The Impact of Gas Turbine Component Leakage Fault on GPA Performance Diagnostics

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Abstract

The leakage analysis is a key factor in determining energy loss from a gas turbine. Once the components assembly fails, air leakage through the opening increases resulting in a performance loss. Therefore, the performance efficiency of the engine cannot be reliably determined, without good estimates and analysis of leakage faults. Consequently, the implementation of a leakage fault within a gas turbine engine model is necessary for any performance diagnostic technique that can expand its diagnostics capabilities for more accurate predictions. This paper explores the impact of gas turbine component leakage fault on GPA (Gas Path Analysis) Performance Diagnostics. The analysis is demonstrated with a test case where gas turbine performance simulation and diagnostics code TURBOMATCH is used to build a performance model of a model engine similar to Rolls-Royce Trent 500 turbofan engine, and carry out the diagnostic analysis with the presence of different component fault cases. Conclusively, to improve the reliability of the diagnostic results, a leakage fault analysis of the implemented faults is made. The diagnostic tool used to deal with the analysis of the gas turbine component implemented faults is a model-based method utilizing a non-linear GPA.

Keywords: aircraft, gas turbine, performance diagnostics, leakage fault, GPA T

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1. Introduction

The deterioration of the gas path components cannot be prevented in gas turbines which operate under normal and excessive environment conditions. The engine performance always degrades increasingly with time, impairing the airworthiness of the aircraft that could lead to catastrophic consequences. During operation, the components and ducts are also subject to an environment of thermal shocks, corrosion, mechanical vibration, and electromagnetic stresses, where the potential for damage and thus air leakage is high. Although, in the early years, gas turbine manufacturers have paid scant attention to the amount of leakage because the impact on performance measures was neglected, the designers' goal recently is to avoid any loss of the core flow to the environment. In this way, the work done by the engine on each amount of air saved can be used to increase thrust power. Therefore, air leakage diagnostics is a key factor in determining energy and accordingly performance losses of the engine. Gas path components efficiencies and engine operating characteristics cannot be reliably determined without good estimates of leakage fault. Specifically, for energy calculations, it is the duct or component leakage air flow to outside environment at operating conditions that is required. Simulating methods should either, precisely measure the size of leaks and thus the air flow along gas path with sufficient accuracy [1].

In an attempt to reduce the risk of such unwanted circumstances, commercial and military gas turbine users have engaged in some form of performance diagnostics [2]. Gas turbine performance diagnostic is a fairly mature methodology to accurately detect, isolate and assess the changes in engine module performance, engine system malfunctions and instrumentation problems from knowledge of measured parameters taken along the engine's gas path. Good estimates allow operators to make safe decisions, regarding the required maintenance actions. Different diagnostic approaches are adapted and developed, in order to restore the integrity and performance of the engine but one of the most popular is Gas Path Analysis (GPA) presented by Louis A. Urban [3]. GPA is a model-based mathematical technique that estimates individual modules and sensor performance shifts from any specified set of engine measurable parameters and component characteristics, through the aero-thermodynamic relationships which exist between them [4]. Non-linear GPA is a diagnostic tool that is preferred for use in this study because it is proved to offer a significant advantage over the severe limitations of linear GPA models since it addresses the non-linear nature of the engine thermodynamic behavior.

In this paper, the impact of the leakage fault is dealt with the diagnosis of implemented single and combined faults. The gas turbine diagnostic program used for this study is the GPA technique developed at Cranfield University [5]. The GPA technique has been applied to a gas turbine model engine, a civil high by-pass ratio turbofan engine, similar to Trent 500 manufactured by Rolls Royce plc [6-8].

2. Methodology

2.1 Gas Path Analysis

Gas Path Analysis (GPA), pioneered by *Urban* is used to assess the condition of individual engine components, based on the aero-thermodynamic relationships that exist between the component and the direct measurements of gas path

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parameters [9]. The theory behind this relationship can be summarised by: The presence of a primary gas-path physical fault induces a change in the component characteristic that shows up as a deviation of the measurable parameters from the baseline conditions [10]. Therefore, the purpose of the GPA is to detect, isolate, and quantify the gas path components faults that have observable impacts on the measurable variables with the hope that will facilitate the subsequent isolation of the underlying physical fault. For a gas turbine engine, the mathematical relationship between dependent (engine component health parameters) and independent parameters (gas path measurements) is expressed analytically as [11]:

$$\vec{z} = h(\vec{x}) \tag{1}$$

The assumption of linearity becomes increasingly false, when deteriorations cause the engine to operate further away from the condition for which the matrix was calculated. Therefore, the non-linear GPA diagnostic technique is preferred at the present paper, instead of the linear technique, due to the consideration of the non-linear nature of the engine thermodynamic behavior [12,13]. The non-linear GPA uses the *Newton-Raphson* iterative technique, where the linear GPA prediction process is applied iteratively until a converged solution is obtained [4].

2.2 Leakage Fault Isolation
The gas turbine operators during the diagnostic analysis barely have an indication of the degraded engine components. The occurrence of a fault is therefore unknown, and so it is necessary for a confident prediction to effectively isolate the degraded component. Consequently, the effective component isolation can lead to an accurate fault prediction of degradation, and for this purpose a GPA Index introduced in [14] and defined as:

$$GPA\ Index = \frac{1}{1 + \varepsilon} \tag{2}$$

The parameter ε is a measure of the difference between the measured deviation ($\Delta zo/zo$) and predicted deviation ($\Delta z/zo$) of engine gas path measurements (fault signatures) in the ith state, expressed with Equation [3]:

$$\varepsilon = \sum_{i=1}^{N} \left| \frac{\Delta z_{0,i}}{z_0} - \frac{\Delta z_i}{z_0} \right| \tag{3}$$

Figure 1 illustrates the methodology that needs to be followed for the calculation of the GPA Index. Initially, the faulty engine components are defined and GPA predicts their degradation at certain ambient and operating conditions. The percentage deviations of the independent parameters are then sent to the model engine to estimate a predicted fault signature. Once both the real and predicted fault signatures are available, ε and thus GPA Index are calculated. If the predefined is the same to the implanted fault, ε tends to 0 and GPA Index gets closer to 1. Consequently, a GPA Index approaching the value of 1 indicates an accurate degradation prediction, otherwise the tendency to reach zero (0) is regarded as a poor degradation prediction result.
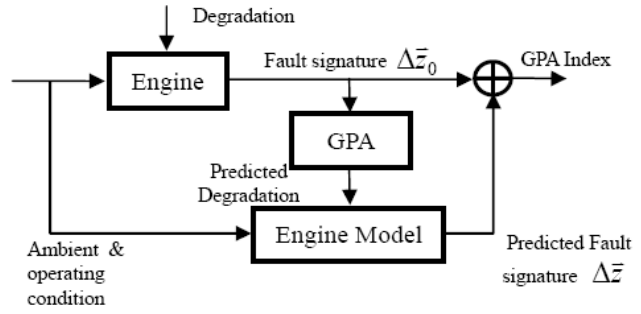

Fig. 1. Calculation of GPA Index [14]

According to [14], for an effective application of GPA Index to gas turbine component fault diagnosis, the maximum number of simultaneous degraded engine components and the component fault cases (CFC) that cover all the combinations of potential degraded components should be pre-defined. Following that, the diagnostic approach is employed to each of the CFC in order for the diagnostic model to cover all pre-defined engine faults (*see* Figure 2). The best solution or else the maximum value of GPA Index among all CFC indicates the most likely engine degradation case.
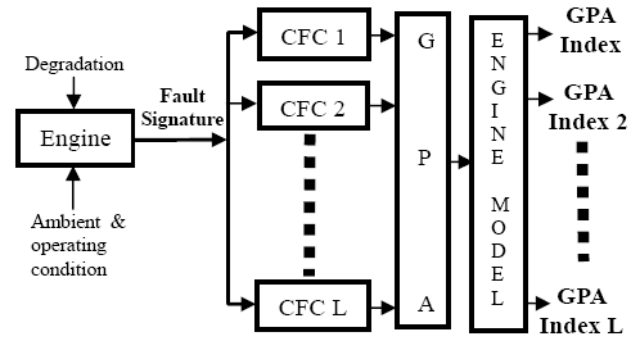

Fig. 2. Diagnostic systems using GPA Index [14]

For testing the diagnostic system, the engine faults implanted into the Trent 500 model engine include a component leakage, since it might impair the interpretation of the diagnostic results.

3. Analysis procedure of leakage fault impact

The proposed methodology in analyzing the impact of leakage fault on gas turbine GPA diagnostics is divided into the following main steps:

- A model engine performance model is created with thermodynamic performance software and therefore any gas path component leakage fault can be implemented.
- One set of gas path measurements were selected. Gas path measurements of the model engine at different engine health conditions were simulated.
- Different component leakage faults in a single or combined fault cases are implemented in the engine. The location of the implanted faults are the compressor and the turbine of the engine.

- The simulated engine leakage faults are used as input to the GPA diagnostic system to isolate and detect them.

4. Case study

4.1 Model Engine

The engine model selected for the leakage impact analysis in this paper is similar to Rolls Royce Trent 500, a three spool, high-bypass turbofan engine rated in 249 kN net thrust at sea level. In Figure 3 there is a schematic representation of the model engine. The model engine was simulated using TURBOMATCH, a FORTRAN-based gas turbine simulator developed at Cranfield University [6,12,14,15]. Normally, it is appropriate to define DP of a gas turbine in cruise conditions because the aircraft spends most of the operational time at this situation. However, in the current paper the DP was chosen at the take-off condition because the available open access database for the performance parameters of this engine refer to the ground testing [16-18]. Therefore, the performance specifications of the engine at the DP are presented under the atmospheric conditions of SLS.
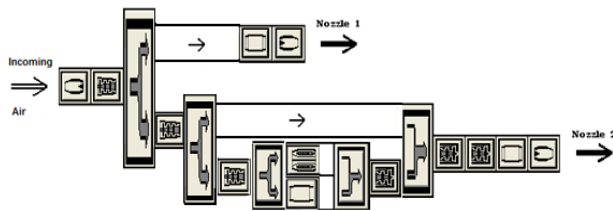

Fig. 3. Model Engine Configuration

Performance Parameter	Value	Units
Ambient Temperature	288.0	*K*
Inlet Mass Flow Rate	879.5	*kg/s*
BPR	7.5	*non-d*
TET	1600.0	*K*
Net Thrust	249.0	*kN*
LP Compressor / Fan PR	1.5	*non-d*
IP Compressor PR	5.9	*non-d*
HP Compressor PR	4.1	*non-d*
OPR	36.3	*non-d*

4.2 Instrumentation set selection

The success of any fault diagnosis technique depends critically on the sensor network, measuring the important observed parameters. An optimally designed sensor network for fault diagnosis should observe all the faults when they occur, and also distinguish between them to the maximum extent possible [19]. Therefore, the instrumentation set should be properly chosen for better detection of engine degradation because the quality of the diagnostic analysis relies on the quality of the measurements. Table 1 shows all the potential gas path measurements for the model engine and Table 2 all the health parameters of potential degraded engine components. For the measurement set to be effective in the GPA diagnostic analysis, the chosen measurements

should be sensitive to engine degradation and independent from each other. To assist the selection of measurements, a sensitivity analysis is carried out, where the response of all the potential gas path measurements, due to unit deviation of each of the engine component health parameters, are obtained, by using performance simulation of the model engine.

Table 1. Potential Gas Path Measurements

Symbol	Measurement Parameter	Unit
PCN1	C1 relative rotational speed	%
PCN2	C2 relative rotational speed	%
PCN3	C3 relative rotational speed	%
P3	C1 exit total pressure	atm
T3	C1 exit temperature	K
P5	C2 exit total pressure	atm
T5	C2 exit temperature	K
P7	C3 exit total pressure	atm
T7	C2 exit temperature	K
P10	CC exit total pressure	atm
FF	Fuel flow rate	kg/s
P14	T1 exit total pressure	atm
T14	T1 exit temperature	K
P16	T2 exit total pressure	atm
T16	T2 exit temperature	K
P17	T3 exit total pressure	atm
T17	T3 exit temperature	K

Table 2. Health Parameters of potential degraded engine components

Fault No.	Meaning	Health Parameter
1	C2 leakage fault	LK_{C2}
2	C3 leakage fault	LK_{C3}
3	C1 isentropic efficiency	IE_{C1}
4	C1 flow capacity	FC_{C1}
5	C2 isentropic efficiency	IE_{C2}
6	C2 flow capacity	FC_{C2}
7	C3 isentropic efficiency	IE_{C3}
8	C3 flow capacity	FC_{C3}
9	T1 isentropic efficiency	IE_{T1}
10	T1 flow capacity	FC_{T1}
11	T2 isentropic efficiency	IE_{T2}
12	T2 flow capacity	FC_{T2}
13	T3 isentropic efficiency	IE_{T3}
14	T3 flow capacity	FC_{T3}

Figure 4 illustrates the plotted sensitivity of all potential gas path measurements against all the model engine health parameters and the number of faults taken from Table 2.
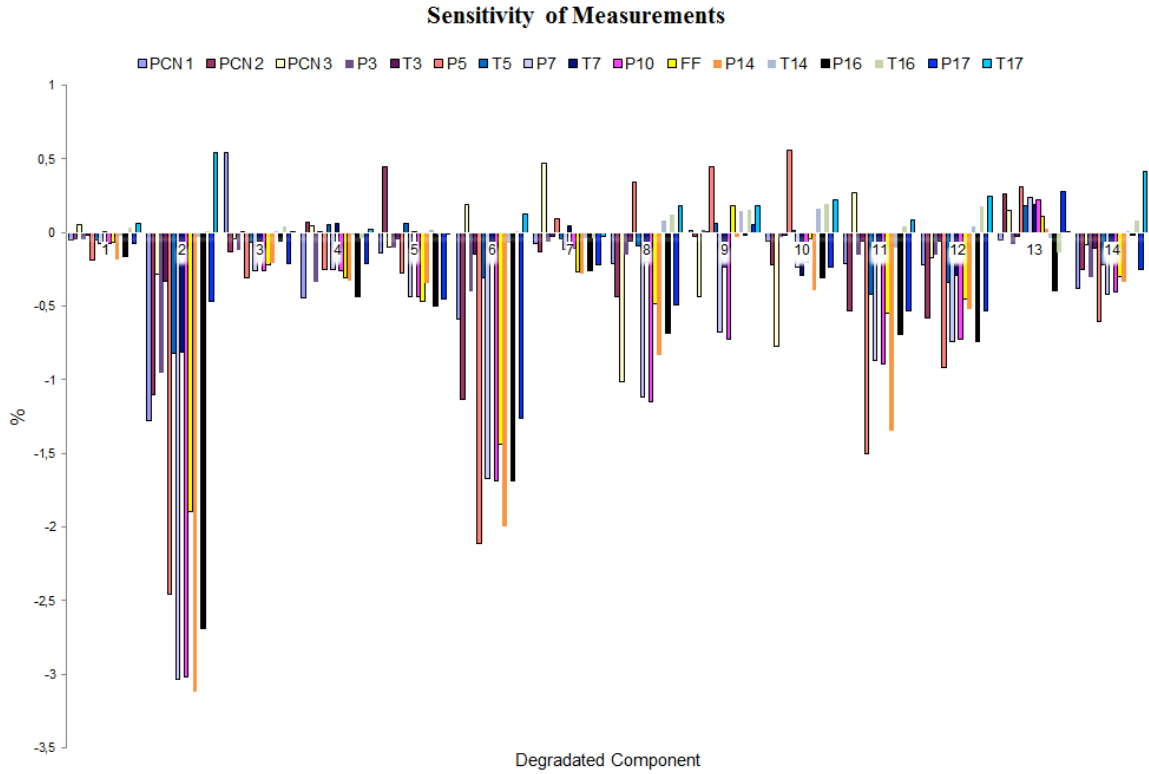
Sensitivity of Measurements

Fig. 4. Sensitivity of measurements

Based on the sensitivity of the measurements, a set of eight measurement parameters is then selected for the diagnostic analysis of the model engine. The selected measurement set is:

- Total pressure at the exit of IP compressor   (P5)
- Total pressure at the exit of HP compressor   (P7)
- Total pressure at the exit of CC
               (P10)
- Total pressure at the exit of HP turbine
               (P14)
- Total pressure at the exit of IP turbine
               (P16)
- Relative rotational speed of LP spool
               (PCN1)
- Relative rotational speed of HP spool
               (PCN3)
- Fuel flow rate
               (FF)
-

In an attempt to investigate the impact of leakage fault on performance diagnostics, engine component leakage fault degradation were implemented into the model engine using TURBOMATCH software and gas path measurements were simulated. The implemented degradation is assumed unknown to the engine users and simulated measurements are used to predict the seeded fault. As the linear GPA is less effective compared to its non-linear partner only the non-linear GPA technique is used in diagnostic analysis.

4.3 Leakage Fault Analysis
4.3.1   Leakage Fault Diagnostics
For the purpose of the leakage fault diagnostics, six (6) different Component Fault Cases (CFC), listed in Table 3 are examined. Every single and combined fault case that is implemented and then diagnosed, include at least one (1)

type of a leakage degradation, with the code name L1 or Leak 1 and L2 or Leak 2. The location of each leakage type in the engine is the IP and HP Compressor respectively.

Table 3. Leakage Fault Cases

CFC No - Type	Degraded Components	Fault Case	Percentage
1 – Single	IP Compressor	Full Leakage	100.0 %
2 – Single	IP Compressor	Half Leakage	50.0 %
3 – Single	HP Compressor	Full Leakage	5.0 %
4 – Single	HP Compressor	Half Leakage	2.5 %
5 - Combined	IP Compressor	Leakage	40.0 %
	HP Compressor	Mass Flow	-3.0 %
	HP Compressor	Isentropic Efficiency	-3.0 %
6 - Combined	HP Compressor	Leakage	-3.0 %
	IP Turbine	Mass Flow	-2.0 %
	IP Turbine	Isentropic Efficiency	-2.0 %

Table 4 and Figure 5 present the GPA predictions results for the first four single fault cases. Table 5 and Figure 6 present the predictions for all the combined fault degradations. From these Tables and Figures, it can be observed that the accuracy of the diagnosis is excellent because of the zero deviations of the detected from the implemented and expected degradation faults. Thereupon, the outcome of this investigation is that, the detection capability of non-linear GPA technique for any type of leakage fault degradation is remarkable.

Table 4. GPA diagnostic results for single leakage faults

		Non-linear GPA		
		Single Leakage Faults		
CFC No	Leakage Type	Implanted (%)	Detected (%)	Accuracy (%)

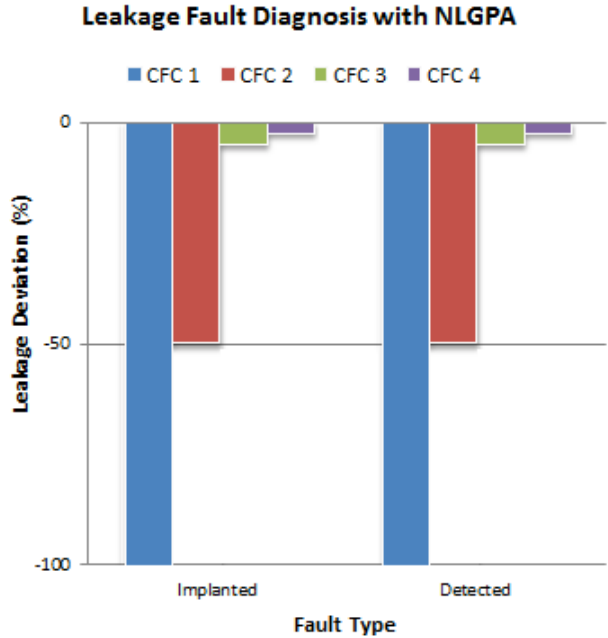|					
Leak 1	1	Full	-100.0	-100.0	100
	2	Half	-50.0	-50.0	100
Leak 2	3	Full	-5.0	-5.0	100
	4	Half	-2.5	-2.5	100

Fig. 5. Plotting form of the GPA diagnostic results for single leakage faults

Table 5. GPA diagnostic results for combined leakage faults

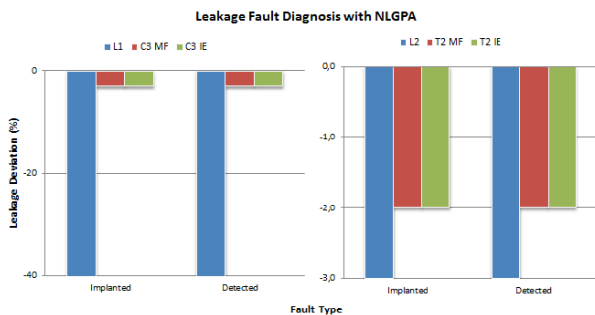|		Non-linear GPA		
		Combined Leakage Faults		
	CFC No	**Implanted (%)**	**Detected (%)**	*Accuracy (%)*
L1 + C3 or HPC MF + C3 or HPC IE	5	-40.0	-40.0	100
		-3.0	-3.0	100
		-3.0	-3.0	100
L2 + T2 or IPT MF + T2 or IPT IE	6	-3.0	-3.0	100
		-2.0	-2.0	100
		-2.0	-2.0	100

Fi. 6. Plotting form of the GPA diagnostic results for combined component faults

4.3.2 Leakage Fault Isolation

For testing the diagnostic system, the engine faults implanted into the Trent 500 model engine include a component leakage, since it might impair the interpretation of the diagnostic results.

Single Degradation

In the case of a single degradation, the fault that is isolated is 50 percent air loss from IP Compressor and the mathematical technique used is non-linear GPA. For the purpose of the fault isolation, there is also an assumption that all gas path components, except of burners, are potential degraded components and the allowed maximum number of simultaneously degraded engine components is two. The exclusion of burner is made because its efficiency is high and the possibility to degrade rare. The GPA diagnostic system using GPA index described in Figure 1 and 2 used for the detection of the component fault cases is listed in Table 6. The results of the diagnostic analysis applied on every single and combined component set illustrated in the form of GPA Indices are shown in Figure 7. In some fault cases, no results and thus diagnostic predictions could be obtained but error messages appeared from the simulation code, reporting the end of the convergence iterations in zero or after very few loops. The reason for the unusual termination of the diagnostic process was that the percentage of health parameters had exceeded the allowed percentage TURBOMATCH can handle.

Table 6. Engine Component Fault Cases and GPA Indices for a single degradation

Component Fault Case	Pre-defined Component	GPA Index
Implemented Fault: 50% Leak 1		
CFC 1	Leak 1	1.00
CFC 2	Leak 2	0.88
CFC 3	Compressor 1	0.87
CFC 4	Compressor 2	0.80
CFC 5	Compressor 3	0.88
CFC 6	Turbine 1	0.73
CFC 7	Turbine 2	0.81
CFC 8	Turbine 3	0.78
CFC 9	Leak 1 + Leak 2	0.81
CFC 10	Leak 1 + Compre 1	0.97
CFC 11	Leak 1 + Compre 2	0.83
CFC 12	Leak 1 + Compre 3	0.96
CFC 13	Leak 1 + Turbine 1	-
CFC 14	Leak 1 + Turbine 2	1.00
CFC 15	Leak 1 + Turbine 3	0.80
CFC 16	Leak 2 + Compre 1	0.88
CFC 17	Leak 2 + Compre 2	0.20
CFC 18	Leak 2 + Compre 3	0.70
CFC 19	Leak 2 + Turbine 1	0.49
CFC 20	Leak 2 + Turbine 2	0.86
CFC 21	Leak 2 + Turbine 3	-
CFC 22	Compre 1 + Compre 2	0.77
CFC 23	Compre 1 + Compre 3	0.87
CFC 24	Compre 1 + Turbine 1	0.82

CFC 25	Compre 1 + Turbine 2	0.83
CFC 26	Compre 1 + Turbine 3	0.79
CFC 27	Compre 2 + Compre 3	-
CFC 28	Compre 2 + Turbine 1	0.83
CFC 29	Compre 2 + Turbine 2	-
CFC 30	Compre 2 + Turbine 3	-
CFC 31	Compre 3 + Turbine 1	-
CFC 32	Compre 3 + Turbine 2	-
CFC 33	Compre 3 + Turbine 3	-
CFC 34	Turbine 1 + Turbine 2	0.80
CFC 35	Turbine 1 + Turbine 3	-
CFC 36	Turbine 2 + Turbine 3	0.46

Fig. 7. GPA Indices for each engine component for a single degradation

Table 7. Predicted engine degradation for a single degradation

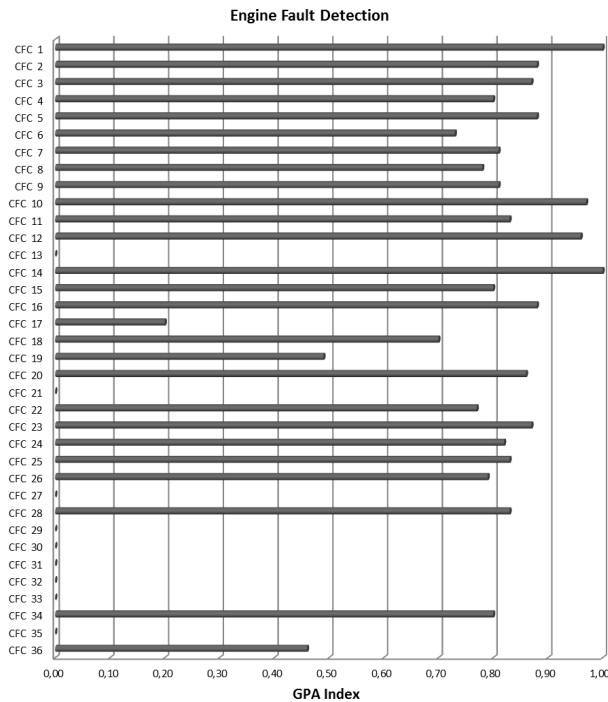| Predicted engine degradation						
Implanted Fault: Leak 1 = -50%						
			CFC 1	CFC 10	CFC 12	CFC 14
	Nm	%	*Detected*	*Detected*	*Detected*	*Detected*
Leakage	1	L1	-50.0	-42.0	-50.0	-49.0
	2	L2				
Compressor 1	3	Δn				
	4	$\Delta\Gamma$				
Compressor 2	5	Δn		-0.1		
	6	$\Delta\Gamma$		-1.9		
Compressor 3	7	Δn			-1.3	
	8	$\Delta\Gamma$			-0.9	
Turbine 1	9	Δn				
	10	$\Delta\Gamma$				
Turbine 2	11	Δn				-0.1
	12	$\Delta\Gamma$				-0.1
Turbine 3	13	Δn				
	14	$\Delta\Gamma$				

Fig. 8. Predicted Engine Degradation for a single degradation

Among all available solutions, Table 7 indicates the solutions with the highest accuracies, particularly with GPA Index over 0.9, and the faults that are most likely to be equal to the implemented one. It is clear from the Table 7 and Figure 8 that the common fault which seems to be appear through all the selected cases, is the leakage degradation, particularly the leakage that comes from the IP Compressor (Leak 1) with an average predicted value of 47.75 percent, is almost the percentage of the implemented value. There are also other degradations with smaller percentages such as 0.1 percent reduction in flow capacity and isentropic efficiency of IP Turbine (Turbine 2) in CFC 14 but they cannot be considered as accurate and *true* predictions. Consequently, it can be regarded that IP Compressor is the most likely degraded component with a detected fault similar to the implemented. A further consideration especially concerning the IP Compressor leakage predictions in Table 7, results that for all the four cases, the maximum deviation from the implanted value is around 2.25 percent, regarding of their average value. This can be explained because of the measurement correction errors and the influence of the unavoidable and unpredictable sensor bias and measurement noise.

Double Degradation

In the case of a double degradation, the fault that is isolated is 2 percent air loss from HP Compressor and 2 percent drop in flow capacity and isentropic efficiency in IP Turbine of the Trent 500 model engine. For the purpose of the current fault isolation, the same assumption holds as it was mentioned before in the single degradation, i.e. all gas path components are considered as potentially degraded except of the burners. The GPA diagnostic system described in Figure 1 and 2 will also be used for the search of all fault cases listed in Table 8. The results of the diagnostic analysis applied on every single and combined component set illustrated in the form of GPA Indices in Figure 9. In some fault cases, no results and thus diagnostic predictions could be obtained but error messages appeared from the simulation code, reporting the end of the convergence iterations in zero or very few loops. The reason for the unusual termination of the diagnostic process was the same as before for the single degradation, namely the percentage of health parameters had exceeded the allowed percentage TURBOMATCH can handle.

Table 8: *Engine Component Fault Cases and GPA Indices for double degradation*

Component Fault Case	Pre-defined Component	GPA Index
Implemented Fault: 2% T2 + 2% L2		
CFC 1	Leak 1	0.87
CFC 2	Leak 2	0.96
CFC 3	Compressor 1	-
CFC 4	Compressor 2	0.78
CFC 5	Compressor 3	0.64
CFC 6	Turbine 1	0.67
CFC 7	Turbine 2	0.94
CFC 8	Turbine 3	0.86
CFC 9	Leak 1 + Leak 2	-
CFC 10	Leak 1 + Compre 1	-
CFC 11	Leak 1 + Compre 2	-
CFC 12	Leak 1 + Compre 3	-
CFC 13	Leak 1 + Turbine 1	-
CFC 14	Leak 1 + Turbine 2	0.86
CFC 15	Leak 1 + Turbine 3	-
CFC 16	Leak 2 + Compre 1	-
CFC 17	Leak 2 + Compre 2	-
CFC 18	Leak 2 + Compre 3	-
CFC 19	Leak 2 + Turbine 1	-
CFC 20	Leak 2 + Turbine 2	1.00
CFC 21	Leak 2 + Turbine 3	-
CFC 22	Compre 1 + Compre 2	-
CFC 23	Compre 1 + Compre 3	-
CFC 24	Compre 1 + Turbine 1	-
CFC 25	Compre 1 + Turbine 2	
CFC 26	Compre 1 + Turbine 3	-
CFC 27	Compre 2 + Compre 3	-
CFC 28	Compre 2 + Turbine 1	-
CFC 29	Compre 2 + Turbine 2	-
CFC 30	Compre 2 + Turbine 3	0.86
CFC 31	Compre 3 + Turbine 1	-
CFC 32	Compre 3 + Turbine 2	-
CFC 33	Compre 3 + Turbine 3	0.85
CFC 34	Turbine 1 + Turbine 2	-
CFC 35	Turbine 1 + Turbine 3	-
CFC 36	Turbine 2 + Turbine 3	-

Fig. 9. GPA Indices for each engine component for double degradation

Table 9. Predicted Engine Degradation for double degradation

			CFC 2	CFC 7	CFC 20
Predicted engine degradation					
Implanted Fault: Leak 2 = -2% + Turbine 2 = 2%					
			Detected	*Detected*	*Detected*
	Nm	%			
Leakage	1	L1			
	2	L2	-1.9		-2.0
Compressor 1	3	Δn			
	4	$\Delta \Gamma$			
Compressor 2	5	Δn			
	6	$\Delta \Gamma$			
Compressor 3	7	Δn			
	8	$\Delta \Gamma$			
Turbine 1	9	Δn			
	10	$\Delta \Gamma$			
Turbine 2	11	Δn		-1.9	-2.0
	12	$\Delta \Gamma$		-2.3	-2.0
Turbine 3	13	Δn			
	14	$\Delta \Gamma$			

Fig. 10. Predicted engine degradation for double degradation

Among all available solutions, Table 9 indicates the solutions with the highest accuracies which are those with over 0.9 for the GPA Index, where the faults seem to be almost equal to the implemented values. It is obvious from Table 9 and Figure 10 that the most common faults that seem to appear through the selected cases, are the leakage degradation in HP Compressor (Leak 2) and the flow capacity with isentropic efficiency drop in the IP Turbine (Turbine 2). The percentages for all the degradations seem to be very close to the percentages values of the implemented faults and therefore it can be regarded that IP Compressor and IP Turbine are the most likely degraded components.
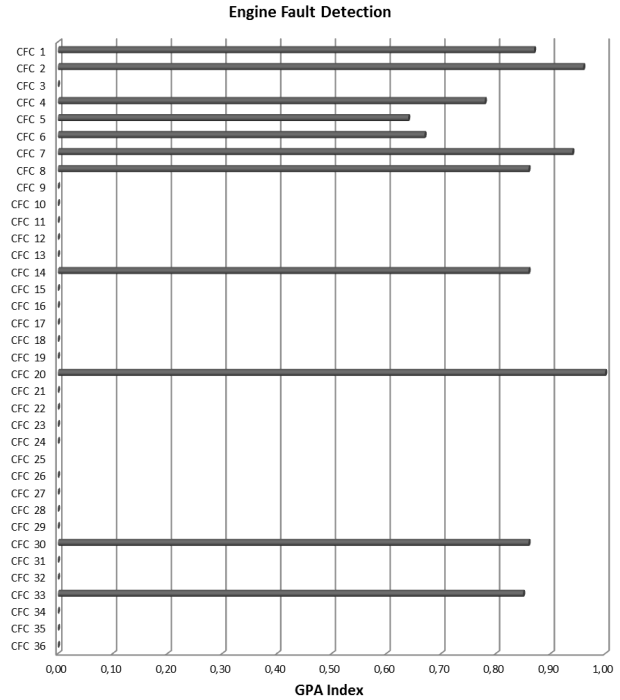
5. Conclusions

The objective of this paper is to diagnose and isolate component leakage faults on a gas turbine engine. The diagnostic program used for this paper was TURBOMATCH, a FORTRAN-based gas turbine simulator code developed at Cranfield University. For the

implementation of the leakage degradation, non-linear GPA diagnostic technique was preferred instead of the linear GPA, due to its significant advantage over the severe limitations of linear GPA models. The aspects of the non-linear GPA were applied to a simulated model of a high BPR turbofan aircraft engine. For the gas path diagnostics of the engine model, an appropriate instrumentation set that

thermodynamically correlated with the desired faults was selected. The leakage degradation was initially implemented into the gas path components of the engine model and then diagnosed and isolated. The outcome of the results was very satisfactory, and proved that non-linear GPA is a very efficient diagnostic tool in building up the confidence in detecting, isolating and quantifying degraded components.

Nomenclature

Acronyms

BPR	- By-pass ratio
CC	- Combustion chamber
DP	- Design point
FC	- Mass flow capacity
FF	- Fuel flow rate
HP	- High pressure
HPC	- High pressure compressor
HPT	- High pressure turbine
IE	- Isentropic efficiency
IP	- Intermediate pressure
IPC	- Intermediate pressure compressor
IPT	- Intermediate pressure turbine
LP	- Low pressure
LPC	- Low pressure compressor
LPT	- Low pressure turbine
N	- Number of measured values
OPR	- Overall pressure ratio
P	- Total pressure
PCN	- Relative rotational speed
PR	- Pressure ratio
SLS	- Sea level static

T	- Temperature
TET	- Turbine entry temperature

Notations

L1 / Leak 1	- IPC Leakage
L2 / Leak 2	- HPC Leakage
C1	- Fan / Low pressure compressor
C2	- Intermediate pressure compressor
C3	- High pressure compressor
T1	- High pressure turbine
T2	- Intermediate pressure turbine
T3	- Low pressure turbine

Subscripts

$\vec{z}$	- Dependent parameter vector
$\vec{x}$	- Independent (component) parameter vector
μ	- Mean value
σ	- Standard deviation
x_i	- Measured (observed) value
$\bar{x}$	- Average measurement

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