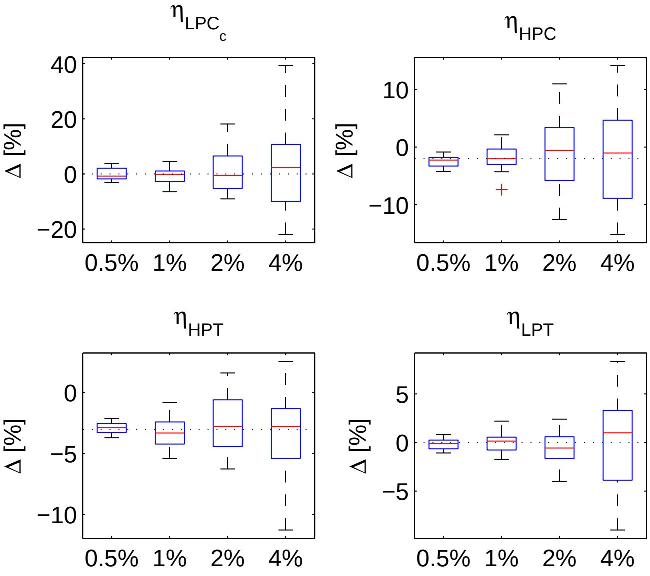

FIGURE 3. COMPARISION OF COMPONENT EFFICIENCY DELTAS FOR 4 DIFFERENT SIMULATED SENSOR NOISE LEVELS. EACH BOXPLOT CONTAINS 20 DATA POINTS.

istics, sensor noise appears to be disastrous for GPA. However, the availability of many on-wing performance data points permits averaging of the diagnostic results. Using the 20 parameter sets for each level of simulated sensor noise, the mean condition deviations were determined. Table 2 presents the deviation of the deterioration percentages relative to the simulated deterioration. The $HPC \Delta Wc$ deviation of -0.7 for $\pm$4% noise, means that the arithmetic mean for this parameter was 1.3%. Although the arithmetic mean of the of the condition deviations does not eliminate the error, it does represent a good approximation of the actual component deterioration. Overall, the error of the arithmetic mean increases for increasing levels of sensor noise.

Component Maps

Off design performance variation of turbomachinery components is captured in component maps. For accurate simulation of gas turbine engines, performance models require correct component maps for each turbomachinery component. However, these component maps are proprietary and therefore only available to the engine manufacturer. To simulate engine performance, component maps for similar turbomachinery available from open sources and literature are scaled to match the desired performance. This scaling technique is generally sufficient to produce good results for GPA applications that use test cell performance data.

During post-overhaul acceptance tests in a test cell, engines are operated at specific power settings, expressed by the low speed shaft RPM. This provides accurate performance data for GPA purposes. Component maps obtained with conventional scaling methods provide sufficient accuracy for GPA of acceptance test performance data.

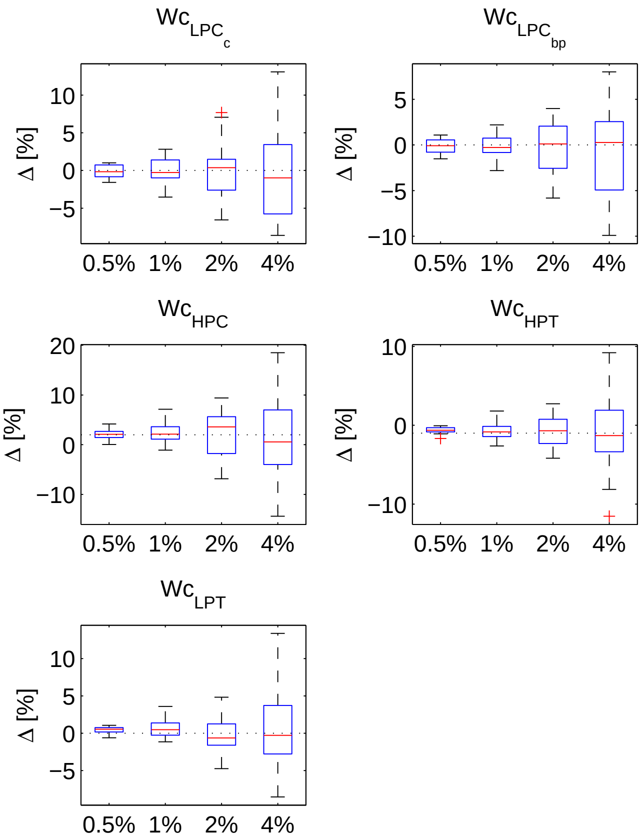

FIGURE 4. COMPARISION OF COMPONENT CORRECTED MASS FLOW DELTAS FOR 4 DIFFERENT SIMULATED SENSOR NOISE LEVELS. EACH BOXPLOT CONTAINS 20 DATA POINTS.

During on-wing operation, engine power setting and operating conditions may vary considerably. For example, the use of reduced take-off thrust to conserve engine life and reduce maintenance costs, or differences between power setting and ambient conditions during cruise and take-off. Therefore, the GPA tool used for on-wing data analysis must be capable of accurate performance simulation over a wider range of engine power settings compared to test cell conditions. Conventional scaling methods, that scale component maps to match performance at one specific point, may not provide the accuracy required for GPA with on-wing performance data. To improve model accuracy, the component maps must be adapted in a way that cannot be achieved with

TABLE 2. GPA RESULTS OF SIMULATED SENSOR NOISE ANALYSIS.

Condition Parameter	Simulated Deterioration	0.0%	0.5%	1.0%	2.0%	4.0%
$LPC_c\Delta\eta$	**0.0**	0.0	-0.1	-0.8	0.8	2.2
$LPC_c\Delta Wc$	**0.0**	0.0	-0.1	0.0	0.0	-0.3
$LPC_{bp}\Delta\eta$	**0.0**	-	-	-	-	-
$LPC_{bp}\Delta Wc$	**0.0**	0.0	-0.1	-0.2	-0.2	-1.2
$HPC\Delta\eta$	**-2.0**	-0.3	-0.4	0.2	0.6	1.1
$HPC\Delta Wc$	**2.0**	0.1	0.1	0.4	0.5	-0.7
$HPT\Delta\eta$	**-3.0**	0.0	0.1	-0.3	0.4	-0.7
$HPT\Delta Wc$	**-1.0**	0.3	0.4	0.3	0.2	0.0
$LPT\Delta\eta$	**0.0**	-0.1	-0.1	0.0	-0.6	-0.1
$LPT\Delta Wc$	**0.0**	0.3	0.4	0.7	-0.2	0.3

a single map scaling factor.

ON-WING GPA APPLICATION
Component Condition Monitoring

One practical application for GPA of on-wing performance data is component condition monitoring. This application has been analyzed for three General Electric CF6-80C2 engines from a single aircraft in the KLM fleet. Because the GPA model including the component maps are optimally tuned to standard take-off conditions, take-off snapshots are used to assess the application of on-wing GPA. For each engine, 25 on-wing take-off snapshots were available. These take-off snapshots were recorded 50 seconds after commencing take-off mode. All engines were equipped with an extended sensor package. This meant that apart from measured performance parameters required to match atmospheric conditions and power setting, 9 additional performance parameters were available for GPA purposes. Table 1 provides a list of the on-wing measured performance parameters. With these 9 performance parameters, 9 component condition parameters could be determined using GPA. For each engine, performance data from the last test cell acceptance test was used as reference.

The GPA diagnostic results for the three CF6-80C2 engines are shown in figures 5 and 6. The graphs show significant variation of the component condition parameters. The results are affected by a combination of sensor error and inaccurate component maps. However, the results of the sensor noise analysis presented in figure 3 and 4, show a larger variation than the on-wing GPA results. This implies that on-wing noise effects are smaller than $\pm1\%$.

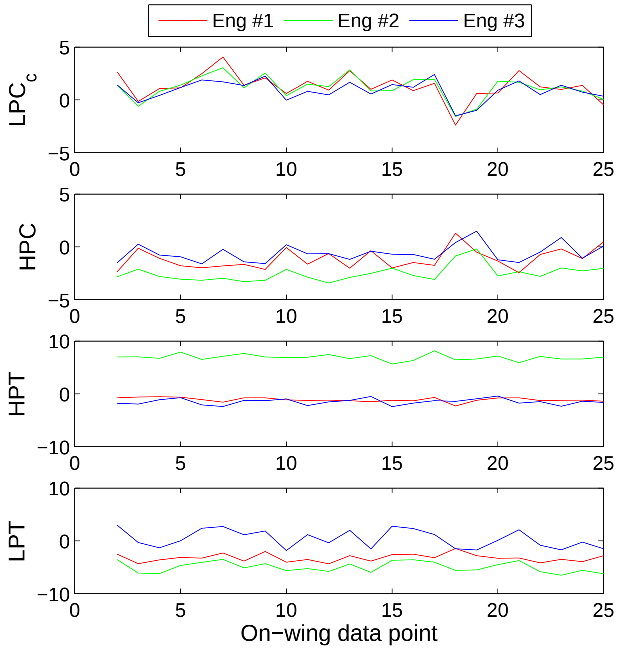

FIGURE 5. GPA RESULTS USING 25 ON-WING PERFORMANCE DATA POINTS: COMPONENT EFFICIENCY DEVIATIONS.

EGT Margin Validation

Another application of GPA is the analysis and validation of important performance parameters used for engine health monitoring such as the EGT margin. In general, the EGT margin, corrected to hot day conditions is used as an indicator for overall engine condition. A relatively small hot day EGT margin may reduce the time between two consecutive overhauls. Therefore, airline operators demand certain EGT margins for overhauled engines.

Recently, KLM Engine Services was notified about hot day EGT margins, which were determined during on-wing operation, that deviated significantly from test cell calculated hot day EGT margins for the CFM56-7B engine. Also, for some engines severe scatter of the hot day EGT margin was observed during on-wing operation. The engines were overhauled at KLM Engine Services and successfully passed the post-overhaul acceptance test. Furthermore, the EGT margins determined during the acceptance test were as expected for an overhauled engine. Upon closer inspection of KLM's own CFM56-7B fleet, no maintenance related cause was identified that could explain this unwanted behavior [16].

To compare on-wing performance to test cell performance, the engine model was adapted to match the engine condition determined from the last post-overhaul acceptance test data using GSP GPA. The component conditions for the GSP model used to

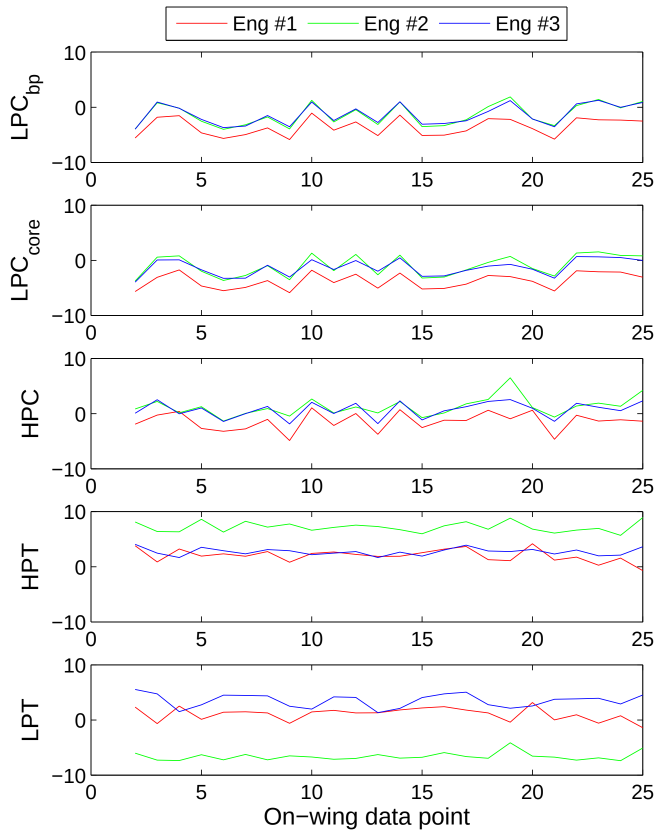

FIGURE 6. GPA RESULTS USING 25 ON-WING PERFORMANCE DATA POINTS: COMPONENT CORRECTED MASS FLOW DEVIATIONS.

simulate on-wing performance, were kept constant and equal to the test cell component conditions. The adapted model was subsequently run at power settings and ambient conditions measured during the 15 first on-wing operations.

The EGT trend, shown in figure 7, indicates that the on-wing measured engine performance thermodynamically corresponds to the simulated engine with a constant condition. The small deviations may be because of model inaccuracies and additional effects not measured, such as: customer bleed and power off-take. Moreover, these deviations are an order of magnitude smaller than the EGT margin variation. A gas turbine with a constant condition should have a constant corrected EGT margin. However, this conflicts with varying on-wing corrected EGT margin values that are determined by the post-processing engine condition monitoring software. Similar results were obtained for a number of engines.

The EGT is affected by power setting, operating conditions and customer bleeds. Consequently, the calculated EGT margin should be corrected for those effects. If done correctly, changes

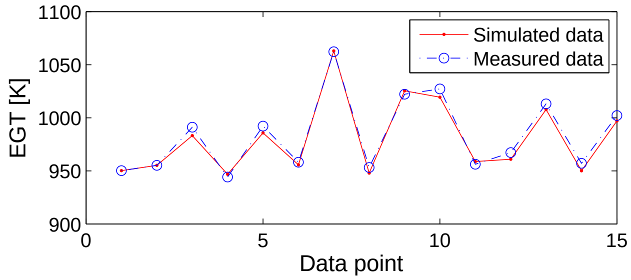

FIGURE 7. SIMULATED AND MEASURED EGT VALUES FOR A CFM56-7B ENGINE.

of the hot day EGT margin should be only because of component deterioration and thus reflect overall engine condition. From the results it was concluded that the cause of the hot day corrected EGT margin deviation and scatter was not the result of engine deterioration or measurement error. It was also concluded that the calculations used to determine the hot day EGT margin are inaccurate or based on false input data.

Performance Restoration Effect Prediction

A third interesting application of GPA of on-wing performance data for the maintenance process is the effect prediction of component performance restoration. The level of overall engine performance restoration depends on the maintenance work scope applied to each component. However, realizing 100% engine performance restoration is difficult –and more important– very expensive.

If component condition data were available prior to maintenance, the effects of each level of restoration on each component could be analyzed using engine performance simulation. Generally, component condition data can be obtained from inbound performance tests in a test cell. Due to the cost related to performance test runs, this option is used only when no clear cause can be identified by other diagnostic methods. With a GPA capability of on-wing performance data, inbound component condition data become available without the need for expensive inbound test runs.

A performance restoration effect analysis has been performed for a CFM56-7B engine with poor post-overhaul performance. The diagnostic results obtained from post-overhaul acceptance test data are presented in figure 8. The component condition deviations relative to the reference engine are shown in the top chart of figure 8. For this component condition deviation chart a threshold of 2% is defined. This treshold is to allow for model errors and small engine differences. Any excursion beyond this treshold results in the bar to turn red. The performance parameter deviations relative to the reference engine are shown in the bottom chart. Overall engine performance restoration is expressed in terms of EGT and SFC gains relative to the

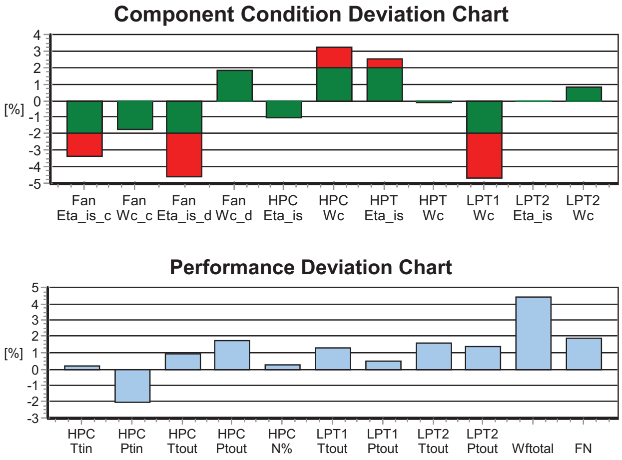

FIGURE 8. GSP GPA DIAGNOSTIC RESULTS OF A CFM56-7B ENGINE WITH POOR POST-OVERHAUL PERFORMANCE.

inbound values. For this analysis performance improvements of 50% and 75% restoration of the LPC and LPT were simulated. The results, presented in table 3, indicate that a 50% improvement of both components can already yield a 22 K reduction of the EGT and a 2% reduction of the SFC. Assuming a 3 K EGT increase for every 1000 flying hours, this 22 K improvement represents approximately 7000 flying hours. A 75% improvement could lead to a 32 K EGT reduction and roughly 3% SFC reduction. Therefore, with this information an informed trade-off can be made between the costs and benefits of the additional maintenance.

TABLE 3. LPC & LPT PERFORMANCE RESTORATION EFFECT PREDICTION.

Component	Condition Parameter	Condition Deviation	50% Restored	75% Restored	
LPC_c	$\Delta\eta$	-3.37	-1.69	-0.84	%
LPC_c	ΔWc	-1.72	-0.86	-0.43	%
LPC_{bp}	$\Delta\eta$	-4.63	-2.32	-1.16	%
LPC_{bp}	ΔWc	1.85	0.93	0.46	%
HPC	$\Delta\eta$	-1.01	-1.01	-1.01	%
HPC	ΔWc	3.19	3.19	3.19	%
HPT	$\Delta\eta$	2.51	2.51	2.51	%
HPT	ΔWc	-0.08	-0.08	-0.08	%
LPT1	ΔWc	-4.66	-2.33	-1.17	%
LPT2	$\Delta\eta$	-0.02	-0.01	-0.01	%
LPT2	ΔWc	0.78	0.39	0.2	%
	ΔEGT	0	22.43	32.27	K
	ΔSFC	0	2.23	3.2	%

CONCLUSIONS

This paper has described the challenges and potential benefits of gas path analysis on on-wing measured performance data. Based on the feasibility study performed, the following conclusions were drawn.

- On-wing GPA with GSP shows good results for CF6-80 engines that have sufficient on-wing measured performance data.
- The diagnostic results are suitable for on-wing component condition monitoring and inbound component condition assessment.
- GPA can also be used for analysis of overall engine condition parameters, such as EGT margin validation, if limited on-wing measured performance parameters are available.
- Performance restoration effect analysis can be used to determine the optimal maintenance work scope.
- The arithmetic mean of multiple component condition parameters obtained from noise affected performance data results in good approximations of the actual component condition. This result indicates that despite measurement uncertainty due to sensor noise, on-wing performance data can be used for GPA applications.
- For GPA in general accurate component maps are beneficial for the diagnostic accuracy. Because of the varying power setting encountered during on-wing operation, accurate component maps are critical for accurate GPA of on-wing performance data.

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