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Application of Multiple Handle Gas Path Analysis on a Twin Spool Turbofan Engine

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ABSTRACT

In this paper the development of multiple handle gas path analysis, an analytical approach that has two advantages over linear gas path analysis is described. Firstly, it allows all instruments to be used for diagnostics purposes, without having to use one to determine the baseline. The other advantage is that diagnostics can be crosschecked against one another to allow greater faith in the result.

A conclusion that can be drawn regarding multiple handle gas path analysis is that it appears to be a promising technique. For some faults it appears to give better diagnostics than linear gas path analysis, without going to the complexity of non-linear gas path analysis. The latter is however more accurate.

The analysis of a high performance twin spool turbofan engine, gave rise to a very useful diagnostic. Several fault sets were analysed and several instrumentation sets were examined, ranging from the minimum available in the cockpit to a much more comprehensive one.

NOMENCLATURE

DOD	domestic object damage	LPT	low pressure turbine
FOD	foreign object damage	HPT	high pressure turbine
GPA	gas path analysis	MH GPA	multiple handle GPA
HPC	high pressure compressor	HAF	Hellenic Air Force
LPC	low pressure compressor	PCN	rotational speed
W	air mass flow (flow capacity)	HOT	high order terms
n_c	compressor isentropic efficiency		
n_T	turbine isentropic efficiency		
n_{cc}	combustion efficiency		
RMS	root mean square		
TET	turbine entry temperature		

INTRODUCTION

Faults like fouling, erosion, corrosion, worn seals, excessive tip clearances and damage from various objects entering the engine (FOD-DOD) affect the performance of each of the gas path components and results in performance deterioration. The need for identifying the effects of faults in the gas turbines led to the study of gas path analysis (GPA) methods, which would give the operator a sign of what's happening inside the engine (Volponi, 1982).

The performance of the gas path components is characterized by parameters like flow capacity and efficiency, which are called 'independent parameters' and degrade because of the effects of the physical faults. These parameters although fundamental in nature are not readily or practically measurable. However changes in independent parameters produce deviations in parameters such as pressures, temperatures, fuel flow and rotational speed throughout the engine, these can be measured; they are called 'dependent parameters' and any difference from their baseline values can be used for the determination and detection of the independent parameters.

Urban conceived a technique (1969, 1974) to assess the independent engine parameter (flow capacity, efficiency) deviation by using the relationship between them and the dependent parameters (pressures, temperatures) based on customized baseline data. Later, more studies were published that focused on either civil (Doel 1994) or military aero-engines (Zedda and Singh, 1996).

The technique of gas path analysis outlined above was based on the assumption of a linear relationship between the dependent and independent parameters. Recognising that the larger faults may invalidate this assumption, complex non-linear gas path analysis techniques were developed in PYTHIA (Escher 1995). Furthermore a major uncertainty is introduced by measurement error in the diagnostics capability of GPA. A large amount of effort is being devoted to this problem (Zedda and Singh, 1999).

The objective of the research described here was the performance analysis of the engine model and the investigation of the fault detection capability using GPA methods. Moreover a new concept, multiple handle gas path analysis (MH GPA), is examined. It is based on the selection of more than one handle and the results are compared to those obtained using the "traditional" method using one handle. The interest in this method arises from the simplicity of the technique, which hopefully addresses the drawbacks of linear GPA without going to the complexity of non-linear one.

For the purposes of the present study the engine selected is a high performance twin-spool turbofan engine, as shown in figure 1.

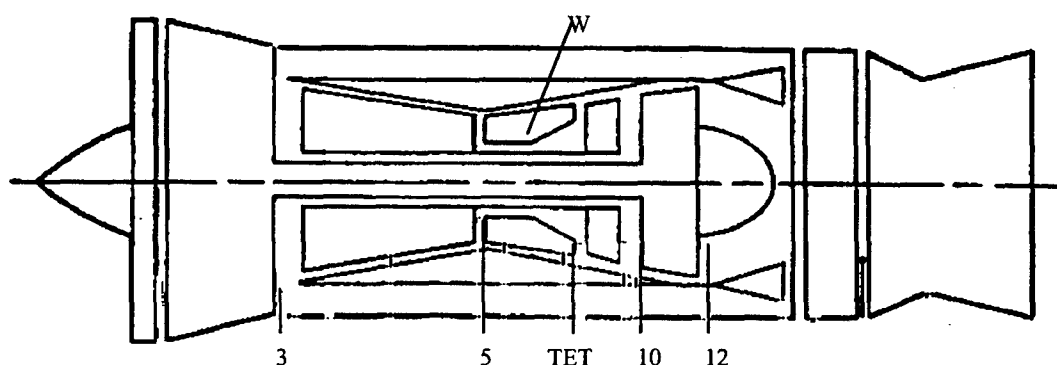


Figure 1: Engine Schematic with station numbers

The standard engine was simulated using the TURBOMATCH Scheme (Palmer 1983), a code developed at Cranfield University to facilitate design point and off-design performance calculations for gas turbine engines using a digital computer. After obtaining the results, the PYTHIA Scheme was used to assess the analysis of the deterioration on the gas path components.

These facilities allowed a meaningful comparison between linear GPA, multiple handle GPA and non-linear GPA. Given that the focus is on the thermodynamic analysis technique, the instrumentation error analysis is not described here. It is assumed that the interested user would apply suitable techniques, (Zedda and Singh 1996) to allow for this very important factor.

MULTIPLE HANDLE GAS PATH ANALYSIS

Principles of GPA

The relationship between dependent and independent parameters can be expressed by:

$$Z_e = H_e \cdot X_e$$

where Z_e is the column matrix of monitored dependent parameters deltas, H_e is the Influence Coefficient Matrix (ICM) and X_e is the column matrix of the independent parameters (gas path component characteristics) deltas. Inverting the ICM, a new matrix the Fault Coefficient Matrix (FCM) is obtained which gives a new relationship between the independent and dependent parameters.

Each row of the ICM is a differential equation wherein the net change in the dependent variable corresponding to that row is the arithmetic sum of the product of the coefficients times the change in the variable specified at the head of each column.

The non-linear concept (Echer, 1995) tries to solve the non-linear relationship between dependent and independent parameters with an iterative method such as Newton – Raphson method. Using this method, the basic assumption is that the noise errors as well as instrumentation errors are not taken into account. The method uses the mathematical model that is described in the following paragraph.

Assuming that $\underline{x}$ stands for the independent variable vector matrix and $\underline{y}$ stands for the dependent one, the relationship between them may be represented as

$$F(\underline{x}) = \underline{y}$$

Then for small changes in the independent variable vector matrix $\underline{x}$

$$F(\underline{x} + \delta \underline{x}) = \underline{y} + \delta \underline{y} \quad \text{or} \quad F(\underline{x} + \delta \underline{x}) = F(\underline{x}) + \delta \underline{y} \quad (1)$$

Using the Taylor series expansion of $\delta \underline{x}$ about $\underline{x}$

$$g(\alpha + \beta) = g(a) + \beta \cdot g'(a) + \frac{\beta^2}{2!} \cdot g''(a) + \dots$$

In order to express the first derivative in the Taylor series expansion of the matrix function $F(\underline{x})$ times the small change in the independent variable $\delta \underline{x}$, the following Jacobean matrix notation is used as follows:

$$J = \begin{pmatrix} \frac{\partial f_1(\underline{x})}{\partial x_1} & \frac{\partial f_1(\underline{x})}{\partial x_2} & \dots & \frac{\partial f_1(\underline{x})}{\partial x_n} \\ \frac{\partial f_2(\underline{x})}{\partial x_1} & \frac{\partial f_2(\underline{x})}{\partial x_2} & & \frac{\partial f_2(\underline{x})}{\partial x_n} \\ \vdots & \vdots & & \vdots \\ \frac{\partial f_m(\underline{x})}{\partial x_1} & \frac{\partial f_m(\underline{x})}{\partial x_2} & & \frac{\partial f_m(\underline{x})}{\partial x_n} \end{pmatrix} \quad \text{and} \quad \delta \underline{x} = \begin{pmatrix} \delta x_1 \\ \delta x_2 \\ \vdots \\ \delta x_n \end{pmatrix}$$

$$\text{Given that } \underline{y} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \quad \begin{matrix} y_1 = f_1(\underline{x}) \\ y_2 = f_2(\underline{x}) \\ \vdots \\ y_n = f_n(\underline{x}) \end{matrix} \quad \text{where } \underline{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \quad \text{and}$$

Therefore the Taylor series expansion can be expressed as follows:

$$F(\underline{x} + \delta \underline{x}) = F(\underline{x}) + J \cdot \delta \underline{x} + HOT$$

since the changes in $\underline{x}$ are expected to be small and therefore we may make the assumption that the HOT (High Order Terms) are negligible, that is to say, the relationship is considered linear, the above equation is expressed as follows:

$$F(\underline{x} + \delta \underline{x}) = F(\underline{x}) + J \cdot \delta \underline{x} \quad (2)$$

From equation (1) and (2), by rearranging

$$\begin{aligned} F(\underline{x} + \delta \underline{x}) - F(\underline{x}) &= \delta \underline{y} \Rightarrow \delta \underline{y} = J \cdot \delta \underline{x} \\ \Rightarrow J^{-1} \cdot \delta \underline{y} &= \delta \underline{x} \end{aligned} \quad (3)$$

The corrections $\delta \underline{x}$ are then added to the solution vector

$$\underline{x}_{new} = \underline{x}_{old} + \delta \underline{x}$$

The above process is iterated to convergence. For each linear GPA calculation an appropriate baseline is required. In the first iteration the actual measured baseline is used. The second iteration uses a calculate baseline that is derived by implanting faults that are detected in the iteration. The same applies to the following iterations where the implanted faults are taken from the previous iteration.

Equation (3) gives the relationship between the independent and dependent parameters. In fact any change in the depended parameter can be related with a change in the independent parameter using the inverse matrix of J , which is referred to as "Fault Coefficient Matrix" (FCM). The J matrix is referred to as "Influence Coefficient Matrix" (ICM). The primary objective of GPA technique is the calculation of the ICM so that by obtaining the FCM after inverting the former, the detection of the implanted faults (independent parameters) becomes feasible.

The concept of MH GPA

An important issue in the GPA technique is the selection of the appropriate baseline to establish the reference conditions with which to compare the measured parameters. The applicable baseline is called the handle, which in this case, the parameter that establishes the matching conditions of the engine. Once selected, it is normally held constant.

The accuracy of GPA is normally tested by implanting a fault, in the engine or model, and using the diagnostic technique to detect it. In linear GPA it is assumed that a change in the independent parameter results in an analogous change of the dependent parameter. In reality gas turbine engines are highly non-linear systems, so the assumption of linear behaviour applies only to small departures (deltas) from the baseline.

Given the unsuitability of linear GPA and the complexity of non-linear GPA, the concept of multiple handle GPA is examined here. The philosophy of the method is to employ the basic linear GPA technique, but to apply it several times for each analysis. So the clean engine baseline is established and then the degraded engine is modelled over a relatively narrow operating range. This will, probably, ensure a uniform influence of each fault.

Then the analysis is carried out several times, each time matching the engine with a different operating parameter (or handle). So, for example, the analysis is carried out once matching the engine on rotational speed, a second time matching the engine on fuel flow, a third time matching the engine on turbine pressure ratio. This analysis can be carried out as many times as pertinent instruments are available. The results can then be collated and a comprehensive analysis carried out.

It is worth noting that once the handle has been selected, it is excluded from the instrumentation set since the deviation of its measurement is by definition zero. The instrumentation set, then, includes the

rest of the instruments so that the number of them must be at least equal to the number of implanted faults.

This method presents several advantages. Firstly it is based on linear assumptions. It also extracts as much information as possible from the instrumentation, because, as explained above, when one measured item is used as handle, some diagnostic capability is lost. The most important question is if it can match the results of non-linear GPA, which is recognised as a superior technique to linear GPA.

CASES ANALYSED

When carrying out gas path analysis, the choice of baseline parameter and the instrumentation available will determine the faults that can be successfully diagnosed. Naturally the need to use a measurement as baseline limits the diagnostics that can be carried out. Multiple handle gas path analysis allows the use of all instruments for diagnostic purposes because different baselines are used in each prediction.

One of the objective of the investigation described here is to examine the viability of multiple gas path analysis in lean and rich instrumentation sets and to compare it with linear and nonlinear gas path analysis.

Selection of the faults

Much work has been published about performance degradation on gas turbines, however, the magnitude of the applied deterioration in most cases is arbitrary or it is based on published experimental results, which are been used as background (Aker 1989, Seddigh 1991, Lakshminarasimha, 1994). This happens mainly because the degree of deterioration, the rating and effect of physical faults on engine performance depend upon the design, the environment condition in which the engine operates and the quality of the applied maintenance on the plant. It is well understood that many non-measurable factors have to be taken into account for the calculation of engine characteristics degradation.

Due to the lack of specific magnitudes for the faults, a general guideline that was presented by Echer (1995) was used in which the physical faults are been expressed as independent parameter changes. The selected magnitudes of the implanted faults are given in Table 1.

	W_c	n_c	W_T	n_T	n_{CC}
Compressor fouling	-5%	-2.5%	-	-	-
Turbine fouling	-	-	-5%	-2.5%	-
Poor combustion	-	-	-	-	-2.5%
Turbine erosion	-	-	+3%	-1%	-

Table 1: Magnitudes of the implanted faults

Selected Instrumentation

The instrumentation selected has been divided into 7 Sets as it is shown in table 2. It varies from a lean to a rich instrumentation set.

	A	B	C	D	E	F	G
P_3			X		X		X
T_3			X		X		X
P_5			X			X	X
T_5			X			X	X
W_f	X	X					X
P_{10}				X		X	X
T_{10}				X		X	X
P_{12}		X		X	X		X
T_{12}	X	X		X	X		X
PCN	X	X					X

Table 2: Instrumentation sets

Set A: Consists of the standard instrumentation provided in a typical aircraft's cockpit.

Set B: Includes the instruments of set A plus the measurement of the pressure at the turbine exit (P_{12}). The main reason for selecting this instrument is that the pressure at the exit of the turbine would be less difficult to implement because the temperature at that position (T_{12}) is already available.

Set C: Includes the instrumentation for the measurement of the parameters in the compressor section. The measured parameters are LPC exit pressure and temperature (T_3 , P_3) and HPC exit pressure and temperature (T_5 , P_5).

Set D: Includes the instrumentation for the measurement of the parameters in the turbine section. The measured parameters are HPT exit pressure and temperature (T_{10} , P_{10}) and LPT exit pressure and temperature (T_{12} , P_{12}).

Set E: Includes the instrumentation for the measurement of the parameters in the low pressure section. The measured parameters are LPC exit pressure and temperature (T_3 , P_3) and LPT exit pressure and temperature (T_{12} , P_{12}).

Set F: Includes the instrumentation for the measurement of the parameters in the high pressure section. The measured parameters are HPC exit pressure and temperature (T_5 , P_5) and HPT exit pressure and temperature (T_{10} , P_{10}).

Set G: Consists of all measurement parameters in the engine.

Fault sets

PYTHIA simulates engine's deterioration using ten parameters;

- LPC mass flow and efficiency (W_{LPC} , η_{LPC})
- HPC mass flow and efficiency (W_{HPC} , η_{HPC})
- Combustion chamber efficiency (η_{CC})
- LPT mass flow and efficiency (W_{LPT} , η_{LPT})
- HPT mass flow and efficiency (W_{HPT} , η_{HPT})
- Pressure drop in the exhaust nozzle (ΔP_n)

The pressure drop in the exhaust nozzle is not used for this study because the main interest for gas path analysis in this study is the gas turbine itself and not the components of the Quick Engine Change kit (QEC kit). Therefore the maximum number of independent parameters is nine.

The full set of implanted faults, from the single ones up to maximum number is shown in table 3, which consists of 30 approaches. Because the number of instruments has to be at least equal to number of faults the whole set of 30 approaches is applied only to instrumentation set G. For the rest of them,

the number of approaches is smaller and depends upon the number of monitored parameters (instruments).

Fault	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
W_{LPC}	X									X				X	
η_{LPC}		X								X				X	
W_{HPC}			X								X			X	
η_{HPC}				X							X			X	
η_{CC}					X										
W_{LPT}						X						X			X
η_{LPT}							X					X			X
W_{HPT}								X					X		X
η_{HPT}									X				X		X

Fault	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
W_{LPC}	X				X		X		X		X		X	X	X
η_{LPC}	X				X		X		X		X		X	X	X
W_{HPC}		X				X		X		X	X		X	X	X
η_{HPC}		X				X		X		X	X		X	X	X
η_{CC}	X	X	X	X					X	X	X	X			X
W_{LPT}			X			X	X			X		X	X	X	X
η_{LPT}			X			X	X			X		X	X	X	X
W_{HPT}				X	X			X	X			X	X		X
η_{HPT}				X	X			X	X			X	X		X

Table 3: Fault sets

Faults 1 to 9 represent single faults including mass flows and efficiencies for the gas path components. Reduction in compressor isentropic efficiency, represents FOD or blade tip rubs. Similarly, decreased turbine efficiency is the result of FOD, blade tip rubbing or worn seals inside the turbine. For the combustion chamber, drop in combustion efficiency is caused by poor combustion, carbon deposits in the chamber and goggled fuel nozzles.

Faults 10 to 13 are double faults and simulate compressor and turbine fouling. The faults are included within all instrumentation sets.

Faults 16 to 19 are triple faults, which are similar to double faults and include the combustion chamber efficiency as the third fault. They represent fouling in combination with combustion efficiency degradation. The prescribed faults are applied for detection by all instrumentation sets.

Faults 14, 15, 20 to 23 comprise four simultaneous faults as a combination of LPC or HPC fouling, with LPT or HPT fouling.

Faults 24 to 27 consist of 5 faults. In fact, they are similar to the faults in the above paragraph with the addition of combustion chamber deterioration. Detection of these faults will not be attempted with the instrumentation sets A, B, C, D, E and F.

Faults 28 to 30 include LPC, HPC fouling and LPT or HPT fouling. Detection of these faults will be attempted only with the instrumentation set G.

For the purposes of the present study, the name "Case" will be given to the combination of the instrument set with the fault set. For example instrument set G with the 30 approaches make up the "Case G".

LINEAR & NON LINEAR GPA

Obtaining the results from GPA method, the Root Mean Square (RMS) error is deployed for the evaluation of the technique. The RMS error is defined as follows:

$$RMS = \sqrt{\frac{\sum_{i=1}^n (\delta x_{\text{implanted}} - \delta x_{\text{detected}})^2}{n}}$$

Where n is the number of independent parameters measured, $\delta x_{\text{implanted}}$ is the implanted fault and $\delta x_{\text{detected}}$ stands for the observed fault or detected one from the diagnostics technique.

Approach 5. Combustion chamber efficiency deterioration is well detected using any one of the instrumentation set since all the measurements are below 0.05 for the linear GPA. Therefore there is no need for calculating the non linear RMS error.

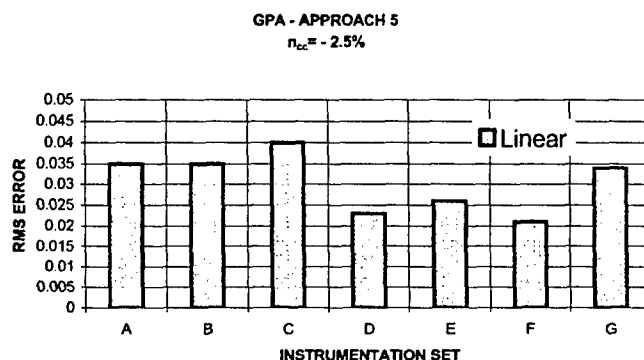


Figure 2: Approach 5, Linear and Non Linear Error

PYTHIA gave great results for all Cases and especially for Set D (figure 2) which contains the turbine area instrumentation. In addition, although Set G includes all instruments, there is no benefit using it for the detection of the combustion fault.

Approach 12. Turbine fouling is represented by a 5% reduction in mass flow and a 2.5% reduction in efficiency. Accurate detection is achieved using any one of the Sets, since all RMS errors are well below 2.0 (figure 3). Case D seems to give better accuracy whilst Case B gives the worst one but the error is still below 2.0. The primary reason for the increased inaccuracy of Case D is the location of the instruments; All of them are installed in the turbine section therefore the detection of turbine faults is accurate.

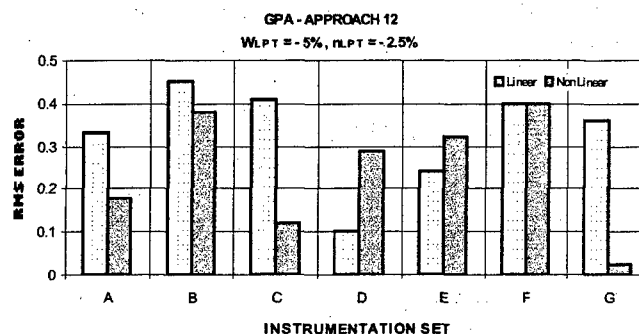


Figure 3: Approach 12, Linear and Non Linear Error

Approach 15. The implanted faults represent fouling of the same magnitude in both turbines. Sets A and B are not diagnosed because the number of implanted faults is higher than the number of instruments (figure 4). It should be noticed that using C, E and F instrumentation sets, the linear error is greater than 2.0, and therefore it is unacceptable. On the other hand, Sets D and G gave the best acceptable results. The latter is obvious since Set D includes instruments from the faulty region and Set G includes all the available instruments.

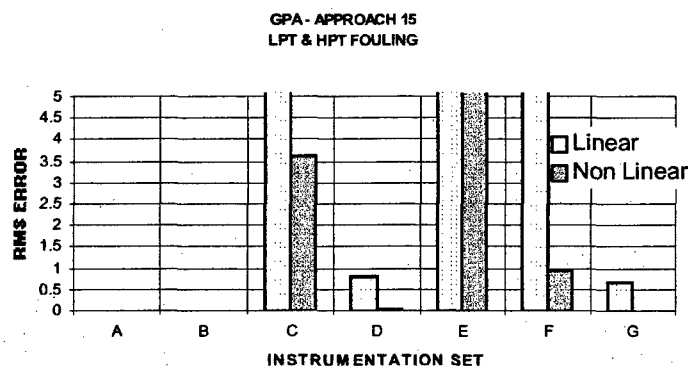


Figure 4: Approach 15, Linear and Non Linear Error

Selected Approaches for MH GPA

As it was shown in the previous paragraphs, most of the implanted single faults were detected successfully using both linear and non-linear GPA. In contrast, less accurate was the detection of the multiple faults like combined LPT and HPT fouling.

The selection of the fault sets and instrumentation for the implementation of the MH GPA is based on the above conclusion. Fault sets representing compressor or turbine fouling are being studied. The selected instrumentation sets are taken from Case G with ten instruments providing full instrumentation for the engine. Additionally, for the evaluation of the new technique, additional approaches have been selected from Case G involving single faults.

For each selected approach employing 10 instruments (as it happens in Case G) the total runs in PYTHIA are 20 (10 for linear and 10 for non-linear). Obviously the number of available approaches, which have been studied with the previous technique, increases under the concept of MH GPA. For

that reason the number of the selected approaches under study is limited. The selected fault sets and instrumentation is given below

Appr	5	6	8	9	10	12	13
P ₃	x	x	x	x	x	x	x
T ₃	x	x	x	x	x	x	x
P ₅	x	x	x	x	x	x	x
T ₅	x	x	x	x	x	x	x
W _f	x	x	x	x	x	x	x
P ₁₀	x	x	x	x	x	x	x
T ₁₀	x	x	x	x	x	x	x
P ₁₂	x	x	x	x	x	x	x
T ₁₂	x	x	x	x	x	x	x
PCN	x	x	x	x	x	x	x
W _{LPC}					x		
n _{LPC}					x		
W _{HPC}							
n _{HPC}							
n _{CC}	x						
W _{LPT}		x				x	
n _{LPT}						x	
W _{HPT}			x				x
n _{HPT}				x			x

Table 4: Selected approaches from Case G

Results for MH GPA

After the study of each approach, it is important to determine the parameter, which gives the best diagnostic when it is used as the engine's handle. An indication is obtained of the most appropriate handle by calculating the error resulting from each handle for all the approaches. Using the RMS error as a statistical calculation tool, the error of each approach for the same handle is determined (figure 5).

The RMS error for each handle has been calculated for all approaches of Case G that have been studied with the MH GPA method. That is to say, the RMS error for the PCN is calculated by the respective RMS errors, which are given by approaches 5, 6, 8, 9, 10 and 13. The comparison between the different handles, including the TET, which was used in the previous sections, highlights the following interesting points:

- All the handles used in MH GPA method give worse accuracy than the TET, except T₅ and P₃.
- The best accuracy is achieved when P₃ is used as the engine's handle.

By the same way, the detection accuracy that is provided by multiple handles for each approach would be an indication of how effective the technique of MH GPA is, as a diagnostic tool. A high RMS also gives an interesting message. It means that the diagnostics do not agree, therefore the instrumentation set is unsuitable for detecting the faults sought.

Using more than one handle for each approach, the user can crosscheck the results. The combined results would be more credible than the single ones in terms of reliability. Using only one parameter as a handle, the risk of failure of the instrument measuring it is a real possibility. The handle is one of the dependent parameters and operates under the same "laws" as the rest of instruments do. Wear and failures make their presence felt through the operational life of the engine and its systems.

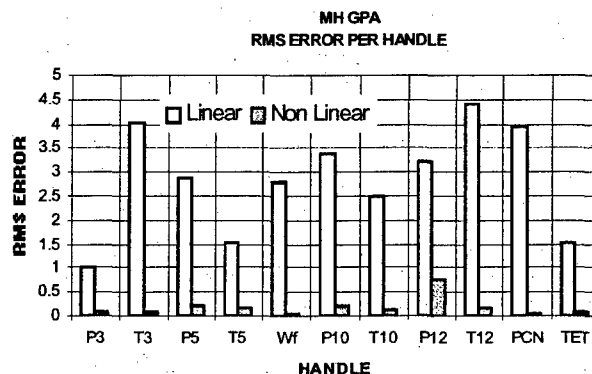


Figure 5: RMS Error for each parameter that serves as the engine's handle for Instrumentation Set (Case) G

In these cases, the baseline would not be the same for all the measurements and therefore the detection accuracy would be poor. The measured parameter deviations would assist the detection of the implanted faults, which, in these circumstances, be based on inaccurate baseline data. For example, using only TET as a handle the risk of failure is higher than using TET and T_{10} in combination in a MH GPA method. Thus many combinations of different handles would give more confidence and a measure of redundancy.

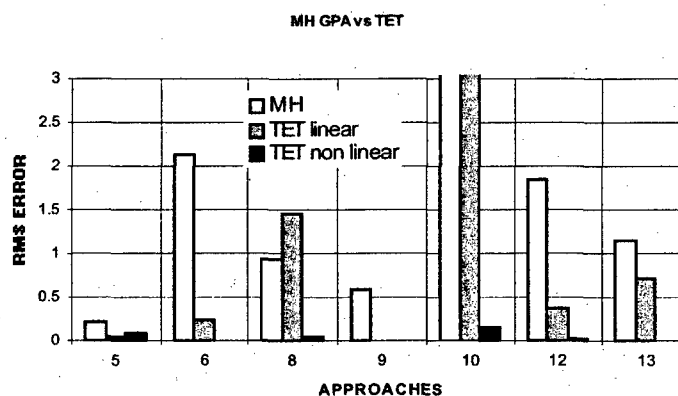


Figure 6: Comparison between multiple handle GPA and single-handle GPA for selected approaches

Using traditional GPA with the TET as the engine's handle, the results shown in figure 6 have been obtained. Obviously for approach 8, MH GPA gave better results than the traditional GPA with TET as the handle. Instead, for the rest of them, although MH GPA accurately detected the faults (except for approach 10) the error is higher than the one from the traditional GPA. Nevertheless, it seems that using the MH GPA there are some benefits especially when the approach under examination includes multiple faults (approaches 10, 12 and 13).

CONCLUSIONS

The application of GPA methods for fault detection on a single spool low bypass turbofan engine revealed the following:

- (1). Non Linear Gas Path Analysis was able to detect the implanted faults more accurately than linear GPA.
- (2). The optimum detection capability is achieved when the instruments are installed in the region where the fault occurs. Detecting compressor faults accurately presumes that the utilized

instrumentation is located inside the compressor section. Similarly, instrumentation that includes instruments in the hot section gives better results in detecting combustor and turbine degradation.

(3). Hot section degradation (i.e poor combustion) is well detectable using any one of the available instrumentation sets.

(4). Although set G involves full instrumentation, there is no benefit of using it for the detection of the single faults (changes in only one dependent parameter). In contrast, the accuracy is better when the deterioration is due to combined faults in the compressor and the hot section of the engine.

(5). The utilisation of P_{12} as instrument gives better results for the detection of multiple faults. In contrast, the accuracy becomes poor when the above instrument is involved for the detection of single faults.

Multiple Handle GPA (MH GPA) is a new technique which is based on the selection of multiple handles. The selection of the handle is related to the capability of accurately using it as the baseline's controlling parameter. The use of multiple handles on the engine model revealed the following interesting points:

(1). The use of other than the TET handle may improve the detection accuracy of linear GPA. Best results are obtained when P_3 serves as the engine's handle. In contrast the accuracy of the method is poor when the handle is T_{12} . This outcome is interesting because T_{12} is already measured.

(2). Although the detection capability is improved, the diagnostic message remains the same. Careful study of figure 6 shows that approaches 5 and 9 are detectable with better accuracy than approaches 10 or 13 for both methods.

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