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Modeling of Degradation in Gas Turbine Engine by Modified Off-Design Simulation

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ABSTRACT

Legacy turbojet engines suffer degradation in performance with usage. Degradations in engine components show different observable symptoms based on the control mode of the engine. Hence, to accurately model the engine and its degradations, a novel off-design modeling method that considers the control settings of the engine is presented. The improvement in degradation modeling due to the modified scheme is presented in detail. The mathematical model used in the degradation simulation is validated by comparing the model outputs to the engine mounted sensor measurements at various ratings in the engine test bed. The estimation component parameters used in the model through nonlinear gas path analysis and optimisation-based routines is also presented.

Keywords: Aero-thermodynamic model; Engine health monitoring; Engine control system; Degradation simulation

1. INTRODUCTION

Physics-based gas turbine simulation models are an essential component of engine health monitoring system (EHM) for gas turbines. The engine simulation model used in the EHM module is initially validated with measurements from the engine at a healthy condition. After the engine is released to service and completes its allowed TBO (time between overhaul), it is returned to the service base for overhauling. The engine is typically tested on arrival at the service base before overhaul to assess its current state. The measurements from the test bed are corrected for reduction of pressure in the test cell and the effect of secondary flow around the engine on the thrust measurements as described by Laskaridis[1]. The corrected measurements from the engine are compared to the output of the validated simulation model. The differences (residuals) between the corrected measurements and the simulation model output indicate degradation/fault in the engine. These residuals are processed by gas path diagnosis algorithms which estimate the probable changes/deterioration in the engine that have led to these residuals. The estimation of the component degradation by gas path analysis in the EHM modules simplifies the targeted maintenance during overhaul of the engine. When these estimated and measured degradations are collected for a fleet of engines, time series regression models can be employed for prognosis of degradation in the engines, which aid in scheduling the maintenance of these engines.

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2. LITERATURE REVIEW

EHM modules of various maturity levels use engine simulation models of different fidelity levels. Individual component models of the gas turbine can also have different fidelity levels in the simulation program. For example, the numerical propulsion system simulator (NPSS) can link together high fidelity CFD models with zero dimensional aero thermodynamic models using custom scripts as described by Russel[2]. The CFD models of components can also be used to generate characteristic maps of components that can be used in the zero dimensional models. Zero dimensional aero thermodynamic simulation models predict the gas path parameters at different stations along the engine, at the exit of individual components of the engine. These engine models are used in EHM systems that monitor the overall performance characteristics of gas turbines in terms of component performance parameters. Saravanamuttoo[3] and more recently Verdland[4] and Li[5] describe the use of these models in engine control system design and health monitoring. Details of engine performance and health monitoring models using both steady-state and transient performance prediction methods is described by Isaac[6]. Aero-thermodynamic models are also used in EHM modules relying on Kalman filters as a diagnosis tool for tracking time evolving faults and degradations[7]. Models of ideal and degraded engines are used to generate data sets consisting of component performance parameters as input and gas path measurement parameters as output. These data sets are used to train and test neural network based health monitoring tools[8]. Similar data sets generated from the degraded engine simulation model are used in the development of non linear filters used for noise suppression in gas path measurements[9]. Probabilistic analysis and statistical pattern recognition tools for fault identification are also developed using such simulated data[10-11]. Zhou[12] proposes a method in which gas path analysis technique is used to get the component health parameters. This information, along with gas path measured parameters are used by a long short term memory neural network to predict the future performance degradation of each component of the gas turbine.

An adapted aero-thermodynamic performance model is used in the performance diagnostics of LM2500 industrial gas turbine, in the works reported by Elias[13-14] and Bechini[15]. Detailed review of the use of simulation models in performance analysis of gas turbines is presented by Li[16] and Tumer[17]. Limited information about the effect of various component degradations on the performance of the engine is available in the open literature[6,18,19]. Specifically, the effect of compressor fouling and cracks in bleed ducts on the measurable parameters such as RPM, fuel flow and exhaust gas temperature is described by Changduk[20]. Effect of fouling of the compressor airfoils, clearance changes in the turbine rotors and changes in the secondary flow pattern of the combustor are discussed by Kurz[21]. Zhou[22] studies the effect of compressor blade thickness increment and roughness change on the performance map of the compressor through numerical simulation. The modified compressor map is used in gas turbine simulation model which is then used for degradation identification from field data. Similar degradation studies of gas turbines using simulation models are also done by the end users for selecting suitable gas turbines for their specific application as described by Agwu[23].

Several resources that detail the methodology of off design and on design performance modeling of gas turbines are available[19,24-27]. Aero thermodynamic simulation models are also built with commercially available tools such as GasTurb[28] and GSP[29] (Gas turbine simulation program) whose development is described by Visser[30]. Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) is a tool for simulation of turbofan engine that is integrated with ProDiMES[31], which is a gas path monitoring and diagnostics framework developed by NASA. A significant hurdle in the development of these models for a legacy engine is the non-availability of realistic component characteristic maps and design data such as bleed schedules, inter duct losses, power off-take and component geometry. Optimization-based and non-linear gas path analysis (GPA) based methods for the estimation of these component parameters is presented by Li[32].

3. SCOPE OF WORK

In gas turbine engine, limiting systems are an integral part of the overall engine control system. The engine fuel flow rate and nozzle throat area is controlled by the control system that maintains a given turbine pressure ratio and compressor pressure ratio for each RPM, under normal operating conditions. The limiters are employed to limit the speeds of low and high pressure spools, slip between the spools, compressor exit pressure and combustor exit temperature within acceptable values. Of these limiters, the combustor exit temperature limiter uses the turbine exit temperature as an input as it is difficult to measure the combustor exit temperature directly. In transient performance models, the operation of these limiters and the control system governing action are modelled as they affect the dynamics of the gas turbine engine directly. In conventional off design performance analysis programs, these limiters are not required as parameters are within limits at the ideal condition. However, if degraded engine off design performance analysis is carried out without accounting for the limiter restriction, erroneous pressure and temperature values are obtained. The novel off design analysis methodology presented in this work replaces the conventional error vector (using mass flow imbalance in the hot end components) with limited gas path parameters (such as turbine exit temperature) so that the effect of operation of control setting and limiters in the gas turbine can be captured in the off-design simulation itself. The major advantage of this methodology is that it does not require additional logic in the off-design simulation program in iterative runs that monitor the limited parameters to check if they are exceeding their assigned limits.

The objective of this work is to present a modified off-design simulation methodology that can account for control setting and limiter operation during degraded engine simulation. The mathematical model required for the simulation and parameter estimation studies carried out for the legacy engine are also presented.

In the next section, a brief description of the engine for which the aero-thermodynamic model is being developed is presented. Next, the parameter estimation routines for estimating the component parameters of the engine are briefly described. Both optimization-based routines and non-linear gas path analysis based routines are used for parameter estimation. Then conventional and modified simulation methodologies are presented and validated with the measurements from engine test bed. The improvements in degradation simulation due to the use of modified methodology are shown by applying both the methods to simulate the engine when the compressor efficiency has degraded.

4. ENGINE DESCRIPTION

A brief description of the legacy aircraft engine and its control system setting is presented in this section.

4.1 Engine Description and Measurement Locations

The legacy engine for which simulation model is developed is a twin spool engine (shown in fig 1) having a five stage low pressure compressor stage and a six stage high pressure compressor. The overall pressure ratio of the engine is around 12 and the mass flow is roughly about 100 kg/sec at design condition at sea level ISA. Low pressure and high pressure turbines drive the respective compressor stages. The engine has an annular main combustor and an after-burner with continuously variable exit area convergent type jet nozzle. The engine has a hydro-mechanical control system that predominantly governs the low pressure spool RPM through main combustion chamber fuel flow rate control $\dot{m}_f$ and nozzle exit area control.

The model is validated using measurements from the engine mounted sensors on the test bed. The engine at the test bed has provisions to measure the parameters shown in Table 1.

Table 1. Measurement available in the test bed

Parameter	Symbol
High pressure compressor exit static pressure	P2
High pressure compressor exit total temperature	T2
Low pressure turbine exit static pressure	P4
Low pressure turbine exit total temperature	T4
Axial Thrust	Th
Dynamic pressure at the inlet	
Total fuel flow rate to the engine (including afterburner fuel flow rate)	
Low pressure spool RPM	N1 $\dot{m}_f$
High pressure spool RPM	N2

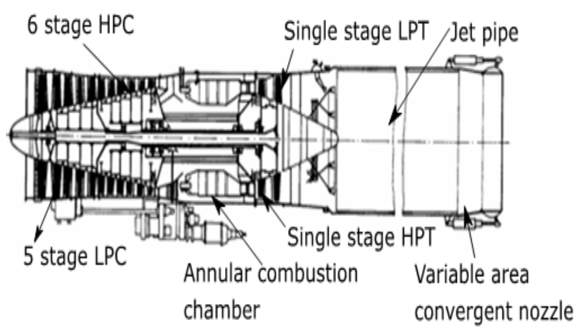

Figure 1. Twin spool engine.

These measurements were made by OEM sensors and recorded through NI-PXI based data acquisition system. In addition to these measurements, the static test cell room depression is also measured using water column manometers. This is used along with dynamic pressure to measure the mass flow rate through the engine inlet. As a part of the engine health monitoring module development, the engine was instrumented with additional sensors to measure the following parameters:

- Low pressure compressor exit static pressure
- Low pressure compressor exit total temperature
- High pressure turbine exit static pressure
- High pressure turbine exit total temperature

More information on these measurements locations and instrumentation adaptors has been previously reported by the authors[28].The annular cross-section flow areas at the different axial locations along the engine were used to derive static condition from total condition for various parameters. The static parameter at the location is calculated iteratively from the mass flow rate, cross section flow area and total parameters at the location following the methodology presented in Fletcher[23].

4.2 Control System

The engine has a hydro-mechanical control system. The engine maintains different set parameters (such as RPM, jet pipe temperature and turbine pressure ratio) at different levels, based on the engine inlet entry temperature of the air. One of the control modes is such that, when the temperature is between 15° C and 45° C, the control system maintains the low-pressure turbine exit temperature at a constant preset value. The variation of this value with reference to RPM is preprogrammed in the control system. The engine controls this T4 value by appropriately controlling the pressure ratio across turbine. The effector for controlling the pressure ratio across turbine is the exit area of the convergent nozzle. In this modeling work, only this control mode has been implemented as the test bed temperature neither exceeds 45° C nor falls below 15° C.

5. PARAMETER ESTIMATION

The design parameters of individual components such as compressors and turbines are required for modeling them. The methodology of modeling the individual components using enthalpy tracking approach is explained by Walsh[25] and is also presented by the authors[34-35]. In this approach, the working fluid is treated as a mixture of various gaseous species whose specific properties are functions of temperature. Using this approach automatically accounts for the change of gas properties due to composition change after combustor. A similar modeling approach is used by Ali[36] in exhaust gas re-ingestion study. Since the design parameters of the various components of legacy engines are not known to the end-user, the component parameters need to be estimated. For example, in the current work, while the overall pressure ratio of the engine is known, the pressure ratio of low pressure and high pressure compressors are not known individually. Several other parameters like the isentropic efficiency of the compressors and turbines are also not known. This problem is tackled using response surface analysis by Seetharama[37] wherein he uses outputs from multiple runs of the design point simulation model to generate the response surface. In this work, in order to estimate these parameters at design condition, optimization-based parameter estimation routine and a non-linear GPA based estimation routines are used because of their simplicity. These routines are used to estimate the parameters of the engine at design condition shown in Table 2.

Table 2. Design parameters to be estimated

Parameter	Symbol
Pressure ratio of low pressure compressor (lpc)	π_{lpc}
Pressure ratio of high pressure compressor (hpc)	π_{hpc}
Isentropic efficiency of low pressure compressor (lpc)	η_{lpc}
Isentropic efficiency of high pressure compressor (hpc)	η_{hpc}
Isentropic efficiency of high pressure turbine (hpt)	η_{hpt}
Isentropic efficiency of low pressure turbine (lpt)	η_{lpt}
Combustion efficiency	η_{burn}

When using non-linear GPA to obtain component parameters, we should recognise that this method provides acceptable estimates of the component values if the gas path measurements are accurate. The quantitative level of the errors in the estimates of the component values "is more or less similar to the measurement noise" of the gas path measurements, as described by Li[38].

5.1 Non-Linear Gas Path Analysis Based Parameter Estimation

The concept of using non-linear GPA for design point parameter estimation was initially applied to LM2500 engine by Li[32]. Non-linear GPA also finds use in prognostic approaches for quantifying component degradation, as shown by Li[38] using the model of Avon Mk 1535 engine. In brief, this procedure attempts to minimise the error between estimated gas path parameters and measured gas path parameters by estimating the component parameters such as pressure ratios and efficiencies. At each iteration, after omitting higher-order terms, the incremental changes in these component parameters can be obtained from the following Eqns. (1 and 2) where the influence coefficient matrix (ICM) is given by

$$\begin{bmatrix} P2 \\ T2 \\ P4 \\ T4 \end{bmatrix}_{exp} = \begin{bmatrix} P2 \\ T2 \\ P4 \\ T4 \end{bmatrix}_{\substack{current \\ sim}} + ICM * \begin{bmatrix} \Delta\pi_{lpc} \\ \Delta\pi_{hpc} \\ \Delta\eta_{lpc} \\ \Delta\eta_{hpt} \\ \Delta\eta_{lpt} \\ \Delta\eta_{burn} \end{bmatrix} \quad (1)$$

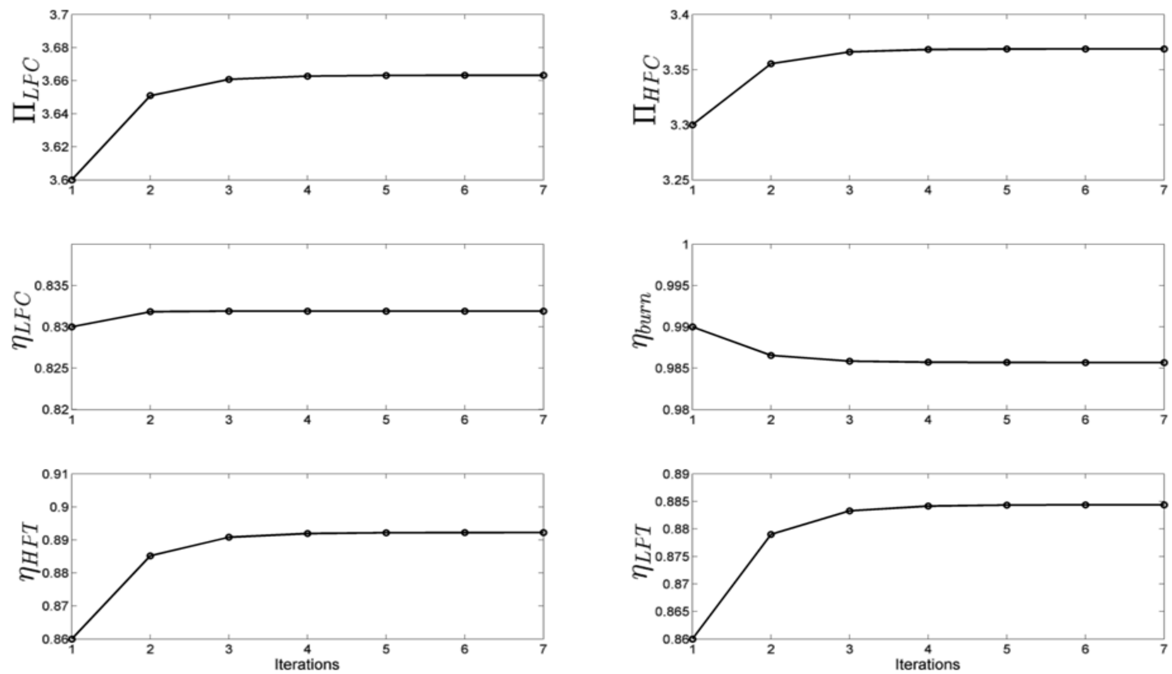

Figure 2. Convergence of component parameters.

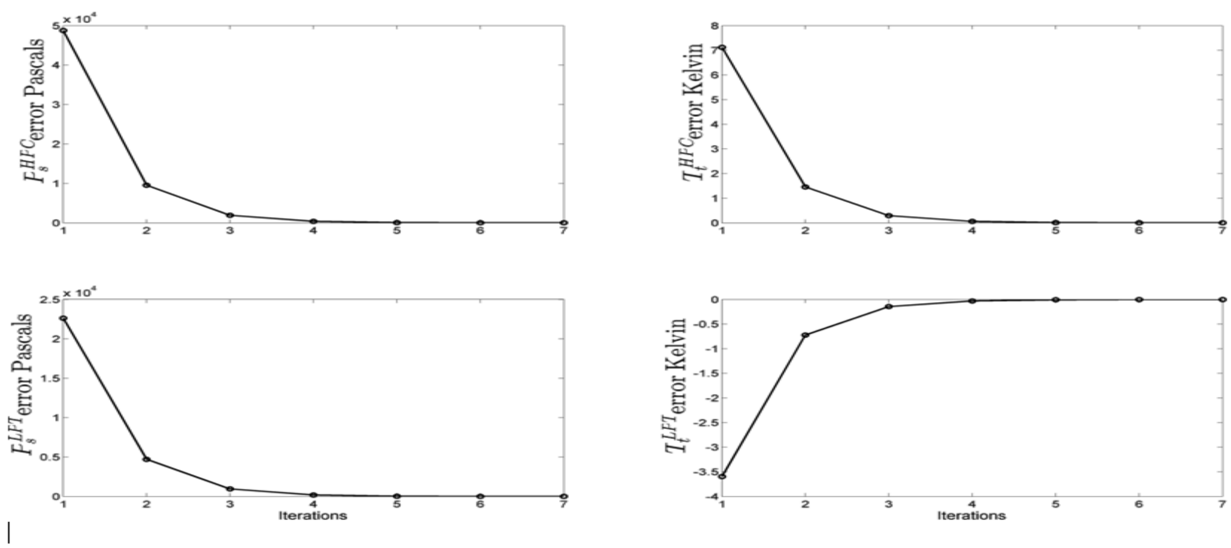

Figure 3. Reduction of error in each iteration.

$$\begin{bmatrix}\Delta\pi_{lpc}\\\Delta\pi_{hpc}\\\Delta\eta_{lpc}\\\Delta\eta_{hpt}\\\Delta\eta_{lpt}\\\Delta\eta_{burn}\end{bmatrix} = ICM'*\left(ICM*ICM'\right)^{-1}*\left(\begin{bmatrix}P2\\T2\\P4\\T4\end{bmatrix}_{exp} - \begin{bmatrix}P2\\T2\\P4\\T4\end{bmatrix}_{current\ sim}\right) \quad (2)$$

Some of the sensor measurements from the test bed such as fuel flow rate and air mass flow rate were given as input to the model so agreement of simulated data with these sensors is guaranteed. Ignoring the higher-order terms and computing the pseudo-inverse of the ICM matrix, gives the change in the assumed component parameters required to minimize the error as given in the following equation (3).

$$\begin{bmatrix}\Delta\pi_{lpc}\\\Delta\pi_{hpc}\\\Delta\eta_{lpc}\\\Delta\eta_{hpt}\\\Delta\eta_{lpt}\\\Delta\eta_{burn}\end{bmatrix} = ICM'*\left(ICM*ICM'\right)^{-1}*\left(\begin{bmatrix}P2\\T2\\P4\\T4\end{bmatrix}_{exp} - \begin{bmatrix}P2\\T2\\P4\\T4\end{bmatrix}_{current\ sim}\right) \quad (3)$$

The iterations are carried out until the successive changes in the component parameters become low enough. The decrease of error and the convergence of the parameters for a sample case is shown in Fig. 2 and 3.

5.2 Optimization-based Parameter Estimation

These unknown parameters can also be estimated using objective function minimization algorithms. By formulating the objective function as the error between the simulated and actual measurements and specifying this function as the function to be minimized, the component parameter set that minimizes this objective function can be obtained. The objective function used in this study is given below in Eqn. (4).

$$error = \left(\begin{matrix}\left|\frac{P2_{sim}-P2}{P2}\right| + \left|\frac{P4_{sim}-P4}{P4}\right|\\ +\left|\frac{T2_{sim}-T2}{T2}\right| + \left|\frac{T4_{sim}-T4}{T4}\right|\\ +\left|\frac{Th_{sim}-Th}{Th}\right|\end{matrix}\right) \quad (4)$$

For a given pilot input and ambient conditions, the pressure ratios and efficiencies of the various components of the engine are fixed. The temperatures and pressures along the engine can be given as a function of these pressure ratios and efficiencies as given below in Eqn. (5).

$$\begin{aligned}&\left[P2_{sim}, T2_{sim}, P4_{sim}, T4_{sim}, Th_{sim}\right]\\&= f(\pi_{lpc}, \pi_{hpc}, \eta_{lpc}, \eta_{hpc}, \eta_{hpt}, \eta_{lpt})\end{aligned} \quad (5)$$

It is important to scale the individual errors of thrust, pressure and temperature as the numerical magnitudes of pressure in Pascal is much higher than the magnitudes of temperature in Kelvin. A constrained non-linear minimization active-set algorithm of Matlab (2013b)® was used to do the minimization while design point simulation code was used to calculate the simulated measurements equation (5) and the objective function value as given in Eqn. (4). The estimated component parameters of the engine at design point are given in Table 3. The estimated component values using both the algorithms agree very closely with each other.

Table 1. Estimated component parameters

Parameter	Value
π_{lpc}	3.66
π_{hpc}	3.36
η_{lpc}	0.83
η_{hpc}	0.83
η_{hpt}	0.89
η_{lpt}	0.88
$\eta_{combustor}$	0.98

6. OFF DESIGN SIMULATION

The methodology followed in this work for off-design simulation is based on the one detailed by Walsh[25]. This approach has earlier been applied to a single spool engine[34] and a twin spool turbojet by the authors[39-40] wherein the limitations and assumptions used in the simulation model are discussed. A brief summary of the conventional approach is given below.

The key requirement for the off-design simulation is the component characteristics map of the engine components like compressors and turbines. In case these are not available, several methods exist to obtain them by scaling maps of engine similar to the target engine[35]. In the conventional approach, the three parameters that determine the operating point of a twin-spool engine are the operating point of low pressure and high pressure compressor (β_{lpc}, β_{hpc}) and the main burner fuel flow rate ($\dot{m}_f$). This operating vector is given as $\left[\beta_{lpc}\ \ \beta_{lpc}\ \ \dot{m}_f\right]^T$. The three errors that have to be minimised in order to obtain the operating vector are mass flow errors at high pressure and low pressure turbines ($\dot{m}_{hpt}^{error}, \dot{m}_{lpt}^{error}$) and nozzle $\dot{m}_{nozzle}^{error}$. This error vector is given as $\left[\dot{m}_{hpt}^{error}\ \ \dot{m}_{lpt}^{error}\ \ \dot{m}_{nozzle}^{error}\right]^T$. A damped Newton-Raphson iterative scheme is used to find the operating vector to minimize the error vector. The Jacobian matrix, which gives the variation of error with respect to operating vector, is re-evaluated during each iteration due to the non-linearity of the problem.

$$\begin{bmatrix}\frac{\partial\dot{m}_{hpt}^{error}}{\partial\beta_{lpc}} & \frac{\partial\dot{m}_{hpt}^{error}}{\partial\beta_{hpc}} & \frac{\partial\dot{m}_{hpt}^{error}}{\partial\dot{m}_f}\\ \frac{\partial\dot{m}_{lpt}^{error}}{\partial\beta_{lpc}} & \frac{\partial\dot{m}_{lpt}^{error}}{\partial\beta_{hpc}} & \frac{\partial\dot{m}_{lpt}^{error}}{\partial\dot{m}_f}\\ \frac{\partial\dot{m}_{nozzle}^{error}}{\partial\beta_{lpc}} & \frac{\partial\dot{m}_{nozzle}^{error}}{\partial\beta_{hpc}} & \frac{\partial\dot{m}_{nozzle}^{error}}{\partial\dot{m}_f}\end{bmatrix}\begin{bmatrix}\beta_{lpc}\\\beta_{hpc}\\\dot{m}_f\end{bmatrix} = \begin{bmatrix}\dot{m}_{hpt}^{error}\\\dot{m}_{lpt}^{error}\\\dot{m}_{nozzle}^{error}\end{bmatrix} \quad (6)$$

6.1 Limitations in the Conventional Approach

In this conventional approach, it is assumed that the exhaust area of the jet nozzle is known for each RPM setting. The exhaust area is required to calculate the $\dot{m}_{nozzle}^{error}$ term of the error vector. For the simulation of an ideal engine, where the nozzle area follows the pre-determined relationship with engine RPM, this approach does not lead to any problems. The nozzle area variation with RPM can be obtained from the test bed measurements or from the operating manual of the engine. This area can then be used to calculate the error term $\dot{m}_{nozzle}^{error}$ between the mass flow rate supplied from the low-pressure turbine and the mass flow rate that satisfies the static properties and exit area of the nozzle.

This approach does not lead to any problems when the simulations are done for the ideal engine condition, where the nozzle area variation with RPM follows the relationship given in the operating manual. However, as the engine deteriorates with usage, the nozzle area does not follow the schedule given in the operating manual. The control system of the engine is usually set to maintain a given performance parameter (such as turbine pressure ratio or compressor pressure ratio) of the engine at a scheduled value for each RPM. Thus, even though the engine deteriorates, the control system adjusts the values of the nozzle area and fuel flow rate in order to maintain the performance parameter at the scheduled value. Also, the limiting circuits of the engine continuously monitor for limit crossing of turbine exit temperature, engine RPM and compressor exit pressure. Thus, for a degraded engine, the nozzle area schedule with RPM may not follow the relationship as that of an ideal engine. One way to account for degradation will be to run the off-design simulation in an iterative manner, tweaking the nozzle area schedule and fuel flow rate schedule until the desired performance parameter is achieved.

6.2 Modified Simulation Methodology

In this modified simulation methodology, control setting of the engine is taken into account directly in the iteration scheme to evaluate the operating vector $\begin{bmatrix}\beta_{lpc}\\ \beta_{hpc}\\ \dot{m}_f\end{bmatrix}$. When the engine control system is trying to maintain constant turbine outlet temperature, it is proposed that the difference between the current T4 and the expected T4 ($T4_{lpt}^{error}$) be used in the error vector in place of $\dot{m}_{nozzle}^{error}$. The nozzle area can then be arrived at by calculating the nozzle throat area required for ingesting the mass flow rate supplied by the low pressure turbine. Hence for this control setting, the iterative scheme can be re-written as in (7)

$$\begin{bmatrix}\frac{\partial \dot{m}_{hpt}^{error}}{\partial \beta_{lpc}} & \frac{\partial \dot{m}_{hpt}^{error}}{\partial \beta_{hpc}} & \frac{\partial \dot{m}_{hpt}^{error}}{\partial \dot{m}_f}\\ \frac{\partial \dot{m}_{lpt}^{error}}{\partial \beta_{lpc}} & \frac{\partial \dot{m}_{lpt}^{error}}{\partial \beta_{hpc}} & \frac{\partial \dot{m}_{lpt}^{error}}{\partial \dot{m}_f}\\ \frac{\partial T4_{lpt}^{error}}{\partial \beta_{lpc}} & \frac{\partial T4_{lpt}^{error}}{\partial \beta_{hpc}} & \frac{\partial T4_{lpt}^{error}}{\partial \dot{m}_f}\end{bmatrix}\begin{bmatrix}\beta_{lpc}\\ \beta_{hpc}\\ \dot{m}_f\end{bmatrix}=\begin{bmatrix}\dot{m}_{hpt}^{error}\\ \dot{m}_{lpt}^{error}\\ T4_{nozzle}^{error}\end{bmatrix} \tag{7}$$

In addition to this, when the control loop maintains a constant turbine pressure ratio instead of constant turbine outlet temperature, the operating vector can be found using the following iterative scheme (8).

$$\begin{bmatrix}\frac{\partial \dot{m}_{hpt}^{error}}{\partial \beta_{lpc}} & \frac{\partial \dot{m}_{hpt}^{error}}{\partial \beta_{hpc}} & \frac{\partial \dot{m}_{hpt}^{error}}{\partial \dot{m}_f}\\ \frac{\partial \dot{m}_{lpt}^{error}}{\partial \beta_{lpc}} & \frac{\partial \dot{m}_{lpt}^{error}}{\partial \beta_{hpc}} & \frac{\partial \dot{m}_{lpt}^{error}}{\partial \dot{m}_f}\\ \frac{\partial \frac{P2}{P4}^{error}}{\partial \beta_{lpc}} & \frac{\partial \frac{P2}{P4}^{error}}{\partial \beta_{hpc}} & \frac{\partial \frac{P2}{P4}^{error}}{\partial \dot{m}_f}\end{bmatrix}\begin{bmatrix}\beta_{lpc}\\ \beta_{hpc}\\ \dot{m}_f\end{bmatrix}=\begin{bmatrix}\dot{m}_{hpt}^{error}\\ \dot{m}_{lpt}^{error}\\ \frac{P2}{P4}^{error}\end{bmatrix} \tag{8}$$

7. VALIDATION

The comparison of simulated sensor measurements with OEM sensor measurements from test-bed is used to validate the simulation methodology. Actual sensor data, simulated sensor data (using conventional methodology) and the simulated sensor data (using modified methodology) are superimposed in Fig. 6 and Fig. 7. The "y" axis of the plots is normalized in order to withhold the actual performance data of the engine. The mean absolute percentage error (MAPE) value is calculated between simulated value and measured value for each parameter from 75 per cent to 100 per cent of N1 RPM. These calculated MAPE values are indicated in the individual plots.

In these plots, it can be clearly seen that at 100 per cent RPM, there is a steep increase in the performance of the engine. This engine has a special control mode at which the system increases the fuel supply markedly once the engine reaches 100 per cent RPM while reducing the nozzle throat area as shown in Fig. 4.

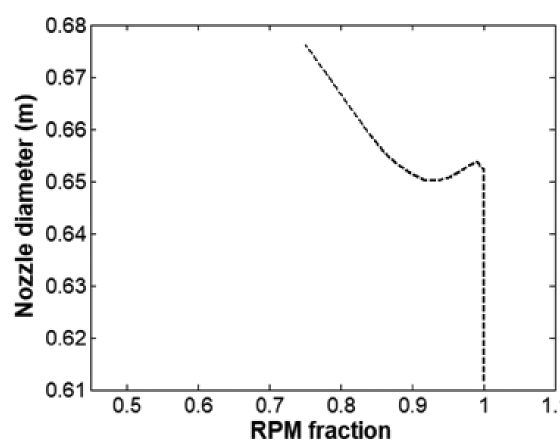

Figure 4. Nozzle throat area variation with RPM fraction.

The LP spool RPM is held constant during this fuel increase. Since the engine cannot run at state in which RPM is 100% but fuel increase and nozzle throat area decrease have not yet happened, there are no experimental data points at this state. All the data points available at 100% RPM are those that were measured after the fuel increase has taken place. This increase in fuel supply can be clearly seen in Fig 5.

As a result, there is a steep increase in the turbine exit temperature as shown in Fig. 6 (a). Such a marked increase in turbine exit temperature and pressure improves the thrust of the engine, which is the objective of fuel flow increase. Since the mass flow of the engine and the rpm is not changed much as shown in Fig. 6(b), the compressor exit conditions are not markedly different from the expected state where the engine is 100 per cent RPM but without fuel increase. The compressor exit conditions are shown in Fig. 6(c) and Fig. 6(d).

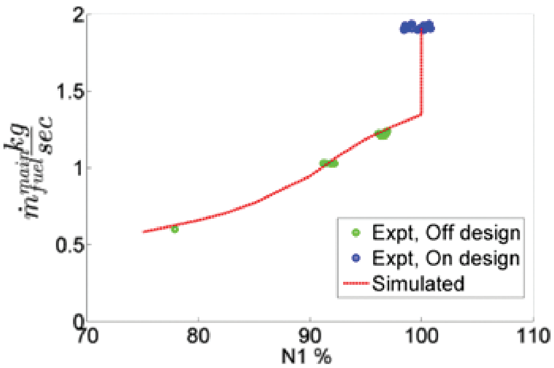

Figure 5. Simulation validation using fuel flow rate.

8. DEGRADATION SIMULATION USING A MODIFIED METHODOLOGY

It has been shown that, for the benchmark engine case, the results of the modified simulation scheme match with conventional simulation scheme and they both closely agree with the experimental data obtained from the test bed. In this section, the advantages of using the modified scheme over the conventional scheme in degradation simulation are presented.

Consider the performance analysis of a degraded engine in which the high pressure compressor efficiency has decreased by 3% from design condition. In the simulation, in order to simulate this reduction in efficiency, the efficiency characteristics map has been scaled down by 3 per cent. This methodology is similar to the compressor fouling simulation carried out by He Xing[41]. The turbine exit temperature is controlled to remain at the set point, as dictated by the control system and limiter. It is common for engine designers to limit the turbine exit temperature at higher ratings in order to extend the life for the blades. Figure 7 shows the results of this degradation simulation. In these plots the simulation performed for the degraded engine using the conventional methodology without T4 control is called

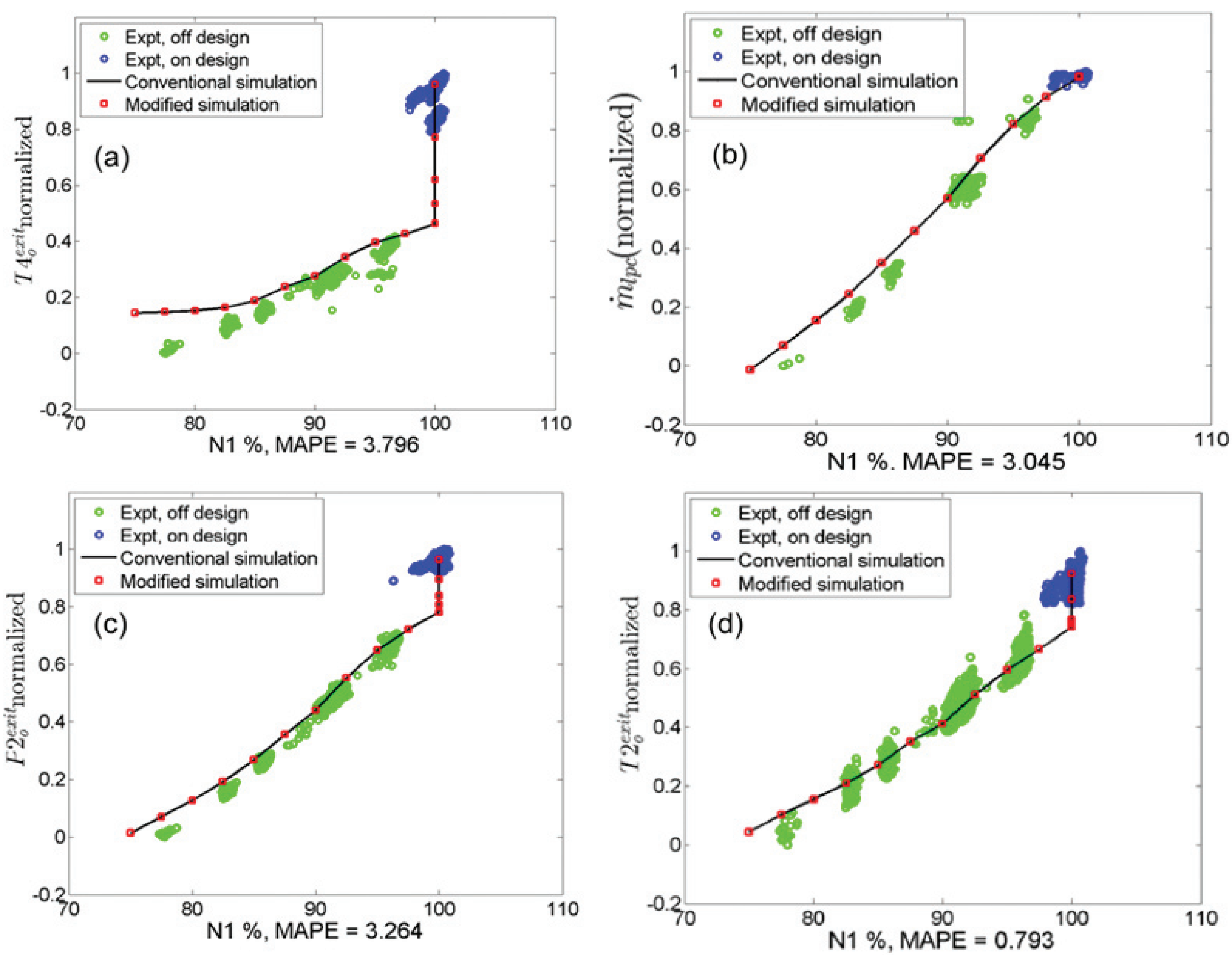

Figure. 6 Simulation validation using: (a) LPT exit temperature, (b) air mass flow rate, (c) HPC exit pressure and (d) HPC exit temperature.

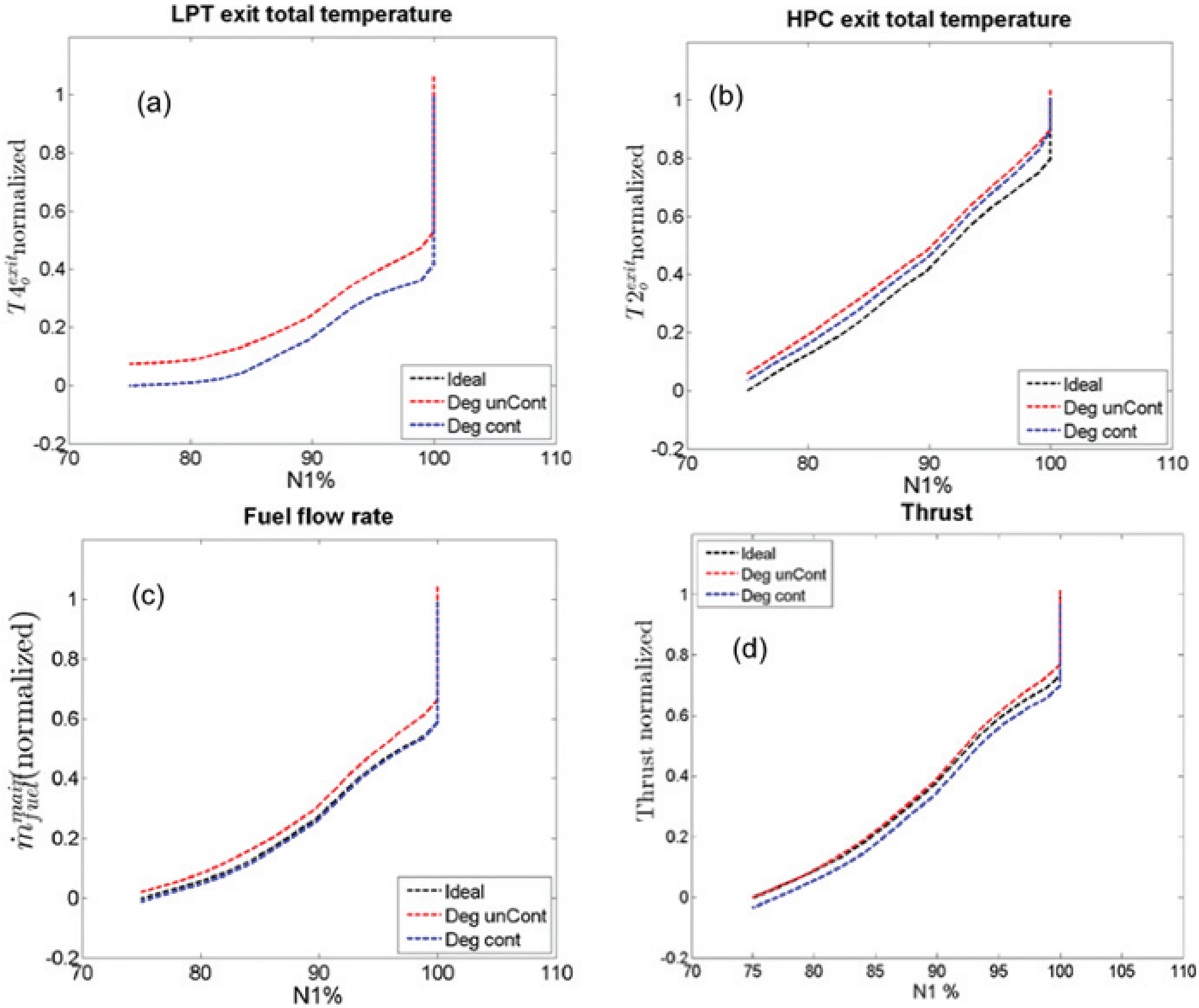

Figure 7. Degraded condition simulation: (a) LPT exit temperature variation with RPM, (b) HPC exit temperature variation with RPM, (c) main burner fuel flow rate variation with RPM and (d) thrust variation with RPM.

as "Deg unCont" (Degraded, un-controlled). The simulation done with the T4 control incorporated in the iterative scheme is called as "Deg cont"(Degraded, controlled). Figure 7(a) shows that the controlled degraded engine maintains the same turbine exit temperature as the ideal engine and the T4 curve of "controlled degraded" engine is identical to the T4 curve of the ideal engine. The T4 value of un-controlled degraded engine is higher than that of the ideal engine and the controlled degraded engine. The un-controlled degraded engine is not a realistic simulation case as increases in turbine exit temperature is not allowed by the limiter in order to ensure required turbine blade life. Due to degradation in the efficiency of the compressor, both the conventional and modified methodologies show an increase in the compressor exit temperature as shown in Fig 7(b). Figure 7(c) shows that the fuel flow rate is marginally lower for the degraded controlled engine compared to the ideal engine. This is partly because of the higher inlet temperature to the combustor, for the same turbine outlet temperature. Consequently, the thrust force delivered by the engine has also reduced when compared to the ideal engine, as shown in Fig 7(d).

However, in the uncontrolled simulation, the thrust of the degraded engine is shown to be higher than that of the ideal engine. Even though the work required by the compressor has increased due to the decreased efficiency, the inlet temperature of the turbine has also increased, and hence the pressure drop across the turbine is reduced for the work required by the compressor. Thus, due to this lower pressure drop across the turbine, turbine exit pressure is higher than the ideal engine case, giving increased thrust than the ideal engine case.

9. CONCLUSION

This paper presented the use of non-linear GPA and optimization-based parameter estimation methods for estimation of the component parameters of a legacy twin-spool engine from gas path measurements available from the test bed. A conventional off-design simulation model was developed for this engine and the output of the simulation model was compared to test bed measurements and validated. A modified scheme that also incorporates the control setting and limiter of the engine was presented and its output was also compared to the conventional simulation model and test bed measurements.. Both conventional and modified mathematical models were used to simulate the degraded engine condition and it is shown that the modified simulation model represents the operation of the degraded engine more realistically than the conventional scheme.

A mathematical model for the engine developed using this methodology for the degraded engine for its various controlled parameters will enable the diagnosis of the degradation in the engine more accurately. The sensor signature when the engine is maintaining constant P2/P4 pressure ratio will be different compared to the sensor signature when the engine is maintaining constant T4 temperature. Knowing the control mode of the engine and by modeling using this methodology, the degraded component and its extent of degradation can be identified without multiple runs to match the controlled parameter, as it is matched inherently in this approach. For engines under development, this modeling approach enables the preparation of a design database that enumerates the component degradation possibilities for various sensor signatures under different control modes of the engine, depending on operating conditions.

In further work, the simulation model will be improved to account for multiple control settings in addition to constant turbine exit temperature mode.

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