DESIGN POINT PARAMETER ESTIMATION OF A LEGACY TWIN SPOOL TURBOJET ENGINE FOR HEALTH MONITORING

Balaji Sankar; Brijeshkumar Shah; Soumendu Jana; Ramamurthy Srinivasan
CSIR National Aerospace Laboratories (NAL)
HAL Airport Road, Post Box No. 1779
Bangalore-560 017, India
Email : balajis_dd@nal.res.in; shahbrij@nal.res.in; sjana@nal.res.in; ramamurthy@nal.res.in

R. K. Satpathy; G. Gouda
Regional Center for Military Airworthiness (RCMA)
HAL Koraput Engine Division
Orissa, India
Email : rd_koraput@rediffmail.com; g.gouda@cemilac.drdo.in

Abstract

The estimation of component parameters of a twin spool turbo jet engine at design point is presented in this paper. Non-linear gas path analysis combined with constrained optimization based technique has been used for the estimation of the engine component parameters and overall performance of the engine. This work needs to be done as the engine manufacturer does not provide these details when supplying the engine to the user. The parameters estimated are pressure ratios and efficiencies of various components such as compressor, turbine and combustor. Parameters estimated were given as input to the simulation model and the error was calculated between simulated gas path parameters and experimental data collected from the engine test bed. It is observed that the simulation results, obtained with estimated parameters, agree closely with experimental data.

Keywords: Aero thermodynamic model; Twin spool turbo jet engine; Non-linear gas path analysis; Optimization; Parameter estimation

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>EHM</td>
<td>Engine health monitoring system</td>
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<td>MBD</td>
<td>Model based diagnostics</td>
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<td>DP</td>
<td>Design point</td>
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<td>T</td>
<td>Total temperature (K)</td>
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<td>P</td>
<td>Static pressure (Pascal)</td>
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<td>Th</td>
<td>Thrust (kN)</td>
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<td>CP</td>
<td>Specific heat at constant pressure</td>
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<td>CD</td>
<td>Coefficient of discharge</td>
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<td>PI</td>
<td>Pressure ratio</td>
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<tr>
<td>ηi</td>
<td>Isentropic efficiency</td>
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<tr>
<td>m</td>
<td>Mass flow rate</td>
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<td>RPM</td>
<td>Rotation per minute</td>
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<tr>
<td>Sim</td>
<td>simulated gas path measurement</td>
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<tr>
<td>Expt</td>
<td>Experimental value</td>
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<tr>
<td>LPC</td>
<td>Low pressure compressor</td>
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<tr>
<td>HPC</td>
<td>High pressure compressor</td>
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<tr>
<td>HPT</td>
<td>High pressure turbine</td>
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<tr>
<td>LPT</td>
<td>Low pressure turbine</td>
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</table>

Subscripts

- 2 = High pressure compressor exit station
- 4 = Low pressure turbine exit station

Introduction

Model based engine health monitoring systems heavily rely on aero-thermodynamic performance analysis model of the engine. This model is used to obtain the performance of the engine concerned at various operating conditions of the aircraft mission and operator inputs. Typically, in the initial conditions, the healthy condition is modeled. Fig.1 shows the scheme of the Model Based Diagnostics (MBD) methodology. This scheme is similar to the scheme attempted by Diao, presented in Ref.[1]. The input values supplied to the performance model are the

same as that of the inputs given to the engine on the fixed engine test bed. For an ideal engine, the output of the performance model and the measurements from the test bed will match. With usage of the engine, the condition of the engine components degrades, as described by Fasching in Ref.[2]. Due to this degradation, performance of the used engine does not match the prediction by performance model. The residuals between the performance prediction and actual measurement are used to analyze the deterioration of components. Several artificial intelligence based methods have been used to analyze these residuals and predict the degradation in the engine.

The development of engine performance model has been covered in great detail in several text books like [3, 4 and 5]. A detailed survey of the engine simulation models for both control system design and monitoring purposes has been presented by Sanghi in Ref. [6]. In order to make an engine performance model, the design point values of the various components such as low pressure compressor pressure ratio ($\pi$) and efficiency ($\eta$) are required. These parameters are not usually provided by engine manufacturer to the user. Unavailable major parameters of the engine have to be determined by the user from the available test bed measurements through various parameter estimation algorithms. In Ref.[7], a software tool called PYTHIA has been used to estimate the design point of the LM2500 turbine engine, manufactured by GE. This work used the non-linear gas path analysis algorithm for the design point estimation, presented by Li in Ref. [8]. Other techniques that are also being used to estimate these parameters are:

- Kalman filter based linear and non-linear approaches
- Genetic algorithm based approaches
- Fuzzy logic
- Bayesian belief networks

A brief summary of these techniques for parameter estimation has been presented by Marinai in Ref. [9].

This paper presents the parameter estimation activities done in order to obtain the component parameters of a twin spool turbo jet engine, shown in Fig.2. The objective of finding these component parameters is to analyze the on-design, off design and transient behavior of the engine as a part of engine Health Monitoring Module (EHM) development for this engine. The primary aim of the EHM module development is to estimate the performance degradation of this legacy engine. This engine was developed in the early 1970’s in Russia and represents 2nd level of technology in the gas turbine component design progress, according to Mattingly [10].

Complete validation of the estimated parameters requires validation in both on design and off design conditions. In this work, only the design point parameters are estimated and the parameters are validated too at design point only. The design point estimation is done first because:

- As detailed by Li in Ref. [8], the estimation of current design point parameters is the first step in identifying the degradation that has happened in the engine. To workout off design condition performance, the component characteristic maps are required, which are not given by the manufacturer. Hence available maps are typically scaled using the reference values. This design point estimation work, gives us the reference values to use in the scaling of characteristic maps.

- Further, the user of the gas turbine has certain component parameters available at the design point of the engine, such as overall pressure ratio of the compressor. The performance of the engine is also standardized at design point and also checked experimentally during overhaul of the engine by certifying agency. Such design information and experimental data is not available at off design ratings for these legacy engines. Hence, the design point parameter estimation is presented here first. In the next stage of this work, off design parameter estimation will be presented.

In this work, the Non-Linear Gas Path analysis has been used in combination with constrained optimization based parameter estimation algorithm to estimate the parameters. Traditionally either of these 2 approaches has been used individually for estimation. The difference in the present work is that the two approaches are combined in the parameter estimation at design point. By using the two techniques in combination, we gain a significant advantage. The NLGPA provides a viable start location for the search algorithm, whose output can be considered as a benchmark. Also by using multiple random starting points in addition to the starting point provided by NLGPA, we reduce the probability of getting stuck in local minima during the parameter estimation.
Assumptions

In a typical estimation problem the number of parameters that have to be estimated is usually much larger than the number of measurements available due to limited measurement locations provided by the manufacturer. Due to this, several minor parameters like duct pressure losses have to be assumed by the user and cannot be estimated. These assumed values affect the values that are being estimated to a limited extent. Hence, it is important to obtain the best available estimate of these assumed parameters based on the available data and past experience.

In this estimation study too, the number of parameters to be estimated (16), is a lot more than the number of measurements available (6). Hence only the major parameters are estimated and the minor parameters such as spool mechanical efficiencies and duct losses are assumed. Major parameters are those parameters whose influence on measured parameters is large, compared to minor parameters. The measured parameters and major parameters that are estimated in this study are shown in Table-1.

The following sections describe the process of obtaining estimates that serve as initial assumptions for the estimation of major parameters.

Compressor Pressure Ratio

The overall pressure ratio of the engine considered for the study is approximately 12.2. However models require the pressure ratios of individual LPC and HPC components. If the number of stages of LPC and HPC are known, an approximate value of the LPC pressure ratio can be obtained from the chart between number of stages in the compressor and its pressure ratio given by Walsh and Fletcher in Ref.[5]. HPC pressure ratio can then be obtained from LPC pressure ratio and overall pressure ratio, which is usually specified by the manufacturer. HPC pressure ratio is usually lower than the LPC pressure ratio when number of stages in LPC and HPC are nearly same. This is in part due to the higher inlet temperature to the HPC. Using this information, initial assumption of LPC and HPC pressure ratios were assumed as 3.6 and 3.38 respectively.

Compressor Isentropic Efficiency

Compressor isentropic efficiency is a key parameter used in the calculation of compressor exit temperature and work to be produced by turbine. An approximate value of the isentropic efficiencies of the 5 stage LPC and the 6 stage HPC are thus required.

LPC Efficiency Estimate

While estimating the LPC efficiency, two assumptions about the distribution of work done among the stages can be made:

- Assuming equal rise of temperature across the stages as given in the design process in Ref.[3].
- Assuming equal pressure ratio across the stages.

<table>
<thead>
<tr>
<th>Table-1 : Parameters of the Performance Model</th>
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<tr>
<td>Parameters</td>
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<tr>
<td>Π LPC</td>
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<td>Π HPC</td>
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<tr>
<td>η LPC</td>
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<tr>
<td>η HPC</td>
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<tr>
<td>η HPT</td>
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<tr>
<td>η LPT</td>
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<tr>
<td>η burner</td>
</tr>
</tbody>
</table>

\[
\text{State loading} = \frac{C_p \Delta T}{\text{rotor peripheral speed}}
\]  

(1)

This moderate stage loading gives a polytropic efficiency of 0.87 according to the trend between stage loading and efficiency [5]. The isentropic efficiency can then be obtained from the polytrophic efficiency, from LPC
pressure ratio and the formula from Ref.[3], shown in Eqn.(2).

\[ \eta_{\text{isentropic}} = \frac{\pi \left( \frac{v - 1}{v} \right) - 1}{\pi \left( \frac{v - 1}{v} \eta_{\text{polytropic}} \right) - 1} \]  

Thus the isentropic efficiency of LPC is estimated as 0.845 using this assumption.

**Case 2 : Equal Pressure Ratio:** For an overall assumed pressure ratio of 3.6 for the LPC with 5 stages, pressure ratio per stage is 1.29. Assuming a polytropic efficiency, a common isentropic efficiency is found for all the stages. Using the individual isentropic efficiencies and individual inlet conditions of each stage, the exit condition of each stage is computed. The initially assumed polytropic efficiency is iterated until the overall temperature rise across the LPC is 130 Kelvin. In this approach, the obtained polytropic efficiency for the individual stages is 0.97. This value is unrealistic for the compressor, because even for a technology level of 4, the maximum polytropic efficiency of the compressor Is 0.90. Hence this assumption is not used.

**HPC Efficiency Estimate**

In a similar way, HPC isentropic efficiency was estimated as 0.846. The polytropic efficiencies of LPC and HPC seen in this engine correspond to technology level 2 as suggested by Mattingly [10]. These values correspond to the period of design of this engine and therefore add to the confidence in our estimates of efficiencies.

**Combustion Efficiency**

Combustion efficiency shows strong correlation with combustor loading and fuel to air ratio [5]. The combustor loading formula shown in Eqn.(3) is used to calculate the loading of the combustor. The enclosed volume used in this formula is the volume enclosed by the can without the outer annulus, which is approximately 0.15 m³.

\[ \text{Combustor Loading} = \frac{m}{\text{volume} \times P^{1.8} \times \frac{\Delta T_{\text{HPT}}}{400} + \frac{C_{\text{pg}} \cdot 10^{0.0145 \times (T - 400) \times 1.861}}{\text{kg} \cdot \text{m}^2}} \]  

Low values of combustor loading improve combustion efficiency and make designing the combustor relatively easier. For an inlet pressure of ~12.2 atm, and an approximate mass flow ~105 kg/s, inlet temperature of ~650 Kelvin, the loading on the combustor is 3.305. For this loading, the combustion efficiency can be between 98% and 99%, as given in the trend between combustor loading and efficiency [5].

**Combustor Pressure Loss**

Combustor pressure loss decreases the total pressure of air entering the turbine. Hence, for a same work output by the turbine, the pressure drop across the turbine is higher. This loss is usually 2 to 8% of the combustor entry static pressure, as given by Boyce in Ref.[11].

**Inlet Pressure Loss**

According to MIL 5008B, for subsonic inlets, the ram recovery factor can be assumed as 1 as given in [4]. Further, there is a total pressure loss in the inlet, which is a function of Mach number at the entrance to the inlet. The cross section area of the inlet is approximately 0.5 sq. m, into which the air flows at a rate of ~105 kg/sec. Since the air accelerates from stagnation into the mouth of the engine in the ground based test bed, the static pressure and density are lower than atmospheric values. These conditions at inlet, give a Mach number of 0.5 at the inlet. The pressure loss for this Mach number is obtained from Ref.[4] as 0.98.

**HPT Efficiency Estimate**

An upper and lower bound to the efficiency of axial flow turbines can be estimated from the loading and velocity ratio of the turbines. As already detailed in the compressor part, loading estimation requires blade tangential speed at mean line and the temperature drop across turbine. The temperature drop can be obtained from energy balance between HPC and HPT. Blade speed of turbine can be estimated in a way similar to that of compressor. The loading of the turbine is given by Eqn. (4) as

\[ \text{loading} = \frac{C_{\text{pg}} \cdot \Delta T_{\text{HPT}}}{P^{1.8} \times \frac{U^2}{\text{kg} \cdot \text{m}^2}} \]  

Where \( C_{\text{pg}} \) denotes the specific heat of combustion products. The velocity ratio at the entry to HPT was found as 0.48 from the Eqn.(5).
velocity ratio $= \frac{V_{axial}}{U}$ \hspace{1cm} (5)

For a loading of 1.861 Joules $s^{-2} kg^{-1}$ and a velocity ratio of 0.48, the turbine efficiency can be obtained from the Swindell’s chart as 0.89. As given in Ref.[5], this value should be taken as the upper limit since it does not account for losses due to tip clearance, windage and cooling air flow. A lower estimate of this efficiency is taken 3 points lower, at 0.86.

LPT Efficiency Estimate

The LPT efficiency is estimated to be in the range 0.925 to 0.895, in a manner similar to the HPT efficiency estimate.

Nozzle Characteristics

The two main parameters that specify the performance of the convergent nozzle are co-efficient of discharge and the coefficient of thrust. Coefficient of discharge is the effective flow area of the nozzle divided by the geometric flow area. The reduction is primarily due to boundary layer growth and separation of flow at the wall. Since the nozzle of this engine is a convergent type, separation of flow at the imperfections in the nozzle surface affects CD to a lesser extent than it would affect a convergent divergent nozzle. This discharge coefficient is mainly a function of pressure ratio across the nozzle and the nozzle cone half angle for a convergent nozzle. For a nozzle expansion ratio of 2.8, discharge coefficient is between 0.93 and 0.97. This value is taken from the relation between nozzle expansion ration and $C_D$ value, given in Ref. [5]. Ref. [4] also gives a relation between $C_D$ and nozzle cone half angle. Cone half angle is calculated as 20 degrees for the design condition of this engine, at which exit area of the nozzle is its lowest. For twenty degree half angle convergent nozzle, the coefficient of discharge is approximately 0.96. The thrust coefficient is also a function of nozzle pressure ratio and is estimated as 0.98 from Ref. [5].

Mechanical Efficiency of Power Transmission

The mechanical efficiency of transmission of power from turbine to compressor accounts for loss of power in the bearings and seals. It also usually made to include the gear box losses. Though empirical relations are available for ball bearings and roller bearings taking both radial and thrust loads, these correlations require the diameter of the shaft at bearing location and oil flow rate to the bearings. In the absence of this information, the mechanical efficiency of the system as whole is assumed to be 99%, according to Ref.[5].

Preliminary Estimates

A summary of the initial estimates of the major parameters and assumed minor parameters is presented in Table-2. These initial values are used in the estimation of major parameters using nonlinear GPA and optimization based methods.

Parameter Estimation

Once the assumptions for the component parameters have been made from the available information, the major component parameters should be tuned further. When these tuned parameters are later used in the simulation, the simulation results will tend to have a close agreement with experimental data.

Non-linear gas path analysis and constrained optimization based algorithms have been implemented and are described below after describing the error evaluation function. Both non-linear GPA and constrained optimization based approaches have similar goals. The goal of both the approaches is to minimize the difference between simulated gas path measurements and experimental values.

<table>
<thead>
<tr>
<th>Table-2 : Initial Estimates for Major Parameters and Assumed Minor Parameters</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Inlet Pressure Ratio</td>
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<tr>
<td>$\Pi_{LPC}$</td>
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<tr>
<td>$\eta_{LPC}$</td>
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<td>$\Pi_{HPC}$</td>
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<tr>
<td>$\eta_{HPT}$</td>
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<tr>
<td>$\Pi_{LPT}$</td>
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<tr>
<td>Nozzle thrust coefficient</td>
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<tr>
<td>Nozzle discharge coefficient</td>
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<tr>
<td>Mechanical spool efficiency</td>
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<tr>
<td>Power take off from HP spool</td>
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</table>
Optimization Based Parameter Estimation

For a given inputs and ambient conditions along with the assumed component parameters, the errors can be evaluated as shown in the flow chart given in Fig.3 and described in the following section on Error Evaluation.

Objective Function Evaluation

The objective function is estimated using the differences between the output of the simulation and the experimental test bed values. These differences could be due to

- Any physical phenomena in the engine that is not sufficiently modeled in the simulation.
- Any errors in the experimental sensor or calibration.

For purposes of this work, it is assumed that the aero-thermodynamic simulation model is satisfactory and the errors in sensors and calibration are negligible. As a result, any discrepancies between the simulation model output and the experimental values are due to the inexact component parameters being used in the simulation model. These discrepancies are evaluated for the following measurements for which experimental values are available:

- HPC exit static pressure
- HPC exit total temperature
- LPT exit static pressure
- LPT exit total temperature
- Thrust

Since the engine was instrumented with static pressure sensors rather than total pressure sensors, the error evaluation is done with static pressure sensors only. The simulated gas path measurements are obtained from the simulation model. An enthalpy function based aero-thermodynamic simulation model has been developed for this purpose, which is described in Ref.[12, 13 and 14]. This model, at design point, also calculates the simulation error by comparing simulation output to the experimental measurements. Once the simulation error is computed, for the optimization based approach, the objective function is written as follows in Eqn.(6).

\[
\text{Objective function} = \left( \frac{P_2^{\text{sim}} - P_2}{P_2} + \frac{P_4^{\text{sim}} - P_4}{P_4} \right) + \left( \frac{T_2^{\text{sim}} - T_2}{T_2} + \frac{T_4^{\text{sim}} - T_4}{T_4} \right) + \left( \frac{T_h^{\text{sim}} - T_h}{T_h} \right)
\]

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.

The objective function is estimated for different values of parameters that are being estimated, which are

- \( \Pi_{\text{LPC}}, \eta_{\text{LPC}} \)
- \( \Pi_{\text{HPC}}, \eta_{\text{HPC}} \)
- \( \eta_{\text{LPT}}, \eta_{\text{HPT}} \)
- \( \eta_{\text{burner}} \)
- \( \Pi_{\text{AB}} \)

The five error terms vary wrt these estimated parameters. Since it is not possible to visualize these errors as a function of all the variables, the variation of each of the five error terms with respect to LPC parameters alone is shown in Fig.4. This figure shows the conflicting nature of the variation of errors. For example, as the LPC pressure ratio increases, the error in LPT exit temperature increases and error in LPT exit pressure decreases. The optimization algorithm finds a combination of component parameters that will minimize the objective function as a whole. A constrained non-linear minimization active-set algorithm of Matlab (Registered trademark of The MathWorks, inc) was used to do the minimization. In order to constrain the variables, limits were given as shown in Table-3. As mentioned in the Introduction section, the output of the NLGPA provides a viable start location for the search algorithm. Further, the additional starting points of the optimization based routine are also randomized.

Non-Linear Gas Path Analysis Based Parameter Estimation

The use of non-linear GPA for design point parameter estimation has been made for LM2500 engine by Li [12]. In brief, the procedure attempts to minimize the error
every iteration. The incremental changes in the component parameters can be obtained from the following Eqn.(7). In this equation HOTs refers to higher order terms.

\[
\begin{bmatrix}
  P_2^2 \\
  T_2^2 \\
  P_4^2 \\
  T_4^2
\end{bmatrix}_{\text{exp}} = \begin{bmatrix}
  P_2^2 \\
  T_2^2 \\
  P_4^2 \\
  T_4^2
\end{bmatrix}_{\text{current sim}} + ICM^* \begin{bmatrix}
  \Delta \pi_{\text{lpc}} \\
  \Delta \pi_{\text{hpc}} \\
  \Delta \eta_{\text{lpc}} \\
  \Delta \eta_{\text{hpc}} \\
  \Delta \eta_{\text{lpt}} \\
  \Delta \eta_{\text{hpt}} \\
  \Delta \eta_{\text{burn}}
\end{bmatrix} + \text{HOTs}
\]

(7)

Where the influence coefficient matrix (ICM) is given by

\[
ICM = \begin{bmatrix}
  \frac{\partial P_2^2}{\partial \pi_{\text{lpc}}} & \frac{\partial P_2^2}{\partial \pi_{\text{hpc}}} & \frac{\partial P_2^2}{\partial \eta_{\text{lpc}}} & \frac{\partial P_2^2}{\partial \eta_{\text{hpc}}} & \frac{\partial P_2^2}{\partial \eta_{\text{lpt}}} & \frac{\partial P_2^2}{\partial \eta_{\text{hpt}}} & \frac{\partial P_2^2}{\partial \eta_{\text{burn}}} \\
  \frac{\partial T_2^2}{\partial \pi_{\text{lpc}}} & \frac{\partial T_2^2}{\partial \pi_{\text{hpc}}} & \frac{\partial T_2^2}{\partial \eta_{\text{lpc}}} & \frac{\partial T_2^2}{\partial \eta_{\text{hpc}}} & \frac{\partial T_2^2}{\partial \eta_{\text{lpt}}} & \frac{\partial T_2^2}{\partial \eta_{\text{hpt}}} & \frac{\partial T_2^2}{\partial \eta_{\text{burn}}} \\
  \frac{\partial P_4^2}{\partial \pi_{\text{lpc}}} & \frac{\partial P_4^2}{\partial \pi_{\text{hpc}}} & \frac{\partial P_4^2}{\partial \eta_{\text{lpc}}} & \frac{\partial P_4^2}{\partial \eta_{\text{hpc}}} & \frac{\partial P_4^2}{\partial \eta_{\text{lpt}}} & \frac{\partial P_4^2}{\partial \eta_{\text{hpt}}} & \frac{\partial P_4^2}{\partial \eta_{\text{burn}}} \\
  \frac{\partial T_4^2}{\partial \pi_{\text{lpc}}} & \frac{\partial T_4^2}{\partial \pi_{\text{hpc}}} & \frac{\partial T_4^2}{\partial \eta_{\text{lpc}}} & \frac{\partial T_4^2}{\partial \eta_{\text{hpc}}} & \frac{\partial T_4^2}{\partial \eta_{\text{lpt}}} & \frac{\partial T_4^2}{\partial \eta_{\text{hpt}}} & \frac{\partial T_4^2}{\partial \eta_{\text{burn}}}
\end{bmatrix}
\]

(8)

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 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 Eqn.(9).

\[
A = ICM^* \ast (ICM \ast ICM^*)^{-1}
\]

The iterations are carried out until the successive changes in the component parameters become lower than the convergence limit specified. The decrease of error and the convergence of the parameters for a sample case are shown in Fig.5. The estimated component parameters of the engine at design point, estimated using a combination of NLGPA and optimization based scheme, are given in Table-4.

### Conclusion

When the estimated values of component parameters were used in the simulation model, the output of the simulation prediction and the experimental data agree with each other within 2% error as shown in column 3 of Table-5. The error in the experimental measurements is not considered during parameter estimation. The estima-

<table>
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<tr>
<th>Table-3 : Limits of Variables</th>
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<tr>
<td>( \Pi_{\text{LPC}} )</td>
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<td>( \eta_{\text{HPC}} )</td>
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<td>( \eta_{\text{LPT}} )</td>
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<tr>
<td>( \eta_{\text{burner}} )</td>
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<tr>
<td>( \Pi_{\text{AB}} )</td>
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<tr>
<th>Table-4 : Estimated Component Parameters</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>( \pi_{\text{LPC}} )</td>
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<td>( \eta_{\text{HPC}} )</td>
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<td>( \eta_{\text{LPT}} )</td>
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<td>( \eta_{\text{burner}} )</td>
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tion work has been done with the time averaged values of each of the sensor in during design point operation. To indicate the spread of the experimental values at design point, the standard deviation of each of the sensor measurement collected during the design point operation of the engine is shown in column 4 of the Table-5. The error value for each parameter shown in the table is estimated using the following Eqn.(10).

$$
Error = \frac{|Expt - Sim|}{Expt} \times 100
$$

This work has presented a methodology of obtaining initial estimates of the major parameters of a twin spool turbojet engine in the absence of such data from the OEM. Both Non-linear GPA and optimization based techniques have been used to further estimate the parameters of the twin spool gas turbine at design point. These estimated values of the parameters are based on several assumptions. The values of the parameters will change if the assumptions are changed. Hence it is important to make the best possible estimate of the assumed parameters. These assumptions can only be obtained from published literature and the justification for making the assumptions have been presented.

Next step in this direction would be to identify parameters at off design ratings of the engine and validate them.

### References


